Green Hydrogen & PtX-Training

Modules prepared by the International PtX Hub Berlin

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What is PtX?

Administrative overview & learning objectives

Learning period:
- Approx. 12 hours in total (facilitated sessions)
- Modular 2-3 day basic training

Technical/IT requirements:
Software – MS Teams
Audio – Headset
Internet – Recommended to use LAN for stable connection

At the end of the training, you will:
- know **key terminology related to H2/PtX**, understanding of context & recent developments
- have identified required **inputs & processes** for sustainable H2/PtX products
- have obtained the ability to **plan consistent decisions regarding H2/PtX projects**
- have identified & differentiated **central techno-economic criteria** on storage & transport of H2/PtX products
- be able to assess **applications & processes** as well as future usage options to substitute current fossil industrial processes
- have developed the ability to evaluate H2/PtX approaches in a **holistic approach** & understood the importance of sustainability criteria (EESG framework)
- have framed PtX projects & put them into larger contexts improving your ability to **market PtX projects**
- understand crucial starting points & instruments to **foster & regulate H2/PtX developments** from the political & institutional frame

Time Schedule – 2-Day Training:

Day 1	
60 min.	Module 1: Introduction
120 min.	Module 2: Production of Hydrogen & PtX
100 min.	Module 3: Hydrogen & PtX Economics
Day 2	
70 min.	Module 4: Hydrogen & PtX Infrastructure
70 min.	Module 5: Sector-specific Overview and Market Knowledge
80 min.	Module 6: Climate & Environment relevant Sustainability Criteria
50 min.	Module 7: Socio-economic and Governance-related Sustainability Issues
110 min.	Module 8: Support Policies and Regulations

or: **menti.com > CODE 123 456**

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What's your knowledge about green hydrogen & PtX?

Please go to **menti.com** and give us an insight!

Please introduce yourself

- in one minute - ☺ -

Your name, organisation and task.
Your expectations and what do you want to learn?

International PtX Hub Berlin – Promoting sustainable PtX worldwide

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Impacts:
(1) PtX contributes to the Paris Climate Agreement
(2) PtX leads to sustainable business and development opportunities worldwide.

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Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit

Official Launch: COP25 (December 2019)

Sustainability

Market development

Knowledge

Partnerships

Goals and Opportunities

- **Exchange of experience** with national and international partners
- Establishing a joint, international **Power to X agenda**
- Ensuring the production of **certified, "sustainable" PtX products**
- Actively **shaping** the global PtX market in the partner countries ("cooperation at eye level")
- Access to **expertise** (e.g. country studies, learning curves, time frames, value chains, sustainability and risk analyses, financing concepts)
- **Training of specialists** in emerging and developing countries (conferences, webinars, training courses)
- **https://ptx-hub.org for more information**

Training | Module 1

Introduction

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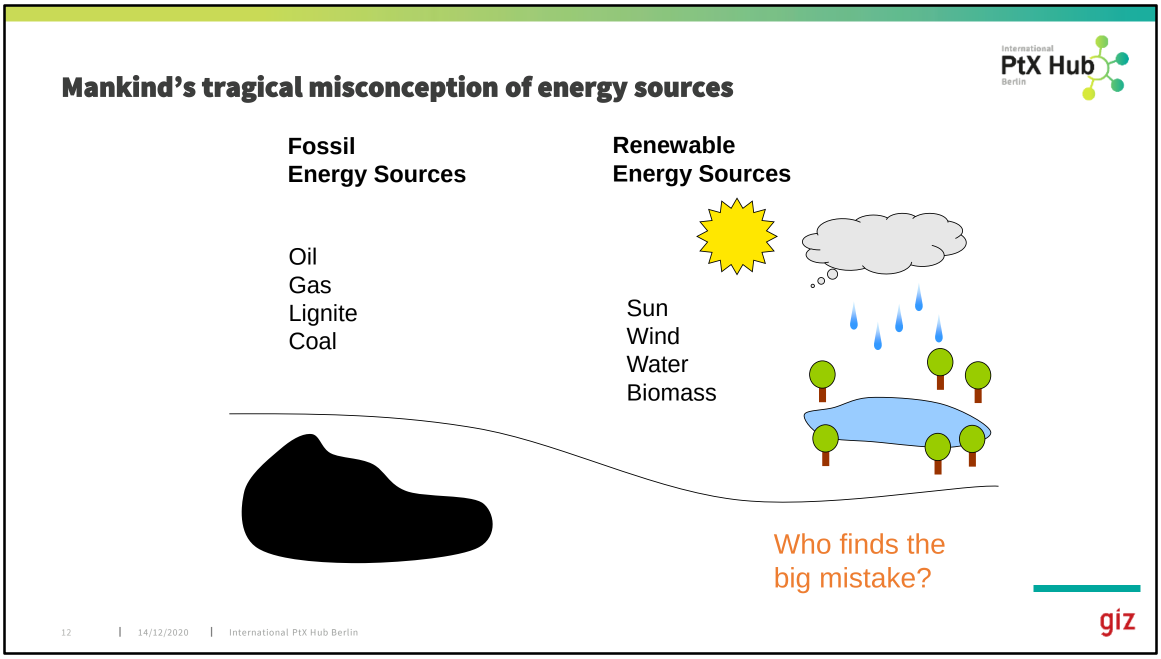
Module 1: Introduction Green Hydrogen & PtX

At the end of this module participants will
- be able to summarise historical and current developments on hydrogen linked to energy
- be able to explain the main drivers behind the current enthusiasm on H2 and PtX products

Benefit for learners:
The ability to use the key terminology related to H2 / PtX and the understanding of historical contexts as well as of recent developments enables participants to follow the remaining modules and enables set their H2 / PtX projects into a larger and consistent framework.

Core messages:
- There are **numerous driving forces for H2 / PtX projects**
- There are **numerous opportunities** and **needs for H2 / PtX projects**
- But there are as well **many stumbling blocks** to achieve it

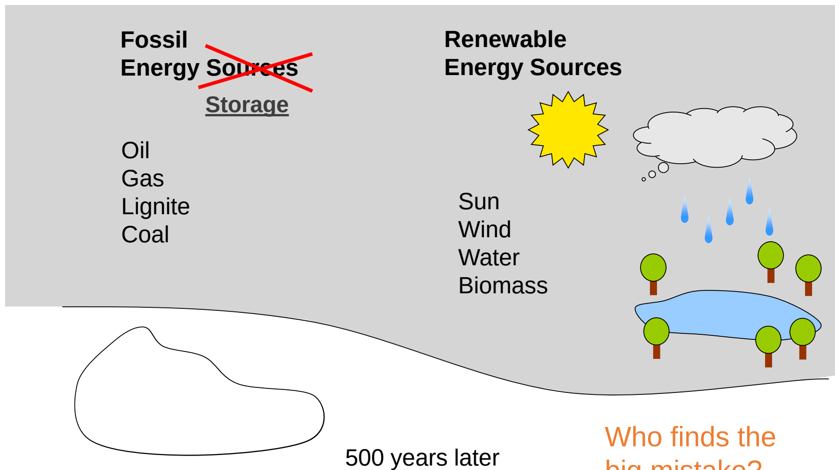


Notes:

- There is a **fundamental difference between an energy source** (a steady or varying flow of energy equivalent to water from a spring or fountain) and **an energy storage** (energy stored in a specific limited amount of material that will be depleted when used).
- In case of planet Earth the **primary energy source available is the sun.**
- **Secondary sources** that are derived from **the sun are wind, hydro and bio energy.**
- **Fossil fuels are** (solar) energy stored in the ground → **energy storage**.
- This storage has been slowly filled up in millions of years, but is emptied by humans at a very fast rate.

- Now, who finds the big mistake within this slide?
  - This picture contains a fundamental misconception that has led to the present critical situation regarding energy and climate stability. The auditory can think a minute about it and try to identify the big mistake.
  - It took myself about 20 years to find it. ☺

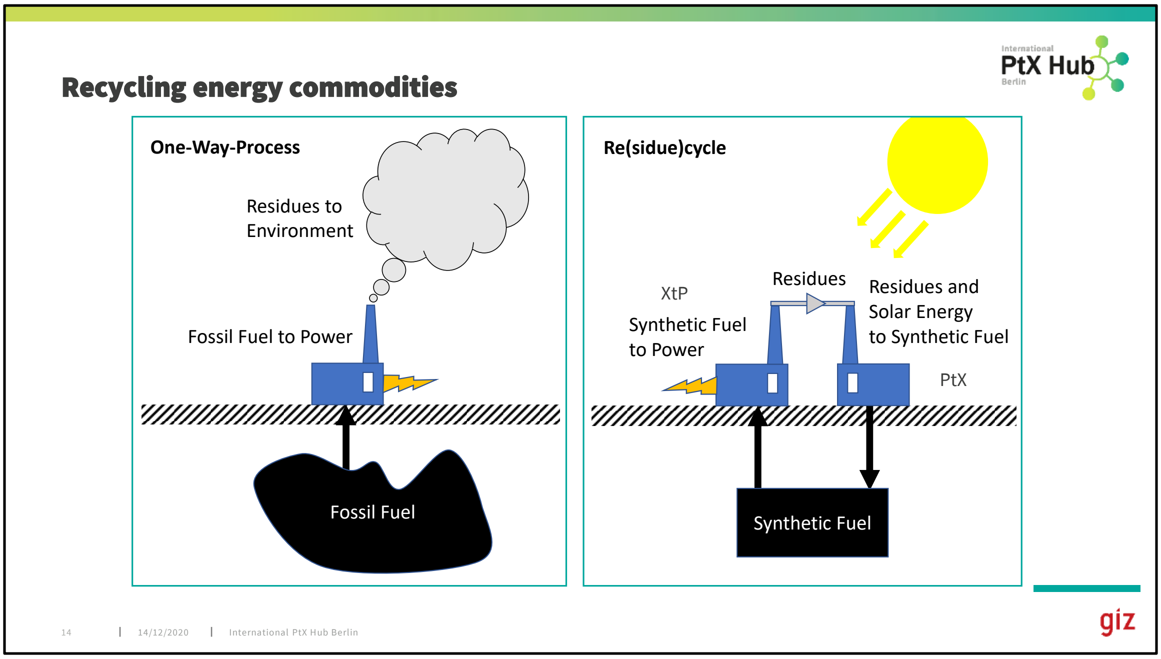
Mankind's tragical misconception of energy sources



Who finds the big mistake?

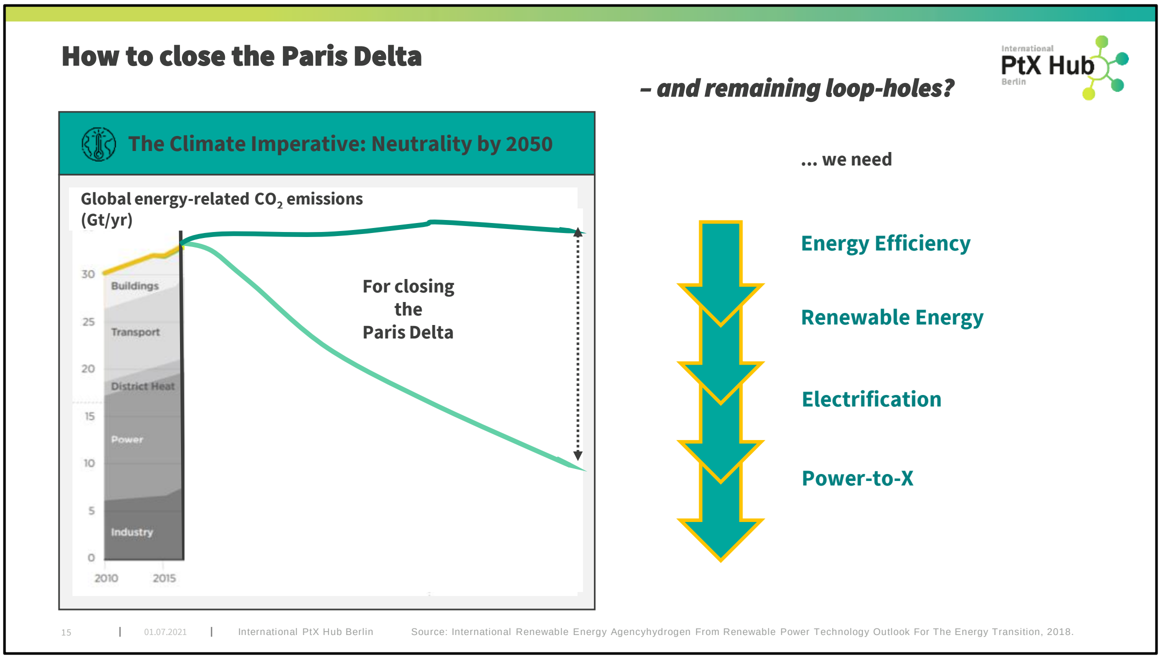
Notes:
- A first hint shows the same picture after about 500 years of using fossil energy.
- Deposits will **be empty and residues will be dissipated in the environment**.
- The worst of all is the fact that filling those deposits and cleaning the **atmosphere from its residues took about 500 million years**.
- At the moment, we are **releasing those residues** (CO_2, CH_4 and water vapor) one **million times faster into the atmosphere than they were deposited in the ground in form of mineral oil, coal and natural gas!**

- The solution of the riddle:
- <u>**Fossil fuels are not a source, but a storage of energy**</u>.
- In fact, the **best storage of energy we have.**
- **Sources of energy are renewables**, of which solar energy is the primary source feeding all others.
- Recognising this fundamental difference between **Fossil Energy Storage** and **Renewable Energy Sources** helps to understand our present energy situation and finding sustainable solutions.



Notes:

- Burning fossil fuels for winning energy **is a one-way process depleting fossil fuel deposits** in the ground and accumulating its **residues, like CO_2**, in the living environment (atmosphere and seawater).
- **Recycling CO_2 with solar energy avoids further resource depletion** and residue accumulation **and creates a carbon sink in form of stored synthetic hydrocarbon fuels.**



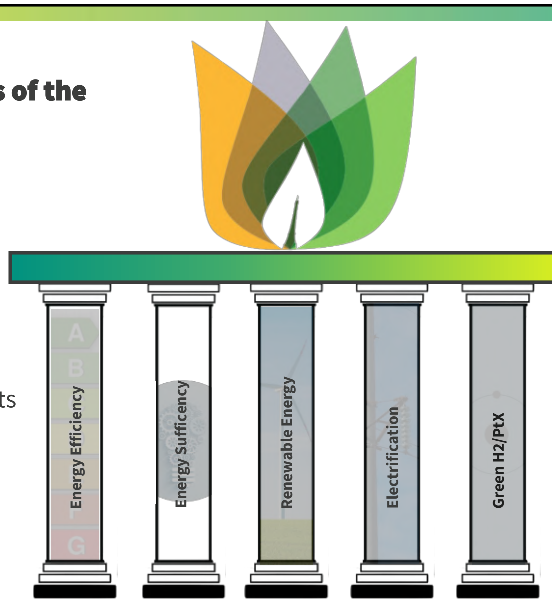
Notes:
- Paris Agreement: limit global warming to well below 2°C (1.5°C)
- Need for decarbonisation of energy systems & economies
- Thus, to achieve the Paris Agreement in time, we need massive increases in:
  - Energy Efficiency,
  - Electrification,
  - Renewable Energy,
  - Green H_2 and PtX.

The supporting pillars of the energy transition

Sufficiency and energy efficiency is a must!

For rest of the energy demand:

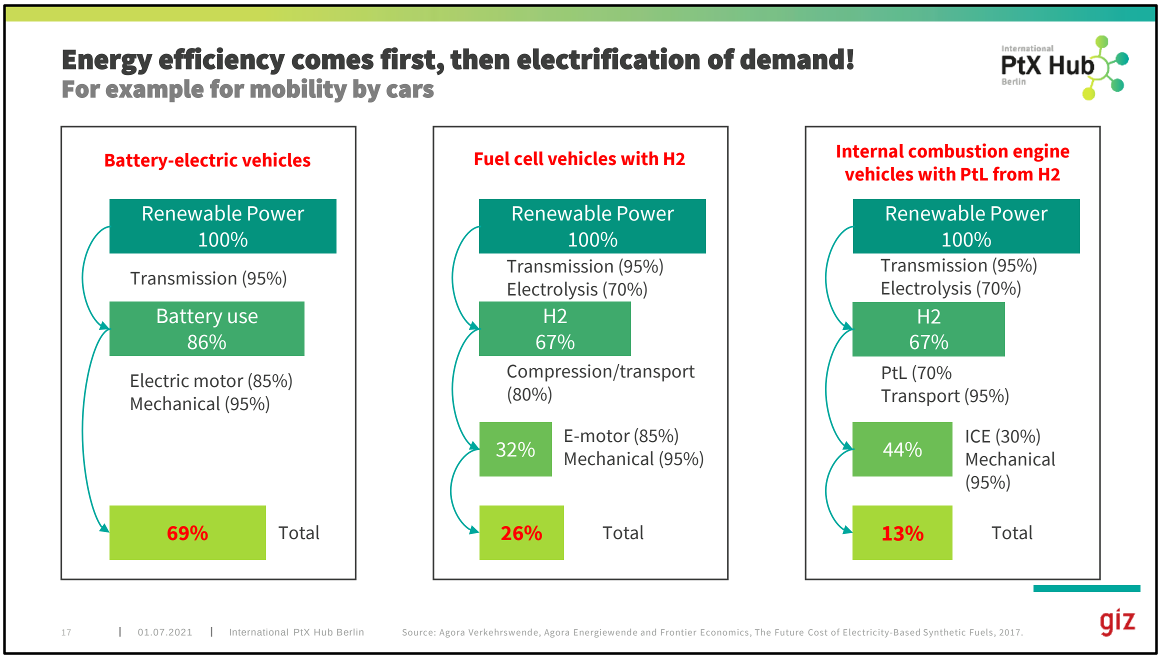
- Renewable energy and its use in further **electrification of demand**!
- Only for **hard to abate sectors: H2 & PtX**



Further comments:
You have been methaned: https://www.youtube.com/watch?v=9KtkiPv5BNg&feature=youtu.be

Sources:

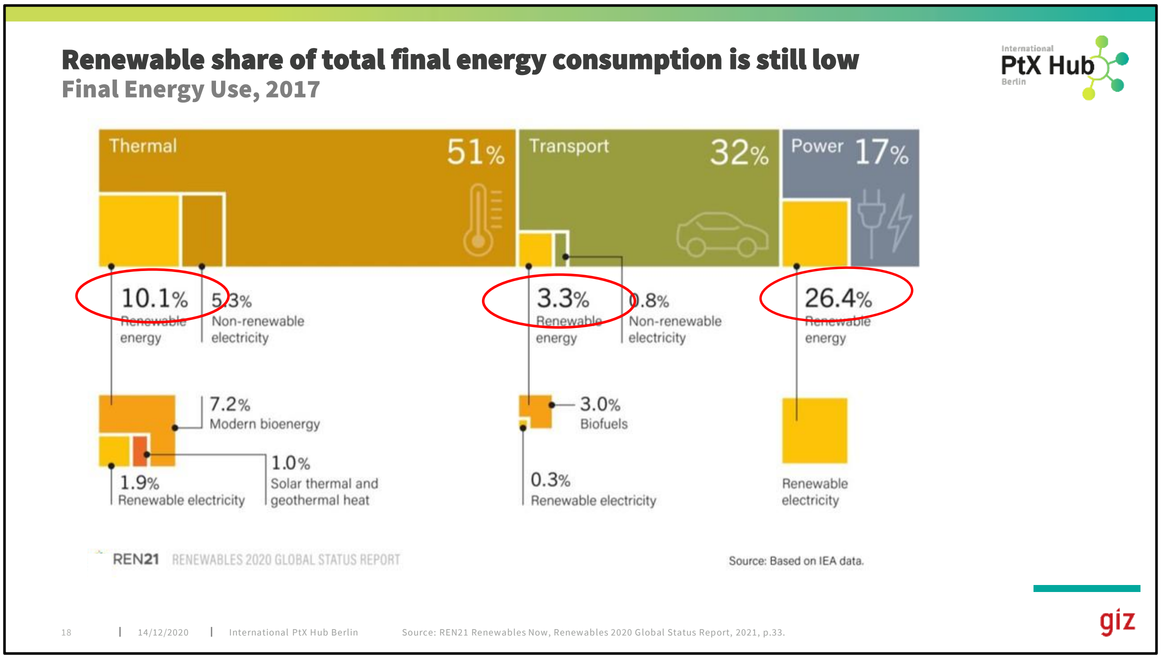
- Säulen: https://www.datendemokratie.org
- COP21: https://www.ecologic.eu/de/12730
- Energieeffizienz: https://pixabay.com/illustrations/consumption-energy-electricity-19150/
- Erneuerbare Energien: https://pixabay.com/photos/windmill-turbine-renewable-resource-932125/
- Elektrifizierung: https://pixabay.com/photos/electricity-transmission-towers-wire-4971006/
- Wasserstoff: https://pixabay.com/vectors/watchmen-manhattan-dc-comics-comics-1613267/



Notes:

- In the **transport sector, electric motors are the best solution** in terms of **efficiency** and **cost for powering trains**, cars, light utility vehicles, municipal buses, and **trucks operating over short distances** and with good charging options.
- With respect to **heavy trucks operating over extended distances,** the situation is different:
    - Vehicle batteries in mass production are not sufficiently strong as a single source of power, nor are they expected to become strong enough in the coming years.
    - As a result, heavy trucks operating over long distances will need to be operated **with overhead power lines** or **alternatively with combustion engines or fuel cells**.
    - A combination of various propulsion technologies might make sense to handle geographic areas in which overhead wires have not yet been installed. In the absence of a comprehensive overhead wire network, the **decarbonised transport system of the future will necessarily contain long-distance trucks that are reliant on synthetic fuels.**
- According to current expert opinion, **direct electricity use is also not an option for air or maritime transport, except on an extremely limited basis.**
- These **two subsectors will thus require climate-neutral synthetic fuels, namely H_2 to power fuel cells as well as CO_2-based synthetic methane** or **liquid fuel to power combustion engines**.
- **Synthetic fuels** will also be required to **operate construction equipment and heavy agricultural vehicles,** as it will only be possible to directly power these vehicle types with electricity in select cases.

Source: https://static.agora-energiewende.de/fileadmin2/Projekte/2017/SynKost_2050/Agora_SynKost_Study_EN_WEB.pdf



Notes:

- The share of **renewable electricity in global final power** consumption has **increased to about 26% in 2017.**
- However, power only makes up for **about 17% of total final energy** consumption, while the core of demand relates to heating and cooling (51%) and transport (32%).
- While many governments are supporting renewables in the electricity sector, **the support of other sectors is still insufficient**, and the share of renewables is much smaller.
- In addition to that, it **is technically more difficult to introduce renewable energy in other sectors.**
- A possible part of the solution can be to use renewable electricity (meantime produced at rather low cost), also in the non-electricity sectors for heating, cooling and transport.
- Examples are:
    - **PV and wind power driving heat pumps to satisfy demand of heating or cooling**.
    - **Charging batteries of electric vehicles with renewable electricity.**
    - **Producing synthetic fuels from renewable electricity (PtX**).
- This will create additional flexibilities in the system, but in the first place it will create additional demand.
- The challenge of adapting renewable supply to this new demand still remains in place.

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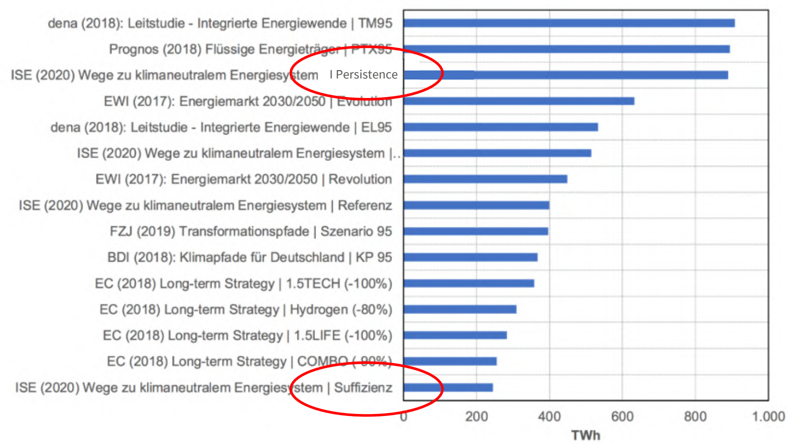
H2/PtX demand in Germany in 2050 depends on our behaviour



→ Either keep wasting or: become energy sufficient & efficient!

Note: The scenarios of the EU Long-Term Strategy were converted with a 20% share of Germany in the values for the EU-28.

Source: Öko-Institut e.V., Wasserstoff und wasserstoffbasierte Energieträger bzw. Rohstoffe, 2020.

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Additional renewable energy capacity to cover all 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.

	C_xH_y-Production	Efficiency 48% (today)			Efficiency 57% (long-term)		
		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 = 1163 TWh CxHy.
If we want to cover this with syn. fuels, the demand for RE electricity would be last column x 11

→ Either we need 1000 GW on-shore wind or 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.

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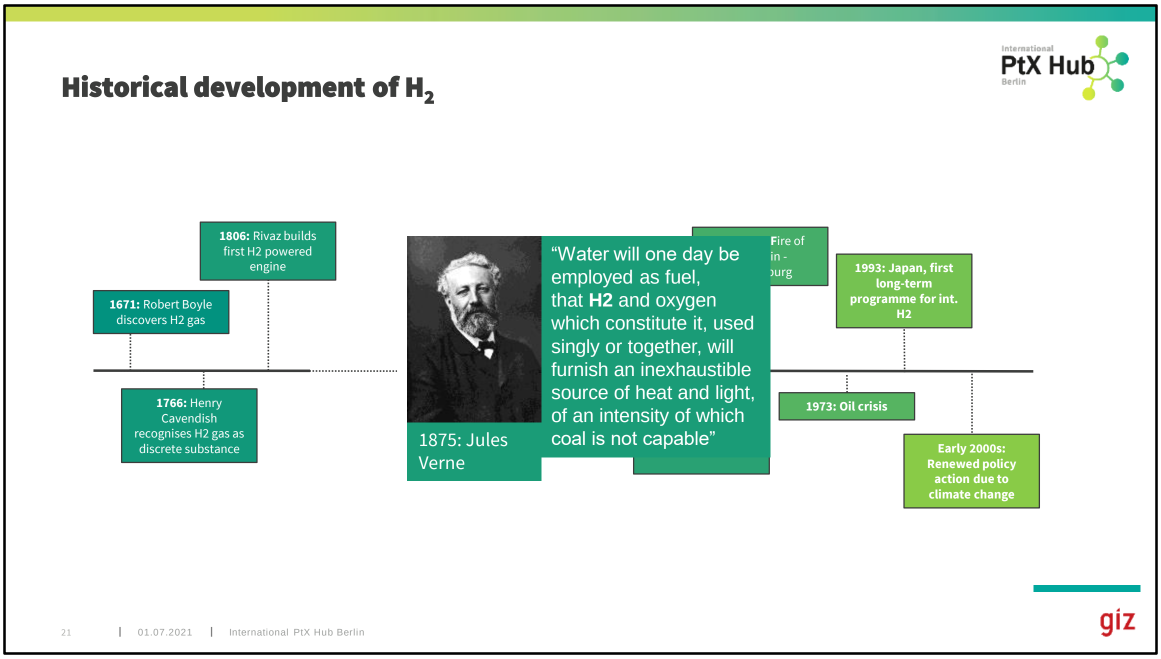


Notes:

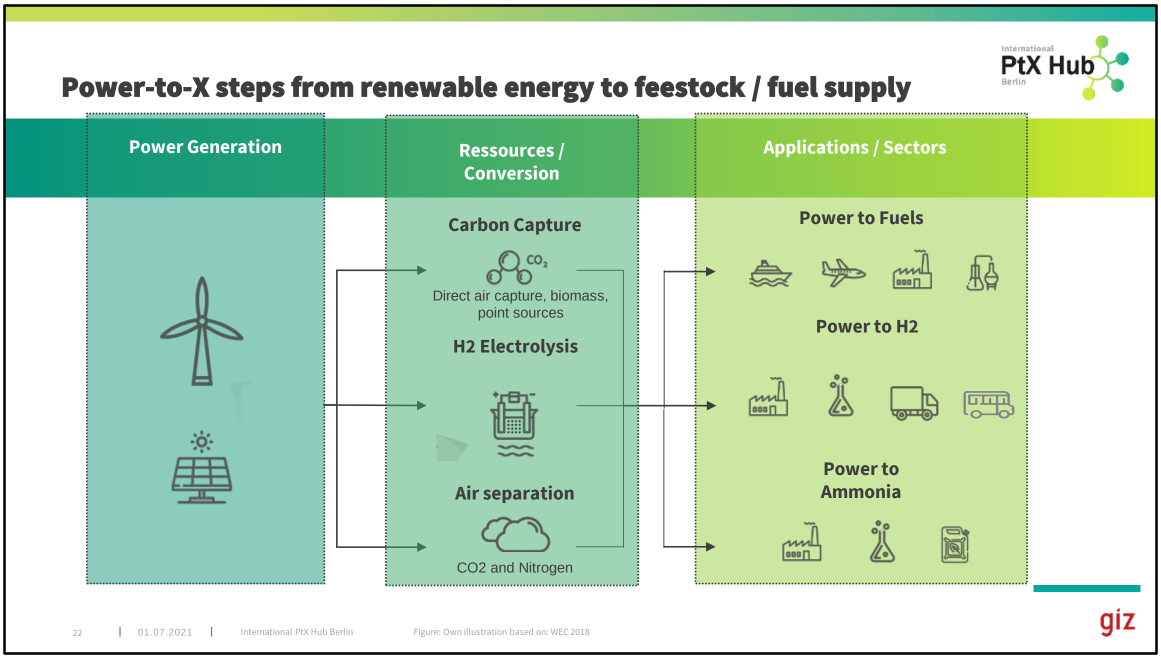
<u>The (complete) history of H_2</u>

- **In 1671: Discovery by Robert Boyle.**
- **In 1766, Henry Cavendish was the first to recognise H2 gas as a discrete substance,** by naming the gas from a metal-acid reaction "inflammable air". He speculated that "inflammable air" was in fact identical to the hypothetical substance called "phlogiston".
- **Further finding in 1781: the gas produces water when burned. Henry Cavendish is usually given credit for the discovery of H2 as an element.**
- In **1783, Antoine Lavoisier** gave the element the **name H2** (from the Greek ὑδρο- hydro meaning "water" and -γενής genes meaning "creator") when he and Laplace reproduced Cavendish's finding of water being produced when H2 is burned.
- **H2 was liquefied for the first time by James Dewar in 1898 by using regenerative cooling** and his invention, the vacuum flask. He produced solid H2 in the next year.
- **Deuterium was discovered in December 1931 by Harold Urey**, **tritium was prepared in 1934 by Ernest Rutherford**, Mark Oliphant, and Paul Harteck. Heavy water, which consists of deuterium in the place of regular H2, was discovered by Urey's group in 1932.

<u>A more detailed look:</u>

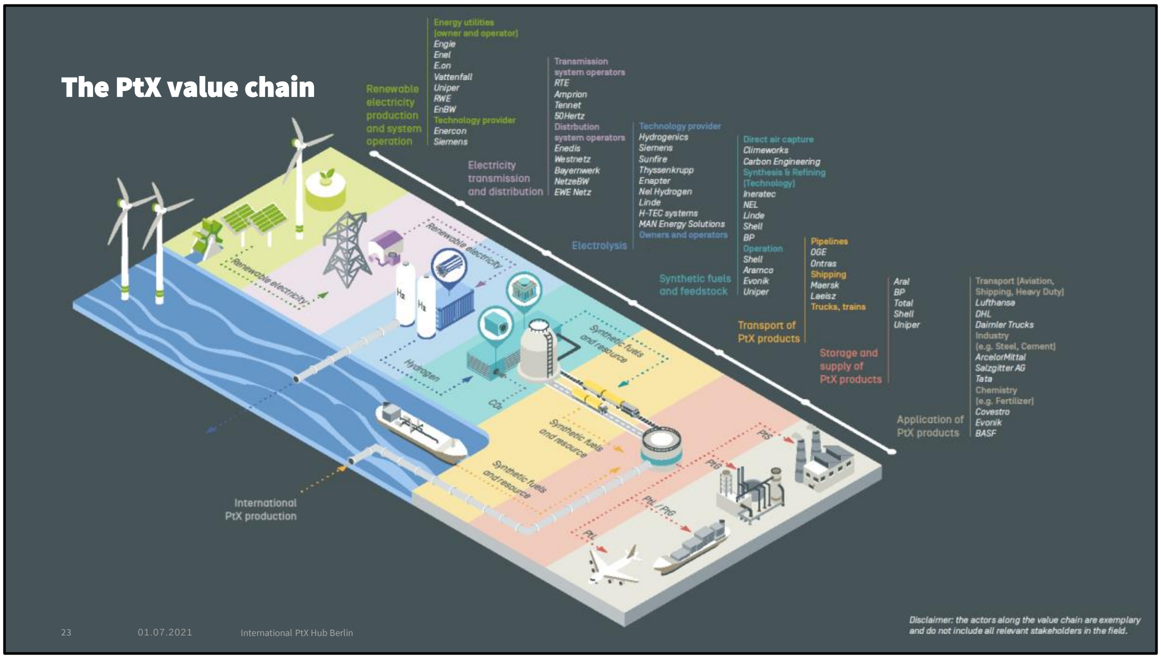
- Edward Daniel Clarke invented the H2 gas blowpipe in 1819.
- The Döbereiner's lamp and limelight were invented in 1823.
- **The first H_2-filled balloon was invented by Jacques Charles in 1783.**
- H_2 provided the lift for the first reliable form of **air-travel following the 1852 invention of the first H_2-lifted airship by Henri Giffard.**
- **German count Ferdinand von Zeppelin promoted the idea of rigid airships lifted by H_2 that later were called Zeppelins; the first of which had its maiden flight in 1900.** Regularly scheduled flights started in 1910.

- By the outbreak of World War I in **August 1914, they had carried 35,000 passengers without a serious incident**. H_2-lifted airships were used as observation platforms and bombers during the war.
- The **first non-stop transatlantic crossing was made by the British airship R34 in 1919**.
- Regular passenger service resumed in the 1920s and the discovery of **helium reserves in the United States promised** increased safety, but the U.S. government refused to sell the gas for this purpose.
- Therefore, **H_2 was used in the Hindenburg airship, which was destroyed in a mid-air fire over New Jersey on 6 May 1937.** The incident was broadcast live on radio and filmed. Ignition of leaking H_2 is widely assumed to be the cause, but later investigations pointed to the ignition of the aluminised fabric coating by static electricity. But the **damage to H2's reputation as a lifting gas was already done and commercial H_2 airship travel ceased**. H_2 is still used, in preference to non-flammable but more expensive helium, as a lifting gas for weather balloons.
- In the same year, the **first H_2-cooled turbo generator** went into service with gaseous H_2 as a **coolant in the rotor and the stator in 1937** at Dayton, Ohio, by the Dayton Power & Light Co.; because of the thermal conductivity and very low viscosity of H2 gas, thus lower drag than air, this is the most common type in its field today for large generators (typically 60 MW and bigger; smaller generators are usually air-cooled).
- The **nickel H_2 battery** was used for the first time **in 1977 aboard the U.S. Navy's Navigation technology satellite-2 (NTS-2).**For example, the ISS, Mars Odyssey and the Mars Global Surveyor are equipped with nickel-H2 batteries. In the dark part of its orbit, the Hubble Space Telescope is also powered by nickel-H_2 batteries, which were finally replaced in May 2009, more than 19 years after launch and 13 years beyond their design life.



Notes:

- **PtX means using additional renewable electricity** (solar, wind, hydro, geothermal, etc.) **to split water (H_2O)** into its components oxygen (O_2) and (emission-free) **H_2.**
- **Power-to-X** refers to the **conversion of electric power to other forms of energy carriers** for use in different sectors (such as transport or chemicals).
- **H_2 is the core of Power-to-X,** serving as input for the production of the other e-fuels
- **H_2 can be further synthesised and refined** by adding either **CO_2** (Fischer-Tropsch Synthesis) or **nitrogen (N_2)** (Haber-Bosch Synthesis) to produce **S4F (S**ustainable **F**ossil-**F**ree **F**uels and **F**eedstocks), the ‚-X'.
- H2 can further be refined to produce:
    - **PtL (Kerosine, Gasoline, Diesel, Methanol)**,
    - **PtG (Methane)** or
    - **Power-to-Chemicals (e.g. ammonia = NH_3)**
  - **This refinement needs Carbon (CO_2) and Nitrogen (N_2) inputs** → these inputs **should also be sourced climate neutral.**
  - The resulting products should then **be used mainly** for „**hard-to-abate" sectors of industry and transport,** which cannot easily be defossilised by directly using renewable electricity and batteries.


The PtX value chain
Renewable electricity production and system operation
Energy utilities (owner and operator)
Engie
Enel
E.on
Vattenfall
Uniper
RWE
EnBW
Technology provider
Enercon
Siemens
Electricity transmission and distribution
Transmission system operators
RTE
Amprion
Tennet
50Hertz
Distrbution system operators
Enedis
Westnetz
Bayernwerk
NetzeBW
EWE Netz
Electrolysis
Technology provider
Hydrogenics
Siemens
Sunfire
Thyssenkrupp
Enapter
Nel Hydrogen
Linde
H-TEC systems
MAN Energy Solutions
Owners and operators
Synthetic fuels and feedstock
Direct air capture
Climeworks
Carbon Engineering
Synthesis & Refining (Technology)
Ineratec
NEL
Linde
Shell
BP
Operation
Shell
Aramco
Evonik
Uniper
Transport of PtX products
Pipelines
OGE
Ontras
Shipping
Maersk
Laeisz
Trucks, trains
Storage and supply of PtX products
Aral
BP
Total
Shell
Uniper
Application of PtX products
Transport (Aviation, Shipping, Heavy Duty)
Lufthansa
DHL
Daimler Trucks
Industry (e.g. Steel, Cement)
ArcelorMittal
Salzgitter AG
Tata
Chemistry (e.g. Fertilizer)
Covestro
Evonik
BASF
Renewable electricity
Renewable electricity
Hydrogen
Synthetic fuels and resource
Synthetic fuels and resource
Synthetic fuels and resource
PtS
PtG
PtL / PtG
PtL
International PtX production
Disclaimer: the actors along the value chain are exemplary and do not include all relevant stakeholders in the field.
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01.07.2021
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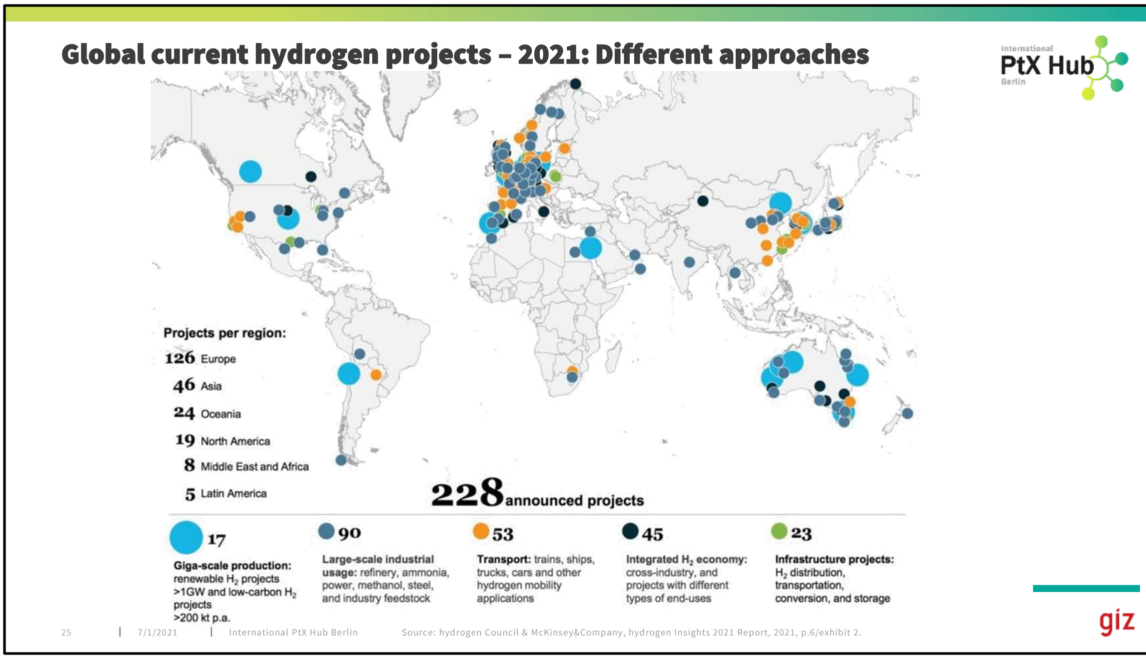
Notes:
Sector coupling in the project *Westküste 100 in Schleswig Holstein*: **Green H_2 and decarbonisation on an industrial scale.**

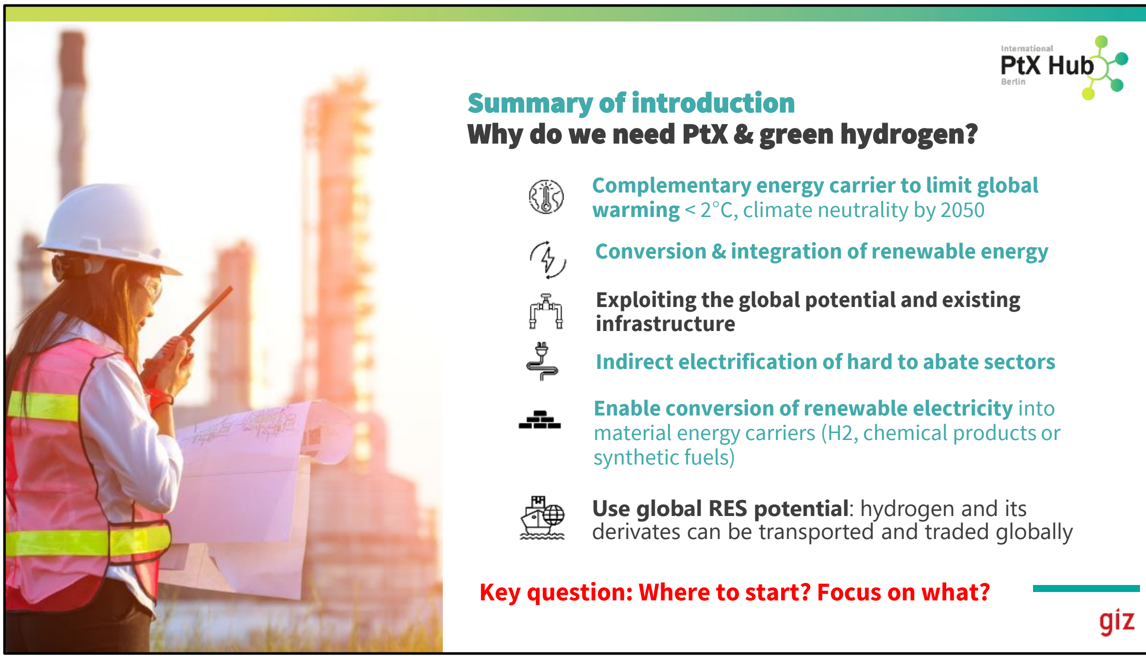
- The north coast of Germany exhibits excellent conditions: **strong wind energy region as well as excellent geological storage conditions** called Westküste100
- 100% electricity sourced by renewable energies (RE) → **region has ‚too much' RE** → grids regularly have to be shut down when strong winds occur, otherwise grids collapse → this project can benefit of this excess RE.
  - → The shutdown of green power generation plants cost €710 million nationwide in 2019. The costs are borne by the consumers via grid fees.
  - → **excess electricity needs to be converted into H_2 to make it accessible for industrial complexes in the project**
    - **Cross-industry partnership**: EDF Deutschland, Holcim Deutschland, OGE, Ørsted, Raffinerie Heide, Stadtwerke Heide, thyssenkrupp Industrial Solutions and Thüga - formed together with the Entwicklungsagentur Region Heide and the Westküste University of Applied Sciences.
    - August 2020: Commissioning of an **electrolyser with a capacity of 30 megawatts** for the production of H_2 targeted for 2023.
- **Planned: storing H_2 in underground caverns** → enable a continuous production process independent of fluctuating amounts of wind power.
- Parts of the H_2 produced will also be fed into the natural gas grid of a local energy provider (Stadtwerke Heide) via a new pipeline.
- H_2 filling station will be supplied.

→ **Vision: Construction of a 700-megawatt electrolysis plant from 2025 onwards**, based on electricity from offshore wind farms.

→ waste heat and oxygen produced during electrolysis will then also be used.
→ Furthermore: Production of climate-friendly fuels for aircraft = milestone on the way to complete sector coupling.

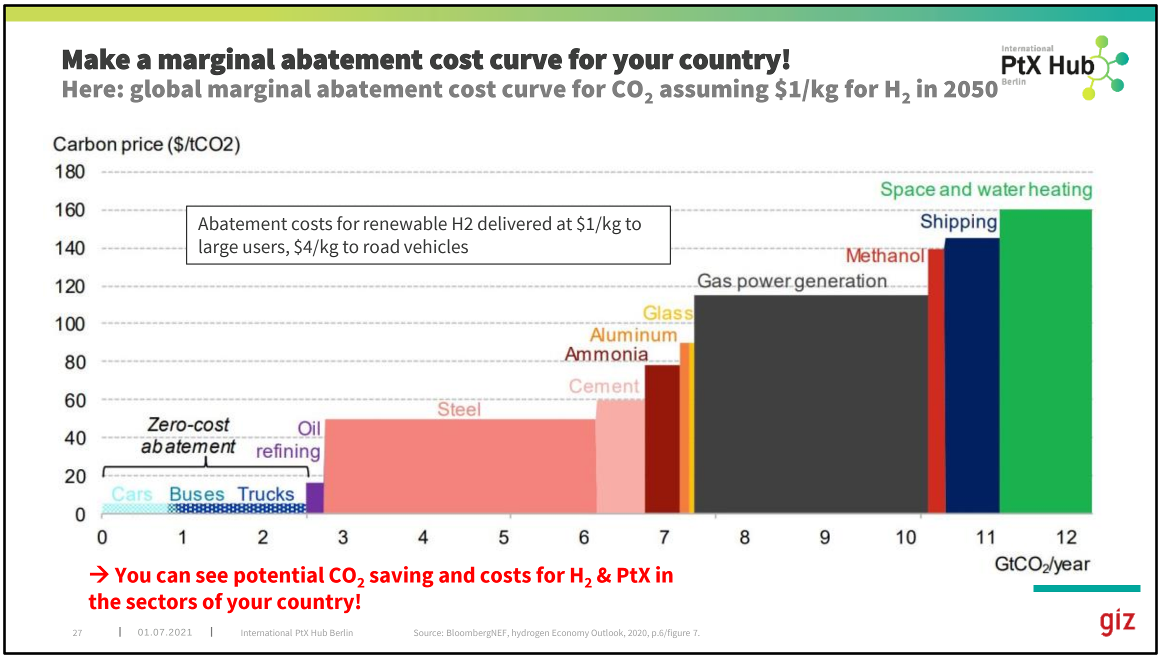


Notes:
There's an increased interest in H_2 projects worldwide, with an overall of 228 announced projects, most of them located in Europe.



Notes:

- **Not all fossil fuels can be replaced by direct use of electricity or sustainable produced biofuels → synthetic fuels and feedstock** could serve as **supplementary alternative to achieve complete decarbonisation by 2050.**
- Non-RE sources represent more than 70% in the energy, transport and heat sector as of 2015.
- Out of the total emissions of 2015, power accounted for 38%, transport for 22%, industry for 19% and heating and cooling for 12% (IRENA, 2017).
- Around **1/3 of energy related emissions currently have no economically viable options for deep decarbonisation.**



Notes:
- Even at $1/kg, carbon prices or equivalent measures valuing emission reductions are still likely to be needed for H_2 to compete with cheap fossil fuels in hard-to-abate sectors.
- **Why is this the case? →** H_2 must be manufactured, whereas natural gas, coal and oil need only to be extracted → H_2 **likely to always be a more expensive form of energy.**
- **H_2's lower energy density also makes it more expensive to handle.**
- But if **policies are in place, up to 34% of greenhouse gas (GHG) emissions from fossil fuels and industry could** be abated using H2 – 20% for less than $100/tCO2.

H_2 is a promising emission reduction pathways for hard-to-abate industry sectors:
- The strongest use cases for **H_2 are manufacturing processes that require physical and chemical properties of molecule fuels in order to work**.
- H_2 can enable a **switch from fossil fuels in many of these applications at surprisingly low carbon prices.**
- For example, **at $1/kg, a carbon price of**
    - $50/t$CO_2$ would be enough to switch to renewable H_2 in **steel making,**
    - $60/t$CO_2$ to use renewable H_2 for **heat in cement production**,
    - $78/t$CO_2$ for **ammonia synthesis**, and
    - $90/t$CO_2$ for **aluminum and glass manufacturing**.

But H2's role in transport should be focused on **trucks and ships:**
- H_2 can play a valuable role in **decarbonising <u>long-haul, heavy-payload trucks</u>**.
- These could be **cheaper to run using H_2 fuel cells than diesel engines by 2031.**

!! But smaller scale transport, like cars, bus and light-truck market looks set to adopt battery electric drive trains, which are a cheaper solution than fuel cells.
- In our view, the **fuel cell vehicle industry will also be the most expensive sector to scale up, requiring**

$105 billion in subsidies to 2030.

- **For ships, green NH_3 (ammonia) from H_2** is a promising option and could be competitive with heavy fuel oil with a carbon price of $145/t$CO_2$ in 2050.
- **Aviation:** (not in the graph) Abatement costs ($/t$CO_2$eq):
  - Commuter: 20-40
  - Regional: 40-80
  - Short-range: 70-130
  - Medium-range: 100-220
  - Long-range: 160-350

  Source: https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200507_H2%20Powered%20Aviation%20report_FINAL%20web%20%28ID%208706035%29.pdf

Further comments:
Sectoral emissions based on 2018 figures, abatement costs for renewable H_2 delivered at $1/kg to large users, $4/kg to road vehicles.
Aluminum emissions for alumina production and aluminum recycling only. Cement emissions for process heat only.
Refinery emissions from H_2 production only.
Road transport and heating demand emissions are for the segment that is unlikely to be met by electrification only, assumed to be 50% of space and water heating, 25% of light duty vehicles, 50% of medium-duty trucks, 30% of buses and 75% of heavy-duty trucks.

Source: https://data.bloomberglp.com/professional/sites/24/BNEF-H2-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

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“Where do you see opportunities for green H2 & PtX in your country?”

“What are the biggest challenges to achieve them?”

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Grab a coffee,

Take 20 minutes to chat with your colleagues in your language &

Get to know each other better!

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Production of Hydrogen and Hydrogen-based Products (PtX)

Training | Module 2

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

International PtX Hub Berlin

Module 2: Production of Hydrogen and Hydrogen-based Products (PtX)

At the end of this module participants will

- be able to distinguish the different **colours** of H2
- be aware of diverse H2 production pathways for H2 based Power-to-X
- be aware of the requirements / conditions for sustainable products based on H2 and PtX

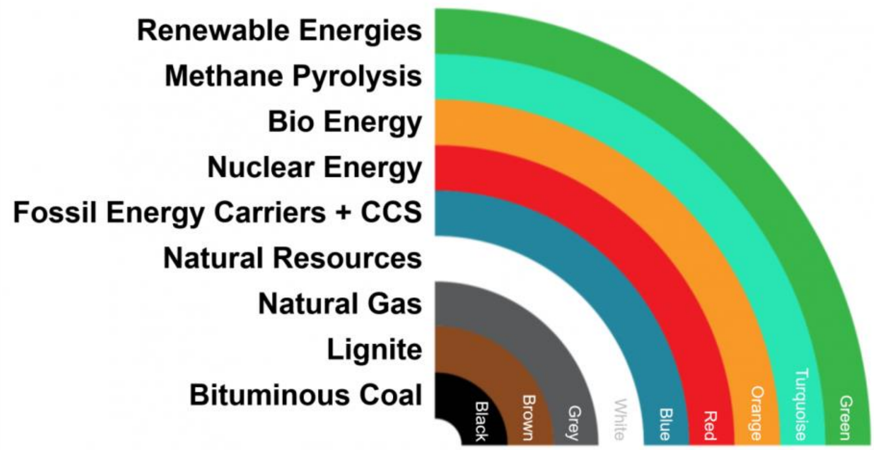
Benefit for learners:

Seeing the big picture enables learners to identify substances and processes required for sustainable final products. Seeing the big picture enable participants to understand the manifold cost elements and considerations which will be taken up in chapter 3.

Core messages:

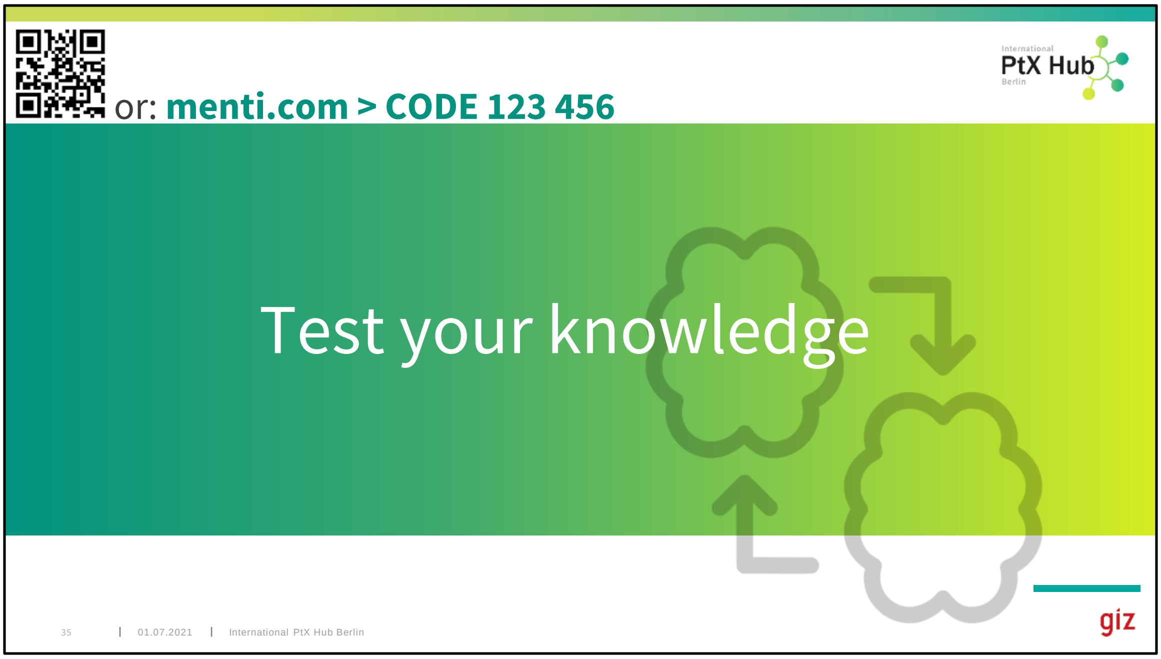
- We can **produce all products** which are produced with oil also with H2 and PtX
- In order to **consider the final products sustainable**, all **substances used and all processes applied must be sustainable**

Colours of hydrogen production and their energy source



Source: Michael Kalis (IKEM), News Details hydrogen: We need a Colour Scheme and a Certification System for Green hydrogen, 2021.

Notes:
H2 is a colourless gas – depending on the production type, different colours are assigned to H_2.
Missing in this slide: **Pink H_2** obtained via electrolysis through an atomic current.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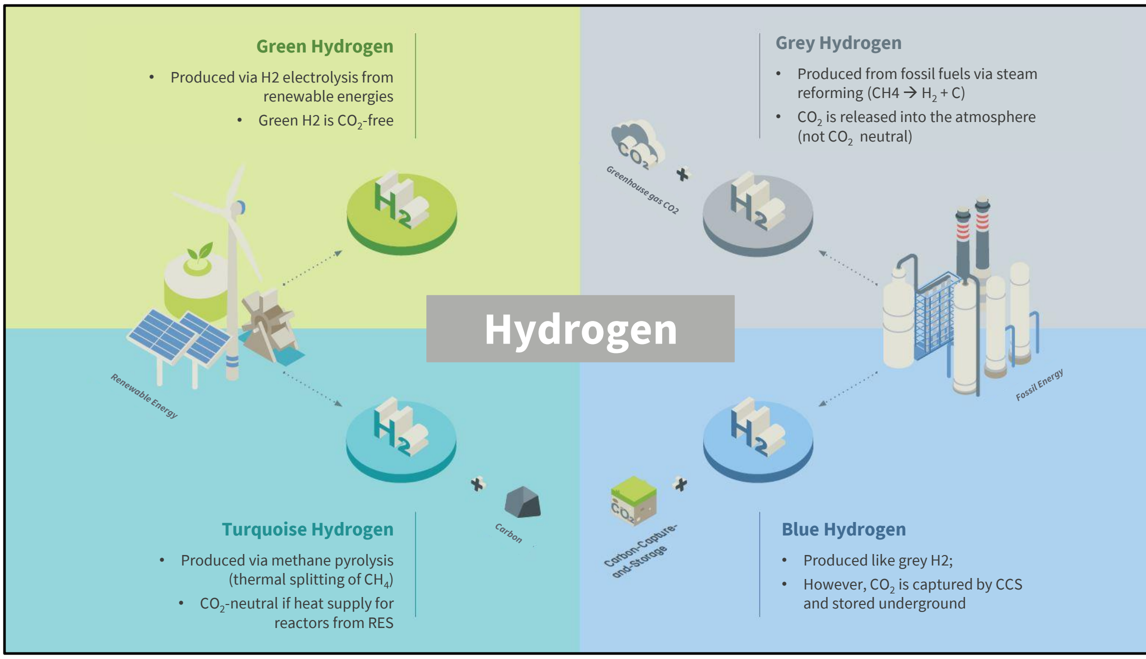
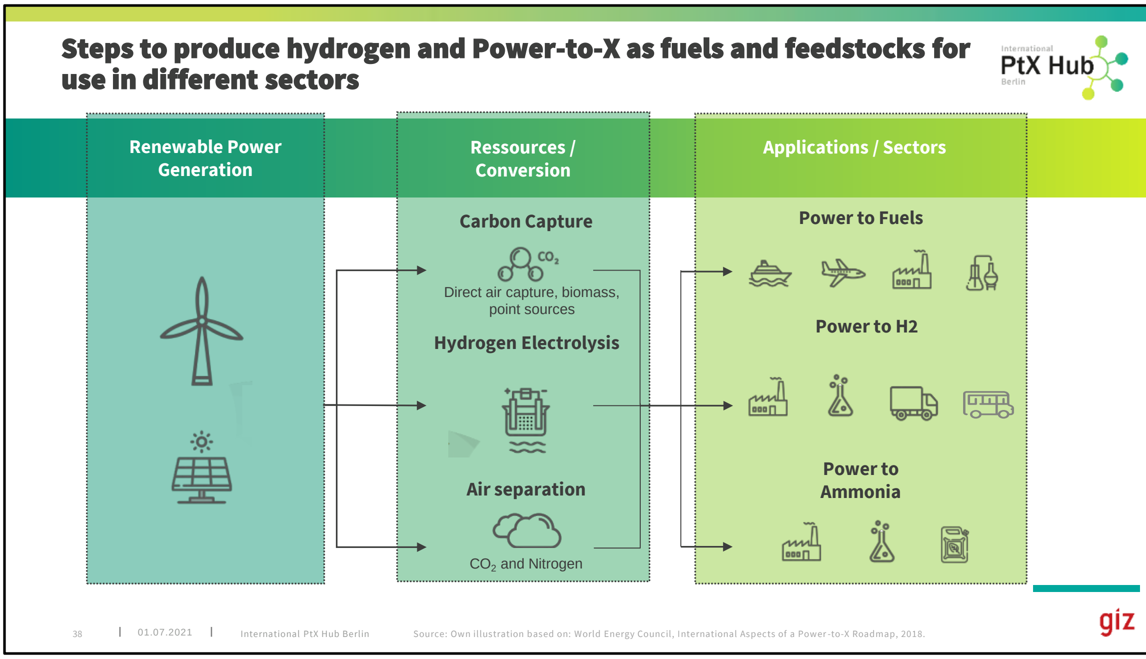
"What do you think - how is H2 currently produced in the world?"

"Which colours of H2 are sustainable?"


Green Hydrogen
Produced via H2 electrolysis from renewable energies
Green H2 is CO_2-free
Grey Hydrogen
Produced from fossil fuels via steam reforming (CH4 → H_2 + C)
CO_2 is released into the atmosphere (not CO_2 neutral)
Greenhouse gas CO2
Hydrogen
Renewable Energy
Fossil Energy
Carbon
Carbon-Capture-and-Storage
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 H2;
However, CO_2 is captured by CCS and stored underground



Notes:

- PtX means using additional renewable electricity (solar, wind, hydro, geothermal, etc.) to split H_2O into its components O_2 and H_2.
- **Power-to-X: conversion of electric power to other forms of energy carriers.**
- **H_2 is the core of Power-to-X.**

Further comments:
Renewable synthetic fuels and feedstocks can replace fossil fuels across all sectors such as transport, heating, industry, power generation.

- Green H_2 can be converted in a **second-stage process to synthetic fuels and feedstocks**.
- Synthetic fuels **and feedstocks require CO_2 or N_2 input.**
- Synthetic **methane incorporating CO_2 via the process of methanisation (PtG).**
- Synthetic **liquid fuels incorporating CO_2 (PtL).**
    - **Methanol synthesis (possibly plus upgrading)**
    - **Fischer-Tropsch synthesis (possibly plus upgrading)**
- NH_3 via the **Haber-Bosch process incorporating N_2.**

1. Step: Hydrogen production – Electrolysis
Different types of electrolysers exists

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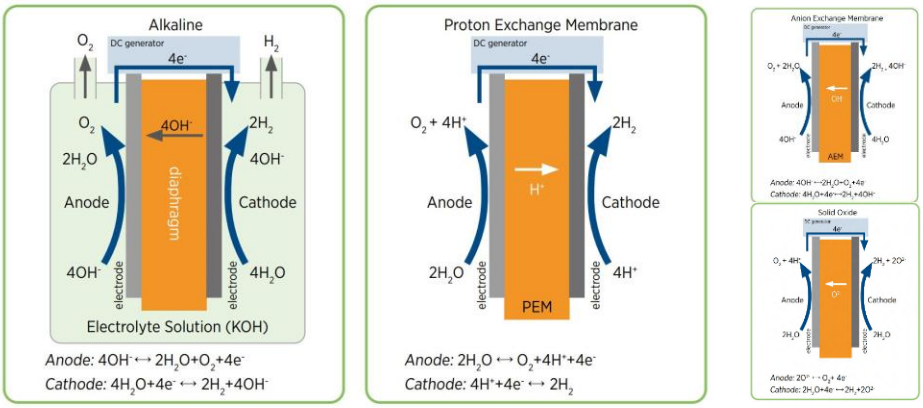

39 | 01.07.2021 | International PtX Hub Berlin   Source: IRENA, Green Hydrogen Cost Reduction, 2020, p.31/figure 6.

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Notes:

Electrolyser technology characterisation:

- The electrolyser is **composed of the stack** (where actual splitting of water into H_2 and O_2 takes place) **and the balance of plant** which comprises **power supply, water supply and purification, compression, possibly electricity and H_2 buffers and H_2 processing.**
- Both components are **important for the cost**, since they have similar cost shares.
- The largest **potential for near term cost reduction is in this balance of plant**, while **R&D is required to reduce stack cost** and increase its performance and durability. Trade offs among these are significant.
- The **flexibility of alkaline and** Polymer Electrolyte Membrane **(PEM) stacks** is enough to **follow fluctuations in wind and solar**.
- **Flexibility** of the system is **limited by the balance of plant** (e.g. the compressors) **rather than the stack**.
- Furthermore, flexibility in the very short-term time scales involved (i.e. sub-second) is not the key value proposition for electrolysers; **their key system value lies in bulk energy storage.**
- **This** effectively **decouples variability of generation from stability of H_2 and power to X (PtX**) demand through **H_2 storage in gas infrastructure (e.g. salt caverns, pipelines) and liquid e-fuels storage.**
- There is **no single electrolyser technology that performs better across all dimensions**.
- The future technology mix will depend on innovation and competition among key technologies and

manufacturers, leading to technological improvements and a better fit for different technologies and system designs in each specific application.

Electrolyser requirement characterisation:

- **Water and land use do not represent barriers to scaling up →** In places with water stress, the **source of water for H_2 production should be explicitly considered** in strategies and further elaborated in project planning.
- Where access to **sea water is available, desalination** can be used with limited impact on cost and efficiency, potentially deploying multi-purpose desalination facilities to provide local benefits.
    - A 1 GW plant could occupy about 0.17 km^2 of land, which means 1000 GW of electrolysis would occupy an area equivalent to Manhattan (New York).

Electrolyser performance characterisation:

- **Improving the performance of the electrolyser stack in one dimension usually goes along with reduced performance in other parameters** (efficiency, cost, lifetime, mechanical strength and manufacturing).
- This leads to **trade offs to be tackled through innovation in materials and manufacturing, leading to a set off specific** system designs tailored to different applications in the future.
- Potential **breakthroughs in technology** development can be disruptive in terms of **accelerating cost reductions for the stack**, while for the **balance of plant, it is more about economies of scale, standardisation** of design and supply chains, **and learning by doing.**

Source:
IRENA – Green H2 Cost Reduction – Scaling up electrolyseres to meet the 1.5°C climate goal

1. Step: Hydrogen production

Key parameter of different electrolyser technologies

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	Alkaline	PEM	SOEC
Operating Temperature	60-80 °C	50-80 °C	650 -1,000 °C
Voltage Efficiency	62-82%	67-82%	< 110%
Stack Lifetime	20,000-90,000h	60,000-90,000h	< 10,000h
Operating Pressure	< 20 bar	< 200 bar	< 25 bar
Maturity	Mature	Commercial	Demonstration

PEM: Proton Exchange Membrane
SOEC: Solid Oxide Electrolyser Cell

Source: Own illustration based on: World Energy Council, International Aspects of a Power-to-X Roadmap, 2018.

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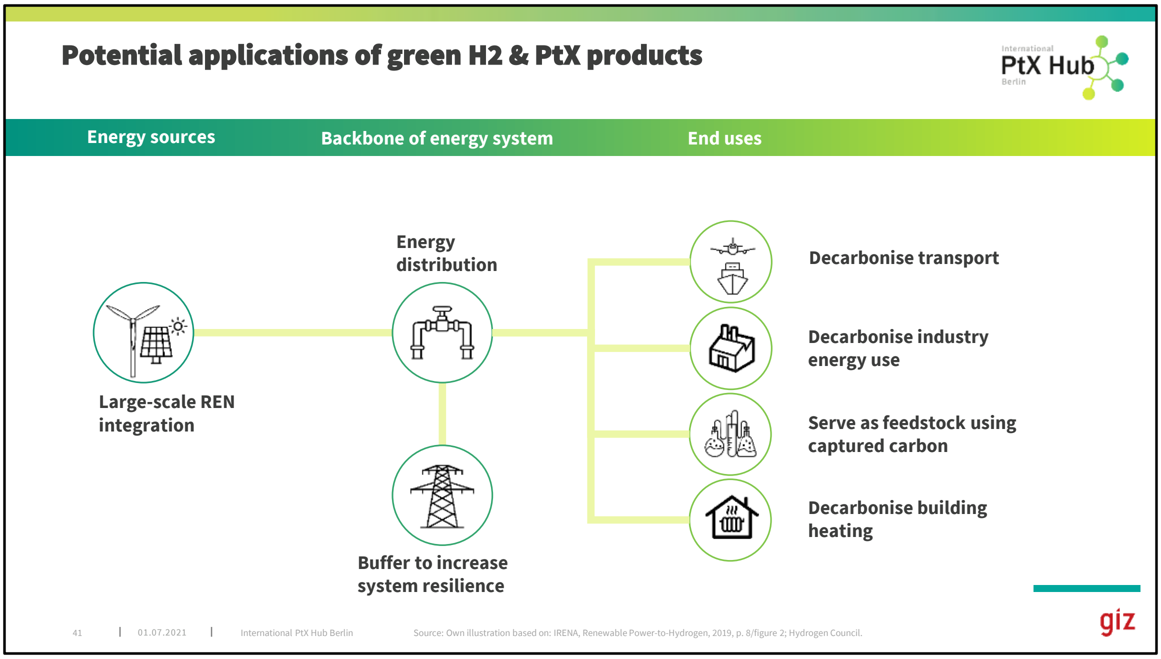
Notes:

- Electrolysers are an **already mature and commercially available technology,** yet there is room for development.
- The 3 main electrolysis alternatives are:
  - **Alkaline water electrolysis** with an alkaline liquid electrolyte; has been used for decades, robust but less flexible than PEM (Polymer Electrolyte Membrane).
  - **PEM** with a polymeric solid electrolyte; **flexible** (responds quicker to load changes), **fast start-up, high pressures involved** allow coupling with subsequent **synthesis processes operating at more than 200 bars; but: higher investments with this technology**.
  - **SOEC** (Solid Oxide Electrolyser Cell) is a high-temperature **steam electrolysis using solid oxide electrolytes; more efficient,** can use heat from synthesis **processes; but lacks flexibility compared** to the former two and is still being developed.

Further comments:
In general, the practical application is likely to determine the technology used. **PEM is (somewhat) better at handling fluctuating electricity and** is more **suitable for direct connection to a wind or PV systems and thus probably more suitable for small applications**.
The end product, e.g. NH_3 or synthetic fuels, also impacts the choice of method. Those plants cannot be regulated or switched off easily, so constant H_2 input is needed. In this case, the advantage of PEM does not matter, ALK is cheaper.

Source:
WEC, 2018



Notes:

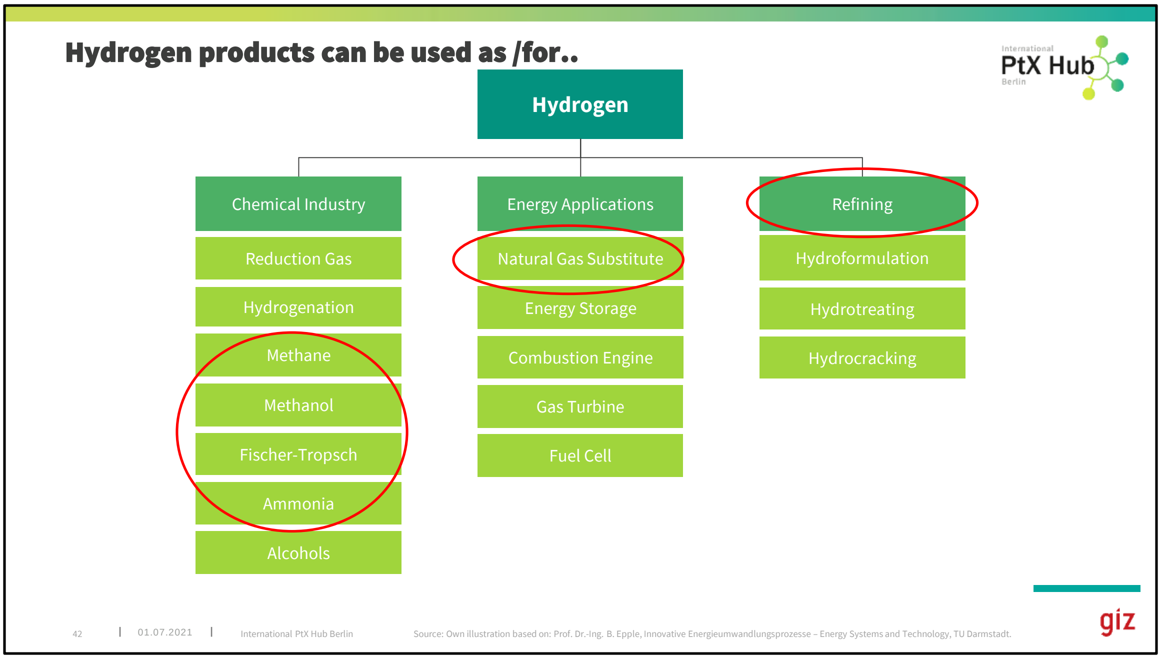
- **Carbon-based synthetic e-fuels can promote decarbonisation** if they are produced **with renewable power and if carbon inputs are climate neutral**.
- Therefore it requires **large-scale REN integration:** Currently, **roughly 95% of worldwide H_2 production comes from fossil fuels**.
- Converting variable renewable energy sources to H_2 via electrolysis can contribute to power sector transformation in several ways:
- **Energy distribution:**
    - **Transporting renewable power over long distances as H_2:**

      Over ~3,500-5,000 km: transport of molecules cheaper, H_2 pipelines being the cheapest option for long distances
      (~3ct/kWh, medium-term 6ct/kWh).
      Shipping is more expensive (~9 ct/kWh).
- **Buffer to increase system resilience:**
    - **Long-term energy storage**:
        - **intraday imbalances caused** by VRE generation might be better managed **with batteries in economic terms,**
        - **while seasonal variations need long-term storage** solutions such as **P2H$_2$** (Eichman and Flores-Espino, 2016).
    - **H_2 can serve as a long-term storage medium**, with **capability of storing energy for several months.**
    - **It can reduce variable RE curtailments**: When **RE cannot be fed into the power grid** due to network constraints or low demand, it could be **supplied to electrolysers for production of H_2** via electrolysis.
        - Procuring excess RE (which is likely to be curtailed or sold at near zero marginal prices) can

significantly help improve the economics of H_2 production.
    - Offtaking excess renewable energy also enables VRE asset owners to gain incremental revenues and reduces their exposure to volatility in power prices.

    But: this option, **requires great availability of renewable power** (at relatively low cost) to **ensure a good load factor at electrolysis facility** (low load factors yield a high levelised cost of H_2 (LCOH), as the *CapEx (capital expenditures)* of the electrolyser, a key component of the H_2 cost, need to be allocated to low production volumes).
  - **Grid-balancing services via the electrolyser**: Frequent fluctuations in power generation from variable sources call for rapid-response balancing options. The electrolyser systems used to produce H_2 can be cycled up and down rapidly. The performance of alkaline and PEM electrolyser technologies differs when used to provide specific grid services.
- **End uses:**
  - **Decarbonise transport**
  - **Decarbonise industry energy use**
  - **Serve as feedstock using captured carbon, such as in the production of fertilisers**
  - **Decarbonise heating of buildings**

Source:
- https://Hydrogeneurope.eu/Hydrogen-applications
- https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Power-to-Hydrogen_Innovation_2019.pdf?la=en&hash=C166B06F4B4D95AA05C67DAB4DE8E2934C79858D#:~:text=Hydrogen%20can%20be%20produced%20by,complementary%20carrier%20of%20renewable%20energy.


Hydrogen products can be used as /for..
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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
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Source: Own illustration based on: Prof. Dr.-Ing. B. Epple, Innovative Energieumwandlungsprozesse – Energy Systems and Technology, TU Darmstadt.
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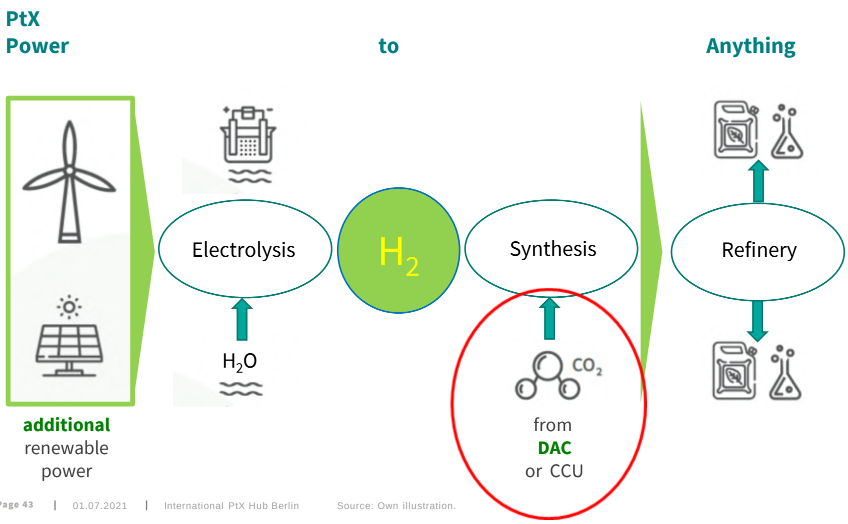
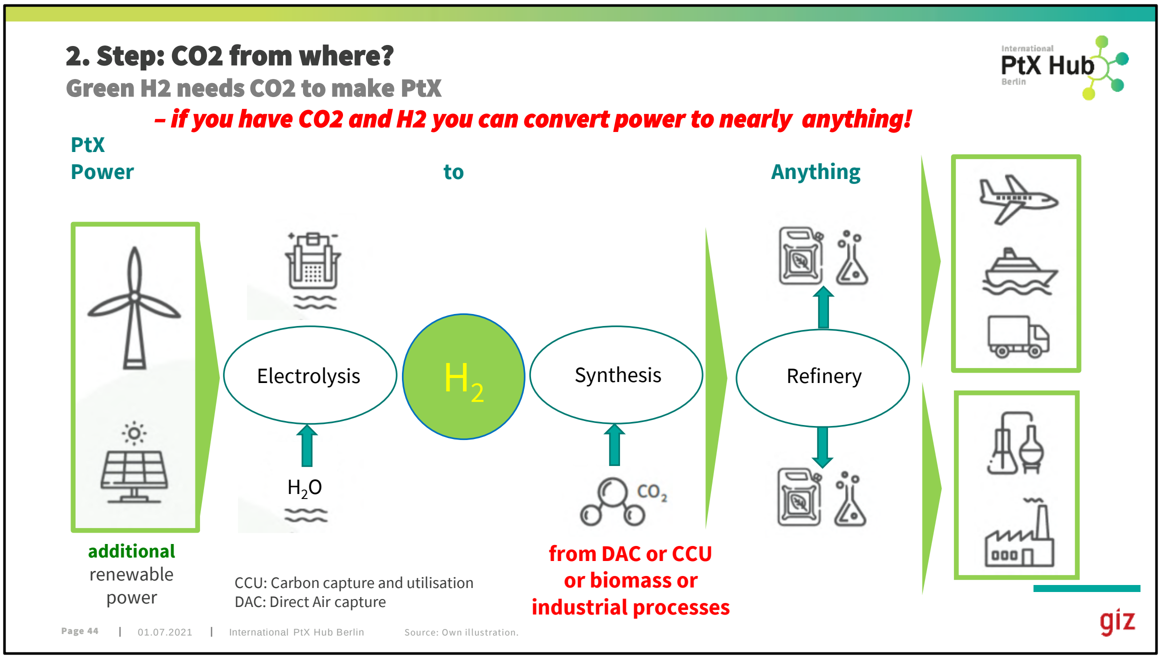
2. Step: CO2 from where?
Green H2 needs CO2 to make PtX



Source: Own illustration.


2. Step: CO2 from where?
Green H2 needs CO2 to make PtX
– if you have CO2 and H2 you can convert power to nearly anything!
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PtX
Power
to
Anything
Electrolysis
H2
Synthesis
Refinery
H2O
CO2
additional
renewable
power
CCU: Carbon capture and utilisation
DAC: Direct Air capture
from DAC or CCU
or biomass or
industrial processes
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Source: Own illustration.
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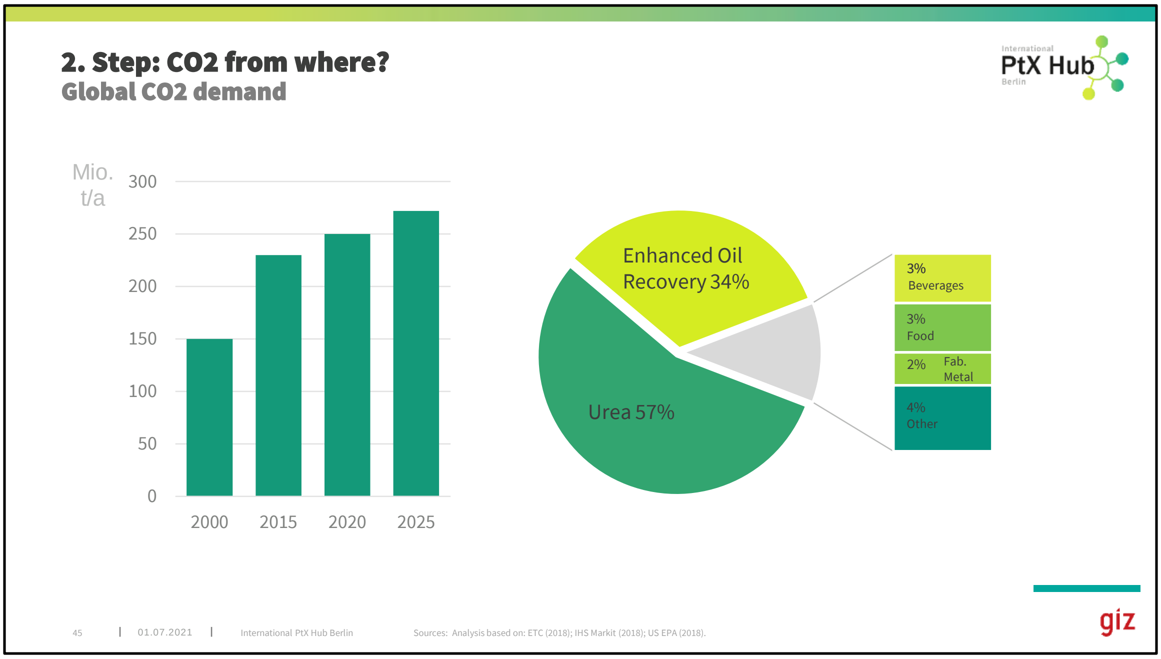

Notes:

- An estimated current global demand **of 80 Mt/year of CO_2 is supplied by natural CO_2 reservoirs** and as a **by-product of several industrial processes**.
- At least **50 Mt/year are used for CO_2 Enhanced Oil Recovery (EOR),** mostly in North America, **80% of CO_2 used for EOR come from natural wells.**
- Projections for future global CO_2 demand are based on an average year-on-year growth rate of 1.7%.

Further comments:

- **EOR**: Gas injection, which uses gases such as natural gas, nitrogen, or CO_2 that expand in a reservoir to push additional oil to a production wellbore, or other gases that dissolve in the oil to lower its viscosity and improves its flow rate.
- **Urea**: To make urea, fertiliser producers combine NH_3 with CO_2, but when farmers apply that urea to the soil, an equal amount of CO_2 is emitted to the atmosphere

Sources:

Analysis based on ETC (2018); IHS Markit (2018); US EPA (2018).

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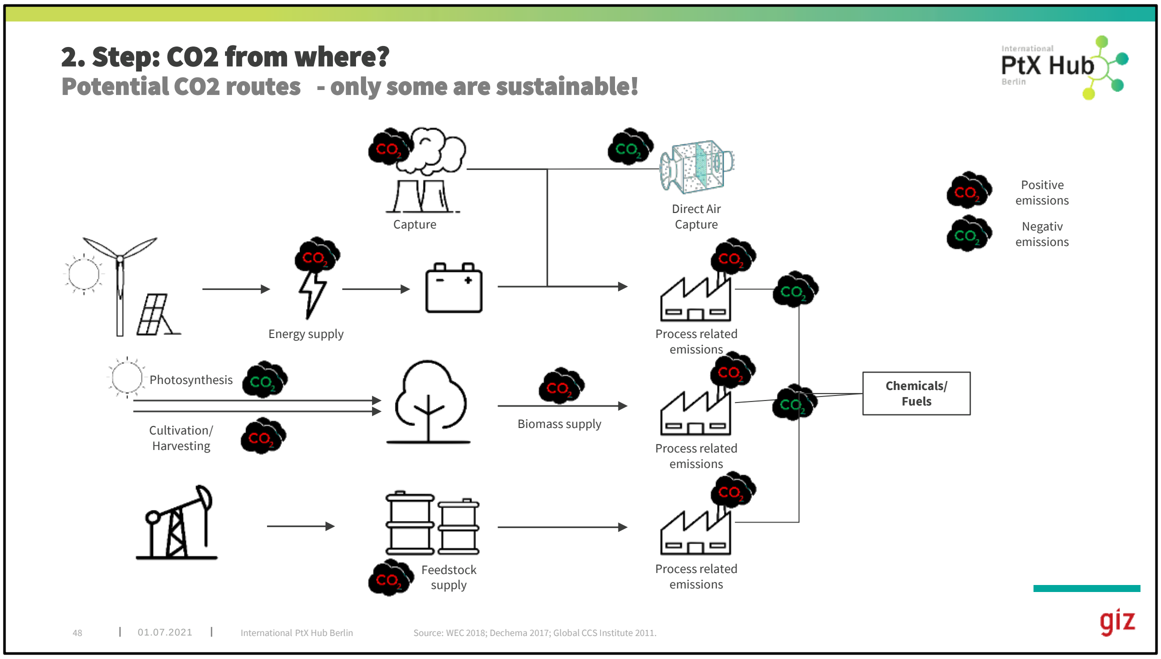
"How can you obtain the CO_2 for green PtX production?"

"Which method to produce CO2 do you think is the most sustainable for PtX?"

- Show next slide for this question -



Notes:

- **Green CO_2 supply is crucial to decarbonise synthetic fuels production** but further cost reductions are needed.
- For synthetic fuels such as methane, diesel, heating oil, gasoline, kerosene etc., CO_2 is required as an input factor alongside H_2
- The CO_2 can be captured directly from the air, from biomass/biogas or from flue gases from the industry.
- Carbon capture is commercially available but expensive
  - Direct Air Capture (DAC) (150-180€/t CO_2)
  - Biomass (90€/t CO_2)
  - Industrial emissions (30-50€/t CO_2)

Source:

- WEC 2018
- Dechema 2017
- https://hub.globalccsinstitute.com/publications/accelerating-uptake-ccs-industrial-use-captured-carbon-dioxide/2-co2-market
- Global CCS Institute, (Ist das diese Quelle: accelerating-uptake-ccs-industrial-use-captured-carbon-dioxide.pdf (globalccsinstitute.com) ?)

2. Step: CO2 capture

→ **Direct Air Capture is the only vastly available and sustainable CO2 source!**

→ **In some places the same counts for biomass**

Challenge
CO2 Costs:

- **Biomass (90€/t CO2)**
- **Industrial emissions (30-50€/tCO2)**
- **Direct Air Capture (150-180€/tCO2)**
- **Some say up to 400 €/tCO2**

 Image Source: Climeworks.com

Notes:

- The price of **bulk CO_2 typically ranges from 2.5€/tCO_2 and 13€/tCO_2.**
- **Carbon capture is commercially available but expensive** (WEC, 2018).
- CO_2 can come from: **biomass (90€/tCO_2), industrial emissions (30-50€/tCO_2), DAC (150-180€/tCO_2)**

Sources:

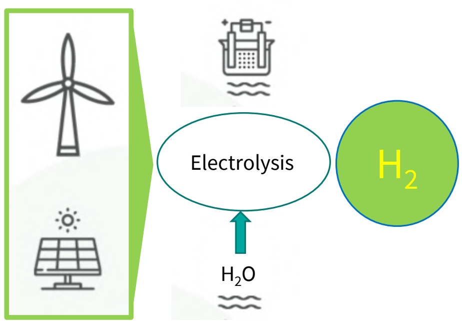
Climeworks.com

3. Step: Production of PtX – via different processes

Converting power to anything

PtX

Power **to** **Hydrogen**



additional renewable power

Example: With the **Fischer-Tropsch** synthesis process

it is possible to synthesise **H_2 and CO_2**

into **hydro-carbon base materials** (FT-SynCrude)

for further **processing or use**

Source: Own illustration.

3. Step: Production of PtX

Different processes to produce different PtX

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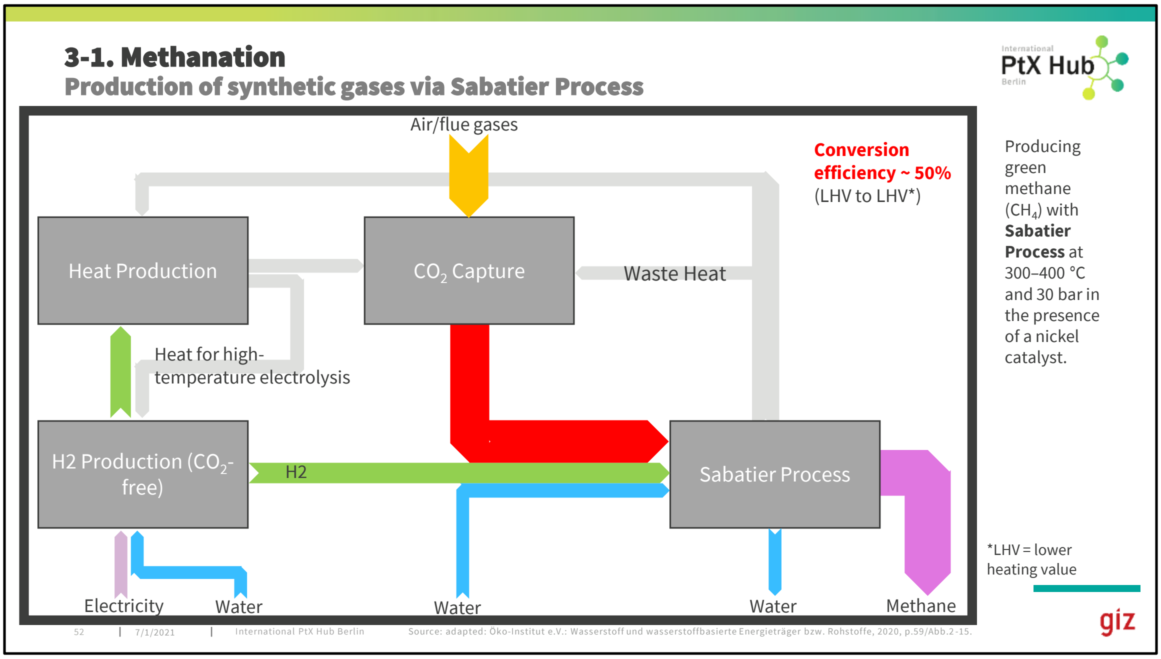
1. Methanation Process

- Production of synthetic “natural gas” - methane
- Process: Sabatier Process, mature, commercially available, complex
- Other process in lab scale/pilot stage
- Overall efficiency around 50%
- Currently very high costs for synthetic methane when using H2

2. Fischer-Tropsch Synthesis

3. Methanol production

4. Green Ammonia



Notes:
From Wikipedia, the free encyclopaedia

“Paul Sabatier (1854-1941) winner of the Nobel Prize in Chemistry in 1912 and discoverer of the reaction in 1897.
The Sabatier reaction or Sabatier process produces methane and water from a reaction of H_2 with CO_2 at elevated temperatures (optimally 300–400 °C) and pressures (perhaps 30 bar) in the presence of a nickel catalyst. It was discovered by the French chemists Paul Sabatier and Jean-Baptiste Senderens in 1897. Optionally, ruthenium on alumina (aluminium oxide) makes a more efficient catalyst. It is described by the following exothermic reaction.”

3-1. Methanation
How are e-fuels produced?

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Methanation costs are high when coupled with hydrogen.

→ but there is room for further development

H2 and CO2 can be transformed into methane by **methanation**.

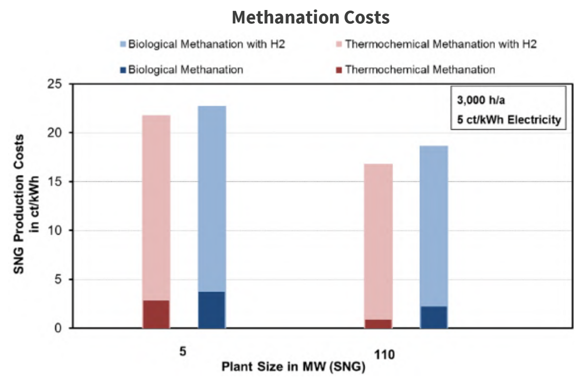
Main methanation options are:

- **Technical-catalytic:** using modified membranes a high quality gas is produced
  - 3PM in lab scale, tolerance for impurities: medium
  - Fixed bed is commercial, tolerance for impurities: low.

  →Attractive for high reaction rates and coupling heat from other processes

  → Lower costs involved for high capacity plants.
- **Biological:** CO_2 from a biogas is treated directly in the fermenter of a biogas.
  - BM in lab scale/pilot stage, simple, tolerant to impurities but slow.

  → Attractive for small plants and impure gas feeds.



→ Both options increase in price when coupled with H2 produced via electrolysis, instead of blue H2

 Source: Manuel Götz, State of the Art and Perspectives of CO2 Methanation Process Concepts for Power-to-Gas Applications, 2014.

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Notes:
Main options to perform methanation:
- **Technical-catalytic:** with the help of modified membranes, a high quality gas is produced
  - → high reaction rated and heat coupling form other processes
  - → high capacity plants have overall lower costs for this method
- **Biological**: CO_2 type equation from a biogas is treated directly in the fermenter of biogas
  - → easy and intolerant to impurities → attractive for smaller plants & impure gas feeds

→ Both ways are getting much more expensive when electrolysis instead of blue H_2 is used

Source: Manuel Götz, Amy McDaniel Koch, Frank Graf, State of the Art and Perspectives of CO2 Methanation Process Concepts for Power-to-Gas Applications, 2014 (https://www.researchgate.net/publication/273139805_State_of_the_Art_and_Perspectives_of_CO2_Methanation_Process_Concepts_for_Power-to-Gas_Applications).

3. Step: Production of PtX
Different processes to produce different PtX

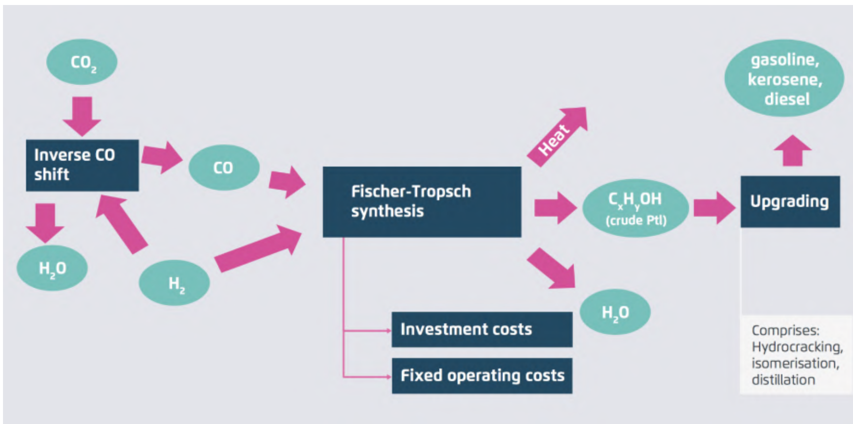
1. **Methanation Process**
   - Production of synthetic "natural gas" - methane
   - Process: Sabatier Process, mature, commercially available, complex
   - Other process in lab scale/pilot stage
   - Overall efficiency around 50%
   - Very high costs for synthetic methane when using H2

2. **Fischer-Tropsch Synthesis**
   - Production of raw liquid fuel (CXHYOH) 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%
   - Smaller processes with DAC in development /pilot stage
   - Very high costs for synthetic fuels when using H2

3. **Methanol production** process to produce olefins for plastics, OME (oxymethylene ether), DME (dimethyl ether)
4. **Green Ammonia**

3-2. Fischer-Tropsch Synthesis: Liquid fuel production

How are e-fuels produced?



Fischer-Tropsch synthesis uses carbon monoxide and H2 to produce a raw liquid fuel (CXHYOH)

Fischer-Tropsch synthesis is a mature process and further cost reductions are not expected.

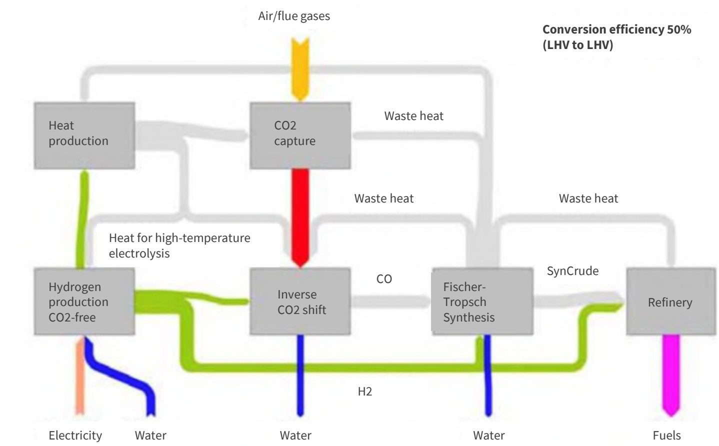
Source: Agora, The Future of Electricity-Based Synthetic Fuels, 2018, p.69/figure 15.

Notes:

- In the production of synthetic liquid fuels using Fischer-Tropsch synthesis, **carbon monoxide and H_2 are used to produce a raw liquid fuel** (CXHYOH) that is then refined.
- Carbon monoxide is obtained from CO_2 using a reverse water-gas shift reaction.
- Fischer-Tropsch synthesis is currently used e.g., in the **Sunfire demonstration plant in Dresden**.
- Nordic Blue Crude plans to use Fischer-Tropsch synthesis to produce synthetic diesel in Norway.
- The Fischer-Tropsch process is a relatively established technology that is already used on a larger scale to obtain synthetic fuels from coal.

Source: https://static.agora-energiewende.de/fileadmin/Projekte/2017/SynKost_2050/Agora_SynKost_Study_EN_WEB.pdf

3-2. Fischer-Tropsch Synthesis
Production of synthetic liquid (schematic diagram)

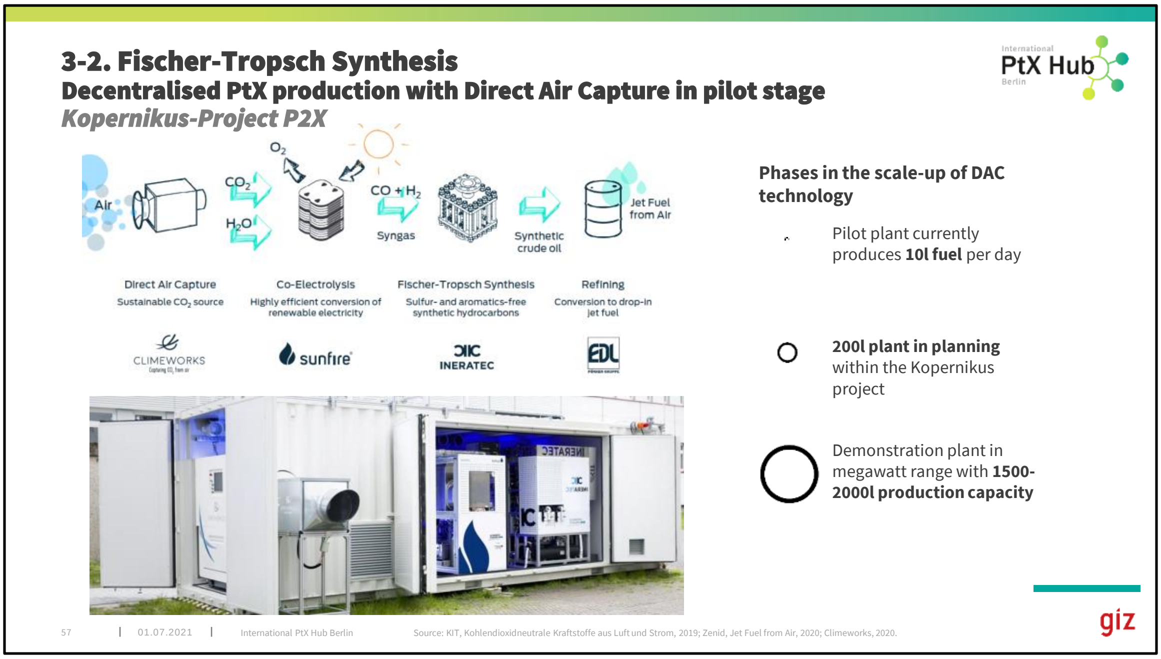


Output of Fischer Tropsch Synthesis depends on final product; (conversion efficiency from CO + H2 to final product)
Diesel fuel: 230 C, 40 bar, 60 – 90%
Gasoline: 340 C, 25 bar 85%

Fischer-Tropsch process to produce syn. fuels exists in large scale

→ But overall efficiency below 50% with H2!

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



Further comments:
Climeworks explanatory movie: https://www.youtube.com/watch?v=63S0t4k_Glw

Sources:

- Karlsruher Institut für Technologie (2019). Kohlendioxidneutrale Kraftstoffe aus Luft und Strom**,** Presseinformation, https://www.kit.edu/kit/pi_2019_107_kohlendioxidneutrale-kraftstoffe-aus-luft-und-strom.php
- Zenid (2020). *Jet Fuel from Air.*

3-3. Methanol synthesis: Liquid fuel production

How are e-fuels produced?

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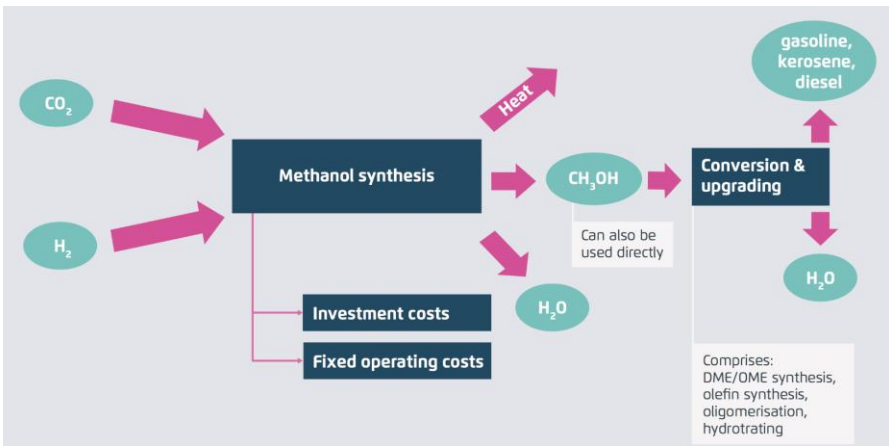

Methanol process at 250 C, 75 bar, efficiency 80%
If one use DAC and RE power costs are 5 x time more costly than from fossil fuel 1100 $/t to 200 $/t

Methanol synthesis is a mature process and further cost reductions are not expected.

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

58 | 01.07.2021 | International PtX Hub Berlin Source: Agora, The Future of Electricity-Based Synthetic Fuels, 2018, p.69/figure 14.

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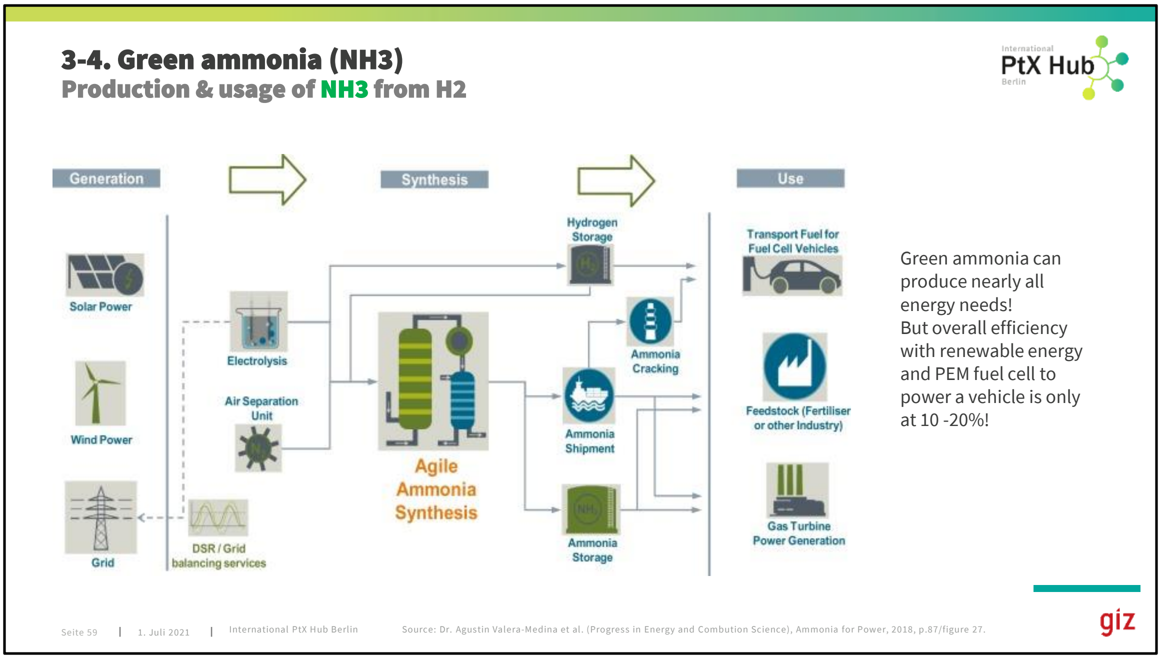
Notes:

- Synthetic liquid fuels are produced from H_2 and CO_2 or carbon monoxide using methanol synthesis or Fischer-Tropsch synthesis.
- In the case of **methanol synthesis, methanol is produced from H_2 and CO_2 or carbon monoxide**.
- **Methanol can either be used directly or converted further to synthetic petrol**, diesel or monomolecular fuels such as **OME (oxymethylene ether)** and **DME (dimethyl ether).**
- The largest methanol synthesis plant is currently in operation in Iceland and generates more than 5 million liters of methanol per year.

Source: https://static.agora-energiewende.de/fileadmin/Projekte/2017/SynKost_2050/Agora_SynKost_Study_EN_WEB.pdf



Notes:

Production of NH_3 from H_2:

- Manufactured via the well-established **Haber–Bosch process.**
- **Approx. 97% of nitrogen fertilisers** are derived from NH3. Here, high purity (99.99%) H_2 and nitrogen are typically reacted together at a temperature between 623.2 - 823.2 K at pressures between 10-25 MPa in the presence of a catalytic material.
- H_2 is currently mainly sourced from **hydrocarbons** obtained from steam reforming of methane and partial oxidation of coal, producing an annual global total of ~290Mt of CO_2, approx. 1% of total CO_2emissions.
- Production of NH_3 consumes ~1.8%−3.0% of all global energy, mainly via fossil fuels, making it one of the single largest producers of CO_2.
- The **production process generates vast quantities of NOx** that through Best Available Techniques need to be removed via selective non-catalytic reduction, thus increasing cost of operation.
- **New technologies seek to produce H_2 from carbon-free sources** such as electrolysis of water using sustainable energy, thus, mitigating the excessive production of carbon emissions while increasing flexibility of production and recovery of stranded sources internationally.
- Recent energy studies using data obtained from the facility at Leuna, Germany, determined that the use of water electrolysis and pressure swing adsorption (PSA) to develop decentralised Haber–Bosch processes are feasible options as potentially competitive systems for the production of NH_3, which can be employed for energy storage.
- Currently, NH_3 production from electrolysed H_2 accounts for approximately 0.5% of global NH_3 production. **Greatest limitation** to this process are the **economics**, which are being improved through studies to show the considerable potential for the production of H_2 and NH_3 via electrolysis product of sustainable sources, with companies already investigating the development of industrial facilities to pursue the reduction of GHGs while improving feedstock and resilience of these NH_3 production methods.
- *(Nuclear power has also been considered, although initial Life Cycle Assessments show their detrimental*

impact on various aspects related to confinement and disposal of radioactive material, Fig. 10, thus making renewable sources the most promising alternative for the near to intermediate future.)

Storing H_2 – NH_3:

- Storage solutions such as **lithium batteries or redox cells are unlikely to be able to provide the required capacity for grid-scale energy storage**.
- Pumped hydro and methods such as compressed gas energy storage suffer from geological constraints to their deployment.
- The only sufficiently flexible mechanism allowing **large quantities of energy to be stored over long time periods at any location is chemical energy storage**.
- Chemical storage of energy can be considered **via H_2 or carbon-neutral H_2 derivatives**. One example is NH_3, which has been identified as a sustainable fuel for mobile and remote applications.
- Similar to synthesised H_2, NH_3 is a product that can be obtained either from fossil fuels, biomass or other renewable sources like wind and PV, where excessive electrical supply can be converted into some non-electrical form of energy.

Advantages of NH_3 over H_2:

- lower cost per unit of stored energy, i.e. over 182 days NH_3 storage would cost 0.54 \$/kg-H_2 compared to 14.95 \$/kg-H_2 of pure H_2 storage,
- higher volumetric energy density (7.1–2.9 MJ/L), easier and more widespread production, handling and distribution capacity, and better commercial viability.

NH_3 produced by harvesting of renewable sources has the following properties:

- **carbon-free** (no direct greenhouse gas effect) and can be **synthesised with an entirely carbon-free process from renewable power sources**,
- **energy density of 22.5 MJ/kg**, comparable to that of fossil fuels (low-ranked coals have around 20 MJ/kg; natural gas has around 55 MJ/kg, LNG 54 MJ/kg, and H_2 142 MJ/kg),
- **can easily be rendered liquid** by compression to 0.8 MPa at atmospheric temperature,
- **reliable infrastructure already exists for both NH_3 storage and distribution** (incl. pipeline, rail, road, ship); today around 180 million tons of NH_3 are produced and transported annually.

Challenges:

- Carbon-free synthesis of NH_3,
- Power generation from small to utility-scale size,
- Public acceptance through safe regulations and appropriate community engagement,
- Economic viability for integration of technologies and green production of NH_3.
- Reduction of NOx emissions and unburned NH_3, contaminants that directly impact on climate change and are toxic to life, respectively. It is recognised that NO_2 can aggravate cardiovascular and respiratory diseases.
- Toxicity of NH_3 is one of the major impediments to deploy these technologies, as public perception is very formative and perception on the nuisance of its smell even at low concentrations is a critical barrier.

Efficiency: Assuming that NH_3 is produced from completely renewable power, cracked into high-purity H_2, and used in a PEMFC to power a vehicle, the net efficiency for worst and best case scenario is between 11% and 19%.

Source: https://www.sciencedirect.com/science/article/pii/S0360128517302320

3-4. Green ammonia
Production & usage of NH3 from H2

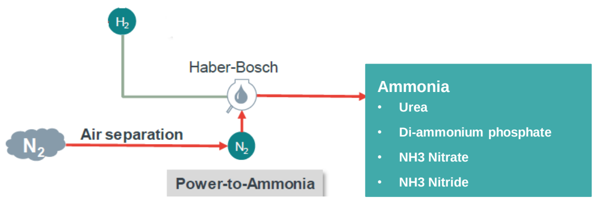
Big advantage: Green ammonia provides a pathway to fully CO_2 neutral electricity generation and storage on a scale that is not limited by scarcity of materials or storage space

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

How can green ammonia be used?

- As an **energy carrier** of H2 to enable transportation (higher energy density compared to H2)
- As **fuel in fuel cells**
- or **directly in combustion engines.**
- And to **decarbonise the fertiliser production**

Green ammonia production



Haber-Bosch Process at 200 bar, 450°C with 3:1 of N2 and H2;
HB Process needs around 1,1% of world energy demand alone

Sources: ISPT 2017, Dena 2019.
Graph: WEC, 2018.

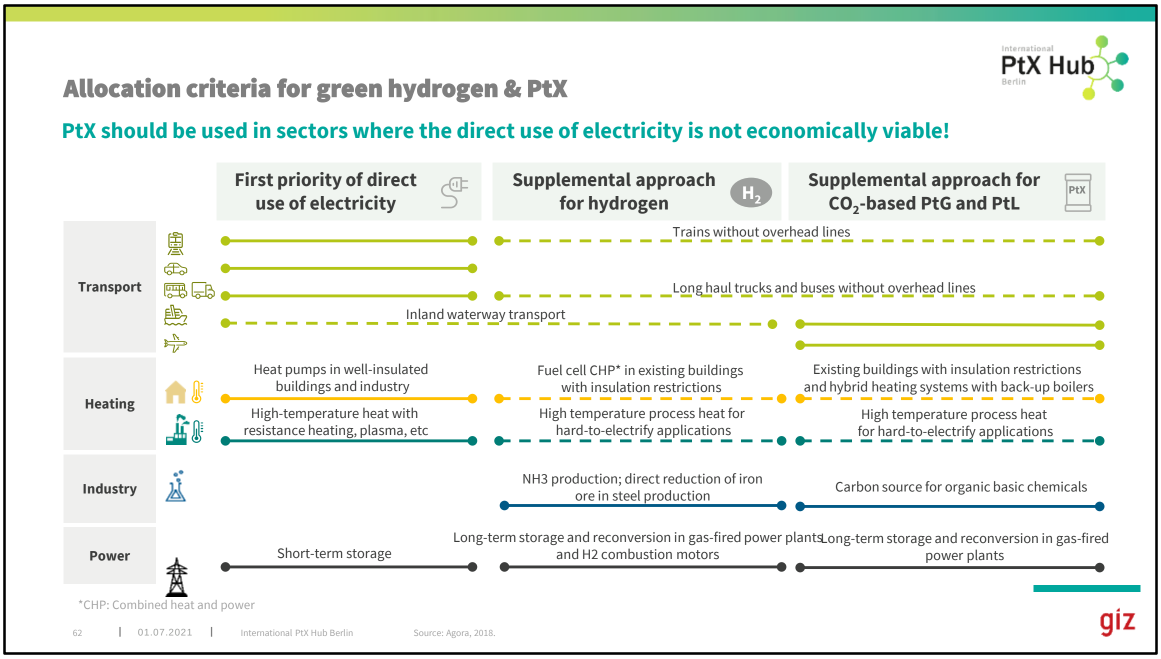
Fertiliser Complexes are large industrial complexes, e.g. Yara Porsgrunn - decentralised Haber Bosch process are possible, are under development

Image Source: ChemieTechnik: Norwegische Firmen planen grünes ammoniakprojekt, 2021, available at: https://www.chemietechnik.de/anlagenbau/norwegische-firmen-planen-gruenes-ammoniakprojekt-113.html

Image Source: Der Tagesspiegel, Kunstdünger ohne Treibhausgase, 2014, available at: https://www.tagesspiegel.de/wissen/ammoniakherstellung-kunstduenger-ohne-treibhausgase/10318420.html

Notes:

The Yara Porsgrunn Fertiliser Complex integrates an NH_3 plant with a **capacity of 530,000t/y,** 3 nitric acid units with a combined capacity of 1.35Mt/y, 2 NPK units, namely NPK2 and NPK3, with a combined capacity of 2Mt/y, and two calcium nitrate (CN) units with a total capacity of approximately 1Mt/y. **The complex also produces gases and chemicals for industrial applications.**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Allocation criteria for green hydrogen & PtX
PtX should be used in sectors where the direct use of electricity is not economically viable!
First priority of direct use of electricity
Supplemental approach for hydrogen
H_2
Supplemental approach for CO_2-based PtG and PtL
PtX
Transport
Trains without overhead lines
Long haul trucks and buses without overhead lines
Inland waterway transport
Heating
Heat pumps in well-insulated buildings and industry
Fuel cell CHP* in existing buildings with insulation restrictions
Existing buildings with insulation restrictions and hybrid heating systems with back-up boilers
High-temperature heat with resistance heating, plasma, etc
High temperature process heat for hard-to-electrify applications
High temperature process heat for hard-to-electrify applications
Industry
NH3 production; direct reduction of iron ore in steel production
Carbon source for organic basic chemicals
Power
Short-term storage
Long-term storage and reconversion in gas-fired power plants and H2 combustion motors
Long-term storage and reconversion in gas-fired power plants
*CHP: Combined heat and power
62 | 01.07.2021 | International PtX Hub Berlin
Source: Agora, 2018.
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2nd challenge: Sustainability standards must be applied at every step!

Towards a comprehensive assessment concept

PtX will not take-off
unless comprehensive

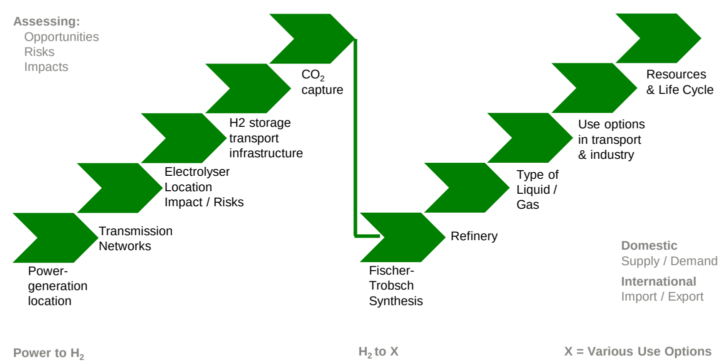
sustainability standards
are met,

ensuring

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

at **different levels**
&
at **every step of the value chain**

Sustainability concerns must be considered - at every step of the PtX global value chain



or: menti.com > CODE 123 456

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Test your knowledge

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or: **menti.com > CODE 123 456**

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

"What do you consider the biggest challenge to establishing PtX process plants in your country?"

Please reflect for a moment on the situation in your country:

“Which products using H2/ PtX have already been developed?”

“What could be possible H2/ PtX options in the future in your country?”

- Break out group discussion -

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Training | Module 3

Green Hydrogen & PtX Economics

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

International PtX Hub Berlin

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Module 3: Green Hydrogen & PtX Economics

At the end of this module participants will

- be able to break down overall cost and cost development of H2 and PtX production
- know the central financial concepts “golden age” and “scale by number”
- be aware of future cost development options
- understand key terminology concerning costs structures (CAPEX and OPEX) and related cost types

Benefit for learners:
Widening the understanding of factors influencing the financial costs and benefit of H2/PtX projects will increase the ability of learners to take consistent decisions on sizes, conditions and financing.

Core messages:

- Sustainability **also** means “**economic sustainability**”
- **RE** have the ability to come **to ”golden ages”;** also for the **downstream PtX processes**
- Knowledge on **full-cost calculation** for projects based on H2 / PtX,
- **Design H2 / PtX projects independently from existing grids**
- Apply the concept of “**scale by number**”

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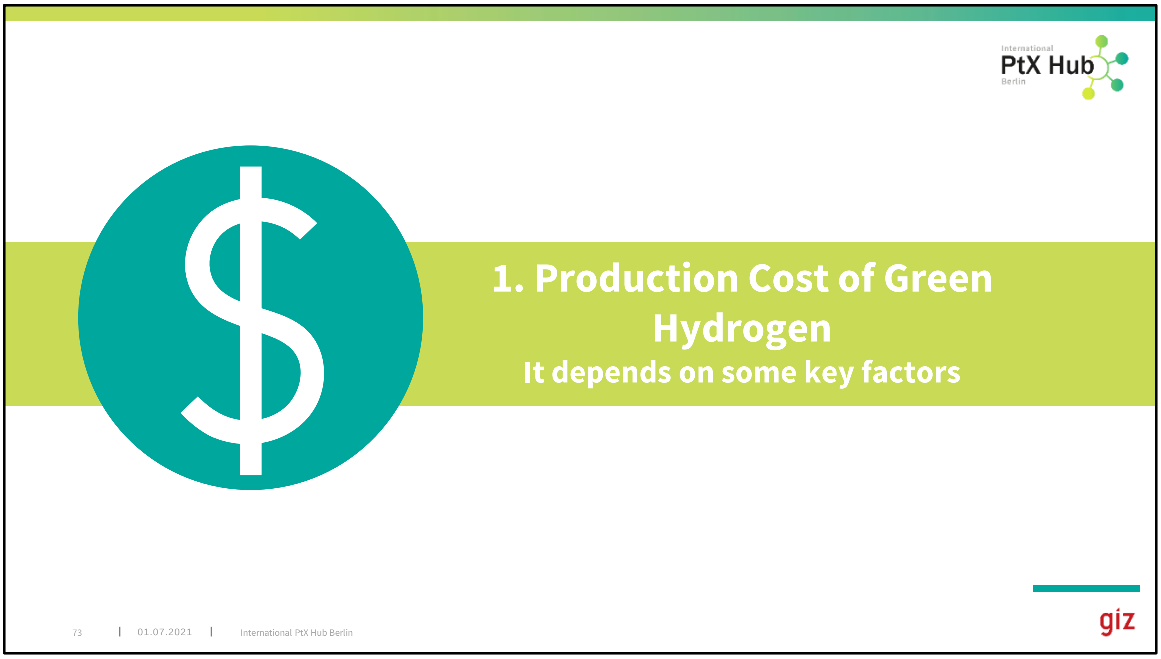
*“What are the biggest challenges to reduce production costs of green **H2**?”*

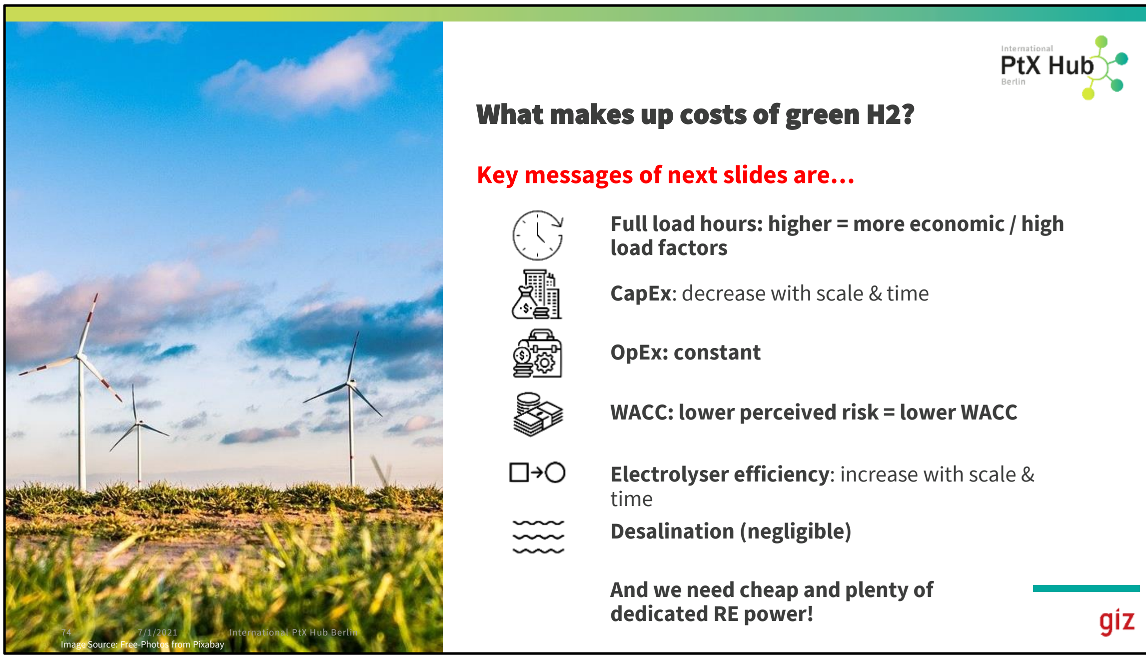
*“What are the biggest challenges to reduce production costs of green **PtX products**?”*



Notes:

- **The major cost component for green H_2 is the electricity supply.**
- **Cost decline in this is already underway through the competitive deployment of renewables.**
- There is a **need to focus on reducing the procurement and construction cost and increasing the performance and durability of electrolysers**, to achieve further cost reductions in green H_2 production.
- Today green H_2 (in ideal locations with the lowest renewable electricity costs) can achieve cost-competitiveness with fossil-based H_2.
- Cost reductions in renewable electricity and electrolysers will continue to a rising number of sites where green H_2 can be produced competitively.
- Policy support in recently unveiled H_2 strategies in many countries is mostly in the form of explicit electrolyser capacity targets and, to a more limited extent, cost targets. These have yet to translated into **specific regulatory instruments**. So far, these explicit targets are not enough to be in line with 1.5°C decarbonisation pathways.

Source: IRENA – Green H2 Cost Reduction – Scaling up electrolyseres to meet the 1.5°C climate goal



Notes:

- Electricity costs **dependent on full load hours (FLH) as CapEx & OpEx/kWh are divided by FLH**; **need for dedicated RE, not „excess“ RE power**

<u>CapEx</u>:

- Capital expenditures are major purchases a company makes that are designed to be used over the long-term, typically for fixed assets like property, plant and equipment.

- One of the defining features of **CapEx is longevity**, meaning purchases benefit the company for longer than one tax year. Fixed assets are depreciated over time to spread out the cost of the asset over its useful life.

Depreciation is helpful for CapEx because it allows the company to avoid a significant dip in its bottom line in the year the asset was purchased.

- CapEx can be **externally financed, which is usually done through collateral or debt financing.**

<u>OpEx:</u>

- Operating expense are the day-to-day expenses a company incurs to keep their business operational**.**

- **Reported on income statements and companies can deduct OpEx from their taxes of the year** in which the expenses were incurred (e.g. rent & utilities, wages and salaries, interest paid on debt etc.).

- OpEx also **consist of R&D expenses and the cost of goods sold**. The goal of any company is to maximise output relative to OpEx. In this way, OpEx represents a core measurement of a company's efficiency over time.

WACC: weighted average cost of capital.

Cost of capital:

- **fixed, one-time expenses** incurred on the purchase of land, buildings, construction, and equipment used in the production of goods or in the rendering of services. In other words, it is the total cost needed to bring a project to a commercially operable status.

Electrolyser efficiency:

- **Conversion costs: The conversion costs of H_2 refer to the operating cost, including** water and other consumable inputs, multiplied by the conversion rate of the electrolyser.
- **Desalination cost negligible**

Further comments:

- Need for cheap financing → **low interest-rates through risk reduction FLH is critical and needs:**
  - **Dedicated RE infrastructure**, both wind and PV, good wind/solar resources
  - Best technology: tracking PV, high hub height wind
- For CapEx & OpEx to decrease & efficency to increase, **we need deployment at scale (scale by number rather than scale by size)**
- **Definition Production Capacity**: **volume of products or services** that can be produced by an enterprise using current resources.
- **Definition Energy efficiency**: refers to the amount of output that can be produced with a given input of energy. Energy efficiency is normally measured as the amount of energy output for a given energy input and listed as a percentage between 0-100%.
- **Energy efficiency is closely linked to cost and production capacity**. For electrolysis, stack and system energy efficiencies are often reported interchangeably. Similarly, efficiencies are being reported both on lower (LHV) and higher (HHV) heating values, leading to further comparison mismatches.

Sources:

- Agora: The Future costs of electricty based synthetic fuels
- The Cost of production and Transport of Green H2 from Africa and unexpected Water Benefits by Thomas Roos (CSIR)
- https://www.europarl.europa.eu/RegData/etudes/BRIE/2015/568361/EPRS_BRI(2015)568361_EN.pdf
- Picture: Windpark Energie Grün - Kostenloses Foto auf Pixabay

H2 production costs: now and in 2050 in Germany

Key figures & trends shows the challenge we are all in!

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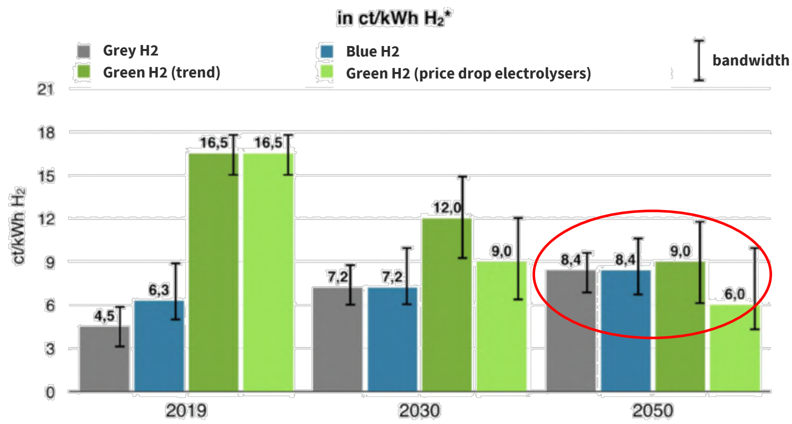

Quelle: Eigene Darstellung auf Basis der Fachliteratur in Kap.2
Annahmen für 2030: CO_2 Preis 100 €/t; Erdgaspreis stabil;
Annahmen für 2050: wie 2030 plus Carbon Import Tax von 100 €/t CO_2
*Zur Umrechnung: 1 €/kg H_2 = 3,0 ct/kWh H_2

Assumption for
CO2 price in Germany:
2030: 100 Euro/t
2050: 100 Euro/t +
Carbon Import tax 100 Euro/t

6 ct/ kWh H2 = 2 Euro/kg H2

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

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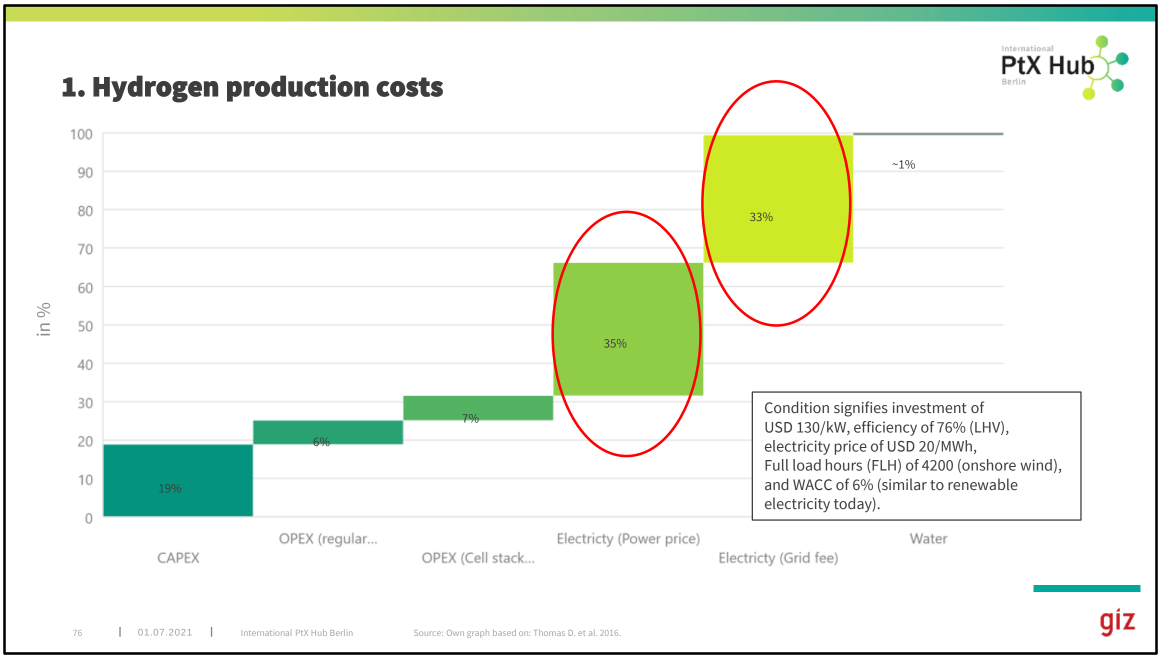

<u>Sources:</u>

- Percentages taken from Thomas D. et al. (2016)
- ‘Today’ captures best and average conditions. ‘
- Average’ signifies an investment of USD 770/kilowatt (kW),
- efficiency of 65% (lower heating value – LHV),
- an electricity price of USD 53/MWh,
- FLH of 3200 (onshore wind),
- and a weighted average cost of capital (WACC) of 10% (relatively high risk).

- ‘Best’ signifies investment of USD 130/kW,
- efficiency of 76% (LHV), electricity price of USD 20/MWh, FLH of 4200 (onshore wind), and a WACC of 6% (similar to renewable electricity today). Based on IRENA analysis

1. Hydrogen production costs: Worldwide expectations look much better

Green H2 should become cost competitive compared to grey and blue H2 → 1 US$/ kg is achievable in 2050

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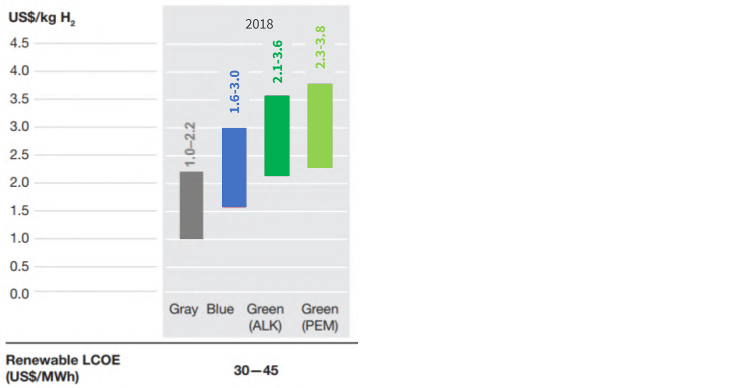
H2 cost development by production type



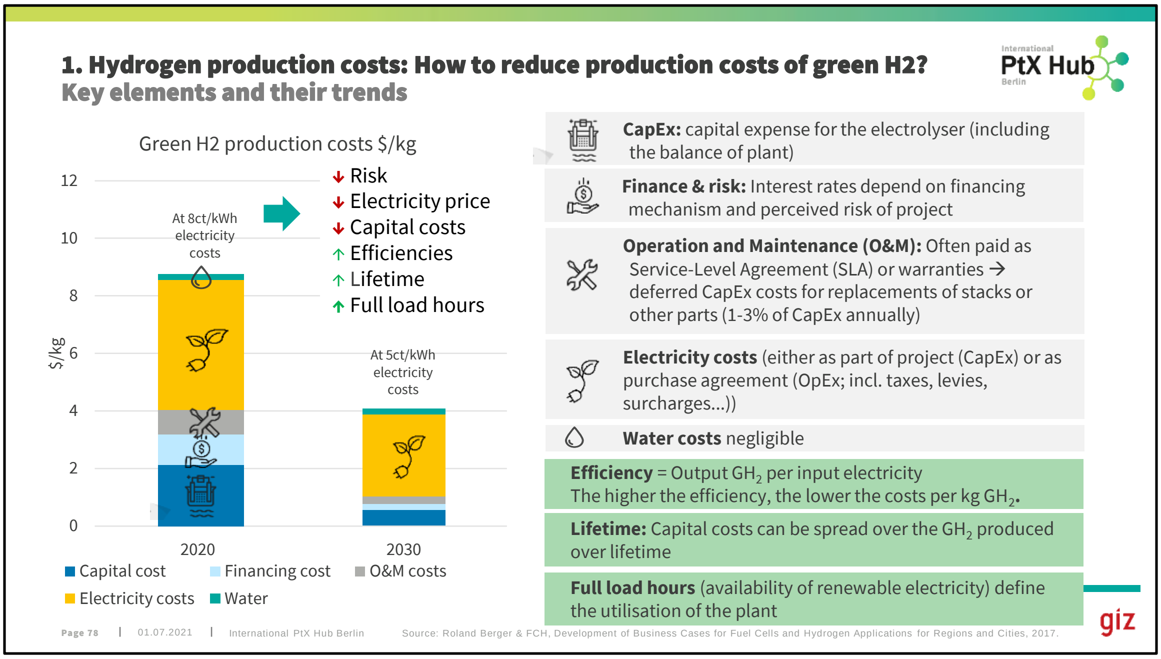
Note: ALK = alkaline water, LCOE = levelised cost of energy, MWh = megawatt hour, PEM = polymer electrolyte membrane.
1 Cost assumptions based on greenfield projects, excluding cost for buildings and cost for building cooling requirements.

 Source: Source: IEA, The Future of Hydrogen: Seizing today's opportunities, 2019.

giz

Sources:

- 2018: IEA Hydrogen production costs by production source, 2018 – Charts – Data & Statistics - IEA
- the-dawn-of-green-Hydrogen.pdf (pwc.com)
- 'Hydrogen Economy' Offers Promising Path to Decarbonization | BloombergNEF (bnef.com)
- Green Hydrogen cost reduction: Scaling up electrolysers to meet the 1.5C climate goal (irena.org)

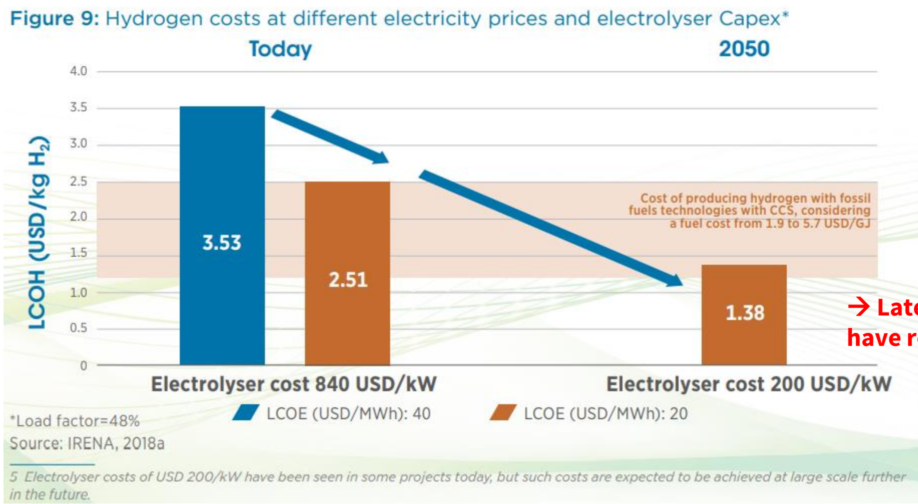


Notes:

- O&M to keep system running in good condition.
- Maintenance costs are significant and differ across AEM, PEM and Alkaline technologies.
- However, the key component to consider here are terms of Service-Level Agreement (SLA) or extended warranties. These include costs that some have described as being practically deferred CapEx costs for replacements of stacks or other parts. Therefore, these OpEx items can quickly amount to annual payments well beyond the often assumed 1-3% to become a significant percentage of total CapEx cost.

Source:
https://www.fch.europa.eu/sites/default/files/FCH%20Docs/171121_FCH2JU_Application-Package_WG5_P2H_Green%20H2%20%28ID%202910583%29%20%28ID%202911641%29.pdf

1. Hydrogen production costs
Impact of electrolyser costs on H2 production costs



→ **Latest in 2050 we have reached it!**

Source: IRENA, Hydrogen – A Renewable Energy Perspective, 2019, p.27.

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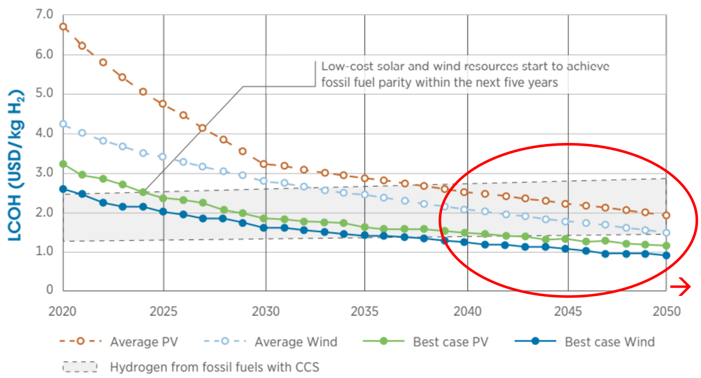
1. Hydrogen production costs:
Impact of renewable energy costs on H2 production costs in 2020 and 2050

Figure 14: Hydrogen production costs from solar and wind vs. fossil fuels



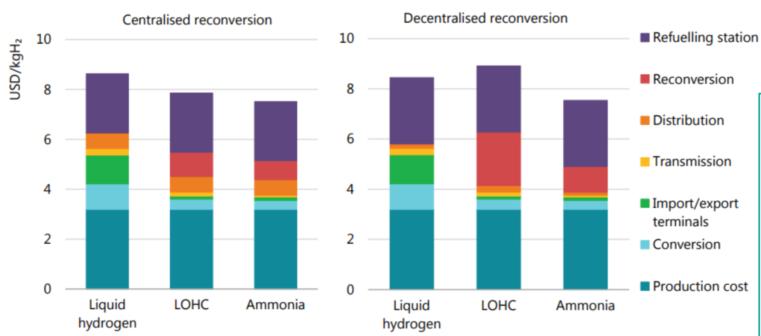
→ Still: need for carbon price of 100-200 \$/tCO_2 in 2040-2050 to be competitive!

Note: Remaining CO_2 emissions are from fossil fuel hydrogen production with CCS.
Electrolyser costs: 770 USD/kW (2020), 540 USD/kW (2030), 435 USD/kW (2040) and 370 USD/kW (2050).
CO_2 prices: USD 50 per tonne (2030), USD 100 per tonne (2040) and USD 200 per tonne (2050).

Source: IRENA, Hydrogen – A Renewable Energy Perspective, 2019, p.34.

Costs of H_2 imports from North Africa to Europe in different energy carriers

→ H_2 production costs are only half of total energy costs at final destination!



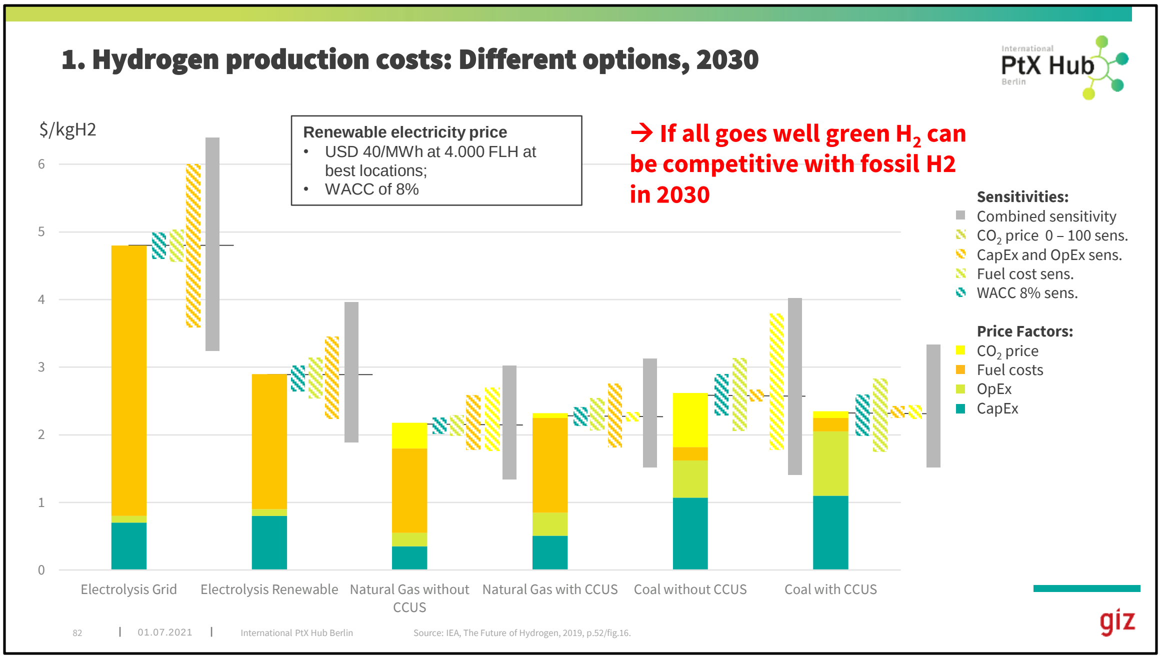
Note: Assumes a distribution distance of 100 km. More information on the assumptions is available at www.iea.org/hydrogen2019.
Source: IEA analysis based on IAE (2019), "Economical Evaluation and Characteristic Analyses for Energy Carrier Systems" and Reuß (2019), "A hydrogen supply chain with spatial resolution: Comparative analysis of infrastructure technologies in Germany"

Delivering hydrogen to European refuelling stations in 2030 is likely to cost USD 7.5–9/kgH₂. The choice of centralised or decentralised reconversion depends on distribution distance.

Main costs drivers:
- → Production of H_2
- → Redistribution in Europe
- → Reconversion

→ Conversion, import, distribution, reconversion doubles costs of H_2 production!

 Source: IEA, The Future of Hydrogen – Seizing today's opportunities, 2019, p.84/Fig.32.



Notes:

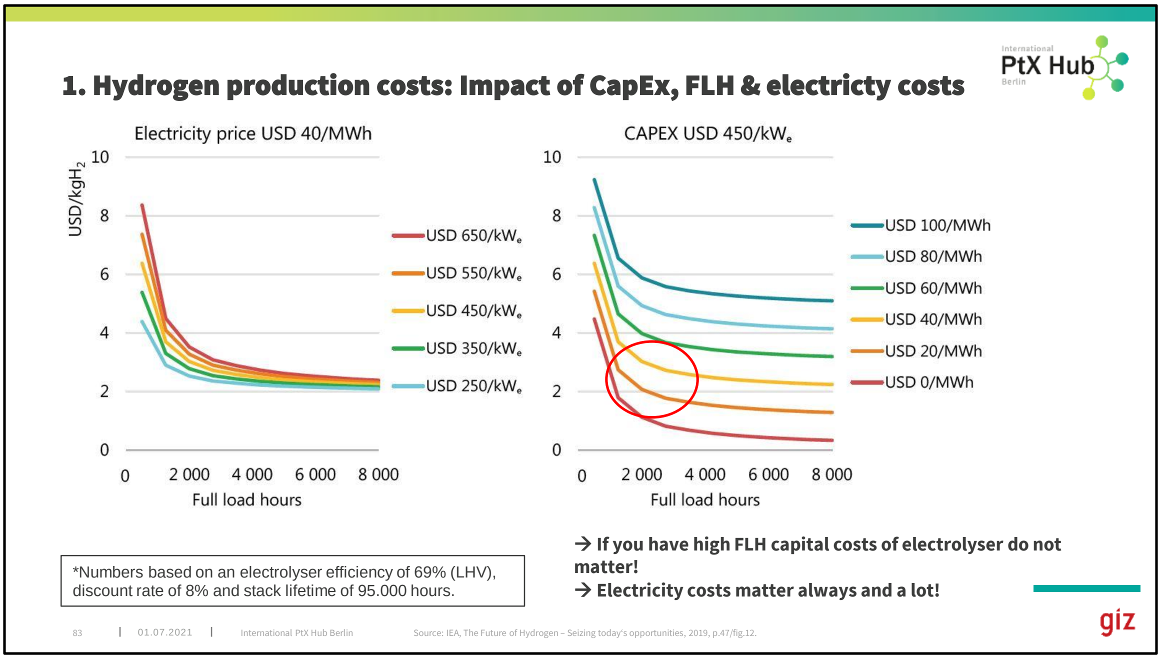
- In the near term – i.e. until 2030 – cost advantage of fossil fuels is likely to continue in most places, with H_2 from natural gas without CCUS costing around USD 1–2/kgH_2, depending on local gas prices.
- Except in the case **of H_2 produced from coal, fuel costs are the biggest single component** of H_2 production costs.
- Future H_2 costs will therefore largely **be influenced by electricity and gas costs, or parameters** influencing these costs such as conversion efficiencies.
- Electrolysis production costs can also be sensitive **to CapEx requirements, in particular** if plants are **operating at low FLH.**

Further comments:

- **WACC assumptions refer to Europe in 2030.**
- Renewable **electricity price = USD 40/MWh at 4 000 FLH at best locations.**
- Sensitivity analysis based on **+/-30% variation** in CapEx, OpEx and fuel **costs; +/-3% change** in default **WACC of 8% and a variation** in default CO_2 price of USD **40/tCO_2** to USD 0/tCO_2 and USD 100/tCO_2.
- Assumption for electricity prices and FLH in Europe:
    - o **Electricity price (USD/MWh), FLH: 5,000**
        - **Today: 98**
        - **2030: 114**
        - **Long-term: 123**
    - o Variable renewable electricity;
        - **Electricity price (USD/MWh), long term: 47**
        - Optimised FLH, long term: 2054

More information on the underlying assumptions is available at www.iea.org/Hydrogen2019.

Source:
The Future of H2 – Seizing today‘s opportunities, Report prepared by the IEA for the G20, Japan



Notes:

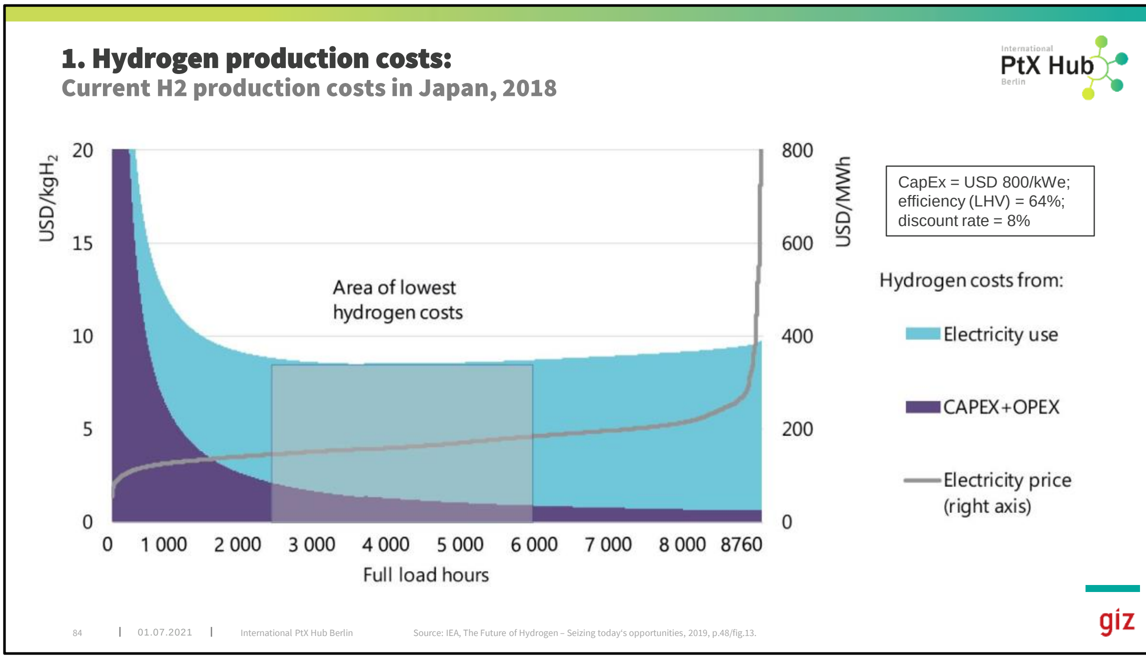
- As **electrolyser operating hours increase**, **the impact of CapEx costs on the levelised cost of H_2 declines** and the impact of electricity costs rises.
- Low-cost electricity available at a level to ensure the electrolyser can operate at relatively high FLH is therefore essential for the production of low-cost H_2.
- In electricity systems with increasing shares of **variable renewables, surplus electricity may be available at low cost.**
- Producing H_2 through electrolysis and storing the H_2 for later use could be one way to take advantage of this surplus electricity, but if surplus electricity is only available on an occasional basis it is unlikely to make sense to rely on it to keep costs down.
- **Running the electrolyser at high FLH and paying for the additional electricity can actually be cheaper** than just relying on surplus electricity with low FLH.

Further comments:

- MWh = megawatt hour. Based on an electrolyser efficiency **of 69% (LHV) and a discount rate of 8%.**
- Stack lifetime:
  - 2020 & 2030: 95,000 hours
  - 2050: 100,000 hours

Source:

The Future of Hydrogen – Seizing today‘s opportunities, Report prepared by the IEA for the G20, Japan



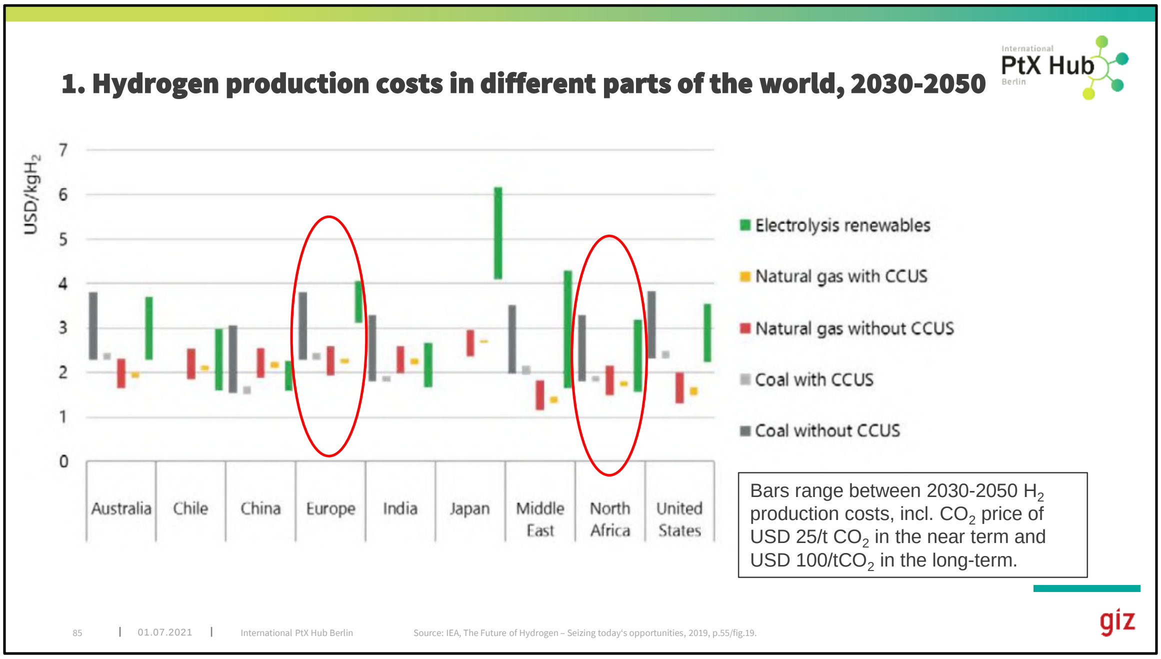
Notes:

- **The relationship between electricity costs and operating hours becomes apparent when looking at electrolysers that use grid electricity for H_2 production**.
- Very low-cost electricity is generally available only for a very few hours within a year, which implies a low utilisation of the electrolyser and high H_2 costs that reflect CapEx costs.
- With increasing hours, electricity costs increase, but the higher utilisation of the electrolyser leads to a decline in the cost of producing a unit of H_2 up to an optimum level at around 3,000–6,000 equivalent FLH.
- Beyond that, higher electricity prices during peak hours lead to an increase in H_2 unit production costs.

Further comments:

- CapEx = USD 800/kWe; efficiency (LHV) = 64%; discount rate = 8%.

Source: IEA analysis based on Japanese electricity spot prices in 2018, JEPX (2019), *Intraday Market Trading Results 2018*.



Notes:

- In countries relying **on gas imports and characterised by good renewable resources**, clean H_2 production **from renewable electricity can compete effectively with production that relies on natural gas.**
- The impact of renewable electricity and gas costs on H_2 production costs becomes apparent when looking at specific countries.
- In countries with **good renewable resources, but dependent on natural gas imports,** in particular in the form of liquefied natural gas, producing H_2 from renewables may be cheaper than producing it from natural gas, while production from natural gas with CCUS may be the cheaper option in regions with cheap domestic gas resources and CO_2 storage availability.
- Other factors are also relevant to the choice between alternative low-carbon H_2 production options.
- For H_2 production from fossil fuels in combination **with CO_2 storage, the geological availability and public acceptance of CO_2 storage are prerequisites.**
- For water electrolysis, **access to adequate supplies of water is a prerequisite,** even if the costs for water treatment (e.g. seawater desalination) are only a small fraction of the total H_2 production costs. Countries could also consider importing H_2 or H_2-based products if they are available at a lower price than domestic alternatives.
- From an investment viewpoint, the **scale of investment** is also relevant.
    - **While CCUS plants require a certain scale to justify the investment in CO_2 transport** and **storage infrastructure**,
    - **Electrolysers** operate at a **smaller scale using more modular technology, which can be gradually expanded and adjusted to demand**.
- For example, the H21 North of England project in the UK plans to produce H_2 **from 12 ATR units with CCUS**, each with a capacity of around 1 350 MWH_2 and requiring an investment of around USD 945 million per unit, whereas the **largest electrolyser module offered today is 20 MWe (14 MWH_2), requiring investment of around USD 18 million (or USD 280 million for 220 MWH_2).**

Assumptions:

- Bars indicate range **between near- (2030) and long-term (2050) H_2 production costs,** which include a CO_2 price of USD 25/t CO_2 in the near term and **USD 100/tCO_2 in the long-term**.
- For options from coal and natural gas, the **higher value indicates the long-term costs** (due to the increasing CO_2 price), whereas for H_2 from renewable electricity the lower value indicates the long-term costs.

Source:

The Future of Hydrogen – Seizing today‘s opportunities, Report prepared by the IEA for the G20, Japan; IEA 2019

2. Renewable Energy Generation Cost Development

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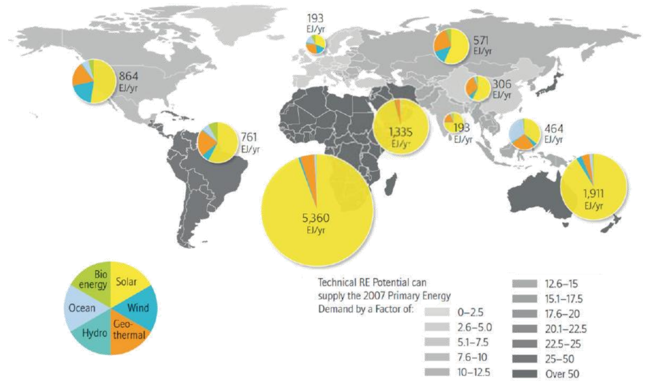
"What are current lowest LCOE costs for large scale PV power worldwide?"

"What are the expected future LCOE costs for PV power in 2030 in your country?"

"What are expected future LCOE costs for wind power in your country for 2030?"

2. Renewable Energy Generation Cost Development

Fact 1: The technical RE potential is often 20 x higher than demand



→ **Potential is available**
→ **But we need to realise it**
→ **Before we can produce green H2, we need much more renewable energies installed!**

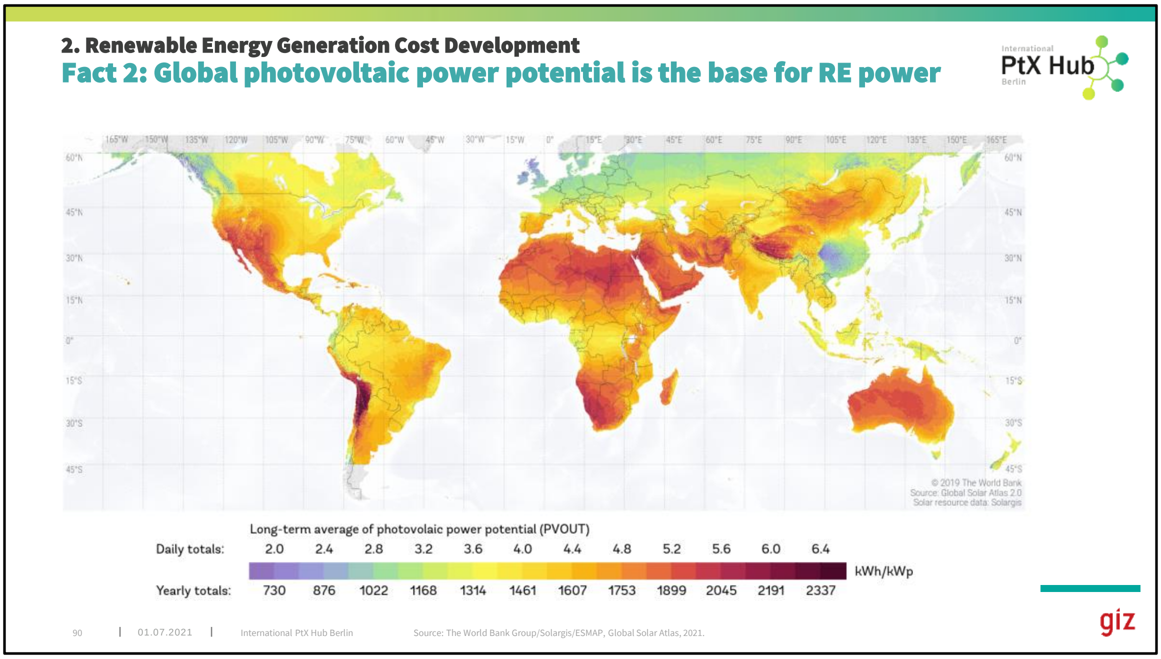
Disclaimer: The boundaries and names shown and the designations used on maps included in this publication do not imply official endorsement or acceptance by the IEA.

Source: Teske et al. (2017), Renewables Global Futures Report based on Edenhofer et al. (2011), Special Report on Renewable Energy Sources and Climate Change Mitigation.

Key message • **The extreme abundance of solar and wind resources in some regions is likely to spur international trade in renewables-based, hydrogen-rich chemicals and fuels.**

 Source: OECD & IEA: Renewable Energy for Industry, 2017, p. 52/Fig.20..

Notes:
We see a high renewable energy potential in the MENA region, Australia and also Latin America and the US, especially regarding solar power.



Notes:

- **Photovoltaic** power plants in **North Africa (2,100 to 2,500 FLH**): relatively low electricity generation costs when constructed in locations with ample solar resources, such as North Africa. The investment costs for PV plants are also expected to fall further until 2050, thus contributing to lower electricity generation costs over the long-term. We assume that ground-mounted PV power plants with single-axis tracking systems will be constructed.
- We also assume that the **water required for H_2 electrolysis will be produced in seawater desalination plants.**
- PV power plants in the **Middle East (2,200 to 2,600 FLH**): The Middle East, like North Africa, has favourable local conditions for renewable energy from PV. As is the case for North Africa, we assume that the **necessary water is produced using seawater desalination plants.**

Source for Notes: Agora: Future Cost of Electricity-Based Synthetic Fuels. [The Future Cost of Electricity-Based Synthetic Fuels (agora-energiewende.de)](agora-energiewende.de)

Source: The World Bank Group/Solargis – www.globalsolaratlas.info

2. Renewable Energy Generation Cost Development

Fact 3: Global wind power potential is the additional RE power to make H2 and PtX possible!

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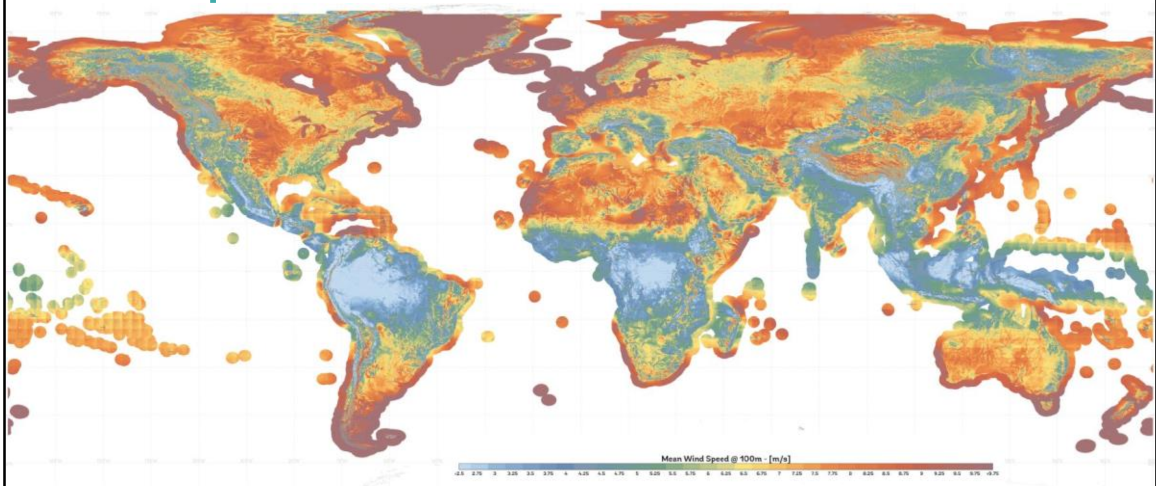
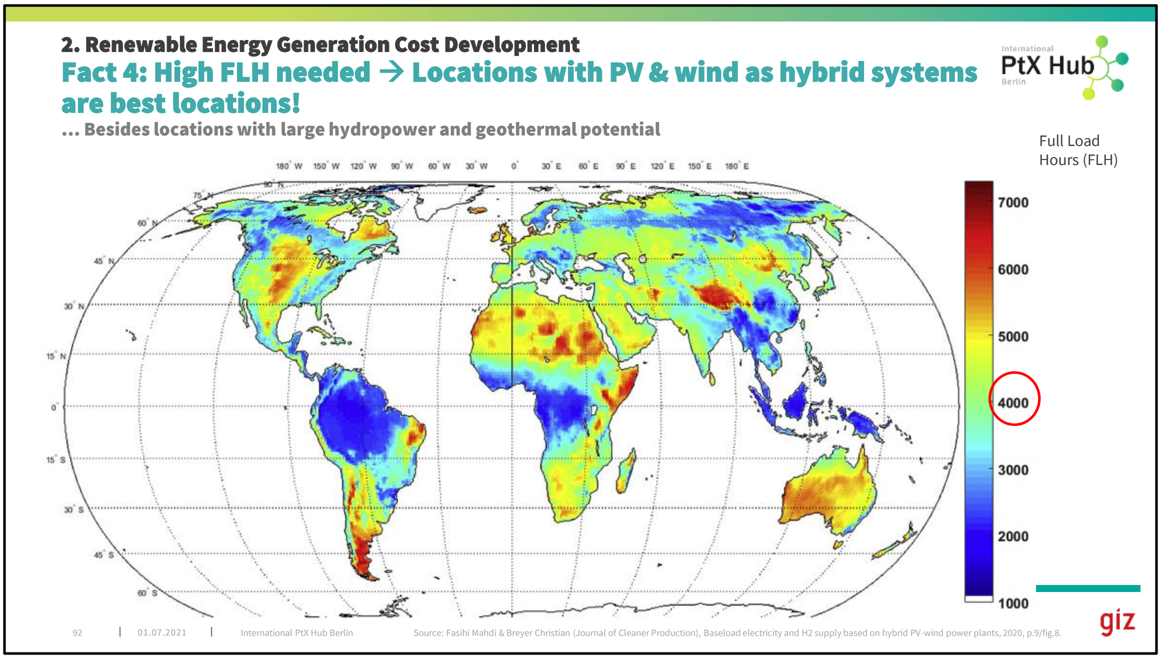


 Source: The World Bank Group/Solargis/ESMAP, Global Wind Atlas, 2021. giz

Further Comments:

- This **wind resource** map provides **an estimate of mean wind power density at 100m above surface level.**
- Power density indicates wind power potential, part of which can be extracted by wind turbines.
- The map is derived from high-resolution wind speed distributions based on a chain of models, which downscale winds from global models (~30 km), to mesoscale (3 km) to microscale (250 m).
- The Weather Research & Forecasting (WRF) mesoscale model uses ECMWF ERA-5 reanalysis data for atmospheric forcing, sampling from the period 1998-2017.
- **The WRF output at 3 km resolution is generalised and downscaled further using the WAsP software**, plus terrain elevation data at 150 m resolution, and roughness data at 300 m resolution. The microscale wind climate is sampled on calculation nodes every 250 m. For the microscale modeling, the terrain data is derived from the digital elevation models from Viewfinder Panoramas.
- The WAsP microscale modeling uses a linear flow model. For steep terrain, this modeling becomes more uncertain, most likely leading to an overestimation of mean wind speeds on ridges and hilltops. Users are recommended to inspect the terrain complexity of their region of interest.

Source: The World Bank Group/Solargis – www.globalwindatlas.info

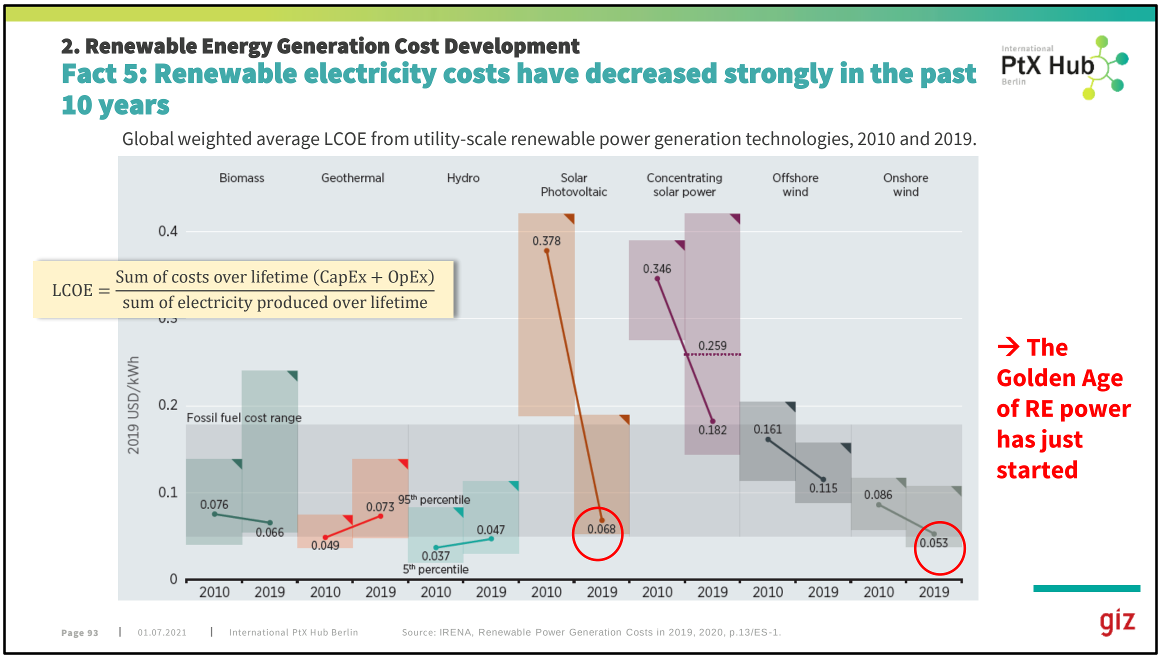


Notes:

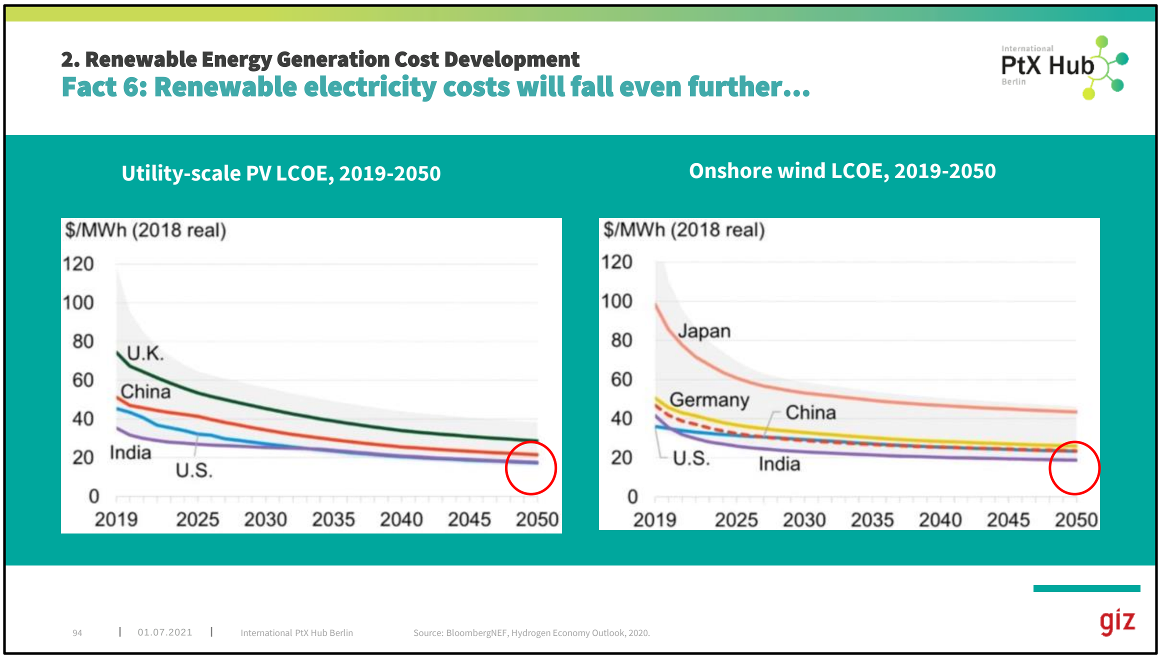
- **Patagonia, the Atacama Desert, the Horn of Africa and Tibet, have extremely good wind conditions during the daytime.**
- In addition to these regions, the **cumulative hybrid PV-wind FLH at the joint border between Libya, Niger and Chad exceeds 6,000 h**, representing high levels of solar **and wind compatibility at very low critical overlaps.**
- **Yet: nowhere in the world does the cumulative hybrid PV-wind FLH exceed 6,500** and is thus unable to **provide baseload electricity.**
- Combining equal actual output capacities of single-axis **tracking PV and wind power plants (132.5% PV and 107.5% wind nominal capacities)** would lead to higher cumulative FLH.
- Yet: nowhere can it reach 8,760 FLH from an electricity uptake perspective.
- In addition, this cumulative FLH only indicates a **physical feasibility of increasing electricity availability by installing equal capacities of PV and wind energy,** while a **cost-optimised solutions would be based on different shares of PV and wind energy and electricity storage options** depending on the electricity generation profiles of each region and the respective cost assumptions of the technologies.

Source: Fasihi Mahdi & Breyer Christian Journal of Cleaner Production, Baseload electricity and H2 supply based on hybrid PV-wind power plants, Volume 243, 10 January 2020

Agora: Future Cost of Electricity-Based Synthetic Fuels



Source:
IRENA, Renewable Power Generation Costs in 2019, 2020, p.13/ES-1.



Notes:

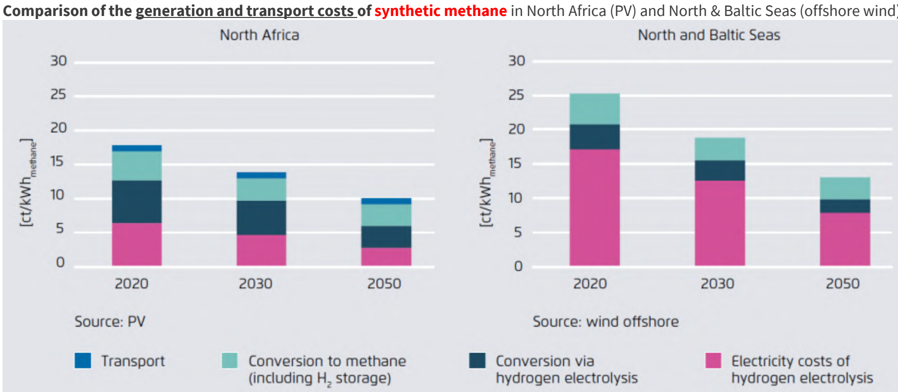
- **Solar PV emerges as the major source of energy by 2050.**
- Practically all global scenarios dramatically fail in the right role of solar PV.
- **Steep cost decline of the last 10 years is ignored by IEA, IPCC, and others.**
- Climate change mitigation could be enhanced, if major institutions would perform better.
- **Massive and fundamental rethinking on solar PV, plus supporting batteries, is needed.**
- **Historic failures of major international institutions** on our energy future must end, asap.
- **Similar cost digression is not unrealistic for electrolysers.**

Source: BloomberNEF – H2 Economy Outlook 2020, Presentation Will H2 be the molecule to power a clean economy?

2. Renewable Energy Generation Cost Development
Why are RE power costs so important?

→ Renewable electricity costs are the **main cost driver** for H2 / PtX
→ Especially when you want to export H2 or PtX to Europe

Comparison of the generation and transport costs of synthetic methane in North Africa (PV) and North & Baltic Seas (offshore wind).



Base: RE Power 3.43 ct/kWhel in 2020 in North Africa, 67% efficiency of hydrogen electrolyser.

 Source: Agora, The future cost of electricity-based synthetic fuels, 2018, p.46.

giz

Notes:

- **The primary drivers of the cost trends** for imported synthetic methane and synthetic liquid fuels are described below. These drivers are:
  - **electricity generation costs,**
  - **conversion plant utilisation rates (load factors),**
  - **conversion plant investment costs.**
- **Transport costs are of secondary importance** which is particularly true for synthetic liquid fuels.
- Electricity generation costs make up a significant fraction of the total cost of synthetic methane and synthetic liquid fuels, as shown in this figure above.
- **In 2020 electricity generation costs are by far the largest cost component.**
- Although electricity generation costs fall by 2050 due to the assumption of decreasing investment costs for renewable energy, **they continue to make up a significant fraction of the total costs in 2050.**
- The **strong impact exerted by the electricity generation costs on the cost of synthetic methane and synthetic liquid fuels** can **be attributed to the inefficiency of the conversion process:**
  - The electricity generation costs of photovoltaic technology in North Africa **are 3.43 ct/kWhel in 2020** (reference scenario). With an efficiency **of 67 per cent for H2 electrolysis, electricity costs of 5.12 ct/kWh H_2 are incurred.**
  - In the case of **methanisation, methanol synthesis, or Fischer-Tropsch synthesis**, there are additional conversion losses, **so that the electricity costs for the final product in this illustrative example are 6.39ct/kWh methane and 6.39ct/kWhPtL.**
- The importance of the electricity generation costs can be seen when comparing the electricity generation costs between different countries and between different years.
- Due to the multiplier effect of the conversion losses described above, **differences in the investment costs and FLH between different regions and at different times exert a strong effect on the total costs.**

Source: Agora 2018: The future cost of electricity-based synthetic fuels

“*What are the biggest challenges to <u>reduce</u> RE power costs in your country?*”

- Open discussion -

3. Hydrogen Electrolyser Cost Development

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“What are current factors influencing electrolyser cost developments?”

“What would you think will drive the cost reduction of electrolyser cost in future?”

3. Hydrogen Electrolyser Cost Development

Techno-economic characteristics of Alkaline and PEM electrolysers

	Alkaline			PEM		
	Today	2030	2050	Today	2030	Long-term
Electrical efficiency	63-70	65-71	70-80	56-60	63-68	67-74
Operating pressure	1-30 bar			30-80 bar		
Stack lifetime (operating hours)	60,000-90,000	90,000-100,000	100,000-150,000	30,000-90,000	60,000-100,000	100,000-150,000
CapEx (USD/kWe)	500-1,400	400-850	200-700	1,100-1,800	650-1,500	200-900

 Source: IEA, The Future of Hydrogen, 2019.

Notes:

Alkaline Electrolyser:

- **Mature and commercial technology**
- Used since the **1920s, in particular for H_2 production in the fertiliser and chlorine industries.**
- Operating range of alkaline electrolysers goes from a **minimum load of 10% to full design capacity**.
- Several alkaline electrolysers with a **capacity of up to 165 MWe were built in the last century** in countries with **large hydropower** resources (Canada, Egypt, India, Norway and Zimbabwe), although almost all of them were **decommissioned when natural gas and steam methane reforming** for H_2 production took off in the 1970s.
- Alkaline electrolysis is characterised by **relatively low capital costs compared to other electrolyser** technologies due to the **avoidance of precious materials**.

PEM electrolyser:

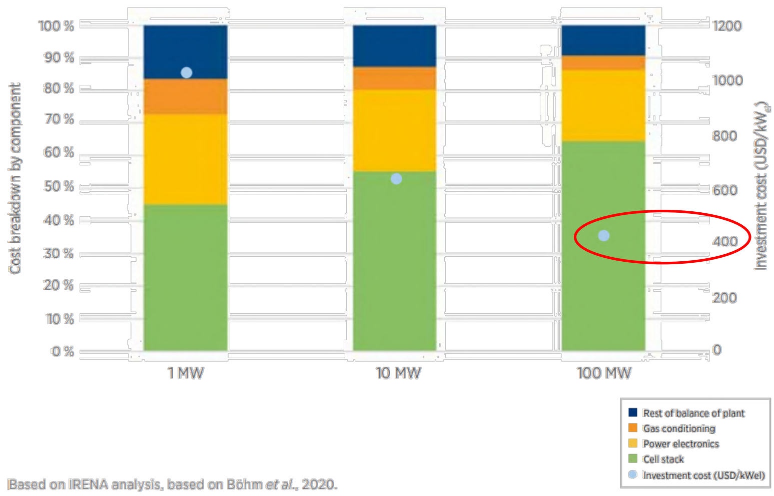
- First introduced in the **1960s by General Electric to overcome some** of the **operational drawbacks of alkaline electrolysers.**
- Use **pure water as an electrolyte solution**, and so avoid the recovery and **recycling of the potassium hydroxide electrolyte solution that is necessary with alkaline** electrolysers
- **Relatively small, making them potentially** more attractive than alkaline electrolysers in dense urban areas.
- Are able to produce **highly compressed H_2 for decentralised production** and storage at refueling **stations (30–60 bar without an additional** compressor and up to 100–200 bar in some systems, **compared to 1–30 bar for alkaline electrolysers)**
- **Offer flexible operation**, including the capability to provide frequency reserve and other grid services.
- Operating range **can go from zero load to 160% of design capacity** (so it is possible to **overload the electrolyser for some time**, if the plant and power electronics have been designed accordingly).

- **Need expensive electrode catalysts (platinum, iridium) and membrane materials,**
- Lifetime is currently **shorter than that of alkaline** electrolysers.
- Overall costs are **currently higher than those of alkaline electrolysers**, and they are less widely deployed.

Source: IEA- The Future of Hydrogen

3. Hydrogen Electrolyser Cost Development

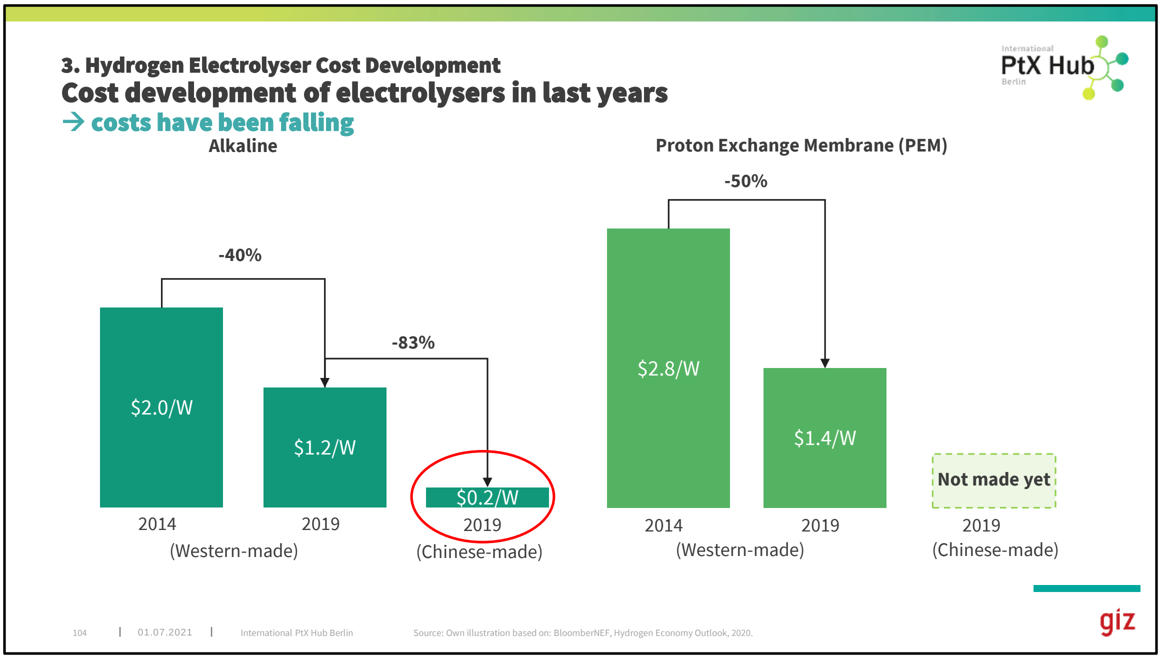
Cost breakdown for alkaline electrolysers (current costs) → Matter of size



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.



Notes:

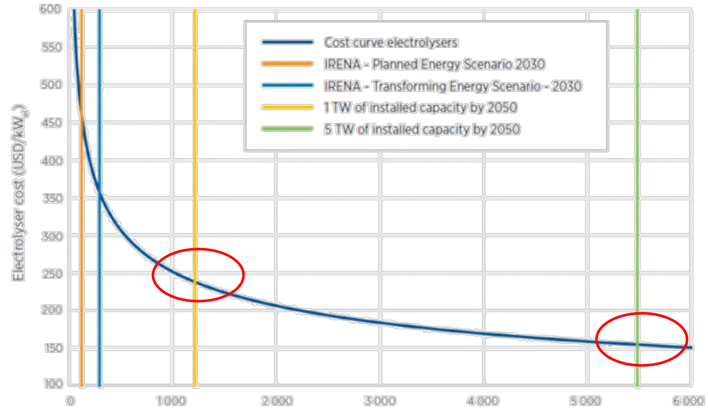
- **Cheaper raw materials and labour**
- **Higher factory utilisation rates**
- Lower spending on R&D and marketing
- But: Problem with **bankability outside of China. Challenge**: **Chinese equipment not seen as bankable in the West** (e.g. wind turbines) before **they have a track-record they are very hard to bank**. Further demonstration projects financed by Chinese investors need to be implemented first.

Further comments: Benchmark CapEx based on large-scale electrolysers, 2014 & 2019.

Source: BloomberNEF – H2 Economy Outlook 2020, Presentation Will H2 be the molecule to power a clean economy?

3. Hydrogen Electrolyser Cost Development

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



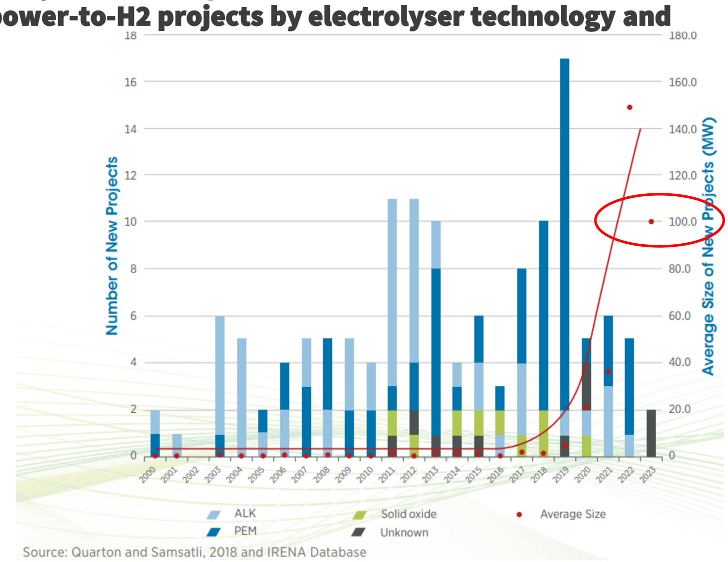
Notes: 1 TW of installed capacity by 2050 is about 1.2 TW of cumulative capacity due to lifetime and replacement. Similarly, 5 TW by 2050 is equivalent to 5.48 TW of cumulative capacity deployed.

Based on IRENA analysis.

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

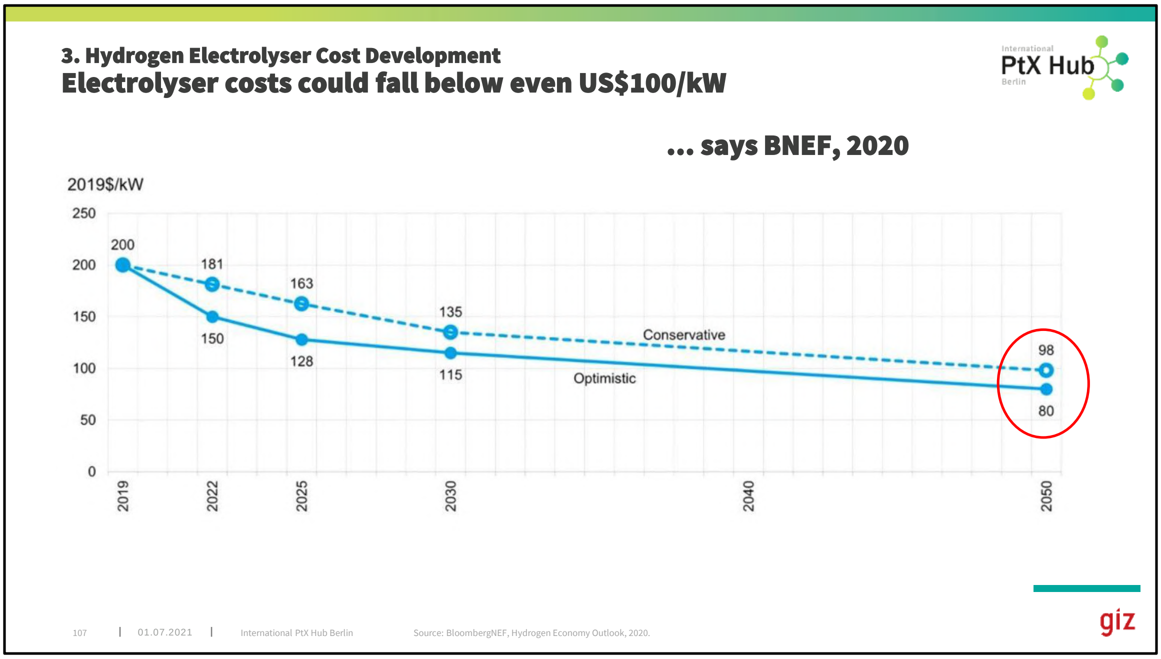
3. Hydrogen Electrolyser Cost Development

Timeline of power-to-H2 projects by electrolyser technology and project scale



Source: Quarton and Samsatli, 2018 and IRENA Database

Source: IRENA, Hydrogen – A Renewable Energy Perspective, 2019, p.13/fig.2.



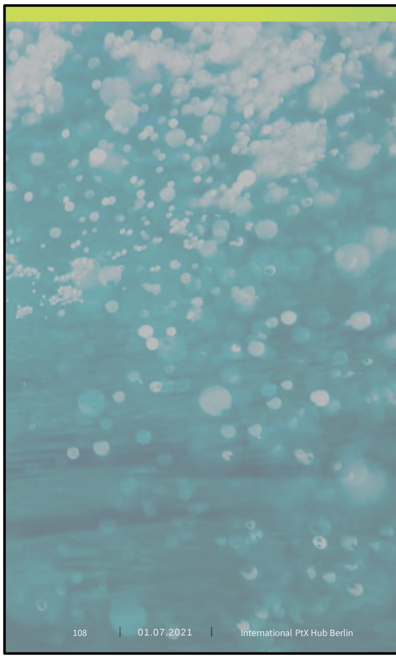
Notes:

- The costs of electrolysers have the potential to decrease **rapidly if electrolyser manufacturing can scale up.**
- Electrolyser costs could **fall to under $100/kW by 2050.**

Further comments:

- **System CapEx forecast of Chinese-made alkaline electrolysis projects (large-scale projects).**

Source: BloombergNEF – Hydrogen Economy Outlook 2020, Presentation Will H2 be the molecule to power a clean economy?



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3. Green H2 production cost factors – Country specific evaluation required

Three main parameters are critical for the economic viability of H2 production from renewables:

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

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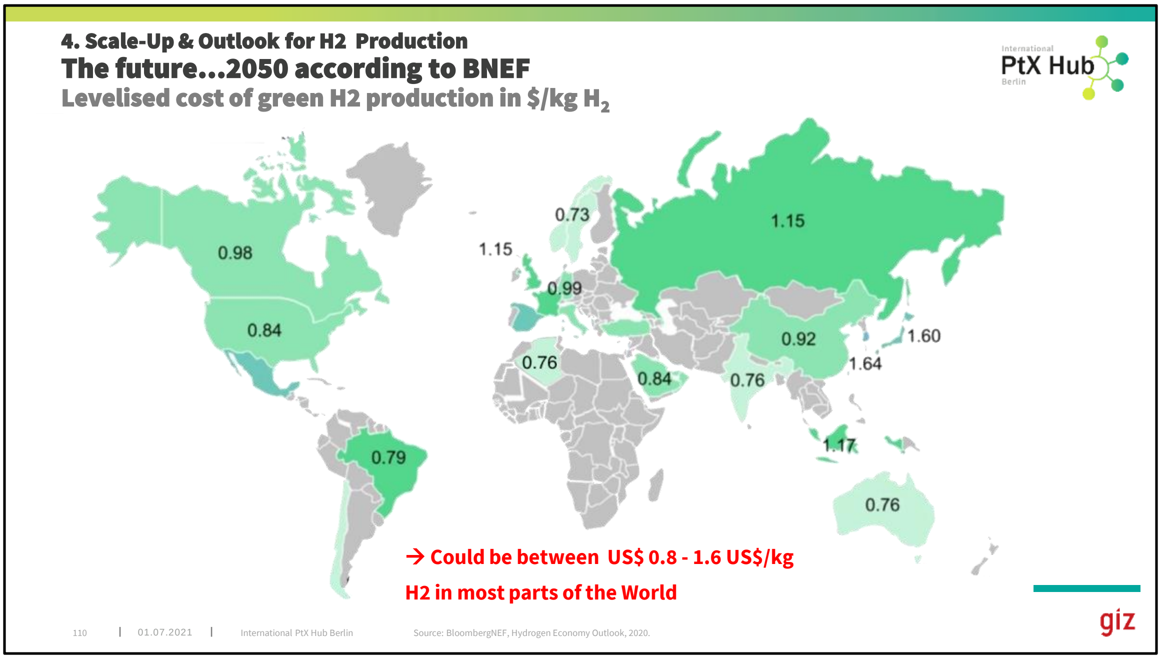
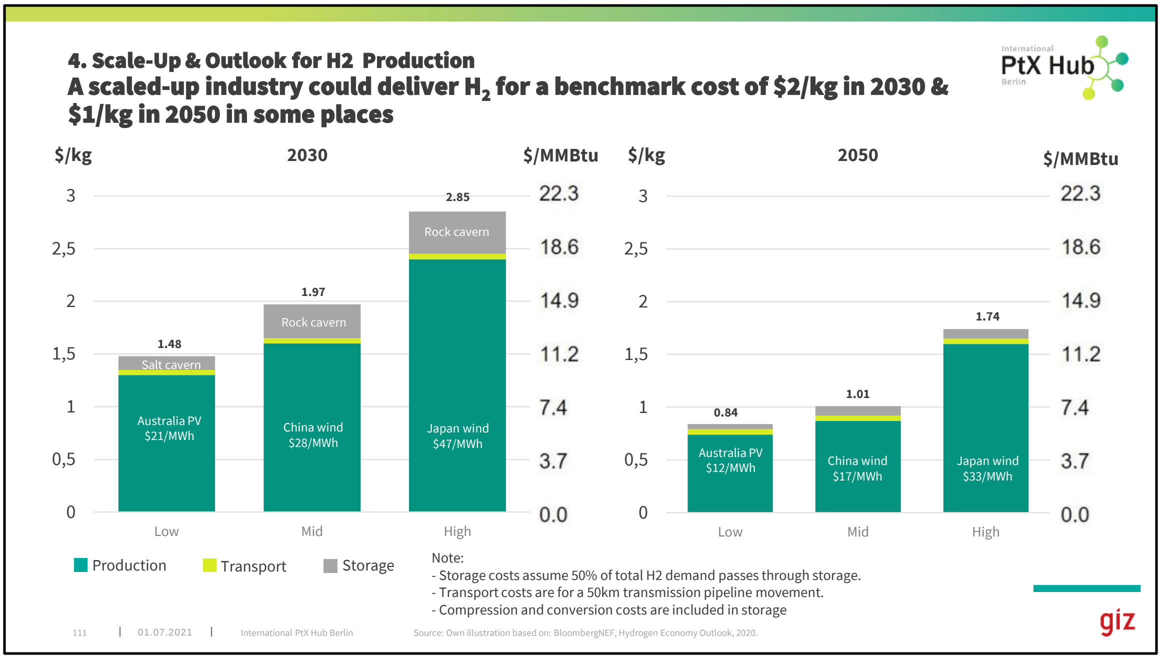
4. Scale-Up & Outlook for Hydrogen Production



Notes:

- Renewable H_2 **could be produced for $0.8 - 1.6/kg in most parts of the world before 2050.**
- **Mosts of the world have the ability to produce low cost H_2.**
- Light green such as **Scandinavia and India will be at the bottom of the cost curves.**
- ***Japan and Korea will be at the top of the cot curve.***
- LCOH assuming the **optimistic projection for alkaline electrolyser costs**.
- **Costs would be 6% higher in 2030 and 18% higher in 2050 if the conservative assumptions are used.**

Source: BNEF Hydrogen Economy Outlook.



Notes:

- **H_2 is likely to be most competitive in large-scale local supply chains**.
- **Clusters of industrial customers could be supplied by dedicated pipeline networks** containing a portfolio of wind-and solar-powered electrolysers, and a large-scale geological storage facility to smooth and buffer supply.
- The analysis suggests that a 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 is achievable**.
- Costs could be **20-25% lower in countries with the best renewable and H_2 storage** resources, such as **USA, Brazil, Australia, Scandinavia and Middle East.**
- However, cost would be up to **50-70% higher in places like Japan and Korea that have weaker renewable resources and unfavorable geology for storage**.

Further comments:

- Power costs depicted are the LCOE used for electrolysis, and are lower than the BNEF's standard LCOE projections in 2050 due to savings from integrated design of the electrolyser and generator, and anticipated additional learning from increased renewable deployment for H_2 production.
- Production costs are based on a large-scale alkaline electrolyser with CapEx of $135/kW in 2030 and $98/kW in 2050.
- Storage costs assume 50% of total H_2 demand passes through storage.
- Transport costs are for a 50km transmission pipeline movement.
- Compression and conversion costs are included in storage. Low estimate assumes a salt cavern, mid and high estimate a rock cavern for both 2030 and 2050.

Source: Own graph adapted after BNEF H2 Economy Outlook Key Messages 30.03.2020

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"How do we achieve future H2 production costs of 1 US$ / kg green H2?"

"What are main drivers for future cost reductions for green H2?"

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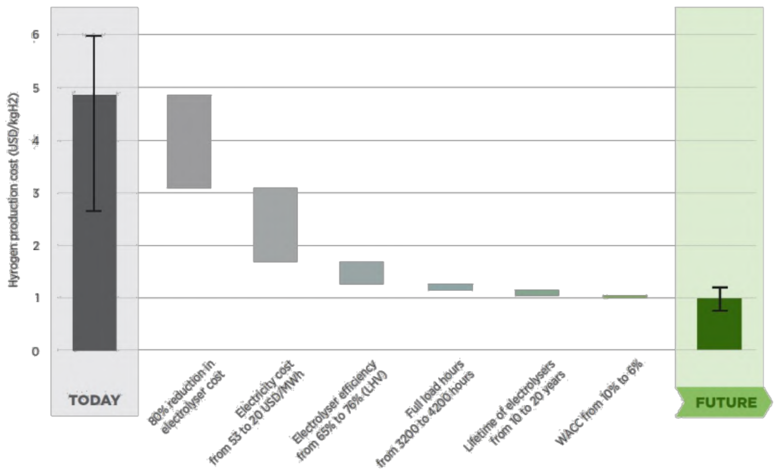
4. Scale-Up & Outlook for H2 Production

How to achieve 85% reduction of green H2 production costs in the long-term?



114 | 01.07.2021 | International PtX Hub Berlin   Source: IRENA, Green Hydrogen Cost Reduction, 2020, p.10/ES1.

Notes:

- The shows how up to **85% of green H_2 production costs can be reduced** in the long-term by a **combination of cheaper electricity and electrolyser CapEx** investment, in addition to **increased efficiency and optimised operation of the electrolyser** .
- **Low electricity cost is not enough for competitive green H_2 production** → reductions in the **cost of electrolysis facilities** are also needed.
- This is the **second largest cost component of green H_2 production.**
- In the context of **decarbonisation, H_2 produced from fossil fuels without capturing most of the CO_2 emissions does not fulfil the criteria** of renewable energy, although it represents the vast majority of H_2 production today.
- The trend over the last decade of falling renewable electricity prices is expected to continue; 82%, 47% and 39% for PV, offshore and onshore wind respectively (IRENA, 2020a) and is the focus of this report, which identifies key strategies to reduce investment costs for electrolysis plants from 40% in the short-term to 80% in the long-term.
- These **strategies** range from the **fundamental design of the electrolyser stack to broader system-wide elements**, including:
  - **Electrolyser design and construction**: Increased **module size and innovation with increased stack manufacturing** have significant impacts on cost. **Increasing the plant from 1 MW (typical today) to 20 MW could reduce costs by over 1/3**.
  - **Cost, is not the only factor influencing plant size**, as each technology has its own stack design, which also varies between manufacturers.
  - The optimal system design also depends on the application that drives system performance in aspects such as efficiency and flexibility.
  - **Economies of scale**: Increasing **stack production to automated production** in **GW scale manufacturing** facilities can achieve a step-change cost reduction. At **lower manufacture rates,**

the stack is about 45% of the total cost, yet at **higher production rates, it can go down to 30%.**
    - For Polymer Electrolyte Membrane (PEM) electrolysers, the tipping point seems to be around 1,000 units (of 1 MW) per year, where this scale-up allows an almost 50% cost reduction in stack manufacturing.
    - The cost of the surrounding plant is as important as the electrolyser stack and savings can be achieved via standardisation of system components and plant design.
    - **Procurement of materials**: Scarce materials can represent a barrier to electrolyser cost and scale-up.
        - Current production of iridium and platinum for PEM electrolysers will only support an estimated 3 GW-7.5 GW annual manufacturing capacity, compared to an estimated annual manufacturing requirement of around 100 GW by 2030.
        - Solutions that avoid the use of such materials are already being implemented by leading alkaline electrolyser manufacturers and technologies exist to significantly reduce the requirements for such materials in PEM electrolysers.
- **Anion Exchange Membrane (AEM)** electrolysers do not need scarce materials in the first place.
- **Efficiency and flexibility in operations**: Power supply represents large efficiency losses at low load, limiting system flexibility, from an economic perspective.
- A **modular plant design with multiple stacks** and power supply **units can address this problem**.
- **Compression could also represent a bottleneck for flexibility**, since it might not be able to change its production rate as quickly as the stack.
- One alternative to deal with this is an **integrated plant design with enough** capacity to deal with variability of production through optimised and integrated electricity and H_2 storage.
- **Green H_2 production** can provide significant flexibility for the power system, if the **value of such services is recognised and remunerated adequately**. Where H_2 will play a key role in terms of flexibility, as it does not have any significant alternative sources to compete with, will be in the seasonal storage of renewables.
- Although this comes at **significant efficiency losses, it is a necessary cornerstone for achieving 100% renewable generation in power systems** with heavy reliance on variable resources, such as solar and wind.
- **Industrial applications:** Electrolysis system **design and operation can be optimised for specific applications.**
- These can range from: **large industry users requiring a stable supply and with low logistics costs**; large scale, off-grid facilities with access to low-cost renewables, but that incur in significant costs to deliver H_2 to the end-user; and decentralised production that requires small modules for flexibility, which compensate for higher investment per unit of electrolyser capacity with reduced (or near zero onsite) logistic costs.
- **Learning rates:** Several studies show that **potential learning rates for fuel cells and electrolysers are similar to solar PV and can reach values between 16% and 21%**.
- This is significantly lower than the **36% learning rates experienced over the last 10 years for PV** (IRENA, 2020). With such learning rates and a deployment pathway in line with a 1.5°C climate target, a **reduction in the cost of electrolysers of over 40% may be achievable by 2030.**

Further comments:
- 'Today' (2020) captures best and average conditions. **'Average' signifies** an investment of **USD 770/kilowatt (kW),** efficiency of 65% (lower heating value – LHV), an **electricity price of USD 53/MWh**, **FLH of 3200** (onshore wind), and a weighted average cost of **capital (WACC) of 10%** (relatively high risk).
- 'Best' signifies investment **of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh**, FLH **of 4200** (onshore wind), and a **WACC of 6%** (similar to renewable electricity today).

Source: https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_H2_cost_2020.pdf

4. Scale-Up & Outlook for H2 Production

Three concepts with financial implications

"Golden Ages"

The term **"Golden Ages"** refers to **the long-term almost cost-free revenue streams**.

Once the CapEx of an installation have been paid off, the cost for operation and maintenance of the plant are marginal. While production remains the same, large long-term profits can therefore be generated. For our purposes, **"Golden Ages" refers to the operational period starting after all debts of CapEx are paid off,** until the decommissioning of electricity generation and PtX plant.

Up-scaling not only **"by size",** but also **"by number"**

In order to induce **innovation impulses and drive cost reductions an up-scaling of the various PtX processes and markets is needed.** In addition to **"up-scaling by size"**, there is also a need for **"up-scaling by number"**, through numerous small, quickly reproducible units.

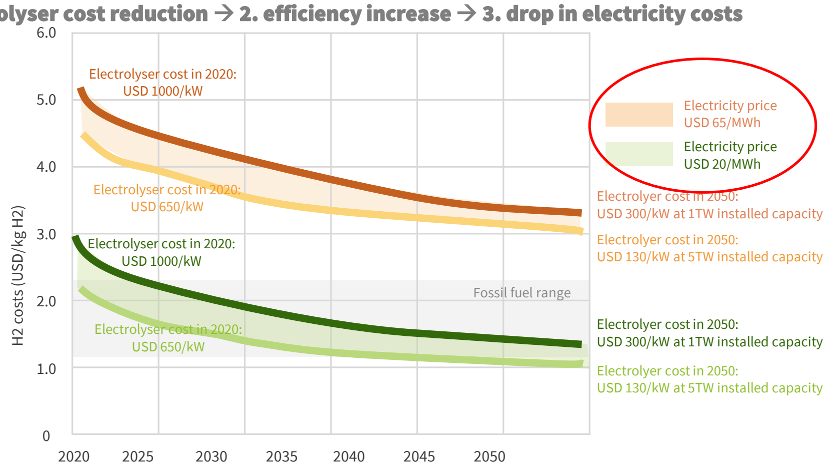
"Decentralisation"

Hydrogen produced **de-centrally (on-site)**, typically at **large consumer clusters,** requires only relatively **minimal infrastructure** for local storage and distribution.

4. Scale-Up & Outlook for H2 Production

Green H2 costs will decrease based on:

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

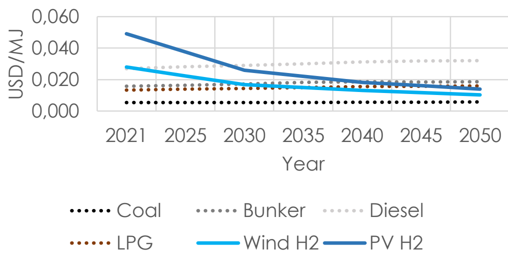


Note: Efficiency at nominal capacity is 65% with a LHV of 51.2 kWh/kg H2 in 2020 and 76% (at an LHV of 45.8 kWh/kg H2) in 2050. A discount rate of 8% and a stack litetime of 80 000 hours. The electrolyser investment cost for 2020 is USD 650-1000/kW. Electrolyser costs reach USD 130-307/kW as a result of 1-5 TW of capacity deployed by 2050.

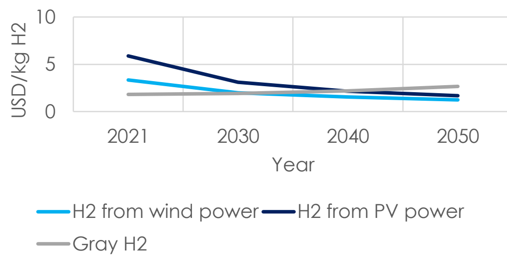
Source: IRENA, Green Hydrogen Cost Reduction, 2020, p.11/ES2.

Costa Rican green hydrogen could be competitive* to replace diesel, bunker and LPG in less than a decade

Green hydrogen v.s. Fossil fuels in Costa Rica[1]



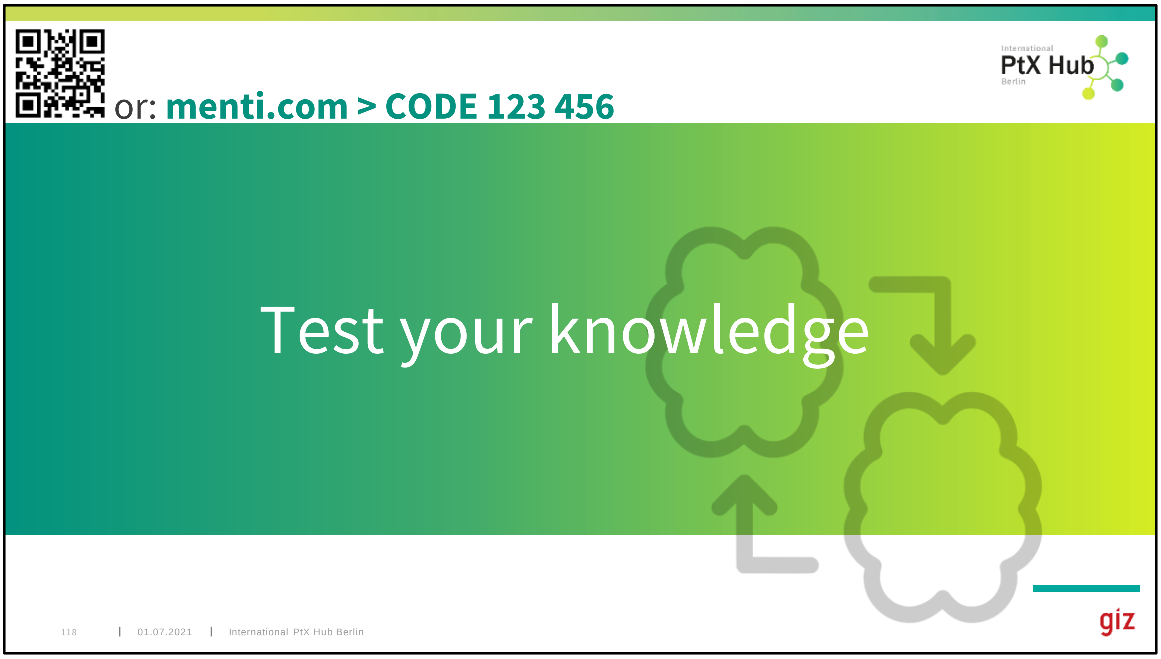
Estimated cost of gray hydrogen v.s. green hydrogen in Costa Rica[2]



1) **Green hydrogen** from wind power will be **competitive with diesel in less than a decade**.*
2) **Gray hydrogen would not be an option for Costa Rica.** Hinicio did not identify existing gray hydrogen plants in Costa Rica. Green hydrogen from wind power could be competitive before methane reforming projects get constructed and operative.

[1]: Hinicio, 2021 with information from ICE, 2018 (Plan de Expansión de la Generación Eléctrica)
[2]: Hinicio calculations with information from ICE 2018 for the hypothetical natural gas price in Costa Rica.
Further information on the LCOH parameters considered on Annex 1 - Methodology

* This cost competitiveness is based on a MJ-to-MJ comparison. Therefore, a more comprehensive analysis considering TCO (i.e. CapEx for technology replacement) is needed to reach more robust and detailed conclusions on cost competitiveness.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“In which countries are the largest potentials for sustainable green H2 & PtX?”

“Which factors are influencing the sustainable PtX production potential?”

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4. Scale-Up & Outlook for H2 Production

Criteria applied for the PtX Altas analysis

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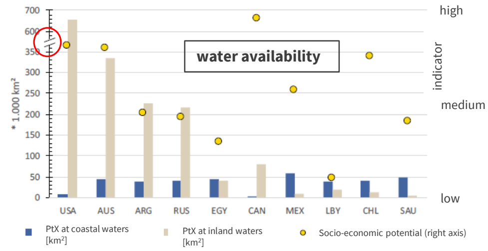
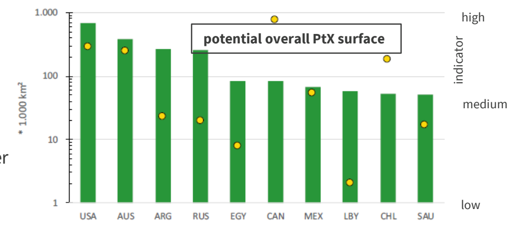
1. **Indicators consist of:**
   - Economy
   - Politics
   - Technology
   - Nature conditions
   - Society
   - Proximity to Germany

2. **Technical surface potential indicators**
   - Sites along coastal or inland waters
   - Pure wind or pure PV sites
   - Hybrid sites

3. **Sustainability criteria are very important**, i.e. no water stress, no land sealing of fertile land, no conflict with nature conservation, criterium of additionality of RE & over 70 socio-economic indicators.





→ **80% of world wide PtX potential* is located in 10 countries only**

*according to the underlying criteria

Source: Fraunhofer IEE, Ptx-atlas: Weltweite Potenziale Für Die Erzeugung Von Grünem Wasserstoff Und Klimaneutralen Synthetischen Kraft- und Brennstoffen, 2021, p.6/Abb.4.

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Notes:

Indicators used for the analysis:

- **Economics**: Primarily macroeconomic indicators, i.e. GDP, investment climate, economic dynamics or import and export of goods and services. Data from the World Bank and the International Monetary Fund were used for this purpose (https://data.worldbank.org/indicator/FP.CPI.TOTL.ZG?view=chart). Countries were also rated positively in the economic field if the development of renewable energies is well advanced and the countries export more energy than they import.
- **Politics**: government action, i.e. rule of law, corruption or legislation in the country to reduce emissions. Numerical values are again available in individual indices. Example of corruption: https://www.transparency.org/en/news/corruption-perceptions-index-2016.
- **Technology**: innovation, already existing RE infrastructure, energy supply in the country, expenditures for education & research. World Bank's Research and Development Expenditure indices, whose values are taken from UNESCO (https://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS?view=chart).
- **Nature conditions**: PV and wind potentials (positive) vs. presence of oil production and coal mining, existing oil and coal reserves (negative). Furthermore, degree of water pollution, nature conservation areas, RE capacity and the size of the country (measured in terms of land and water area).
  - → The larger the geographical area of a country, the greater its PtX potentials: geographically large countries were therefore rated positively in the analysis. The following indicator is an example of this: https://www.laenderdaten.de/geographie/flaeche.aspx.
- **Society**: satisfaction and peace, health system, energy demand, educational attainment or health system, absence of repressive state violence or acts of war → important prerequisites for retaining highly qualified skilled workers in knowledge-intensive technology sectors in the country. Various indices based on data from the World Bank (https://data.worldbank.org/indicator/SH.MED.PHYS.ZS?view=map&year=2012).
- **Proximity to Germany**: crucial for the profitability of exporting and were examined in the analysis using various indicators, such as logistics infrastructure, geographical distance, economic relations and cultural

proximity. Furthermore, possible PtX export countries were rated positively if energy partnerships with Germany already exist. These energy partnerships can be viewed at the Federal Foreign Office (https://www.auswaertiges-amt.de/de/aussenpolitik/themen/energie/energiepartnerschaften/238784).

2. Technical criteria: (see above)

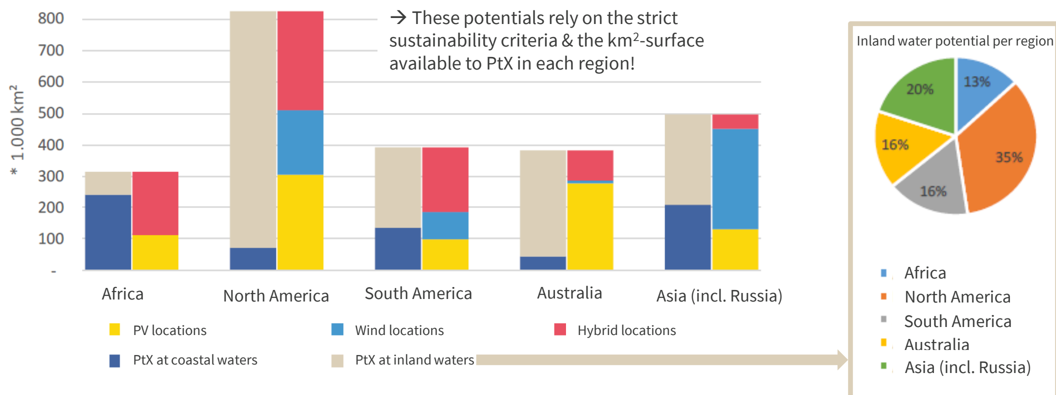
- Since **freshwater is needed for electrolysis**, **inland waters are often very attractive locations for PtX** - **provided** they offer good conditions for **wind energy and/or photovoltaics** and do **not have a water stress** indicator.
- The largest potentials for inland waters are in the USA, Argentina and Australia.
- Globally, <70% of the PtX potential is located on inland waterways under the underlying conditions.

Overall good results of: USA, Canada & Chile achieve such high ratings, because (partly):

✓ Large countries
✓ High surface potential
✓ High potential on inland waters (freshwater favourable for PtX)
✓ (Relatively) stable political & economic conditions
✓ Good social prerequisites
✓ High degree of technology
✓ Proximity (already existing trading infrastructure) to Germany

4. Scale-Up & Outlook for H2 Production

PtX potentials in RE resources and water sources



→ These potentials rely on the strict sustainability criteria & the km^2-surface available to PtX in each region!

Source: Fraunhofer IEE, Ptx-atlas: Weltweite Potenziale Für Die Erzeugung Von Grünem Wasserstoff Und Klimaneutralen Synthetischen Kraft- und Brennstoffen, 2021, p.6/Abb.2,3.

Notes:

- This graph shows the distribution of **potentials** for PtX in Africa, North & South America, Australia and Asia (incl. Russia) in relation to predominant RE resources according to already exiting infrastructure & its potential in km^2.
- Greatest potentials on inland waters are in the USA, Argentina and Australia.
- Globally, under the underlying conditions, over 70% of the PtX potential is located on inland waterways.
- Largest shares of **pure PV sites:** North America and Australia.
- Largest shares of **pure wind sites:** Asia (mainly Russia).
- African continent is characterised by **hybrid** (2/3) **and PV sites** (1/3). Pure wind sites can only be identified sporadically there, the same applies to Australia.

4. Scale-Up & Outlook for H2 Production

Socio-economic potentials for the creation of a PtX infrastructure

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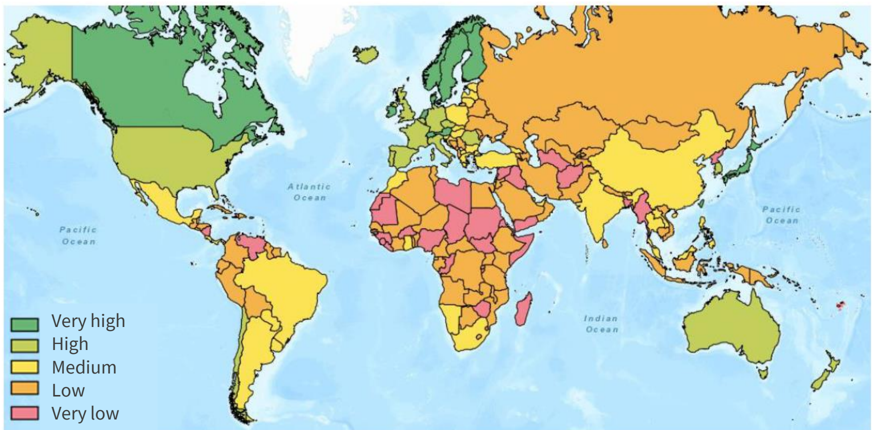

Source: Fraunhofer IEE, Ptx-atlas: Weltweite Potenziale Für Die Erzeugung Von Grünem Wasserstoff Und Klimaneutralen Synthetischen Kraft- und Brennstoffen, 2021, p.7/Abb.4.

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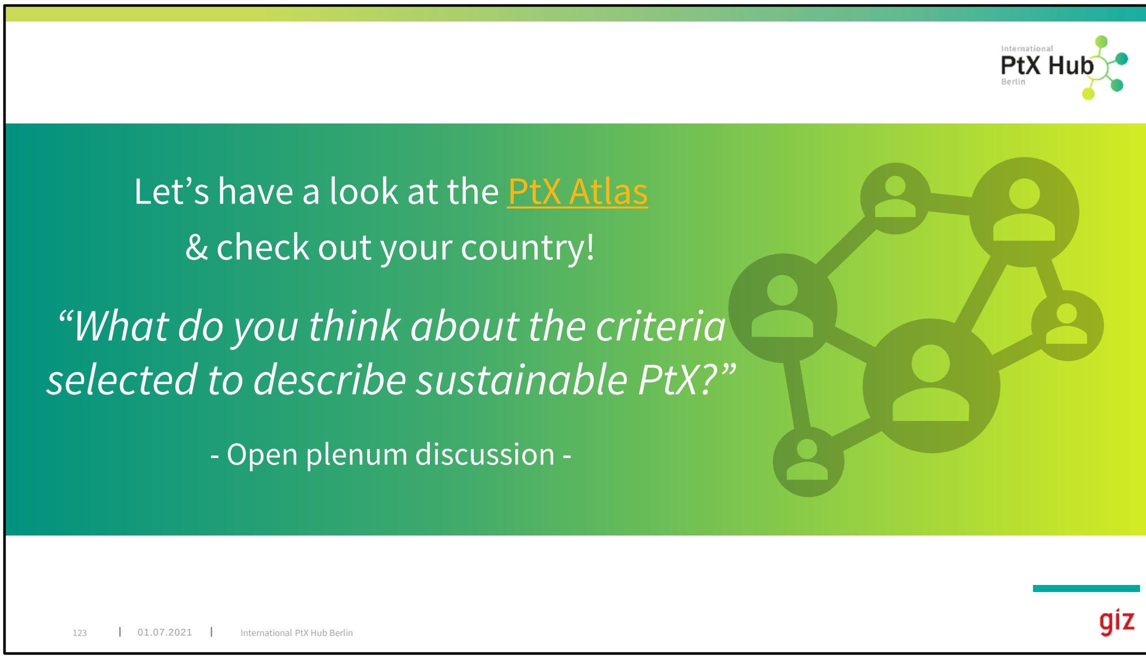
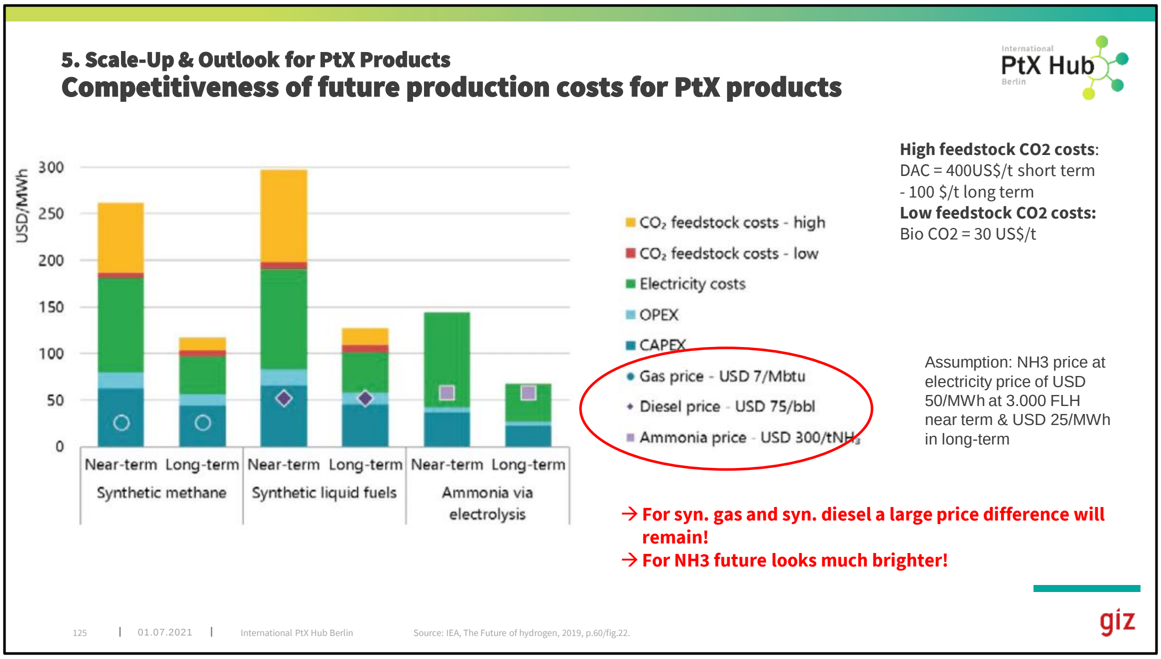
Notes:
Socio-economic indicators, e.g.: political stability, investment security, unemployment rate, satisfaction and peace, health system.



Check it out yourself: https://maps.iee.fraunhofer.de/ptx-atlas/

5. Scale-Up & Outlook for PtX Products

Examples for synthetic jet fuel & green ammonia



Notes:

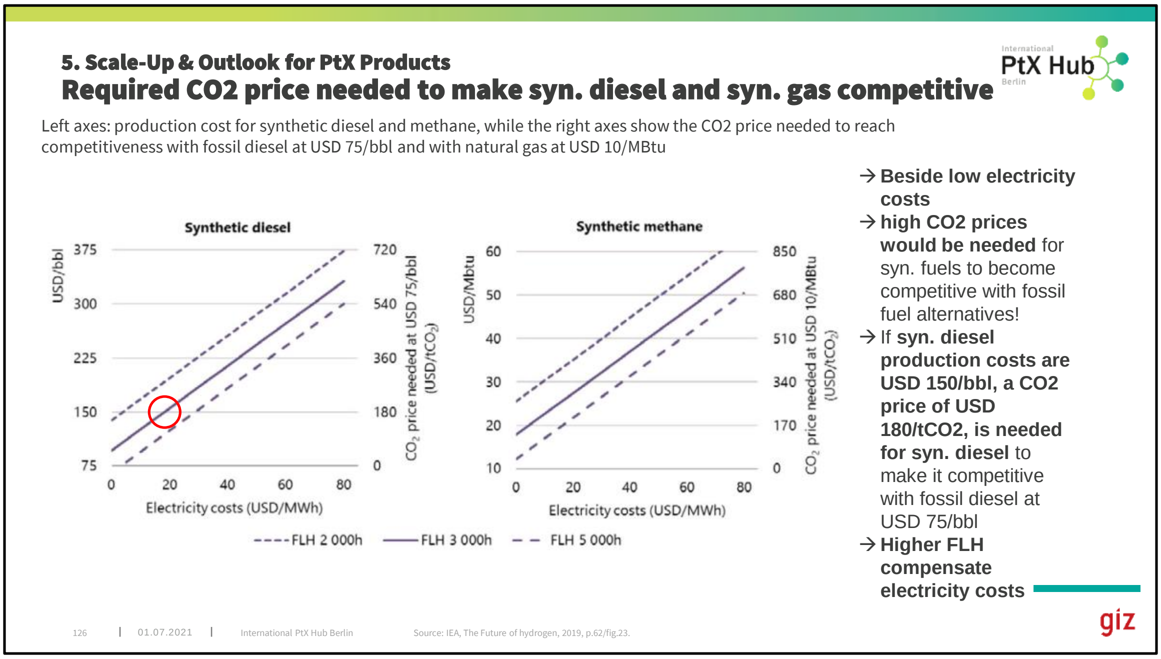
- Future **cost reductions for H_2-based products from** electricity will depend on **lowering the cost of electricity**, with **cost reductions for CO_2 feedstocks also being critical for synthetic hydrocarbons.**
- The **main cost components** for the production **of NH_3 and synthetic hydrocarbons are the CapEx** and the **H_2 costs**, together with **the electricity costs if the H_2 is produced through electrolysis** and, for **synthetic hydrocarbons, the CO_2 feedstock costs.**
- **Capital costs constitute around 30–40% of the total production costs** for NH_3 and synthetic hydrocarbons if the H_2 is produced from electricity.
- **CapEx costs are dominated by the costs of the electrolyser,** while the synthesis process and other equipment components have a smaller impact.
- **Learning effects could roughly halve the CapEx costs of the different production pathways** in the long-term, thereby bringing down the cost of production.

Further comments:

- NH_3.; renewable electricity price = USD 50/MWh at 3,000 FLH in near term and USD 25/MWh in long-term;
- CO_2 feedstock costs lower range based on CO_2 from **bioethanol production at USD 30/tCO_2** in the near and long-term;
- CO_2 feedstock costs upper range based **on DAC = USD 400/tCO2 in the near term** and **USD 100/tCO_2 in the long-term**; discount rate = 8%.
- CO_2 prices (USD/tCO_2):
    - Advanced economies:
        - o Today: 5-16
        - o 2030: 100
        - o Long term: 160
    - Emerging economies:

    - Today: 0-5
    - 2030: 75
    - 2050: 145
- Electricity prices, grid, 5,000 FLH (USD/MWh):
  - Europe:
    - Today: 98
    - 2030: 114
    - 2050: 123
  - China:
    - Today: 113
    - 2030: 140
    - 2050: 137
  - USA:
    - Today: 70
    - 2030: 100
    - 2050: 108
- Variable renewable electricity long-term (USD/MWh) with optimised FLH:
  - Europe:
    - 2050: 47
    - FLH: 2,054
  - China:
    - 2050: 18
    - FLH: 2,822
  - USA:
    - 2050: 31
    - FLH: 2,425
- More information on the underlying assumptions is available at www.iea.org/hydrogen2019.

Source:
The Future of Hydrogen – Seizing today's opportunities, Report prepared by the IEA for the G20, Japan.



Notes:

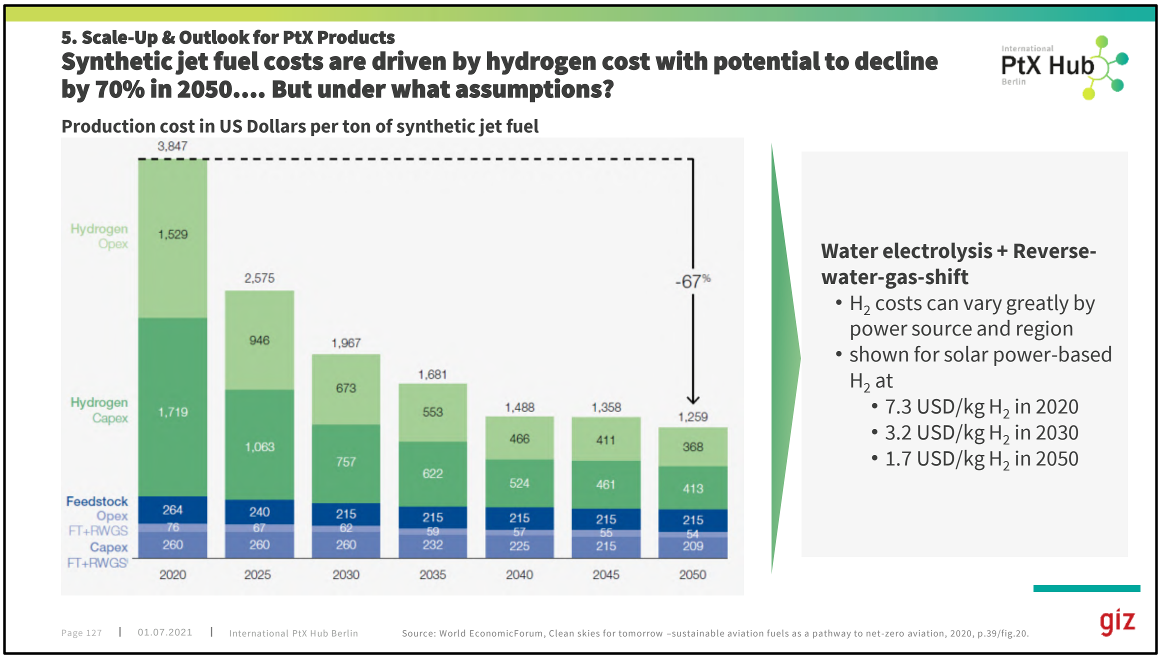
- High CO_2 prices (or equivalent policies discouraging fossil fuel use) would be needed for synthetic hydrocarbon fuels to become competitive with fossil fuel alternatives.
- If, for example, synthetic diesel can be produced at a cost of USD 150/bbl, a CO_2 price of USD 180/tCO_2, or equivalent policy measure, would be needed for synthetic diesel to become competitive with fossil diesel at USD 75/bbl.
- The high level of equivalent CO_2 prices that would be needed for synthetic hydrocarbon fuels from electricity to compete with fossil fuels suggests that the use of synthetic hydrocarbon fuels at a larger scale is unlikely to happen in the near term.
- The economics of H_2-based fuels and feedstocks does, however, depend on the specific local conditions and the configuration of the different process components, for the case of NH_3 production at different locations in China.

Further comments:

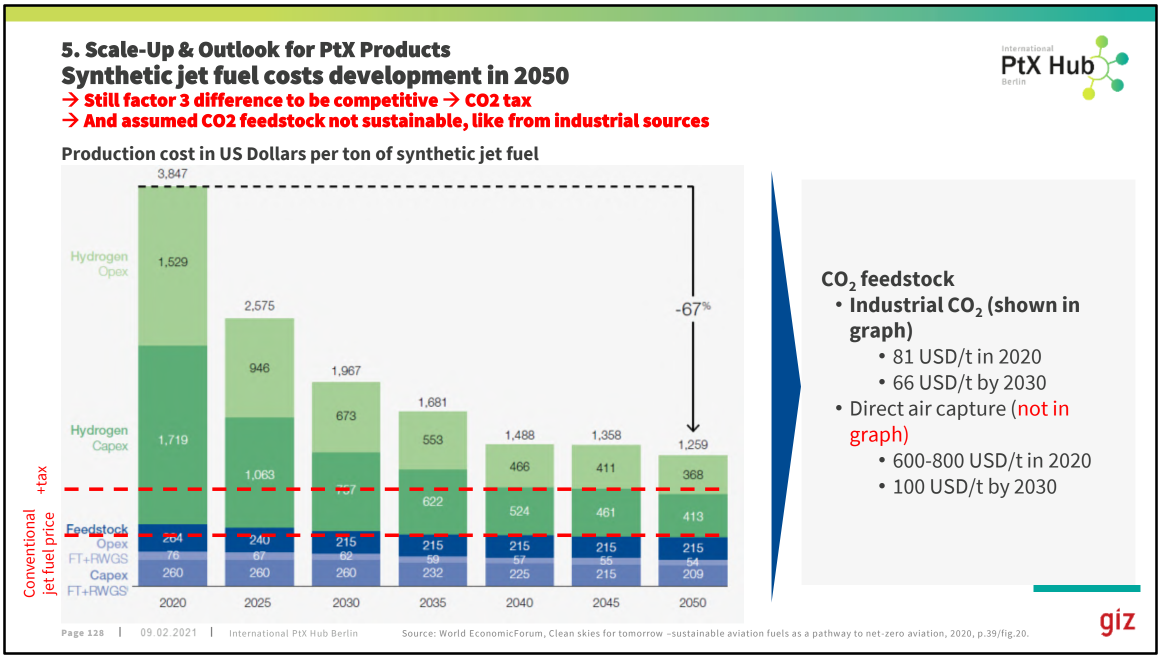
Left axes show the production cost for synthetic diesel and methane, while the right axes show the CO_2 price needed to reach competitiveness with fossil diesel at USD 75/bbl and with natural gas at USD 10/MBtu. More information on
the underlying assumptions is available at www.iea.org/hydrogen2019.

Source:

The Future of Hydrogen – Seizing today's opportunities, Report prepared by the IEA for the G20, Japan.



Source: World Economic Forum(2020) Clean skies for tomorrow –sustainable aviation fuels as a pathway to net-zero aviation.

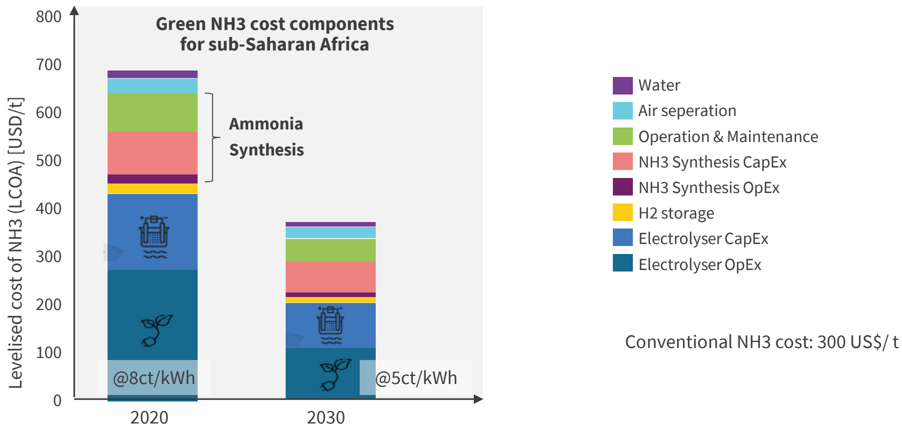


Source: World Economic Forum(2020) Clean skies for tomorrow –sustainable aviation fuels as a pathway to net-zero aviation

5. Scale-Up & Outlook for PtX Products

Cost development of green ammonia prodution

→ Costs are determined by costs of green hydrogen



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.

Notes:

- The **operation & maintenance is considered here as a fraction of CapEx** per annum instead of being specific to a location.

Source: Royal society of chemistry (2020) Techno-economic viability of islanded green NH3 as a carbon-free energy vector and as a substitute for conventional production; https://pubs.rsc.org/en/content/articlepdf/2020/ee/d0ee01707h

5. Scale-Up & Outlook for PtX Products

But disadvantage of all PtX: Overall efficiency is very low when end product is power!

Example: Power-to-Power efficiency of using NH_3 by electrolysis technology

Table 1. **Power-to-power efficiencies of various intermediate hydrogen-rich fuels**

Fuel	PtP efficiency CO_2 from air	PtP efficiency CO_2 from fumes
CH_4	27%	31%
MeOH	27%	32%
DME	23%	28%
NH_3		35%
NH_3 PEM		29%
NH_3 SOEC		39%

Sources: Based on Grinberg Dana et al. (2016), "Nitrogen-Based Fuels: A Power-to-Fuel-to-Power Analysis" and ISPT (2017), *Power to Ammonia.*

→Whenever possible **electricity should be used via more effective storage technologies** (batteries, pumped-storage hydropower)

→ **Use of syn. fuel should be limited** to cases where ease of portability or long-term storage are required

 Source: OECD & IEA, Renewable Energy for Industry - from green energy to green materials and fuels, 2017, p.49/table1.

Notes:

- Main lesson: Not the relative superiority of NH_3 over HCs, but rather PtP's low efficiencies.
  - → Whenever possible electricity should be used via more effective storage technology (batteries, pumped-storage hydropower)
  - → Use of syn. fuel should be limited to cases where ease of portability or long-term storage are required (at least with respect to electric or mechanical force, incl. motion).
- **Key message: Synthetic hydrocarbons and NH_3 have low PtP efficiencies → should only be used when electricity cannot be used directly or via more efficient energy storage technologies!**

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

- Open discussion -

Training | Module 4

Storage and Transport Infrastructure

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

International PtX Hub Berlin

Module 4: Storage and Transport Infrastructure

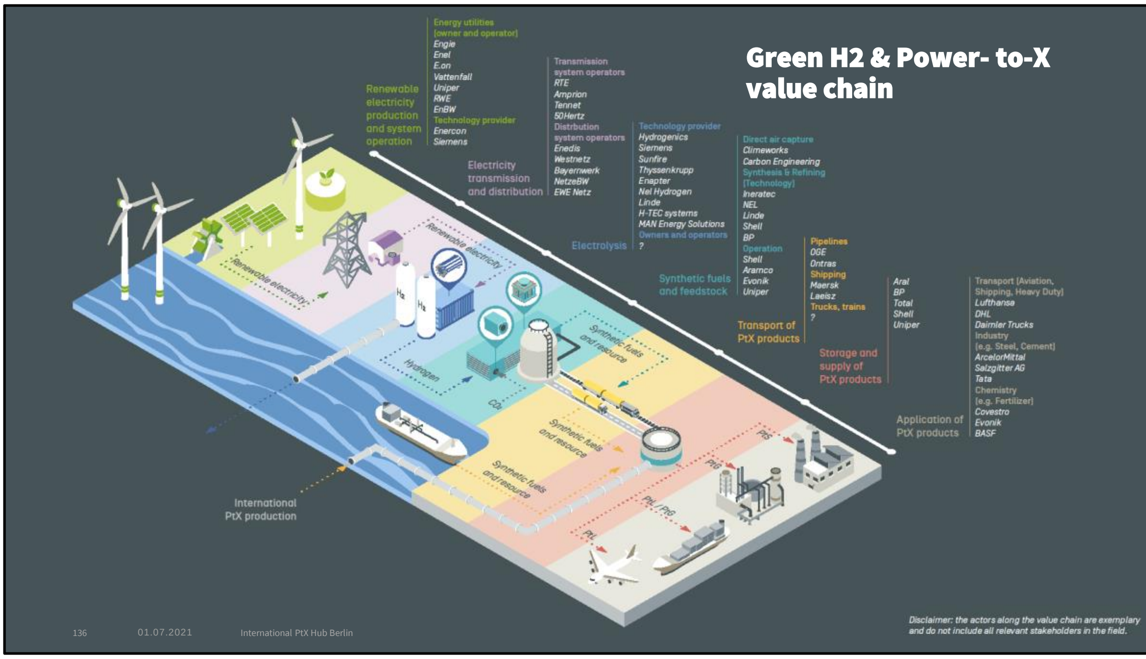
At the end of this module participants will

- know the **different storage options for H2** and derivates and their specific characteristics incl. financial aspects
- be able to **differentiate various transport options for H2 carriers** and derivates incl. financial aspects
- understand **where PtX products will be used in the specific country** and what kind of storage and transport is needed for this specific case

Benefit for learners:
The participants will be able to identify possibilities in their own countries existing infrastructure and can identify possible alternatives or best practices for the national hydrogen transport and storage.

Core messages of the module:

- H2 and its derivates can be **stored in different ways**. Each of the storage options has specific characteristics.
- H2 and its derivates can be **transported in different ways** for different distances. Each of the transport options has specific characteristics.
- **Selection of products and selection of approaches for transport** considering **already existing infrastructure**


Green H2 & Power- to-X value chain
Renewable electricity production and system operation
Energy utilities (owner and operator)
Engie
Enel
E.on
Vattenfall
Uniper
RWE
EnBW
Technology provider
Enercon
Siemens
Electricity transmission and distribution
Transmission system operators
RTE
Amprion
Tennet
50Hertz
Distrbution system operators
Enedis
Westnetz
Bayernwerk
NetzeBW
EWE Netz
Electrolysis
Technology provider
Hydrogenics
Siemens
Sunfire
Thyssenkrupp
Enapter
Nel Hydrogen
Linde
H-TEC systems
MAN Energy Solutions
Owners and operators
?
Synthetic fuels and feedstock
Direct air capture
Climeworks
Carbon Engineering
Synthesis & Refining (Technology)
Ineratec
NEL
Linde
Shell
BP
Operation
Shell
Aramco
Evonik
Uniper
Transport of PtX products
Pipelines
OGE
Ontras
Shipping
Maersk
Laeisz
Trucks, trains
?
Storage and supply of PtX products
Aral
BP
Total
Shell
Uniper
Application of PtX products
Transport (Aviation, Shipping, Heavy Duty)
Lufthansa
DHL
Daimler Trucks
Industry (e.g. Steel, Cement)
ArcelorMittal
Salzgitter AG
Tata
Chemistry (e.g. Fertilizer)
Covestro
Evonik
BASF
Renewable electricity
Hydrogen
Synthetic fuels and resource
International PtX production
PtS
PtG
PtL / PtG
PtL
Disclaimer: the actors along the value chain are exemplary and do not include all relevant stakeholders in the field.
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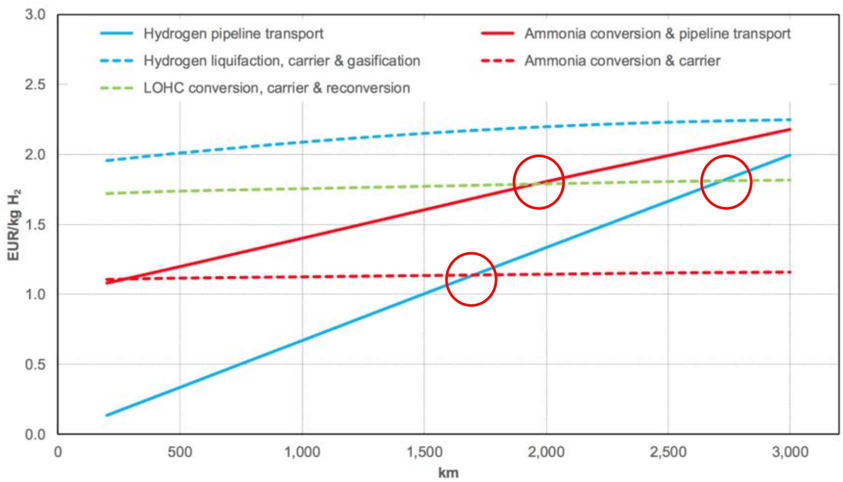
“What is the best option to transport H2 over a distance of up to 1500 km?”

“What is the most expensive option for H2 transport?”

Costs of different options for the long-distance transport of H2 depending on transport distance



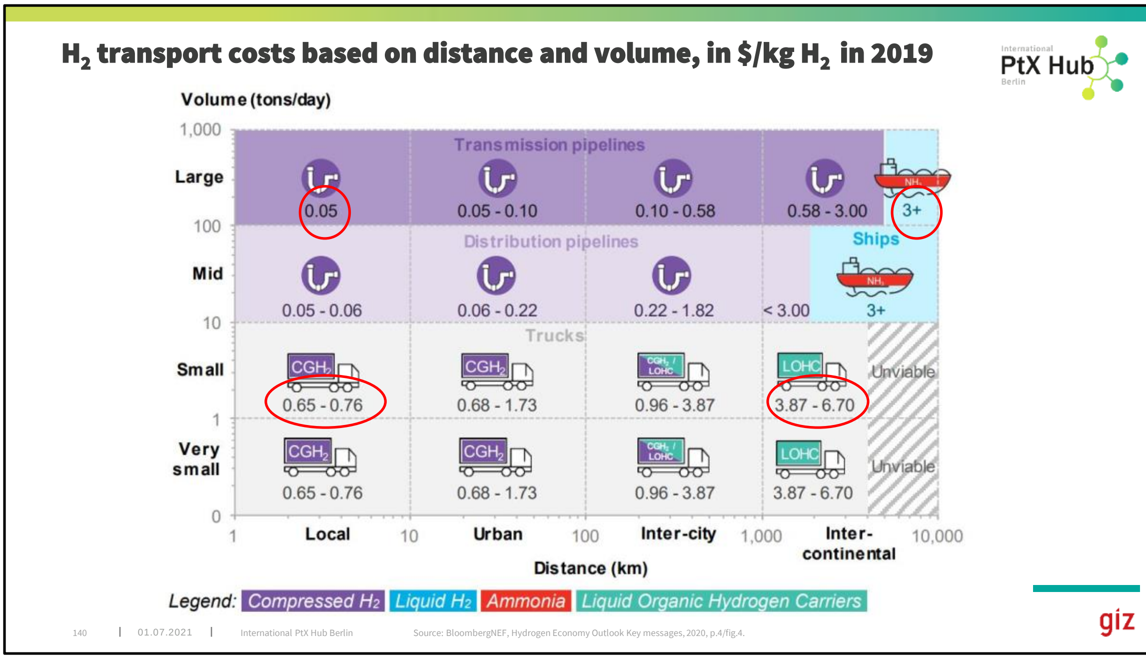
Graph figures take into consideration:
- pure transport costs,
- necessary storage facilities,
- necessary conversion and
- LOHCs for shipping (*)

& assuming new construction of transport facilities.

Source: Öko-Institut e.V.: Wasserstoff und wasserstoffbasierte Energieträger bzw. Rohstoffe, 2020, p.98/Abb.4-4.
(*) according to nach IEA (2019), Niermann et al. (2019) sowie hydrogenC (2020).

Notes:

- While H_2 and NH_3 pipelines as well as NH_3 tankers represent a widely tested technology, the shipping of liquid H_2 or Liquid Organic Hydrogen Carriers (LOHCs) in the respective process chain is still relatively at the beginning of technological development or scaling.



Notes:

- **Low density also makes H_2 expensive to transport via road or ship**.
- H_2 **flows nearly 3 times faster through pipes than methane**, making it a cost-effective option for large-scale transport.
- Need for a huge, coordinated program of infrastructure upgrades and construction, as H_2 is often incompatible with existing pipes and systems.
- H_2 is likely to be most competitive in large-scale local supply chains.
- Clusters of industrial customers could be supplied by dedicated pipeline networks containing a portfolio of wind- and solar-powered electrolysers, and a large-scale geological storage facility to smooth and buffer supply.

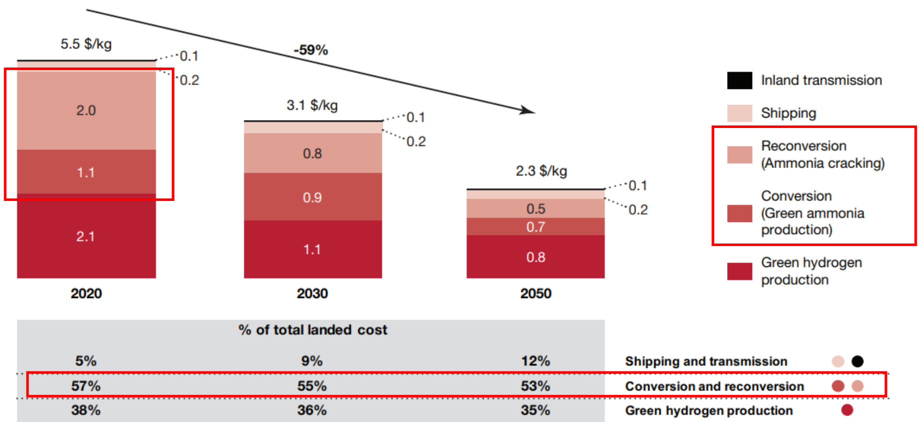
Further Comments: Figures include the cost of movement, compression and associated storage (20% assumed for pipelines in a salt cavern). NH_3 assumed unsuitable at small scale due to its toxicity. While LOHC is cheaper than liquid H_2 (LH_2) for long distance trucking, it is less likely to be used than the more commercially developed LH_2.

Source: https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

Ammonia as a transport option for green H2 for the future?

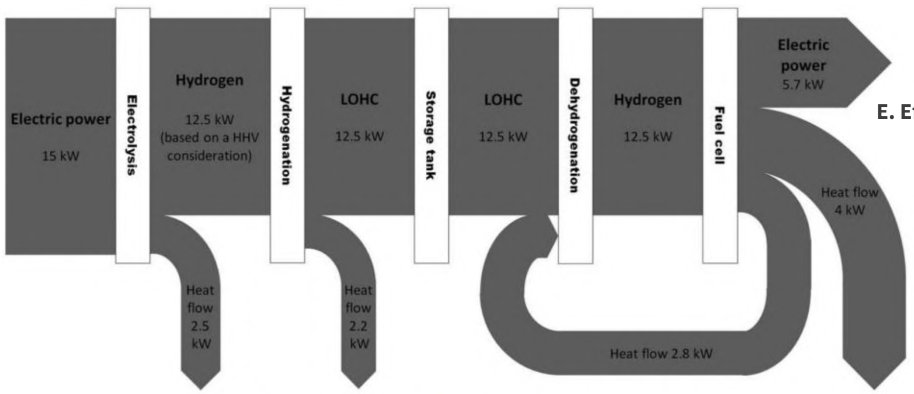
→ For large quantities an option if infrastructure can be build up

The landed cost of supplying green H2 to Europe will drop by 2050 ($/kg)



Source: Koegler et al., (Strategy&), How the gcc can become a force in global green Hydrogen, 2020, p.4/1.

Liquid Organic H2 Carrier (LOHC) is an option for transport and storage, but has high losses when final energy is power



E. Efficiency = 38%

Fig. 5 Sankey diagram of energy fluxes of the complete process, case (1).

Source: Daniel Teichmann et al. (Energy & Environmental Science), Energy storage in residential and commercial buildings via Liqui Organic Hydrogen Carriers (LOHC), 2012, p. 9048/fig.5.

Notes:

- **LOHC systems offer a very attractive way to store and transport H_2**, a technical feature that is highly desirable to link unsteady energy production from renewables with the vision of a sustainable, CO_2-free, H_2-based energy system.
- LOHCs can be charged and discharged with considerable amounts of H_2 in cyclic, catalytic hydrogenation and dehydrogenation processes.
- As their physicochemical properties are very similar to diesel, today's infrastructure for liquid fuels can be used for their handling thus greatly facilitating the step-wise transition from today's fossil system to a CO_2 emission free energy supply for both, stationary and mobile applications.

Source:
https://pubs.rsc.org/en/content/articlehtml/2015/ee/c4ee03528c
https://epub.ub.uni-muenchen.de/18079/1/oa_18079.pdf

Advantages:

- Low delivery frequency to HRS
- **Lowet cost for H_2 bulk storage**
- **No boil-off losses / discharge**
- **Safe handling**
- **Small footprint through underground storage**
- **Highest social acceptance through oil handling**
- **Liquids can be used multiple times, but with degredation**

Energy balance:
Exothermic hydrogenation → heat 250°

Endothermic dehydrogenation

Source: https://pubs.rsc.org/en/content/articlehtml/2015/ee/c4ee03528c

Challenge for all PtX: Overall efficiency is very low when end product is power!

Example: Power-to-Power efficiency of using NH_3 by electrolysis technology

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 Source: OECD & IEA, Renewable Energy for Industry - from green energy to green materials and fuels, 2017, p.49/table1.

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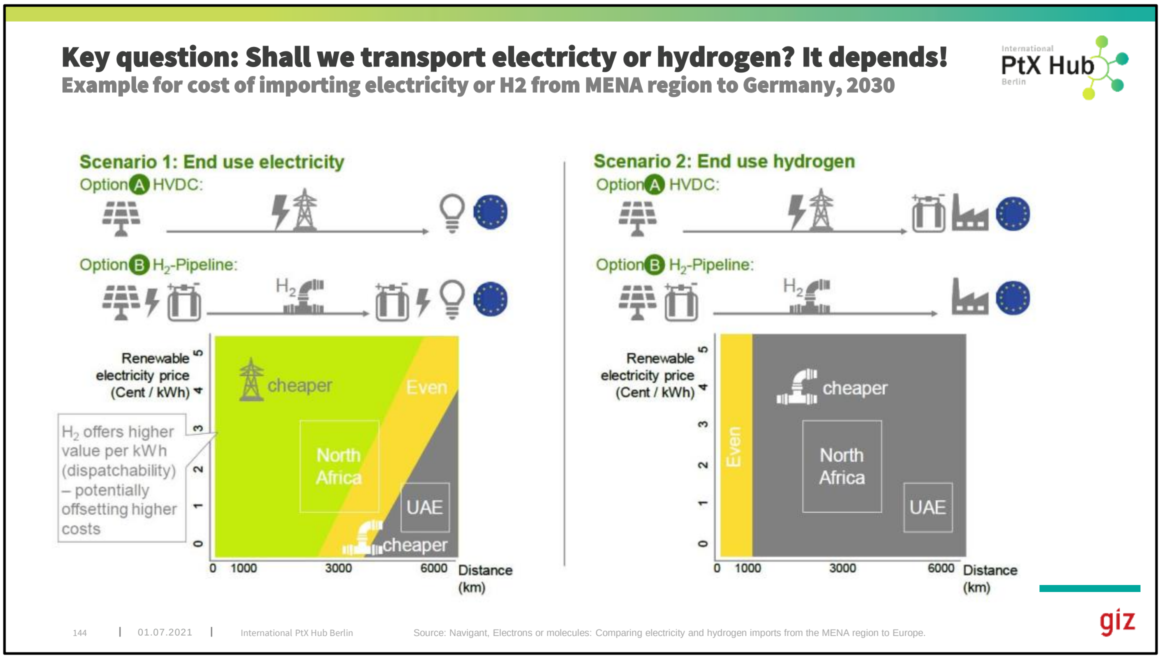
Key message: **Synthetic hydrocarbons and NH_3 have low PtP efficiencies → should only be used when electricity cannot be used directly or via more efficient energy storage technologies.**



Notes:

<u>Scenario 1: End use ELECTRICITY</u>

<u>(left)</u>

- Indicative cost comparison of options **A and B in the case that the end user in Europe requires electricity.**
- For electricity transmission, a **newly constructed high-voltage direct current (HVDC) line is assumed**, for the **transportation of H_2 a newly constructed H_2 pipeline.**
- *Green* indicates a costs advantage of electricity transmission, *yellow* a parity between costs of electricity or H_2 transmission and *grey* a cost advantage of H_2 transmission.
- The figure displays these cost differentials as functions of the main variable cost drivers:
  - Distance of energy transmission: longer distances are cost advantage for H_2 because one km pipeline is cheaper per unit of energy than one km HVDC
  - Renewable electricity price: lower prices are a cost advantage for H_2 because conversion losses become less of an economic issue
- This means that for **higher renewable generation prices (>1 Cent / kWh)** and **shorter distances (<3000km),** it is **cheaper to import electricity directly**.
- From a distance of **around 3000 km, H_2 becomes competitive**, albeit **only for electricity prices between 0-4 cents/kWh**.
- Starting from a distance of **around 4000 km and electricity prices between 0-3 cents/kWh, the import of H_2 and reconversion to electricity** becomes cheaper than importing electricity directly.

Disclaimer: This comparison is only concerned with costs and makes no assumption on the value of a kWh of electricity under either option A or B.

As electricity production from H_2 would be dispatchable, it could be the case that importing H_2 is economical even if importing electricity is cheaper, as H_2-based electricity could be sold in times of higher prices in European electricity markets.

Scenario 2: End use of HYDROGEN
(right)

- Similar steps as in scenario 1, but for **the end use of H_2 and not electricity.**
- Correspondingly, imported electricity needs to be converted to H_2, and imported H_2 does not need to be reconverted to electricity.
- In this scenario, it **is always cheaper to import H_2 directly (option B), than electricity and convert it to H_2 in Europe**.
- This is because the **conversion losses of electrolysis are inevitable in both options** and the only differentiator that remains are the higher CapEx costs of a HVDC transmission line compared to a pipeline.
- The comparison is for made for **the year 2030, which means that a range of assumptions were made.**

Assumptions:

- The basic assumption underlying this modelling is that a **new renewable electricity generation asset in the MENA region is connected** to an energy consumer in Europe with a **new-built HVDC line or H_2 pipeline**.
- Either transmission system is built **without major geographical restrictions**.
- The model **makes assumptions about 4 different technologies**:
    1. costs for H_2 electrolysis,
    2. costs for the reconversion of H_2 into electricity by fuel cell,
    3. transportation cost of electricity via a HVDC transmission line,
    4. transportation cost of H_2 via a newly constructed H_2 pipeline.
- The costs of H_2 electrolysis are based on **available technology in 2020 with an annual cost reduction until 2030 derived** from IEA.9
- Cost assumptions for **the fuel cell are based on JRC estimates for 2030** directly.
- The costs for **HVDC transmission line are based on estimates by Dii for 2050** and were adapted for 2030.
- The model assumes an unweighted average of marine and land MENA and EU HVDC transmission cost for the entire distance.
- Weighted **average costs of capital were assumed to be 8% for all technologies**.
- New assets – both pipelines and HVDC – could however be (co-)financed with **concessional loans e.g. by the European Investment Bank or the World Bank**. That would lead to a slight cost advantage of the more capital-intensive HVDC option, but would probably not fundamentally change the relative economics of the two options

Source: Navigant – Electrons or molecules: Comparing electricity and H2 imports from the MENA region to Europe.

Comparision of transport as electricty as H2 or as PtX:
Each option has its specific charecteristics

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	Transport Options	Transport Costs	Existing Infrastructure	Infrastructure Investment Cost
Electricity		Below **3,500 – 5,000 km cheaper** than H_2 (1-2 ct/kWh) → no conversion losses	**800 MW capacity** between EU and North-Africa	~5-12€ bn. for 1.200 km with 10 GW capacity[1]
Hydrogen		• **Over ~3,500-5,000 km: transport of molecules cheaper** • H_2-pipelines cheapest option on TWh-scale (~3ct/kWh, medium-term 6ct/kWh) • Shipping expensive (~9 ct/kWh);	• Retrofitting of existing natural gas pipelines • Upgrading of LNG terminals	• ~12€ bn. for 1.200 km pipeline with 60 GW capacity[2] • 1€ bn. for import-terminal with 11 GW capacity + investment into ships[3]
Derivates		In-expensive transport (< 1ct/kWh)	Usage of existing ships and trucks	Most infrastructure already existing

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Sources: Zickfeld & Wieland, 2050 Desert Power Perspectives on a Sustainable Power System from EUMENA, 2012; Fact Sheet: Das Nord Stream 2-Projekt - 20% Mehrkosten für Hydrogen statt CH4 basierend auf Expertenworkshop in Abu Dhabi am 20.02.; PPIAF, World Bank, Regional Gas Trade Projects in Arab Countries, 2013; Navigant, Electrons or molecules: Comparing electricity and Hydrogen imports from the MENA region to Europe.

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Sources:

- Zickfeld & Wieland (2012) „2050 Desert Power Perspectives on a Sustainable Power System from EUMENA“
- Fact Sheet: Das Nord Stream 2-Projekt. 20% Mehrkosten für H2 statt CH4 basierend auf Expertenworkshop in Abu Dhabi am 20.02.
- PPIAF, World Bank (2013): Regional Gas Trade Projects in Arab Countries.
- Navigant – Electrons or molecules: Comparing electricity and H2 imports from the MENA region to Europe

Advantages and disadvantages of transport options:
H2 derivatives are cheaper to transport than gaseous H2, but have much higher losses

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	Advantages	Disadvantages
Electricity	• Existing infrastructure between EU and North-Africa • Low transport cost (<3.500-5.000km)	• Security of supply: limited electricity storage capacity • Value in the power system: Feed-ins only at times of RE-generation in the supplier country
Hydrogen	• Retrofit existing pipeline/terminal infrastructure • 25-250GWh storage capacity (single cavern) • Feed-in at times of higher spot market prices increases revenues and system benefits • Low transport cost (>3.500-5.000km)	• Understanding of material science issues
Derivates	• Usage of existing transport routes & infrastructure • Safer handling and distribution • Liquid NH3 capable of storing 1.5 times more H2 than liquified H2	• Low conversion efficiency • Poor avilability and delivery schedule • Lack of terminal infrastructure

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Sources: FuelCellsWorks, Hydrogen Economy with Mass Production of High-purity Hydrogen from Ammonia, 2020; Energy.Gov, Gaseous Hydrogen Delivery, n.d.; Navigant – Electrons or molecules: Comparing electricity and Hydrogen imports from the MENA region to Europe.

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Notes:

Gaseos H_2:

- **Existing natural gas pipelines**: H_2 can be transported by pipelines, opening up the opportunity to use existing natural gas pipelines, e.g. by blending it into these pipelines.
    - This can currently be done at up to 2%. Blending ratios of up to 10% are also possible without major effects on distribution networks or end-users.
    - Blending would reduce the value of H_2 to the much lower value of natural gas.
    - Furthermore, some off-takers cannot flexibly adjust to varying shares of H_2 in the gas mix. It is therefore not an option to linearly ramp up H_2 in the grid.
- **Dedicated pipelines** to transport more valuable pure H_2.
    - New dedicated pipelines could be constructed with investment costs roughly 20% higher than those of natural gas pipelines.
    - Alternatively, existing natural gas pipelines could be retrofitted. Especially pipeline material and compressors would need to be overhauled, leading to cost savings of only around 20% compared to newly built H_2 pipelines.
    - The cost of pipeline transport per ton decreases strongly with the transported volume as energy flow through a pipe is proportionate to the square of its radius. Pipelines are hence usually constructed only for large capacities.
    - The combined Nord Stream pipelines between Germany and Russia for example will have a capacity of 110 billion cubic meters (bcm) per year (for comparison: natural gas consumption in Germany 2017 was 106 bcm).
    - **H_2 pipelines also only feasible if the partners commit to large trade volumes upfront →** pipelines are competitive only at large volumes and based on high upfront investment, they tend to create supply oligopolies. The EU for example currently covers 82% of its natural gas imports from just three countries it has pipeline connections with: Russia, Norway and Algeria. This creates

geostrategic dependencies and a **lack of market liquidity** and should therefore be avoided in the set-up of future international H_2 markets.

Liquid H_2:

- H_2 is most commonly transported and delivered as a liquid when **high-volume transport** is needed in the absence of pipelines. To liquefy H_2 it must be **cooled to cryogenic temperatures** through a liquefaction process. Trucks transporting liquid H_2 are referred to as liquid tankers.
- Gaseous H_2 is liquefied by cooling it to below −253°C (−423°F). Once H_2 is liquefied it can be stored at the liquefaction plant in large insulated tanks. It takes energy to liquefy H_2.
    - Using today's technology, liquefaction consumes more than 30% of the energy content of the H_2 and is **expensive**.
    - In addition, some amount of stored H_2 will be lost through evaporation, or **"boil off"** of liquefied H_2, especially when using small tanks with large surface-to-volume ratios.
    - Research to improve liquefaction technology, as well as improved economies of scale, could help lower the energy required and the cost.
- Liquid tankers:
    - Currently, for longer distances, H_2 is transported as a liquid in super-insulated, cryogenic tanker trucks. After liquefaction, the liquid H_2 is dispensed to delivery trucks and transported to distribution sites where it is vaporised to a high-pressure gaseous product for dispensing.
    - Over long distances, trucking liquid H_2 is more economical than trucking gaseous H_2 because a liquid tanker truck can hold a much larger mass of H_2 than a gaseous tube trailer can. Challenges with liquid transportation include the potential for boil-off during delivery.

H_2 carriers:

- H_2 carriers store H_2 in some **other chemical state rather than as free H_2 molecules**. Additional research and analyses are underway to investigate novel liquid or solid H_2 carriers for use in delivery.
- Carriers are a unique way to deliver H_2 by hydriding a chemical compound at the site of production and then dehydriding it either at the point of delivery or once it is onboard the fuel cell vehicle. This method of H_2 delivery is still in the early stages of research and development, and as of yet it has not been shown to be energy or cost efficient.
- Potential carriers include metal hydrides, carbon or other nanostructures, and reversible hydrocarbons or other liquids, among others in the early stages of research. Using such novel carriers would constitute a significant departure from the way transportation fuels are delivered today.

Further comments:

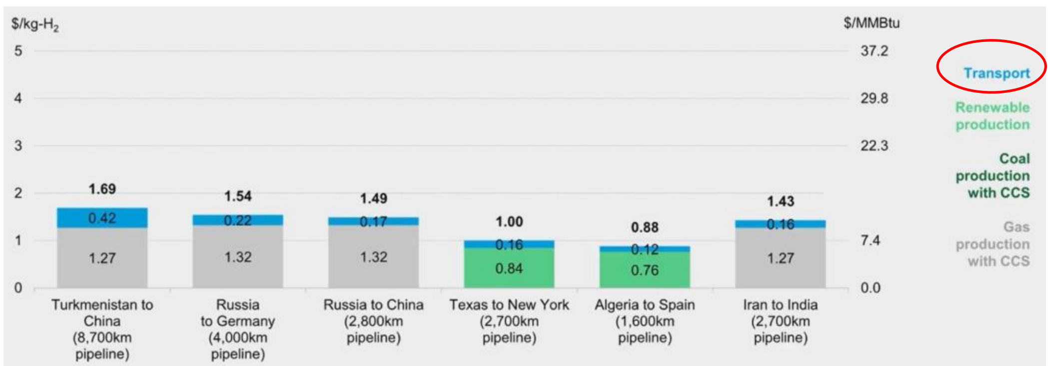
- Lack of understanding of material science issues: There is **insufficient understanding of H_2 embrittlement, fracture toughness, crack propagation, and permeation issues for steel pipeline materials under aggressive H_2 service conditions**.
- **Poor availability and delivery schedule**: Lack of timely scheduling and transport to avoid excessive H_2 boil-off and the lack of ships, trucks capable of handling cyrogenic liquid H_2.
- **Lack of terminal infrastructure**: Almost not terminal infrastructure exists for rail/ship delivery options.

Sources:

1. Zickfeld & Wieland (2012) „2050 Desert Power Perspectives on a Sustainable Power System from EUMENA"
2. Fact Sheet: Das Nord Stream 2-Projekt. 20% Mehrkosten für H2 statt CH4 basierend auf Expertenworkshop in Abu Dhabi am 20.02.
3. PPIAF, World Bank (2013): Regional Gas Trade Projects in Arab Countries.
4. https://fuelcellsworks.com/news/Hydrogen-economy-with-mass-production-of-high-purity-Hydrogen-from-Ammonia/
5. https://www.energy.gov/eere/fuelcells/gaseous-Hydrogen-delivery
6. Navigant – Electrons or molecules: Comparing electricity and H2 imports from the MENA region to Europe

If you can run a pipeline, than do it!

Long distance pipeline imports could be as cheap as natural gas - Example for some existing pipelines



→ Cost to move very large volumes of H2 (> 5,000t/day) over 1.000km could **be 9cts/kg H2** (= long distance transport cost of natural gas today)
→ Extra investment cost for a new pipeline for H2 instead of gas is **around 20%** (North stream 2 project)

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Notes:

- Outside of industrial clusters H_2 transport via pipeline is an economic option.
- The cost to move very large volumes of H_2 (more than 5,000t/day) over the distance of 1,000km should be 9cts/kg which is similar to the long distance transport cost of natural gas today.
- Compression and storage costs in transport. Assumes a 6,600t/day pipeline.

Source: BNEF Hydrogen Economy Outlook

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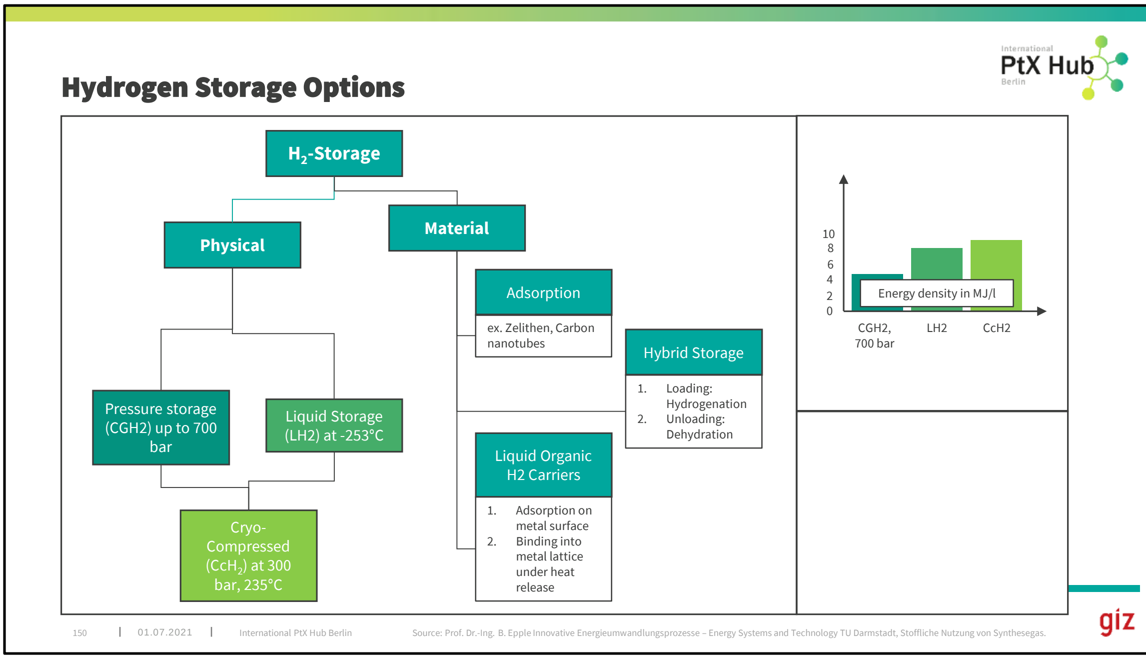
“What is the best option to store large quantities of H2?”

“What is the biggest challenge to store H2?”



Notes:

Pressure Storage:

- H_2 has a high diffusivity
- Suitable dense material for storage and pipelines is correspondingly expensive

Liquid storage:

- Cooling from very low temperatures requires a lot of energy
- Storage tanks are usually double-walled for insulation (vacuum in the middle).

The complex storage and distribution (expensive, energy-intensive) of H_2 is one of the biggest disadvantages of the technology as direct energy storage.

Further comments:

- **Cyro-compressed:** The term "**cryo-compressed**" was coined by Salvador Aceves and colleagues at Lawrence Livermore National Laboratory (LLNL) and refers to their concept of storing H_2 at **cryogenic** temperatures but within a pressure capable vessel – in contrast to current liquid (or **cryogenic**) vessels which store H_2 at low pressures.
- **Hydrogenation:** chemical reaction between molecular H_2 and another compound or element, usually in the presence of a catalyst such as nickel, palladium or platinum. The process is commonly employed to reduce or saturate organic compounds. Hydrogenation typically constitutes the addition of pairs of H_2 atoms to a molecule, often an alkene. Catalysts are required for the reaction to be usable; non-catalytic hydrogenation takes place only at very high temperatures. Hydrogenation reduces double and triple bonds in hydrocarbons.
- **Dehydration:** During dehydration synthesis, either the H_2 of one monomer combines with the hydroxyl group of another monomer releasing a molecule of water, or two H_2s from one monomer combine with one

oxygen from the other monomer releasing a molecule of water. The monomers that are joined via dehydration synthesis reactions share electrons and form covalent bonds with each other. As additional monomers join via multiple dehydration synthesis reactions, this chain of repeating monomers begins to form a polymer. Complex carbohydrates, nucleic acids, and proteins are all examples of polymers that are formed by dehydration synthesis. Monomers like glucose can join together in different ways and produce a variety of polymers. Monomers like mononucleotides and amino acids join together in different sequences to produce a variety of polymers.

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

Comparision of H2 storage options

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→ suggests that a **delivered cost of green H2 of around \$2/kg (\$15/MMBtu) in 2030 and \$1/kg (\$7.4/MMBtu)** in 2050 in China, India and Western Europe is achievable.
→ **Costs could be 20-25% lower in** countries with the best renewable and H2 storage resources, like **U.S., Brazil, Australia, Scandinavia and Middle East.**

	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

[1] Benchmark levelised cost of storage (LCOS) at the highest reasonable cycling rate. LOHC – liquid organic H2 carrier.

→ Low cost, large-scale options like salt caverns are geographically limited
→ Cost of using alternative liquid storage technologies often greater than cost of producing H2 in the first place

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

Notes:
- **H_2's low density makes it considerably harder to store than fossil fuels.**
- If H_2 were to replace natural gas in the global economy today**, 3-4 times more storage infrastructure** would have to be built at a cost of \$637 billion by 2050 to provide the same level of energy security.
- **Storing H_2 in large quantities will be one of the most significant challenges for a future H_2 economy.**
- Low cost, large-scale options like **salt caverns are geographically limited** (if not available **more expensive rock caverns will have to be drilled**), and the cost of using alternative liquid storage technologies is often greater than the cost of producing H_2 in the first place.
- **If H_2 needs to be shipped overseas, it generally has to be liquefied or transported as NH_3 or in liquid organic H_2 carriers (LOHCs).** For distances below 1,500 km, transporting H_2 as a gas by pipelines is likely to be the cheapest delivery option; above 1,500 km, shipping H_2 as NH_3 or an LOHC is likely to be more cost-effective.
- These alternatives are **cheaper to ship, but the costs of conversion before export and reconversion back to H_2 before consumption are significant.**
- They may also sometimes give rise to safety and public acceptance issues.

Advantages and disadvantages of NH_3 and liquid H_2 carriers (LOHCs):
- **NH3:**
  - Converting H_2 to NH_3 requires **energy equivalent to 7-18% of the energy contained in the H_2,** depending on the size and location of the system (Aakko-Saksaa et al., 2018; Hansen, 2017; Bartels, 2008).
  - A similar level of energy is lost if the NH_3 needs to be **reconverted back to high-purity H_2 at its destination** (Brown, 2017; Giddey, 2017).
  - Nevertheless, **NH_3 liquefies at -33°C,** a much higher temperature than is the case for H_2**, and contains 1.7 times more H_2 per m³ than liquefied H_2 → NH_3 much cheaper to transport than H_2.**

  - While NH_3 already has a well-established international transmission and distribution network, it is **a toxic chemical** and this may limit its use in some end-use sectors.
  - There is also a risk that some **not combusted NH_3 could escape**, which can lead to the formation of particulate matter (an air pollutant) and acidification.

- **LOHCs:**
  - Making an **LOHC involves "loading" a "carrier" molecule with H_2**, transporting it, and then extracting pure H_2 again at its destination.
  - LOHCs have similar properties to **crude oil and oil products**, and their key advantage is that they can be **transported as liquids without the need for cooling**.
  - However, as with NH_3, there are costs associated with the conversion and reconversion processes involved.
  - These processes would require energy equivalent to **35-40% of the H_2 itself** (Wulf and Zapp, 2018; Reuß et al., 2017).
  - In addition, the carrier **molecules in an LOHC are often expensive** and are not used up when H_2 is created again at the end of **the process, so need to be shipped back to their place of origin.**
  - Several different LOHC molecules are under consideration, each with various benefits and drawbacks. In this chapter LOHCs refers to **methylcyclohexane (MCH),** a relatively low-cost option with **toluene as the carrier molecule**. Around 22 Mt of toluene is currently produced annually (for commercial products), a quantity that could carry 1.4 MtH_2 if it were to be used as an LOHC. It **costs around USD 400–900 per ton**. But: **toluene is toxic and would require careful handling**.
  - A **non-toxic alternative LOHC is di-benzyltoluene.** Although this is much more expensive than toluene today, scaling up could make it a more attractive option in the long run, especially given its nontoxic nature.
  - Methanol and formic acid are other options, but they lead to greenhouse gas emissions if used directly (unless produced with non-fossil sources of carbon).
  - For both NH_3 and LOHCs, effective utilisation of the heat released in the conversion process could increase the efficiency of the value chain and reduce overall costs.

Source Text: IEA – The future of H2 transport
Source Slide: https://data.bloomberglp.com/professional/sites/24/BNEF-H2-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

Summary of potential applications of H2 and PtX in the future
Best option depends on circumstances – no easy quick solution

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Transport:

- **Short distance**: electrification, battery powered ships already existent
- **Long distance: low carbon fuels needed** (H_2, NH3, drop-in fuels, methanol etc.)
- But: Each technology comes with advantages/disadvantages
- **Ammonia in shipping** is at an early stage of technological maturity
- In general the following factors should be considered for the prioritisation process:
  - **Energy density of the fuels,**
  - **Infrastructure,**
  - **Potential to scale up the production,**
  - **Cost prospects**.

Option: Ammonia

- Easy to store and higher energy density than H2
- Expensive, but compared to other options relatively low priced
- Toxic to humans / environment

Option: Drop-in fuels

- Could use conventional fuel oil tank
- No adjustment on board needed
- Even a blend-in quota could reduce emissions significantly
- Highest costs

Option: Hydrogen

- Must be stored at -253°C and low energy density
- Reasonable fuel production costs, but high storage and transport costs
- Requires high safety standards (explosive and flammable)

Option: Methanol

- Can be stored in conventional fuel tanks
- Higher energy density than H2
- High costs

Source: International Transport Forum, Navigating Towards Cleaner Maritime Shipping, 2020.

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“Which storage and which transport options did you consider and why?”

“What is the best option for your country?”

- Open discussion -

Training | Module 5

Sector-specific Overview and Market Knowledge (Demand Markets for Hydrogen and PtX)

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

International PtX Hub Berlin

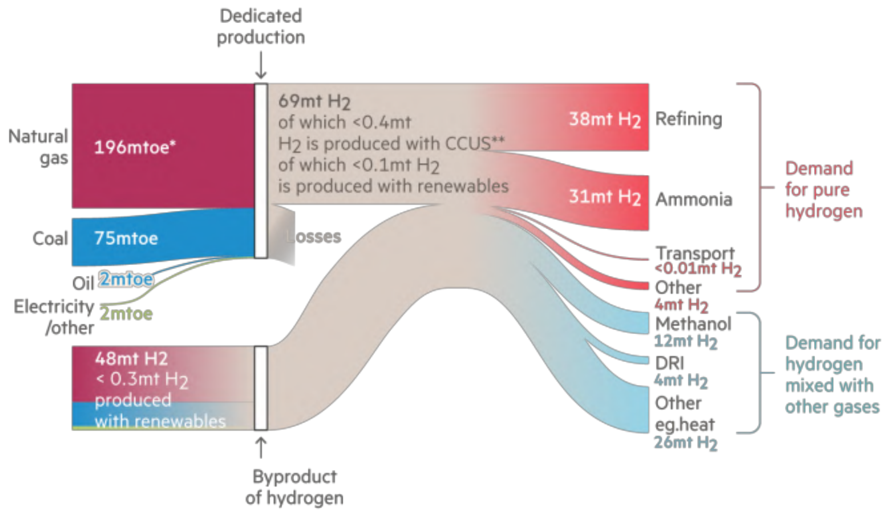
Module 5: Sector-specific Overview and Market Knowledge

At the end of this module participants will
- know the most important applications for H2 and PtX
- developed ideas for additional future applications of H2 and PtX
- reflected on different applications of H2 and PtX fulfil selected allocation criteria

Benefit for learners:
Being able to identify possible future demand markets or niche developments to elaborate a founded green hydrogen and PtX strategy based on (inter-)national outlooks.

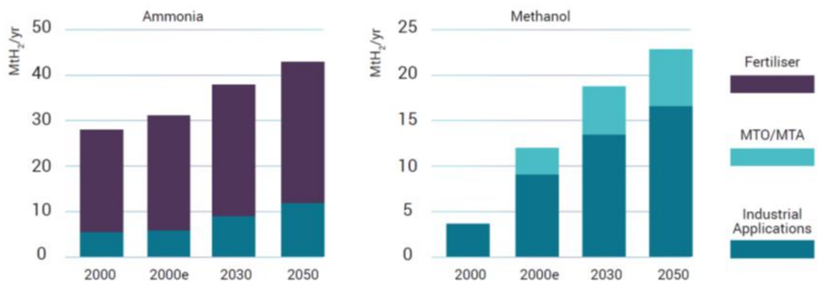
Core messages of the module:
- There are many **existing usages today and in future**
- There **is room for future usages** even in new fields
- Reflect in the **development of political strategies** on criteria for selecting potential usages of H2 / PtX

Today's hydrogen value chains



Source: Financial Times, The race to scale up green H2, 2021.

Hydrogen demand from primary chemical production for existing applications under currents trends



Notes: MTO= methanol-to-olefins, MTA = methanol-to-aromatics. Industrial applications for methanol include fuel additive uses (e.g. methyl-tert-butyl-ether) and thermoset plastics (e.g. phenol formaldehyde). Industrial applications for ammonia include explosives (e.g. ammonium nitrate) and plastics (e.g. urea formaldehyde). Demand figures for 2030 and 2050 are consistent with those on the Reference Technology Scenario (IEA, 2018b), in which current trends are maintained. data for 2018 are estimates based on previous years' figures from sources below.

Sources: IFA (2019), International Fertilzer Association database, WoodMackenzie (2018), Methnaol Production and Supply Database.

 Source: World Hydrogen congress, Mariyana Yaneva, The Role Of Hydrogen For A Low-carbon Economy, 2019.

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"In which sectors do you want to use green H2 & PtX first in your country?"

"Which sectors have the largest potentials for green H2 & PtX in country in the long run?"

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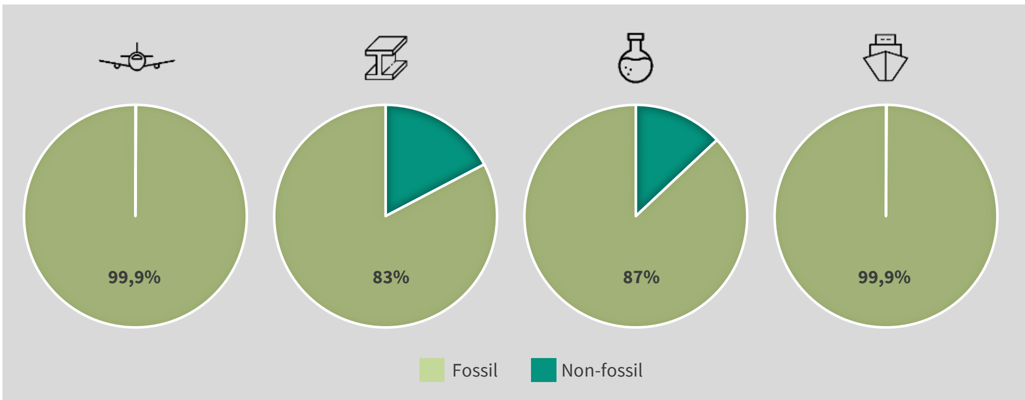
Industrial sectors still use fossil fuels



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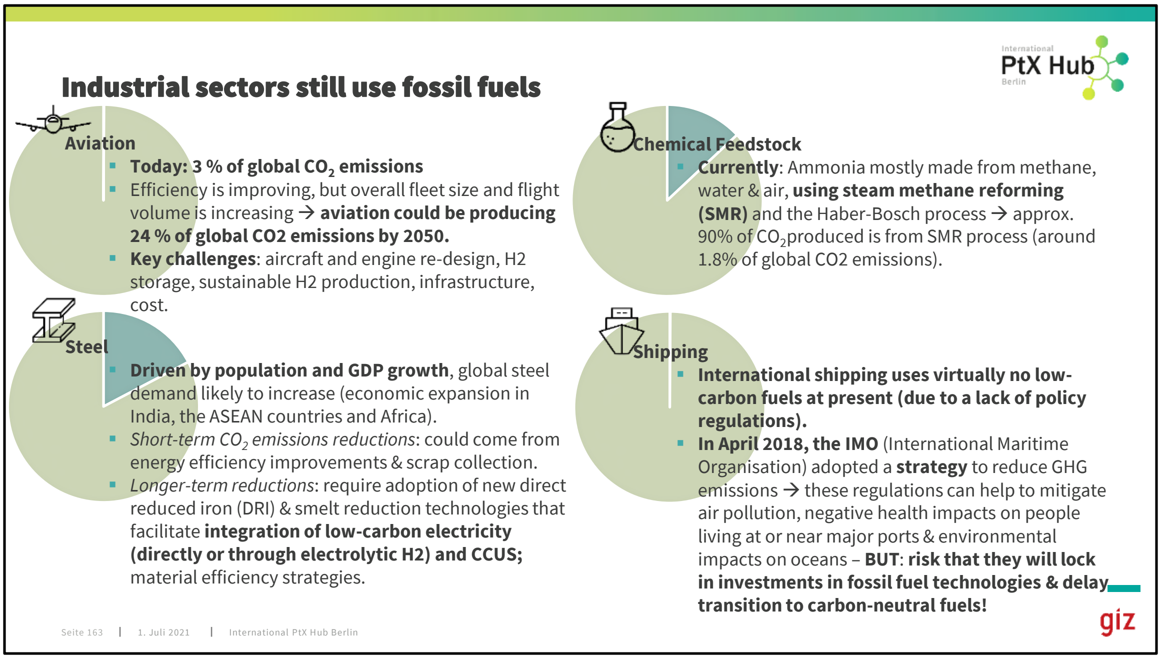
Source: IEA, Iron & Steel, 2020; IEA, International Shipping, 2020; dena, Feedstocks for the chemical industry, 2019.

Notes:
See the following slide.



Notes:

1) Aviation

- Efficiency is improving, but overall fleet size and flight volume is increasing.
- **Aviation may be producing as much as 24% of global CO_2 emissions by 2050**, compared to roughly **3% today.**

- Even with a hypothetical acceleration of **improvements in aircraft efficiency to around 2.5% per annum** – over twice of today's pace – **aviation could be producing 19% of global emissions by 2050.**
- H_2 offers several benefits over SAFs and batteries as a power storage technology:
  - Benefits over SAFs:
    - Ability to reduce aviation's GHG emissions
    - Potential to leverage scale from other industries
  - Benefits over batteries:
    - High gravimetric density
    - Relatively fast refueling capability
- **Key challenges:**
  - **Aircraft and engine redesign**
  - **H_2 storage**
  - **Sustainable H_2 production**
  - **Infrastructure**
  - **Cost**

2) Steel

- **Direct CO_2 intensity of crude steel has been relatively constant** (within a 20% range) **during the past 2 decades**.
- To align with SDS, the CO_2 intensity of crude steel **needs to fall an average of 2.5% annually between**

2018 and 2030.

- **Driven by population and GDP growth**, global steel demand will likely continue to increase, especially because of economic expansion in India, the ASEAN countries and Africa, even as demand in China gradually declines.
- Adopting material efficiency strategies to reduces losses and optimise steel use throughout the value chain can curb demand growth and thus help the subsector get on track with the SDS.
    - Material efficiency strategies include increasing steel and product manufacturing yields, light weighting vehicles, extending building lifetimes and directly reusing steel (without melting).
- **Short-term CO_2 emission reductions could come largely from energy efficiency improvements and increased scrap collection** to enable more scrap-based production.
- **Longer-term reductions would require the adoption of new direct reduced iron (DRI) and smelt reduction technologies that facilitate the integration of low-carbon electricity (directly or through electrolytic H_2) and CCUS, as well as material efficiency strategies to optimise steel use**. The groundwork for commercialising these technologies needs to be laid in the next decade.

3) Chemical Feedstock

- Currently, NH_3 is mostly made from methane, water and air, using **steam methane reforming (SMR) and the Haber-Bosch process**.
- **Approximately 90% of the CO_2 produced is from the SMR process**. This process consumes a lot of **energy and produces around 1.8% of global CO_2 emissions.**
- **Reducing the amount of CO_2 produced during the NH_3 manufacturing process is critical to achieve net-zero targets by 2050**.
    - **green NH_3** (where the process is 100% renewable and carbon-free) is by using H_2 from water electrolysis and **nitrogen separated from the air**.
    - then fed into the **Haber-Bosch process, all powered by sustainable electricity.**
    - In the Haber-Bosch process, H_2 and nitrogen are reacted together at **high temperatures and pressures to produce NH_3**
- The production **of green NH_3 could offer further options** in the transition to net-zero CO_2 emissions. These include:
    - **Energy storage** – **NH_3 is easily stored in bulk as a liquid at modest pressures**. This makes it an ideal chemical store for renewable energy. There is an **existing distribution network, in which NH_3 is stored in large refrigerated** tanks and transported around the world by pipes, road tankers and ships.
    - **H_2 carrier** – there are **applications where H_2 gas is used (e.g. in PEM fuel cells),** however H_2 is difficult and expensive to store in bulk (needing cryogenic tanks or high-pressure cylinders). **NH_3 is easier and cheaper to store, and transport** and it can be **readily "cracked" and purified** to give H_2 gas when required.
    - **Zero-carbon fuel: NH_3 can be burnt in an engine or used in a fuel cell to produce electricity**. When used, NH_3's only by-products are water and nitrogen. This could for example be adopted by the maritime industry.

4) Shipping

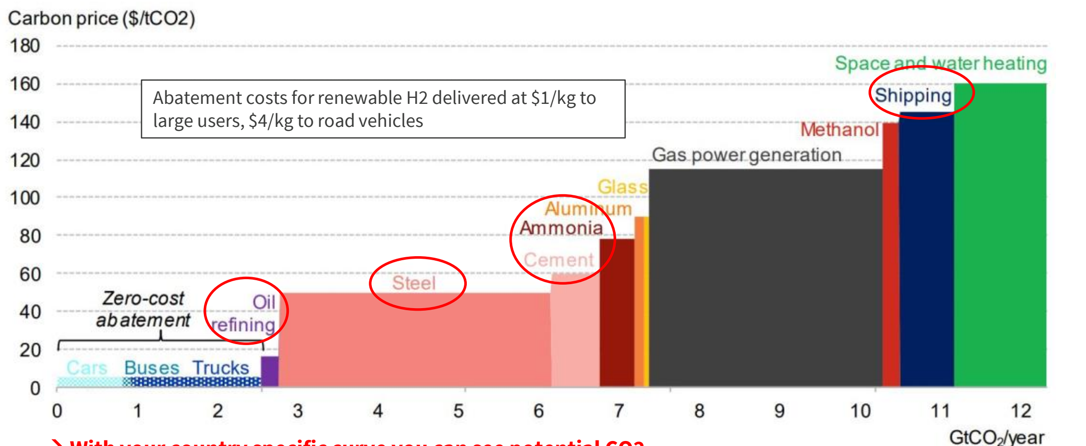
- Key enabler of international trade, **accounting for about 3/4 of total freight transport activity**. It is **also the most energy-efficient way to carry cargo in terms of energy use per tonne-kilometre (tkm).**
- **International shipping uses virtually no low-carbon fuels at present (due to a lack of policy regulations)**, but by 2050 in the SDS they supply almost one-third of total energy consumed.
- **In April 2018, the IMO** (International Maritime Organisation) adopted a **strategy to reduce GHG emissions** from international shipping to align the sector with Paris Agreement climate goals. The strategy proposes to **cut absolute GHG emissions by at least 50% by 2050, and thereafter to attempt to eliminate them altogether**. It also aims to reduce the carbon intensity of international shipping by at least 40% by 2030 and to pursue efforts to reduce emissions intensity 70% by 2050 compared with a 2008 baseline.
- A number of policies aiming to reduce air pollution from shipping have been announced in the past decade, many of which have already been enforced. The global sulphur cap mandated by the IMO entered into effect in January 2020. It requires shipping vessels to either use maritime fuels with a maximum sulphur content of 0.5% or install a scrubber to comply with sulphur dioxide emissions regulations.
- **While these regulations can help curtail air pollution as well as continue to reduce the health impacts**

on populations living at or near major ports and the environmental impacts on the oceans, there is a risk that they will lock in investments in fossil fuel technologies and delay the transition to carbon-neutral fuels.

1. Step: Make a marginal abatement cost curve for your country to determine your priorities

International PtX Hub Berlin

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 CO2 saving and costs for H2 & PtX in the sectors of your country!

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

giz

Notes:

- Even at $1/kg, carbon prices or equivalent, **measures that place a value on emission reductions are still likely to be needed for H_2 to compete with cheap fossil fuels** in hard-to-abate sectors.
- **Why is this the case?** This is because **H_2 must be manufactured, whereas natural gas, coal and oil need only to be extracted**, **so it is likely always to be a more expensive form of energy.**
- **H_2's lower energy density also makes it more expensive to handle.**
- But if the required **policy is in place, up to 34% of GHG emissions from fossil fuels and industry could be abated** using H_2 **– 20% for less than $100/t$CO_2$.**

H_2 is a promising emissions reduction pathway for the hard-to-abate industry sectors:

- The strongest use cases for **H_2 are the manufacturing processes that require the physical and chemical properties of molecule fuels in order to work**.
- H_2 can enable a **switch away from fossil fuels in many of these applications at surprisingly low carbon prices.**
- For example, at $1/kg, a carbon price of
  - $50/t$CO_2$ would be enough to switch to renewable H_2 in steel making,
  - $60/t$CO_2$ to use renewable H_2 for heat in cement production,
  - $78/t$CO_2$ for NH_3 synthesis, and
  - $90/t$CO_2$ for aluminum and glass manufacturing.

But its role in transport should be focused on trucks and ships:

- H_2 can play a valuable role **decarbonising long-haul, heavy-payload trucks**.
- These could be **cheaper to run using H_2 fuel cells than diesel engines by 2031.**
- But the bulk of the car, bus and light-truck market looks set to adopt battery electric drive trains, which are a cheaper solution than fuel cells.

- In our view, the **fuel cell vehicle industry will also be the most expensive sector to scale up, requiring $105 billion in subsidies to 2030**.
- For ships, green NH_3 from H_2 is a promising option, and could be competitive with heavy fuel oil with a carbon price of $145/$tCO_2$ in 2050.
- **Aviation:** Not in the graph, abatement costs (USD/tCO_2eq):
  - Commuter: 20-40
  - **Regional: 40-80**
  - **Short-range: 70-130**
  - **Medium-range: 100-220**
  - Long-range: 160-350

  Source:
  https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200507_H2%20Powered%20Aviation%20report_FINAL%20web%20%28ID%208706035%29.pdf

Further comments:

- Sectoral emissions based on 2018 figures, abatement costs for renewable H_2 delivered at $1/kg to large users, **$4/kg to road vehicles**. Aluminum emissions for alumina production **and aluminum recycling only. Cement emissions for process heat only**. **Refinery emissions from H_2 production only**. Road transport and heating demand emissions are for the segment that is unlikely to be met by electrification only, assumed to be 50% of space and water heating, 25% of light duty vehicles, 50% of medium-duty trucks, 30% of buses and 75% of heavy-duty trucks.

Source: https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

Economics of green H2 in different demand sectors for Europe (I)

International PtX Hub Berlin

Demand Sector	Substitute	Competitiveness	CO_2-price
	• Coking coal + CCS • Direct reduction using electricity	• To compete with the most expensive steel: **2.5€/kg** • Cheapest: **0.6€/kg**	• **Today**: **107€/t** of CO_2 at green H2 price of 1.7€/kg • **In 2050**: **43€/t** of CO_2
	• Natural gas + CCS • Industrial heat pumps	• **In Europe**: H2-price of **0.4€/kg** needed • **Outside Europe**: price of **0.2€ to 0.5€/kg** of H2 • But: Potential in batch processes	• **Today**: EU-ETS price/support mechanism worth **350€/t** of H2 • **Future**: **120€/t** of CO_2
	• Natural gas + CCS • Heat pumps	• **Unlikely to be competitive**	• **In 2050: 47€/t – 90€/t** of CO_2

Source: Liebreich: Separating Hype from Hydrogen – Part Two: The Demand Side, 2020.

giz

Notes:
Steel:
- In its 2019 analysis of the cost of making fossil-free steel, BloombergNEF **concluded that H_2-based steel would become competitive with the most expensive current steel production as soon as it can be made for 2.5€/kg, which is any time now**.
- Out-competing the cheapest steel production in the world would require a H_2 price of 0.6€/kg, which it is unlikely even in 2050.
- A **green H_2 price of \$2/kg by 2030 would require a CO_2 price of \$125/m³**, dropping to **\$50/t by 2050** as H_2 prices continue to fall.

Industrial Heat:
- The EU Hydrogen Strategy targets a **H_2 price of 1.1-2.4€ by 2030** – which translates into a **heat cost of \$11.4-\$21.1 per MMBtu. Natural** gas in Europe, by contrast, **costs \$4 per MMBtu.**
- The **European glass industry** is covered by the EU-ETS. Assuming H_2 can reach the low end of the EU's 2030 target, competing with natural gas at \$4 per MMBtu would still require an EU-ETS price **of 120€ (\$140)/m³ of CO_2 –** over four times today's price. And if you want to get started using green H_2 in the European glass industry right now, with the cheapest currently available at 2.5€/kg, you would need an EU-ETS price or other support mechanism worth no less than 350€/t.

Water and space heating:
- Because of efficiency losses between renewable power and green H_2, if electricity can be used as a heat source, it should be.
- Even if green H_2 is available at BloombergNEF's lowest 2050 price of \$0.8/kg, it would still need a CO_2 price of 47€ (\$57)/t to compete with European gas at \$4/MMBtu, and \$94/t to compete with gas at \$2/MMBtu.

Source: Liebreich: Separating Hype from Hydrogen – Part Two: The Demand Side, October 16, 2020

Economics of green H2 in different demand sectors for Europe (II)

International PtX Hub Berlin

Demand Sector	Substitute	Competitiveness	CO_2-price
	• Natural gas + CCS • Overcapacity building • Demand response measures • Pumped storage • Biogas • Biomass • Batteries	10% provision of power from green H2 providing 100% network uptime costs → average electricity price of 42€/MWh	**In 2050: 90€/t** CO_2 price (to be competitive)
	• Biogas • Solid state batteries for small ranges	long-haul competitiveness likely	> $50/t
	• Solid state battery for small ranges • Biogas	long-haul competitiveness likely; but final product not decided	> $50/t
	• Products from refined oil, gas and coal + CCS	Increase in extracting costs for fossil-fuels drives competitiveness of green H2 products	depends on sub sector

Source: Liebreich: Separating Hype from Hydrogen – Part Two: The Demand Side, 2020.

giz

Notes:

<u>Electricity:</u>

- According to BloombergNEF's August 2019 Economics of Hydrogen Production from Renewables, by 2050, green H_2 may achieve a price of $0.8/kg, dependent on directly connected renewable power **being available at $14 - $17/MWh.**
- To compete **with $2/MMBtu gas** in the heat market, green electricity at those prices **would need a $56-per-ton CO_2 price**.
- However, the green H_2 it could produce for $**0.8/kg would require a price of $94/t to be competitive**. In Europe, where natural gas currently sells for **$4 per MMBtu, renewable electricity at $17 per MWh would not need a carbon price at all, but the green H_2 it could produce would still need a CO_2 price of $57/t.**
- Moving towards net zero, we are likely to see electricity demand proportion quadruple. It is this all-encompassing use of electricity that is going to provide green H_2 with its most substantial opportunity – making sure, quite simply, that the lights stay on in absolutely all circumstances.
- It is perfectly possible to envisage a power system reaching 80% capacity factor based on reasonably priced renewables plus interconnections, demand response and batteries. You might even get to 90%. The remaining 10% to 20%, however, will be much tougher to deliver.
- There are a number of technologies that can provide energy even during these periods, which we can put in a cost merit order.
- The cheapest will be demand response – ask energy-intensive users to turn down if necessary.
- Batteries will be good for a few hours, maybe a few days. We can do a bit more with pumped storage and biomass or biogas.
- Then there is overcapacity – build your generation fleet to meet peak demand at the worst time of year, as grid designers have done since time immemorial.
- Green H_2 can **provide unlimited amounts of flexible power**. Will the resulting energy system be prohibitively expensive?

- Assume that 80-90% of power is super-cheap wind and **solar at $20 per MWh or less**; perhaps it will be $30 per MWh once you have added some storage and interconnections. If the remaining 10-20% of flexible power delivered from net-zero H_2 and **providing 100% network uptime costs $150/MWh**, that gives a blended wholesale power price of around $50/MWh = **42€/MWh (12.04.2021).** That's not so far from where most industrialised countries are today – and seems a small price to pay for a high-performing, resilient net-zero economy.

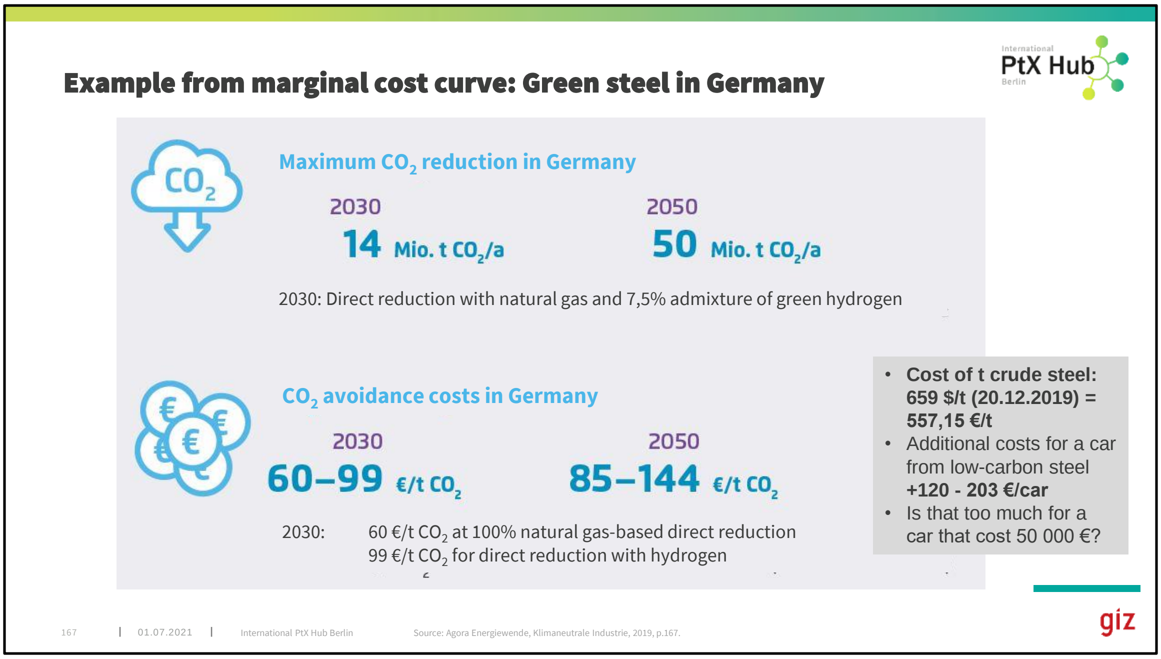
Aviation:

- **Electrification looks highly promising for general aviation and short haul, up to around 500 miles**; maybe that will push **out to 1,000 miles over the coming** couple of decades, with solid state battery technology.
- Beyond that, however, even though the propulsion system will almost certainly be electric, aircraft will be hybrids.
- The fuel of choice will either $\mathbf{H_2}$ – Airbus recently revealed a range of H_2-powered concepts – or $\mathbf{NH_3}$**,** or a synthetic liquid fuel made by combining green H_2 with carbon either captured from the air or produced via biomass.

Shipping:

- We are seeing **a rush of electrified ferries**, but the poor energy density of batteries today makes it **difficult to serve routes over 40 nautical miles (75km).** Even with a breakthrough in battery chemistry, it's hard to see the 150 nautical-mile (280km) barrier being breached electrically.
- For longer routes, and certainly for ocean-going vessels, **zero-carbon shipping means zero-carbon fuel**. **Biogas might meet some of the demand**, if it is not all snapped up for heating. Far more likely, however, will **be either $\mathbf{H_2}$ or a derivative molecule like methanol**. Maersk Shipping is looking at a range of **alcohols and $\mathbf{NH_3}$**. The latter, according to the International Energy Agency and many others, looks like the leading contender.

Source: Liebreich: Separating Hype from Hydrogen – Part Two: The Demand Side, October 16, 2020



Notes:

- Specific **additional costs per ton of crude steel** (comparison blast furnace-converter route 2019 with direct reduction with H_2 (2050): **+36-61%**
- A car with an unladen weight of one ton **consists of about 600kg of steel**
- **Cost of ton crude steel: 659$/t (20.12.2019) = 55.15€/t** (06.04.2021, exchange rate of 0.85)
- Additional costs stemming from low-carbon steel for the **production of a car: +120.34-203.92 €/car**

Assumptions:

- Spec. capital cost of crude steel through H_2-DRI (DRI plant, electric furnace): **40 €/t crude steel**
- Operating costs use of green H_2: 105-191 €/t crude steel
  - Assumption: Supply costs for green H_2: **2.78-5.04 €/kg**
    - Elektrolyser (FLH): 250 €/kW (3,000) – 500€/kW (6,000)
    - Transport costs H_2: **0.35-2.0 €/kg**
- Operating costs for electricity use in the steel mill (incl. replacement of metallurgical gases): 59-71 €/t crude steel (at electricity price of 50-60 €/MWh)
- Other costs (labour, 17% scrap content, alloys, lime, biomethane): 328 €/t crude steel
- Production costs of **low-CO_2-steel:**
  - **Lower limit: 532 €/t crude steel**
  - **Upper limit: 630 €/t crude steel**

Sources:

- Agora Klimaneutrale Industrie Studie
- https://www.stahlpreise.eu/2020/01/aktuelle-stahlpreise-je-tonne-1000-kg-januar-2020.html#:~:text=Aktuelle%20Stahlpreise%20je%20Tonne%20(1.000%20kg),-Der%20Stahlpreis%20f%C3%BCr&text=Dezember%202019%2C%20meldet%20Steel%20Benchmarker,je%

20Tonne%20(1.000%20kg).

Example: Decarbonising the German steel industry
Impact on power and product costs

Increase in electricity demand?

- Production cost of **1kg H2**: €3.6 - €5.3 /kg, using **50-55 kWh**
- **50 kg** of H2 required to produce **1 ton of steel**
- **Germany** (EU's largest steel producer): **100 terawatt-hours (TWh)** of renewable energy needed to fully decarbonise the annual production of **42 megatons (Mt) of steel**
- This **100 TWh** of additional renewable electricity demand is an **20 % increase in the total electricity demand in Germany**!
- To compare: Yearly production of solar park Benban (Egypt): 3800 GWh; land use 37,2 km^2

→ 3.8% of the electricity needed to decarbonise the German steel industry

Increase in steel production costs?

- Price of 1t steel: around €400, including €50 required for the coal used
- @ €3.6/kg H2: Replacing coal with H2 cost extra €180/t steel → **1/3 increase of total price**
- @ €1.80/kg H2 (2030): **Price difference would drop to the order of 10%**

Notes:

- **Options for closing the price gap between traditional and green steel:**
- There are three main drivers that will help tip the balance from coal to H_2 in the steel industry:
  1. **Increases in the price of carbon emissions;**
  2. **Large scale roll-out of H_2 production driving down the cost of electrolyser facilities;**
  3. **Further cost reductions of the price of renewable electricity.**
- It is estimated that, at a carbon emission price of over **€60/t of CO_2, H_2 would become the most economical option**.
- The price of emission certificates within the EU Emissions Trading System depends on the overall number of certificates put up for auction. The price per ton recently jumped from €5 - €20 when the European Commission reduced the offer in late 2018, but it is difficult to predict whether it will further increase to reach €60/t anytime soon. Electrolytic, green H_2 is currently typically produced in small scale facilities of around 2 MW.
- As the industry moves to larger facilities (up to 90 MW), producing larger quantities, the contribution of investment costs (for electrolysis facilities) in the price of H_2 could be reduced by as much as 60-80 %. The cost of electricity produced by wind energy could be 50 % lower in 2030, compared to 2017. The combined effect of lower investment costs and lower prices of electricity could drive down the prices of H_2 by 60% by 2030.

Source: https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/641552/EPRS_BRI(2020)641552_EN.pdf

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Example from marginal cost curve: Chemical industry in Germany

Maximum CO_2 reduction in Germany

2030	2050
8–14 Mio. t CO_2/Jahr	**190** Mio. t CO_2/Jahr

Reduction potential compared to reference process of steam reforming; 2050: CO2 reduction with production of 700 THW hydrogen (domestic and foreign)

CO_2 avoidance costs in Germany

2030	2050
170–430 €/t CO_2	**110–360** €/t CO_2

Calculation of the CO_2 avoidance costs on the basis of the CO_2 reduction compared to the reference process of steam reforming.

Source: Agora Energiewende, Klimaneutrale Industrie, 2019, p.187.

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“What could be the role of H2 and PtX in your country?”

“Where do you see market opportunities?”

- Grab a coffee and discuss among your group -

Training | Module 6

Environment and Climate-related Sustainability Dimensions

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

International PtX Hub Berlin

Module 6: Environment and Climate-related Sustainability Dimensions

At the end of this module participants will

- are able to point out which sources of carbon for PtX products are sustainable
- are aware that other scarce resources such as land and water are needed to produce hydrogen and reflected on related implications
- be aware of the crucial sustainability criteria defining green hydrogen and PtX
- be aware that situations differ between regions; stakeholders have to be involved

Benefit for learners:
Participants learn that H2 / PtX devises have to be seen in a holistic approach. They will understand that applying sustainability criteria are critical for the success of H2 / PtX projects in order to gain e.g. support by stakeholders and access to regulated markets

Core messages:

- H2/PtX projects have to be **embedded in SDGs**
- Input factors (energy) have to be **renewable**
- H2/PtX projects have to manage challenges in getting and using raw materials (e.g. availability, ways of producing them, political dependencies, etc.)
- **Certified sustainability** will be necessary for access to some markets

or: **menti.com > CODE 123 456**

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Test your knowledge

or: **menti.com > CODE 123 456**

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*"Which are the **top 5 sustainability criteria** for green H2 & PtX production?"*

*"Which sustainability criteria do you consider the **hardest to meet in your country**?"*

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“Which are sustainability-related challenges that need to be managed in H_2/PtX projects in your country?”

“How could this be done?”

- Open discussion -

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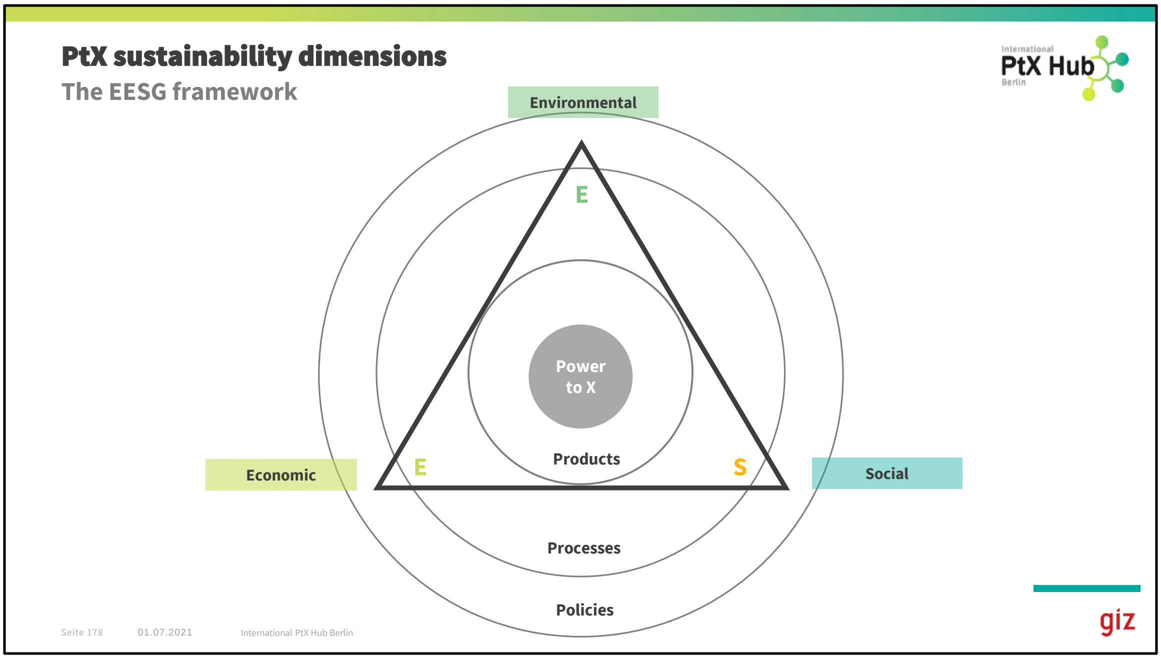
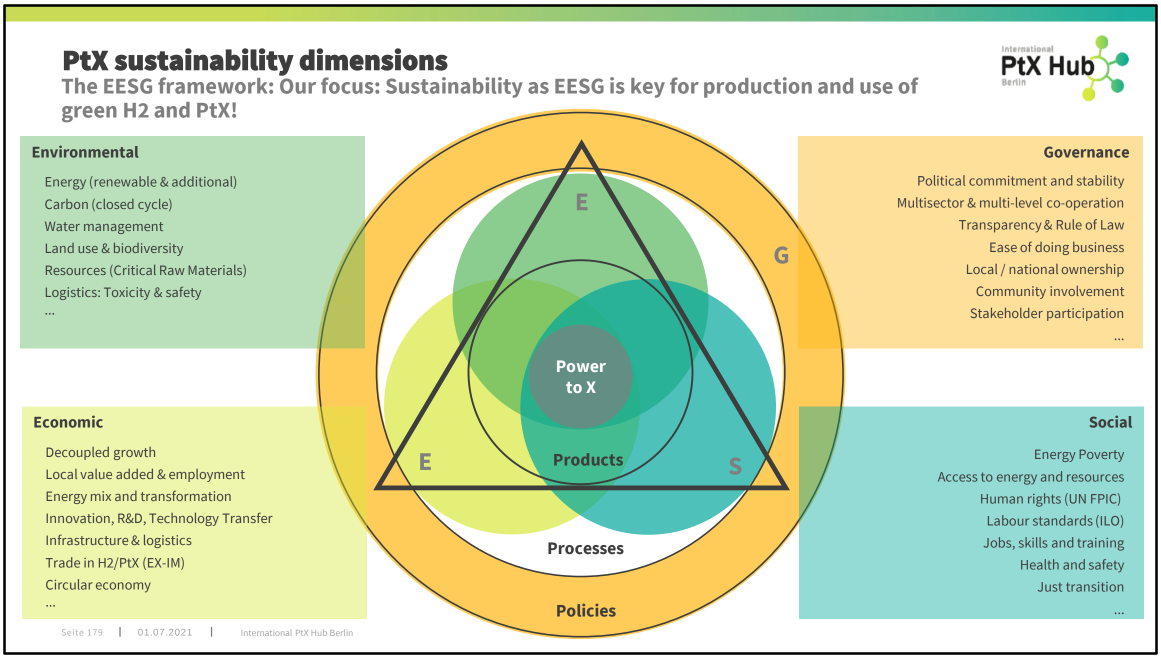


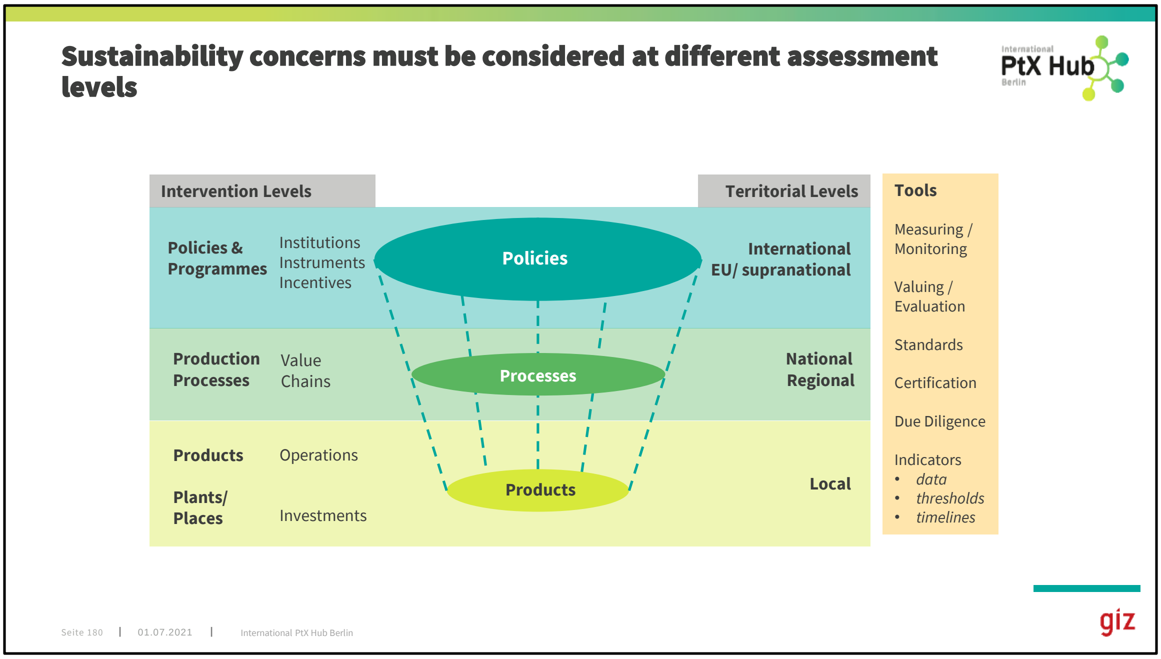
Notes:

- Without PtX - converting green electrons into green molecules – the Paris Climate Goals cannot be achieved.
- PtX is key for reaching climate neutrality by 2050.
- The critical bottleneck for launching PtX production and ramping-up PtX markets is neither technology nor finance.
- What is missing are reliable regulatory frameworks for green H1 and PtX products, processes and policies. Conceptualising such frameworks, defining derived PtX sustainability standards and establishing corresponding certification schemes is a priority task for all stakeholders involved.
- They must finally be enforced and enforced by national policy and international agreements.
- Advancing international discussions on relevant sustainability dimensions and concerns related to H2 and PtX is a priority for the International PtX Hub Berlin, established in 2019 to catalyse green H2 and PtX solutions on a global scale.
- The Hub is providing a platform for the exchange of ideas and experiences in the field of PtX production and promotion.
- It brings together practitioners and academic researchers, potential PtX producers and users as well as civil society organisations, policy shapers and regulatory agencies.



Notes:

- **Ensuring sustainability of PtX is a complex challenge.**
- Thus it is necessary to **develop a framework** that is capable of covering the various dimensions and dynamics of PtX production and market development as well as the different concerns and conflicts to be taken into account.
- **Credible sustainability standards** must help to ensure
  - **a) ecosystem integrity,**
  - **b) economic prosperity**,
  - **c) social inclusion,**
  - **d) decent work and human rights**,
  - **e) transparency,**
  - **f) public acceptance and**
  - **g) financial support.**



Notes:

- Focussing on **PtX product characteristics** is **not enough.**
- In addition it is necessary to consider the **entire production process**.
- Both **up-stream**, along the supply chain, from the generation of renewable energy and the conversion of water by electrolysis into oxygen and H_2, as well as **down-stream** towards the final feedstock and fuel use options, taking into account synthesis and refinement processes, as well as storage, transport and logistics. Finally, beyond the levels of PtX products as well as PtX processes of their production and dissemination it is important to also assess the **wider policy context and governance frameworks** set for regulation and support.

- Accordingly, sustainability assessments will have to distinguish and identify the appropriate **territorial levels of analysis**.
- They reach from the **local level**, where the focus is **on plant operations and investments**, and **their impact on local ecosystems, economies and societies**, to the **regional and national level**, **where structural and systemic inter-linkages** must be analysed.
- Finally at international level even global **geo-physical and geo-political balances** might be affected.

PtX and sustainability

A comprehensive assessment

Sustainability concerns must be considered at **every step of the value chain**

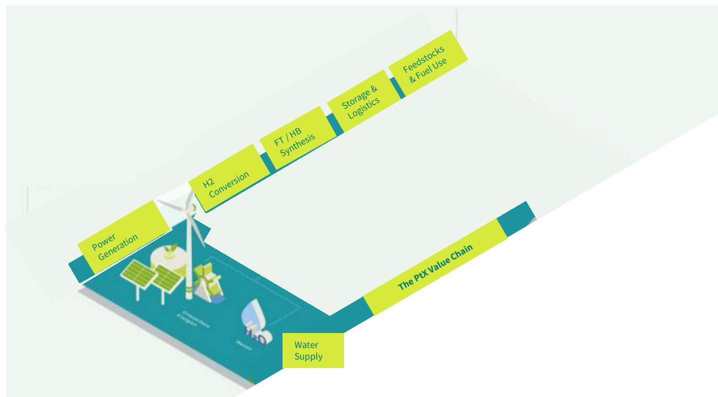
Power to X (PtX)
products, processes and policies

must meet comprehensive
sustainability standards

ensuring:

- 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**



1. Energy

Sustainability dimensions

Electricity is the **main input** for PtX production. For it to be **sustainable**, it must meet two requirements:

1. Renewability

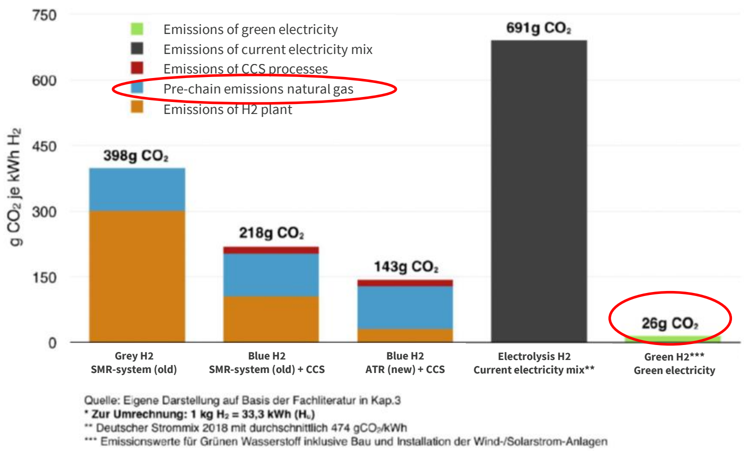
The **type of electricity** used has the **largest impact** on **the carbon footprint** of PtX production (e.g. to achieve a 70% emission reduction, approx. 90% of the electricity used must be carbon-free).
Therefore, it is essential for the production process to be based on **renewable electricity**.

2. Additionality

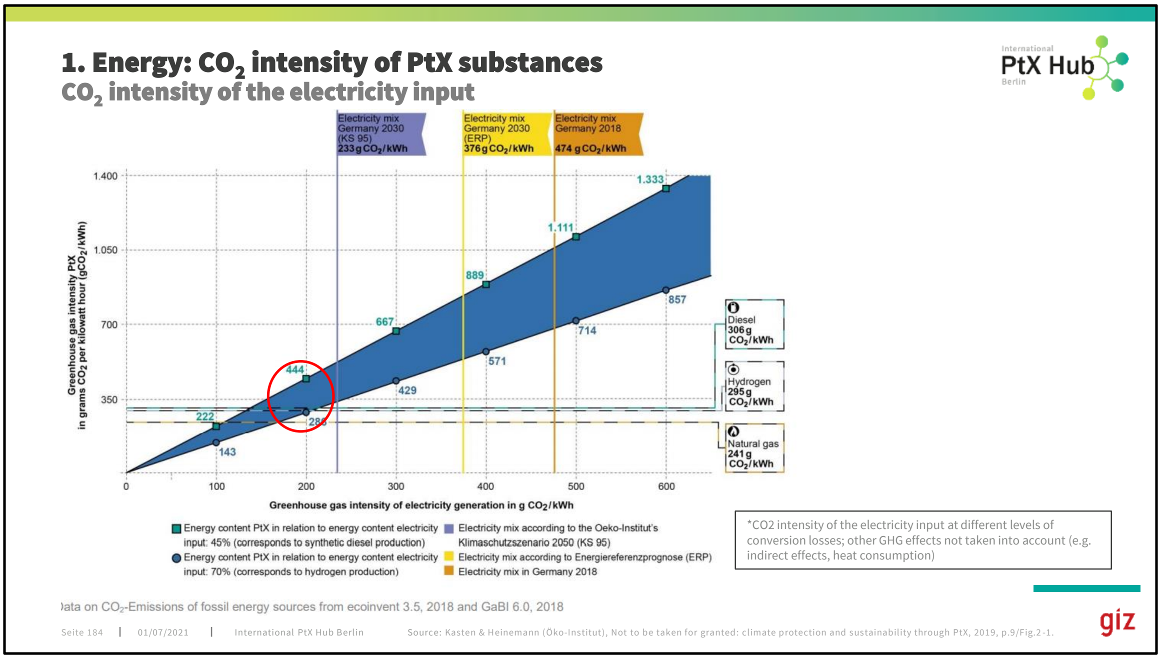
Additional demand for renewable electricity created by PtX production must **not hinder the efforts to increase the share of renewables in the electricity supply.** Without adding to the renewable electricity supply, **PtX could counteract the phase out of fossil power plants.**

1. Energy: Emissions of hydrogen production (g CO_2/kWh H_2)

Even blue H_2 has a CO_2 emission due to methane leakage



Source: Bukold (Greenpeace Energy), Blauer Wassestoff, 2020, p.11.



Notes:

- PtX products have **lower carbon footprints** than conventional counterparts in the case of **electricity supply with a very low CO_2 intensity.**
- Not only energy source: multiple dimensions must be considered!

Electricity is the **main input** for PtX production. For it to be **sustainable**, it must meet two requirements:

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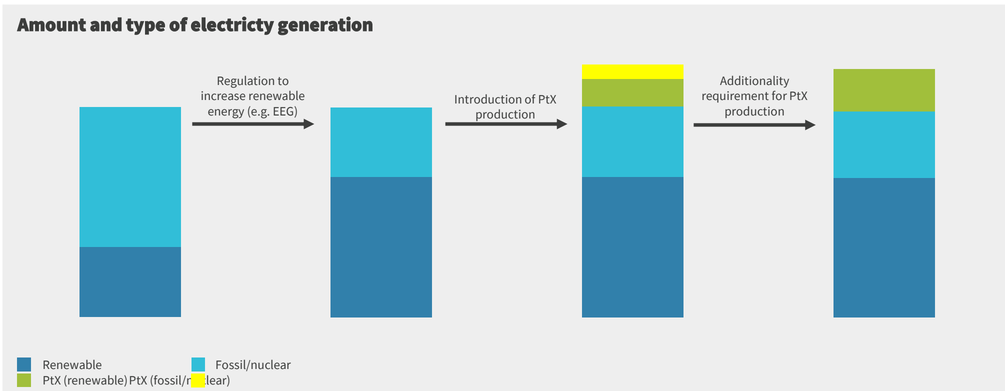
2. **Additionality**
   Additional demand for renewable electricity created by PtX production must **not hinder the efforts to increase the share of renewables in the electricity supply**. Without adding to the renewable electricity supply, PtX could counteract the phase out of fossil power plants.

Source: P. Kasten und C. Heinemann, “Not to be taken for granted: climate protection and sustainability through PtX. Öko Institute”, 09 September 2019. https://www.oeko.de/fileadmin/oekodoc/Impulse_ paper_criteria_for_e-fuel_production.pdf.

1. Renewable energy: Additionality criteria is important

→ Best if you have a national plan to decarbonise your power system as well



185 | 01.07.2021 | International PtX Hub Berlin   Source: Öko-Institut e.V., Not to be taken for granted: climate protection and sustainability through PtX, 2019, p.12.

Notes:

<u>Additionality:</u>

The fuel producer is adding to the renewable deployment or to the financing of renewable energy.

1. Needed to ensure that additional **demand** for renewable electricity for power fuels **does not interfere** with the **efforts** to **increase** the **share of renewable electricity** in existing electricity demand.
2. PtX production **increases demand** for electricity. Without adding to the renewable electricity supply, the demand is met by fossil or nuclear plants.

Source: P. Kasten und C. Heinemann, "Not to be taken for granted: climate protection and sustainability through PtX. Öko Institute", 09 September 2019. https://www.oeko.de/fileadmin/oekodoc/Impulse_ paper_criteria_for_e-fuel_production.pdf.

1. Energy
Additionality

When assessing the **compliance** to the additionality criterion, different dimensions must be considered, depending on **where the electricity is sourced:**

Electricity source	Characteristics	Relevant dimensions to assess additionality		
		Temporal correlation	Geographical correlation	Independence from subsidies
Electricity is produced by a stand-alone plant, "in situ"	The capacity is built apart from the grid	High	High	High
Electricity is produced by a contracted plant	**Additional capacity is contracted** to provide electricity in temporal correlation with the PtX plant demand. **Grid is only used as a transport mean**	Must be included in regulation (to some degree)	Must be included in regulation (to some degree)	Must be included in regulation
Electricity is purchased from the grid	**Additional capacity** is installed somewhere considering the **sum of energy needed by the plant** **Grid is used as battery**: electricity generation is subject to all overhead costs of the electricity system and market	Low	Low	Must be included in regulation

Notes:

Temporal Correlation:

PtX products are only produced when the contracted renewable generation unit is generating electricity.

- It is technically possible to run the electrolyser when the relevant renewable power plant is not generating electricity
- This could lead to a scenario where the PtX plant is operating and renewable energy asset is not, and **marginal plant** covering this supply gap **could be fossil → renewability** criterion would be violated and CO_2 balance would be worse than when using fossil transport fuels (Global Alliance Powerfuels, Sustainable Electricity Sources - Renewable fuels of non-biological origin in the RED II).
- It is crucial to **commercial viability:** determines the load factor of the capital asset and the degree of oversizing renewable generation assets.

Geographical correlation:

*There is **proximity** between the electricity production unit and the PtX production unit*

- Intention is to **limit** the extent to which the production of power fuels contributes to the **need for additional grid capacity** → prevent the exacerbation of any existing **bottlenecks** in distribution and transmission grids by power fuels production.
- Example of potential bottleneck: Germany much of the wind capacity is situated in the North large part of industrial power demand(and larger population density) is in the South.
- Continuous necessity for the re-dispatch of million Euros worth of electricity (351.5 in 2018 Global Alliance Powerfuels, Sustainable Electricity Sources - Renewable fuels of non-biological origin in the RED II).

1. Summary: Energy sustainability criteria for PtX and green H2

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(1)Renewability: the electricity used for PtX production **is of renewable origin**.

(2)Additionality: the PtX producer is **adding to the renewable deployment** or to the financing of renewable energy

(3)Temporal Correlation: PtX products are produced **when the contracted renewable generation unit is generating electricity**

(4)Geographical Correlation: there is **proximity** between the electricity production unit and the PtX production unit

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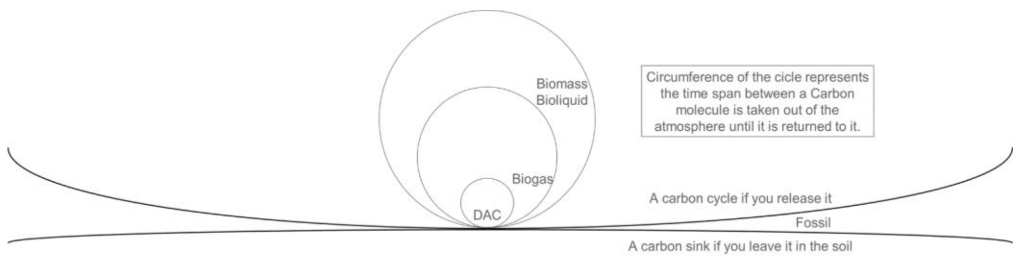
2. Carbon

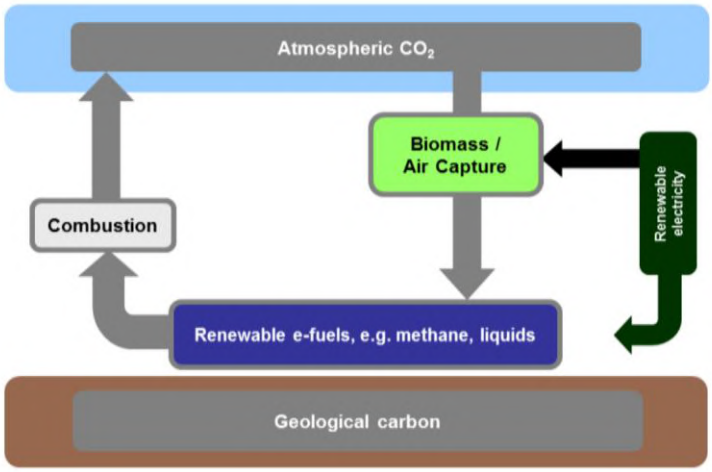
Sustainability dimensions

- 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



2. Carbon

Cycle with renewable carbon sources is best option



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2. Carbon:
CO_2 source: Ambient air Direct Air Capture (DAC) is best!

Carbon capture from ambient air (**DAC**) is the best option on a long-term perspective:

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

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

Criticalities:

- Process is very **energy intensive**
- 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

Requirements:

- Same energy requirements as electrolysers
- Land use management

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

giz

Notes:

- **Electricity requirements:** Long-term energy requirement projections based on current technology assumptions for the DAC process are expected at **around 2,000 kWh/t of CO_2** (source: Beuttler C, Charles L and Wurzbacher J (2019)
- **Land use**: according to Climeworks' estimations, **around 2,000 km² of non-arable land would be needed to remove 1 gigaton of CO_2 net from** the atmosphere, including the required renewable energy production. This calculation is based on the assumption that solar PV is the sole energy source. The footprint of the actual DAC plants would cover just 62 km². It is important to point out that depending on the location these footprints may vary and their calculation should receive further analysis.
- Moreover**, DAC does not require arable land, and has a much smaller physical footprint than bio-based approaches**

Source:

P. Kasten und C. Heinemann, “Not to be taken for granted: climate protection and sustainability through PtX. Öko Institute”, 09 September 2019. https://www.oeko.de/fileadmin/oekodoc/Impulse_ paper_criteria_for_e-fuel_production.pdf

The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions. Front. Clim. 1:10. doi: 10.3389/fclim.2019.00010, https://www.frontiersin.org/articles/10.3389/fclim.2019.00010/full)

2. Carbon
Biomass sources

- Can come from **residual waste or biomass**
- **Closed carbon loop: renewable**

Criticalities:

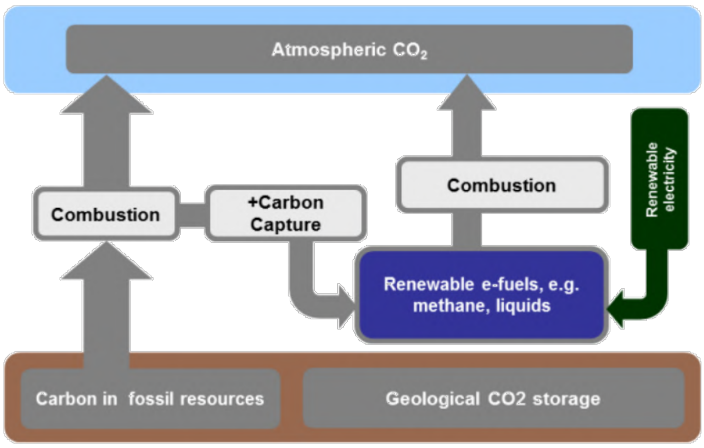
- The overall **availability** of biomass is very **limited** compared to the carbon volumes required for large scale synthetic fuel production.
- The respective biomass sources might also **not be available at the potential locations** of synthetic fuel production sites (e.g. Middle East).
- **Land use and biodiversity risk**
- **Efficient allocation**: possible competition with other uses of biomass (e.g. biofuels) that might have more efficient yields

Requirements:

- **Same criteria as biofuels**, especially for **biodiversity** and **land use** (international frameworks)
- The most efficient process must always be prioritised

2. Carbon

Cycle with industrial point carbon sources is not sustainable: carbon is still released into atmosphere

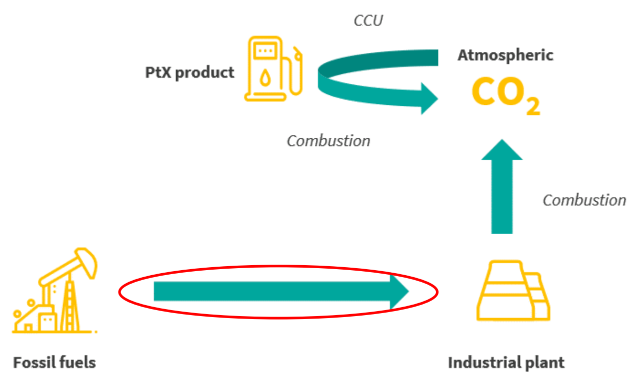


2. Carbon: Industrial point sources are not sustainable!

Cycle with industrial point carbon sources is not sustainable: carbon is still released into atmosphere

International PtX Hub Berlin

- Potential for "**recycling**": large amounts of fossil carbons can be captured and reused via **Carbon Capture technologies** (**CCU**)
- Criticalities:
  - **Not renewable:** no *additional* CO_2 emissions, but still net flux of carbon from geological reservoirs to the air. Cannot ensure a closed carbon cycle
  - Fossil carbon sources should become scarce and might not be available in the required amounts
  - Significant risk of **lock-in effect** for CO_2-intensive technologies and industrial processes



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2. Carbon Summary of Carbon Sources

Sources

Potential carbon sources for PtX products are:

Sources	Closed carbon cycle	Carbon cycle type	Availability	Long term availability	Scalability	Technology maturity	Costs	Other potential issues	Sustainability requirements
Ambient air	✓	Immediate	High	High	High	Low	High (currently)	**No existing applications at scale** (currently) **(Limited) land use** risk	**Energy requirements** **Land use management**
Biogenic sources	✓	Renewable	Regional	Low	Low	High	**Low,** but depend on **regional availability**	**Land use** risk **Biodiversity** risk **Efficient allocation** (e.g. biofuels)	**Same criteria as biofuels,** especially for biodiversity and land use **(international frameworks)**
Industrial point sources	X	Open	**High,** but **varies regionally**	Low	Low	Medium-high	Low	**Lock-in potential** for technologies that need to be phased-out **Reduced efficiency of industrial process:** potentially inflating the fossil energy demand	**Long term:** limit use to sectors with **inevitable GHG emissions** **Short term:** proportion of the plant's **emissions must be reduced over time** **Contracts** only to plants with **highly efficient processes**

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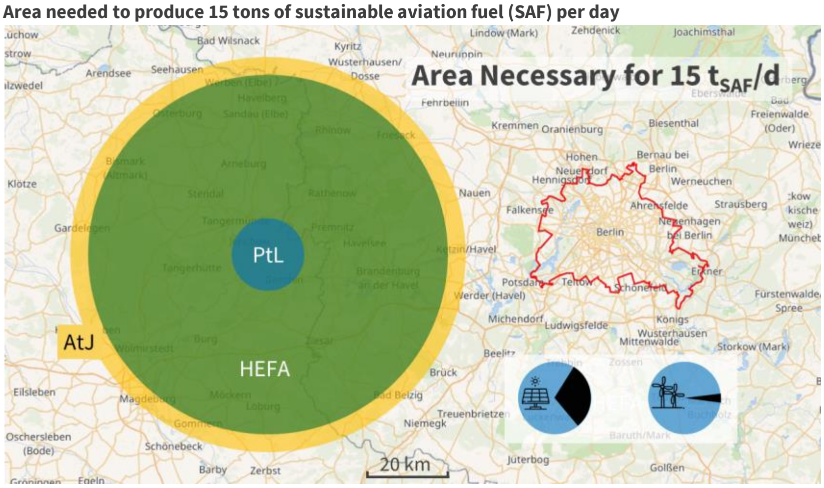
Notes:
Costs:

- **DAC**: as the technology has yet to **be demonstrated at large scale**, the future cost of DAC is uncertain. Capture cost estimates reported in the literature are wide, typically ranging anywhere from **USD 100/t – 1,000/t** (Source: IEA https://www.iea.org/reports/direct-air-capture).
- **Biogenic**: depending on regional availability. The cost varies between process routes and depending on if there are synergies with the main product of the biomass conversion process. CO_2 utilisation related to biomass gasification and anaerobic digestion is advantageous in this regard. In the case of methanol obtained through synthesis and purification, the total cost could be 6.8 M€/yr or €13/t methanol (source: Ericsson, K. (2017). Biogenic CO_2 as feedstock for production of chemicals and fuels: A technoeconomic assessment with a European perspective. Miljöoch energisystem, LTH, Lunds universitet).
- **CCU**: the cost can vary greatly by CO_2 source, from a range of **USD 15-25/t CO_2 for industrial processes producing** "pure" or highly concentrated CO_2 streams (such as **ethanol production or natural gas processing**) to **USD 40-120/t CO_2 for processes with "dilute" gas streams**, such as **cement production and power generation** (Source: IEA https://www.iea.org/commentaries/is-carbon-capture-too-expensive)

3. Land use

Sustainability dimensions

Area needed to produce 15 tons of sustainable aviation fuel (SAF) per day



PtL: Power-to-Liquid
AtJ: Alcol-to-Jet fuel
HEFA: Hydro processed Esters and Fatty Acids fuel (N.B. air capture not considered)
PV/Wind: % land coverage

→ PtL needs much less land than AtJ or HEFA option to produce SAF!

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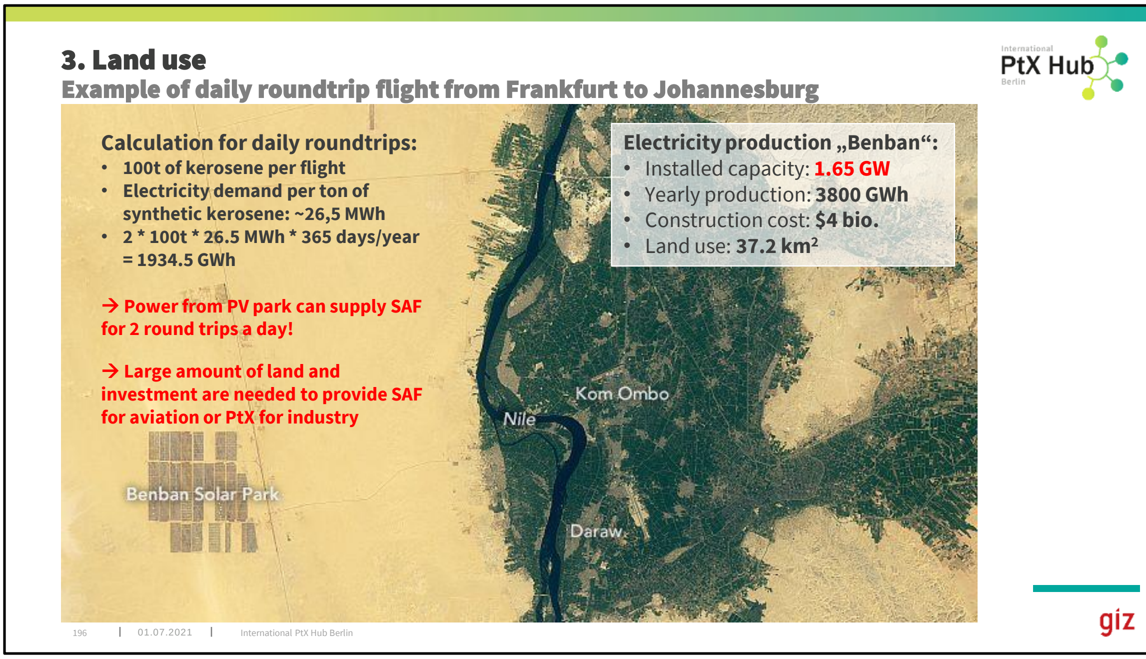
Notes:
Two potentially land-intensive inputs:

- **Renewable capacity**
- **Direct Air Capture technologies**

However, compared to similar technologies (e.g. biofuels) PtX products have:

- Very **superior yields** → picture: Area needed to produce 15 tons of sustainable aviation fuel (SAF) per day, comparison between Power-to-Liquid (PtL), Alcol-to-Jet fuel (AtJ), and (Hydro proccessed Esters and Fatty Acids HEFA) fuel (N.B air capture not considered).
- Wind and PV have relatively **low land coverage** (especially wind – approx. 5% land coverage): the utilised land can still be used for other purposes.
- **Different land requirements**: does not need to be arable, fertile land (e.g. desert regions have particularly advantageous conditions) → **little competition with food production.**
- **Biodiversity risk:** same requirements as biomass products (international frameworks) ***+ limiting the use to hard to electrify sectors.***

Source: own calculations (Torsten) based on UBA (2016) Power-to-Liquids Potentials and Perspectives for the Future Supply of Renewable Aviation Fuelhttps://www.umweltbundesamt.de/sites/default/files/medien/377/publikationen/161005_uba_hintergrund_ptl_barrierrefrei.pdf



Notes:

Calculation for daily roundtrips:

- 100t of kerosene per flight
- Electricity demand per ton of synthetic kerosene: ~26,5 MWh
- 2 * 100t * 26.5 MWh * 365 days/year = 1934,5 GWh

Electricity production of solar park Benban in Egypt:

- Installed capacity: 1.65 GW
- Yearly production: 3,800 GWh
- Construction cost: $4 bio.
- Land use: 37.2 km^2

Conclusion:

Even under ideal production conditions in Egypt, large amounts of land and investment will be needed to decarbonise the entire aviation industry on the basis of green H_2.

Source: GIZ – Wasserstoff Task Force im MT des Afrikabereichs

3. Land use

Relevant international frameworks (for reference and further considerations)

Framework	Content
SDGs	The SDGs, also called the "Global Goals", are 17 Sustainable Development Goals which include 169 targets. For land and soils, **goal 15 and target 15.3** are of highest relevance.
UN Convention on Biological Diversity (CBD)	Three main goals: **conservation of biological diversity** (or biodiversity); **sustainable use of its components**; **fair and equitable sharing** of benefits arising from genetic resources. Objective: develop national strategies for the conservation and sustainable use of biological diversity.
UNFF "Non-legally Binding Instrument on All Types of Forests"	Non-binding international policy to **promote sustainable forest management**. Specifics of its goals include reversing the loss of forest cover, increasing the area of protected forests and the share of products from sustainably managed forests.
RAI Principles	Voluntary principles aiming to **increase the responsibility of (private, public) investments in agriculture and food systems.**
FAO Global Soil Partnership	Public private network with the mandate to **improve the governance of soil resources**. The GSP's scientific advice body is the Intergovernmental Technical Panel on Soils (ITPS).
World Bank "Environmental and Social Framework"	World Bank safeguard policies requiring borrowing governments to **address specific environmental and social risks in order to receive Bank financing** for development projects. These address, among others, land acquisition, restrictions on land use and involuntary resettlement; biodiversity conservation and sustainable management of living natural resources; and indigenous peoples.
Private standards (e.g. RSB, ISCC)	Broad set of **voluntary instruments for the private sector**, including certification schemes that label products whose production complies with a set of (land-use relevant) sustainability principles and criteria.

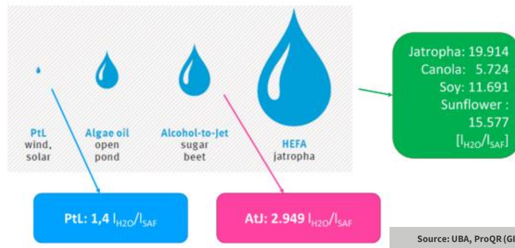
4. Water use

Sustainability dimensions

Water intensity of electrolysis is **relatively low** compared to other applications, requiring approximately **9–10 L/kg** of hydrogen produced

Imported good	Water use L/kg
Potatoes	240 - 400
Rice	2 600 - 3 400
Cotton	11 000 India: 23 000
Beef	15 000
H2 (electrolysis)	9 - 10

Source: WWF



Source: UBA, ProQR (GIZ)

Source: WWF; UBA, ProQR (GIZ)

4. Water use

Sustainability dimensions

Regional water risk can be high (some promising locations are among the driest regions in the world)

This means PtX production **could compete with other water uses**, so:

1. **Sustainability** must be assessed **upfront,** in the **context of the catchment,** considering **regional data for the water stress level.**

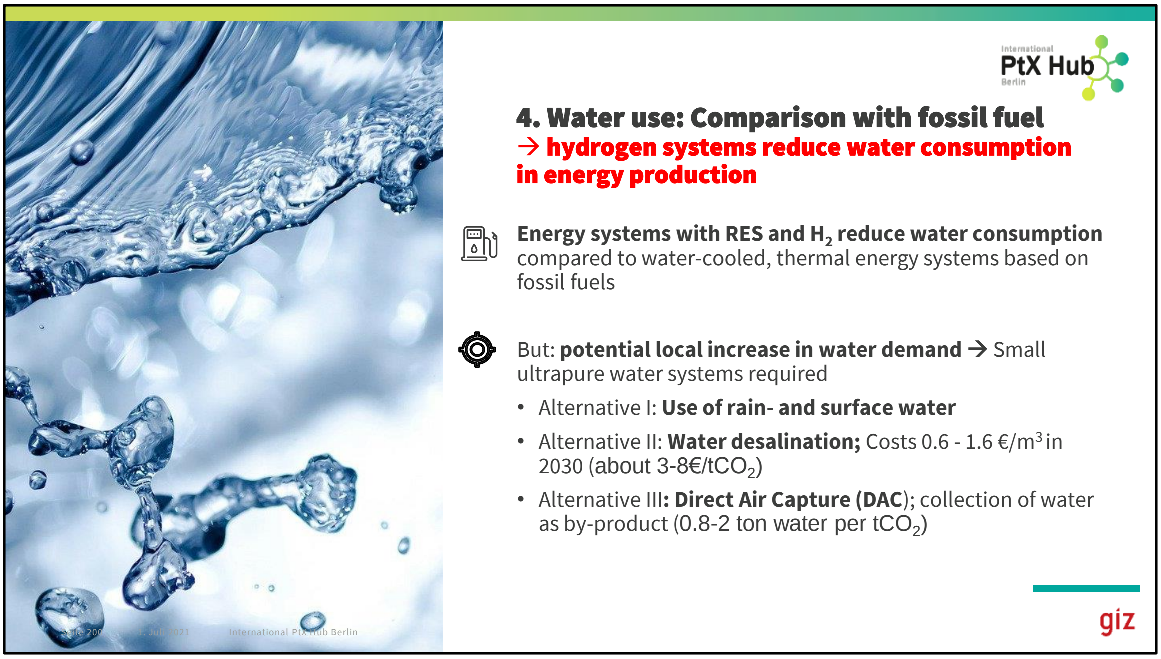
2. In case **water stress** is significant, the solution could be **water desalination**

Pros ✓

- **Costs** 0.6 - 1.6 €/m3 in 2030 **(<2%** of total H_2 production costs)
- Potential to create **local added value**

Risks X

- **Very energy intensive** process: the electricity must meet the **same requirements as PtX plants**.
- **Brine disposal**: to **minimize** negative externalities, **independent ecological assessment based on local indicators** (especially with regards to impact on fresh water) must be mandatory and enshrined in legislation



Notes:

Desalination:

- **Effects of desalination processes on the ecosystem**: In most **desalination processes**, for every litre of potable water produced, **about 1.5 litres of liquid polluted with chlorine and copper are created**. When pumped back into the ocean, the **toxic brine depletes oxygen and impacts organisms** along the food chain. Increased **salinity and temperature can cause a decrease in the dissolved oxygen content**, resulting in conditions called hypoxia (Source: United Nations University Institute for Water, Environment and Health).
- **Desalination cost** compared to overall PtX cost: The costs of **supplying water are negligibly low,** even in countries in which the water must be obtained from desalination plants. (Source: Agora The Future Cost of Electricity-Based Synthetic Fuels).
- In case of water stress in the region, water desalination and transportation could cost 0.6 - 1.6€/m^3 in 2030 (Caldera et al., 2016), which would add about 3-8€/tCO_2, according to water cost impact in Keith et al.(2018) → 4.5m^3 of water needed/kg H_2
- The production of 1 mol of CH_3OH ideally requires 3 mol of H_2 and 1 mol of CO_2 (Source: https://www.pnas.org/content/116/25/12212)

Capturing water DAC:

Climeworks technology can capture 2-5 mol of water per mole CO_2 captured, equal to 0.8-2 ton water per tCO_2. Generally, from an energy point of view, it is their goal to capture as little water as possible. However, at 2 mol water per mole CO_2 the energy demand would be in the lower end of energy consumption range of Climeworks technology (Kronenberg, 2015). According to Bajamundi et al. (2018), Hydrocell's DAC system operated in the Finnish climate has also produced 4.6 mol of water per mole of captured CO_2, equal to 1.9 ton water per tCO_2. Thus, water demand would not be a constraint for LT DAC systems, quite to the contrary DAC systems could provide water needed for subsequent water electrolysis processes, as required for power-to-fuel and power-to-chemical conversion (Fasihi et al., 2017a,2017b).4.6. CO_2 compression, transport and storage. The captured CO_2could be stored or utilised as feedstock for other applications. For these matters, additional steps such as purification, compression and transportation (in gaseous or liquid phase) may be needed, which could be energy and cost intensive(Aspelund and Jordal, 2007;Johnsen et al., 2011;Knoope et al.,2014).CO_2 could be liquefied by compression to a critical pressure of73.8 bar and then can be pressurised further by pumps (McCollumand Ogden, 2006). When compressing CO_2, recoverable heat is generated and can be utilised in other parts of the system (Lackner,2009). In PSCC, prior to compression, CO_2needs to be cleaned from a wide range of impurities associated with flue gases. Thus, the Fig. 7.LCOD cost breakdown for the fully electrified HT DAC system (left) and LT DAC system (right) for 8000 FLh and conditions in Morocco in 2040.M. Fasihi et al. / Journal of Cleaner Production 224 (2019)

Source picture:
Bild von PublicDomainPictures auf Pixabay

5. Critical raw materials

Sustainability dimensions

The **energy transition** will likely cause an **increase in the use of some scarce raw materials**. Today more than 50 million tons of minerals are needed. This value is estimated to increase to 3.1 billion tonnes by 2050 to meet the 2-degree scenario.

The various **PtX electrolysers** have different rare raw material demands:

Amount of critical materials (% of yearly global production) needed for different stack types (PJ/y of H2)				
Critical material	**100% PEM***	**100% AEL****	**100% SOEC*****	**50% PEM - 50% AEL**
Iridium	213%			106%
Tantalum	67%			33%
Platinum	2.2%	45%		24%
Raney-Ni		0.7%		0.4%
Nickel (class 1)		5%	0.7%	3%
Cobalt		0.1%	0%	0.1%
Gadolinium			2%	
Ziconium			7%	
Lantharum			0.1%	
Cerium			0.1%	
Yttrium			4%	

*PEM: Polymer electrolyte membrane electrolysis; **AEL: Alkaline water electrolysis; *** SOEC: Solid oxide electrolyser cell

 Source: Volta Chem.

5. Critical raw materials

Strategies to decrease the amount of needed CRM

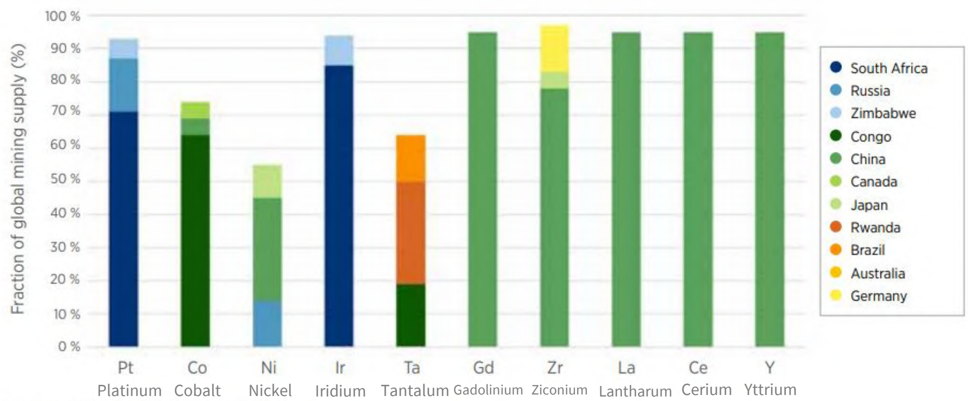
Type	Strategy	Short description	PEM	AEL
Prevention	Reduction	Reduction of the amount of CRM used	Ir, Ta, Pt	Pt, Ni
	Substitution	Replacement of CRM by other material	-	Pt, Co
	Technology mix	Balance between AEL, PEM, and (later) SOEC	Ir, Ta, Pt	Pt, Co, Ni
Extension	Higher productivity	Higher productivity 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**

Source: Volta Chem.

5. Critical raw materials

Top producers of critical materials in electrolysers



Source: European Commission, 2020.

Source: IRENA, Scaling Up Electrolysers To Meet The 1.5°c Climate Goal, 2020, p.69/Fig.24.

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

looking at:

- *Energy (renewable & additional)*
- *Carbon source*
- *Land use issues*
- *Water availability*

- Open discussion -

Training | Module 7

Socio-economic and governance-related sustainability issues

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

International PtX Hub Berlin

Module 7: Socio-economic and Governance-related Sustainability Issues

At the end of this module participants will

- understand the potential positive socio-economic impacts of H2/PtX projects
- be able to communicate H2/PtX projects to decision-makers better
- be able to identify the relevant positive and negative potential impacts of PtX projects and policies at national/regional as well as local level
- be able to assess the potentials for job creation at different competence levels and corresponding needs for qualifications and capacity building

Benefit for learners:
Participants develop their ability to frame PtX projects and to put them into larger contexts. That improves their ability to "market" PtX projects.

Core messages:

- PtX allows creating **more value within our country** / region compared to other sources and processes
- PtX projects allow the **creation of qualitative jobs**. They may even offer new work places to persons losing their job in the context of the change away from fossil energies
- PtX projects constitute a move to **technological innovation**, just transition and have the potential to reduce external dependencies

or: **menti.com > CODE 123 456**

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Test your knowledge

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or: **menti.com > CODE 123 456**

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"Which ***socio-economic & governance issues*** *do you consider important when developing green H2 & PtX* ***in your country****?"*

PtX and sustainability

A comprehensive assessment

Power to X (PtX)
products, processes and policies

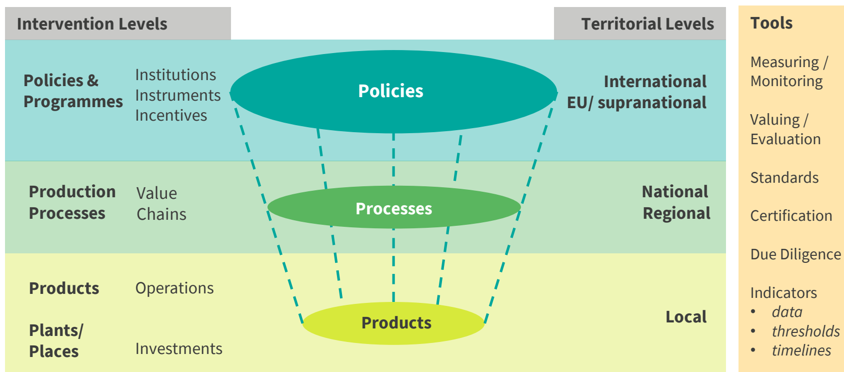
must meet comprehensive **sustainability standards**

ensuring:

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

at **different levels**

Sustainability concerns must be considered **at different assessment levels**



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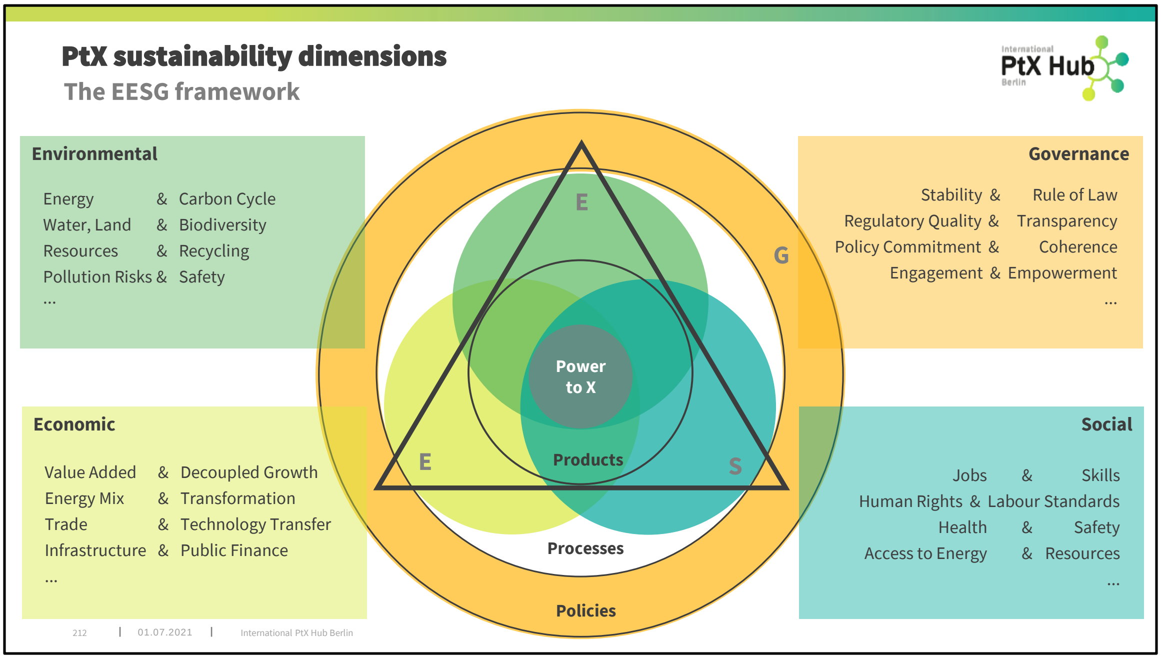


Notes:

Social

- Developing a PtX economy based on renewable energy has **many fold social and societal repercussions**.
- It is promising additional **jobs, yet energy transition may also result in job losses in fossil energy sectors**.
- To ensure a just transition, **capacity building, training have to focus on new skills required**.
- Ensuring respect of **human rights and of core ILO labour standards along the entire value chain is non-negotiable**.
- ILO conventions against **forced labour, child labour, or discrimination must be respected**. In practice, however, this is unfortunately often not the case. Corresponding to the environmental **concerns health and safety risk of PtX production, transport** and use must be monitored and avoided.
- On the other hand it is essential, that **PtX production does not negatively affect access to energy or resources like water and land**.
- On the contrary, PtX projects such as new installations of additional renewable capacity or desalinisation plants might even generate **co-benefits by exploiting potential win-win synergies.**

Governance

- Governance concerns are relevant both **for public administration as well as for corporate business conduct**.
- For investment decisions domestic as well as **international political stability**, the **rule of law and regulatory quality are essential parameters**.
- **Transparency is key to avoid and fight bribery and corruption**. The **policy commitment to climate protection** (e.g. reflected in a country's Nationally Determined Contribution (NDC) to the Paris Agreement and the coherence of its climate policy, integrating across economic sectors and societal groupings, is an important indication of its sustainability.

- Only if all **relevant stakeholders are not only informed and involved but actively engaged** and empowered will the transition to a PtX energy system also result in a **strengthened and sustainable economy and society.**

PtX sustainability dimension: Environment

ENV	Concerns
Energy & Carbon	
Water, Land & Biodiversity	**Water** -- water stress (demand / supply) -- desalinisation -- local needs **Land** -- land use footprint -- cultural heritage **Biodiversity** -- fauna and flora -- marine habitats -- protected areas ...
Resources & Recycling	
Pollution Risks & Safety	
...	

PtX sustainability dimension: Social

SOC Concerns
Jobs & Skills
Human Rights & Labour Standards
Health & Safety
Access to Energy & Resources
...

some examples

Jobs

-- ***gains*** in renewables

-- ***losses*** in fossils

Jobs and Just Transition

-- ***regional disparities / diversity***
Case 1: net-positive
Case 4: net negative

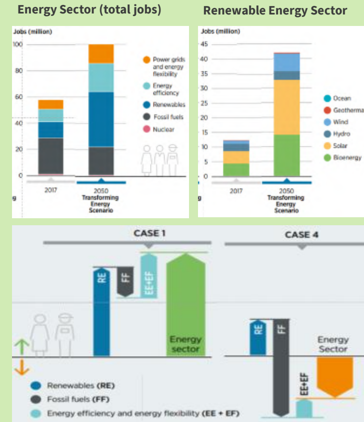
Skills and Training

-- ***qualifications*** & skills profile

-- ***trainings***
\# courses
\# participants

...

Energy Sector (total jobs) | **Renewable Energy Sector**



*2050 Scenaros - based on IRENA 2020

PtX sustainability dimension: Social

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SOC Concerns
Jobs & Skills
Human Rights & Labour Standards
Health & Safety
Access to energy & Resources
Voice & Inclusion

some examples

International Labour Organization

ILO 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

...

The New York Times

Chinese Solar Companies Tied to Use of Forced Labor

A new report shows some of the world's biggest solar companies work with the Chinese government to absorb workers from Xinjiang, programs that are often seen as a red flag for forced labor.

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Article

China: Solar companies reportedly linked to forced labour allegations in Xinjiang

pv magazine

Why human rights protection is pushing up PV module prices

The solar industry typically sees itself as being supportive of the environment, humanity, and human rights. Even large Chinese PV manufacturers publish statements to this effect, particularly if they are listed on Western stock exchanges. But what do human rights have to do with the solar industry? What connections exist, asks Martin Schachinger of pvXchange, and how are they important to the future success of the European PV market?

MARCH 15, 2021 PV MAGAZINE

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PtX sustainability dimension: Social

SOC Concerns	some examples
Jobs & Skills	
Human Rights & Labour Standards	
Health & Safety	**Air pollution** -- # premature deaths **Explosion risks and toxicity** of PtX products such as -- H_2 Hydrogen -- NH_3 Ammonia ... in particular also related to **transportation and storage** ...
Access to energy & Resources	
...	

Source: Water: https://www.jstor.org/stable/pdf/resrep06915.pdf based on WHO

PtX sustainability dimension: Social

International PtX Hub Berlin

SOC Concerns
Jobs & Skills
Human Rights & Labour Standards
Health & Safety
Access to energy & Resources
...

some examples

Access to:

Energy

-- connection to electricity (SDG7)

Water

-- water stress

-- clean dringing water (SDG6)

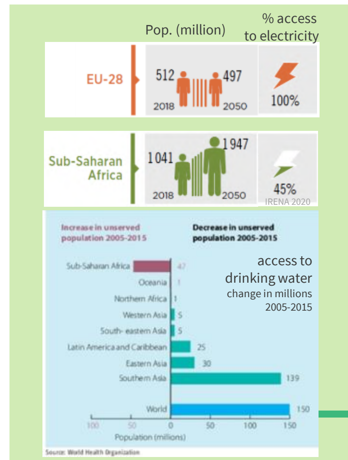
-- irrigation

-- desalinisation (opportunities and risks) for H2/Ptx and local needs

Land

-- land use conflicts

...



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PtX sustainability dimension: Governance

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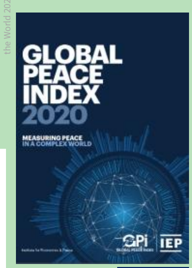
GOV Concerns	some examples
Stability & Rule of Law	**Country Assessment Indices** on:
Regulatory Quality & Transparency	-- democracy and voice
Policy Commitment & Coherence	-- political stability
Stakeholder Engagement & Empowerment	-- peace and fragility
...	-- violence and security
	-- rule of law
	-- human rights
	...

Freedom House (2021): Freedom in the World 2021

Democracy

Fragility

TheGlobalEconomy (2021): Security Threats Index – Country Ranking



GPI & IEP (2020): Global Peace Index

Peace

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PtX sustainability dimension: Governance

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GOV Concerns	
Stability & Rule of Law	
Regulatory Quality & Transparency	
Policy Commitment & Coherence	
Stakeholder Engagement & Empowerment	
…	

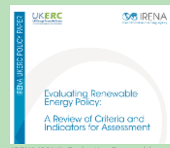
some examples

Government effectiveness
-- executive capacity

Policy monitoring & evaluation
-- executive accountability

Bribery and corruption prevention
-- CPI
-- Anti-Bribery Law and practice
-- whistleblower protection

…



IRENA (2014): Evaluating Renewable Energy Policy.

OECD (2021): Environmental Performance Reviews.

Transparency International (2020): Corruption Perception Index.

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PtX sustainability dimension: Governance

International PtX Hub Berlin

GOV Concerns
Stability & Rule of Law
Regulatory Quality & Transparency
Policy Commitment & Coherence
Stakeholder Engagement & Empowerment
…

some examples

PA implementation
(PA: Paris Agreement on GHG)

-- ***NDC***
(Nationally Determined Contribution)

-- ***Art.6***
(Cooperative Meachanisms)

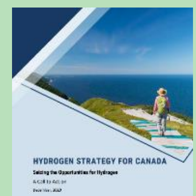
-- **Carbon neutrality committment**

-- **National hydrogen strategy**

-- **PtX roadmap**

…

Gobierno de Chile (2020): Chile's nationally determined contribution.



Canada's Minister of Natural Resources (2020): hydrogen Strategy for Canada.

PtX sustainability dimension: Governance

GOV	Concerns
Stability & Rule of Law	
Regulatory Quality & Transparency	
Policy Commitment & Coherence	
Stakeholder Engagement & Empowerment	
…	

some examples

Multistakeholder Participation
-- Hydrogen councils or round tables

Stakeholder training

Multilevel cooperation and community ownership

Involvement of Civil Society and Indigenous people
-- free prior informed consent

…

SDG Helpdesk (2002)

PtX sustainability dimension: Economic

ECO Concerns	some examples
Value Added & Decoupled Growth	**Value added** ***national GDP*** -- per capita -- overall growth -- sectoral mix -- carbon intensity
Energy Mix & Transformation	**Value added and employment** ***local /regional*** -- regional disparities
Innovation & Technology Transfer	**Energy trade (EX/IM)**
Infrastructure & Logistics	**Tax revenue and national debt**
…	**Circular economy**

…

PtX sustainability dimension: Economic

International PtX Hub Berlin

ECO Concerns	some examples
Value Added & Decoupled Growth	
Energy Mix & Transformation	**Energy mix** -- fossil -- renewables **Energy trends and scenarios** **H_2 and PtX** -- potentials -- actual **Infrastructure and investments** **Market design** (ETS, CDM etc.) …
Innovation & Technology Transfer	
Infrastructure & Logistics	
…	

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PtX sustainability dimension: Economic

International PtX Hub Berlin

ECO Concerns
Value Added & Decoupled Growth
Energy Mix & Transformation
Innovation & Technology Transfer
Infrastructure & Logistics
...

some examples

Domestic R&D

-- overall / energy

-- public / private

Technology cooperation

Knowledge and human capacity development

Training and capacity building

...

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PtX sustainability dimension: Economic

ECO Concerns	some examples
Value Added & Decoupled Growth	Water supply and treatment
Energy Mix & Transformation	Transport infrastructure
Innovation & Technology Transfer	Refineries etc.
Infrastructure & Logistics	Pipelines
...	Ports
	Industry clusters
	...

“What are possible positive socio-economic impacts of your projects?”

“How could potential negative impacts be avoided or mitigated”

- Open discussion -

Training | Module 8

Support Policies and Regulations

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

International PtX Hub Berlin

Module 8: Support Policies and Regulations

At the end of this module participants will

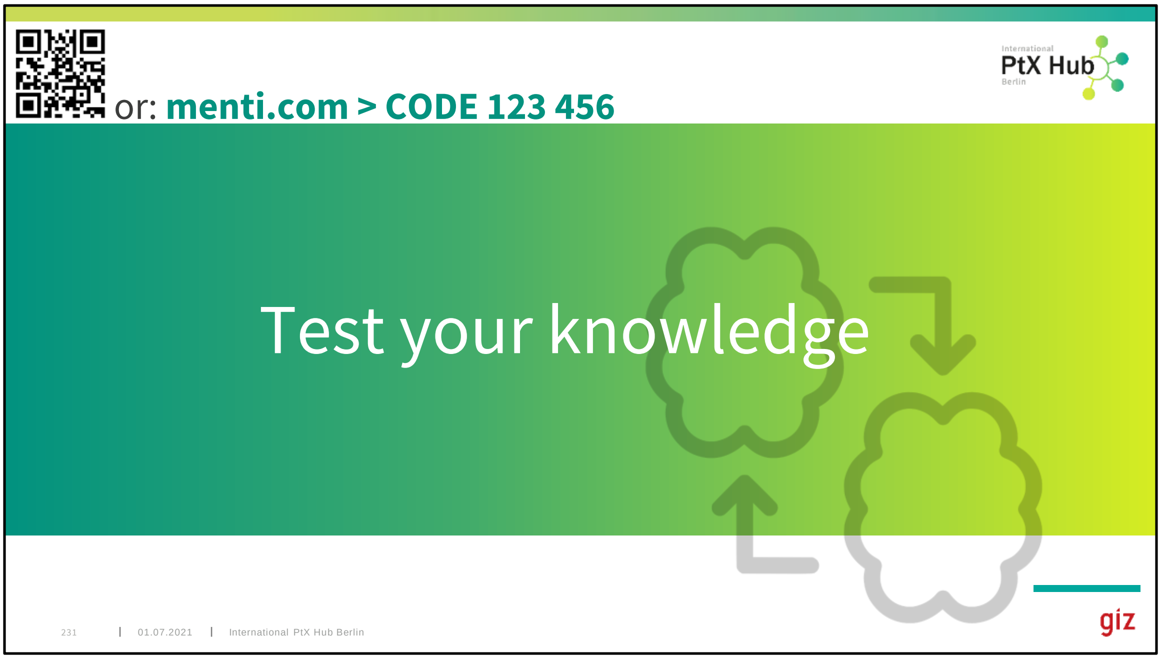
- understand the crucial starting points and instruments or leverages to foster and regulate H2 and PtX developments from the political and institutional frame
- understand central policy instruments and regulations to foster H2 and PtX developments
- know feasible policy support and regulations to frame a market ramp-up for H2 and its derivatives

Benefits for learner:

Knowing what is happening internationally concerning political strategies for promoting H2 / PtX and understanding the related tool box for a market ramp-up enables the participants to select core elements of their own strategies. By having ideas on issues related to certification and on options for funding they get a first orientation while checking the feasibility of their H2 / PtX project.

Core messages:

- **Developing a national / supra-national strategy for H2 / PtX is the starting point**
- Select appropriate **tools for ramping-up the market for H2 / PtX**
- Set your **H2 / PtX project into the larger context of international cooperation** and development policies and benefit from opportunities offered
- That are the **development steps for setting up a conducive environment** for a H2 / PtX project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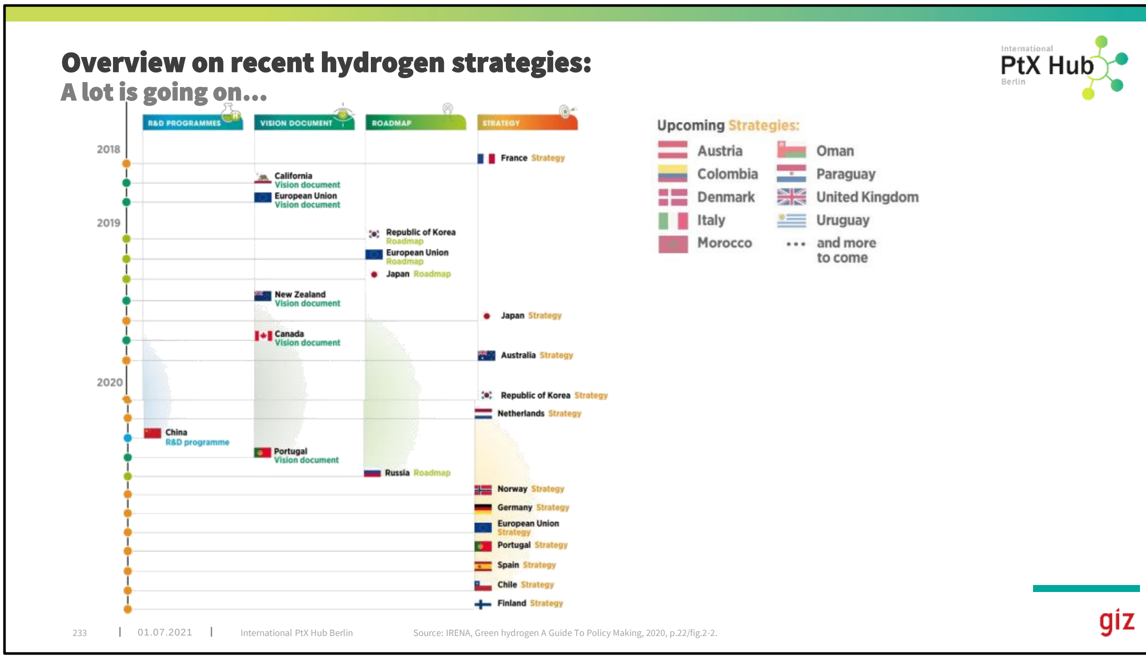
“What are the key elements to develop a national green H2 & PtX strategy in your country?”

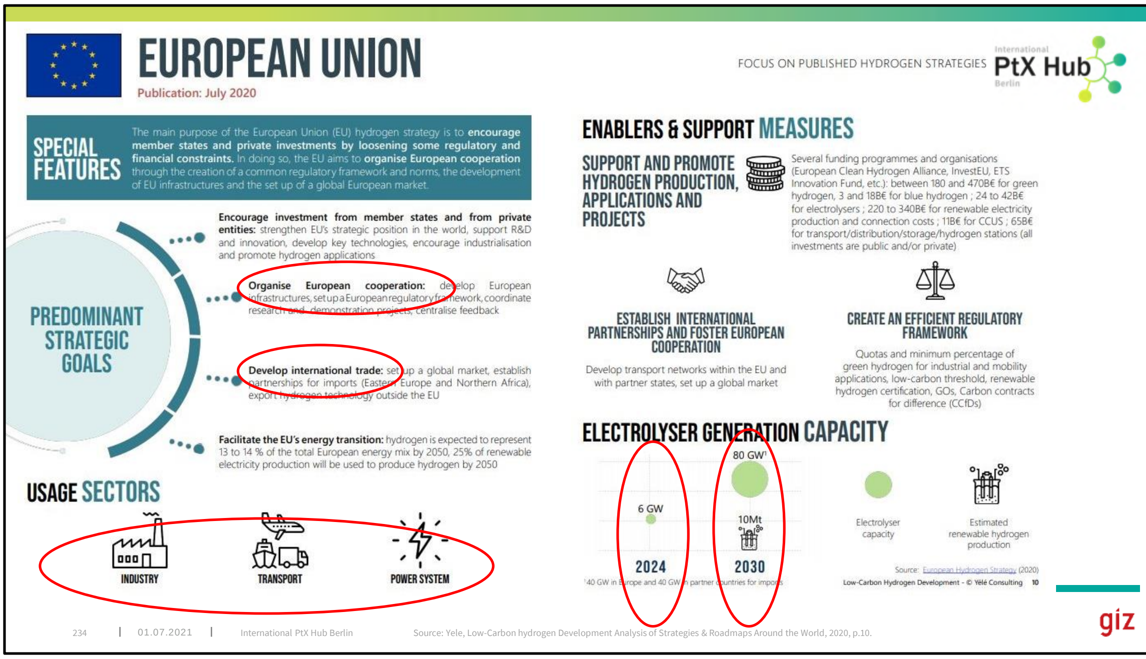
Name up to 4.



Notes:

- In the last two years, given the new wave of interest in H_2 for a low-carbon economy, many countries have issued their own national strategies.
- Many countries are expected to publish their H_2 strategies in the coming years. Progress is expected in Latin America, following the launch of Chile's national strategy Arabian Peninsula member states of the European Union, following the EU strategy (e.g. Austria and Italy already included H_2 as part of their NECPs).
- **H_2 policies are evolving rapidly**. Information on this figure has been kept as detailed and complete as possible at the time of writing, however more countries may have announced, drafted and published vision, roadmap and strategy documents.

Source: Green hydrogen: A guide to policy making (irena.org); https://www.irena.org/publications/2020/Nov/Green-hydrogen



Notes:

1ST PHASE (2020-2024):

- **promote 1 million tons of renewable** H_2, with at least **6 GW of renewable H_2 electrolysers installed.**
- new end-use application fields: **industrial processes and possibly heavy-duty transport.**

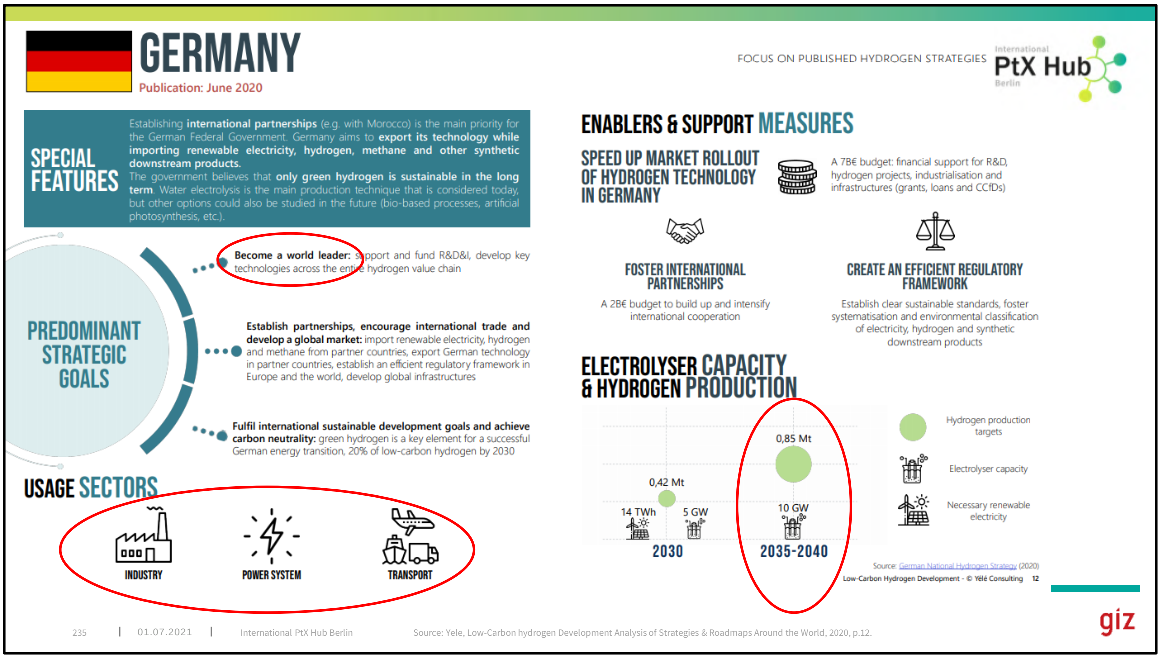
2ND PHASE (2025-2030):

- **10 million tons of RH** and at least **40 GW of RH electrolysers** installed.
- New applications: **steel-making** and **shipping, balancing energy system.**
- **"Hydrogen Valleys"** (**regional H_2 clusters**) will develop, relying **on local production of H_2 based on decentralised renewable energy production** and local demand, transported over short distances.
- EU-wide Infrastructure emerges.

3RD PHASE (2030-2050):

- Large scale deployment reaching **all hard-to-decarbonise sectors**, including **aviation.**
- Biogas will also play a role.

Source: https://www.yele.fr/wp-content/uploads/2020/12/hydrogen-strategies-and-roadmaps-analysis_Yele-Consulting_2020.pdf



Notes:

- The National Hydrogen Strategy states the following goals as the main objectives:
  - **Establish H_2 technologies as core elements of energy system,**
  - **Create the regulatory conditions for the market take-off,**
  - **Strengthen German companies and their competitiveness by promoting research and development,**
  - **Securing and shaping the future national supply of CO_2-free H_2.**
- Among others, this means: promote H_2 globally, make H_2 competitive by boosting market, develop a H_2 market in Germany.
- For **H_2 €7 bil. are foreseen to be invested in Germany and €2 bil. in international cooperation.**
- Constructing **5 GW of electroyser capacity and renewables until 2030.**
- Only H_2 produced with renewable energy **(green H_2) considered to be sustainable in the long-term**.
- **However, carbon-free, blue or turquoise, H_2 will be traded temporarily.**

Source:

- German National Hydrogen Strategy
- https://www.yele.fr/wp-content/uploads/2020/12/hydrogen-strategies-and-roadmaps-analysis_Yele-Consulting_2020.pdf

“What is a political strategy and which are its core elements?”

“Which aspects need be taken into account when thinking about a political strategy to support H_2/PtX products?”

- Open discussion -

Notes:

Steps to establish a political strategy:

- Initiation of **R&D programs**: to develop the knowledge base that will inform future stages and to explore multiple technologies and possibilities.
- **Vision document:** clarifies the "why H_2", "why this jurisdiction", and "why now". It guides research, industry efforts and early demonstration programs. Such documents are often co-created by governments and private actors attracted by the growth prospects of breakthrough applications.
- **Roadmap:** defines an integrated plan with the activities needed to better assess the potential for H_2. It identifies the short-term actions needed to advance deployment, and defines the research areas with the highest priority and the applications where demonstration projects are most needed.
- **Strategy** itself: defines the targets, addresses concrete policies and evaluates their coherence with existing energy policy.

Source: https://www.irena.org/publications/2020/Nov/Green-hydrogen

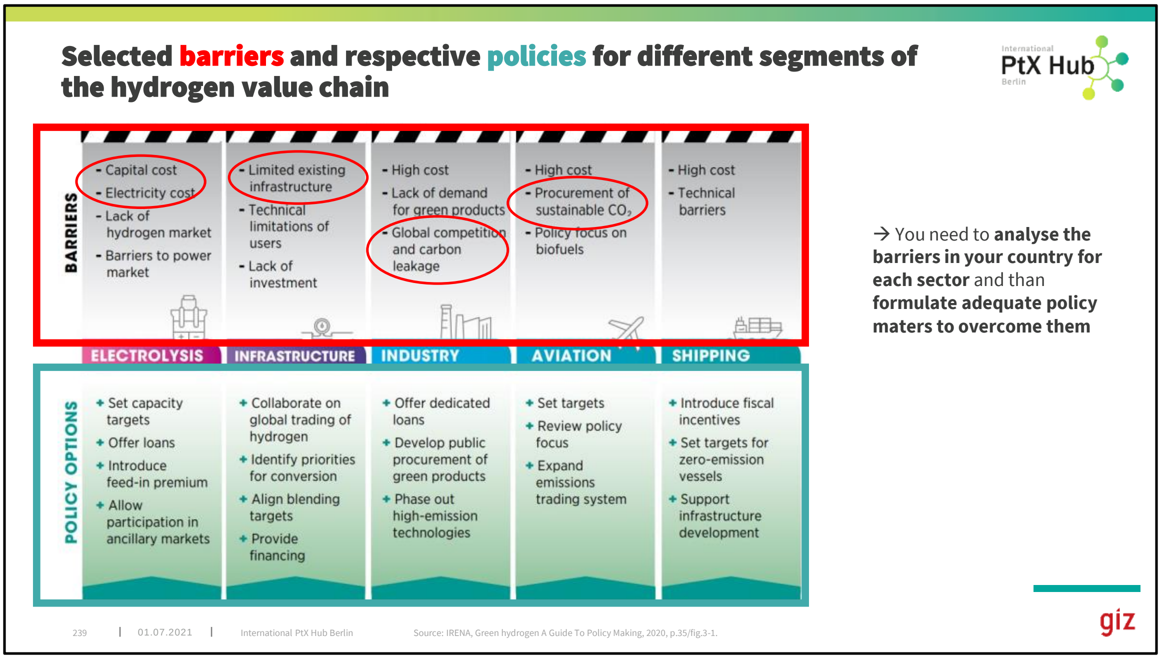
Policy instruments

Green hydrogen is at an **early stage** in most applications and needs policy support be part of the energy transition.

Main policy tools

1. **Target and commitments**
2. Setting **policy priorities**
3. **Financial tools**: investment incentives, funds and loans
4. **Fiscal tools**: tax incentives, carbon pricing
5. **Regulations**: sustainability criteria and methodologies
6. **Public procurement**
7. **Research** support
8. **International collaboration**: facilitate international trade, international market agreement

The deployment of green hydrogen faces various **barriers**, some sector specific, some more consistent (the main one being the **cost**).



Notes:

- Electrolysis:
  - **Barriers:** Capital cost, Electricity cost, Lack of H2 market & Barriers to power market.
  - **Policy instruments:** Capacity targets, Loans, Feed-in premium & Allow participation in ancillary markets.
- Infrastructure:
  - **Barriers:** Limited existing infrastructure, Technical limitations of users & Lack of investment.
  - **Policy instruments:** Collaborate on global trading of H2, Identify priorities for conversion, Align blending targets & Provide financing.
- Industry:
  - **Barriers:** High cost, Lack of demand for green products & Global competition and carbon leakage.
  - **Policy instruments:** Offer dedicated loans, Develop public procurement of green products & Phase out high-emission technologies.
- Aviation:
  - **Barriers:** High cost, Procurement of sustainable CO2 & Policy focus on biofuels.
  - **Policy instruments:** Set targets, Review policy focus & Expand emissions trading system.
- Shipping:
  - **Barriers:** High cost & Technical barriers.
  - **Policy instruments:** Introduce fiscal incentives, Set targets for zero-emission vessels & Support infrastructure development.

Source: IRENA A guide to global policy making
Green hydrogen: A guide to policy making (irena.org)

Multiple steps for market run-up and trade to overcome barriers

Short-term policies: help to close the investment & operational cost gaps. These include:

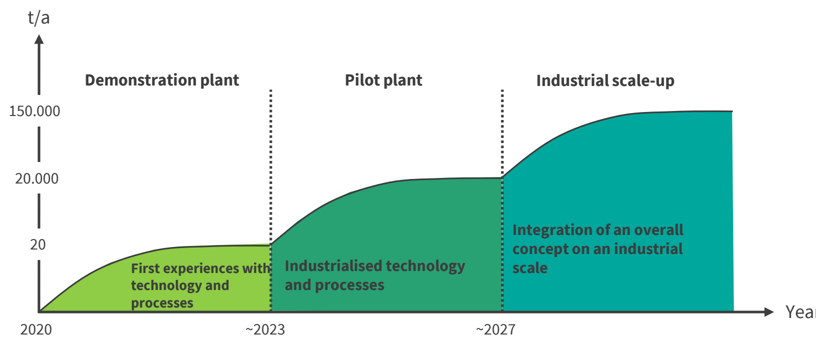
- Research and development (R&D)
- Funding
- Clear regulatory frameworks
- Risk mitigation policies
- Co-funding of large prototypes and demonstration projects to decrease the cost of capital

- **Scaling-up** technologies and developing experience through **learning-by-doing** reduces costs and helps **close the profitability gap**.

- Benefits from **synergies between applications**, increasing hydrogen demand and economies of scale for production and infrastructure. These synergies can take place in **industrial clusters, H2 valleys** (*e.g.* cities) or **hubs** (*e.g.* ports).

- **Industrial users** can drive the development of dedicated "**green hydrogen corridors**" that connect regions generating low-cost renewable energy with demand centers

Steps of scaling-up



- **PtX faces the typical hen-egg-dilemma: technologically** ready for take-off, but **economically** the rocket is not yet flying.
- On **supply side: investors** claim there is not yet sufficient solvent demand.
- On **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!

Notes:

- **PtX faces the typical hen-egg-dilema**. It is **technologically ready** for take-off, yet, **economically** the rocket is **not yet** flying.
- On the **supply side: investors** claim that there is not yet sufficient solvent demand.
- On the **demand side: potential customers** (such as 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 suffient.
- **Policy intervention** will be required providing regulatory frameworks, R&D and financial support, **on both sides of the market**, supply and demand.
- The **Renewable Energy sector** is offering **valuable lessons** of unexpected **steep learning curves** and **dramatic cost degressions.**
- Take **the example of solar PV modules.** It is reasonable to assume, that similar developments could be triggered also for **modular electrolyser units.**
- The **up-scaling debate** is often twisted to looking at **scale in terms of size** instead of **scaling by number**.
- Yet, PV costs came down not by increasing the size but by **serial production of** a rapidly **increasing number of modules.**
- There will be **no global market without compliance** with comprehensive sets of **sustainability standards**

and criteria. **Impact assessments** must cover a broad range of EESG sustainability concerns and criteria.

- For **supply chain due dilligence** they must be considered **at every step** of the value chain and **at every level** from local projects to national programmes to international planetary perspectives

Further comments:

- The costs of synthetic fuels may sink considerably during this period. This is mainly because of the digression of the investment costs for renewable energy power stations and conversion facilities due to the learning effect of a growing global market. In addition, the efficiency of water electrolysis is likely to increase over time, further cutting costs.
- The savings from importing synthetic fuels depend on the investment costs for offshore wind and the FLH at each site Another factor are the differences in cost of capital the exporting countries are subject to country-specific risk premiums on account of political or regulatory instability, and these premiums could increase the costs of imported synthetic fuels
- The most important determining factors for the future cost of synthetic fuels are the costs of power generation, investment in production facilities, and the capacity utilisation of conversion facilities. Transport costs play a less significant role, especially when it comes to liquid fuels.

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

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Policy instruments for a market ramp-up

Policies	Instruments	Examples
Long term policy signals	• Hydrogen roadmaps • targets • industrial strategies • international agreements and commitments	NDCs Paris Agreement; EU Green Deal; Germany's National H2 Strategy; Japan's Basic H2 Strategy; China's Ecological Civilisation commitment; Make in India […]
Demand creation	• CO2 and pollution pricing • mandates and bans • performance standards • tax credits • reverse auctions	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 […]
Investment risk mitigation	• Loans/ export credits • risk guarantees • trading of "guarantees of origin" • Risk mitigation: Carbon Contracts for Difference • 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 […]
Removing barriers	• safety and sustainability standards • avoiding double taxation of energy • certification of CO2 intensity and provenance • benchmarks for processes • international frameworks	International Partnership for H2 and Fuel Cells in the Economy (IPHE); International Organisation for Standardisation (ISO); HySafe; EU CertifHy […]
R&D and knowledge sharing	• direct project funding • concessional loans • multilateral collaboration initiatives • communication campaigns • prizes	Japanese NEDO Roadmap for fuel cells and H2; EU Horizon 2020; Germany National Innovation Program for H2 and Fuel Cell Technology, US Department of Energy H2 and Fuel Cells Program and H2@Scale […]

Source: IEA, The future of hydrogen, 2019.

Example of tool for market development and risk mitigation: Carbon Contracts for Difference scheme (UK)

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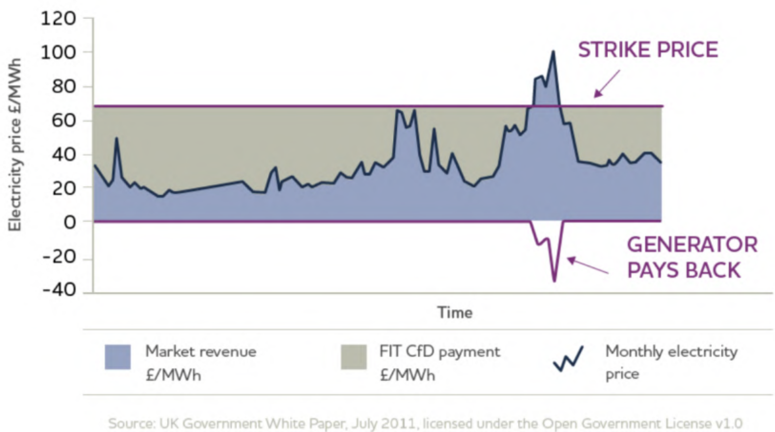
→ Can be applied to steel, cement & fertiliser, too!



CfD (Contract for Difference): long-term contract between electricity **generator &** Low Carbon Contracts Company (**LCCC**).

The contract enables **generator to stabilise its revenues at a pre-agreed level** (**strike price**) for the duration of the contract.

Under CfDs, payments can flow from LCCC to generator & vice versa:

- When **market price for electricity** generated by CfD generator (**reference price**) is **below strike price** from the contract, **LCCC** (see below) **pays** the difference to **CfD generator**.
- However, when **reference price is above strike price**, **CfD generator pays LCCC** the difference.

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 Source: EMR Settlement limited, Contracts for Difference, n.d.

Source: https://www.emrsettlement.co.uk/about-emr/contracts-for-difference/#:~:text=CfD%20is%20a%20long%2Dterm,the%20generator%2C%20and%20vice%20versa.

Important policy instrument/regulation: Standards and certifications

- PtX and H2 products can have a significant role in decarbonising the economy only if they meet rigorous **sustainability standards**.
- These standards have to be developed through **comprehensive and harmonised legislation**, but **certifications must be in place** to then ensure they are respected.

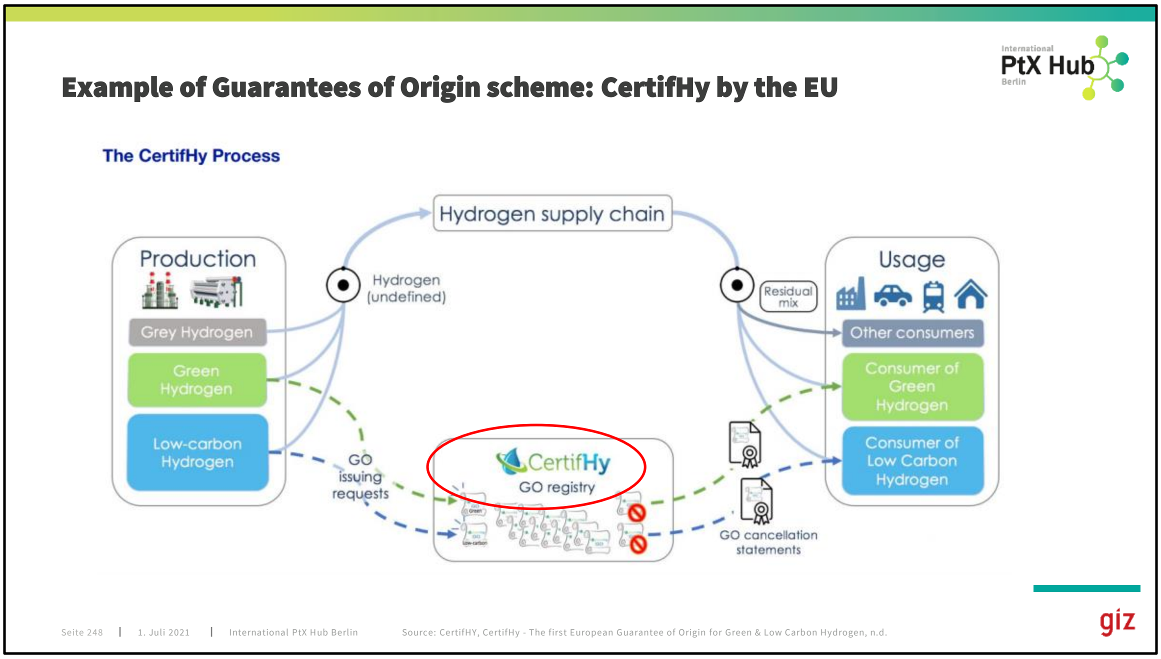
Key aspects of an certification scheme:

- The schemes used to **track origin** are providing a **"guarantee of origin" (GO).**
- **Third-party evaluations** have proven to be successful in existing sustainability certification of alternative fuels (e.g**. CertifHy project in EU).**
- **Guarantees of Origin for H2 and PtX products** will play a big part in the upcoming market, and their **credibility** is likely to influence the **success of these technologies**.

Key elements for credible Power-to-X certifications

- **Simplicity**: requirements should be simple and easy to verify, to avoid creating loopholes and suffocating the market
- **Transparency**: criteria and assessment processes must be transparent
- **Coherence with existing regulation:** certification schemes must be based and updated on existing regulations
- **Stakeholder approach**: it is important to have input and feedback from a wide spectrum of stakeholders to facilitate market recognition and gather information.

- **Sustainability requirements** along the **whole supply chain** and for each relevant element
- Practical **mass balancing** along the supply chain
- Ensuring a **level playing field across different sectors** through certifications principles that apply to all markets and products
- Attention to **human and labour rights,** including socio-economic aspects in the assessment, especially when operating in areas with high social risk.



Notes:
How **CertifHy works for the EU market:**

- CertifHy Guarantees of **Origin enable EU-wide consumption of Green and Low Carbon H_2 regardless of the location; by using a GO (Guarantee of Origin)**, the corresponding **quantity of H_2 consumed acquires the properties of the H_2 covered by the GO**.
- The CertifHy GO scheme is **managed and operated from a central registry that takes care of issuance, transfer and cancellation of a GO.**
- **The GO is cancelled upon use,** so that it may only be used once for claiming H_2 consumed as Green or Low Carbon H_2.
- The **provided electronic cancellation statement includes** a link for on-line access to full GO content
- H_2 that is consumed without being covered by a GO is considered to be from the "**residual mix**", which is an attribute designating the combination of all the H_2 for which no GOs were issued (or for which GOs were issued but not used before expiration).

CertifHy GOs disclose

- Energy source of the H_2.
- Information on **the plant which produced the H_2** (location, start date of operation, operator…)
- **Time of production of the H_2.**
- **Green House Gas intensity (amount of CO_2 equivalent per unit of energy) of the H_2.**
- Date of issuing of the GO.

Source: http://www.certifhy.eu/images/media/files/CertifHy_Leaflet_final-compressed.pdf and https://www.certifhy.eu/ for further research

Examples of other guarantee of origin 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.

Notes:

- Guarantees of Origin for H_2 and PtX products will play a big part in the upcoming market, and their **credibility** is likely to influence the success of these technologies.
- H_2 and PtX GOs should include some key elements:
  - **Sustainability requirements along the whole supply chain** and for each relevant element.
  - **Practical mass balancing along the supply chain.**
  - **Ensuring a level playing field** across different sectors through certifications principles that apply to all markets and products.
  - **Attention to human and labour rights**, including socio-economic aspects in the assessment, especially when operating in areas with high social risk.

Further comments:

- REDII = Renewable Energy – Recast to 2030;
- NOx = nitrogen oxides; gCO_2 /MJ = grams of CO_2 per megajoule;
- gCO_2 /kWh = grams of CO_2 per kilowatt hour;
- tCO_2/tH_2 = tonnes of CO_2 per tonne of H_2.

Source: https://www.irena.org/publications/2020/Nov/Green-Hydrogen
Green Hydrogen: A guide to policy making (irena.org)

“Which questions around standards and certification in the context of H_2/PtX projects are you aware of?”

- Open discussion -

"How can you ramp-up a market?"

"What are related instruments in your country?"

\- Open discussion /Group work -

Example for an International market ramp-up roadmap in Europe

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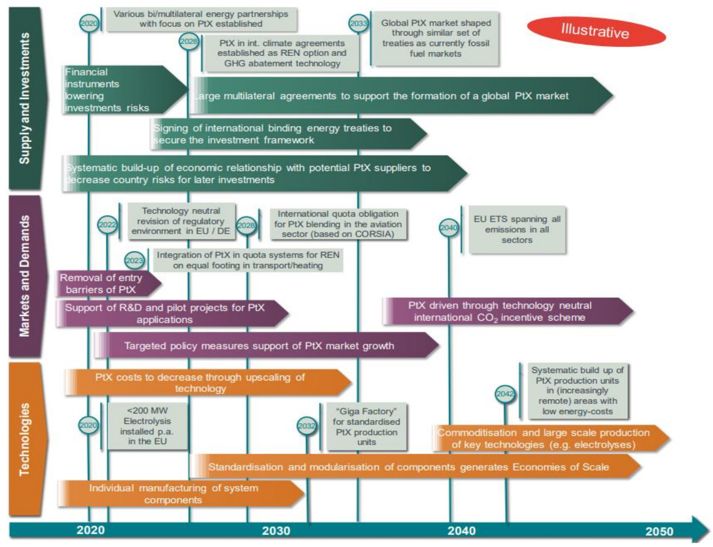

Page 252 | 19-Nov-2020 | International PtX Hub Berlin Source: WEC, International Aspects Of A Power-to-x Roadmap, 2018, p.12/fig.3.

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Notes:

Roadmap for international market rump up:

1. Place PtX on the international climate policy agenda. **PtX should be treated as an innovative option to reduce CO_2 emissions** and to foster the use of renewable energies. PtX should therefore be on the international climate policy agenda.
2. **Recognise international production and trade of PtX as a chance**. PtX importing and exporting countries benefit from a global market and international trade.

→ These benefits should be recognised by the public and policy makers alike.

- **Further development of R&D, pilot projects and demonstration plants on a larger scale**. Large scale PtX pilot projects, including renewable power production, conversion plants and transport of green synthetic fuels to Europe**, could demonstrate the feasibility of international PtX trade** and its benefits over the course of the next decade(s).
- **Create a level playing field for PtX. Regulations such as energy taxes and levies should be adjusted** in order to support the realisation of early-stage PtX projects and to eliminate barriers for market entry for PtX.
- **Capture the green value of PtX. The green value of PtX should be reflected in current climate policy regulations** at least in industrialised countries. PtX should be recognised as an option to fulfil CO_2-abatement and renewable obligations of sectors, market participants as well as states.
- **Enable support of an international PtX production and trade / facilitated international cooperation and backing of investments** in third countries. Energy partnerships (on a German as well as on an EU-level) and energy treaties can be used to promote the concept of producing and exporting green electricity and PtX – both for the domestic as well as for international energy markets. This approach can help to improve the accessibility to energy as well as the economic development in the respective countries.
- **Increase acceptance of international PtX production and trade by minimum standards and certification**. **Environmental and social standards for international** PtX production and trade (including

additionality of renewable installations and carbon neutrality) can increase the acceptance of imported synthetic fuels in energy consuming countries. Transparency can be achieved by a system of certification.

Source: Frontier Economics, INTERNATIONAL ASPECTS OF A POWER-TO-X ROADMAP - A report prepared for the World Energy Council Germany
https://www.weltenergierat.de/wp-content/uploads/2018/10/20181018_WEC_Germany_PTXroadmap_Full-study-englisch.pdf

Policy Instrument: Finance and investment

Financing should follow four main directions

- **Public support**: subsidies, adequate carbon pricing, pilot projects, Carbon Contracts for Difference
- **R&D and large-scale deployment:** cost reduction of production and utilisation
- **Economies of scale**: supply chains, widespread infrastructure
- **Massive investments in additional production** of renewable energy

Is the hydrogen age really starting now?

Seven signposts of scale-up towards a H2 economy from BNEF

International PtX Hub Berlin

Event	Effect
1) Net-zero climate targets are legislated	Makes it clearer that hard-to-abate sectors will need to decarbonise
2) Standards governing usage of H2 are harmonised and regulatory barriers removed	Clears or minimises obstructions to H2 projects
3) Targets with investment mechanisms are introduced	Provides a revenue stream for producers, increases competition, builds capacity and experience, and gives equipment manufacturers confidence to invest in plan
4) Stringent heavy transport emissions standards are set	Provides an incentive for manufactures to produce, and users to buy, fuel cell trucks and NH3-powered ships
5) Mandates and markets for low-emission products are formed	Provides an incentive for manufacturers to produce low-emission goods (e.g. steel, cement, fertilisers, plastics) that will often require the use of H2
6) Industrial decarbonisation policies and incentives are put in place	Helps to coordinate infrastructure investment and scale efficient use of H2. Provides incentives for H2 use
7) Hydrogen-ready equipment becomes commonplace	Enables and reduces the cost of fuel switching to H2

 Source: BNEF, Hydrogen Economy Outlook, 2020.

giz

Notes:

- H_2 has experienced a **hype cycle before**, and right now, **there is still insufficient policy to support investment** and to scale up a clean H_2 industry.
  But the growing number of **countries getting serious about decarbonization** could change this.
- Investors **should watch out for the following key events** to help **determine whether a H_2 economy is emerging**:

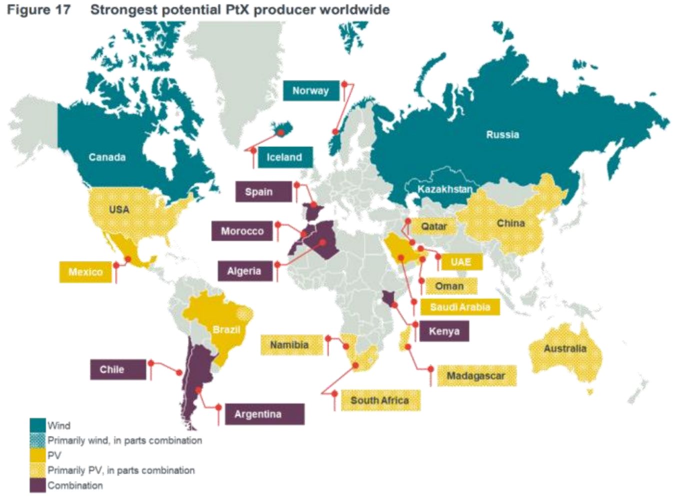
1) net-zero climate targets are legislated,
2) standards governing H_2 use are harmonised and regulatory barriers removed,
3) targets with investment mechanisms are introduced,
4) stringent heavy transport emission standards are set,
5) mandates and markets for low-emission products are formed,
6) industrial decarbonisation policies and incentives are put in place and
7) H_2 ready equipment becomes commonplace.

Source: BNEF Hydrogen Economy Outlook 2020

What is happening worldwide in H2/PtX?

Overview on national H2 policies based on different RE sources

Figure 17 Strongest potential PtX producer worldwide



255 | 01.07.2021 | International PtX Hub Berlin Source: WEC, International aspects of a Power-to-X Roadmap, 2018, p.43/fig.17.

Notes:

Based on various criteria, such as:

- The **costs of generating renewable energy sources power** as the main input to PtX production, primarily driven by FLH of installed capacities.
- Additional **area-specific resource potentials or constraints**, such as surface area or availability of water.
- Further factors **beyond the natural resource potential**, such as a country's political stability, its development status and the embedded energy framework.

- Various countries can be identified as having a strong potential for PtX production.

- It has to be noted that the selection of countries is neither complete nor constant over time: For example, there may be vast RES potentials on a regional basis in certain countries that are not included in this list, which may be captured for PtX production and export. Furthermore, a number of countries may not be identified as high potentials for political reasons (e.g. Somalia), however, the assessment can change over time with the development of the political environment. Consequently, the following map provides an indicative evaluation of countries from today's perspective.

Source: https://www.weltenergierat.de/wp-content/uploads/2018/10/20181018_WEC_Germany_PTXroadmap_Full-study-englisch.pdf

Types of possible PtX producers and example countries

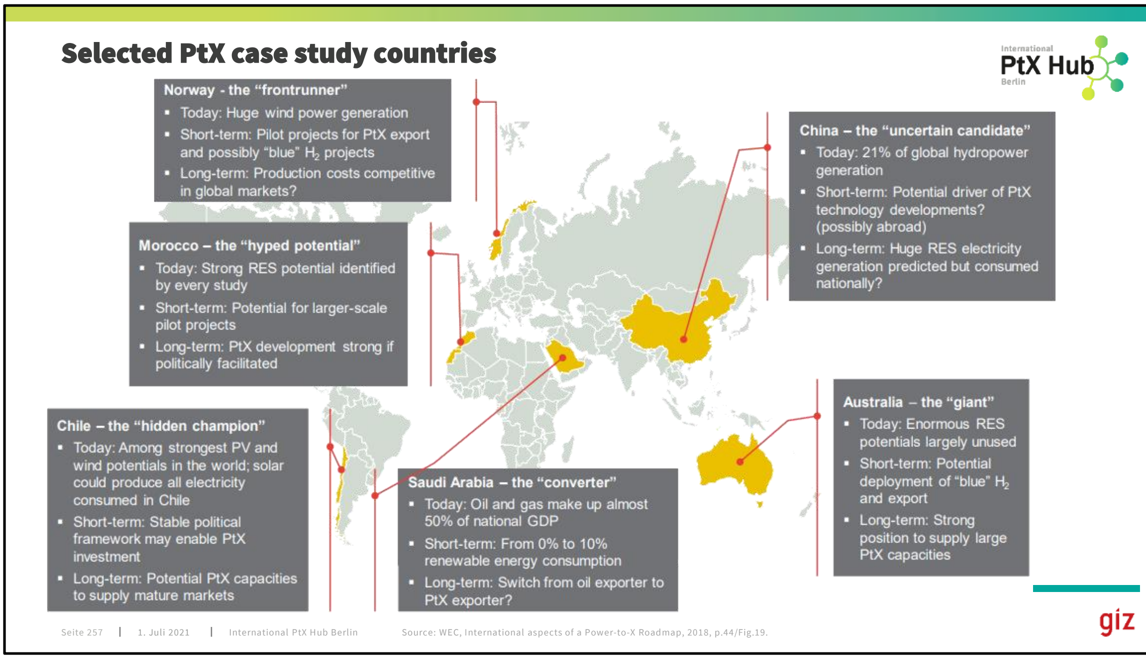
Type	PtX motivation and readiness	Selected example
Frontrunners	▪ PtX already on countries (energy) political radar ▪ Export potential and PtX readiness evident ▪ Uncomplicated international trade partner ➢ Especially favourable in early stages of market penetration	Norway
Hidden Champions	▪ Fundamentally unexplored RES potential ▪ Largely mature, but often underestimated, (energy) political framework with sufficiently strong institutions ➢ PtX could readily become a serious topic if facilitated appropriately	Chile
Giants	▪ Abundant resource availability: massive land areas paired with often extensive RES power ▪ PtX readiness not necessarily precondition, may require facilitation ➢ Provide order of PtX magnitudes demanded in mature market	Australia
Hyped Potentials	▪ At centre of PtX debate in Europe with strong PtX potential ▪ Energy partnerships with Europe foster political support ➢ Potential to lead technology development; may depend strongly on solid political facilitation	Morocco
Converters	▪ Global long term conversion from fossil to green energy sources ▪ PtX to diversify portfolio as alternative long-term growth strategy ➢ Strong motivation for PtX export technology development; may requires political facilitation and partnership with the EU/DE	Saudi Arabia
Uncertain Candidates	▪ Partially unexplored RES potentials, possibly paired with ambitious national climate change policies ▪ PtX export in competition with growing national energy demand ➢ PtX export motivation and potential unclear – may drive PtX technology development, however export uncertain	China

Seite 256 | 1. Juli 2021 | International PtX Hub Berlin   Source: WEC, International aspects of a Power-to-X Roadmap, 2018, p.44/Fig.18.

Notes:
- Each country will have an **individual story and diverse underlying incentives** to take part in a developing PtX market as outlined across the varying criteria in the previous section.
- The **potential suppliers are at different levels of readiness and willingness to participate** and to enter this market. However, for illustrative purposes and to provide a concept on how these countries might be clustered with regard to their part in a global PtX market, we identify several types of "PtX stories" using the criteria defined previously (details in the table)

- Abbreviations:
- PtX= Power-to-X
- RES= Renewable Energy Sources

Source: https://www.weltenergierat.de/wp-content/uploads/2018/10/20181018_WEC_Germany_PTXroadmap_Full-study-englisch.pdf



Notes:

- For each of the previous types, we provide a selected example of a country that may fall within each of these categories, and is considered representative for a wider group of potential suppliers (Figure 19).

Source: https://www.weltenergierat.de/wp-content/uploads/2018/10/20181018_WEC_Germany_PTXroadmap_Full-study-englisch.pdf

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Important policy instruments: Development and international cooperation

1. **Harmonising standards and remove barriers**: international standardisation will be crucial across all value chain, including for **"guarantees of origin"**. Some regulations may need to be revised and new ones established
2. **R&D, strategic demonstration projects and knowledge sharing:** improving the access to essential technological knowledge will be fundamental to ensure a fair international market
3. **Co-financing** (e.g. for pilot projects) between countries can re-distribute access to financial resources
4. **International stakeholder dialogues**: involvement of all different stakeholders will facilitate international trade and create an inclusive international framework
5. **International agreements** to set up international trade routes
6. **Strict regulations to ensure sustainability and respect of human & social rights** will be crucial to guarantee just international cooperation

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Source: own reflections and IEA, The future of H2: https://www.iea.org/reports/the-future-of-Hydrogen

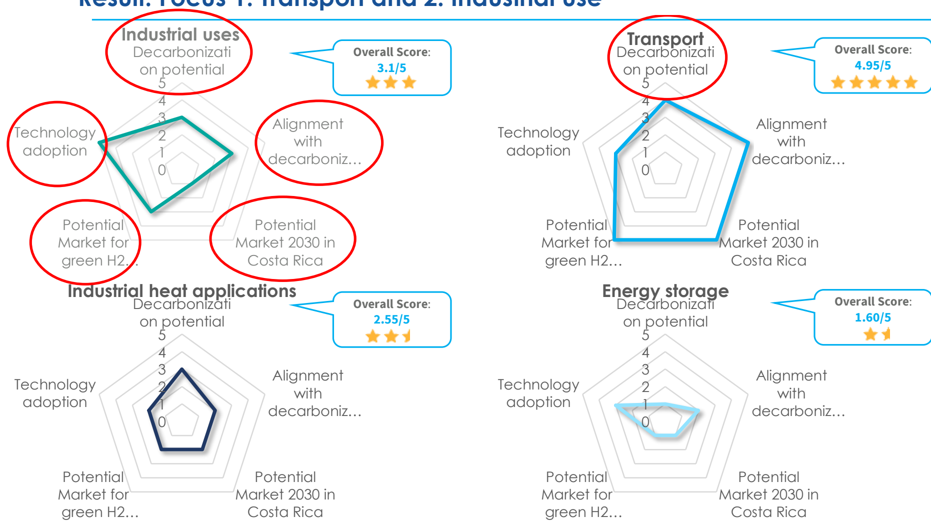
International lessons learned for the successful development of a hydrogen market (1)

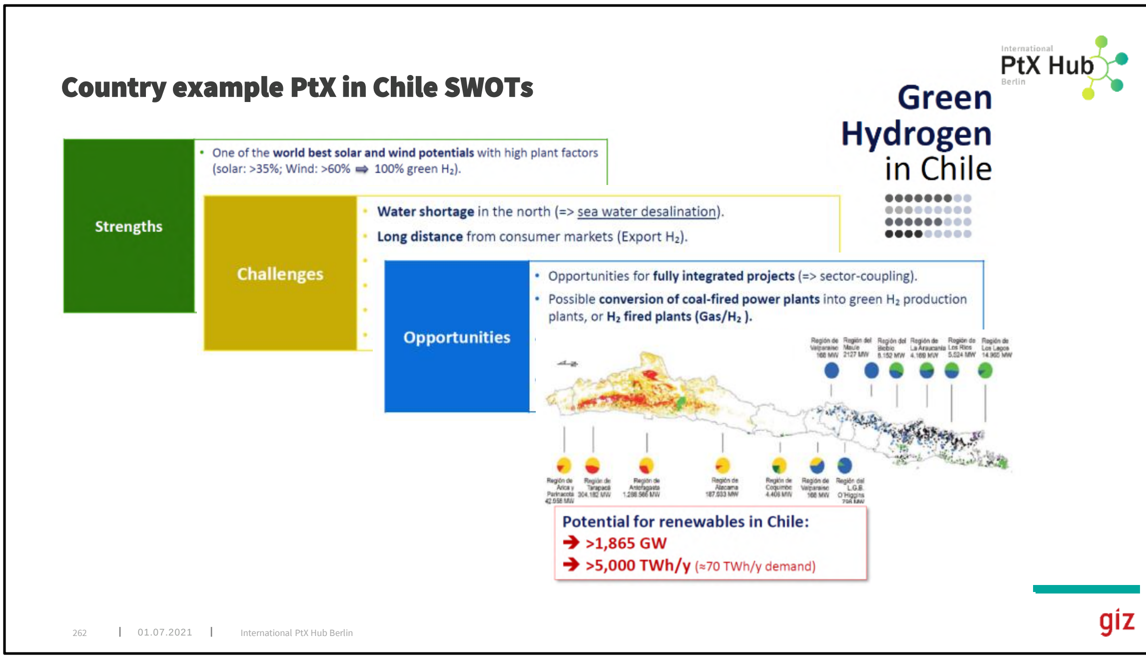
	Topic	Learned from:	Lesson
1	**Promotion of renewable energy to ensure the parallel development of green hydrogen**	European Union	New projects for the production of H2 through electrolysis on a GW scale go along with the development of new renewable electricity generation plants. For example: in the North Sea the NorthH2 project plans to install 10 GW off-shore wind power by 2040 for the production of green H2.
2	**Extensive base of stakeholders**	Chile	Countries with a large number of stakeholders around the hydrogen economy development generate plans and execute projects in a more agile way. An example is Chile, who convened roundtables with public and private actors and even international cooperation organizations for the planning of its National hydrogen Strategy.
3	**Importance of a strategy / roadmap as a guideline for actions at the national level around hydrogen**	Chile and Japan	A National Strategy or Roadmap for hydrogen establishes guidelines for the development of projects by stakeholders in the countries. An example of this are Chile and Japan. Japan has a clearly focused roadmap on the development and adoption of H2 consuming technologies. Japan envisions itself as an H2 importer. Chile positions itself as an exporter of H2 and its derivatives on its H2 strategy. As a consequence, it has already attracted investments for 4 large projects of e-fuels production in less than 2 years.
4	**Establishment of explicit hydrogen adoption goals.**	Japan	Japan has a hydrogen strategy with a large number of quantitative goals. Japan's goals are set as numbers of FC vehicles or buses, number of residential combined heat & power systems, or electricity generated in large power plants by 2025, 2030 or 2050. This establishes a commitment for adoption and allows predicting the volumes of H2 required to satisfy the Japanese market.

International lessons learned for the successful development of a hydrogen market (2)

	Topic	Learned from:	Lesson
5	**Creation of hydrogen hubs to aggregate demand and accelerate the adoption of higher volumes of hydrogen in concentrated areas.**	European Union	The European Union has identified seaports as potential hubs for the adoption of green H2. Seaports gather a high volume of cargo truck traffic, heavy industries and thermal power plants installed in their vicinity and have preferential access to off-shore renewable energy and international shipments of H2 and its derivatives. The aforementioned characteristics allow ports to group multiple H2 off takers, while having the potential to produce the required H2 in a semi-centralised way. This concept of H2 hubs can be transferred to centers of accumulated H_2 demand inland as well.
6	**International collaboration at the regional level to increase leverage towards equipment providers when aggregating demand**	Uruguay	Throughout more than 5 years developing projects for the Latin American region, Hinicio has seen the need to generate push for aggregating regional demand for equipment to attract technology providers and promote the local installation of aftersales service centers. Sometimes a single project does not demand the necessary volumes of equipment (for example: FC buses) for a manufacturer to establish after-sales services in Latin American countries, particularly the smaller ones like Costa Rica.
7	**Creation/adoption of green hydrogen guarantee of origin schemes in the early stages of the adoption**	European Union	Green hydrogen Guarantee of Origin schemes were proposed for the first time in Europe, being CertifHy the most important. This scheme helps create market pull for Green and Low-carbon hydrogen, EU-wide, independently from production sites. It improves the business case and ensures transparency & consumer empowerment
8	**Provide financial incentives to reduce the cost gap between hydrogen and fossil fuel applications**	United States	Financial incentives that reduce the cost gap between fossil technologies and the hydrogen alternative allow the consumer to make decisions oriented not only by price. In California, for example, FCEV buyers can get a rebate of up to $ 4,500. Other forms of financial incentives may be tax discounts, subsidies, or benefits for the importation of H2 equipment.

Example: Costa Rican approach to focus its efforts to develop hydrogen: Detailed evaluation of key criteria's for its sector development Result: Focus 1. Transport and 2. Industrial use





Notes:

Green H_2 in Chile -Overview

- Government and private sectors are strongly **committed in green H_2**.
- National Green H_2-Strategy**:** Launched on 03.11.2020 and in implementation
- Actual projects (production of green H2/derivates) in development: >**15 big** (export); >**20 small H_2-projects** (local demand)
- Application: >**30 H_2-projects** in development (transport, industry applications).
- International agreements: With several countries like Singapore, Port of Rotterdam (NL), GB, Correa, Japan, …. Germany: Energy-Partnership..

- **Goals of National Green H2 Strategy of Chile until 2025:**
  - **5 Billion USD** of investments committed in H2 infrastructure in Chile
  - **5 GW** installed capacity of electrolyser in development

- **Until 2030:**
  - **<1,5 USD/ kg** production cost for green H2 (most economic worldwide)
  - **>2,5 Billion USD exports** of green H2/ derivates
- Chile is among the **top 3 exporters** of green H_2 and its derivates.


GIZ support in Chile for a national hydrogen strategy (I)
International PtX Hub Berlin
10/2014
Green H_2 as an option in the north of Chile (Potential of RE, gas network & mining, etc.)
02/2015
Cooperation with the strategic solar program of CORFO
COMITÉ SOLAR
COMITÉ CORFO
05/2017
1st international H2 conference in Chile (40 → 120 part.)
06/2017
Support in international tender for H2 in mining transport (by CORFO)
03/2018
"H2 Tool" for the economic evaluation of integrated H2 projects
06/2018
Creation of the Chilean Hydrogen Association: H2 Chile
H2 Chile
09/2018
2nd international H2 conference in Chile (200 → 420 part.)
04/2019
Release of the 2nd edition of the book: "H2 en Chile"
HIDRÓGENO
11/2019 - 05/2020
International benchmarking regulatory strategy of H2 in Chile
11/2019 - 05/2020
Proposal for Chilean H2 norms and regulation
01/2020 - 11/2020
Collaboration in the elaboration of Chilean national H2 strategy
NATIONAL GREEN HYDROGEN STRATEGY
02./20 -11/2020
Collaboration in "Mission Cavendish" H2-Information seminars (8 with >1.800 part.)
MISIÓN CAVENDISH
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Berlin
GIZ support in Chile for a national hydrogen strategy (II)
ENERGY PARTNERSHIP
CHILE-ALEMANIA
Mesa de Trabajo
Compensaciones
H2
02.06.2020
Bilateral political H2 dialogue of the Energy Partnership
06/2020 - 08/2020
Positioning of Chile in calls for projects (6 project outlines and proposals for support elaborated for BMWI)
07/2020 - 03/2021
Elaboration H2 norms and regulations for Chile
07/2020
Initiation of round table for elaboration of CO2 tax compensation
09/2020
Call for proposals for technical support (21 proposals submitted and 6 projects selected for technical assistance)
05/2020 – 09/2020
Identification of green financing options for H2 projects (178 options/ 14 for Chile)
25.06.2020
Regular H2-Technical workshops (8 workshops in 2020 with 1.480 part/ 3.350 unique views)
07/2020 - 10/2020
Analysis of environmental aspects/permits for H2 projects
07/2020 – 09/2020
Analysis potential of job creation and local value chain in H2 economy - NDC (22-/2030; 87-/2040 and 94.000 in 2050)
08/2020
Analysis of necessary infrastructure and logistic for H2 export
Electrolizadores PEM: Soluciones para proyectos de hidrógeno
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GIZ support in Chile for a national hydrogen strategy (III)

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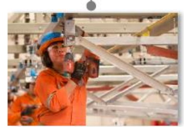
11/2020
Initiation of **green H2 platform** for America Latina and the Caribbean

3. and 4. 11.2020
3rd International H2 conference in Chile: **"Green H2 Summit"** (>5.700 participants!)

11/20 – 03/2021
Analysis of the "state of the art" of **Carbon Capture and Utilization** and potentials in Chile

12/2020 – 03/2021
Add-on to the analysis of **job potential** for H2 projects not related to NDC (≈320.000 new jobs until 2050)



11/2020 – today
Technical assistance for selected hydrogen projects in Chile (feasibility studies, consulting, etc.)

02/2021 – today
Analysis of requirements for **certification of green H2 projects**

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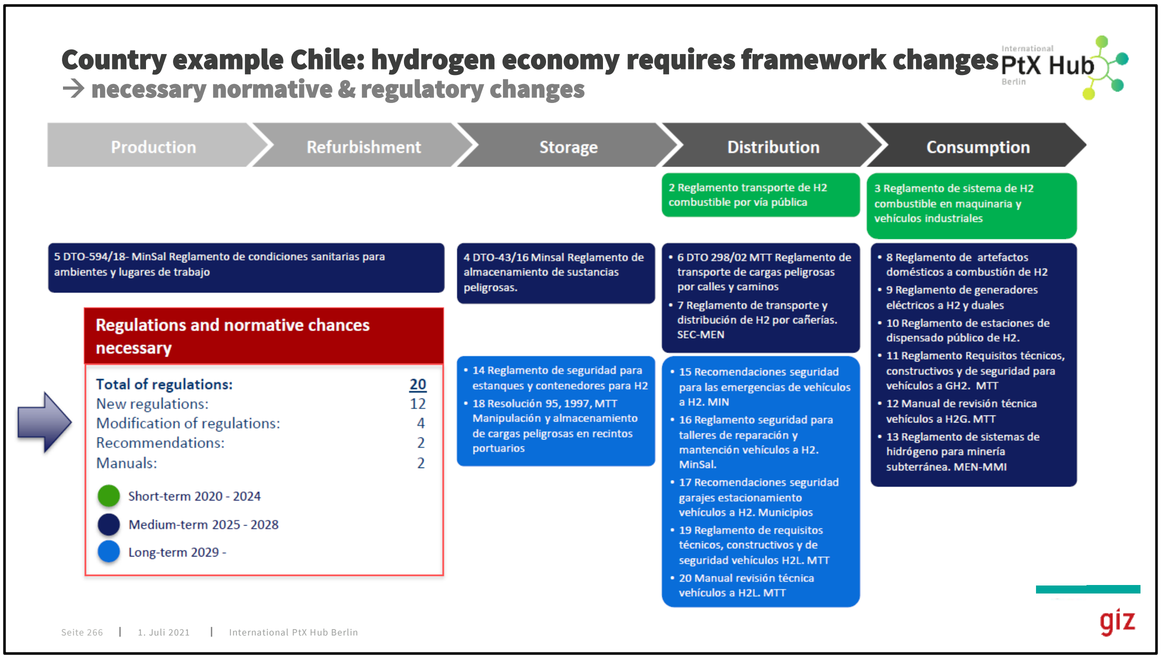

Country example Chile: hydrogen economy requires framework changes
→ necessary normative & regulatory changes
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Production
Refurbishment
Storage
Distribution
Consumption
2 Reglamento transporte de H2 combustible por vía pública
3 Reglamento de sistema de H2 combustible en maquinaria y vehículos industriales
5 DTO-594/18- MinSal Reglamento de condiciones sanitarias para ambientes y lugares de trabajo
4 DTO-43/16 Minsal Reglamento de almacenamiento de sustancias peligrosas.
• 6 DTO 298/02 MTT Reglamento de transporte de cargas peligrosas por calles y caminos
• 7 Reglamento de transporte y distribución de H2 por cañerías. SEC-MEN
• 8 Reglamento de artefactos domésticos a combustión de H2
• 9 Reglamento de generadores eléctricos a H2 y duales
• 10 Reglamento de estaciones de dispensado público de H2.
• 11 Reglamento Requisitos técnicos, constructivos y de seguridad para vehículos a GH2. MTT
• 12 Manual de revisión técnica vehículos a H2G. MTT
• 13 Reglamento de sistemas de hidrógeno para minería subterránea. MEN-MMI
Regulations and normative chances necessary
Total of regulations: 20
New regulations: 12
Modification of regulations: 4
Recommendations: 2
Manuals: 2
Short-term 2020 - 2024
Medium-term 2025 - 2028
Long-term 2029 -
• 14 Reglamento de seguridad para estanques y contenedores para H2
• 18 Resolución 95, 1997, MTT Manipulación y almacenamiento de cargas peligrosas en recintos portuarios
• 15 Recomendaciones seguridad para las emergencias de vehículos a H2. MIN
• 16 Reglamento seguridad para talleres de reparación y mantención vehículos a H2. MinSal.
• 17 Recomendaciones seguridad garajes estacionamiento vehículos a H2. Municipios
• 19 Reglamento de requisitos técnicos, constructivos y de seguridad vehículos H2L. MTT
• 20 Manual revisión técnica vehículos a H2L. MTT
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Consistant approach for a sustainable national H2/PtX strategy

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- 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.
- **PtX is offering bright perspectives** for achieving the Paris Agreement and contributing to the SDGs.

"When shall you start activities for green H2 & PtX?"

- Principle considerations -

Fundamental difference between fossil and renewable energies

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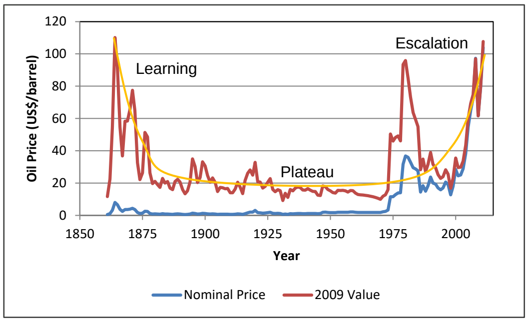
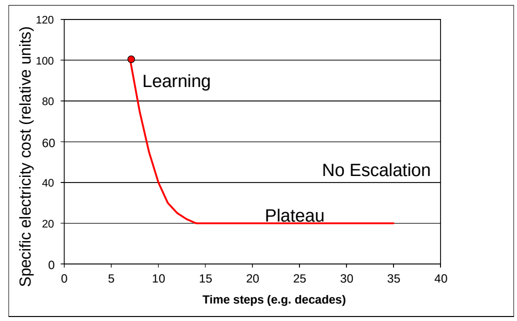


Fossil fuel cost perspectives



Renewable energy cost perspectives

Source: ChartsBin, Historical Crude Oil prices, 1861 to Present, 2011.

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Notes:

- The cost of fossil fuel is high at the first day, then goes down to a minimum by learning and mass production, and will rise again when fuel becomes scarce or too dangerous for the environment.
- The cost of renewable energy is high at the first day, then goes down to a minimum by learning and mass production, and then it stays there, unless mankind looses it's related know how.
- With this in mind ….

Source:
http://chartsbin.com/view/oau

When is the best time to start investing in renewables and H_2/PtX?

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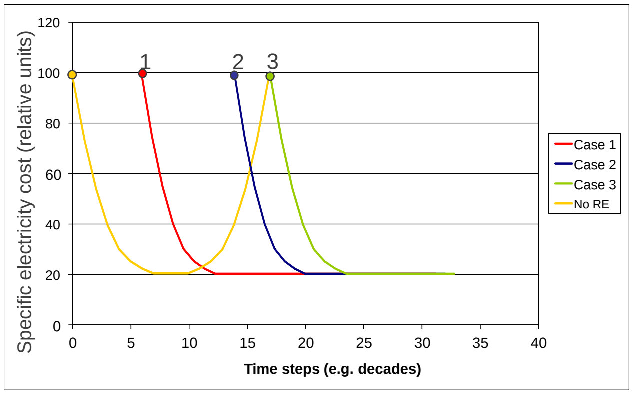

1. at once the RE learning curve can be started and as fast as possible?
2. when fuel prices obviously exceed the expected long-term renewable energy cost?
3. as soon as renewable energy becomes competitive?

Source: Dr. Franz Trieb, Lecture Renewable Energy, Executive Academy, MBA Energy Management, Vienna University of Economics and Business, 2010-2020.

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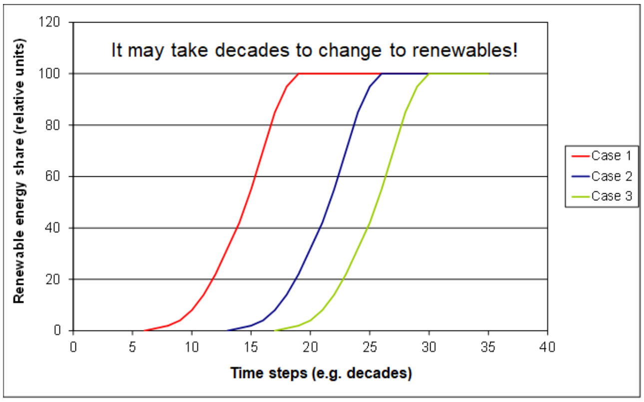
Notes:
What is the best moment to start developing renewable energy sources?

Source:
Dr. Franz Trieb, Lecture Renewable Energy, Executive Academy, MBA Energy Management, Vienna University of Economics and Business, 2010-2020

When is the best time to start investing in renewables and H_2/PtX?



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3. as soon as renewable energy becomes competitive?

Source: Dr. Franz Trieb, Lecture Renewable Energy, Executive Academy, MBA Energy Management, Vienna University of Economics and Business, 2010-2020.

Notes:

- Consider that changing a **national energy economy from fossil fuels to renewable energy will take some decades** …. Assume you can change from zero to 100% renewables **within 10 decades**.
- So, when is the best moment to start investing in renewables?

When is the best time to start investing in renewables and H_2/PtX?

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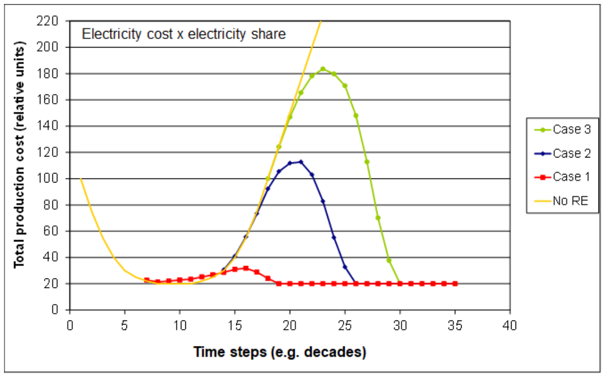

1. at once the RE learning curve can be started and as fast as possible!
2. ~~when fuel prices obviously exceed the expected long-term renewable energy cost?~~
3. ~~as soon as renewable energy becomes competitive?~~

Source: Dr. Franz Trieb, Lecture Renewable Energy, Executive Academy, MBA Energy Management, Vienna University of Economics and Business, 2010-2020.

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Notes:

- **The answer is perfectly clear: As soon as possible!** (Answer No.1)
- The electricity mix will become a little bit more expensive in the beginning, when renewables are more expensive than fossil fuels, but renewable shares will still be small, so the overal cost difference to conventional supply will remain small.
- **Renewables will become less expensive when renewable shares become higher and higher,** so increasing shares and lower cost of renewables will compensate each other, keeping differences to conventional supply small.
- In the long-term with high renewable shares, renewables will prevent national power supply to become expensive once fossil fuel prices start to rise.
- The worst case you can do is waiting until your complete power supply is as expensive as renewables in their first day (answer No.3).
- Your country will probably be bankrupt by that time. And worse: after that **point it will take 100 years to change to cheap renewables.**

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“Which mix of policy instruments could be appropriate in your country/region to foster H_2 / PtX developments?”

- Open discussion -

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or: **menti.com > CODE 123 456**

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Your opinion is important to us!

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


Thank you for your kind attention!
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Deutsche Gesellschaft
für Internationale
Zusammenarbeit (GIZ) GmbH
On behalf of:
Federal Ministry
for the Environment, Nature Conservation
and Nuclear Safety
of the Federal Republic of Germany

Selection of Resources

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