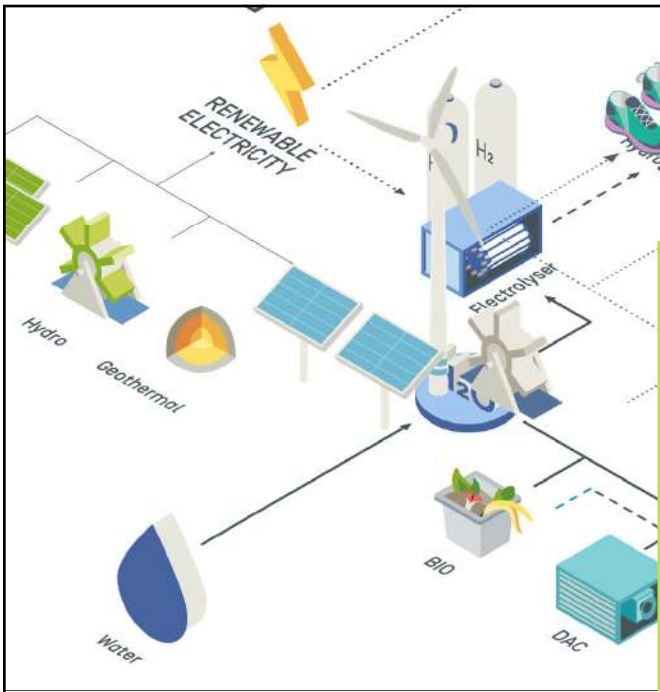
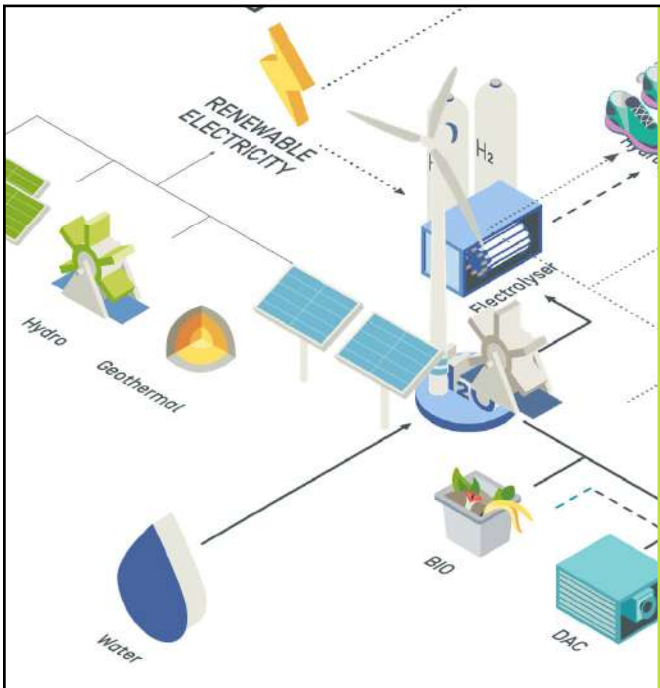


Renewable POWER TO X

Training: August 2023
Modules prepared by the International PtX Hub
Trainer: Prof. Thorsten Schneiders



Renewable POWER TO X

Part 1: Introduction to Renewable PtX

Training: August 2023
Modules prepared by the International PtX Hub
Trainer: Prof. Thorsten Schneiders

Disclaimer

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The PtX Hub only guarantees the quality of the lecture if the training has been conducted by authorised trainers.

The International Power-to-X Hub is a knowledge and exchange platform working on the breakthrough of sustainable Power-to-X, incl. green hydrogen around the globe

We work with ministries and governments, industry, NGOs, think tanks and experts

We focus on

- International networks & cooperations
- Sustainability
- Capacity building & knowledge exchange
- Ramping up local and global markets for Power-to-X

We offer

- Cutting-edge research and insights on Power-to-X
- A global network of 120 partner countries
- Training workshops on green hydrogen & Power-to-X
- Expertise on the sustainability of green hydrogen & Power-to-X
- Advisory on partnerships and financing for Power-to-X projects

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Our Team: over 40 people in 4 continents

Our funders

The Power-to-X Hub is implemented by the **Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH** on behalf of the **German Federal Ministry for Economic Affairs and Climate Action** (BMWK).
Financed by the **International Climate Initiative (Internationale Klimaschutzinitiative, IKI)**, the PtX Hub is a contribution to the **German National Hydrogen Strategy of 2020.**

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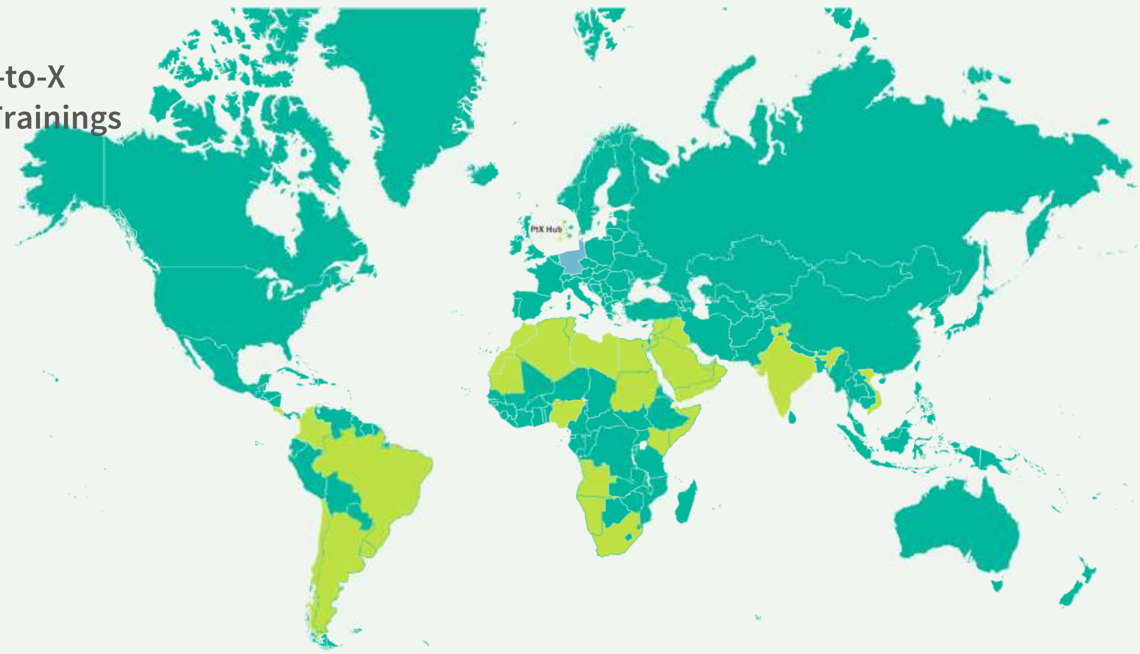
Power-to-X Basic Trainings



Countries in which renewable PtX trainings have been conducted

Agenda

9:00 am – 4:00 pm	
9:00	Welcoming and Introduction
9:15	Module 1: Introduction to Renewable PtX
10:15	Break – 30 mins
10:45	Module 2: Production Pathways of Renewable PtX
12:15	Module 3: Renewable PtX Economics I
13:00	Lunch break
14:00	Module 3: Renewable PtX Economics II
14:45	Over to you: Q&A + Transfer
15:45	Wrap up & Outlook – 15 mins

9:00 am – 4:00 pm	
9:00	Module 4: PtX Infrastructure
10:00	Module 5: Markets for Renewable PtX
11:00	Break – 15 mins
11:15	Module 6: Sustainability Criteria for Renewable PtX
12:45	Lunch break
13:45	Module 7: Support Policies and Regulations for Renewable PtX
14:45	Over to you: Q&A + Transfer
15:45	Wrap up & Evaluation – 15 mins

KEY LEARNING OBJECTIVES

- ✓ Acquire key **terminology** and understand main **drivers** of Power-to-X development
- ✓ Identify necessary **inputs** and **processes** for sustainable PtX products
- ✓ Assess **applications, processes, future applications and markets** for PtX
- ✓ Identify techno-economic criteria on **transportation, storage and trade** of PtX products
- ✓ Understand importance of **sustainability** with the **EESG framework** along the entire value chain and product's lifecycle
- ✓ Learn about crucial **instruments** to strengthen PtX in the **political and institutional framework**

Access the atingi online room for the PtX Training

1. Create an account with atingi.org and log into the platform.
2. Enter the course: PtX Hub Training Alumni & Community or put "PtX" in the "Search" function.
3. Enter the Enrolment Key: XXXXXX

- ➢ download Training Material
- ➢ use the Alumni Forum
- ➢ fill out the Feedback Survey
- ➢ get your Certificate

Atingi is the learning management system by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. It is compliant with European General Data Protection Regulation (GDPR). Find out more on Data Protection at atingi here.

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What is PtX? (film)

https://u.pcloud.link/publink/show?code=XZJysTVZmdeKeWsdQB4bI5u9f448xuF37CPV

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The Path to 2050 with Power-to-X (film)

https://ptx-hub.org/wp-content/uploads/2023/03/International-PtX-Hub-Path-to-2050-with-PtX.mp4

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Let's get to know each other

What's your…

- ✓ Institution
- ✓ Academic background
- ✓ Knowledge on energy topics including renewable energy
- ✓ Knowledge on PtX
- ✓ Relation/ work with PtX

Agenda

1
Introduction to Renewable PtX
Why are we talking about renewable PtX now?

2
Production Pathways of Renewable PtX
What is needed for PtX, incl. green hydrogen

3
Renewable PtX Economics
How will the cost of renewable PtX and RE develop? What are the parameters to lower them?

4
PtX Infrastructure
How to transport and store PtX products (incl. gH_2) best?

5
Markets for Renewable PtX
How to determine where to start a PtX market in your country?

6
Sustainability Criteria for Renewable PtX
Which sustainability criteria will be applied for renewable PtX? Why are they so important?

7
Support Policies and Regulations for Renewable PtX
Which policies and regulations are useful and necessary to start your national strategy? How to ramp up the market and business?

List of abbreviations

CAPEX: Capital cost expenditures
CCfD: Carbon contracts for difference
CCS: Carbon Capture and Storage
DAC: Direct Air Capture
FLH: Full-load hours
GW: Gigawatt
HVDC: High voltage, direct current
LCOE: Levelised cost of electricity
LOHC: Liquid organic hydrogen carrier
LHV: Lower heat value

- **OPEX:** Operating cost expenditures
- **PEM:** Proton Exchange Membrane
- **PtX / PtL / PtG:** Power-to-X / -Liquid / -Gas
- **PV:** Photovoltaic
- **RE:** Renewable Energy/ies
- **RES:** Renewable Energy System(s)
- **RWGS:** Reverse Water Gas Shift Reaction
- **SMR:** Steam methane reforming
- **SOEC:** Solid Oxide Electrolyser Cell
- **TWh:** Terawatt hours
- **WACC:** Weighted average cost of capital

Key Conversion Data
- 1 kWh H_2= 3.6 MJ H_2
  1 MWh H_2 = 3.4 MMBTU H_2
  1 MJ H_2 = 0.277 kWh H_2

Conversion kWh and kg H_2:
- 1 kg H_2 = 33.3 kWh H_2 *(heat unit Hu /calorific value)*
- 1 MWh H_2 = 30 t H_2
- 1 Mio t H_2 = 33 TWh H_2

Monetary value per weight or calorific value
- 4.5 ct/kWh H_2 = 45 €/MWh H_2 = 1.5 €/kg H_2
  or: 1€/kg H_2 = 3 ct/kWh H_2
- 100 €/MWh H_2 = 3.33 €/kg H_2
  or: 1€/kg H_2 = 30 €/MWh H_2

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Why are we here today?

Myers (03/2021) New Climate Change Minor Prepares Students for Solving One of the World's Most Pressing Problems. https://drexel.edu/coas/news-events/news/2021/March/new-climate-change-minor-prepares-students-for-solving-one-of-the-worlds-most-pressing-problems/

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Module 1

Introduction

1. Energy Storage vs. Energy Source
   - Recycling energy commodities
2. Power-to-X (PtX)
   - The concept behind hydrogen
   - Sustainable carbon
3. Energy Efficiency and Electrification
   - The Paris Delta
   - Efficiency and sufficiency
   - Supporting pillars of the energy transition
4. PtX Demand Predictions
5. PtX Value Chain and Projects

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1. Energy Storage vs. Energy Source

- Recycling energy commodities

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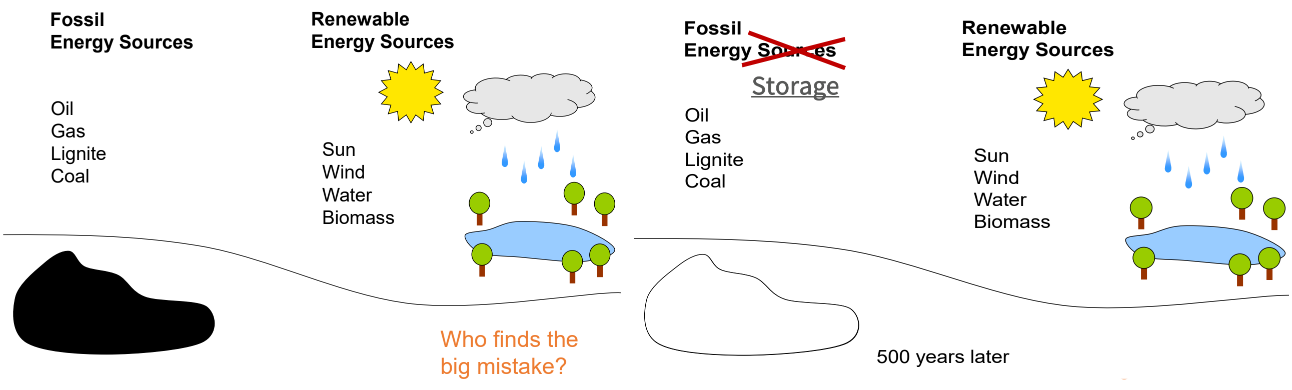
1. Energy storage vs. energy source

Mankind's tragical misconception of energy sources



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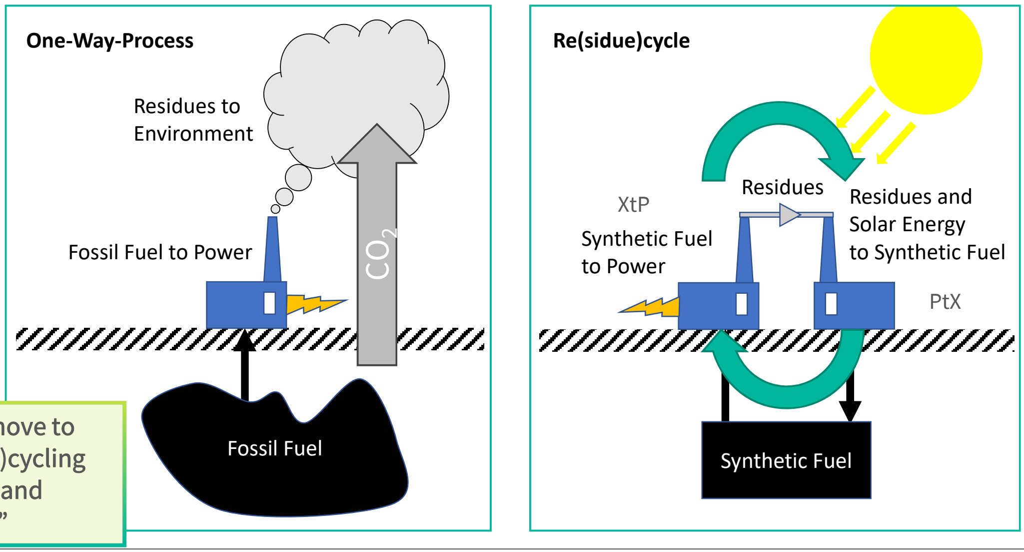
1. Energy storage vs. energy source

Carbon Cycle - Recycling energy commodities



Need to move to "Re(sidue)cycling of energy and materials"

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2. Power-to-X (PtX)

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

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2. Power to X (PtX)

What is Power to X about?

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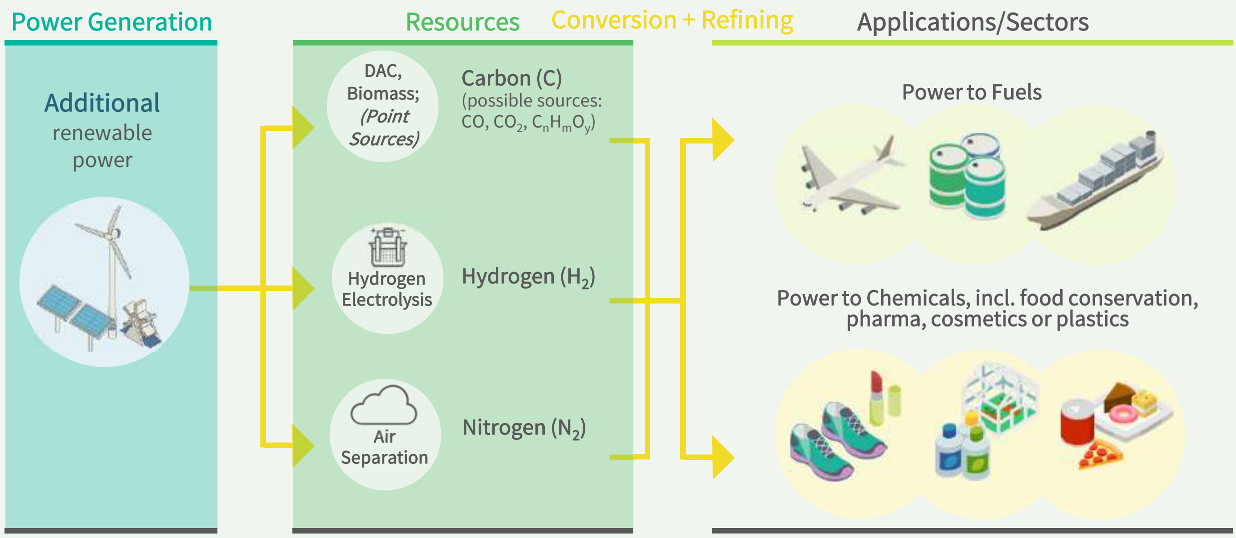
2. Power to X (PtX)

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



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

2. Power-to-X

The Concept beyond hydrogen

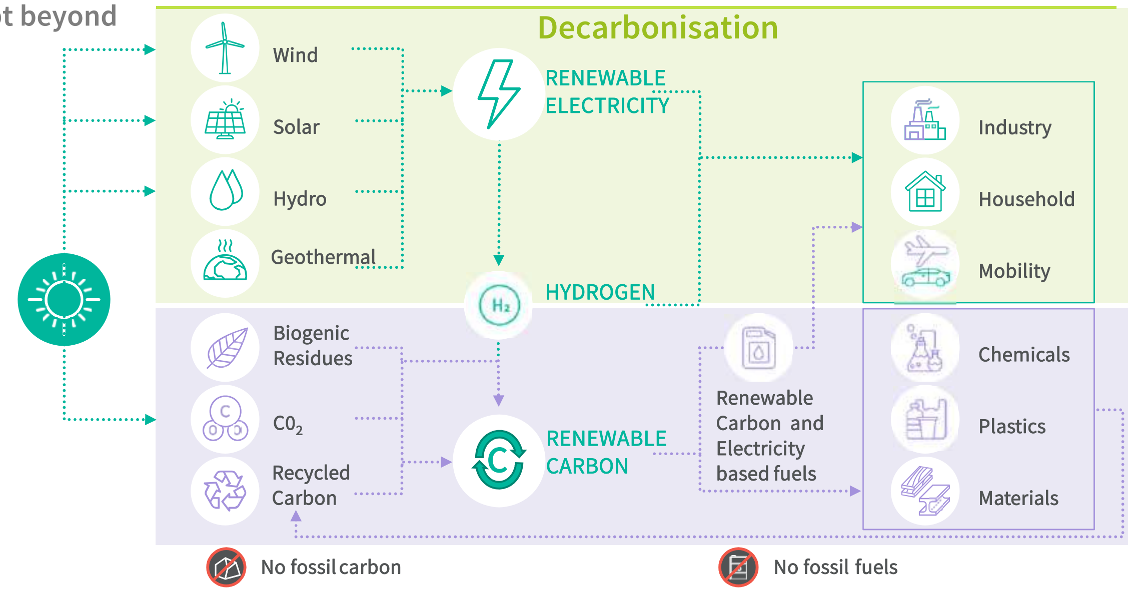


Figure: Adapted from Nova Institute (2020), *Renewable Carbon – Key to a Sustainable and Future-Oriented Chemical and Plastic Industry: Definition, strategy, measures and potential.*, p.6, fig. 2.

2. Power to X

Power to X: Facilitating defossilisation

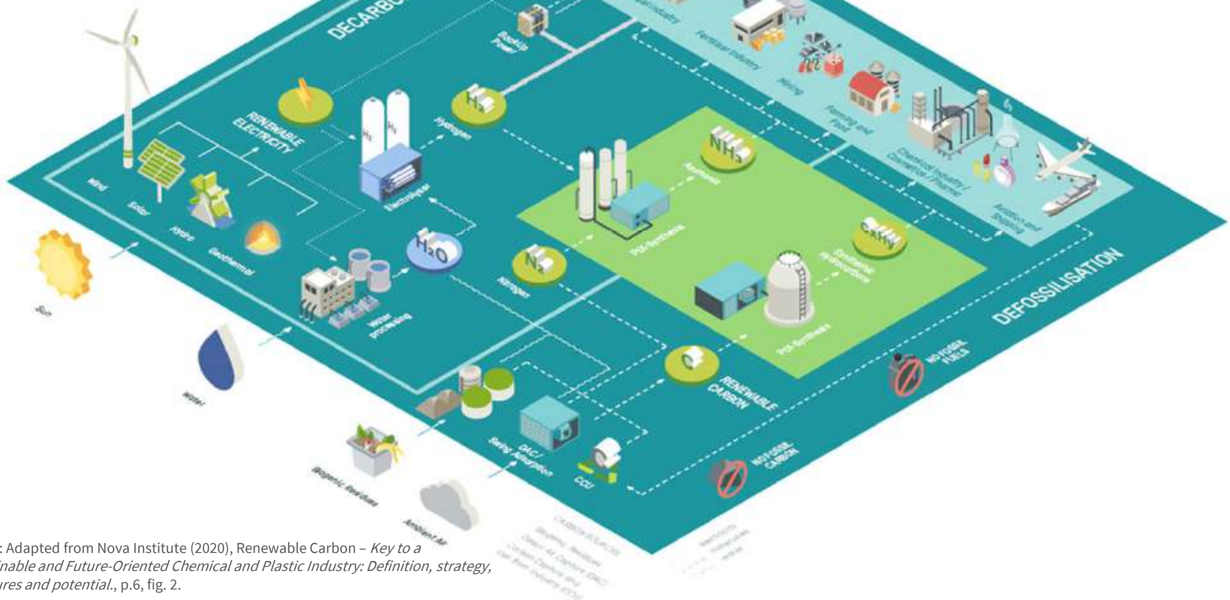


Figure: Adapted from Nova Institute (2020), Renewable Carbon – *Key to a Sustainable and Future-Oriented Chemical and Plastic Industry: Definition, strategy, measures and potential.*, p.6, fig. 2.

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2. Power to X (PtX)

What does “Sustainable Carbon” mean and why is it important?

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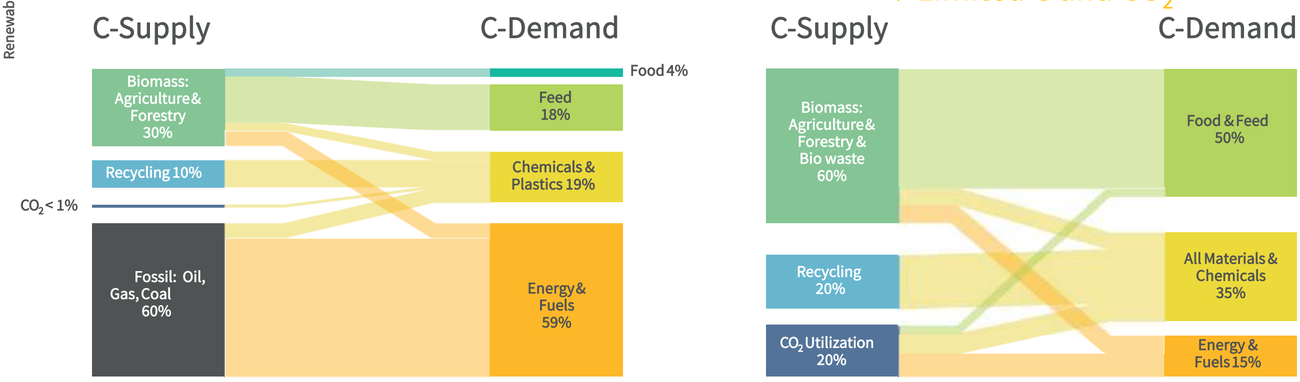
2. Power to X

Global carbon flows today and in the future – carbn will be scarce in a defossilized future

World C-flows today
Fossil mobility + fossil energy

Global C-flows 2050
electric mobility + no fossil

⇒ Limited C and CO_2



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

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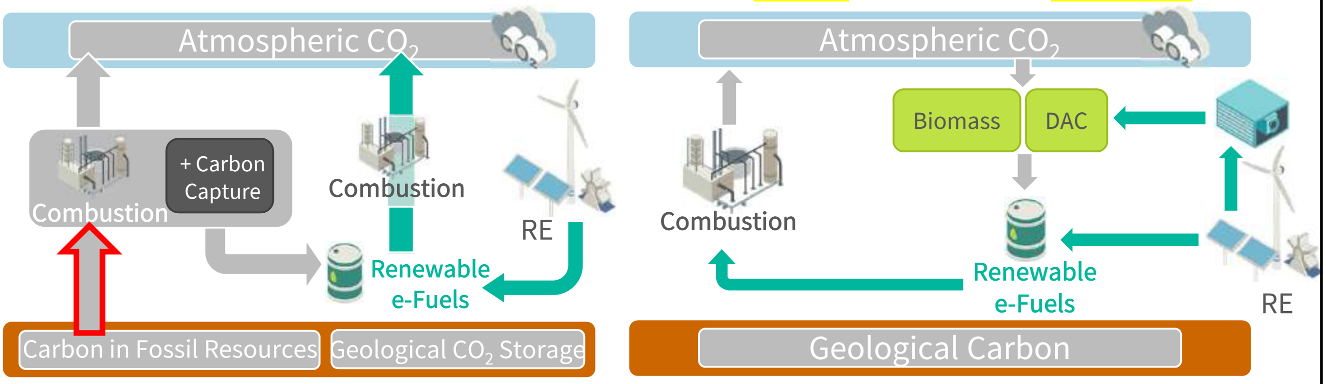
2. Power to X (PtX)

Today´s open and tomorrow´s closed carbon cycle

Open: Tapping into fossil resources

Closed: Carbon in soil remains untouched



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2. Power to X (PtX)

CO_2 capture from the air by Direct Air Capture (DAC)

Challenge CO_2 costs:

Biomass (90€/tCO_2)
Industrial emissions (30-50€/tCO_2)
Direct Air Capture (150-180€/tCO_2)

- Currently around 400 €/tCO_2

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

In some places biomass can be an option.

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Image Source: Climeworks.com

Key take-aways: 2. Power to X (PtX)

- Hydrogen is mainly an energy carrier, sustainable if based on renewable energy sources and renewable carbon, but may also be used as a feedstock
- Green hydrogen is a multi-talent
  - to provide CO2-free energy (e.g. in high temperature processes)
  - to substitute fossil-based hydrogen in industrial processes (e.g. in refineries)
  - to enable new carbon-free industrial processes **(e.g. green steel)**
  - to provide the green base material for a lot of products - PtX products
- Power to X (PtX) refers to the complex conversion from renewable electricity (power) to molecules (X) which are used as energy carriers or chemical feedstock, resembling the required knowledge from up- and downstream markets like in the oil and gas business.

3. The Paris Agreement and the Pillars of the Energy Transition towards carbon neutrality

- The Paris agreement and Paris Delta
- Efficiency and sufficiency
- Supporting pillars of the energy transition

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3. Paris Agreement and Pillars of Energy Transition

What is the Paris Agreement about and what does the Paris Delta mean?

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3. Paris Agreement and Pillars of Energy Transition

The Paris Agreement – global treaty on the way to limit global warming to 1.5°C

PARIS2015 COP21·CMP11

After the Kyoto Protocol, the Paris Agreement is oto be the global treaty to tackle global warming and climate change (currently yet under discussion)

- Limit temperature increase by greenhouse gas emissions (especially CO_2) to **1.5° Celsius**
- Reduce GHG Emissions to **Net-Zero by 2050**

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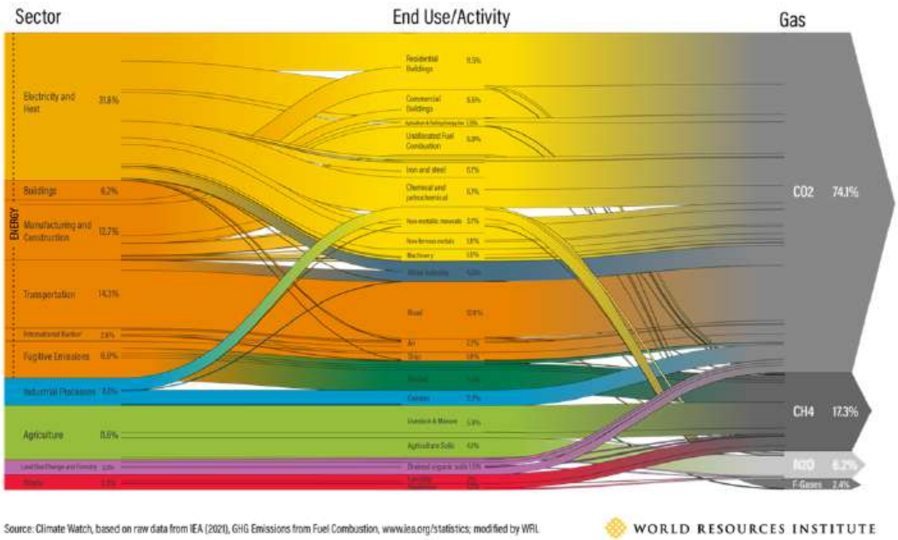
3. Paris agreement and Pillars of Energy Transition

Tackling climate change



World Greenhouse Gas emissions in 2019 (49.8 $GtCO_2e$)

Even though the energy sector (including electricity, heat/cold & transport) is contributing about 75%, other sectors also have to contribute to CO2 reductions

https://www.climatewatchdata.org/key-visualizations?visualization=3

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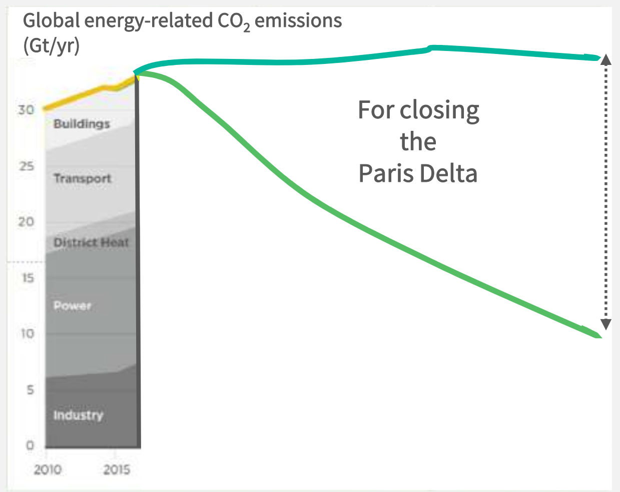
3. Paris agreement and Pillars of Energy Transition

Closing the gap of the Paris Delta

The Climate Imperative: CO_2 Neutrality by 2050



… and remaining loop-holes?

We need:

- ENERGY EFFICIENCY
- RENEWABLE ENERGY
- ELECTRIFICATION
- POWER-TO-X

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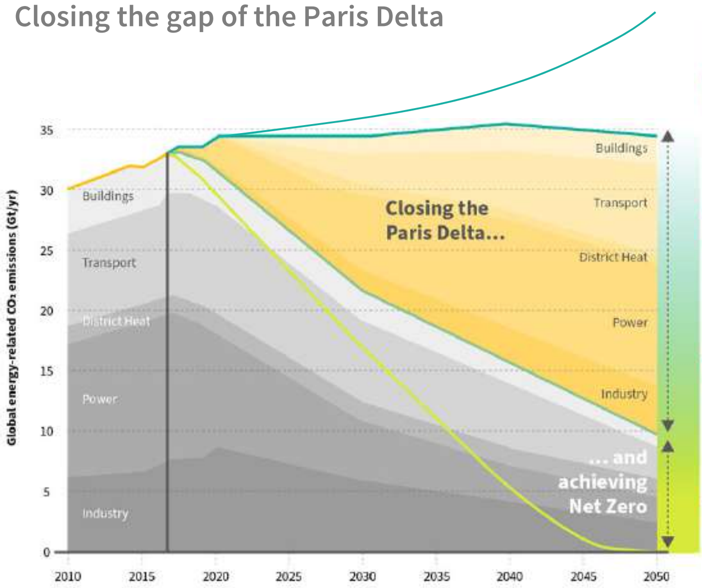
Source: International Renewable Energy Agency Hydrogen From Renewable Power Technology Outlook For The Energy Transition, 2018, p.10/1.

3. Paris agreement and Pillars of Energy Transition

Closing the gap of the Paris Delta



1 Maintaining/improving living standard while opting for **less energy intensive** approaches

2 Improving energy **efficiency** in all sectors

3 Reaching 100 % **renewable energy**

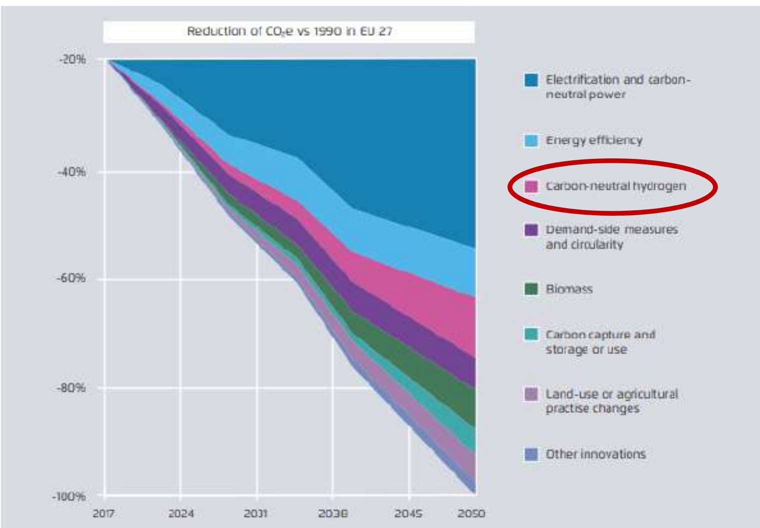
4 **Electrifying** all sectors such as heating and transport

5 **Power-to-X** for the sectors and industries that cannot directly electrify

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

3. Paris agreement and Pillars of Energy Transition

Share of GHG Abatement in the EU by Mitigation Measures



Carbon-neutral, i.e. green hydrogen is 3rd largest component in achieving carbon neutrality by 2050 in the European Union!

Figure: Agora Energiewende, Agora Industry (2021), *12 Insights on Hydrogen*, p.8, fig.1.

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3. Paris Agreement and Pillars of Energy Transition

What are the supporting pillars of the energy transition?

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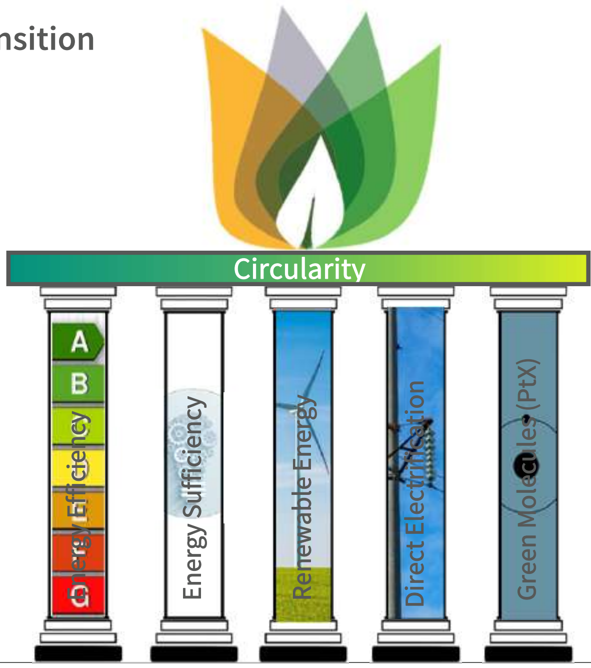
3. Paris agreement and Pillars of Energy Transition

Role of Green Molecules in Energy Transition

- Considering the total energy demand energy sufficiency and efficiency are the mandatory starting point
- To cover the rest of the demand, renewable energy and its use in further electrification of hard to abate sectors (PtX, incl. green H_2) is important
- Acceleration of the energy transition is also essential for long-term energy security, price stability and national resilience



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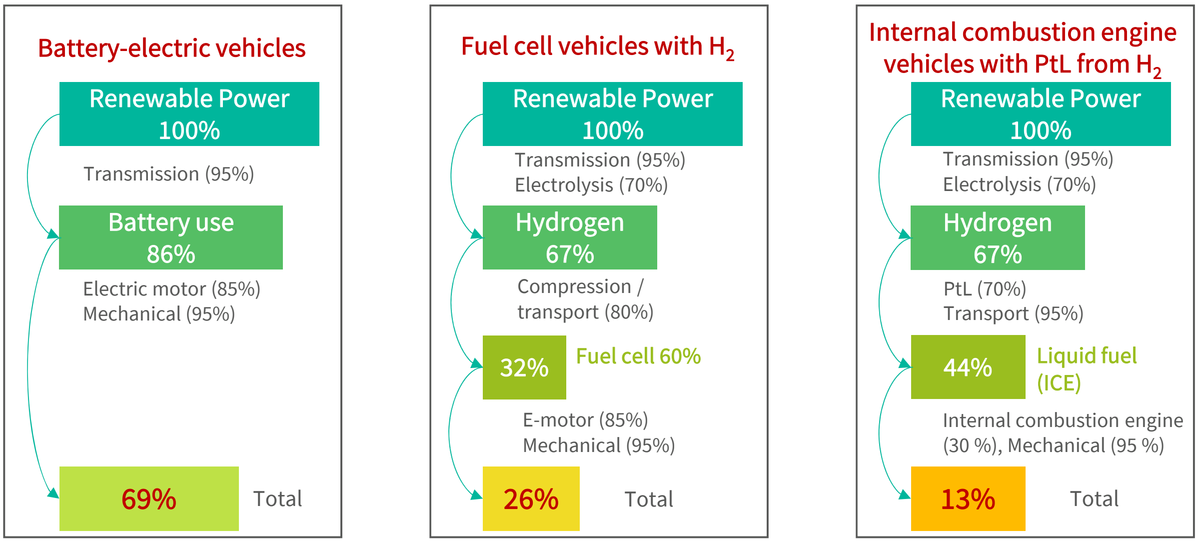
Energy Efficiency and Electrification

Energy Efficiency before Electrification of Demand - Example for mobility by cars



14 Figure: Adapted from Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018*), The Future Cost of Electricity-Based Synthetic Fuels*, p.12, fig.2.

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Key take-aways: 3. The Paris Agreement and the Pillars of the Energy Transition towards carbon neutrality

- After the Kyoto Protocol, the Paris Agreement is to be the global treaty to tackle global warming and climate change (currently yet under discussion)
  - Limit temperature increase by greenhouse gas emissions (especially CO_2) to **1.5° Celsius**
  - Reduce GHG Emissions to **Net-Zero by 2050**
- The Paris delta is the difference between today´s greenhouse gas emissions and the required net-zero in 2050 – the aim is nto just to limit but to stop greenhouse gas emissions
- To close the Paris delta, the following measures are required
  - **Energy sufficiency:** improving living standard with less **energy**
  - **Energy efficiency:** improving energy **efficiency** in all sectors
  - **Renewables:** reaching 100 % renewable energy
  - **Electrification:** electrifying all sectors such as heating and transport
  - **Power to X: use** Power-to-X for the sectors and industries that cannot directly electrify

Any questions?

4. PtX Demand Predictions

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4. PtX Demand Predictions

Which quantities of PtX porducts will be needed in the future?

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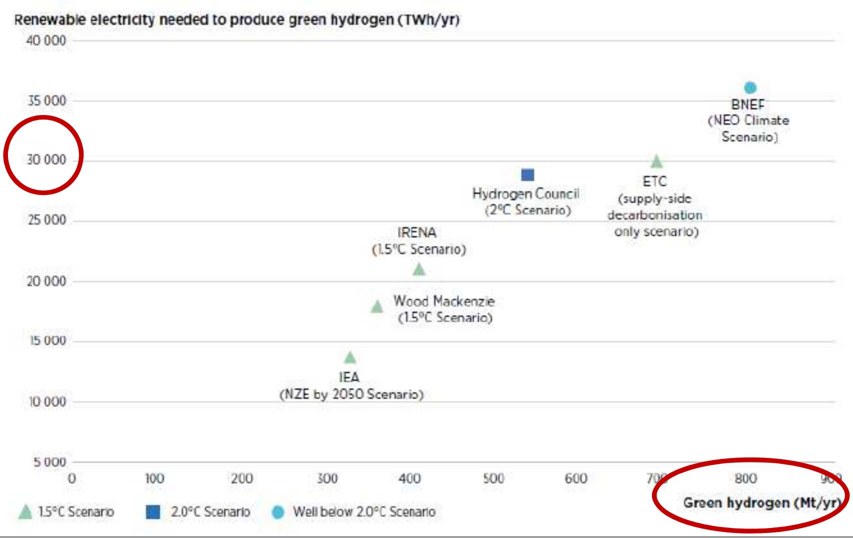
PtX Demand Predictions

Global Demand for Renewable Electricity to Produce Green Hydrogen by 2050



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

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

Note: The ETC supply-side decarbonisation only scenario is an illustrative scenario considering 2050 final energy demand without application of energy productivity levers. This scenario assumes green hydrogen will make up 85% of total hydrogen production in 2050.
Source: IEA: Global energy review 2021

18 Figure: IRENA Coalition for Action, (2021), *Decarbonising end-use sectors: Practical insights on green hydrogen*, p.11/fig.2.

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PtX Demand Predictions

Additional Renewable Energy Capacity to Cover Oil Demand by PtX (German Example)

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.

To satisfy German oil demand:

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

20 Figure: Öko-Institut e.V., (2020), *Wasserstoff und wasserstoffbasierte Energieträger und Rohstoffe*, p.64, fig.2-6.

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Any questions?

5. PtX Value Chain and Projects

5. PtX Value Chain and Projects

Steps from Renewable Energy to Feedstock/Fuel Supply

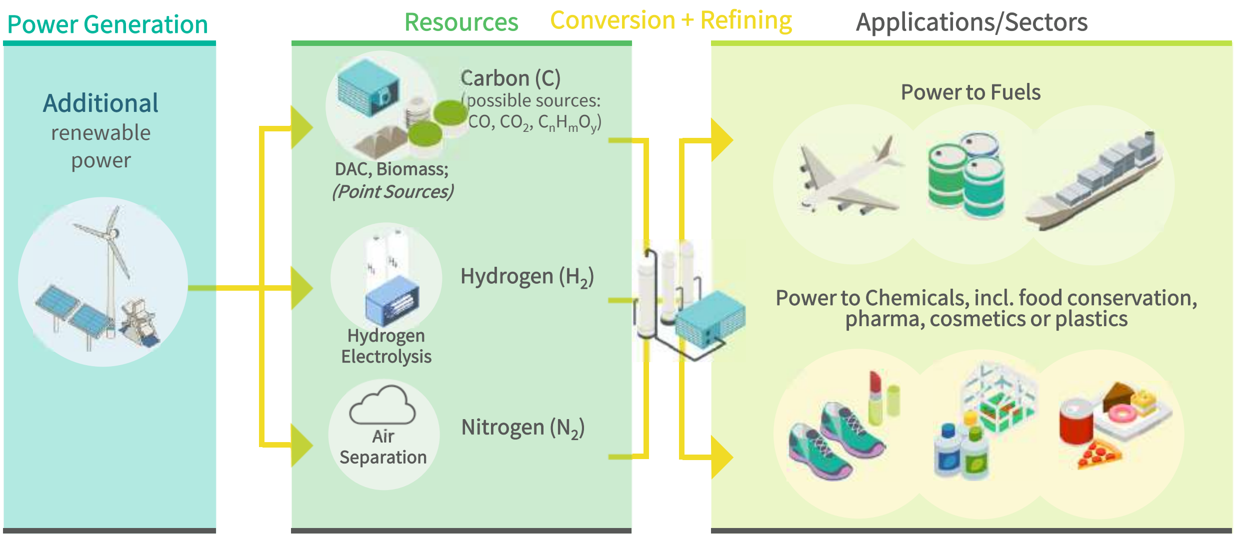

Figure: Adapted from Frontier Economics & Word Energy Council, (2018), *International aspects of a Power-to-X Roadmap,* p.15, fig.4.

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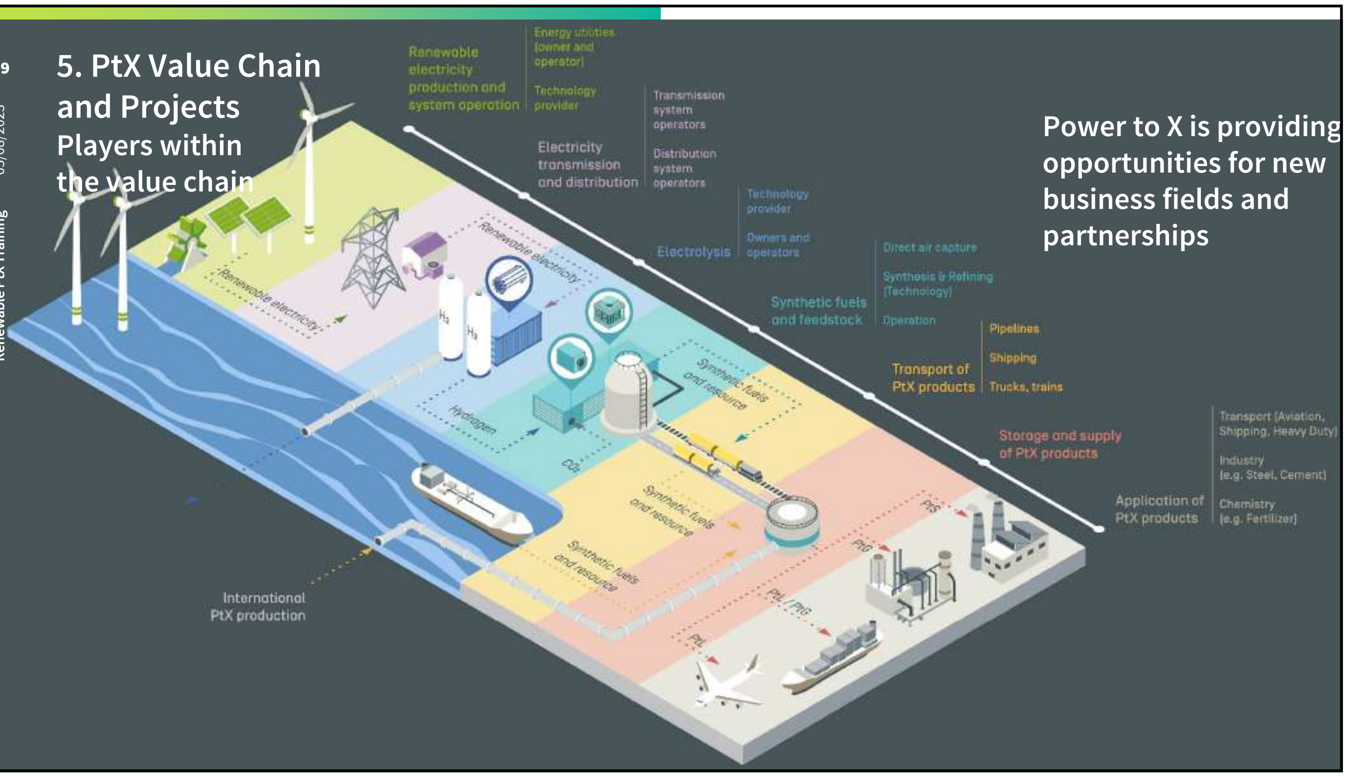
5. PtX Value Chain and Projects
Players within the value chain



Power to X is providing opportunities for new business fields and partnerships

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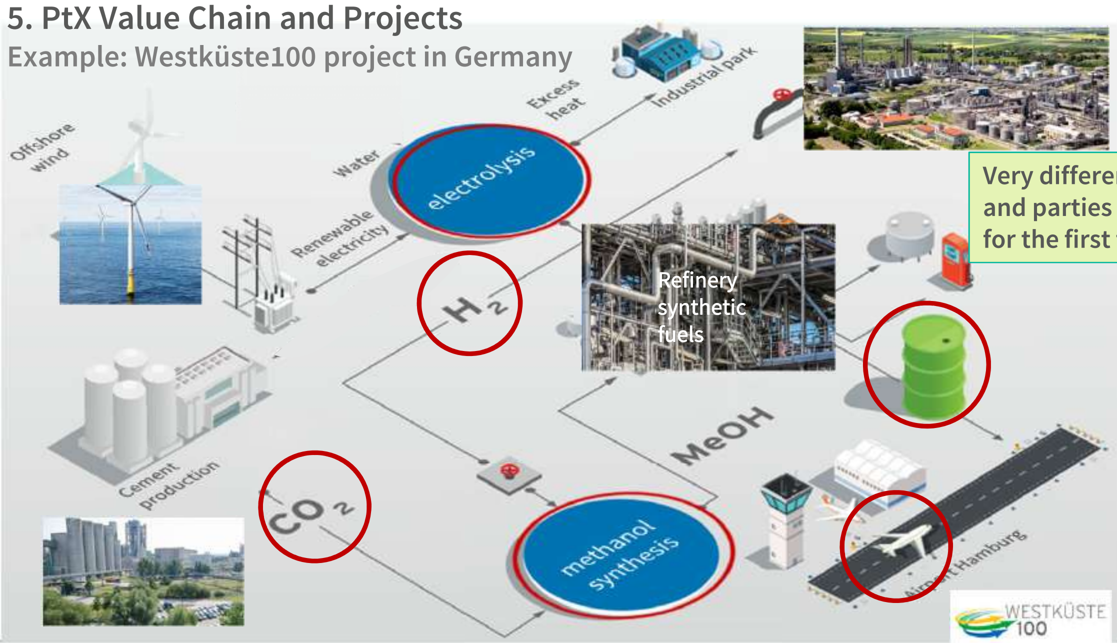
5. PtX Value Chain and Projects
Example: Westküste100 project in Germany



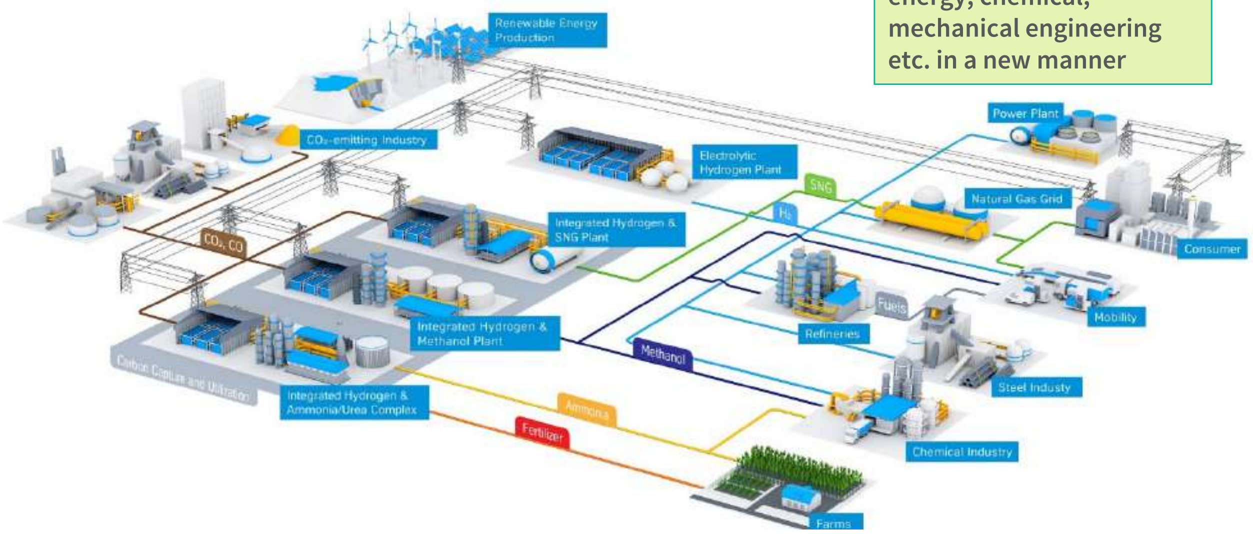
Very different companies and parties cooperating for the first time

Figure: Westküste 100, (2020), *Grüner Wasserstoff und Dekarbonisierung im industriellen Maßstab*, p.3, fig.1.

5. PtX Value Chain and Projects

Sector Coupling for green chemicals according to Thyssenkrupp

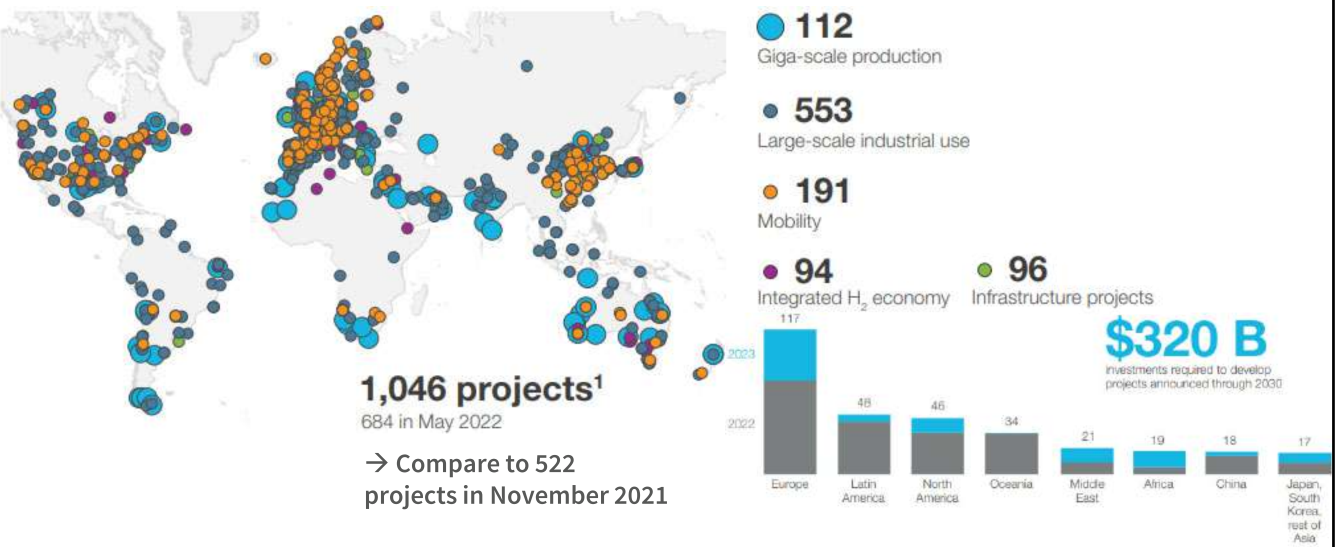
Bringing together competencies from differnt disciplines like energy, chemical, mechanical engineering etc. in a new manner



Source: Thyssenkrupp, Renewable energy integration: "Power-to-X" balances supply and demand, 2020.

5. PtX Value Chain and Projects

Global PtX Projects in 2022



→ Compare to 522 projects in November 2021

Hydrogen Council & Mac Kinsey (05/2023) Hydrogen Insights 2023, p.5/exhib.1.

[1] Projects above 1 MW

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Key take-aways: 5. PtX Value Chain and Projects

- The PtX value chain includes all partis on all steps of the value chain
  - New opportunities for new business fields and partnerships
- First PtX projects gather very differnet companies and stakeholders (e.g. municipalities) and cover a wide range of enginerring disciplines in a new manner
- The global PtX project pipeline I s growing continuously, with a steep increase from 2021 to 2022 – leaving the planning stage stepping into the realisation phase
  - First visible results to be expected soon

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Any questions?

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Conclusions

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MODULE 1: Introduction into Renewable PtX - Key Take-Aways

1. Energy Storage vs. Energy Source

- **Fossil fuels are not a source** but a **storage of energy**, being emptied by humans at very fast pace.
- **Renewables** are **energy sources.**
- **Burning fossil fuels** for winning energy is **a one-way process**!

2. Power-to-X (PtX)

- **Hydrogen is mainly an energy carrier, sustainable** if **based on renewable energy** sources and **renewable carbon.**
- PtX refers to the complex conversion from renewable electricity (power) to molecules (X) which are used as energy carriers or chemical feedstock, resembling the required knowledge from up- and downstream markets like in the oil and gas business.

3. The Paris Agreement and the Pillars of the Energy Transition towards carbon neutrality

- After the Kyoto Protocol, the Paris Agreement is to be the global treaty to limit global warming to 1.5° C
- The Paris delta is the difference between today´s greenhouse gas emissions and the required net-zero in 2050 – the aim is not just to limit but to stop greenhouse gas emissions, which requires **full decarbonisation** of energy systems and **full defossilisation** of product value chains.
- Closing the Paris delta requires the 1st energy sufficiency, 2nd energy efficiency, 3rd reaching 100 % renewable energy, 4th electrifying all sectors such as heating and transport and 5th Power-to-X for sectors and industries that cannot directly electrify
- Since renewable electricity is still a constraint, **hardest to abate sectors should be first to apply PtX.**
- Overall **PtX efficiency** is **low**, but **it's the only way to defossilise fully**

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MODULE 1: Introduction into Renewable PtX - Key Take-Aways

4. PtX Demand Predictions

- There is a very **high demand of additional renewable power** if we want to change from conventional oil and gas consumption to synthetic fuels → Behavioural changes and modal shifts are required as well as shifting demand to electrification of energy services.

5. PtX Value Chain and Projects

- The PtX value chain includes all partis on all steps of the value chain
  - New opportunities for new business fields and partnerships
- First PtX projects gather very differnet companies and stakeholders (e.g. municipalities) and cover a wide range of enginerring disciplines in a new manner
- The global PtX project pipeline I s growing continuously, with a steep increase from 2021 to 2022 – leaving the planning stage stepping into the realisation phase
  - First visible results to be expected soon

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Test your knowledge

"Where do you see opportunities for PtX in your country?"

"What are the biggest challenges on the way?"

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A
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Hydrogen
Electrolyse
Chemicals
Geothermal
Synthese
RENEWABLE CARBON
DEFOSSILISATION
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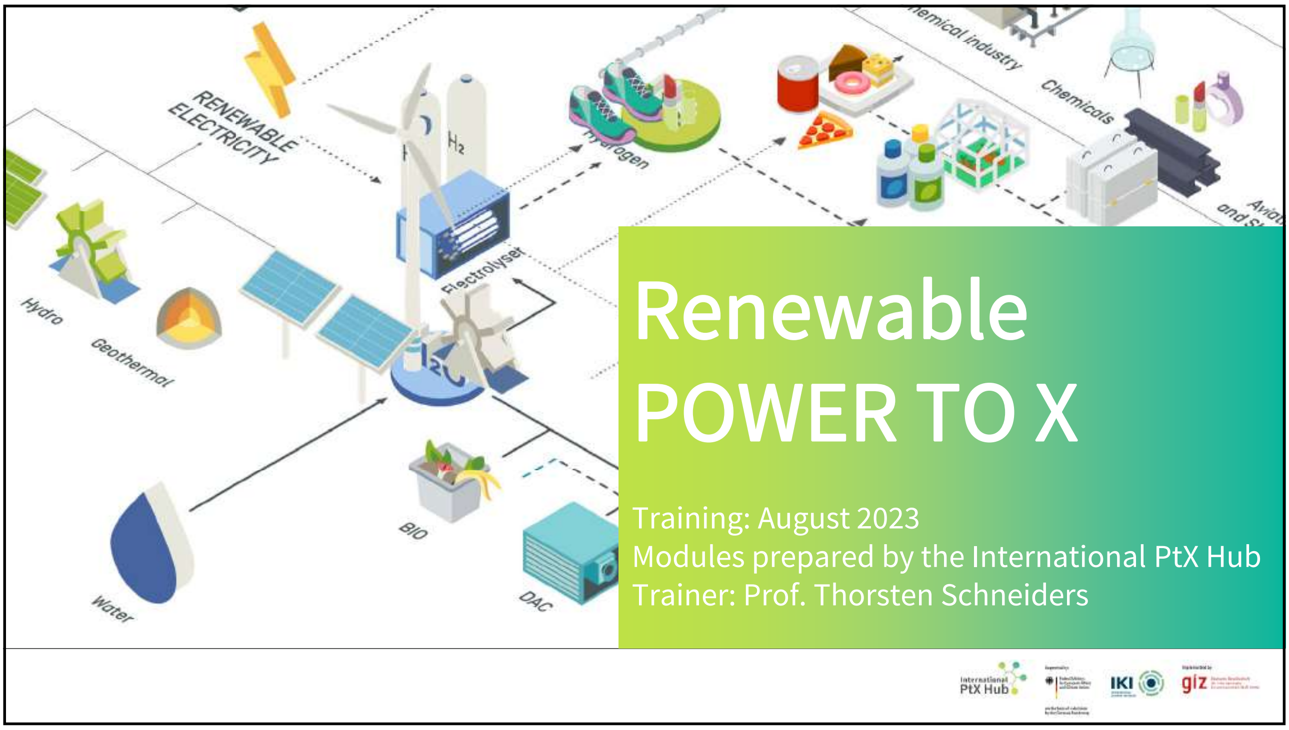
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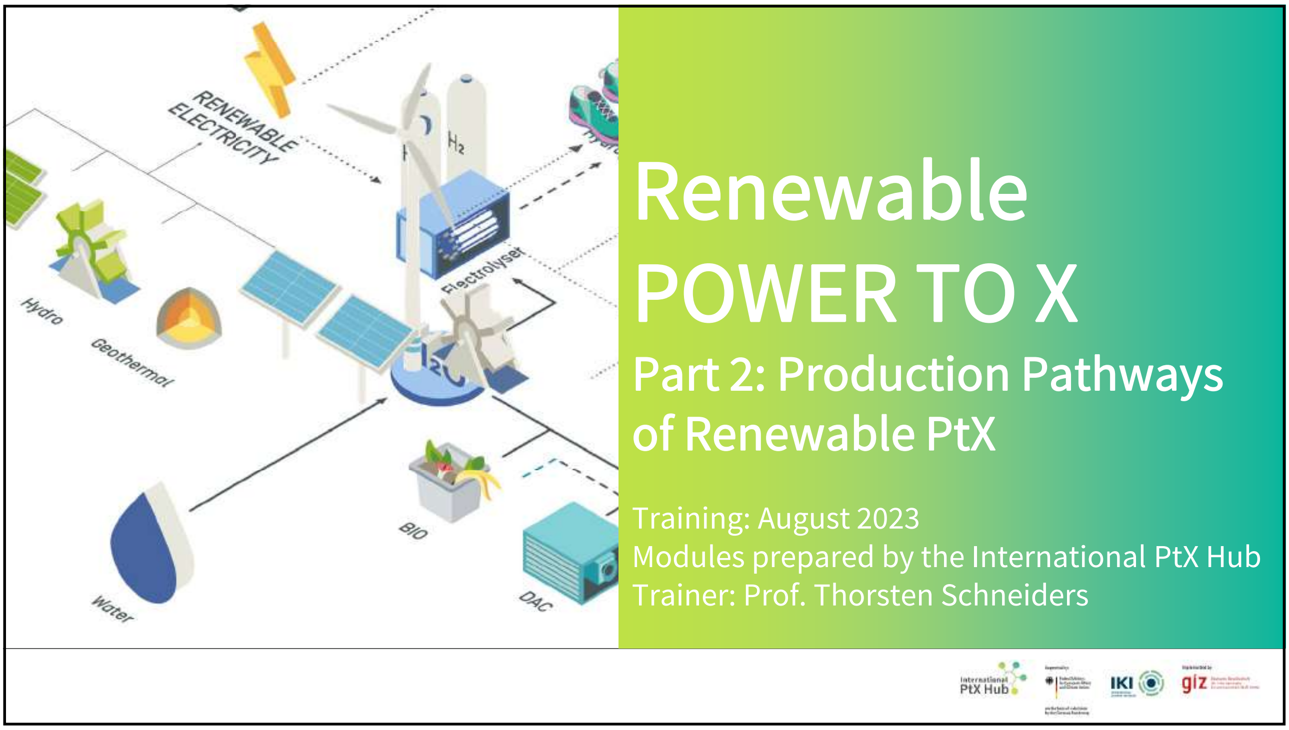
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Agenda

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

2 **Production Pathways of Renewable PtX**
What is needed for PtX, incl. green hydrogen

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

4 **PtX Infrastructure**
How to transport and store PtX products (incl. gH_2) best?

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

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

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

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List of abbreviations

CAPEX: Capital cost expenditures
CCfD: Carbon contracts for difference
CCS: Carbon Capture and Storage
DAC: Direct Air Capture
FLH: Full-load hours
GW: Gigawatt
HVDC: High voltage, direct current
LCOE: Levelised cost of electricity
LOHC: Liquid organic hydrogen carrier
LHV: Lower heat value

- **OPEX:** Operating cost expenditures
- **PEM:** Proton Exchange Membrane
- **PtX / PtL / PtG:** Power-to-X / -Liquid / -Gas
- **PV:** Photovoltaic
- **RE:** Renewable Energy/ies
- **RES:** Renewable Energy System(s)
- **RWGS:** Reverse Water Gas Shift Reaction
- **SMR:** Steam methane reforming
- **SOEC:** Solid Oxide Electrolyser Cell
- **TWh:** Terawatt hours
- **WACC:** Weighted average cost of capital

Key Conversion Data

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

Conversion kWh and kg H_2:

- 1 kg H_2 = 33.3 kWh H_2 *(heat unit Hu /calorific value)*
- 1 MWh H_2 = 30 t H_2
- 1 Mio t H_2 = 33 TWh H_2

Monetary value per weight or calorific value

- 4.5 ct/kWh H_2 = 45 €/MWh H_2 = 1.5 €/kg H_2
  or: 1€/kg H_2 = 3 ct/kWh H_2
- 100 €/MWh H_2 = 3.33 €/kg H_2
  or: 1€/kg H_2 = 30 €/MWh H_2

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Module 2

Production Pathways of Renewable PtX

1. Options for Hydrogen Production
   - Colours of H2 (blue vs. green) and its applications
   - Ways of producing H2

2.1 PTX Production Step 1: Electrolysis
- Alkaline Electrolyser (AEL)
- Proton-Exchange-Membrane Electrolyser (PEM)
- Solid Oxide Electrolysis Cell (SOEC)

2.2 PtX Production Step 2: Carbon Sourcing
- Sustainable carbon sources
- Direct-Air-Capture (DAC)

2.3 PtX Production Step 3: PtX Production Processes and Products
- Methanation process: syngas
- Fischer-Tropsch synthesis: synthetic crude
- Methanol process: olefins
- Haber Bosch process: green ammonia

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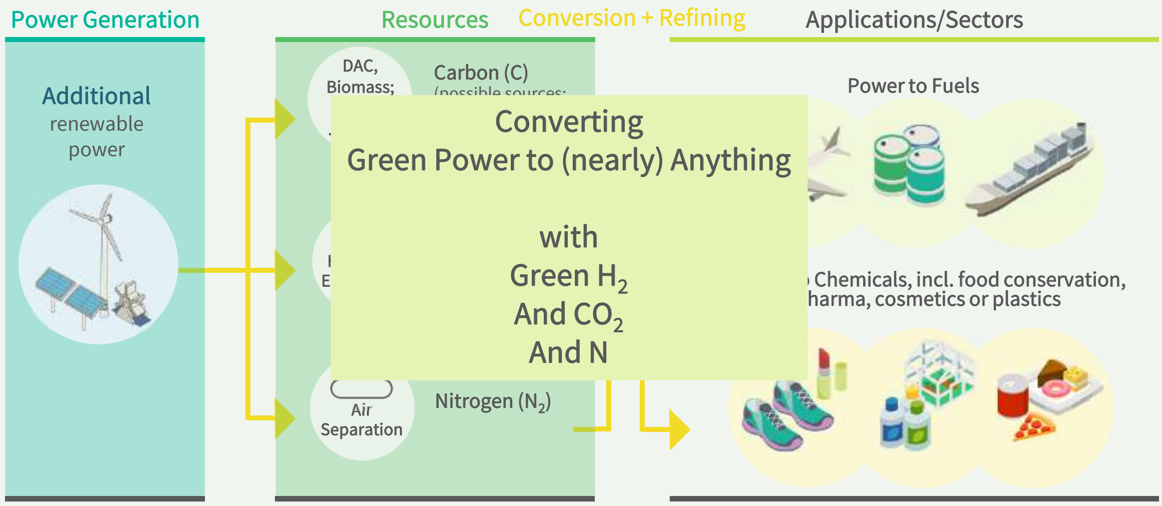
Test your knowledge

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

"Which colours of hydrogen do you consider sustainable?"

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



Converting
Green Power to (nearly) Anything

with
Green H_2
And CO_2
And N

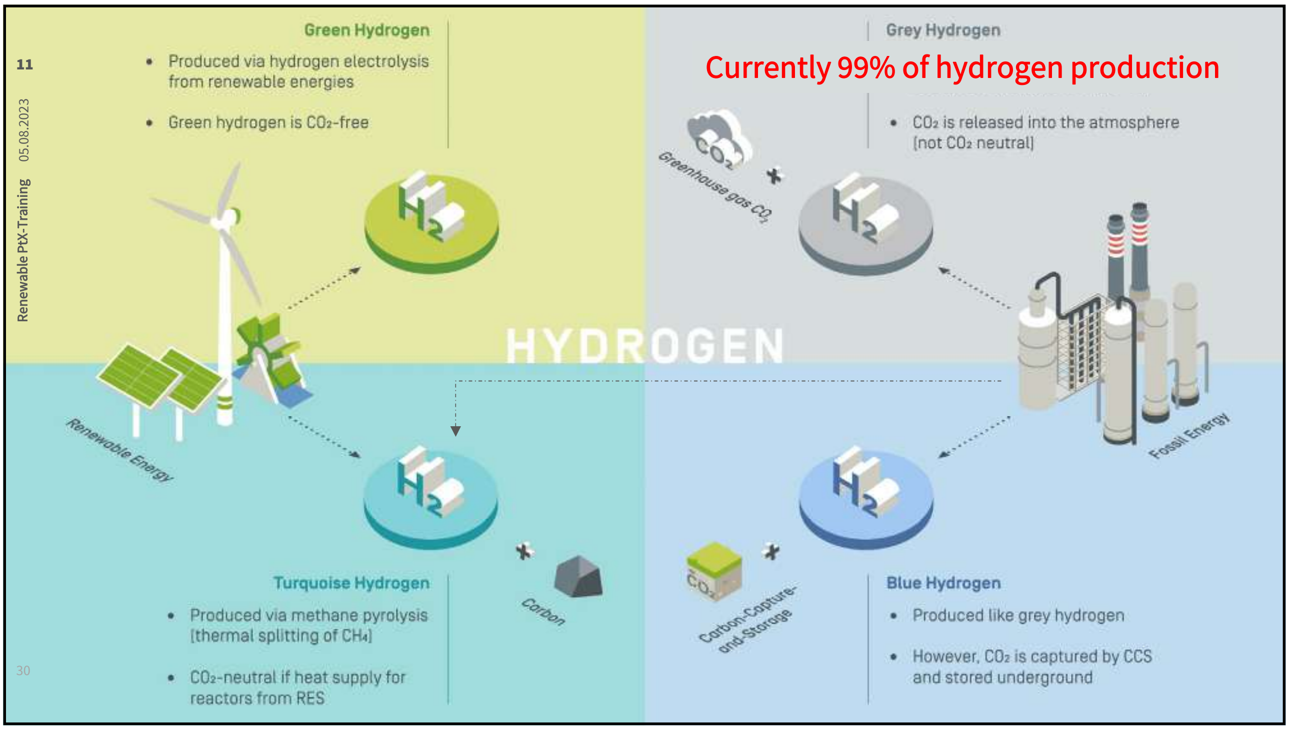
Source: Own illustration based on: Frontier Economics/Word Energy Council, International aspects of a Power-to-X Roadmap, 2018, p.15/4.

1. Options for Hydrogen Production

- Colours of H2 (blue vs. green) and its applications
- Ways of producing H2

1. Options for Hydrogen Production

Are there different types of hydrogen?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Green Hydrogen
Produced via hydrogen electrolysis from renewable energies
Green hydrogen is CO2-free
Grey Hydrogen
Currently 99% of hydrogen production
CO2 is released into the atmosphere (not CO2 neutral)
Greenhouse gas CO2
HYDROGEN
Renewable Energy
Fossil Energy
Carbon
Carbon-Capture-and-Storage
Turquoise Hydrogen
Produced via methane pyrolysis (thermal splitting of CH4)
CO2-neutral if heat supply for reactors from RES
Blue Hydrogen
Produced like grey hydrogen
However, CO2 is captured by CCS and stored underground
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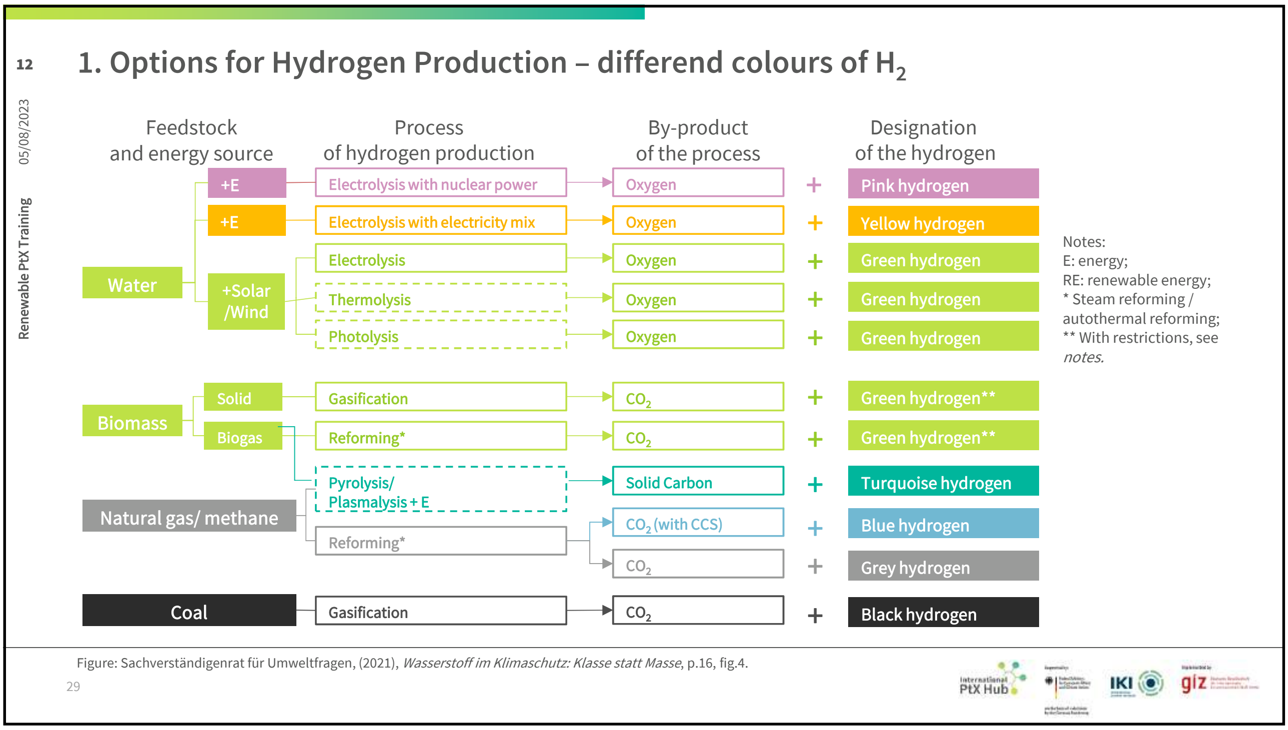
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1. Options for Hydrogen Production – differend colours of H2
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Feedstock and energy source
Process of hydrogen production
By-product of the process
Designation of the hydrogen
Water
+E
+E
+Solar /Wind
Electrolysis with nuclear power
Electrolysis with electricity mix
Electrolysis
Thermolysis
Photolysis
Oxygen
Pink hydrogen
Yellow hydrogen
Green hydrogen
Biomass
Solid
Biogas
Gasification
Reforming*
CO2
Green hydrogen**
Natural gas/ methane
Pyrolysis/ Plasmalysis + E
Solid Carbon
Turquoise hydrogen
CO2 (with CCS)
Blue hydrogen
Grey hydrogen
Coal
Black hydrogen
Notes:
E: energy;
RE: renewable energy;
* Steam reforming / autothermal reforming;
** With restrictions, see notes.
Figure: Sachverständigenrat für Umweltfragen, (2021), Wasserstoff im Klimaschutz: Klasse statt Masse, p.16, fig.4.
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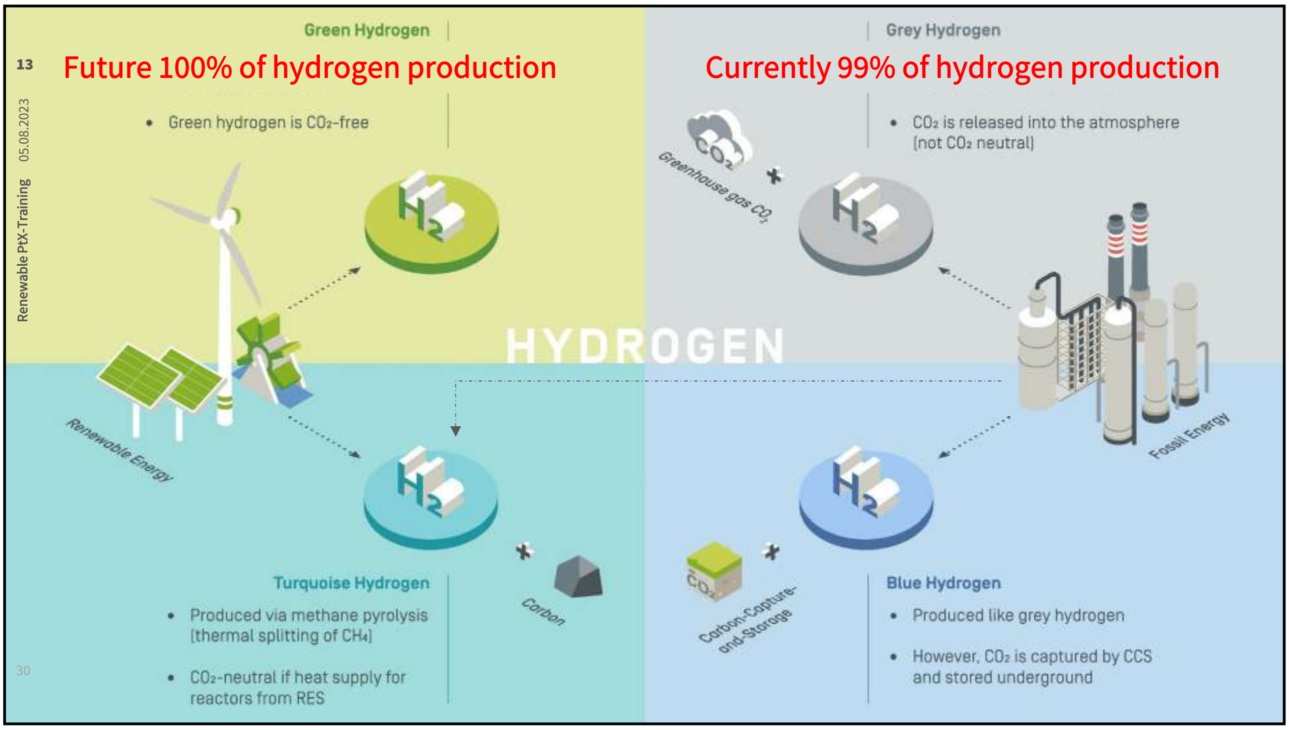

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1. Options for Hydrogen Production

Are there different types of hydrogen?

No, hydrogen is always the same chemical element, but the „hydrogen color“ refers to its origin from fossil sourcs or renewable energy

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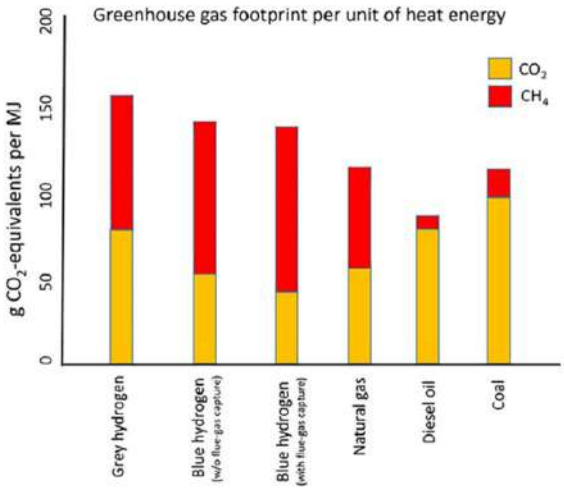
1. Options for Hydrogen Production - How Green is Blue Hydrogen?

Lifecycle GHG Emission Analysis of Blue H_2 Compared to Natural Gas, Diesel and Coal



CO_2 and fugitive CH_4 emissions for **blue H_2** (gas leakage) can be **higher than** those from **natural gas!**
→ **Blue H_2 is only 10% better than grey H_2!**

Clean blue H_2 depends on reliable audit and constant checking of obedience to regulations!

31 Figure: Howarth, R. W., & Jacobson, M.Z., (2021), *How green is blue hydrogen?*, p.8, fig.1.

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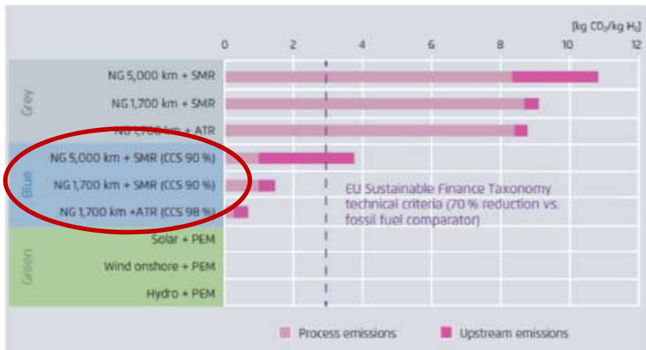
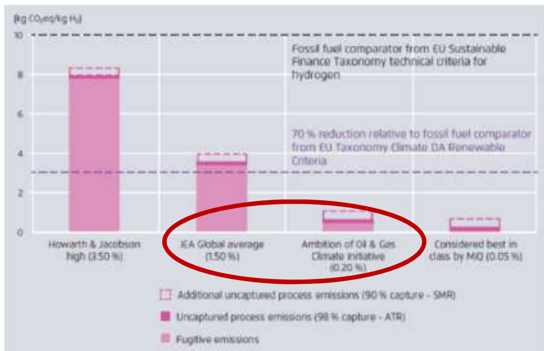
1. Options for Hydrogen Production - Lifecycle GHG Emissions of Hydrogen

Using Blue Hydrogen Requires Substantial Reduction of Methane Leakage

Lifecycle GHG emissions of hydrogen production pathways
On a GWP 20 basis, 2050



Total GHG emissions on a GWP 20 basis from fossil-based hydrogen with CCS
Methane leakage as percentage of consumed gas in brackets



32 Left Figure: Agora Energiewende, Agora Industry, (2021), *12 Insights on Hydrogen*, p.43, fig.26.
Right Figure: : Agora Energiewende, Agora Industry, (2021), *12 Insights on Hydrogen*, p.44, fig. 27.

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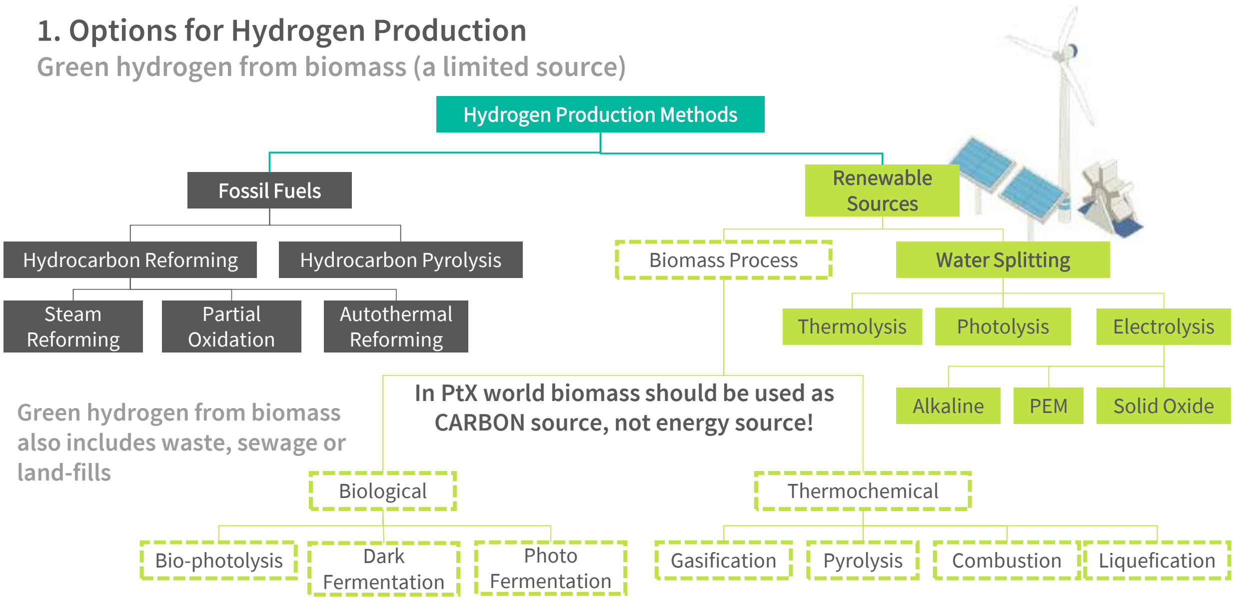
1. Options for Hydrogen Production

Green hydrogen from biomass (a limited source)



33 Figure: Kumar, S. S., & Himabindu, V. (2019). *Hydrogen production by PEM water electrolysis–A review*, p.443, fig.1.

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Key take-aways: 1. Options for Hydrogen Production

- There are **various ways of producing** H_2, often expressed by the colour of hydrogen
  - **Grey hydrogen** is today´s main hydrogen source (99%) from fossil fuels
  - **Blue hydrogen** combines grey hydrogen with Carbon Capture and Storage
  - **Green Hydrogen** is produced vie electrolysis of green electricity or from biomass
- **Emissions for blue H2 can be higher than those from natural gas**, methane leakage and corruption-proof audits must be considered!
- For a **defossilised future** we need the 3 elements from sustainable sources: **C, N2, H2.**
- **Hydrogen plays a central role** and is the element which **contains the reactive energy** for production pathways that can **replace fossil fuels across many sectors .**

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Any questions?

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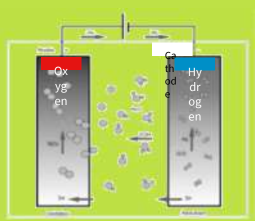

2.1 PTX Production Step 1: Electrolysis

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

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How does an electrolyzer work and are there different types of elecrolyzers?

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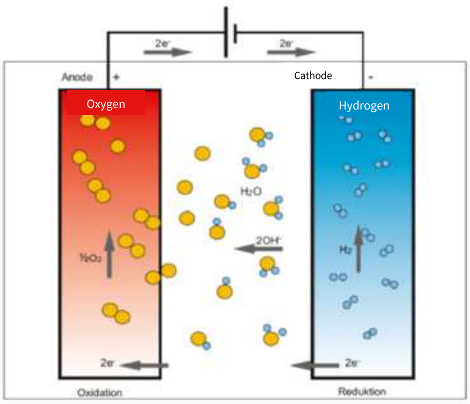
2.1 Electrolysis

Basic Functioning of an Electrolyser

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



Due to **different types of electrolyte material** used and the **ionic species it conducts, different electrolysers** function differently:

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

34 Left Figure: Schmidt, T., (2020), *Wasserstofftechnik*, p.257.
Right Image: PtX Hub, (2022), *Green hydrogen production is underway: Visiting ENERTRAG in the Uckermark, Germany.*

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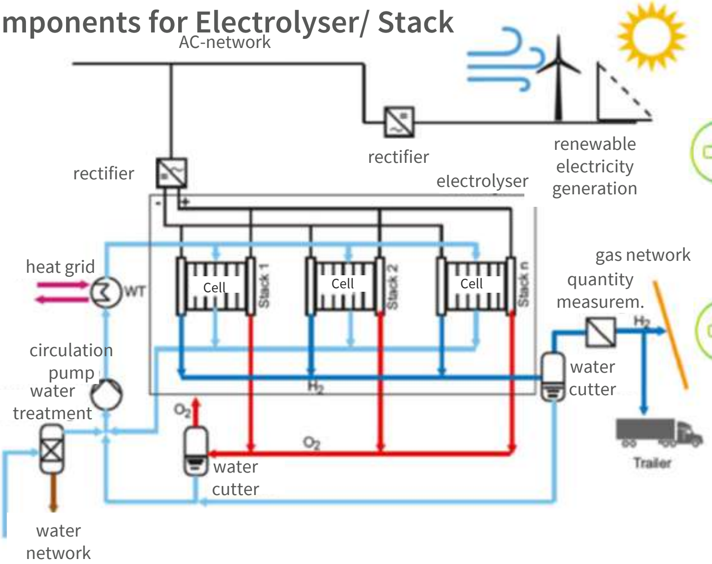
2.1 Electrolysis
Balance of Components for Electrolyser/ Stack



Stacks alone don't work, a broader structure is needed

Eletrolyser stacks size is limited, but easy scaling and shared infrastructure

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

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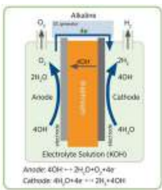
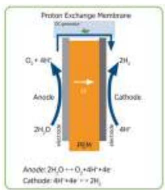
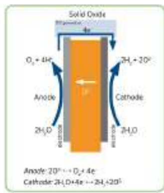
2.1 Electrolysis
Key Parameters of Different Electrolyser Technologies

		Alkaline	PEM (Proton-Exchange-Membran)	SOEC (Solid Oxide Electrolysis Cell)
Technological maturity (TRL - Technology Readiness Level, 1-9)		TRL = 9[4] (mature process)	TRL = 6-8[4] (industrial scale commercially available)[1]	TRL = 4-6[4] (so far only pilot plants)[1]
Investments (€ /kWel)[1,3,5]	Current	500-1,500	900-1,850	2,200-6,500
	Long-term	200-700	200-900	270-1,000
Process temperature[2] (°C)		50-80	50-80	700-1.000
Cold start time		approx. 50 minutes	approx. 15 minutes	Several hours
Efficiency in %	Current	63-70[3]; 62-82[5]	56-60[3]; 65-82[5]	74-81[3]; 65-85[5]
	Long-term	70-80[3]; 78-84[5]	67-74[3]; 75-84[5]	77-90[3]; 87-95[5]
Voltage Efficiency		62-82%	67-82%	< 110%
Stack Lifetime		20.000-90.000 h	60.000-90.000 h	< 10.000 h
Operating Pressure		approx. 30 bar	< 50 bar	approx. 1 bar
Disadvantages of the process[1]		In partial-load operation the gas purity, degradation problems occur[1]	Demand for rare metals (iridium and platinum)[1,4]	Technology more suited to high number of full load hours (FLH) suitable; high process temperature
Advantages of the process[1]		Long service life of electrolysers; process requires practically no critical raw materials	High purity of the product even in partial and overload operation	Process suitable for coupling with industrial processes (waste heat utilisation)

Table: Adapted from Sachverständigenrat für Umweltfragen, (2021), *Wasserstoff im Klimaschutz: Klasse statt Masse*, p.17, tab.4.

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2.1 Electrolysis
Alkaline Electrolysis

The reaction occurs **between two electrodes in a solution** composed of **water and liquid electrolyte**.

1. Water electrolysis deals with **decomposition of H_2O into H_2 and O_2** by passing an electric current (DC) between two electrodes separated by an **aqueous electrolyte** with high ionic conductivity.
2. Transport of hydroxide ions (OH^-) through the electrolyte from cathode to anode → H_2 generated on cathode side.
3. $H_2O \rightarrow H_2 + \frac{1}{2} O_2$

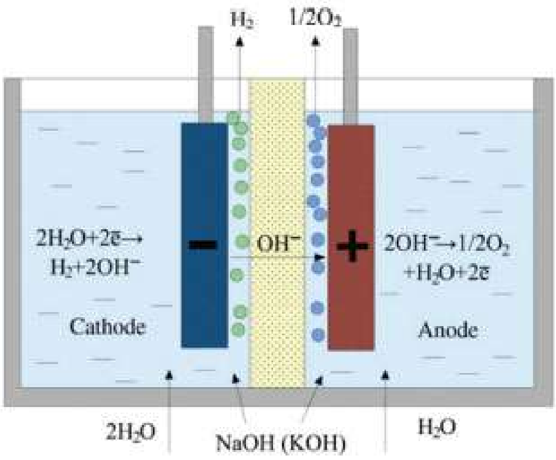

Figure: Kamrudin, M. F. A., Sabli, N., & Abdullah, T.A.T., (2018), *Hydrogen Production by Membrane Water Splitting Technologies*, p.30, fig.4.

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2.1 Electrolysis
Alkaline Electrolysis)

Lurgi AEL, 760 Nm^3/h at 30 bars

- Electrical energy: 4.3 – 4.65 kWh/Nm^3 H_2
- Feedwater: 0.85 l/Nm^3 H_2, Cooling water: 80 l/Nm^3 H_2
- Coomonöly used technolog y in industry for chlorine production
- Originally large-scale and 24/7 operations
- Now downscaling and modification to more flexible operation required

Source: Lurgi

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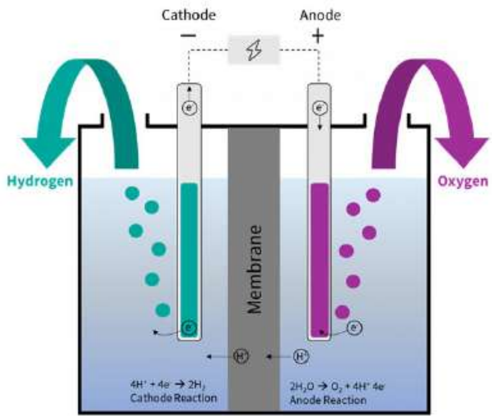
2.1 Electrolysis

Proton-Exchange-Membran Electrolysis (PEM)

The **solid polymer electrolyte** that conducts proton ion is **sandwiched between two electrodes** to construct a membrane electrode assembly (MEA).

1. H_2O reacts at the **anode** to form O_2 **and positively charged hydrogen ions** (protons) $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$.
2. Electrons flow through an external circuit and **hydrogen ions selectively move across the** PEM **to the cathode.**
3. At the **cathode, hydrogen ions combine with electrons** from external circuit to **form hydrogen gas:** $4H^+ + 4e^- \rightarrow 2H_2$.



PEM technology replaces the liquid electrolyte (as in Alkaline) by a solid polymer electrolyte, which selectively conducts positive ions such as protons!

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Figure: International PtX Hub, (2021), *Water electrolysis explained – the basis for most Power-to-X processes.*

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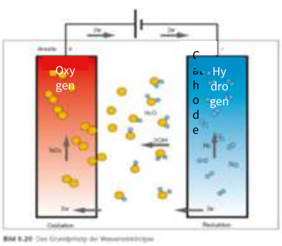
2.1 Electrolysis

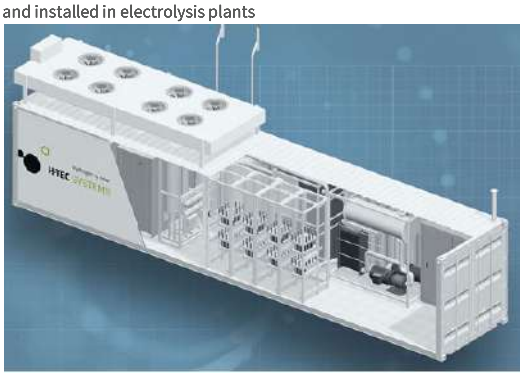
How does an electrolyser system look like (example PEM electolyzer)?

Individual PEM electrolytic cells...



are combined into PEM stacks...

and installed in electrolysis plants



Electrolyzer systems can be set up **modularly, scaleable in size via the size and number of stacks**
A PEM system container can provide up to 2 MW of power

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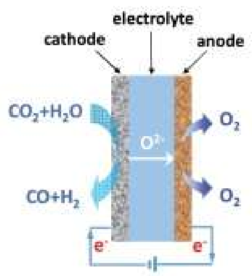
2.1 Electrolysis

Solid-Oxide-Electrolyser-Cell (High Temperature Co-Electrolysis of CO_2 and Steam in SOEC)

1. **Steam** at the cathode **combines with electrons** from external circuit **to form H_2 gas** and **negatively charged oxygen ions.**
2. **Thermal energy** (in addition to electrical energy supplied) is then used to **split gasses** → electrolysis products and unreacted feed gasses then **flow outwards through the cathode.**
3. **Oxygen ions** pass through solid **ceramic membrane** and **react at anode** to **form O_2 gas and generate electrons** for the external circuit.



Cathode: $CO_2(g) + 2e^- \rightarrow CO(g) + O^{2-}$

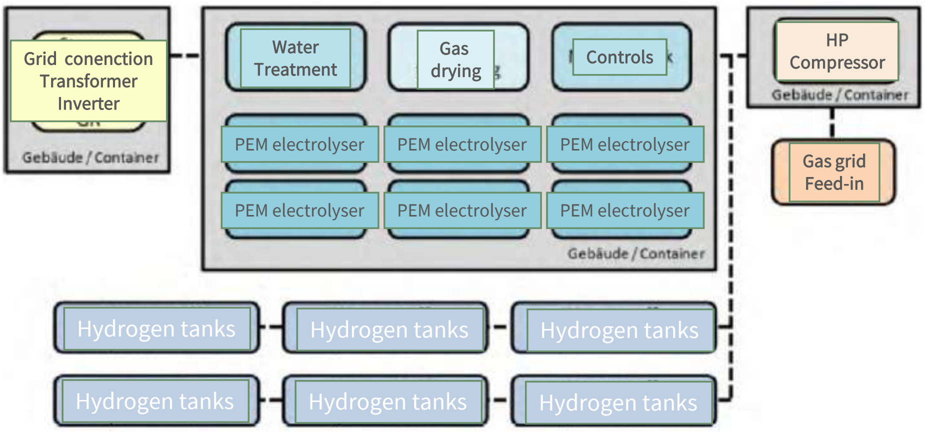
$H_2O(g) + 2e^- \rightarrow H_2(g) + O^{2-}$

Anode: $2O^{2-} \rightarrow O_2(g) + 4e^-$

Electrolysis at high temperatures requires less electrical energy, but requires heat-resistant tubing and hardware (no steel possible above 650°C) – technology is still at R&D stage

Figure: Journal of Energy Chemistry, (2027), *Co-electrolysis of CO_2 and H_2O in high-temperature solid oxide electrolysis cells: Recent advance in cathodes*, p.839-853.

More than just electrolysis: PtG plant with H_2 feed-in



- In addition to the electrolyser stacks, electrolysis plant includes water treatment, H_2 treatment and H_2 storage.
- For feeding H_2 into the gas grid, the required pressure level is important, e.g. transport grid with 70 bar requires H_2 compression (with cooling)

[Source: DVGW] 30

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Key take-aways: 2.1 PTX Production Step 1: Electrolysis

- Eletrolyser technologies all work with the electrical splitting of water into hydrogen and oxygen, but differ in properties, size, flexibility and costs
- Alkaline-Exchange-Membrane (AEM) have been used since 100 years in chemical industry
  - Adopted to constant 24/7 operations and large-scale installations, they now have to adopt to more flexible operations and smaller sizes
- Proton-Exchange-Membrane (PEM) have undergone strong development since 2010
  - Originally used for lab –scale production, they are now commonly used due to their flexibility and scaleability
- As a new technology to combine the best characterstics of AEL and PEM, Alcaline Electrolysis with Membrane (AEM) is under development
- Solid-Oxide-Electrolyser-Cell (SOEC) are working at high temperatures around 1,000°C
  - Higher efficiency, but tough requirements on heat-resistant materials,
  - Technology is still at the R&D stage
  - Applicable only in combination with solar-thermal or industrial heat source

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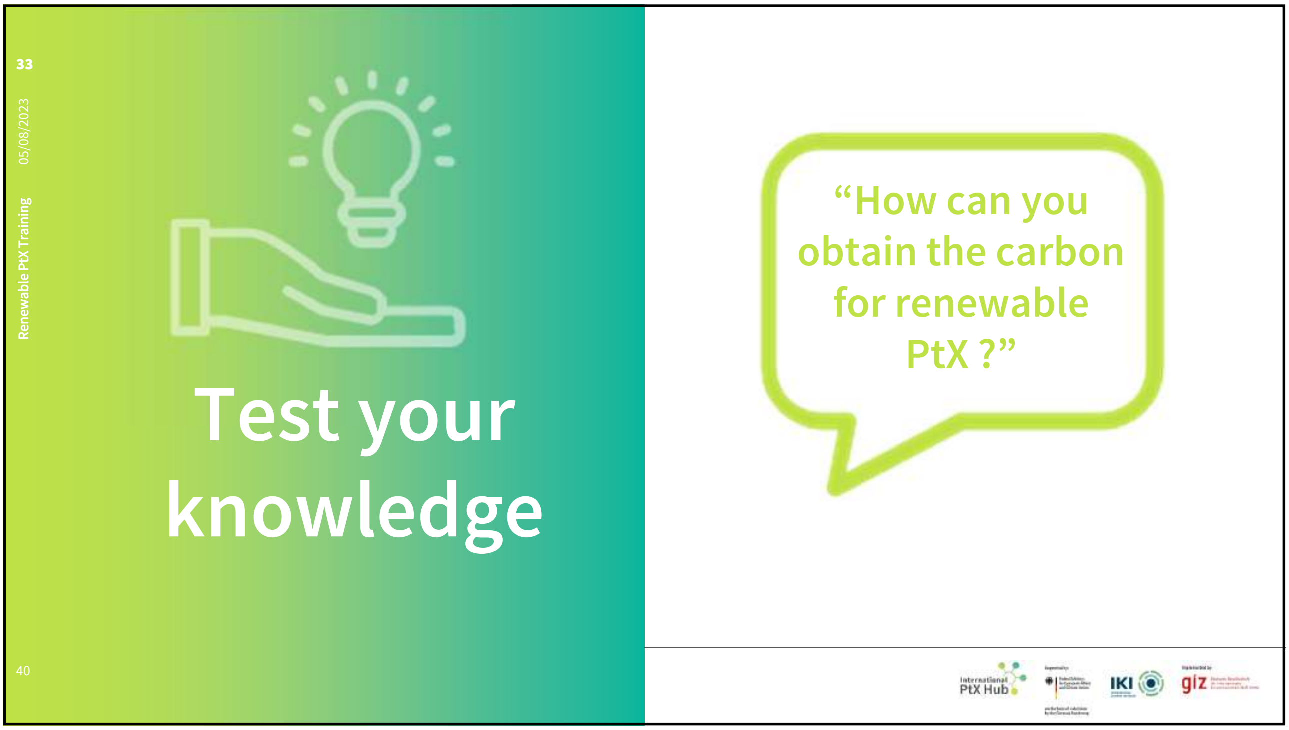
Any questions?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Test your knowledge
“How can you obtain the carbon for renewable PtX ?”
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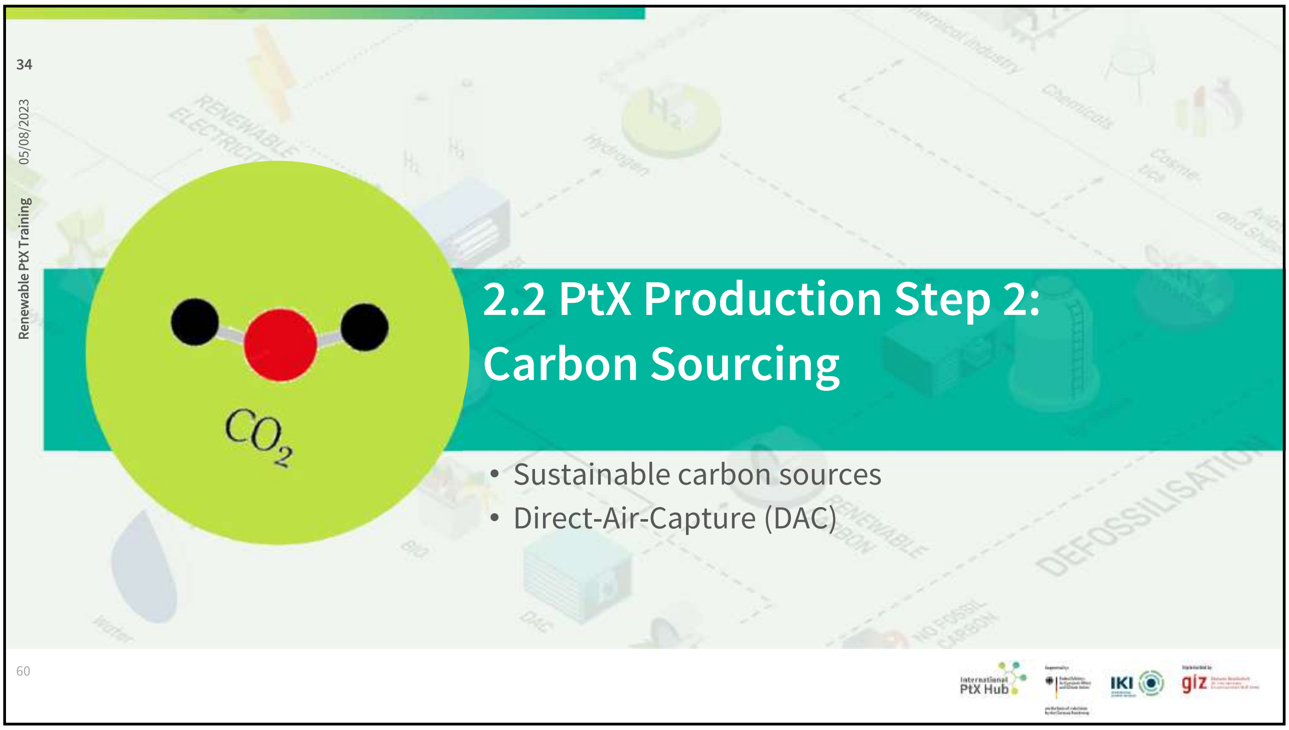
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CO2
2.2 PtX Production Step 2: Carbon Sourcing
• Sustainable carbon sources
• Direct-Air-Capture (DAC)
DEFOSSILISATION
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2.2 PtX Production Step 2: Carbon Sourcing

How can we source the needed CO_2?

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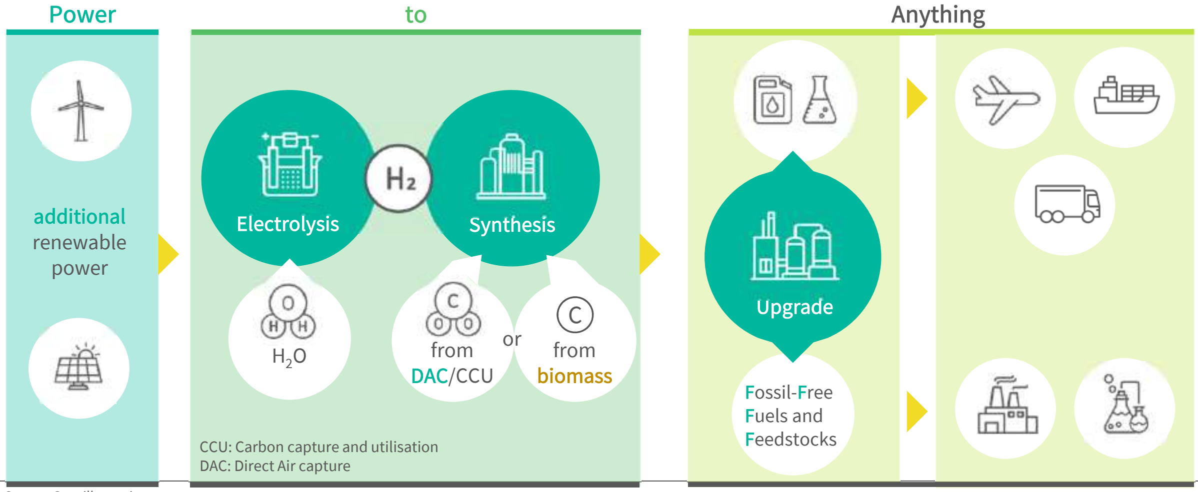
2. Carbon Sourcing
How to produce PtX products?
We need as well **SUSTAINABLE CARBON**

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



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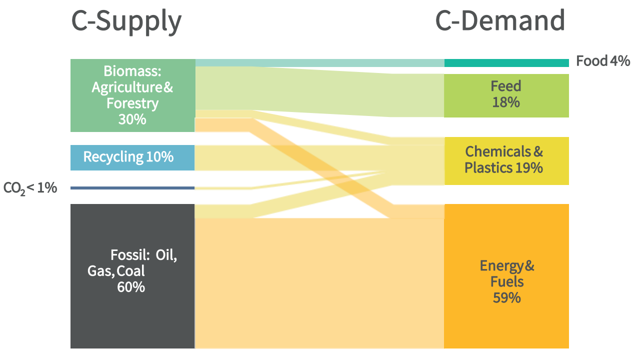
Source: Own illustration

2. Carbon Sourcing

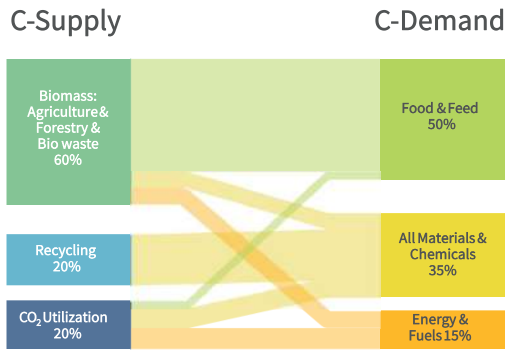
World C-flows will change and carbon will become rare in a defossilized future

World C-flows today
Fossil mobility + fossil energy



Global C-flows 2050
electric mobility + no fossil

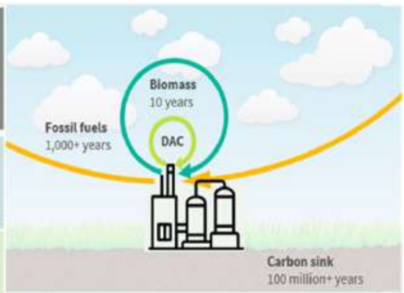
⇒ Limited C and CO_2

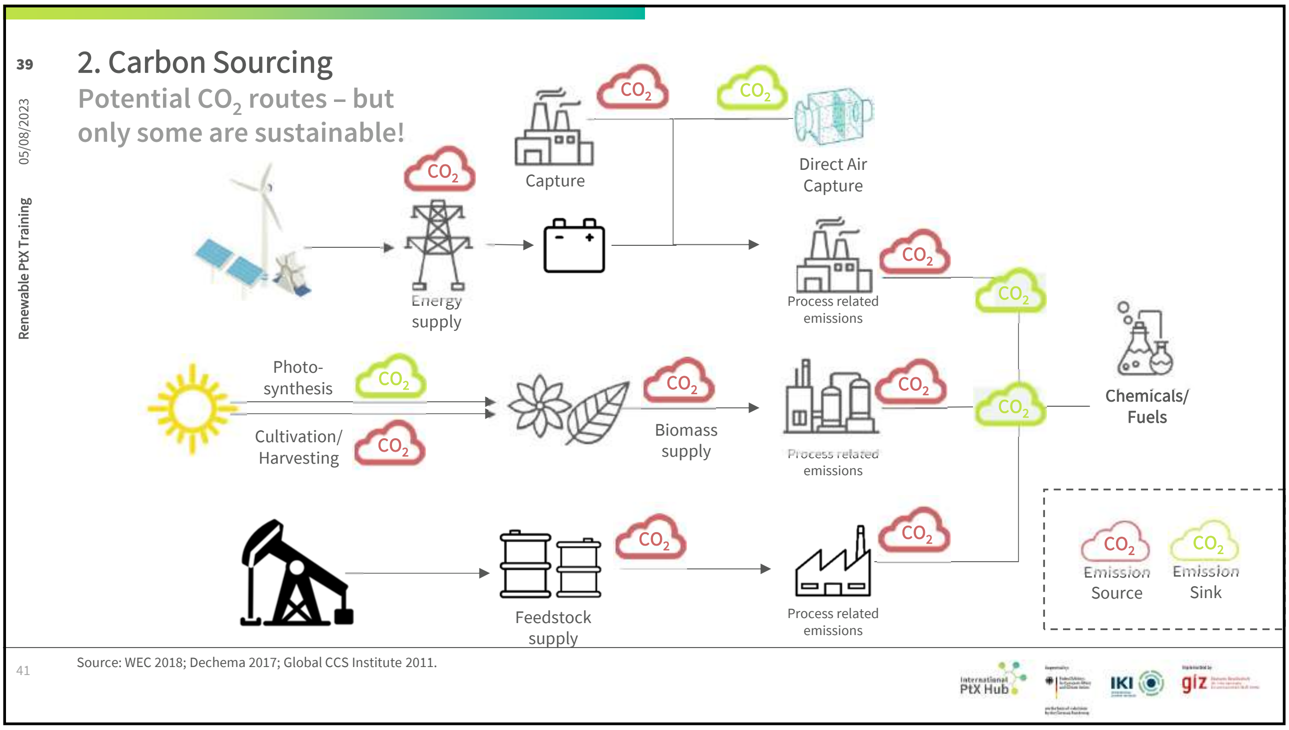


Based on nova-Institut 2020 (nova-Paper #12 on renewable carbon 2020-09)

The Carbon Cycle

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

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2. Carbon Sourcing
Potential CO_2 routes – but only some are sustainable!
Capture
Direct Air Capture
Energy supply
Process related emissions
Photo-synthesis
Cultivation/ Harvesting
Biomass supply
Process related emissions
Chemicals/ Fuels
Feedstock supply
Process related emissions
Emission Source
Emission Sink
Source: WEC 2018; Dechema 2017; Global CCS Institute 2011.
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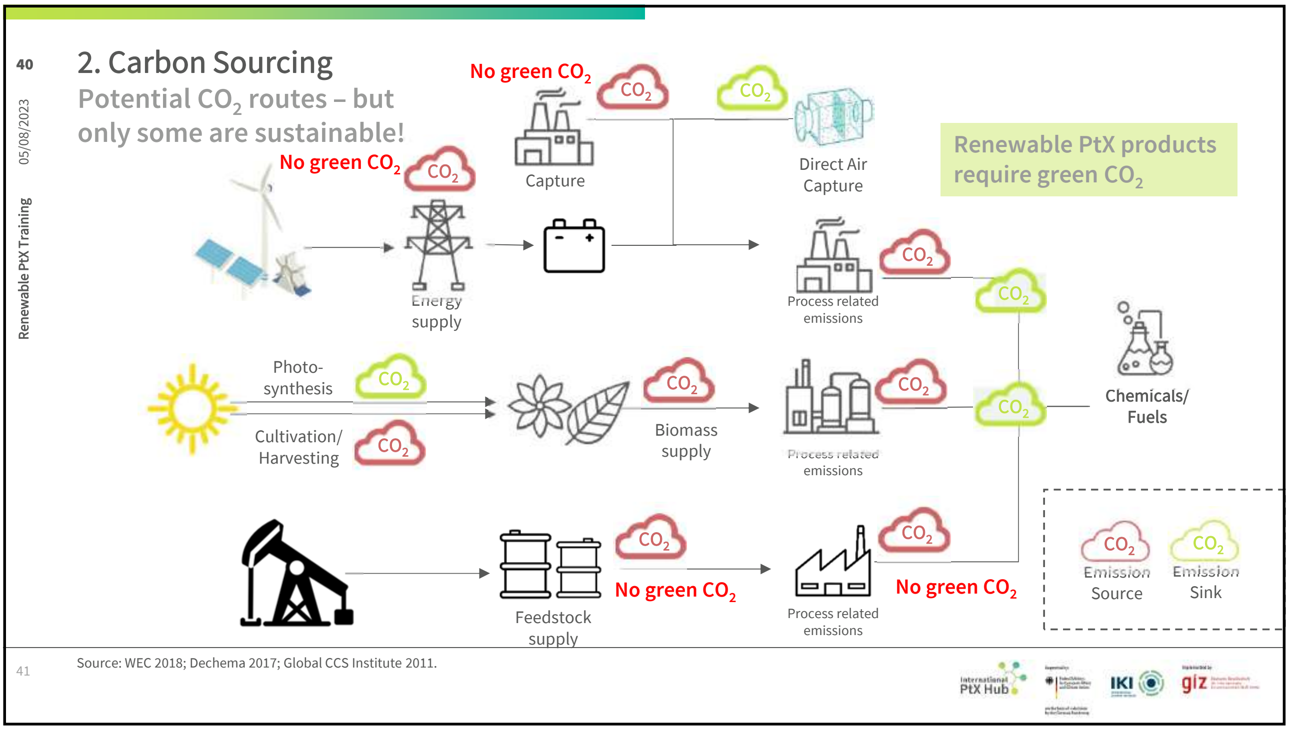
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2. Carbon Sourcing
Potential CO_2 routes – but only some are sustainable!
No green CO_2
No green CO_2
Capture
Direct Air Capture
Renewable PtX products require green CO_2
Energy supply
Process related emissions
Photo-synthesis
Cultivation/ Harvesting
Biomass supply
Process related emissions
Chemicals/ Fuels
Feedstock supply
No green CO_2
Process related emissions
No green CO_2
Emission Source
Emission Sink
Source: WEC 2018; Dechema 2017; Global CCS Institute 2011.
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2.2 Carbon Sourcing

Direct Air Capture (DAC) – collecting CO_2 from the ambient air

Challenge of CO_2 costs:

- CO_2 from biomass (90€/tCO_2)
- Industrial CO_2 emissions (30-50€/tCO_2)
- CO_2 from Direct Air Capture (150-180€/tCO_2) Currently around 400 €/tCO_2

- Direct Air Capture is the one always available and sustainable CO_2 source.
- In some places biomass can be an option.

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First image: Climeworks.com
Second image: Climeworks.com

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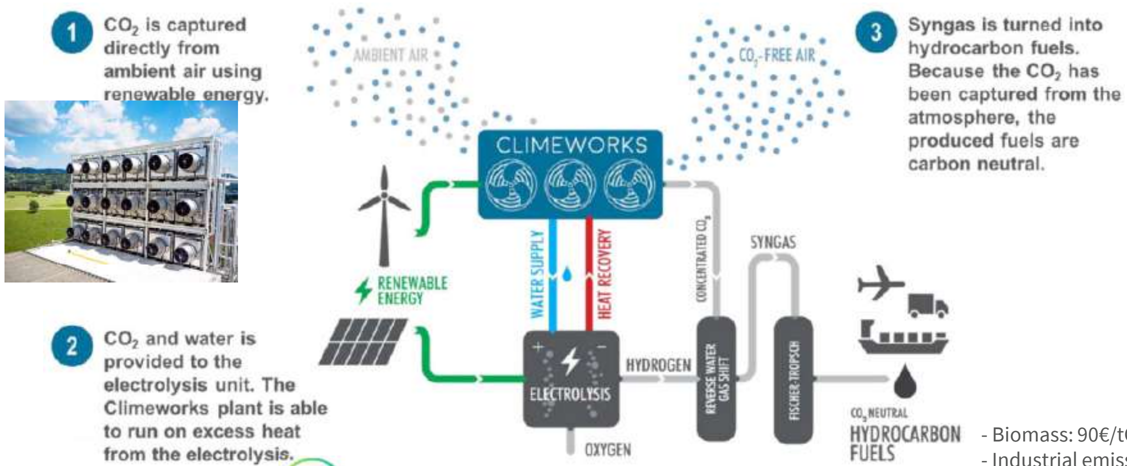
2. Carbon Sourcing

How CO_2 capture by Direct Air Capture (DAC) works



- Biomass: 90€/tCO_2
- Industrial emissions: 30-50€/tCO_2
- DAC: 150-180€/tCO_2 Currently approx. 400 €/tCO_2

DAC is always available + a sustainable CO_2 source!
In some places biomass can be an option
Challenge: Cost for DAC

Source: Beuttler C, Charles L and, Wurzbacher J (2019) The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions. Front. Clim, p.5/fig.5.

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Key take-aways: 2.2 PtX Production Step 2: Carbon Sourcing

- CO_2 is an important feedstock for PtX products and should be produced or collected on-site
- Some industrial processes (e.g. steel, cement) release CO_2 in large amounts and high concentrations, but these do not count as green CO_2
- So far, green CO_2 is produced by gas-washing biogas for biomethane production
- Direct Air Capture allows to filter CO2 out of the ambient air, but this requires high technical efforts due to the low concentration of CO_2 in the ambient air

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Any questions?

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PtX

2.3 PtX Production Step 3: PtX Production Processes and Products

- Methanation process: syngas
- Fischer-Tropsch synthesis: synthetic crude
- Methanol process: olefins
- Haber Bosch process: green ammonia

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2.3 PtX Production Step 3: PtX Production Processes and Products

Now that we have green H_2 and CO_2 (and N_2), how can we use it and which PtX products can we produce from it?

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2.3 PtX Production Processes and Products

Versatile Hydrogen Applications in Different Sectors

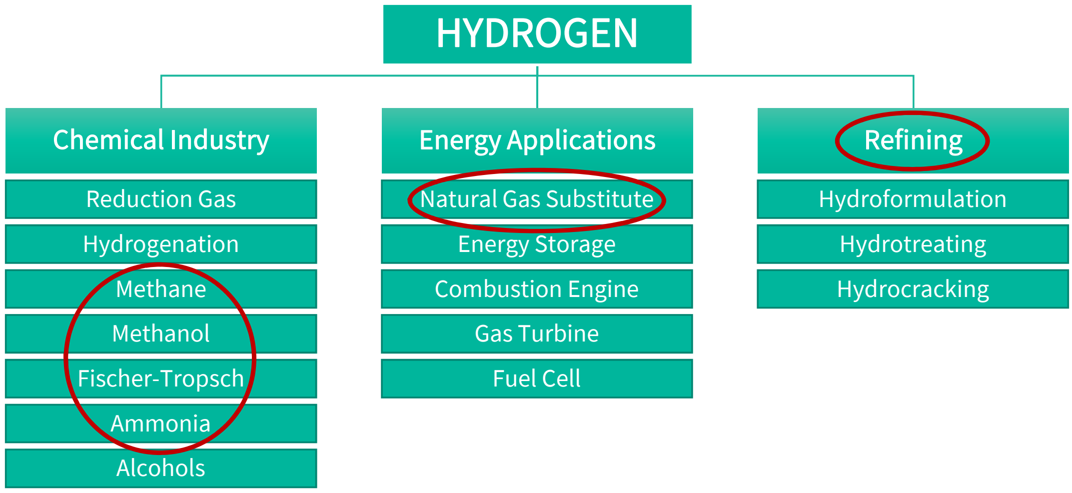

Figure: Adapted from Prof. Dr.-Ing. Epple, B., Innovative Energieumwandlungsprozesse – Energy Systems and Technology, TU Darmstadt.

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2.3 PtX Production Processes

1. Methane

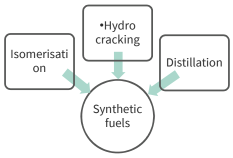
- Product: synthtic **"natural gas"** – CH_4 (SNG)
- Process: Sabatier (mature, commercially available, complex)
- Efficiency ≈ 50%
- High costs for synthetic CH_4

3. Methanol

- Products from methanol:
  - olefins for plastics,
  - OME (oxymethylene ether),
  - DME (dimethyl ether)
- CO^2 & H_2 Produce → Methanol

2. Fischer-Tropsch Synthesis

- Refining **Synthetic crude** (CXHY)



(Mature, commercially available)

- Efficiency > 50%
- Requires: CO and H_2 + RWGS process
- Smaller processes with DAC in pilot stage
- High costs for synthetic fuels ~~(when using H2)~~

4. Haber-Bosch

- Production of green ammonia
- Requires green H_2 & Nitogen

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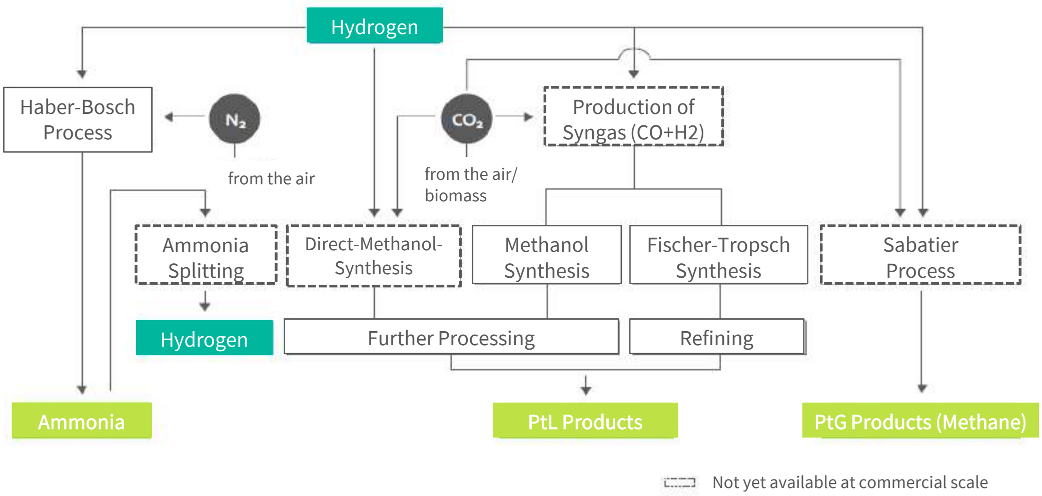
3. PtX Production

Converting power to anything with hydrogen and CO_2



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

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2.3 PtX Production Processes

	1. Methanation	2. Fischer-Tropsch Synthesis	3. Methanol	4. Haber-Bosch (Ammonia)
Input	CO, CO^2 & H_2	CO and H_2 + RWGS process	CO^2 & H_2	H_2 & N_2
Process	Sabatier	Hydro cracking, isomerisation, distillation		Haber-Bosch
Output	Natural gas – CH_4	Synthetic fuels	Olefins, OME, DME	Green Ammonia
Efficiency	≈ 50%	> 50%		Ca. 40%
Socio-Eco impact in current value chain				

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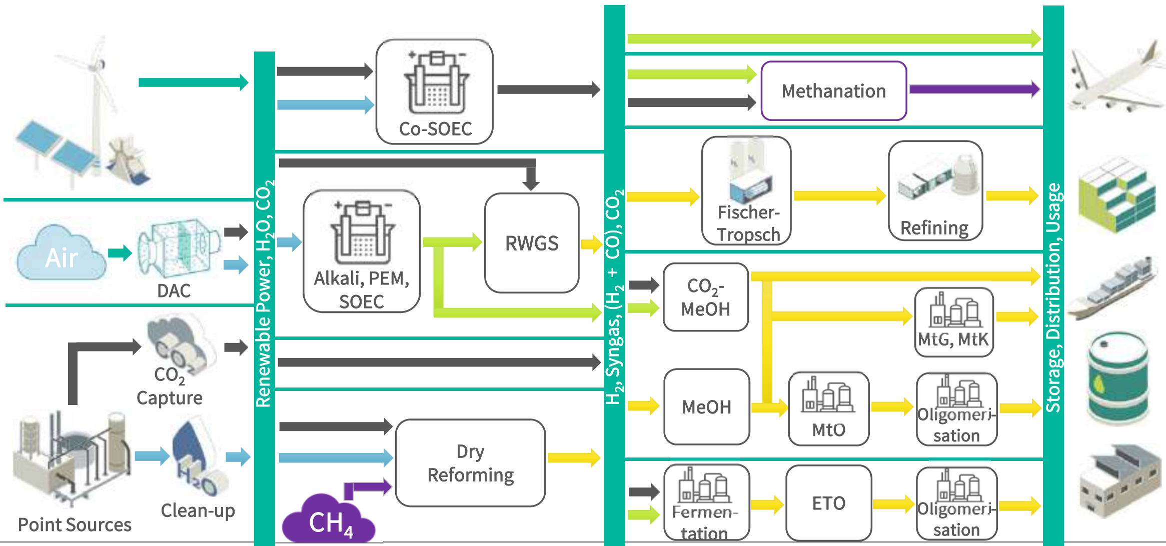
PtX Production Pathways



46 Source: EDL Pörner Gruppe (M. Haid), Power to Liquid Routes, 10/2021.

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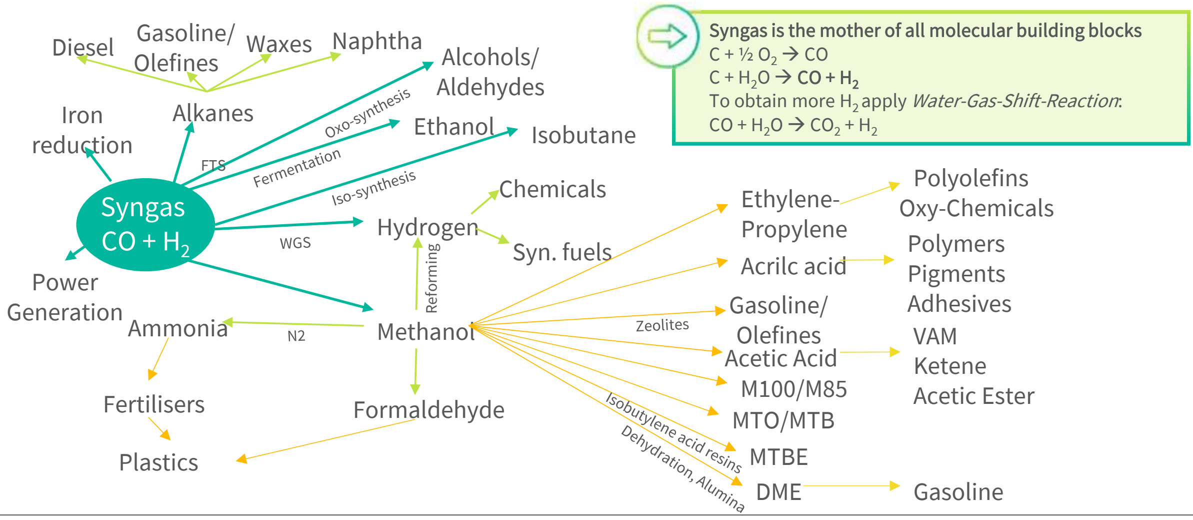
2.3 PtX Production Processes and Products

Syngas for Production of Hydrocarbons, Alcohols and Dimethyl Ether (DME)



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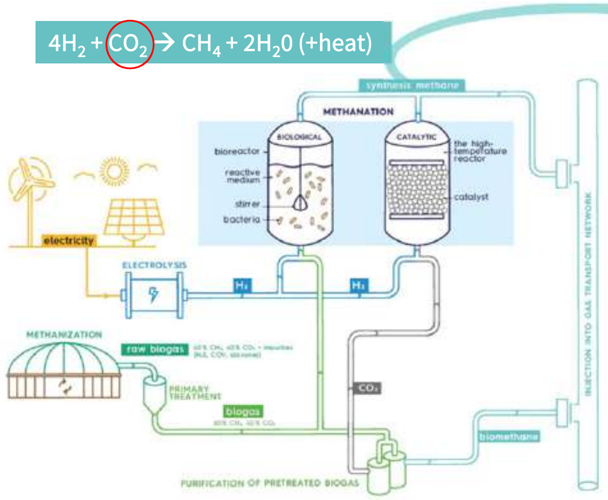
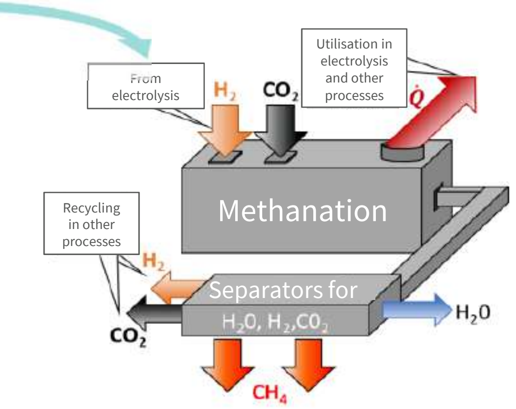
2.3 PtX Production Processes and Products

1. Methanation: Production of Syngas via Sabatier Process

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





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

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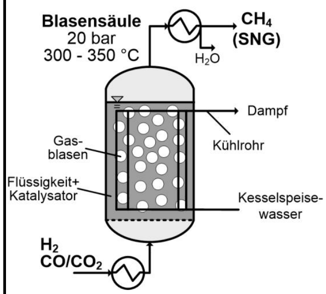
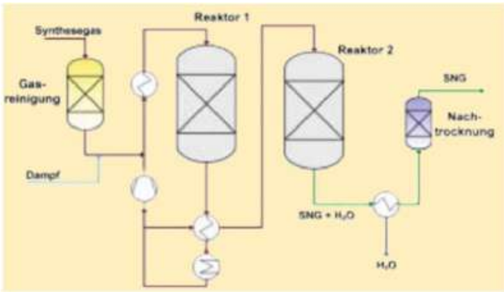
Left figure: Terega, (2022), *Synthetic Methane: Teréga working today for the future of gas.*
Right figure: Technische Universität Berlin, (2018), *Technischer Stand und Flexibilität des Power-to-Gas-Verfahrens*, p.4., fig. 2-2.

Methanation requires complex system design

Methanation requires...



complex process engineering with catalyst towers



- Existing plant technology for the methanation of coal gas must be adapted to new, more dynamic operation and the use of CO_2
- In addition to CO_2 procurement, there is still room for improvement in plant technology, costs, efficiency and dynamic driving.

[Source: ITM Power, ZSW.] 55

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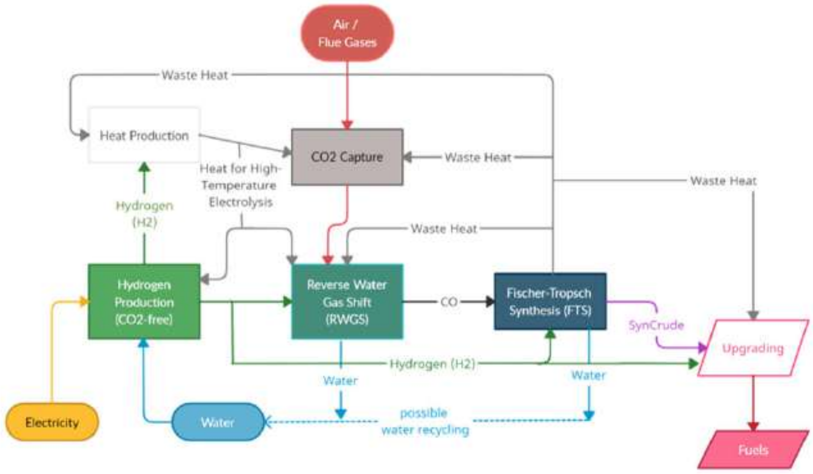
2.3 PtX Production Processes and Products

2. Fischer-Tropsch Synthesis: Production of Synthetic Crude (I)

- FTS reaction is one of the reactions for growing carbon chains (–CH_2–) to produce hydrocarbons of various lengths (paraffins or olefins).
  - large scale and mature
  - further cost reductions not expected
  - commercial RWGS still a technological challenge
  - overall efficiency below 50% with green H2
- The output of FTS depends on final product (conversion efficiency from CO + H_2 to final product)
  - **Diesel fuel:** 230°C, 40 bar, 60 – 90%
  - **Gasoline:** 340°C, 25 bar 85%



50 Figure: Adapted from Öko-Institut e.V, (2020), Wasserstoff und wasserstoffbasierte Energieträger und Rohstoffe, p.63, fig.2-16.

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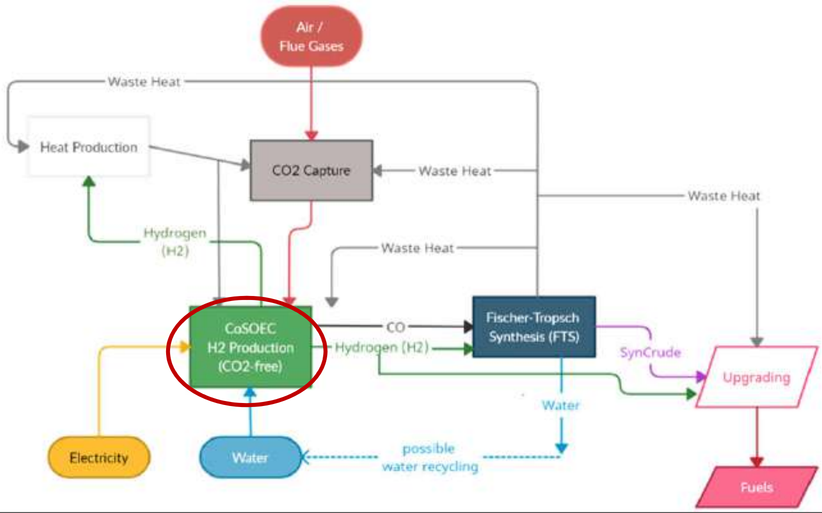
2.3 PtX Production Processes and Products

2. Fischer-Tropsch Synthesis: Production of Synthetic Crude (II)

- Reminder: Traditionally an electrolyser produces hydrogen. In order to use the Carbon from DAC or biomass for the syngas production, additional Reverse Water Gas Shift (RWGS) is needed.
- The advantage here: The **CoSOEC** (Co-electrolyser) directly produces syngas in one step.
- When coupled with **CoSOEC**, this process can be scaled to commercial level.



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2.3 PtX Production Processes and Products

2. FTS: Decentralised PtX Production with DAC (pilot stage)

Kopernikus-Project PtX
Phases in the scale-up of DAC technology:

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

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

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2.3 PtX Production Processes and Products

3. Methanol (CH_3OH) Synthesis: Liquid Fuel Production

- further cost reductions not linked to electrolysis development nor to the synthesis process itself/ therefore not expected in large scale
- mature process
- Methanol process: 250°C, 75 bar, efficiency 80%.
- If one uses DAC and RE power, costs are 5-times higher than from fossil fuel 100$/t to 200$/t.

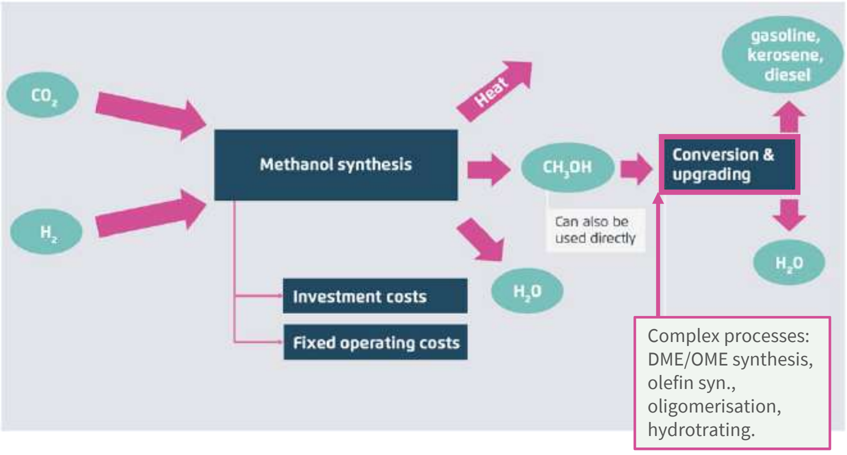

Figure: Adapted from: Agora Verkehrswende, Agora Energiewende and Frontier Economics, (2018*), The Future Cost of Electricity-Based Synthetic Fuels,* p.69, fig. 14.

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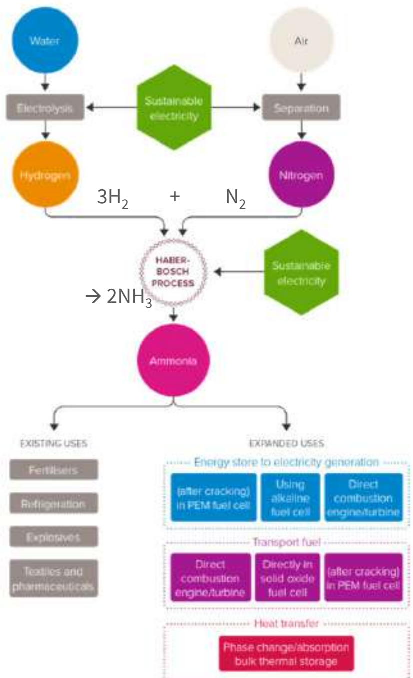
2.3 PtX Production Processes and Products

4. Haber-Bosch-Process: Green Ammonia

- N_2 is extracted from air with a **cryogenic air separation unit (ASU) and electric power.**
- **Green NH_3** is **produced from green hydrogen** (H_2) and nitrogen (N_2) via the industrial **Haber-Bosch process** (high technology maturity).
- **NH_3 provides a pathway to fully CO_2 neutral electricity generation + storage; not limited by scarcity of materials or storage**
- *Use of green NH_3*:
  - as **energy carrier** of H_2 to enable transportation (higher energy density compared to H_2)
  - as **fuel in fuel cells**
  - **directly in combustion engines**
  - **to decarbonise the fertiliser production**



53 Figure: The Royal Society, (2020), *Ammonia: zero-carbon fertiliser, fuel and energy store*, p.5, fig.1

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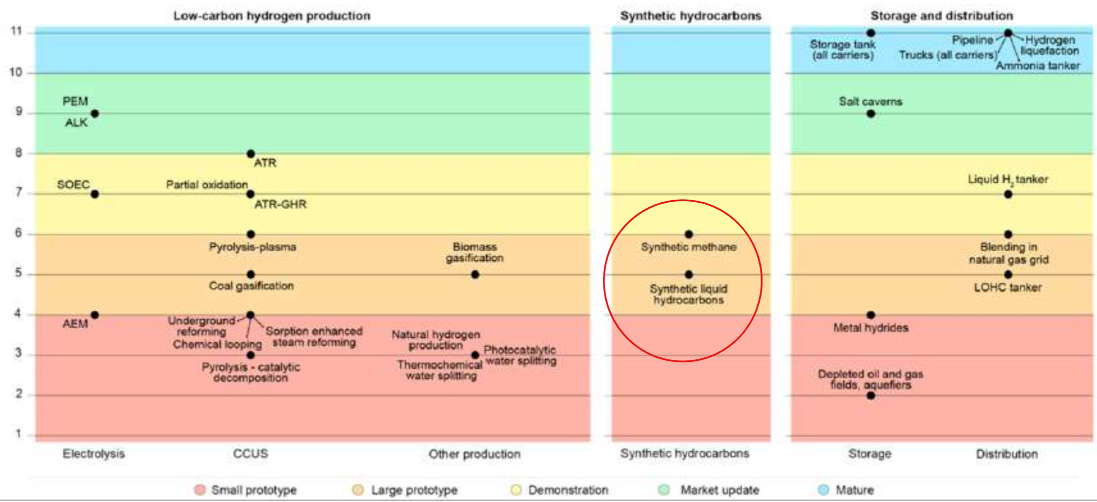
2.3 PtX Production Processes and Products

Technology Readiness Levels of Key PtX Production, Storage and Distribution Technologies



55 Figure: IEA, (2021), *Global Hydrogen Review*, p.170.

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Key take-aways: 2.3 PtX Production Step 3: PtX Production Processes and Products

- **H2** is used as product and energy input in chemical industry, as substitute in energy applications and as material input for further refining, **mainly e-fuels** and **platform chemicals like methanol, ethene or ammonia. Here, Renewable PtX comes into play!**
- There are **different processes to produce different PtX products:**
  - **Synthetic natural gas is** produced by methanization of green hydrogen with CO_2, yielding pure CH4 that can be used like natural gas
  - **The Fischer Tropsch Synthesis** for production of **e-fuels** like methanol, gasoline, diesel or jet fuel requires syngas (CO + H2) as input.
  - **The Haber Bosch process** for production of **ammonia** requires hydrogen and nitrogen (from ambient air). No carbon is required.
- Some adjustments of the existing well-established might be needed (e.g. using CO_2 instead of CO), some porecesses are still at low TRL levels


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MODULE 2: Key Messages

1. Options for Hydrogen Production

- There are various ways of producing H_2, often expressed by the colour of hydrogen
  - Grey H2 = from fossil fuels, Blue H2 = from fossil fuels with CCS, Green H2 = from renewables
- Emissions for blue H2 can be higher than those from natural gas, methane leakage and corruption-proof audits must be considered!
- For a defossilised future we need the 3 elements from sustainable sources: C, N2, H2.
- Hydrogen plays a central role and is the element which contains the reactive energy for production pathways that can replace fossil fuels across many sectors

2.1 PTX Production Step 1: Electrolysis

- **Green Hydrogen** and **oxygen** are derived from the **electrolysis** of water using **renewable energy. Water electrolysis** is therefore the **base technology** for the PtX process.
- There are three relevant **electrolyser types:**
  - AEL – Alcaline Electrolyser is most established, in use since 100 years in chemical industry
  - PEM - Polymer electrolyte membrane electrolyser is most flexible and have undergone strong development since 2010
  - (Co)SOEC - solid oxide electrolyzer cell works is most effieicient but most challenging due to the high temperature level

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MODULE 2: Key Messages

2.2 PtX Production Step 2: Carbon Sourcing

- For PtX processes, also **Carbon (C)** and **Nitrogen (N2)** are needed.
- Carbon can be used from industries (no green CO_2), biomass (green CO_2) or Direct Air Capture (DAC, green CO_2).
- Renewable carbon from sustainable biomass or **DAC is a significant constraint**. This is why volume matters significantly to reach cost reduction.

2.3 PtX Production Step 3: Production Processes and Products

- **H2** is used as product and energy input in chemical industry, as substitute in energy applications and as material input for further refining, **mainly e-fuels** and **platform chemicals like methanol, ethene or ammonia. Here, Renewable PtX comes into play!**
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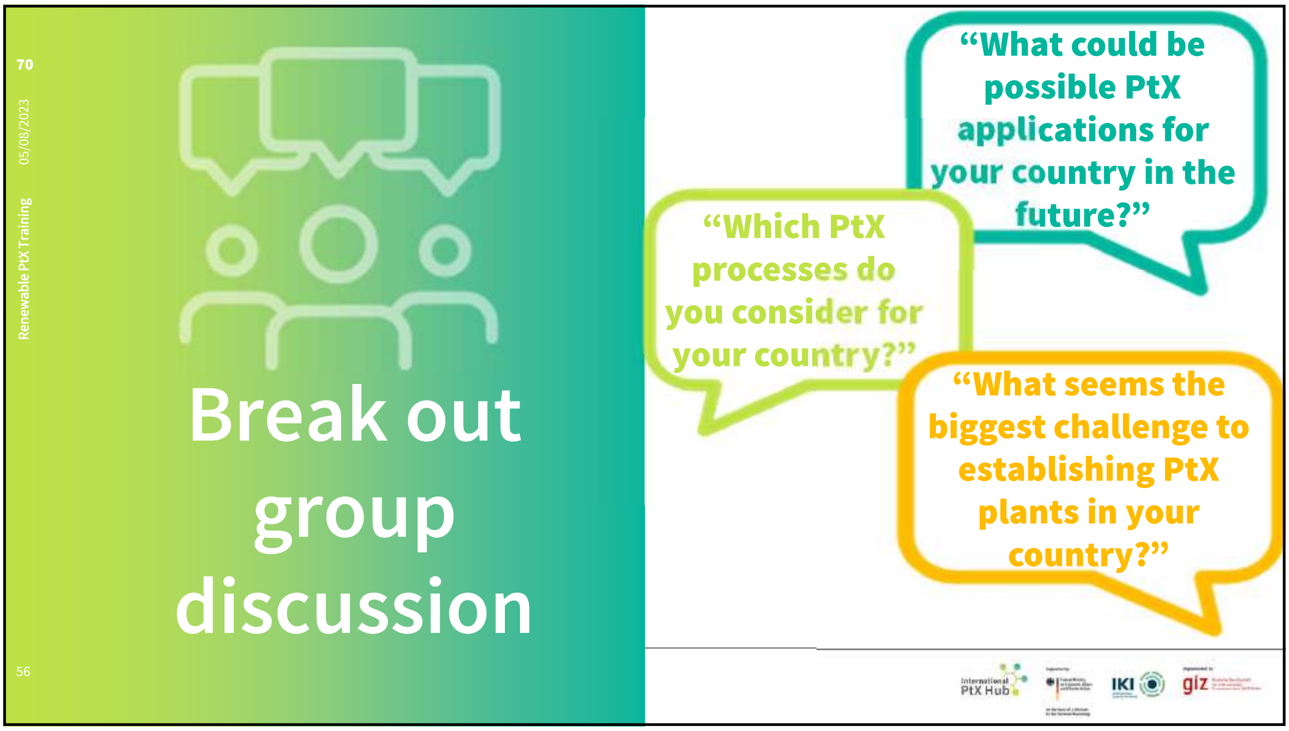
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Break out group discussion
"What could be possible PtX applications for your country in the future?"
"Which PtX processes do you consider for your country?"
"What seems the biggest challenge to establishing PtX plants in your country?"
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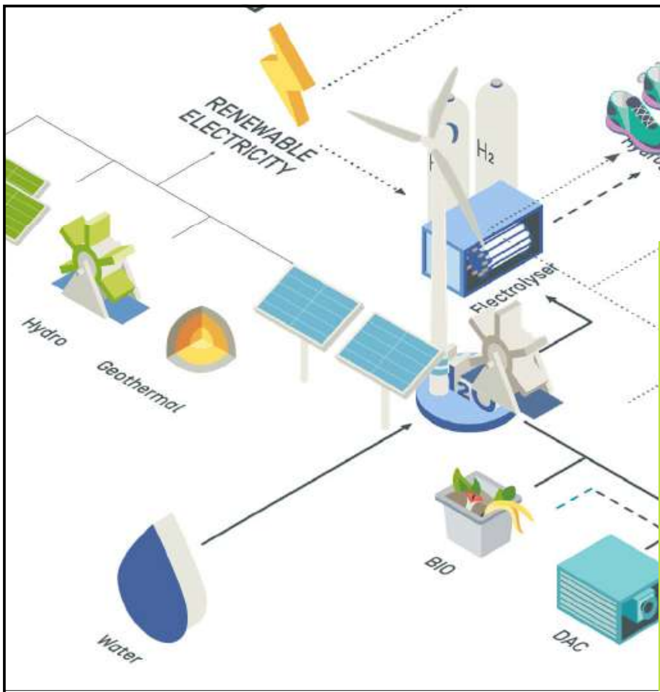
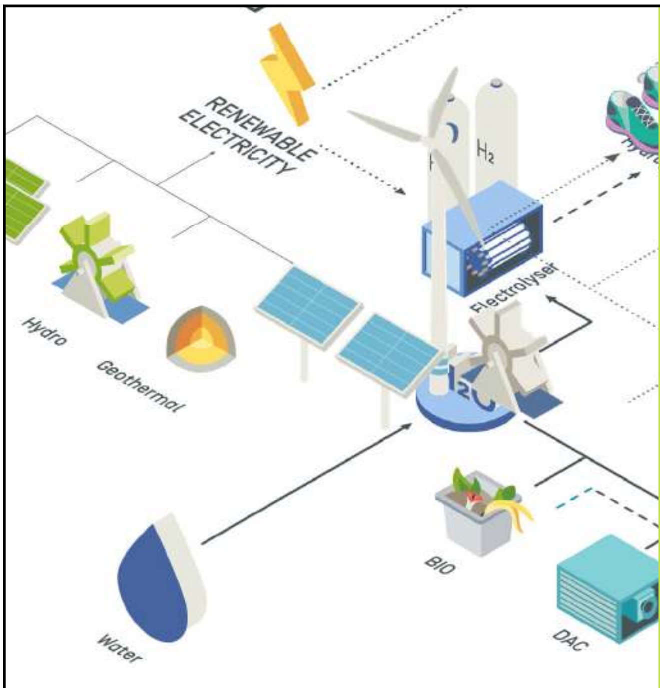


Renewable POWER TO X

Training: August 2023
Modules prepared by the International PtX Hub
Trainer: Prof. Thorsten Schneiders



Renewable POWER TO X

Part 3: Renewable PtX Economics

Training: August 2023
Modules prepared by the International PtX Hub
Trainer: Prof. Thorsten Schneiders

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Agenda

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

2 **Production Pathways of Renewable PtX**
What is needed for PtX, incl. green hydrogen

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

4 **PtX Infrastructure**
How to transport and store PtX products (incl. gH_2) best?

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

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

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

List of abbreviations

- **CAPEX:** Capital cost expenditures
- **CCfD:** Carbon contracts for difference
- **CCS:** Carbon Capture and Storage
- **DAC:** Direct Air Capture
- **FLH:** Full-load hours
- **GW:** Gigawatt
- **HVDC:** High voltage, direct current
- **LCOE:** Levelised cost of electricity
- **LOHC:** Liquid organic hydrogen carrier
- **LHV:** Lower heat value

- **OPEX:** Operating cost expenditures
- **PEM:** Proton Exchange Membrane
- **PtX / PtL / PtG:** Power-to-X / -Liquid / -Gas
- **PV:** Photovoltaic
- **RE:** Renewable Energy/ies
- **RES:** Renewable Energy System(s)
- **RWGS:** Reverse Water Gas Shift Reaction
- **SMR:** Steam methane reforming
- **SOEC:** Solid Oxide Electrolyser Cell
- **TWh:** Terawatt hours
- **WACC:** Weighted average cost of capital

Key Conversion Data

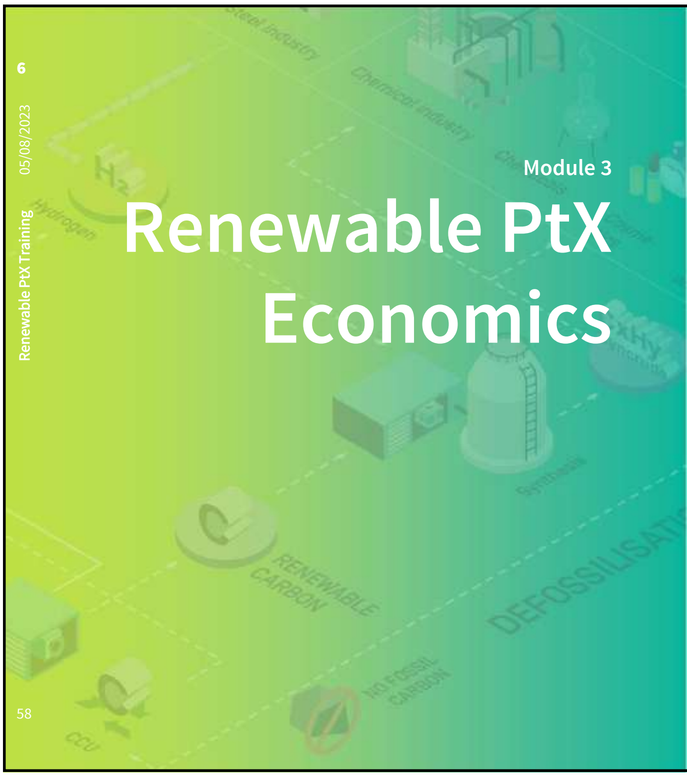
- 1 kWh H_2= 3.6 MJ H_2
  1 MWh H_2 = 3.4 MMBTU H_2
  1 MJ H_2 = 0.277 kWh H_2

Conversion kWh and kg H_2:

- 1 kg H_2 = 33.3 kWh H_2 *(heat unit Hu /calorific value)*
- 1 MWh H_2 = 30 t H_2
- 1 Mio t H_2 = 33 TWh H_2

Monetary value per weight or calorific value

- 4.5 ct/kWh H_2 = 45 €/MWh H_2 = 1.5 €/kg H_2
  or: 1€/kg H_2 = 3 ct/kWh H_2
- 100 €/MWh H_2 = 3.33 €/kg H_2
  or: 1€/kg H_2 = 30 €/MWh H_2



Module 3

Renewable PtX Economics

1. Production Cost of Green Hydrogen
   - Cost factors (electricity cost, full load hours, etc.)
   - Reduction of cost factors
2. Renewable Energy Generation Cost Development
   - RE costs and RE potential worldwide (wind, PV, etc.)
   - Additionality
   - Full Load Hours
3. Electrolyser Cost Development
   - Cost Factors (f. e. electrolyser type, installed capacity)
   - Cost Forecasts
4. Scale-Up and Outlook for Hydrogen and PtX Production
   - Green hydrogen
   - Green ammonia
   - Synthetic fuels etc.

Test your knowledge

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

Basics: What do we mean by

- LCOE (levelised cost of energy): the **average net present cost of electricity generation** for a generator over its **lifetime,** *or*
  average minimum price at which the electricity generated by the asset **is required to be sold in order to offset** the total costs of production over its lifetime

$$\text{LCOE} = \frac{\text{NPV of Total Costs Over Lifetime}}{\text{NPV of Electrical Energy Produced Over Lifetime}} \qquad \text{LCOE} = \frac{\sum \frac{(I_t + M_t + F_t)}{(1+r)^t}}{\sum \frac{E_t}{(1+r)^t}}$$

- FLH (full load hours): the **time for which a plant would have to be operated at nominal power** in order **to convert the same amount of electrical work as the plant has actually converted** within a defined period of time, during which breaks in operation or partial load operation can also occur

$$\text{FLH} = \frac{kWh}{kWp} = \frac{energy}{power}$$

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Basics: What do we mean by (cont‘d)

- The **capacity factor** represents the **annual energy output** from a wind farm, **expressed as a percentage of the farm's maximum output.** It is predominantly determined by two factors: the *quality of the wind resource* where the wind farm is sited; and the *turbine and balance-of-plant technology* used.
  - Capacity factor CPF $= \frac{FLH\ per\ year}{hours\ per\ year} = \frac{FLH}{8.760\ h}$

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What we know already from experience

There are numerous examples for successful cost reduction in energy sector

- With a market scaling up, technologies are developed further and production is optimized, leading to lower costs due to economies of scale
  - Economies of scale: higher production numbers allows for improvements and fixed costs are sread over a larger number of units
  - Lower costs allow for larger scale project which leads to further market growth and economies of scale
- Renewable energy technologies have already undergone strong cost declines over the last two decades
  - It all started with small exotic companies in the backyard what is now a multi-billion dollar business
  - Exponential growth of wind and solar energy worldwide has lead to more reliabe and cheaper technology and more refined production, planning, installations and operation
- In the last 10 years, battery storage systems have undergone the same grwoth path
  - Cost reduction of 20% per year and improved quality
  - Gigawatt factories installed and battery projects reaching size of several 100 MW
- In many aspects, electrolyser industry is at the same point battery industry was 10 years ago
  - First steps from manual engineering and production (especially PEM) to professional industry

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1. Production Cost of Green Hydrogen

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What are the green hydrogen costs and how can they develop in future?

1. Green Hydrogen Production Cost

Levelized costs of Hydrogen (LCOH)

$$\text{LCoH} = \frac{\text{(CAPEX + OPEX + DECEX)}}{\text{(Total amount of } H_2\text{)}} \quad (\$/\text{kg})$$

CAPEX: Total value of investments
OPEX: Overall cost during the life cycle of the project
DECEX: Total decommissioning expenditure

- Levelized costs are indicators for the evaluation of the economic efficiency and competitiveness of technology to quantitatively measure the economic feasibility of a certain technology
- Similar to the concept of the levelized cost of energy (LCOE), which refers to the cost of electricity generation per unit of energy, the concept of the LCOH refers to the cost of hydrogen production per unit of hydrogen.
- If the market price of hydrogen is equal to the average cost of hydrogen production over the life of a project, the investor will break even on an investment project.

1. Green Hydrogen Production Cost

Levelized costs of Hydrogen (LCOH)

$$\text{LCoH} = \frac{\text{(CAPEX + OPEX + DECEX)}}{\text{(Total amount of } H_2\text{)}} \quad (\$/\text{kg})$$

CAPEX: Total value of investments
OPEX: Overall cost during the life cycle of the project
DECEX: Total decommissioning expenditure

CAPEX: mainly hardware costs (electrolyzer, installation etc.)
OPEX: mainly electricity costs, water, etc.

- Levelized costs are indicators for the evaluation of the economic efficiency and competitiveness of technology to quantitatively measure the economic feasibility of a certain technology
- Similar to the concept of the levelized cost of energy (LCOE), which refers to the cost of electricity generation per unit of energy, the concept of the LCOH refers to the cost of hydrogen production per unit of hydrogen.
- If the market price of hydrogen is equal to the average cost of hydrogen production over the life of a project, the investor will break even on an investment project.

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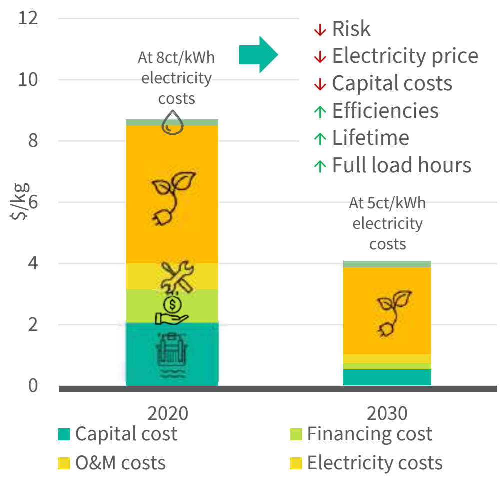
1. Green Hydrogen Production Cost

Cost Reduction: Key Elements and Their Trends



- **CAPEX:** capital expense for the electrolyser (including the balance of plant)
- **Finance & risk:** Interest rates depend on financing mechanism and perceived risk of project
- **Operation and Maintenance (O&M):** Often paid as Service-Level Agreement (SLA) or warranties → deferred capex costs for replacements of stacks or other parts (1-3% of capex annually)
- **Electricity costs** (either as part of project (CAPEX) or as purchase agreement (OPEX; incl. taxes, levies, surcharges...))
- **Water costs** negligible

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

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

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

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

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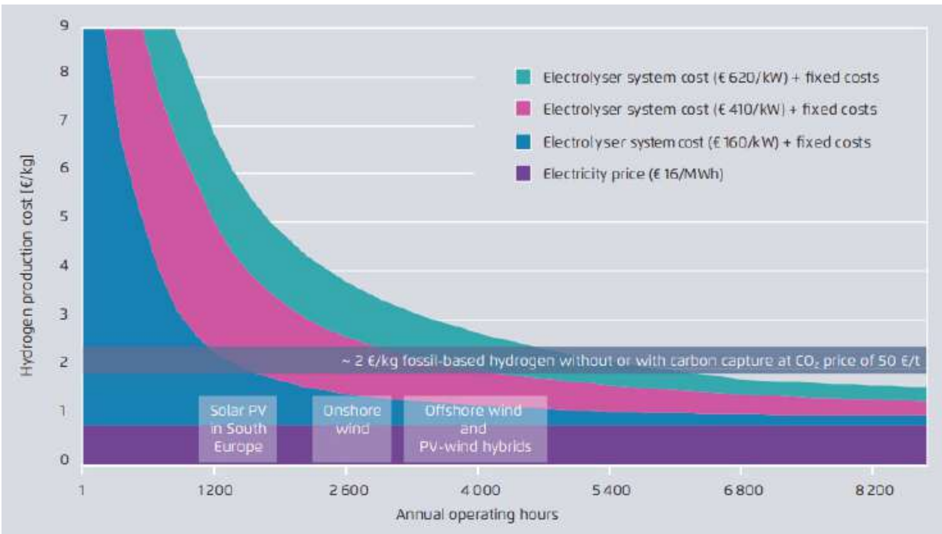
1. Green Hydrogen Production Cost

Cost Factor: Operating Hours of electrolyzers in combination with renewable energy sources



- With growing number of FLH, the CAPEX of the electrolyzers makes up a shrinking share of overall H2 costs, while the renewbales electricity price is a fiwed component of the H2 costs.
- The higher the FLH, the more relevant the RES costs and the less releveant the electrolyzer costs

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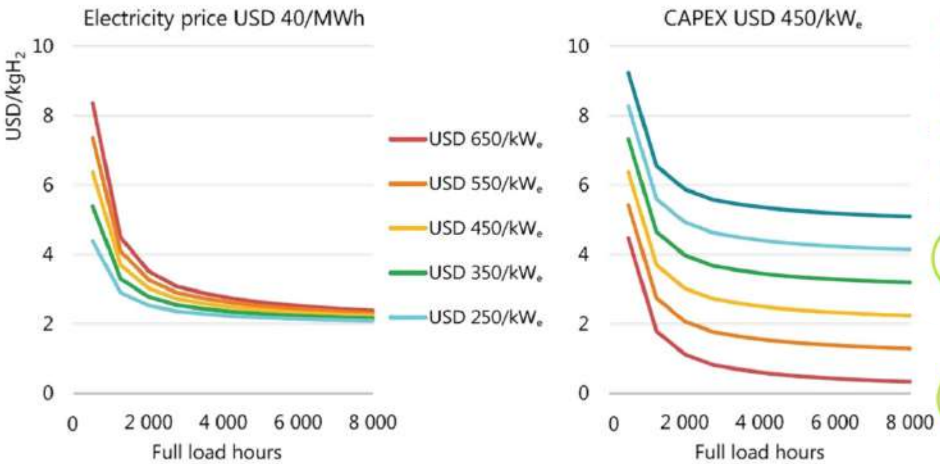
Source: Agora Energiewende, Making renewable hydrogen cost-competitive, 2021, p.12/fig.2.

1. Green Hydrogen Production Cost

Cost Factors: CAPEX, Full Load Hours (FLH) and Electricity Price



If FLH are high, capital costs of electrolysers do not matter.

Electricity price matters!

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

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

1. Green Hydrogen Production Cost

Summary: What makes Up Costs of Green Hydrogen?

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

Four main parameters are critical for economic viability of H_2 production from renewables (Country specific evaluation required):

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

We need cheaper electrolyzers!

We need cheap and plenty of dedicated RE power for PtX!

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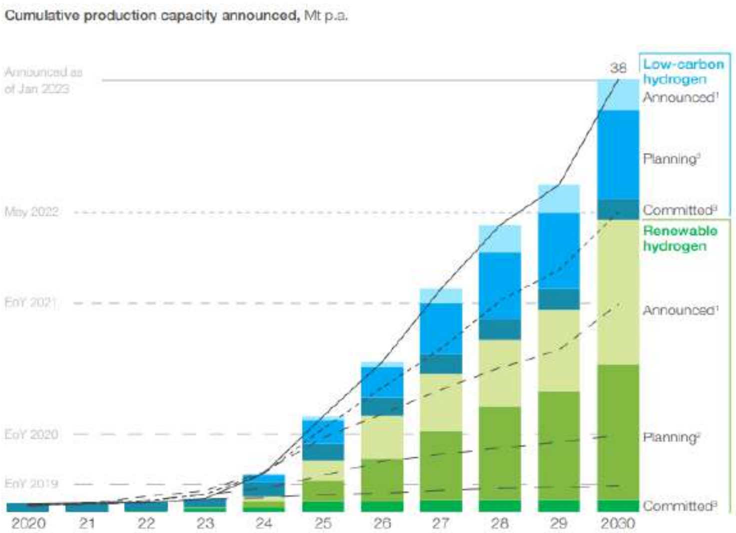
Announced production volumes increased by more than 40% to 38 Mt p.a., reaching half the volume needed in 2030 to be on track to net zero



- Significant market growth forecasted, which will lead to significant economies of scale especially for electrolyzers
- > 70% share of new capacity in top 3 markets (Europe, North America, Latin America)

Hydrogen Council & Mac Kinsey (05/2023) Hydrogen Insights 2023, p.8/exhib.4.

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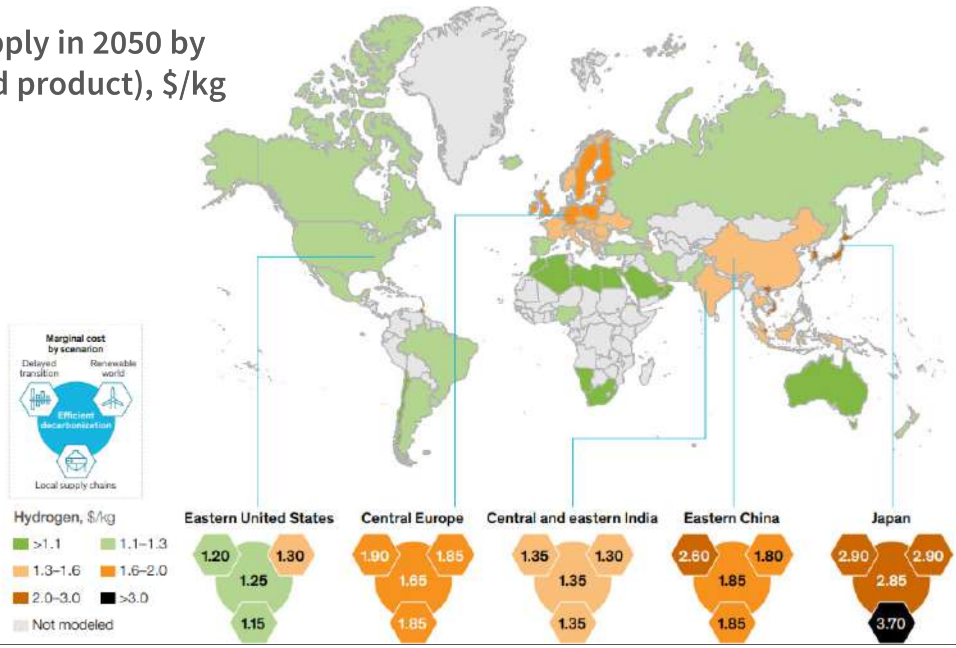
Marginal cost of supply in 2050 by region for H_2 (as end product), $/kg

The global marginal costs for H_2 in major markets will range from **$1.25 to $2.85 per kg** in the **efficient decarbonization scenario.**
Under other scenarios, the range widens to $1.15 to $3.70/kg.



Hydrogen Council, McKinsey & Company (10/2022) Global Hydrogen Flows: Hydrogen trade as a key enabler for efficient decarbonization, p.32/exhib.19.

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Any questions?

How do costs for green hydrogen compare with costs of blue or grey hydrogen – today and in future?

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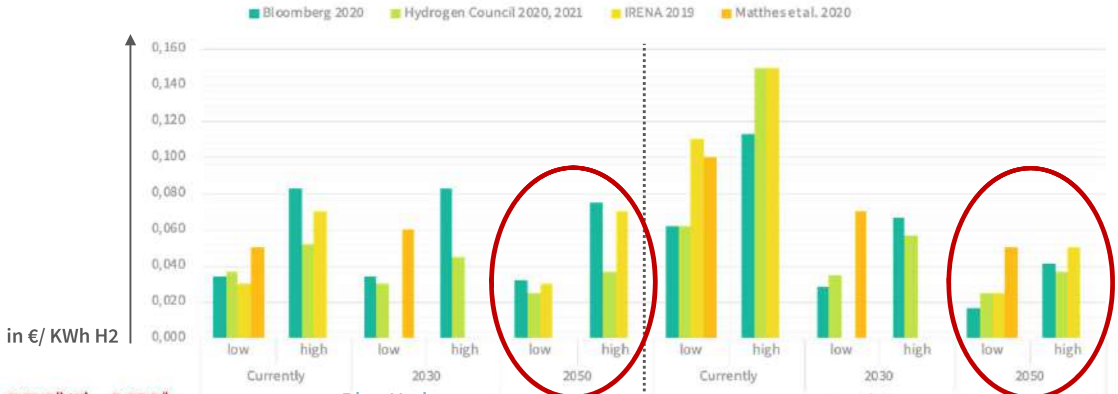
1. Green Hydrogen Production Cost

Different studies compare blue and green hydrogen costs



0.02 €/kWh = 0.66 €/kg

	Blue Hydrogen						Green Hydrogen					
	Currently low	Currently high	2030 low	2030 high	2050 low	2050 high	Currently low	Currently high	2030 low	2030 high	2050 low	2050 high
Bloomberg 2020	0,034	0,083	0,034	0,083	0,032	0,075	0,062	0,113	0,029	0,067	0,017	0,041
Hydrogen Council 2020, 2021	0,037	0,052	0,030	0,045	0,025	0,037	0,062	0,149	0,035	0,057	0,025	0,037
IRENA 2019	0,030	0,070			0,030	0,070	0,110	0,149			0,025	0,050
Matthes et al. 2020	0,050		0,060				0,100		0,070		0,050	0,000

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

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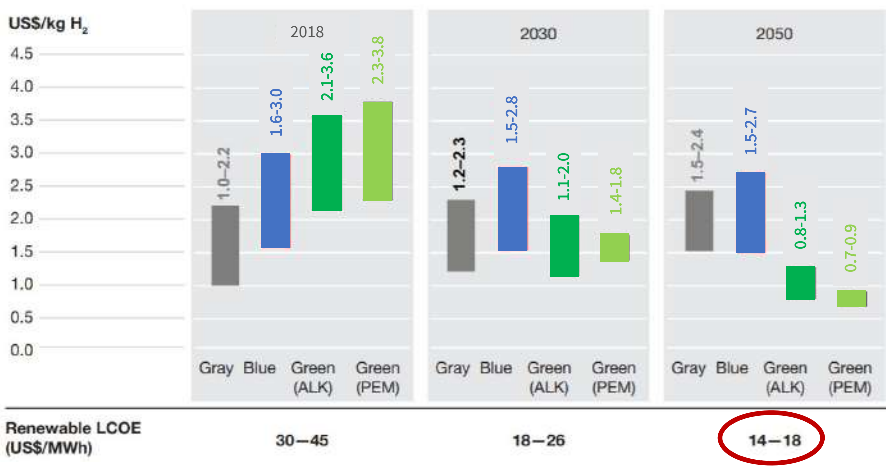
1. Green Hydrogen Production Cost

Cost Factor: H2 Production Type



Green H_2 will become cost competitive compared to grey and blue H_2 depending on LCOE of renewable power.

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

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

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

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

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Key take-aways: Production costs of Green Hydrogen

- The levelized cost of hydrogen is an indicator to identify the competitiveness of one project. If the index is less than the price of the commercial hydrogen, the project could be attractive.
- Prospective studies (IRENA, IEA, Energy Council) consider the cost reduction in the electrolyser price and the electricity from renewable source. It is estimated that around 2035 the green hydrogen could be cheaper than blue hydrogen.
- The two main costs to produce green hydrogen are: electricity (approximately 70-80%) and electrolyser (8-15%).

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Any questions?

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2. Development of Renewable Energy Costs

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Test your knowledge

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

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

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

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What is the status of renewables power generation and what is its growth perspective?

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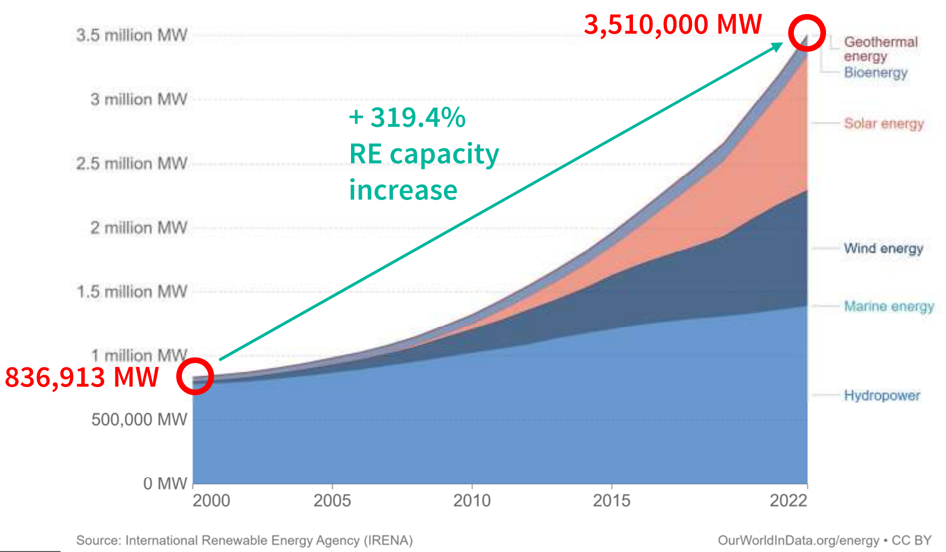
Installed global renewable energy capacity by technology
⇨ tremendous growth has been driving cost reduction



Our Wold in Data (2023) Installed global renewable energy capacity by technology.

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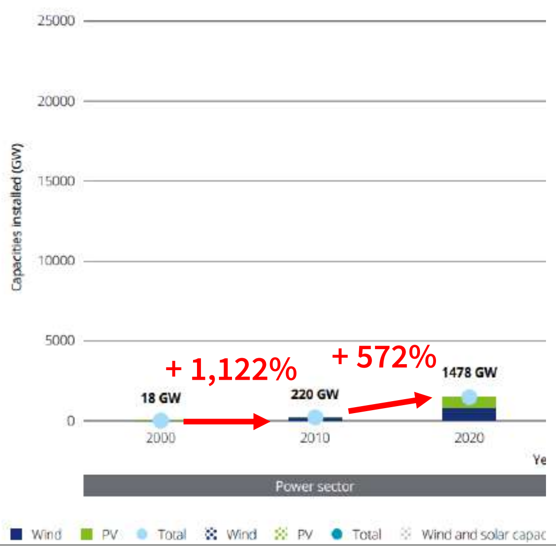
Global RE capacities installed from 2000 to 2020



Deloitte (2023) Green hydrogen: Energizing the path to net zero, p.33/fig.13.

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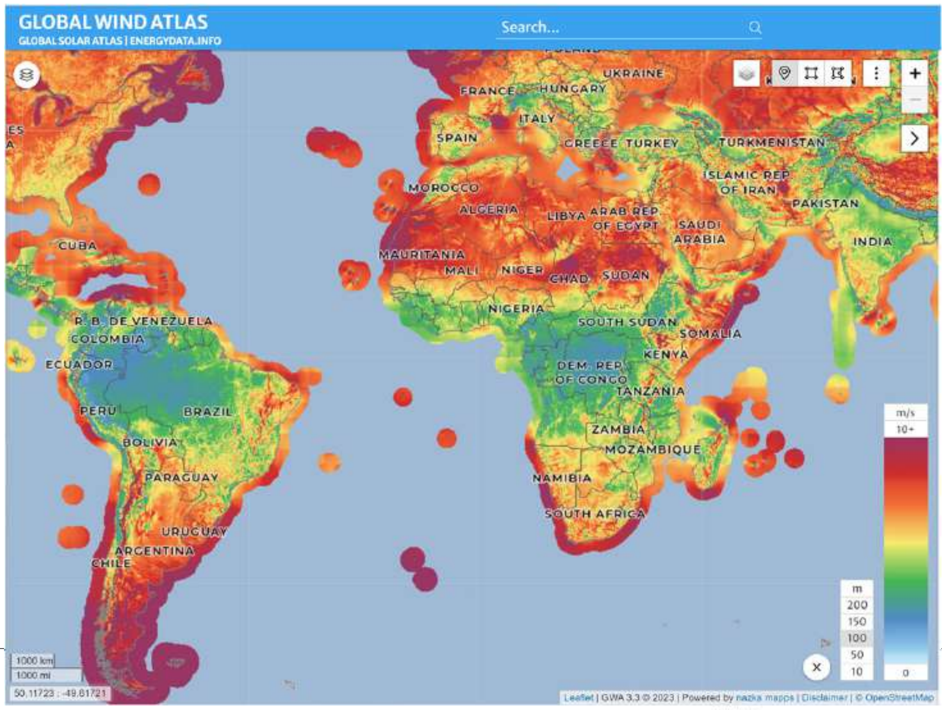
2. RE Development

Wind Energy Potentials



Source: global wind atlas.

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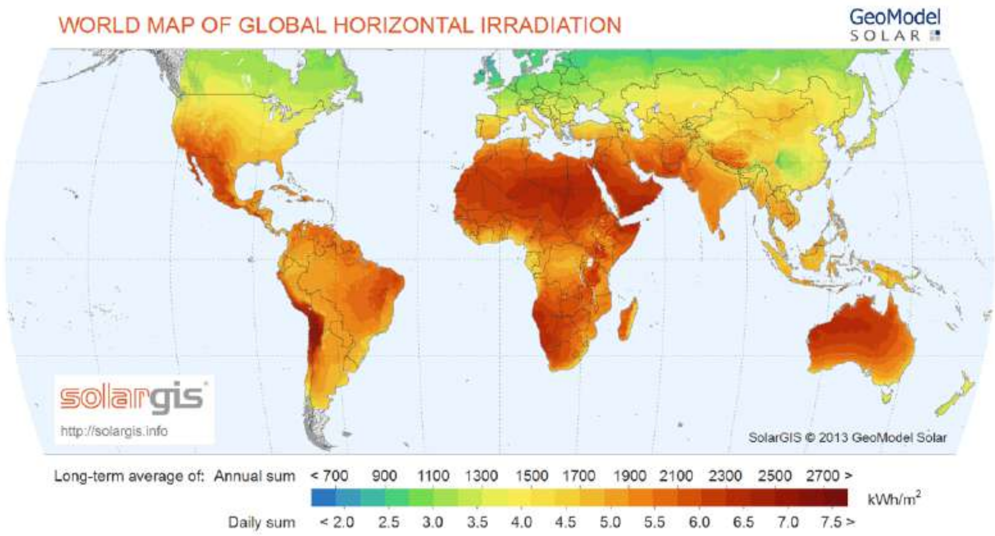
2. RE Development
Solar Energy Potentials



74 Source: Solargis.com

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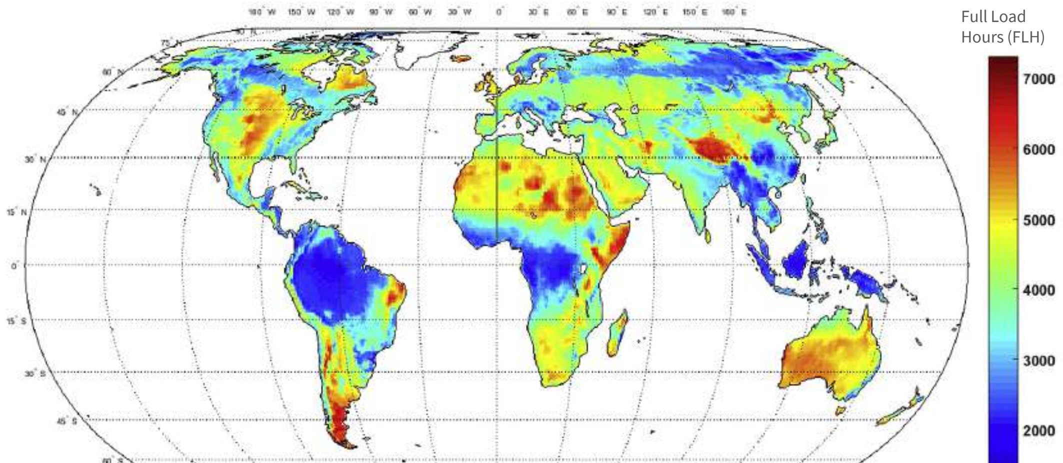
2. RE Cost Development
Cost Factor: Full Load Hours



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

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

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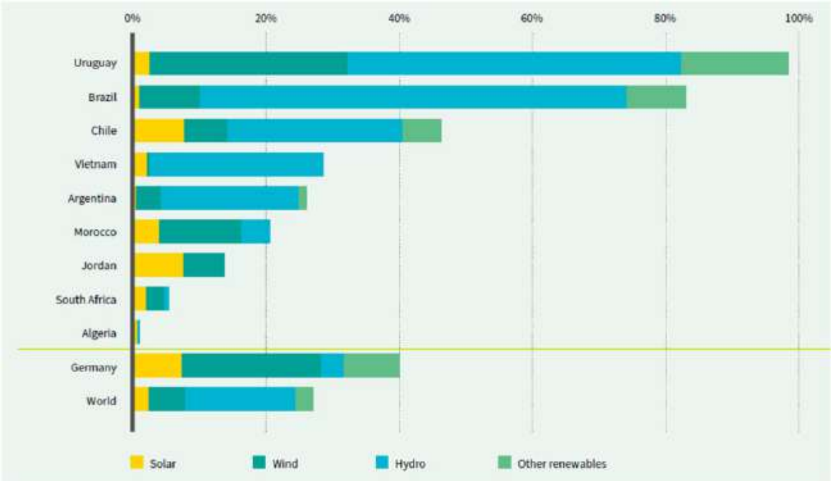
2. RE Development

Share of RE in Total Power Generation –vast potentials yet untapped

Country examples from 2020 - recent



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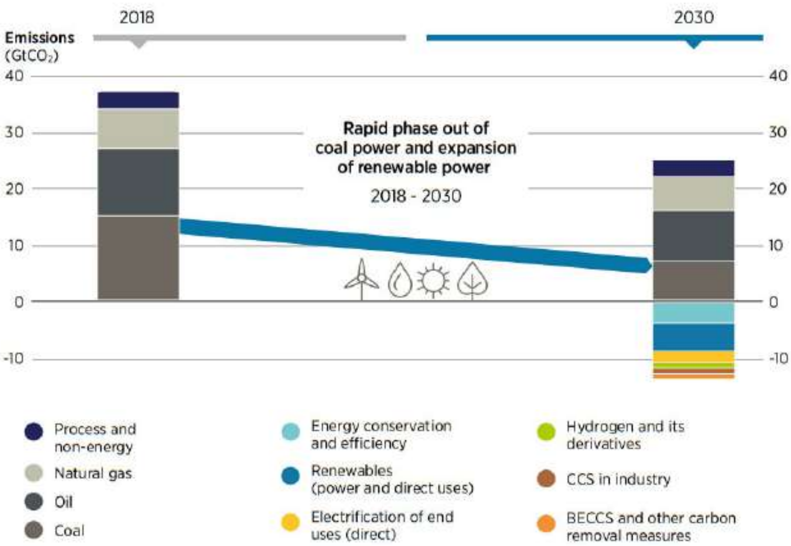
Necessary Emission Reductions from 2018-2030 trigger renewables growth



- RE share in electricity generation must increase to 65% in 2030
- Share of direct electricity consumption (TFEC) must rise from 21% to 30%
- Deployment of energy efficiency measures mus increase 2.5 times
- Direct renewables in end use sectores must grow from 12% (2019) to 19% (2030)

IRENA (n.d.) World Energy Transition Outlook 2022. https://www.irena.org/Digital-Report/World-Energy-Transitions-Outlook-2022

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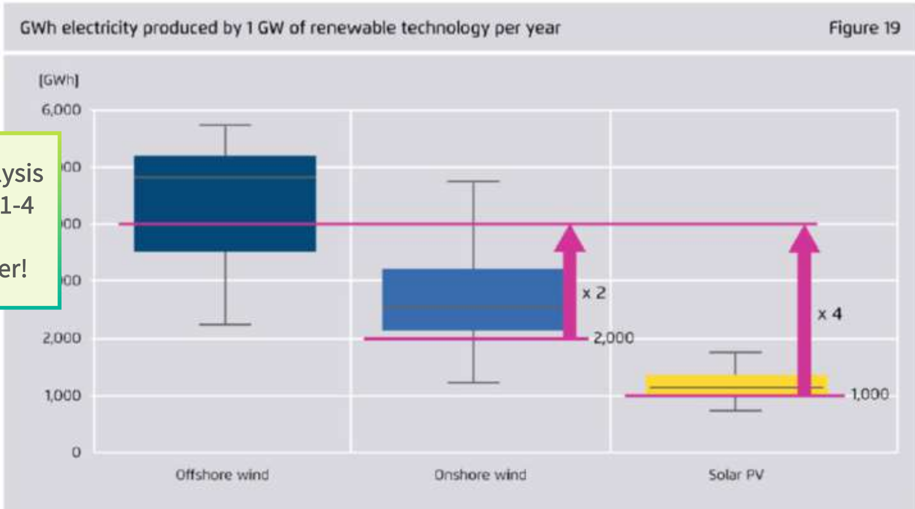
2. RE Cost Development

Cost Factor: Additional Renewable Electricity is needed for green hydrogen

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



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

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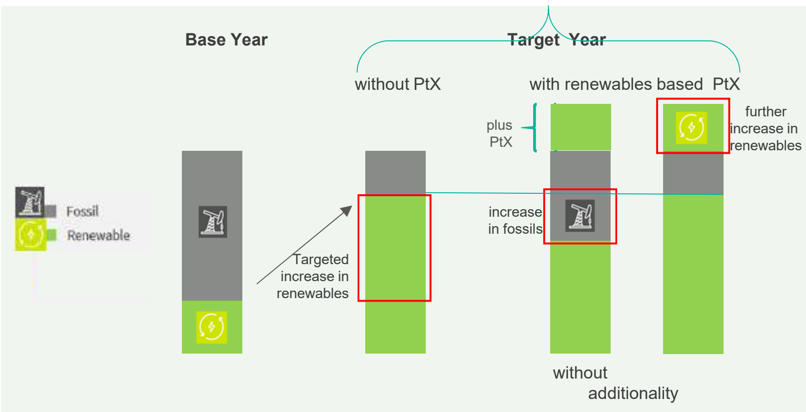
2. RE Cost Development

Cost Factor: Additional Renewable Electricity on top of regular renewables expansion needed for sustainable PtX production



Introduction of PtX production should

… not lead to an increase in fossil energy use,

but

… be based on additional renewables.

The PtX demand for additional renewable electricity should be integrated in energy and climate strategies (NDCs).

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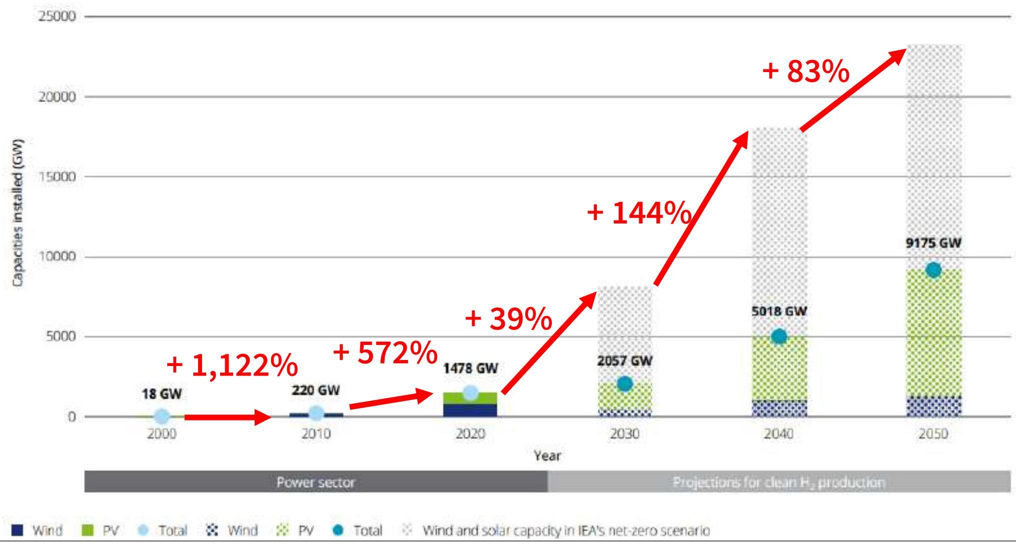
Global RE capacities installed, 2000 to 2020 (history for the power sector), 2030 to 2050 (clean H_2 production)



Deloitte (2023) Green hydrogen: Energizing the path to net zero, p.33/fig.13.

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Key take-aways: Development of Renewable Energy costs

- The levelized cost of energy from renewables has been decreasing with the tremendous growth over the last decades (e.g. solar photovoltaics by 90%), driven by economies of scale, cost reduction in production and improved efficiency
- There are vast renewables potentials yet untapped over the world to cover the local energy demand and the future demand for green hydrogen production.
    - Wind and solar energy will be the main power sources globally to drive renewables growth
- Altogether, cheap renewable energy is available all over the world

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Any questions?

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Break out group discussion

“What are the biggest challenges to increase renewables capacities and reduce RE power costs in your country? What can be done?”

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Access to renewable energy is critical, as it is responsible for 70%–80% of the green hydrogen production costs
- so what is the status and perspective of renewable energy costs?

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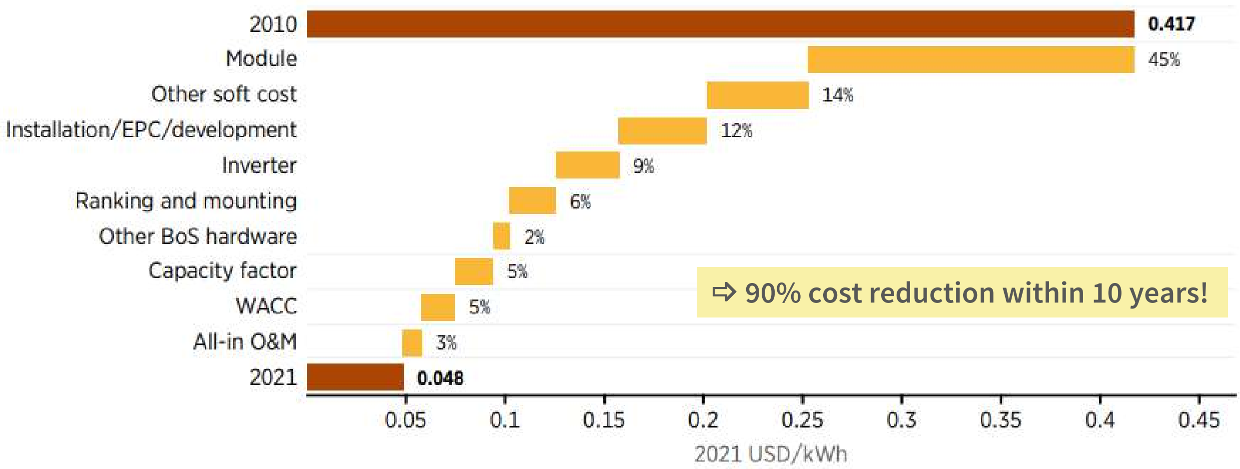
2. RE Cost Development

Decline of LCOE of utility-scale solar PV (2010-2021) - a good example for the effects of economies of scale



IRENA (07/2022) Power Generation Costs 2021, p. 97/fig.B3.3.

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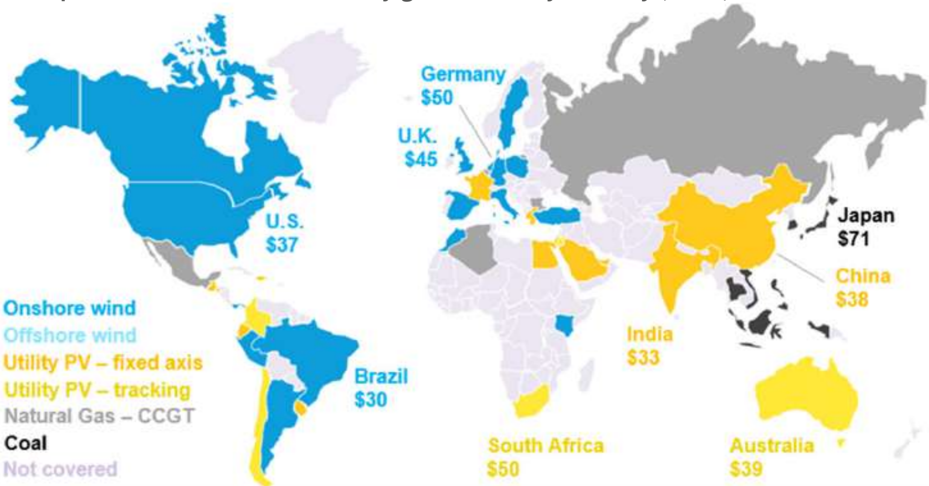
2. RE Cost Development

Cost Factor: Source of Bulk Electricity Generation

Cheapest source of bulk electricity generation by country (2020)



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

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

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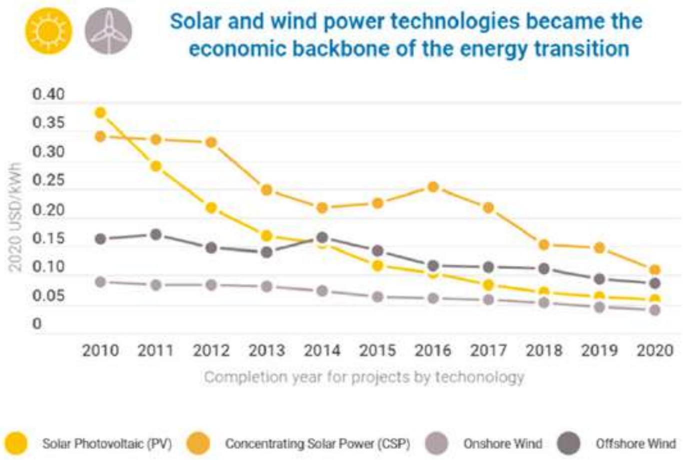
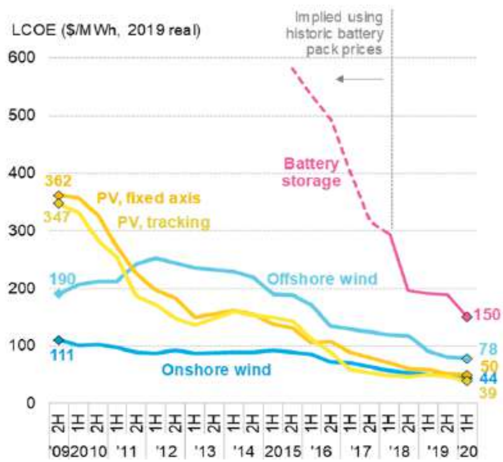
2. RE Cost Development

Cost Factor: generation costs of solar and wind power as main renewables power source



Global LCOE benchmarks of PV, wind and batteries



73 Source: Renewable Market Watch, Renewable Power Generation Costs Reduction - 2020 Overview in the Recent Study of IRENA Released in 2021 with LCOE of Renewable Energy Technologies, 2020.
Source: BloombergNEF, Scale-up of Solar and Wind Puts Existing Coal, Gas at Risk, 2020.

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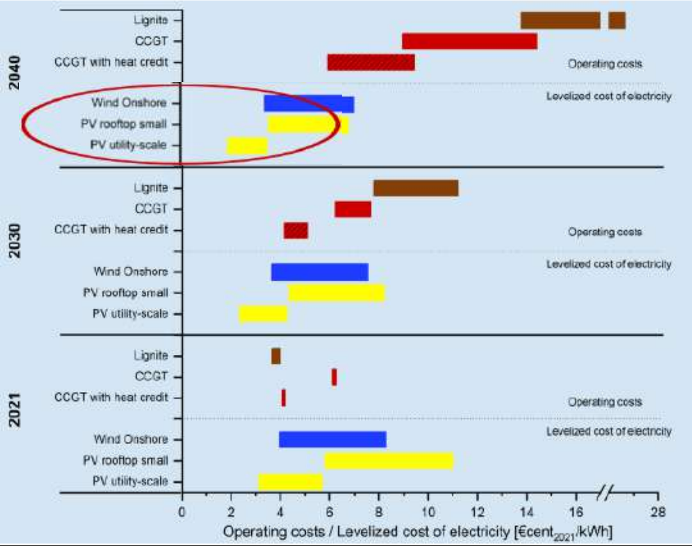
2. RE Cost Development

Cost Factor: Renewables vs. Conventional Fossil Fuels Power Plants



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

Today, renewables can already produce cheaper electricity than fossil generation.

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

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

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

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Key take-aways: Production costs of Green Hydrogen

- The levelized cost of hydrogen is an indicator to identify the competitiveness of one project. If the index is less than the price of the commercial hydrogen, the project could be attractive.
- Prospective studies (IRENA, IEA, Energy Council) consider the cost reduction in the electrolyser price and the electricity from renewable source. It is estimated that around 2035 the green hydrogen could be cheaper than blue hydrogen.
- The two main costs to produce green hydrogen are: electricity (approximately 70-80%) and electrolyser (8-15%).

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Any questions?

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3. Electrolyser Cost Development

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Will the increased demand for electrolysers lead to cost reductions?

Test your knowledge

“What do you think will drive the reduction of electrolyser costs in future?”

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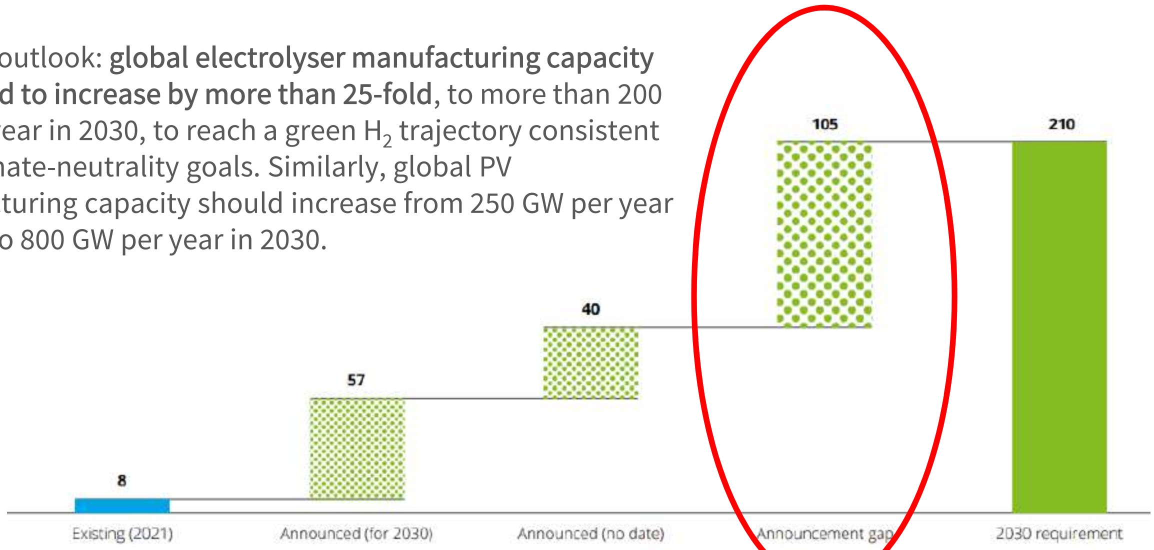
Global electrolyzer manufacturing capacity required by 2030 (GW per year)

Deloitte outlook: **global electrolyser manufacturing capacity** may **need to increase by more than 25-fold**, to more than 200 GW per year in 2030, to reach a green H_2 trajectory consistent with climate-neutrality goals. Similarly, global PV manufacturing capacity should increase from 250 GW per year in 2021 to 800 GW per year in 2030.



Deloitte (2023) Green hydrogen: Energizing the path to net zero, p.24/fig.9.

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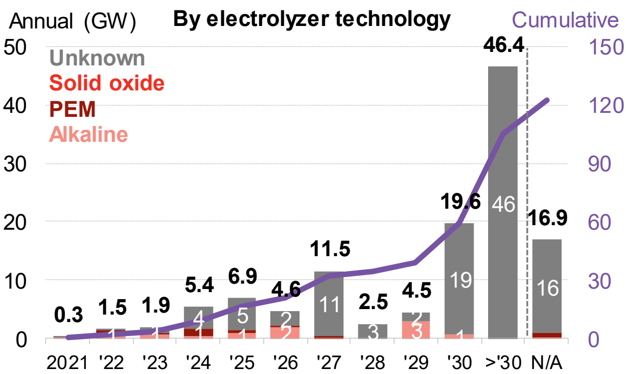
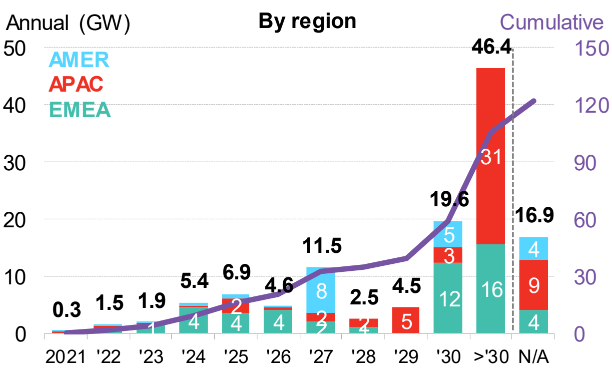
3. Electrolyser Cost Development

Forecast: Announced Electrolysis Pipeline – siginifcant increase of capacities worldwide will lead to further cost reductions





Source: BloombergNEF, 2022.

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Critical material content of key electrolysis technologies

Different electrolyser technologies have **complementary critical material(CRM) requirements**
→ **protection** against disruption in **supply** of some CRM + can put **strategic value on technology diversification.**

Currently, most widespread: alkaline electrolysis, largely reliant on nickel with no significant risk of reserve depletion

*Table for material consumption to install **1 MW** of electrolysis*

Technology	Mineral	Content (kg/MW)
Alkaline	Nickel	800 to 1,000
	Zirconium	100
PEM	Platinum	0.3
	Iridium	0.7
Solid oxide electrolysis cells (SOEC)	Nickel	150–200
	Zirconium	40
	Lanthanum	20
	Yttirum	< 5

Deloitte (2023) Green hydrogen: Energizing the path to net zero, p.25/fig.10.

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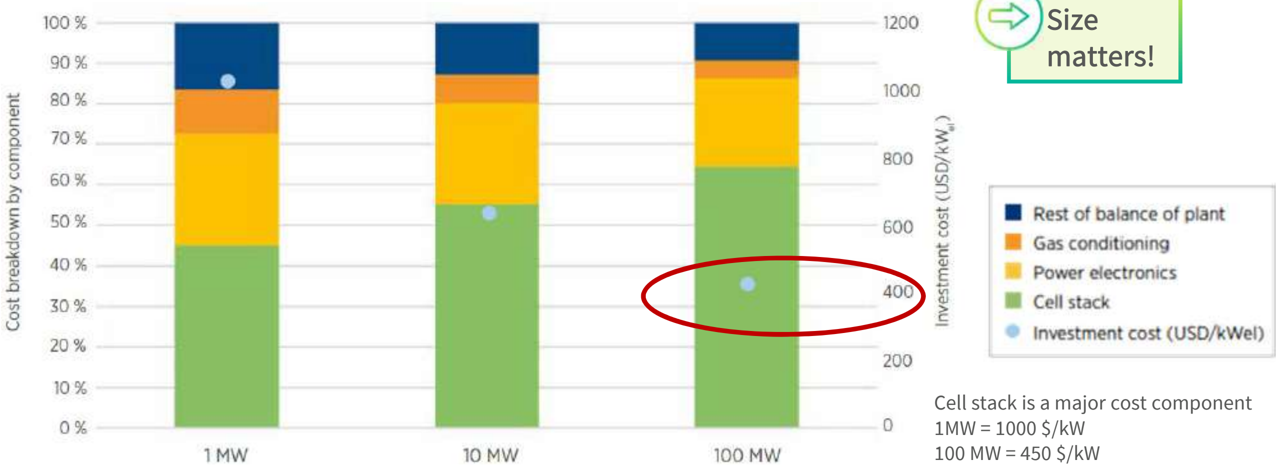
3. Electrolyser Cost Development

Cost Factor: Type of Electrolyser

Cost breakdown for alkaline electrolysers (2020)



Size matters!

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

Source: Based on IRENA analysis, based on Böhm et al. 2020
Source: IRENA, Green Hydrogen Cost Reduction, 2020, p.71/fig.25.

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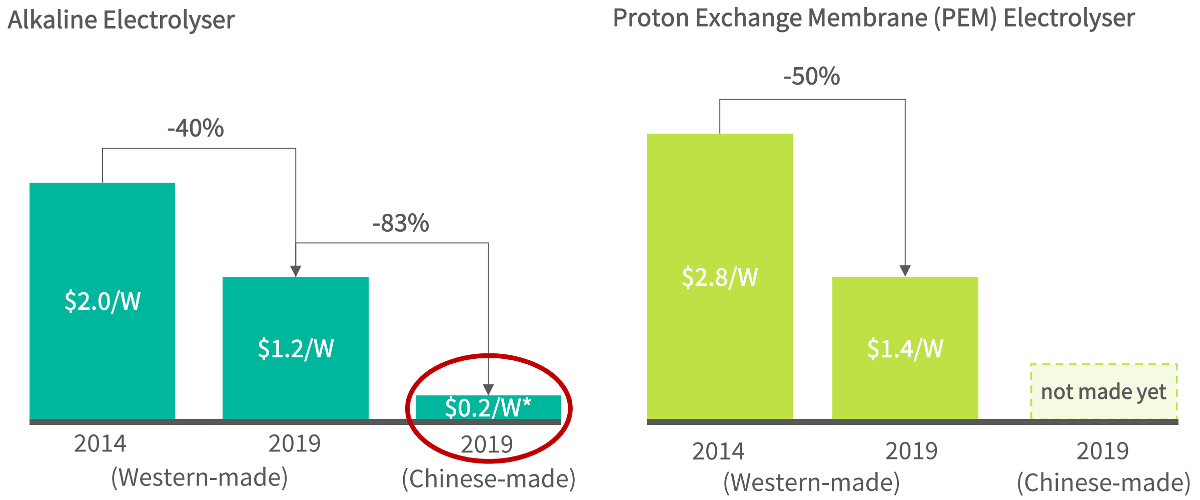
3. Electrolyser Cost Development

Cost Factor: Type of Electrolyser

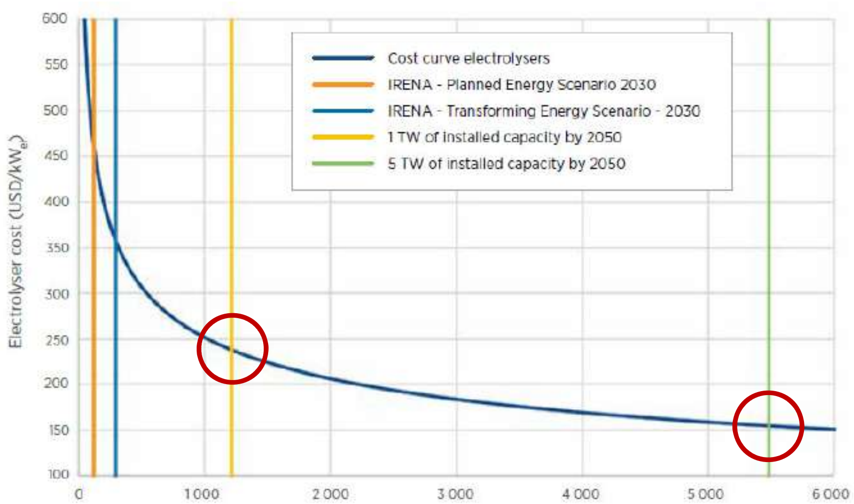
Costs have decreased due to increased demand



*approximate values and subject to change according to technological improvements and material costs.
Source: Own illustration based on: BloomberNEF, Hydrogen Economy Outlook, 2020.

3. Electrolyser Cost Development

Cost Forecast: Development 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.

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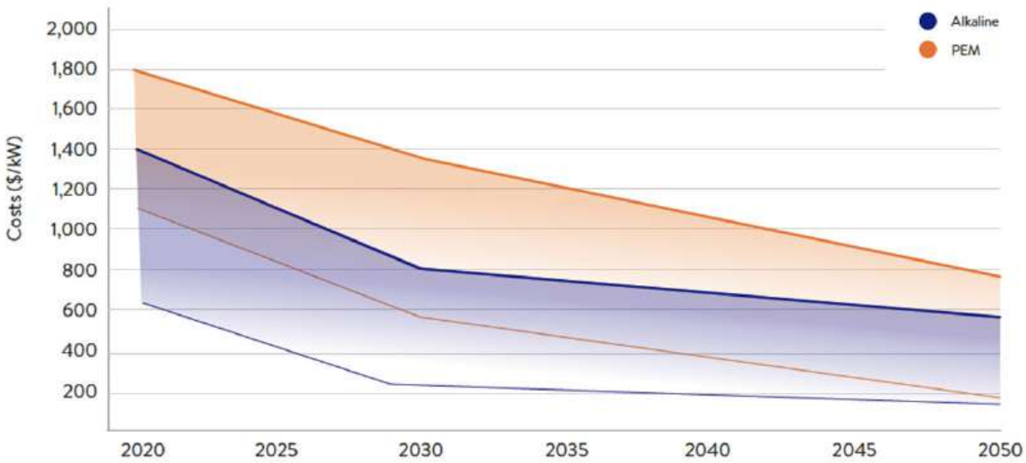
3. Electrolyser Cost Development

Costs for PEM and alkaline electrolyzers expeted to decrease due to market ramp-up



World Energy Council. Hydrogen demand and cost dinamics. Working paper, 2021. <https://www.worldenergy.org/assets/downloads/Working_Paper_-_Hydrogen_Demand_And_Cost_Dynamics_-_September_2021.pdf

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Key take-aways: Electrolyser Cost Development

- Over the last years, several new electrolyser projects have been initiated and build, leading to an off-take of the electrolyser industry
    - Currently largest installation of 10 MW PEM will soon be passed by 100 MW installations
- With the growing demand, the industry is maturing and costs are decreasing due to economies of scale, improved production and higher efficiency
- Thus, electrolysers – both Alkaline and PEM technology – will be developed further with costs decreasing


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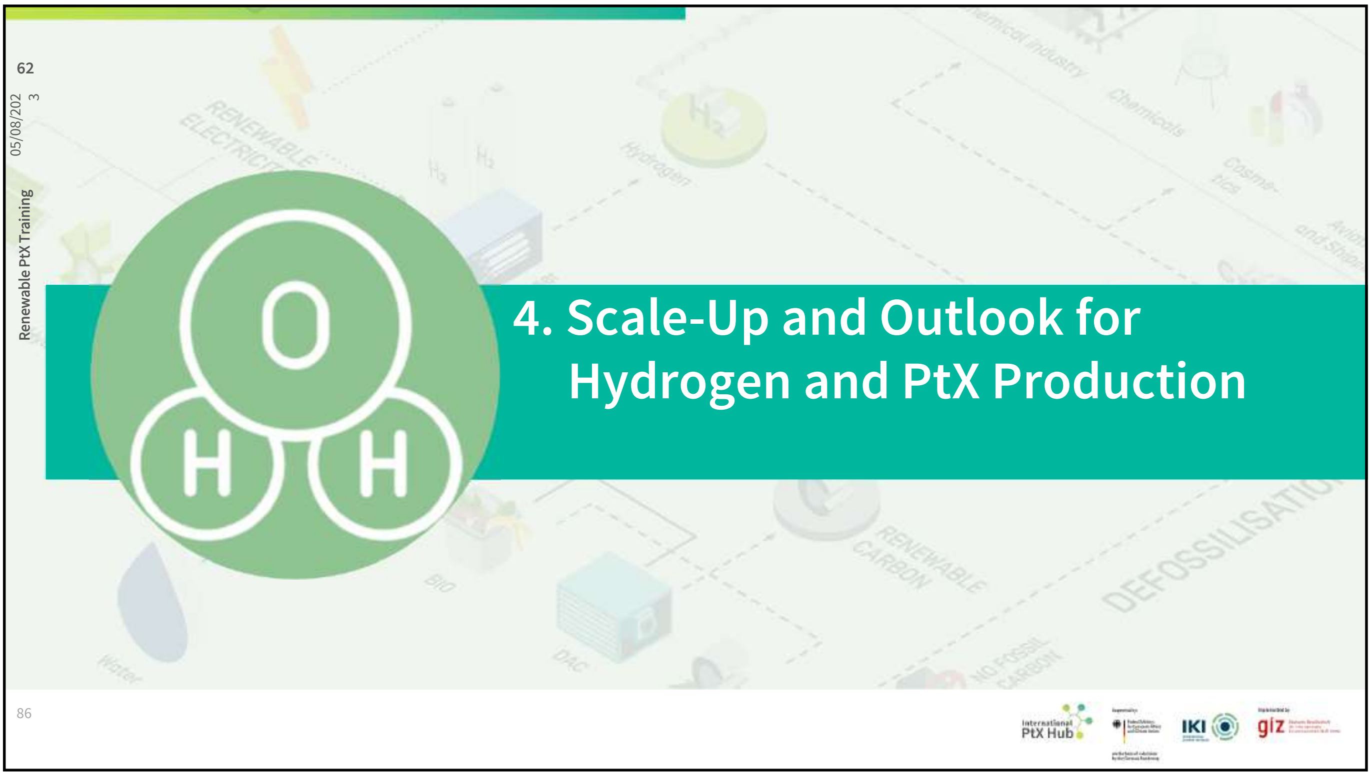
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Renewable PtX Training
4. Scale-Up and Outlook for Hydrogen and PtX Production
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RENEWABLE ELECTRICITY
Hydrogen
Chemicals
RENEWABLE CARBON
DEFOSSILISATION
Water
DAC
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How may the cost s of green hydrogen develop in the future?

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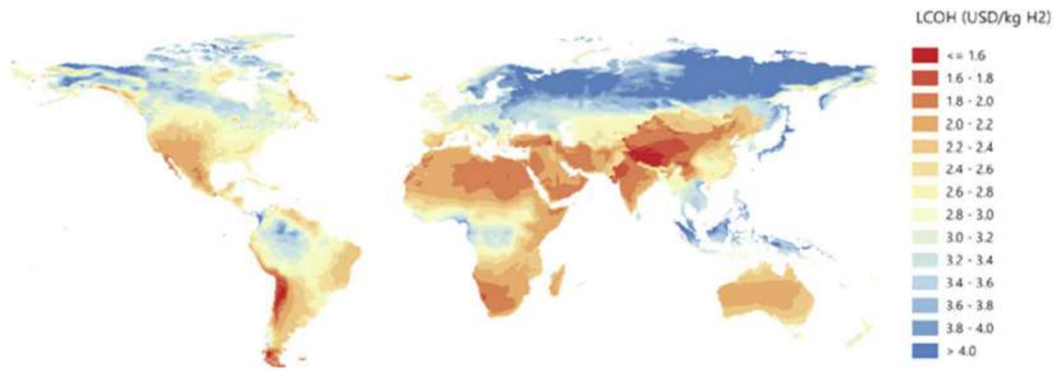
4. Scale-Up and Outlook for H2 and PtX Production

Cost Factor: Combination of Wind and PV

Current production cost of green hydrogen depending on combination of Wind and PV



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

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

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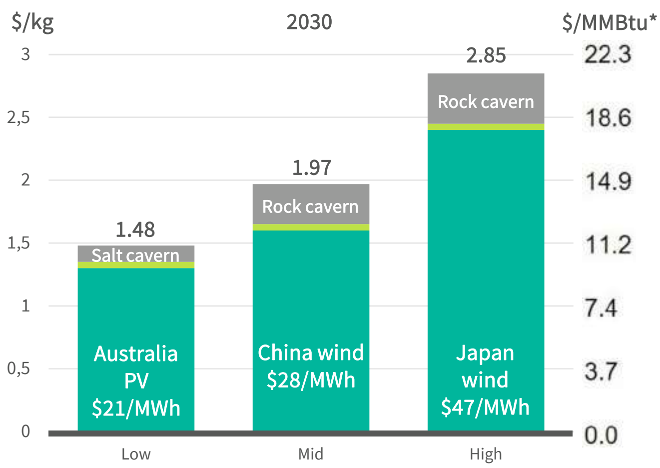
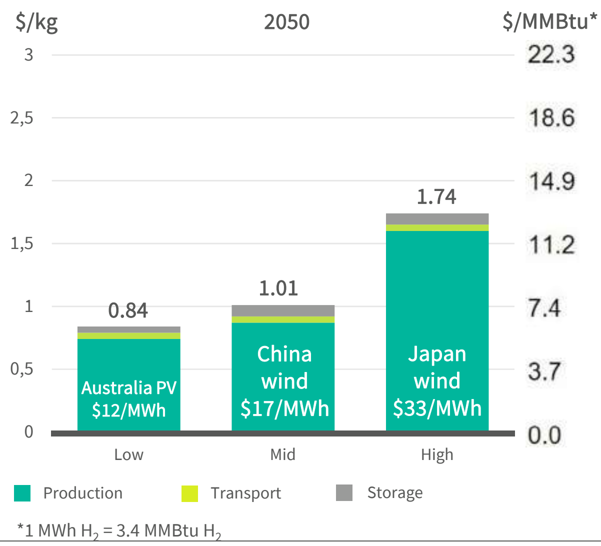
4. Scale-Up and Outlook for H2 and PtX Production

Cost depends mainly on RE power costs!





Note:
- Storage costs assume 50% of total hydrogen demand passes through storage.
- Transport costs are for a 50km transmission pipeline movement.
- Compression and conversion costs are included in storage

89 Source: BloombergNEF, Hydrogen Economy Outlook, 2020, p.5.

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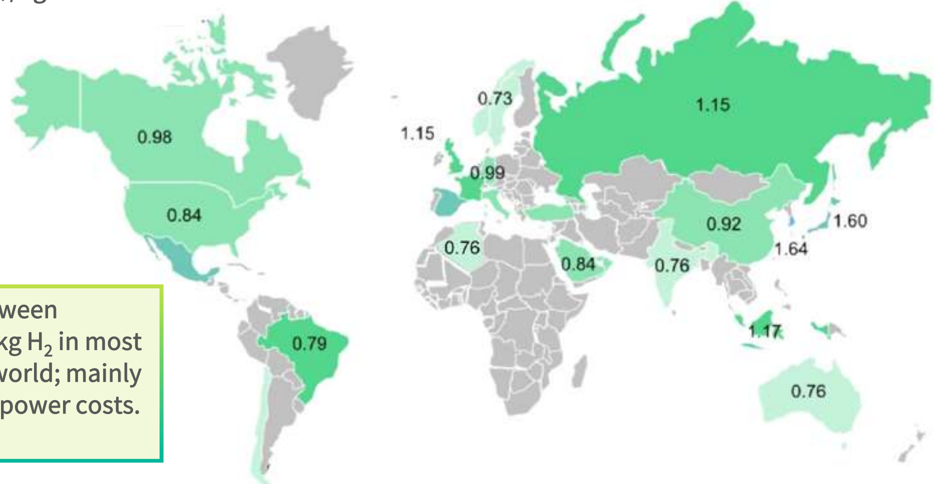
4. Scale-Up and Outlook for H2 and PtX Production

Outlook: Green Hydrogen Production Costs

LCOH2 (green) in $/kg H2 for latest 2050



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

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

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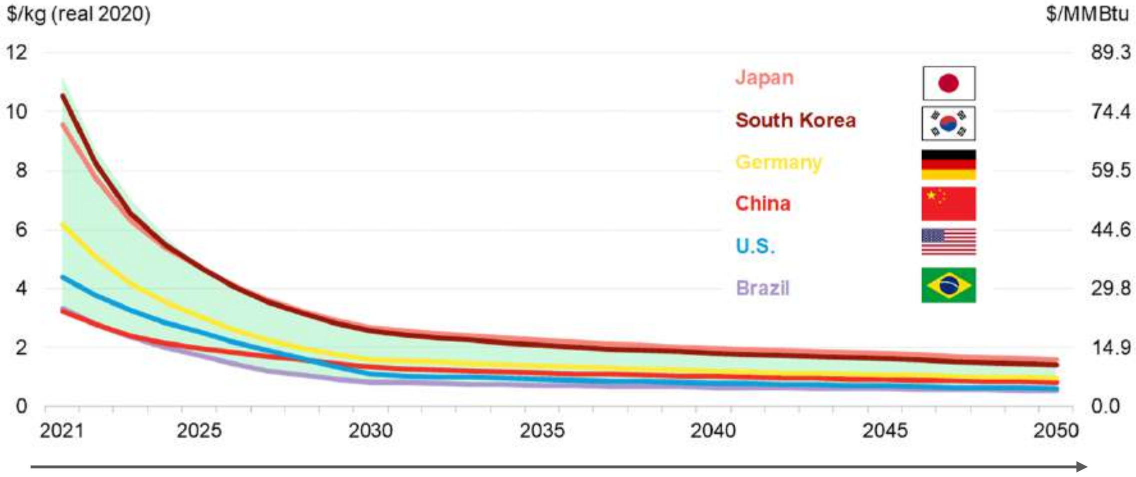
4. Scale-Up and Outlook for H2 and PtX Production

Outlook: Green Hydrogen Production Costs

LCOH2 from renewable electricity



Source: BloombergNEF.

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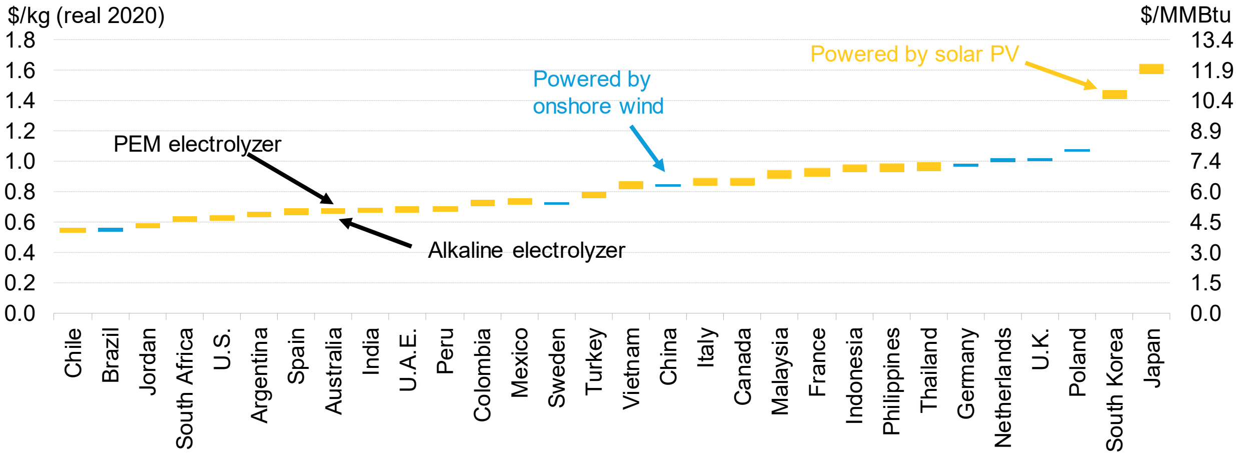
Outlook: Green Hydrogen Production Costs – great chances for countries with rich renewbales potentials

LCOH2 from renewable electricity (2050)



Source: BloombergNEF, 2022.

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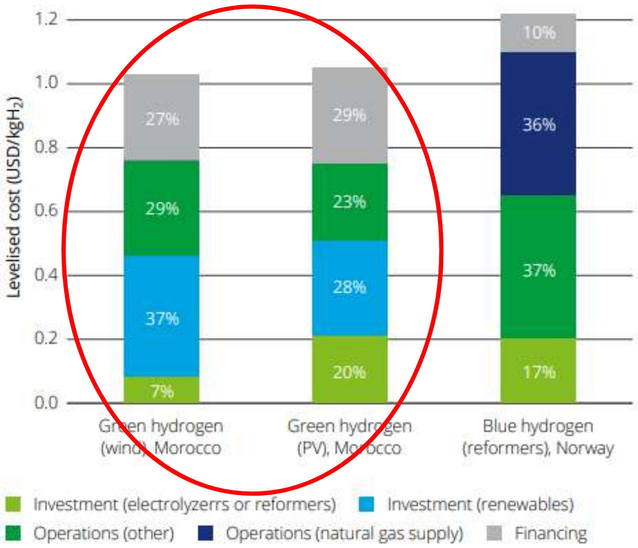
Example: Breakdown of pure clean H_2 production cost in Morocco 2050 (illustration)



Investment costs only cover depreciation of assets, while financing costs incl. interests and dividends payments over asset lifetime.

*Note: For greenH_2, this analysis **assumes electrolysers are powered solely by off-grid RE capacities**, hence a crucial impact of load factors. As wind technologies have higher load factors than photovoltaic cells (PV), they require less electrolyser capacity to produce the same amount of hydrogen. However, the cost of wind turbines is higher than solar panels.*
Hence, investments in installed capacities of electrolysers and RE are optimized to take advantage of local wind and solar irradiation patterns.

Deloitte (2023) Green hydrogen: Energizing the path to net zero, p.19/fig.6.

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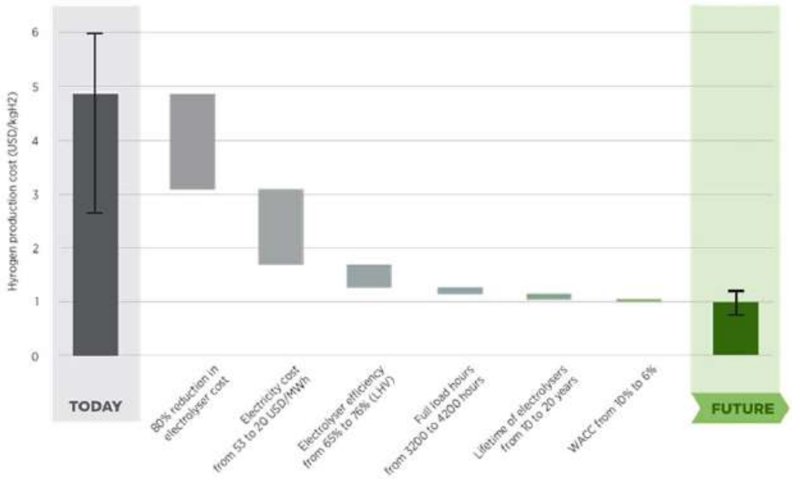
4. Scale-Up and Outlook for H2 and PtX Production

Outlook: Green Hydrogen Production Costs

85% reduction of green hydrogen production costs in the future



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

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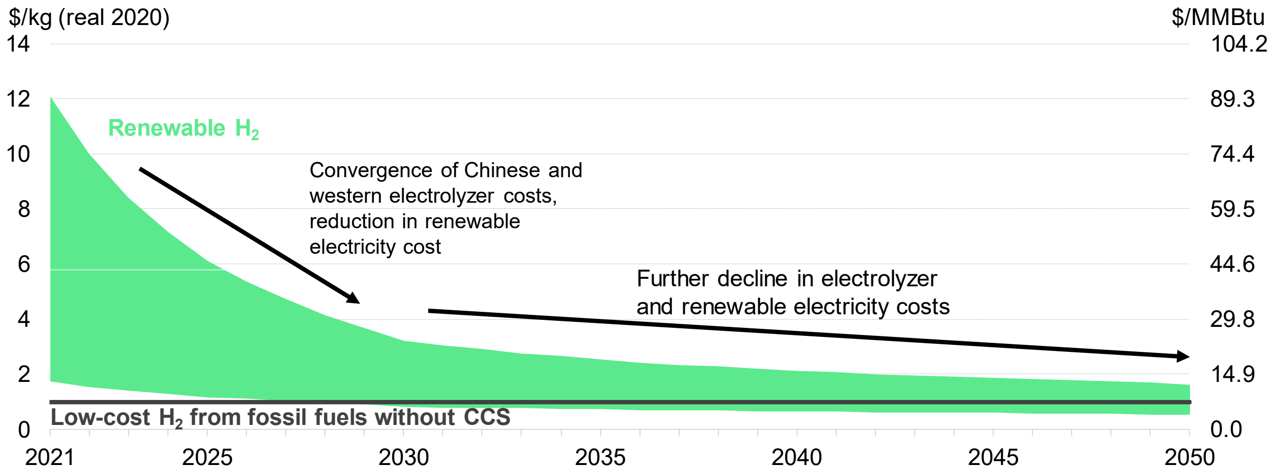
Outlook: Green Hydrogen Production Costs

LCOH2 from cheapest available renewable power in 30 countries



91.1 Source: Bloomberg NEF, 2022.

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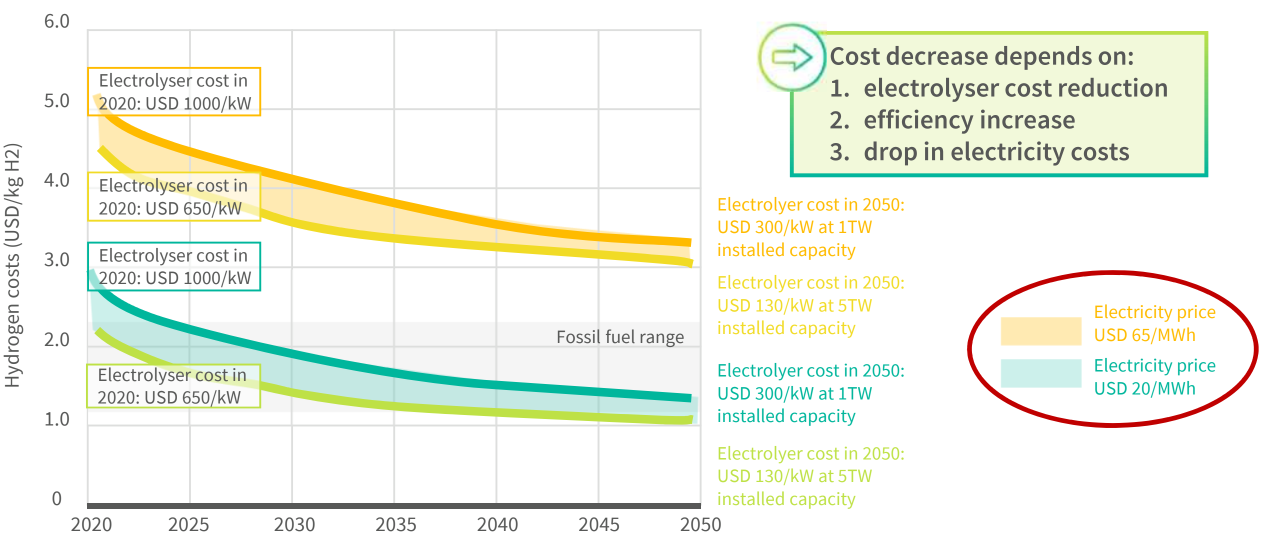
4. Scale-up and Outlook for H2 and PtX Production

Outlook: Green Hydrogen Production Costs



Cost decrease depends on:
1. electrolyser cost reduction
2. efficiency increase
3. drop in electricity costs

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

Any questions?

And what does this mean: is there a chance that green hydrogen will become cheaper than blue or grey hydrogen, or even natural gas?

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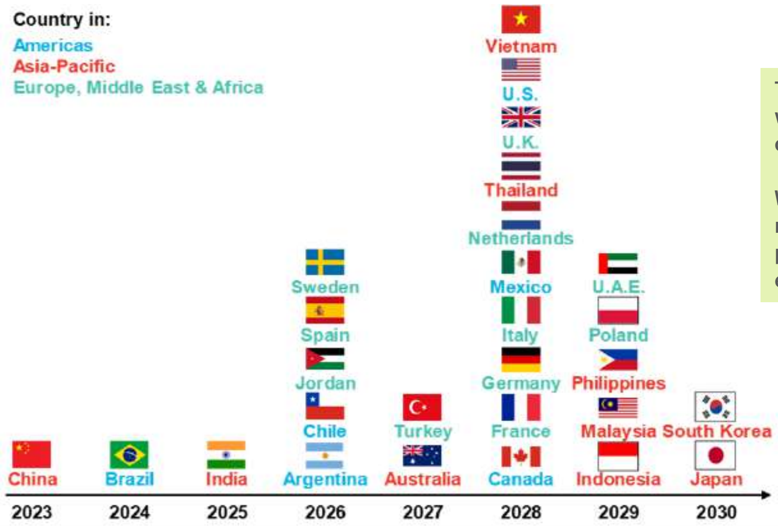
4. Scale-Up and Outlook for H2 and PtX Production

Outlook: Green H2 becoming more competitive than Blue H2



The graph shows where and when green hydrogen will be cheaper than blue hydrogen

With curent high price levels of natural gas, this break-even point may be reached even earlier

Source: BloombergNEF, 2022.

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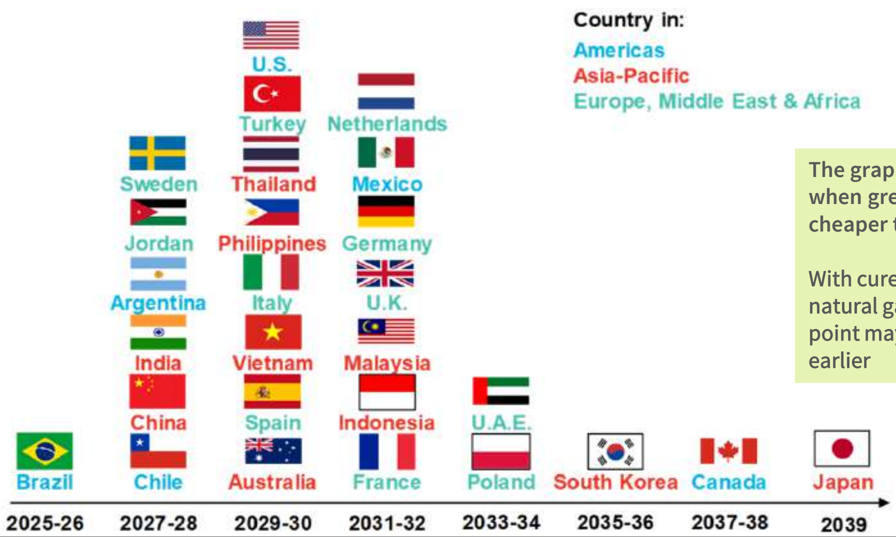
Outlook: Green H2 becoming more competitive than Grey H2



The graph shows where and when green hydrogen will be cheaper than grey hydrogen

With curent high price levels of natural gas, this break-even point may be reached even earlier

Source: BloombergNEF, 2022.

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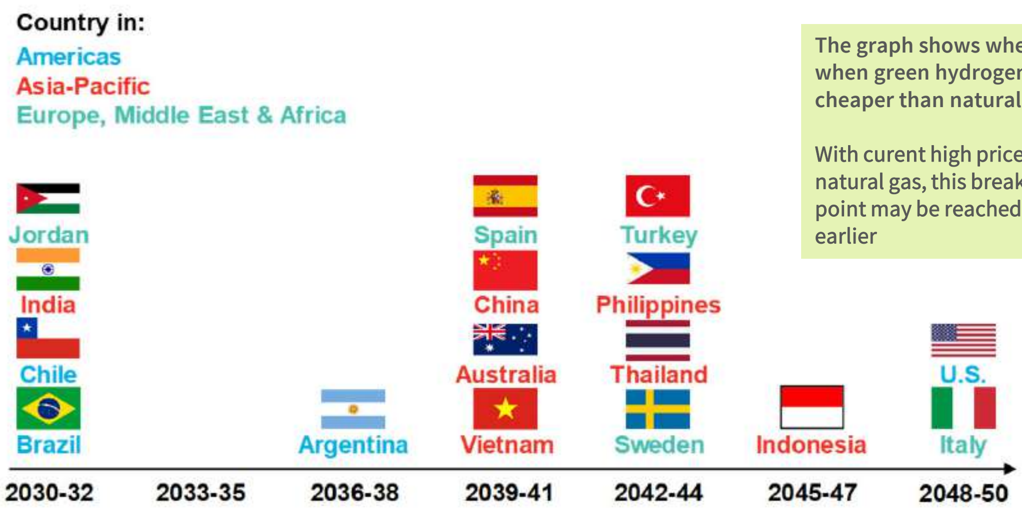
Outlook: Green H2 becoming more competitive than Natural Gas



The graph shows where and when green hydrogen will be cheaper than natural gas

With curent high price levels of natural gas, this break-even point may be reached even earlier

Source: BloombergNEF, 2022.

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Any questions?

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Test your knowledge

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

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Which impact has the scale-up and cost decrease of green hydrogen on the costs of PtX products?

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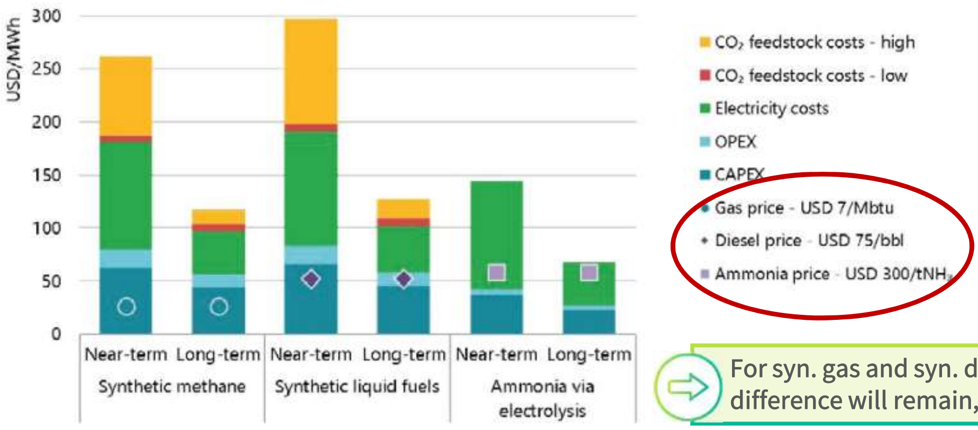
4. Scale-up and Outlook for H2 and PtX Production

Outlook: Production Costs of Different PtX Products



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

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

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

For syn. gas and syn. diesel a large price difference will remain, not for ammonia.

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

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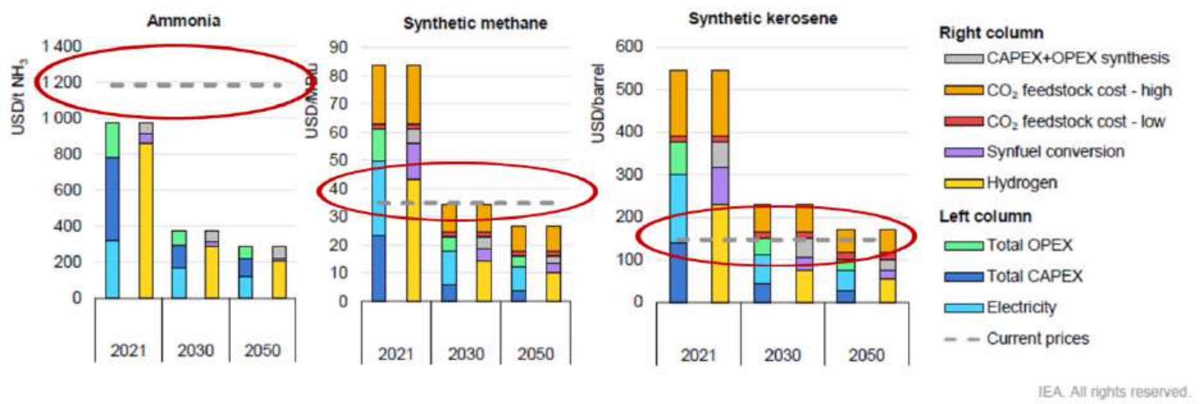
4. Scale-up and Outlook for H2 and PtX Production

Outlook: Production Costs of Different PtX Products

Levelised costs of ammonia, synthetic methane and synthetic kerosene for electricity-based pathways in the Net Zero Emissions by 2050 Scenario, 2021, 2030 and 2050



Source: IEA, (2022), *Global Hydrogen Review*, p. 103

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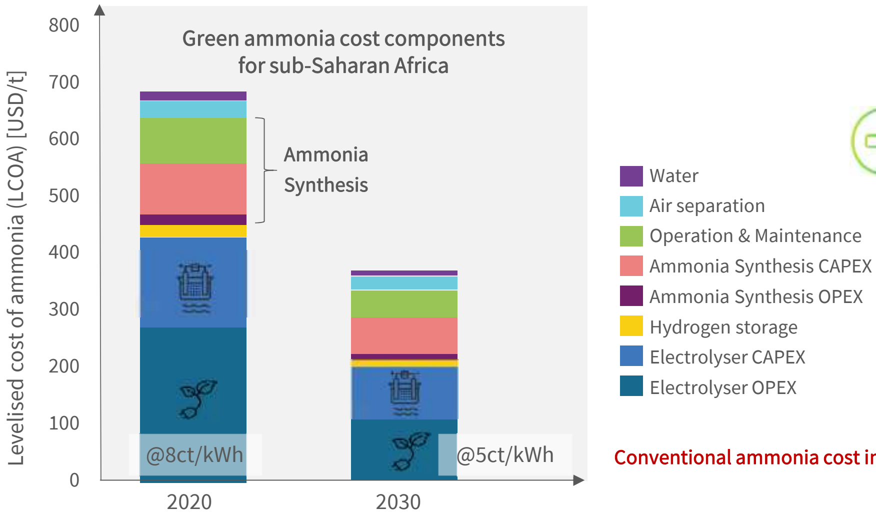
Outlook: Green Ammonia Production Costs



Costs are determined by costs of green hydrogen.

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

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

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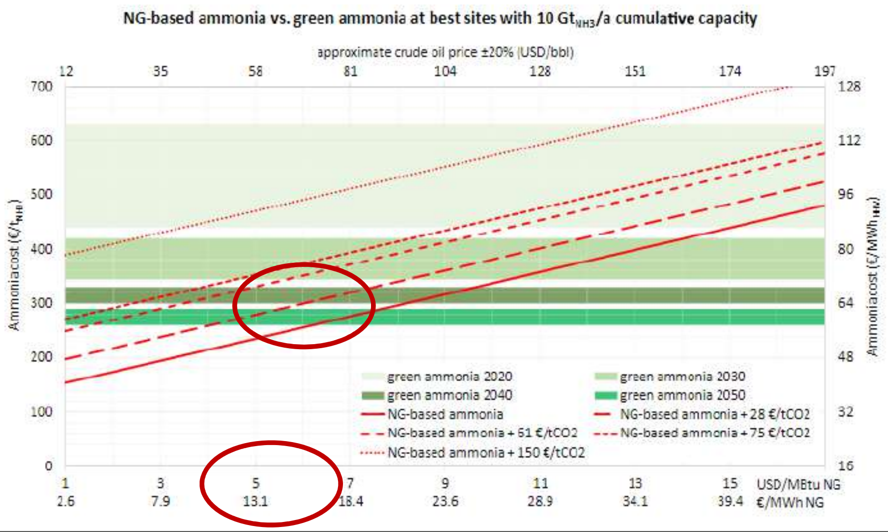
Outlook: Green Ammonia Production Costs



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

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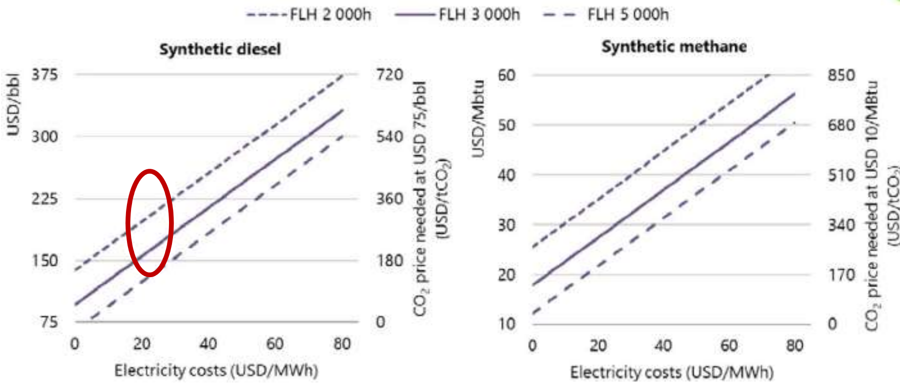
4. Scale-up and Outlook for H2 and PtX Production

Outlook: Synthetic Diesel and Synthetic Gas Production Costs

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



For syn. fuels and syn. gas to be competitive to fossil fuels,

- low electricity costs
- high CO_2 prices
- and higher FLH compensate electricity costs

are needed!

- **Production cost for synthetic shipping fuel and methane.**
- **CO_2 price needed to reach competitiveness with fossil fuel at USD 75/bbl and with natural gas at USD 10/Mbtu.**

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

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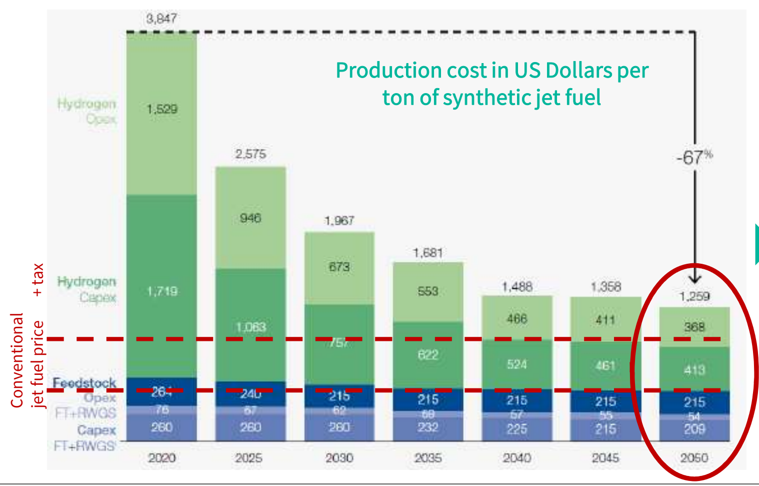
4. Scale-up and Outlook for H2 and PtX Production

Outlook: Synthetic Jet Fuel Production Costs

Potential for cost decline by 70% in 2050



Water electrolysis + RWGS

H_2 costs can vary greatly by power source and region

shown for solar power-based H_2 at

- 7.3 USD/kg H_2 in 2020
- 3.2 USD/kg H_2 in 2030
- 1.7 USD/kg H_2 in 2050

CO_2 feedstock

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

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

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Any questions?

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How will the scale-up of green hydrogen and renewable PtX creat value and business opportunities?

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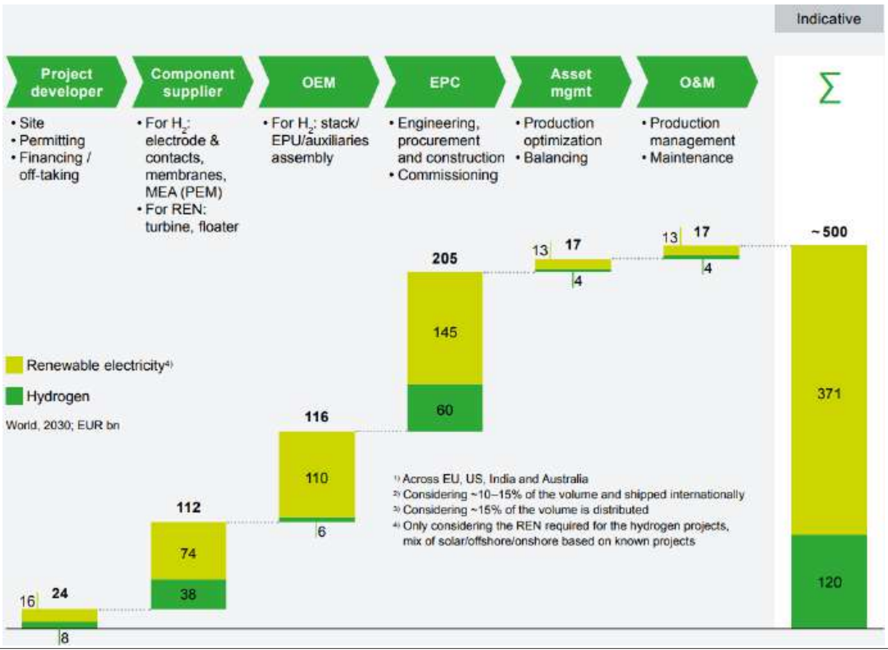
Where does the value lie? Global green H_2 value added pool along the value chain, 2030

- value-added pool for the H_2 part of projects up to EUR 120 billion
- value added pool for RE part up to EUR 371 billion
- Europe accounts for 40%



Roland Berger (05/2023) How to capture value in the emerging hydrogen market, p.7/C.

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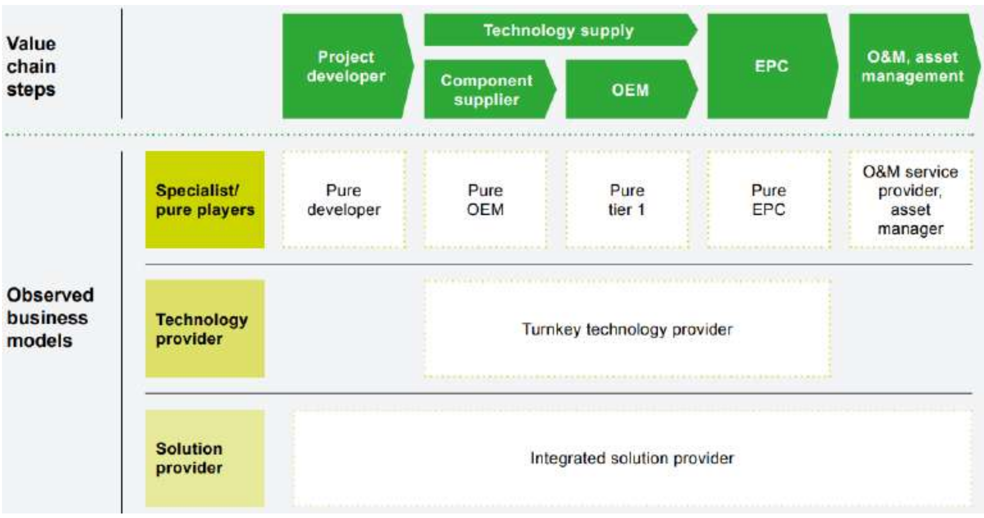
Who's doing what? Current business models in green hydrogen production projects

- Currently, players often participate in green H_2 projects as part of a **consortium, to gain experience while sharing the risk** with others
- Mature markets: companies **understand risks and profit pools better** and will **adapt their business models** to capture more value



Roland Berger (05/2023) How to capture value in the emerging hydrogen market, p.8/D.

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Key take-aways: Scale-Up and Outlook for Hydrogen and PtX Production

- With the ramp-up of the global green hydrogen market, prices are expected to fall
- Countries with rich and abundant renewables potentials will provide cheap green hydrogen to the world market, with the perspective of prices below $1 per kg hydrogen in 2050
- In the long run, green hydrogen has the perspective to be more competitive (= cheaper) than blue hydrogen, than grey hydrogen and finally outcompete natural gas
    - When and where depends mainly on the countries renewables resources
    - The recent increases of gas market prices will accelerate this process
- Thus, in the long run, green hydrogen will be a competitive option in the energy market

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Any questions?

Conclusions

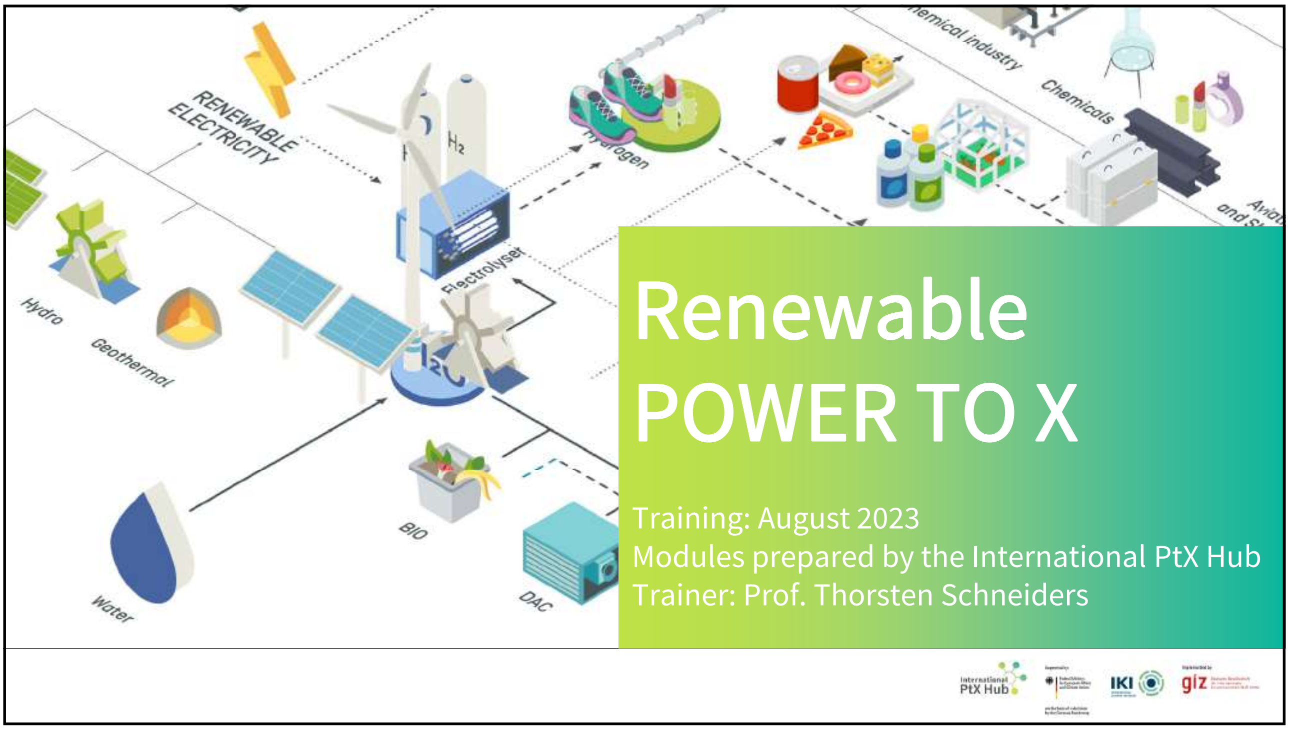
MODULE 3: Renewable PtX economics - Key Take-Aways

1. Production Cost of Green Hydrogen

- Four **main parameters are critical for economic viability of green hydrogen production**:
  - cost of renewable electricity used in the process (levelised cost of electricity: LCOE, u p to 80% share)
  - electrolyser capital expenditure (up to 15% share)
  - number of operating hours (load factor) on a yearly basis (which depends of the renewable energy mix)
  - transport and storage considerations

2. Renewable Energy Generation Cost Development

- Levelized Cost of Electricity **(LCOE) of Renewables** has **come down by 80-90%** in the last decades while technologies and production technology matured. **Further cost reduction is expected**, especially for solar **(PV).**
- Many countries and regions in the world have good wind and solar conditions to **achieve sufficient Full Load Hours (FLH) through a combination of PV and Wind.**
- **However, massive RE deployment is necessary** since **1 GW electrolysis comes with 1-4 GW** of **additional** renewables! But this represents a chance for additional investments into renewables driven by the PtX market.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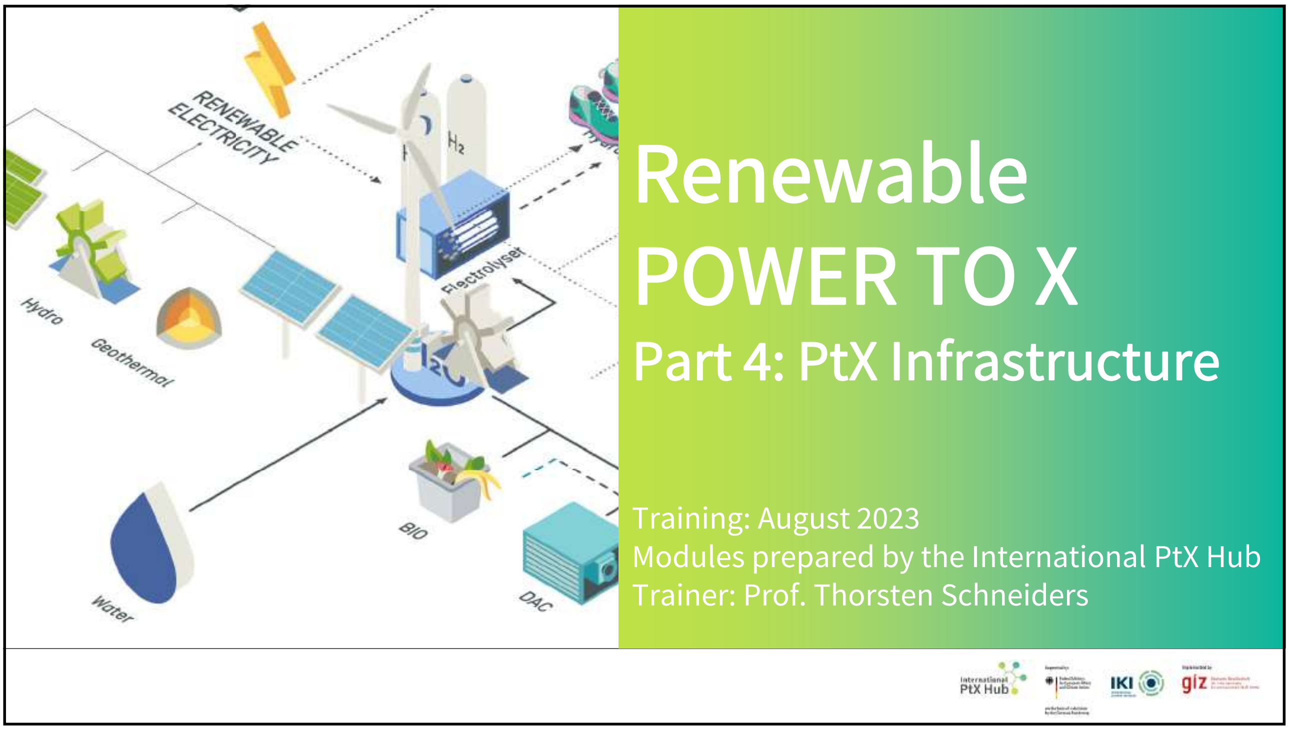
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Agenda

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

2 Production Pathways of Renewable PtX
What is needed for PtX, incl. green hydrogen

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

4 PtX Infrastructure
How to transport and store PtX products (incl. gH_2) best?

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

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

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

List of abbreviations

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

Key Conversion Data

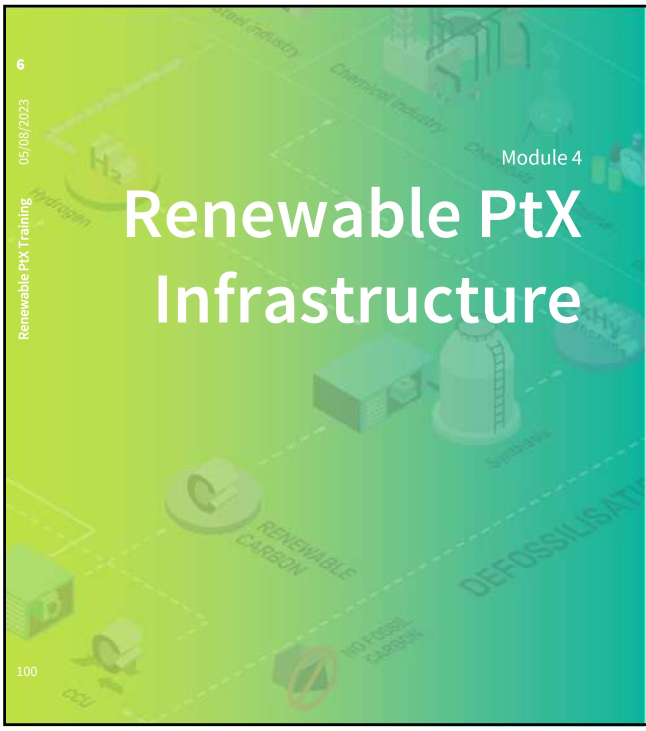
- 1 kWh H_2= 3.6 MJ H_2
  1 MWh H_2 = 3.4 MMBTU H_2
  1 MJ H_2 = 0.277 kWh H_2

Conversion kWh and kg H_2:

- 1 kg H_2 = 33.3 kWh H_2 *(heat unit Hu /calorific value)*
- 1 MWh H_2 = 30 t H_2
- 1 Mio t H_2 = 33 TWh H_2

Monetary value per weight or calorific value

- 4.5 ct/kWh H_2 = 45 €/MWh H_2 = 1.5 €/kg H_2
  or: 1€/kg H_2 = 3 ct/kWh H_2
- 100 €/MWh H_2 = 3.33 €/kg H_2
  or: 1€/kg H_2 = 30 €/MWh H_2



Module 4

Renewable PtX Infrastructure

1. Transport Options
   - Long vs. shorter distances
   - Different PtX products (hydrogen derivatives)
2. Storage Options
   - Physical storage vs. Material storage
   - Storage stages of the product (liquid, gaseous)

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1. Transport Options

- Long vs. shorter distances
- Different PtX products (hydrogen derivatives)

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What are the properties of hydrogen in terms of energy per kg and m^3, which we need to consider for the transport?

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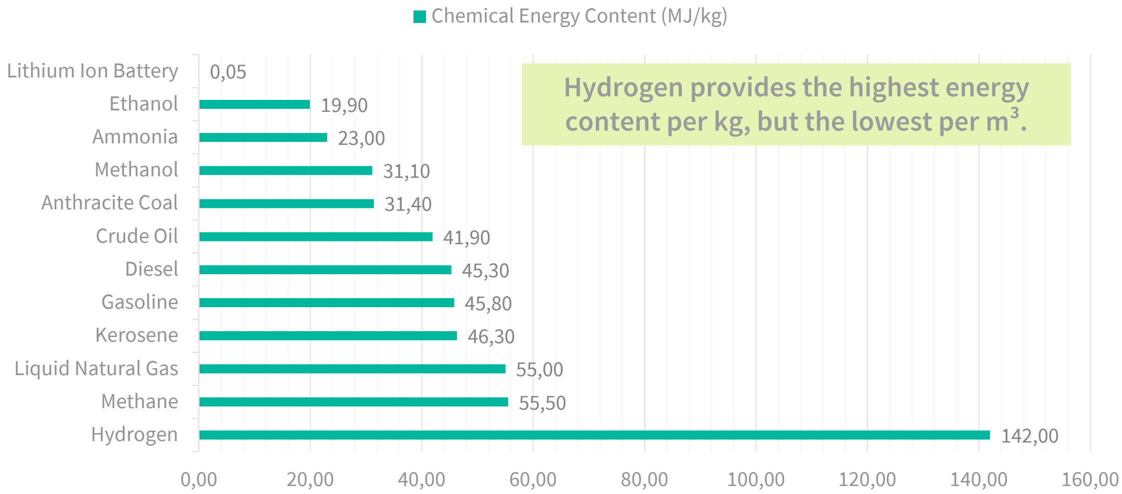
1. Transport Options

Energy Content per Unit Weight (MJ/kg)



16 Figure: Adapted from strategy&, (2020), Unlocking South Africa's Hydrogen Potential, p.6, fig.1.

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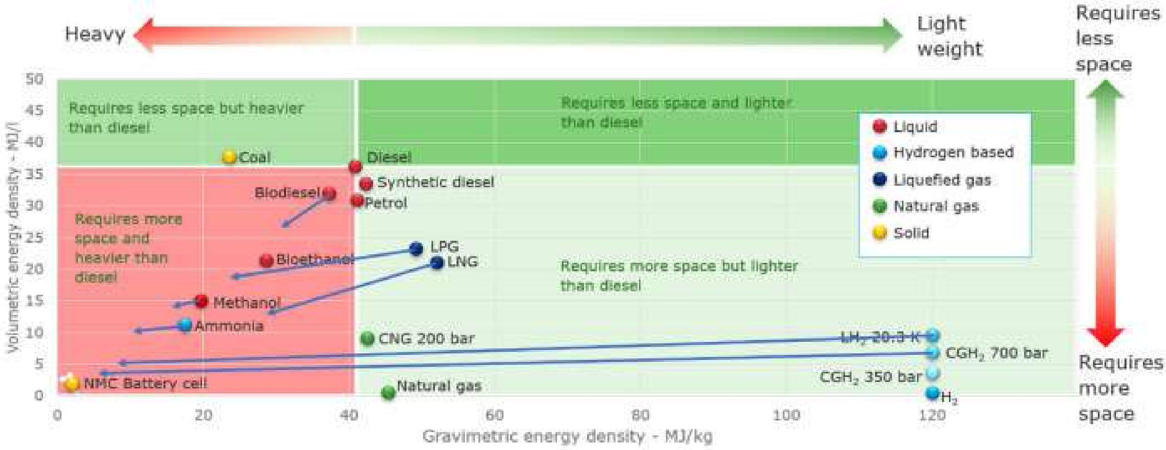
1. Transport Options

Energy Content per Unit Weight (x) and Volume (y)



17 Figure: DNV GL AS Maritime Environment Advisory, (2019), *Comparison of Alternative Marine Fuels*, p.4/fig.1.

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Test your knowledge

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

"What is the most expensive option of H_2 transport?"

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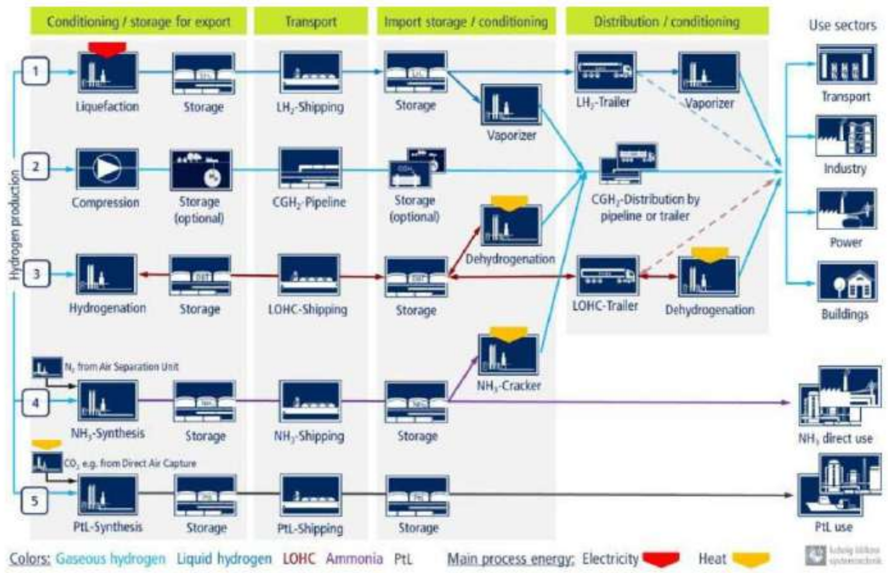
How can we transport Green H_2 or renewable PtX products over a local, international or even global distance?

13 Will we soon see LH2 vessels sailing on the seas? (Compare to LNG vessels)

14 **3.1. Transport**

Different transport route pose different challenges and infrastructure needs



1. Liquid H_2 (LH_2) per ship
2. Compressed H_2 (CGH_2) per pipeline
3. Liquid Organic H_2 Carrier (LOHC) per ship or pipeline
4. Ammonia (NH_3) per ship (pipeline)
5. Power-to-Liquid (FT-Crude or methanol) per ship/pipeline

Source: Heinrich Böll, Grundkurs Wasserstoff Teil II, 10/2021.

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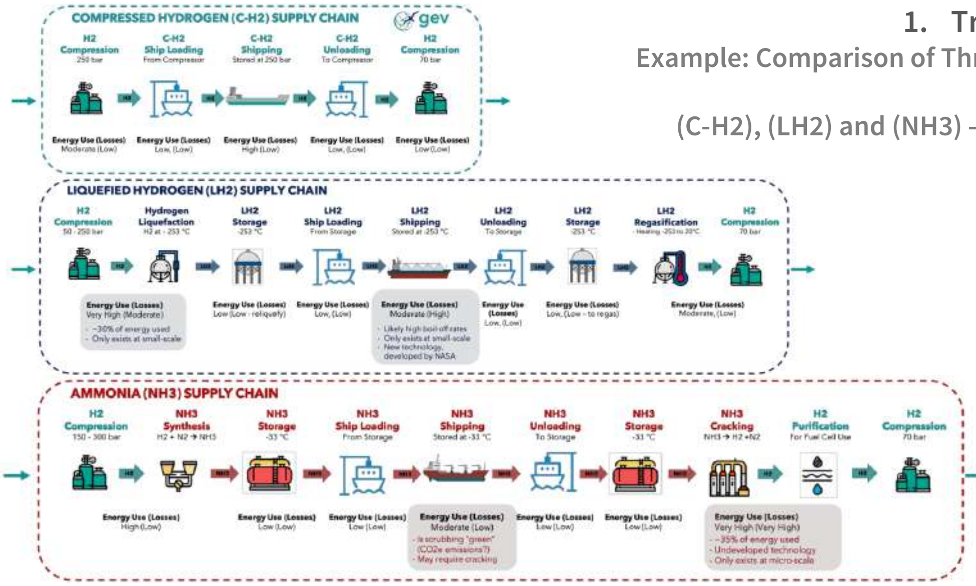
1. Transport Options

Example: Comparison of Three Main Hydrogen Supply Chains:
(C-H2), (LH2) and (NH3) – Western Australia



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

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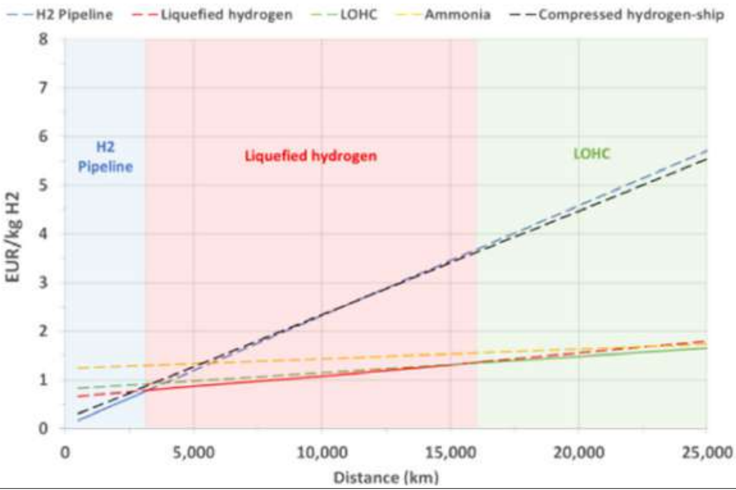
1. Transport Options

Cost Factor: Distance – the furher away the customer, the more economic is the conversion of H2 into PtX products



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

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

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

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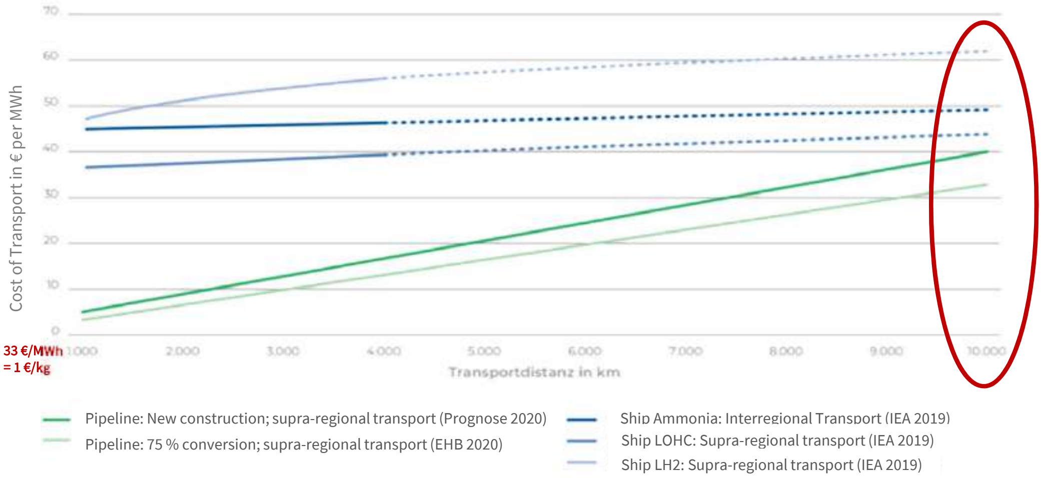
1. Transport Options

Cost Factor: Distance



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

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

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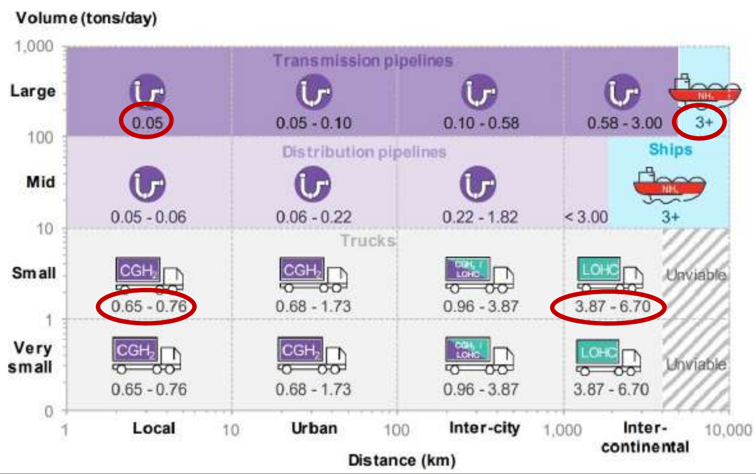
1. Transport Options

Cost Factor: Distance and Volume – trucks should only be used for short distance

H_2 transport in \$/kg H_2 in 2019



Legend:

Compressed H2
Liquid H2
Ammonia
Liquid Organic Hydrogen Carriers

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

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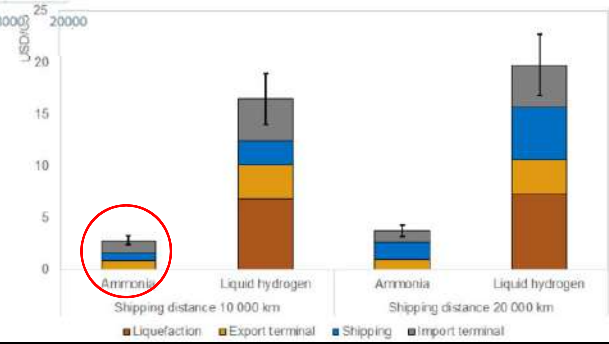
1. Transport Options

Marine transport cost estimates for ammonia and liquid H_2

Shipping H_2 in the form of NH3 has advantages over LH2 shipping!

Estimated green ammonia shipping cost (using a fuel cost of 500 USD per t ammonia)
The dashed lines represent estimated shipping costs for a low (300 USD per t) and high (700 USD per t) case.



107 Sustainable Energy Fuels, Green ammonia as a spatial energy vector: a review,2021 (5), p.2821/f
Source: IEA, The Role of Low-Carbon Fuels in the Clean Energy Transitions of the Power Sector, (

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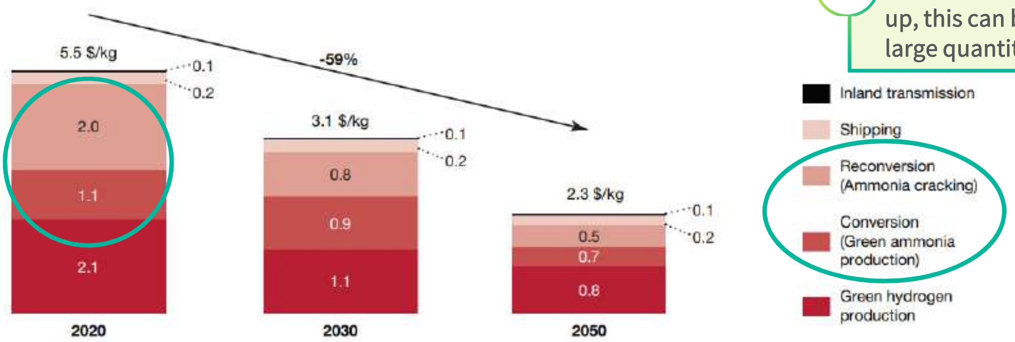
1. Transport Options

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

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

If infrastructure can be build up, this can be an option for large quantities



% of total landed cost			
5%	9%	12%	Shipping and transmission
57%	55%	53%	Conversion and reconversion
38%	36%	35%	Green hydrogen production

Source: Dr. Ulrich Koegler, James Thomas, and Susie Almasi, "How the GCC can become a force in global green hydrogen: The green ammonia supply chain," Strategy&, 2020.https://www.strategyand.pwc.com/m1/en/reports/2020/how-the-gcc-can-become-a-force-in-global-green-hydrogen.html.

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1. Transport Options

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

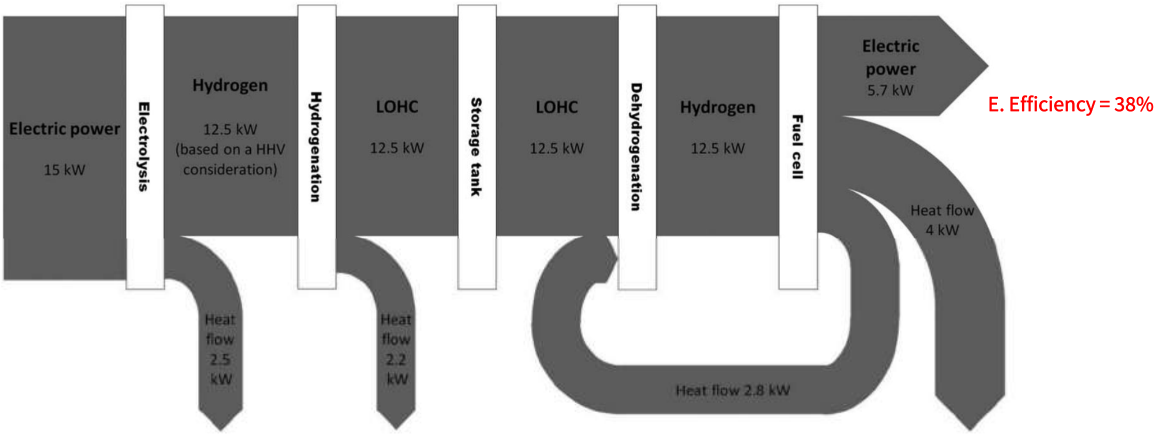

Fig. 5 Sankey diagram of energy fluxes of the complete process, case (1).

Source: Daniel Teichmann et al., Energy storage in residential and commercial buildings via Liquid Organic Hydrogen Carriers (LOHC) in: *Energy & environmental science*, 20 Sep 2012, Vol. 5, Issue 10, p. 9048/fig.5.

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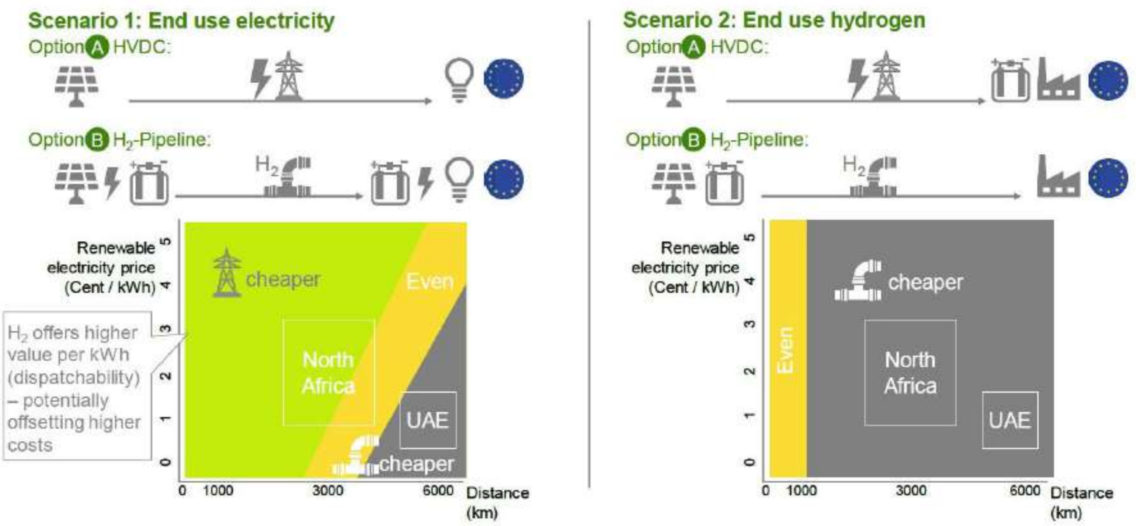
3.1. Transport

Key question: Transport electricity or hydrogen? It depends!

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



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

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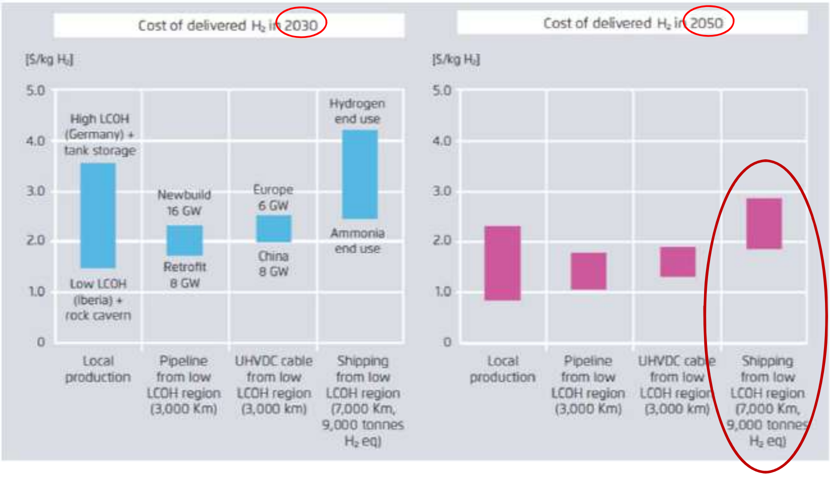
1. Transport Options
Cost Factor: Transport Routes



- Retrofitted pipelines (if available) are cheapest
- Ship-based trade is more suitable for hydrogen-based products or where pipelines are not feasible
- Long-distance transport may be more expensive in the long run than local production in Europe, but Europe will probably have to import in addition to its own production!

110 Source: Agora Energiewende/Agora Industry, 12 Insights on Hydrogen, 2021, p. 33/fig.20.

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1. Transport Options
Cost Factor: Import vs. Domestic Production (2030)

- **Hydrogen pipelines** will keep European industry in business and ensure a firm power market.
- The **EU** should **foster international Power-to-X markets** for sustainable chemicals and for sustainable maritime and aviation fuels.
- **Importing sustainable methanol or synthetic fuels** from places with cheap renewables is more cost-effective than producing them in Germany.

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

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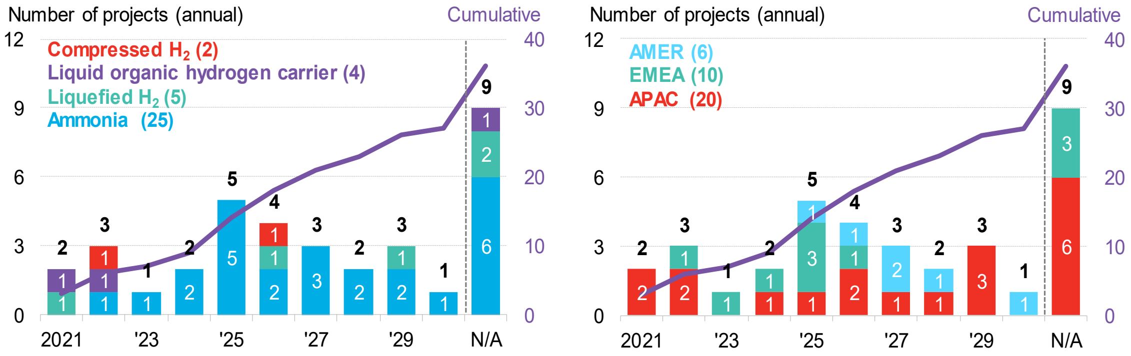
1. Transport Options

Announced pipeline of H_2 shipping projects – so far, only few vessels are available and they are fueld by Disel, not CO2-free fuels (producing transport CO_2 footprint)

By segment | By region



Source: BloombergNEF

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Key take-aways: 1. Transport Options

- Hydrogen can be transported in compressed or liquified from, chemically bound (LOHC) or bound in chemical substances (ammonia, methanol)
- The choice of transport and transport costs of green H_2 or PtX products depends on the distance between producer and consumer, depending on the following factors:
  - **Distance and volume:** H2 pipelines and compressed H2 for smaller quantities and distances are cheaper than liquid organic H2 carriers.
  - **Electricity vs. hydrogen**: The best transportation option between electricity, H2 or higher aggregated products depends mostly on **end use**
  - **Import vs. domestic production:** Importing sustainable methanol or synthetic fuels from places with cheap renewables is more cost-effective than domestic production
- Where available and possible, H2 pipelines (new/refurbished gas pipelines) for compressed H2 can be used
- For large distance overseas transport via ships, liquid H_2 , LOHC or PtX products provide better economics than compressed H_2 due to higher amounts of energy transported in one ship


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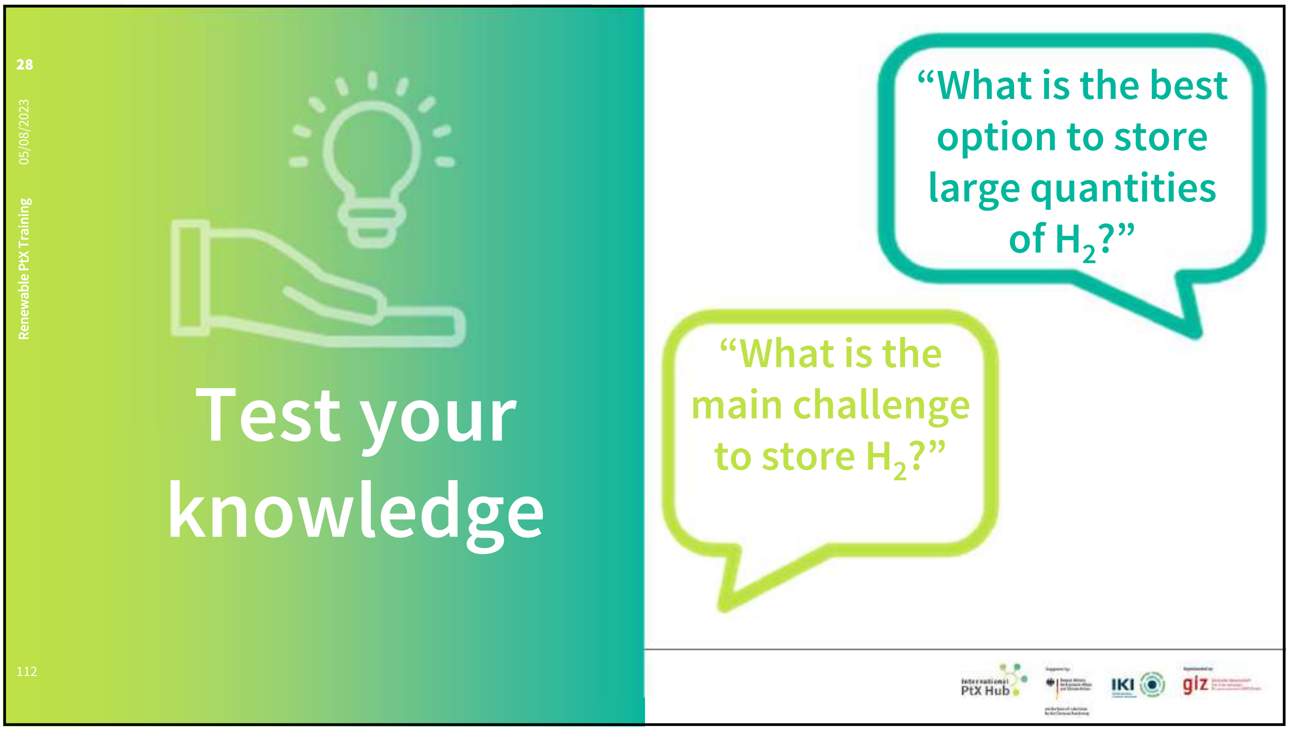
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Test your knowledge
“What is the best option to store large quantities of H2?”
“What is the main challenge to store H2?”
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2. Storage Options

- Physical storage vs. Material storage
- Storage stages of the product (liquid, gaseous)

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How can we store H_2?

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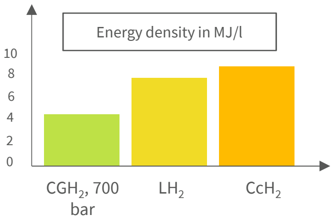
2. Storage Options

Hydrogen storage options

H_2-Storage

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



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

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

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

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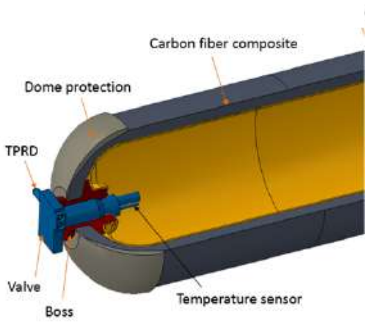
2. Storage Options

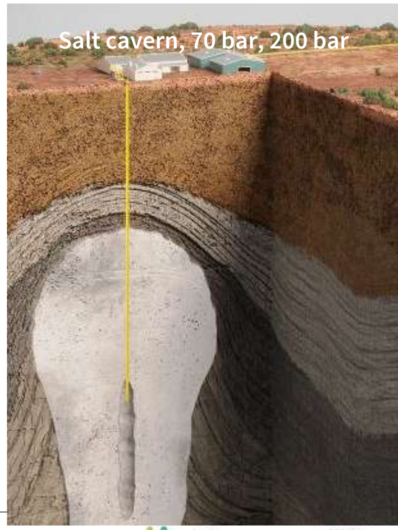
Hydrogen storage options

H_2 tank for vehicles, 700 bar



Stationary H_2 tank, 200 bar

Salt cavern, 70 bar, 200 bar



Source: Geosciene Australia, 2022

Source: Office of Energy Efficiency and Renewable Energy, 2022

Source: Office of Energy Efficiency and Renewable Energy, 2022

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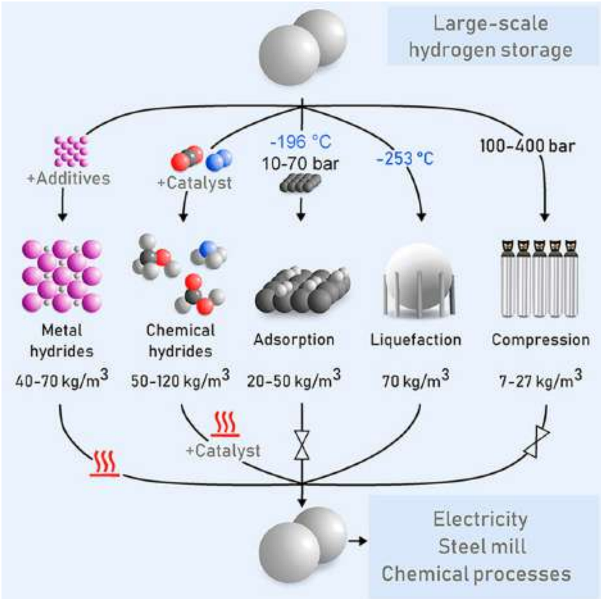
2. Storage Options

Comparison of different storage options in terms of kg H_2 stored per m^3 of storage volume



Source: International Journal of Hydrogen Energy, 2019. https://doi.org/10.1016/j.ijhydene.2019.03.063

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2. Storage Options

Cost Factor: Kind of Storage and Usage Cycle

- **Geological storage** is the **cheapest** form of **large-scale** hydrogen storage.
- **BUT**: Low cost/ large-scale options like salt caverns are geographically limited.
- The cost of using alternative liquid storage technologies is often greater than the cost of producing H_2 in the first place.

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

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2. Storage Options

Comparision of Hydrogen Storage Options

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

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

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

*1 MWh H_2 = 3.4 MMBtu H_2

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

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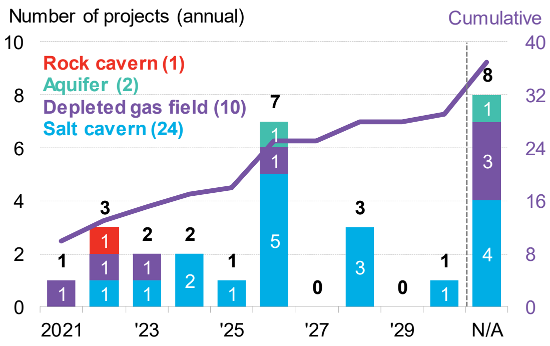
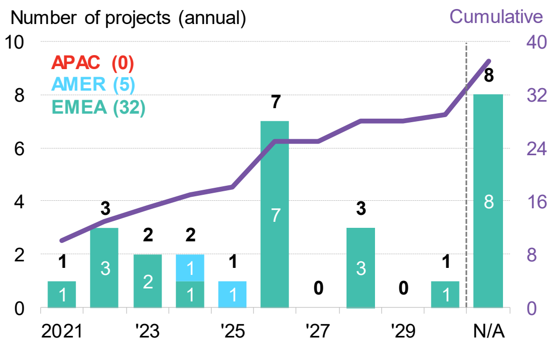
2. Storage Options

Announced Pipeline of Underground H_2 Storage Projects

By segment



By region



Source: BloombergNEF, 2022.

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Key take-aways: 2. Storage Options

- Hydrogen can be stored in compressed or liquefied form, or bound in materials (metal hybrid, LOHC) – energy losses due to storage are unavoidable
  - **Storage costs** depend on the **kind of storage** and number of **usage cycles**
- **Geological storage (salt caverns)** is the **cheapest** form of **large-scale** hydrogen storage but availability of salt caverns is geographically **limited and requires gas infrastructure**
- **Storing H_2 in large quantities** will be one of the most **significant challenges** for a future H_2 economy.
  - Storage technologies are available, but not all are suitable and viable for large quantities
  - Metal gas tanks are certainly too expensive for large quantities
- At the same time, the complex storage and distribution (expensive, energy-intensive) of H_2 is one of the biggest disadvantages of the technology as direct energy storage

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Any questions?

Conclusions

MODULE 4: PtX Infrastructure – Key Take-Aways

1. Transport Options

- International green hydrogen trade requires transport options for large quantities over long distances > 5,000 km
- Hydrogen can be transported in compressed (GH_2) or liquified (LH_2) form, chemically bound (LOHC) or bound in chemical substances (ammonia, methanol)
- The choice of transport and transport costs of green H_2 or PtX products depends on the distance between producer and consumer, depending on the following factors:
  - **Distance and volume**: H2 pipelines and compressed H2 for smaller quantities and distances are cheaper than liquid organic H2 carriers and should be used where available (refurbished pipelines).
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  - **Import vs. domestic production:** Importing sustainable methanol or synthetic fuels from places with cheap renewables is more cost-effective than domestic production
- For large distance overseas transport via ships, liquid H_2 , LOHC or PtX products provide better economics than compressed H_2 due to higher amounts of energy transported in one ship

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MODULE 4: PtX Infrastructure – Key Take-Aways

2. Storage Options

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Open discussion
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“What are the best transport and storage options for your country?”
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Renewable POWER TO X

Training: August 2023
Modules prepared by the International PtX Hub
Trainer: Prof. Thorsten Schneiders

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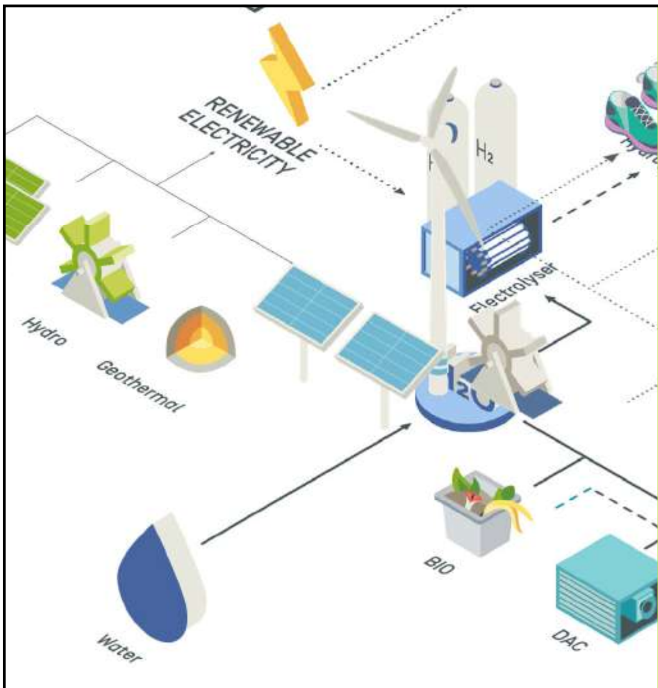

Renewable POWER TO X

Part 4: Markets for Renewable PtX

Training: August 2023
Modules prepared by the International PtX Hub
Trainer: Prof. Thorsten Schneiders

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Agenda

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

2 **Production Pathways of Renewable PtX**
What is needed for PtX, incl. green hydrogen

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

4 **PtX Infrastructure**
How to transport and store PtX products (incl. gH_2) best?

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

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

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

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List of abbreviations

CAPEX: Capital cost expenditures
CCfD: Carbon contracts for difference
CCS: Carbon Capture and Storage
DAC: Direct Air Capture
FLH: Full-load hours
GW: Gigawatt
HVDC: High voltage, direct current
LCOE: Levelised cost of electricity
LOHC: Liquid organic hydrogen carrier
LHV: Lower heat value

- **OPEX:** Operating cost expenditures
- **PEM:** Proton Exchange Membrane
- **PtX / PtL / PtG:** Power-to-X / -Liquid / -Gas
- **PV:** Photovoltaic
- **RE:** Renewable Energy/ies
- **RES:** Renewable Energy System(s)
- **RWGS:** Reverse Water Gas Shift Reaction
- **SMR:** Steam methane reforming
- **SOEC:** Solid Oxide Electrolyser Cell
- **TWh:** Terawatt hours
- **WACC:** Weighted average cost of capital

Key Conversion Data
- 1 kWh H_2= 3.6 MJ H_2
  1 MWh H_2 = 3.4 MMBTU H_2
  1 MJ H_2 = 0.277 kWh H_2

Conversion kWh and kg H_2:
- 1 kg H_2 = 33.3 kWh H_2 *(heat unit Hu /calorific value)*
- 1 MWh H_2 = 30 t H_2
- 1 Mio t H_2 = 33 TWh H_2

Monetary value per weight or calorific value
- 4.5 ct/kWh H_2 = 45 €/MWh H_2 = 1.5 €/kg H_2
  or: 1€/kg H_2 = 3 ct/kWh H_2
- 100 €/MWh H_2 = 3.33 €/kg H_2
  or: 1€/kg H_2 = 30 €/MWh H_2

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What we see in the market

Growing interest of industry in green hydrogen and PtX

- Hydrogen is already a commonly used feedstock in chemical industry (e.g. for ammonia, methanol or fertilizer production) or refineries, currently 99% based on grey hydrogen
  - 100 years of experience in using hydrogen in processes safely
  - Green hydrogen could substitute grey hydrogen without changing the processes
- Green hydrogen could be an energy source in "hot industry processes" to substitute natural glass or coal, e.g. in steel, glass or cement industry (which are hard-to-abate industries)
  - Green hydrogen use represents essential options to reduce their CO2 emissions
  - Modification of processes needs to be tested in pilot projects before roll-out
- PtX products (e.g. green ammonia, methanol) allow long-distance transport of green hydrogen which is not economically viable with compressed or liquid H2
- PtX products can substitute fossil fuels (e.g. green ammonia, methanol) or be modified to "imitate" fossil fuels (synfuels, syndiesel, e-fuels)

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What we see in the market

Growing interest of industry in green hydrogen and PtX

- Hydrogen is already a commonly used feedstock in chemical industry (e.g. for ammonia, methanol or fertilizer production) or refineries, currently 99% based on grey hydrogen

Shift in mind-set: Green hydrogen and PtX is no longer regarded as just an energy source in the power sector, but as an important feedstock and energy source for decarbonizing hard-to-abate industry as well

- PtX products (e.g. green ammonia, methanol) allow long-distance transport of green hydrogen which is not economically viable with compressed or liquid H2
- PtX products can substitute fossil fuels (e.g. green ammonia, methanol) or be modified to "imitate" fossil fuels (synfuels, syndiesel, e-fuels)

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Module 5

Markets for Renewable PtX

1. Current and Future Demand for Green Hydrogen and Renewable PtX products
   - Current hydrogen sources and applications
   - New roles and trading flows in a global market
2. Initial Steps to Find and Evaluate Your Domestic PtX Potential
   - Marginal Abatement Cost Curve
   - Clean Hydrogen Ladder
   - No regret Options
   - Technology readiness levels
3. Use Cases: Green Steel, Green Methanol, Fuels and aviation, offgrid power supply

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1. Current and Future Demand for Green Hydrogen and Renewable PtX products

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1. Current and Future Demand for Green Hydrogen and Renewable PtX products

How will the global market for green hydrogen and renewable PtX develop? Who will export, who will import?

New roles in the future Green H_2 and renewable PtX market

Decarbonization will drive demand for green H_2 and renewbale PtX

Exporters

- their renewable energy production is larger than their demand
- Examples: Australia, Chile, North Africa and Spain

Importers

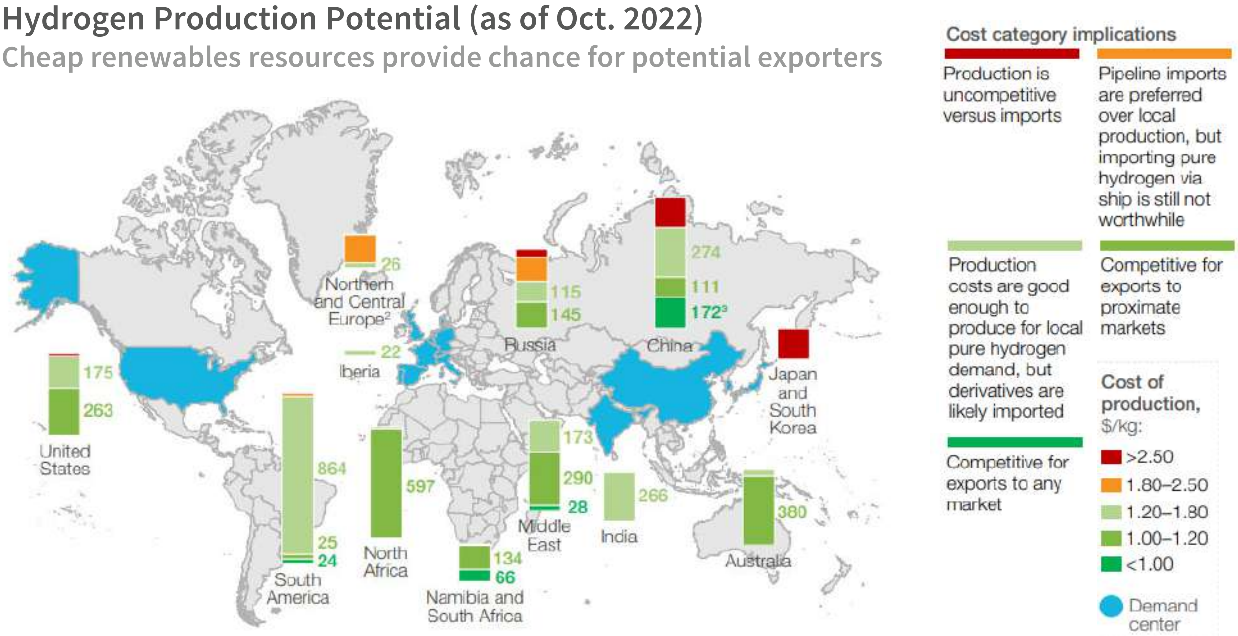
- regions where the domestic resources have either higher costs than imported hydrogen or where there is not enough renewable potential to satisfy the domestic demand (e.g. Germany, EU, Japan, South Korea)

Self-sufficient

- enough good-quality renewable resources to meet their hydrogen demand with local production
- hydrogen production is a viable proposition to meet their own demand at least cost, with limited need for international trade (e.g. China, USA and Brazil)

Hydrogen Production Potential (as of Oct. 2022)

Cheap renewables resources provide chance for potential exporters



Hydrogen Council, McKinsey & Company (10/2022) Global Hydrogen Flows: Hydrogen trade as a key enabler for efficient decarbonization, p.12/exhib.5.

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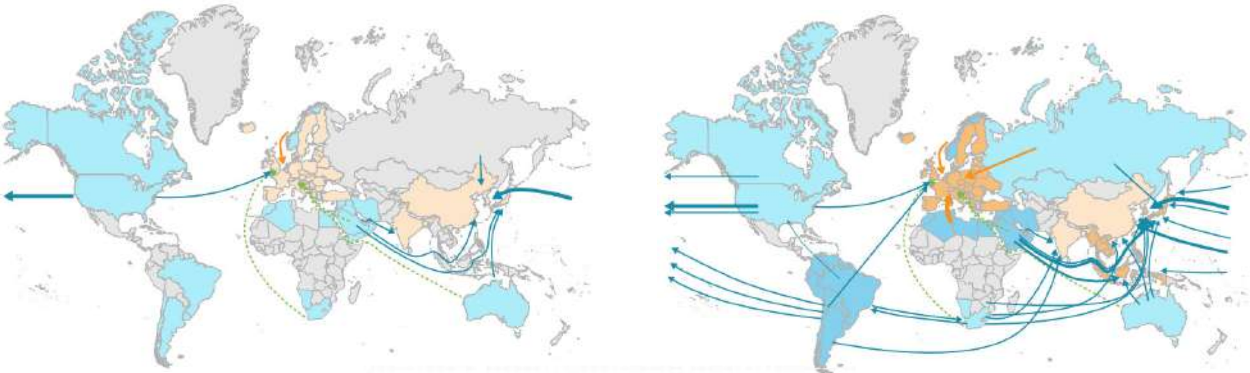
The perspective: future flows of H_2 and derivatives in a global market

Global market is expected to grow substantially – Green H2 and PX as global commodities



By 2030, early trade routes can be established

By 2050, extensive and deep trade links could connect the globe

Hydrogen Council, McKinsey & Company (10/2022) Global Hydrogen Flows: Hydrogen trade as a key enabler for efficient decarbonization, p.18,19/exhib.9,10.

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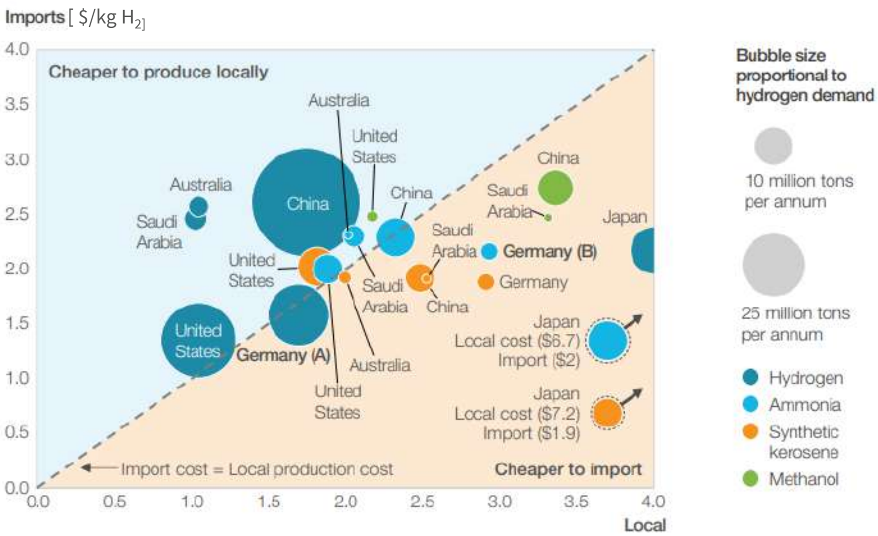
Cost of PtX imports versus local production in 2050

Large industry countries need to rely on cheaper imports than domestic production



Hydrogen Council, McKinsey & Company (10/2022) Global Hydrogen Flows: Hydrogen trade as a key enabler for efficient decarbonization, p.13/exhib.6.

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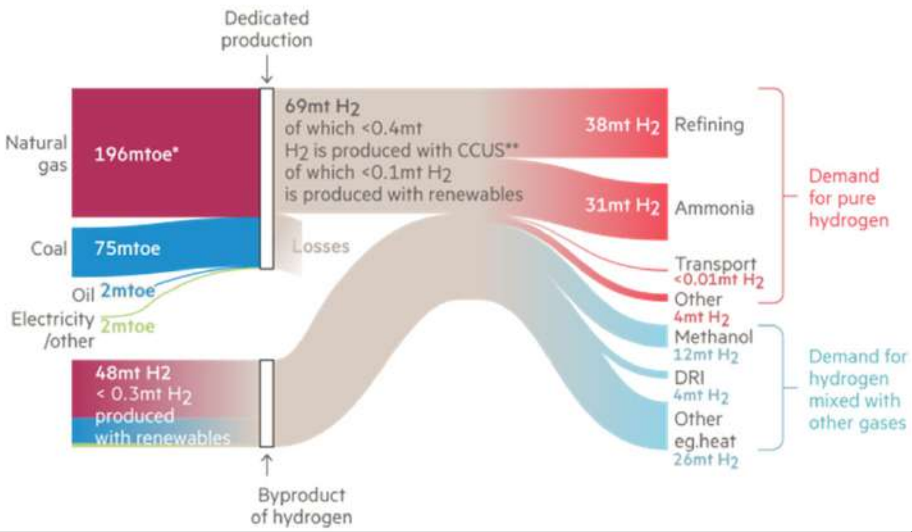
1. Current and Future Demand for Hydrogen
Current Hydrogen Sources and Applications



*mtoe: Million ton of oil equivalent

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

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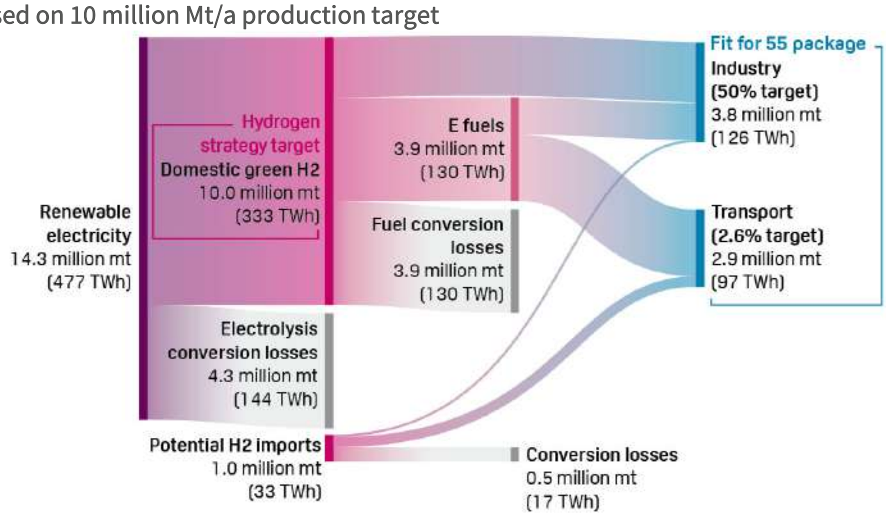
1. Current and Future Demand for Hydrogen
Hydrogen Supply Flow in 2030 (EU)

Based on 10 million Mt/a production target



119.1 Source: S&P Global, Feature: Hydrogen targets in EU 2030 climate package will need huge renewable power, 08/2021.

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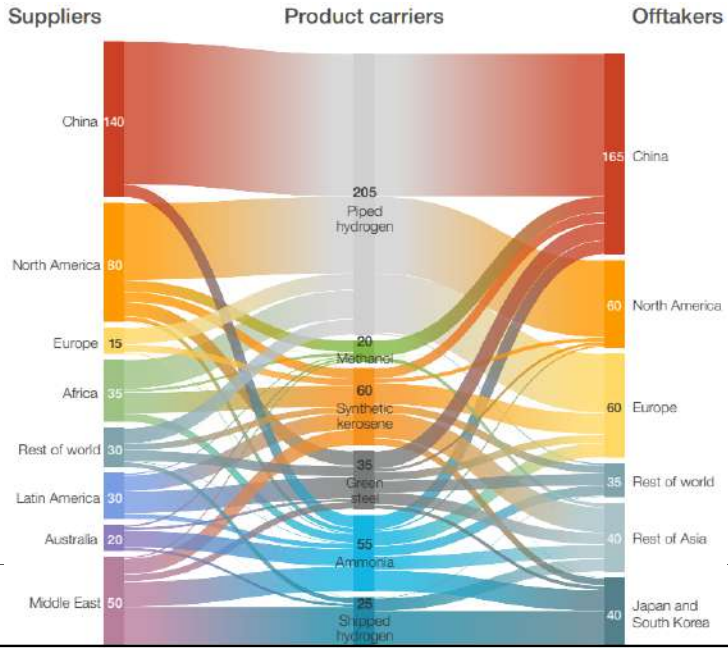
Global H_2 and derivative interregional long-distance* supply (million tons per annum)



2050 Pipeline **transportation** will be the largest **long-distance** carrier; major flows within China, North America and to Europe

(*) Excludes local production and distribution.

Hydrogen Council, McKinsey & Company (10/2022) Global Hydrogen Flows: Hydrogen trade as a key enabler for efficient decarbonization, p.20/exhib.11.

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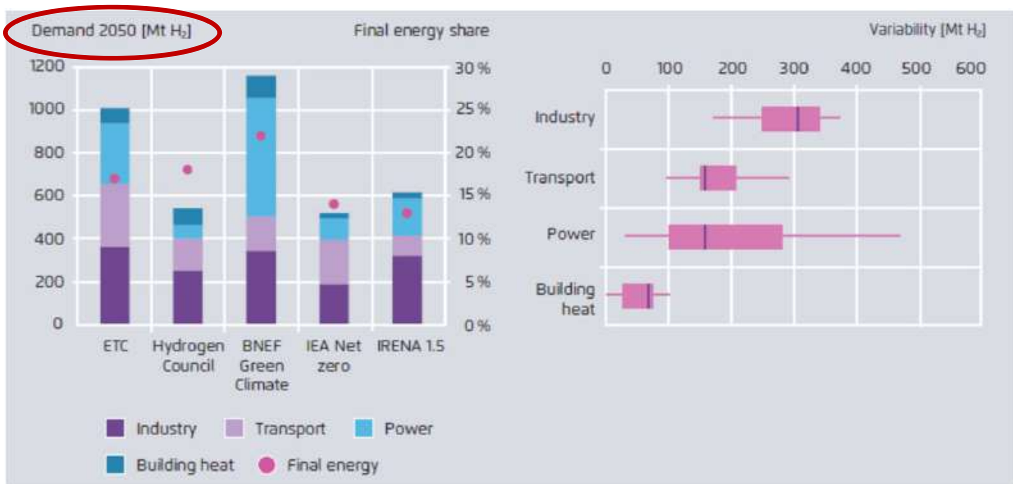
1. Current and Future Demand for Hydrogen

Hydrogen as Key to Industrial Decarbonisation



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

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

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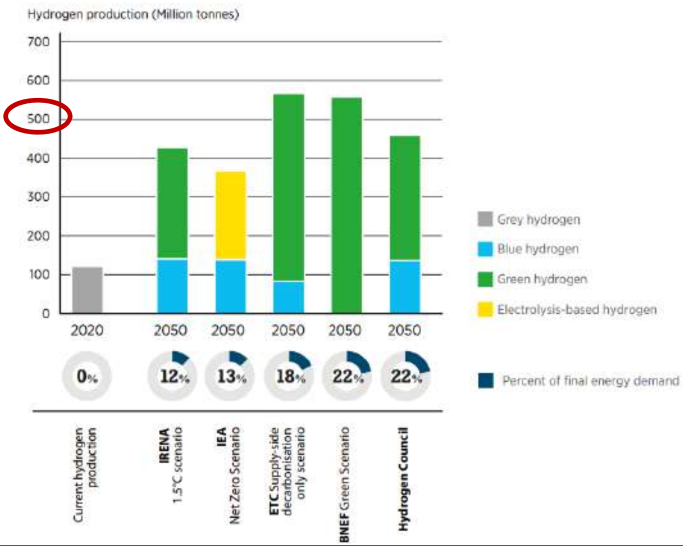
1. Current and Future Demand for Hydrogen

Estimates of Future Global Hydrogen Demand



Estimates for hydrogen demand converge to 500 Mio t H2/a by 2050.

121

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

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1. Current and Future Demand for Green Hydrogen and Renewable PtX products – Key Take-Aways

- Decarbonization is the main driver for the global demand of green hydrogen and renewable PtX
- Today, the markets for green hydrogen and renewbale PtX are still at the very beginning
- Over the next decades, the development of a global green hydrogen and renewbale PtX market is expected, with new trading flows and partnerhsips emerging between exporting and importing countries all over the globe
- As a result, green hydrogen and renewbale PtX will become globally traded commodities, similar to LNG or oil today

Any questions?

Test your knowledge

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

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

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2. Initial Steps to Find and Evaluate Your Domestic PtX Potential

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24 2. Initial Steps to Find and Evaluate your PtX Potential

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What the intitial steps to find and evaluate your PtX potential for domestic use of green hydrogen and renewable PtX?

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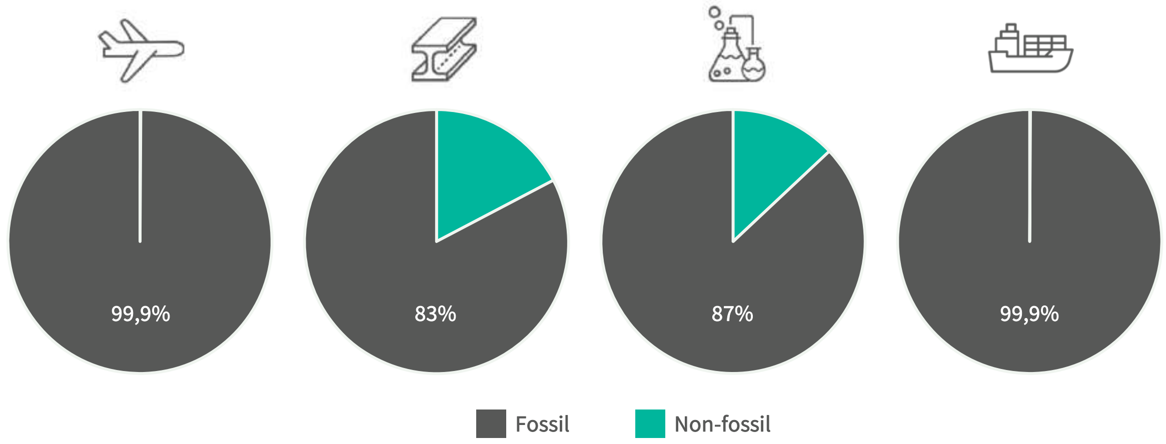
2. Initial Steps to Find and Evaluate your PtX Potential

PtX Potential in Hard to Abate Sectors



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

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Where doe we stand today: Industrial sectors still depend on fossil fuels

Aviation

Today: 3 % of global CO_2 emissions

Efficiency is improving, but overall fleet size and flight volume is increasing → **aviation could be producing 24 % of global CO_2 emissions by 2050.**

Key challenges: aircraft and engine re-design, hydrogen storage, sustainable fuel production, new infrastructure vs. drop-in, cost.

Steel

Driven by population and GDP growth, global steel demand likely to increase (economic expansion in India, the ASEAN countries and Africa).

Short-term CO_2 emissions reductions: could come from energy efficiency improvements & scrap collection.

Longer-term reductions: require adoption of new direct reduced iron (DRI) & smelt reduction technologies that facilitate **integration of low-carbon electricity (directly or through electrolytic hydrogen) and CCUS;** material efficiency strategies.

Chemical Feedstock

Currently: ammonia mostly made from methane, water & air, **using steam methane reforming (SMR)** and the Haber-Bosch process → approx. 90% of CO_2 produced is from SMR process (around 1.8% of global carbon dioxide emissions).

Shipping

International shipping uses virtually no low-carbon fuels at present (due to a lack of policy regulations).

In April 2018, the IMO (International Maritime Organisation) adopted a strategy to reduce GHG emissions → these regulations can help to mitigate air pollution, negative health impacts on people living at or near major ports & environmental impacts on oceans – **BUT: risk that they will lock in investments in fossil fuel technologies & delay transition to carbon-neutral fuels!**

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

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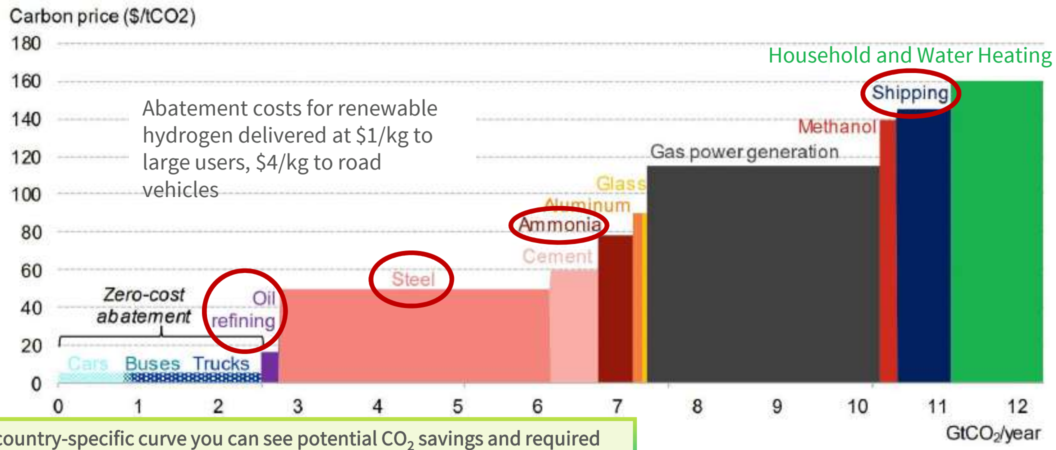
2. Initial Steps to Find and Evaluate your PtX Potential

Step 1: Create a Country-Specific Marginal Abatement Cost Curve

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



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

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

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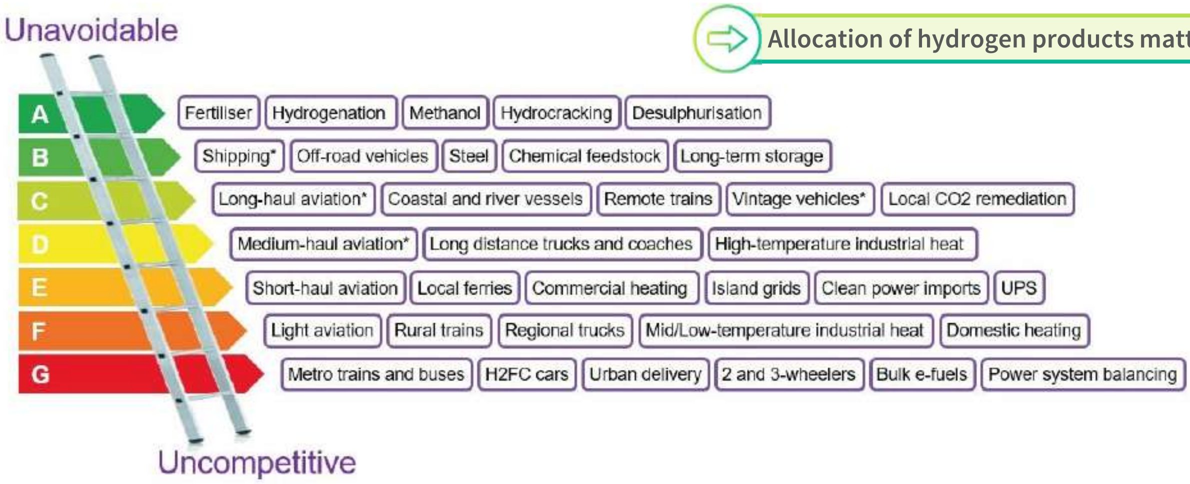
2. Initial Steps to Find and Evaluate your PtX Potential

Step 2: Check the Clean Hydrogen Ladder

Allocation of hydrogen products matters!



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

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

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2. Initial Steps to Find and Evaluate your PtX Potential

Step 3: Start with No Regret Options

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

* After using renewable energy, ambient and waste heat as much as possible. Especially relevant for large existing district heating systems with high flow temperatures. Note that according to the UNFCCC Common Reporting Format, district heating is classified as being part of the power sector.

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

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

No regret options differ from country to country.

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

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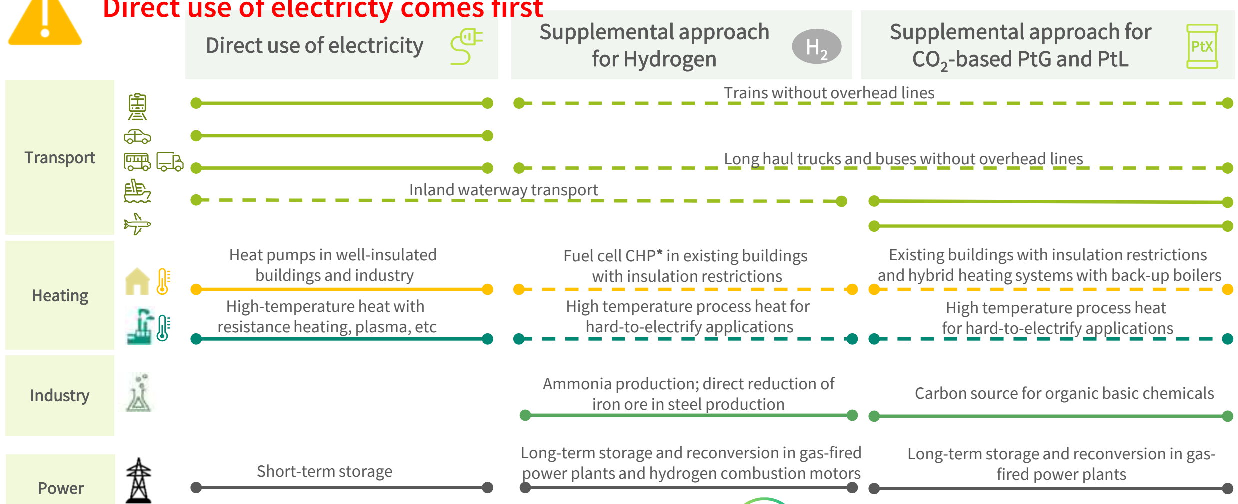
4. Step: Apply allocation criteria for green H_2 and PtX

Direct use of electricty comes first



***CHP: combined heat and power.** Note that CHP plants with H_2 in general may also play a role in district heating for covering the residual heat load [– after using renewable energy, ambient and waste heat as much as possible. Especially relevant for large existing district heating systems with high flow temperatures.]

PtX is most efficient in sectors where direct use of electricity is not economical or possible.

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Source: Own illustration adapted from: Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018): The Future Cost of Electricity-Based Synthetic Fuels, p.15/1.

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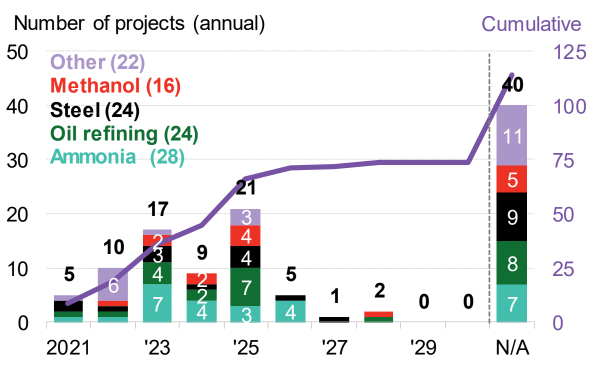
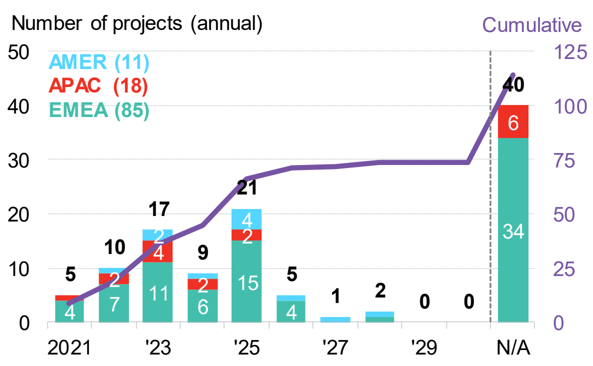
2. Initial Steps to Find and Evaluate your PtX Potential

Announced Pipelines of Industrial Hydrogen Projects

By segment



By region



Source: BloombergNEF

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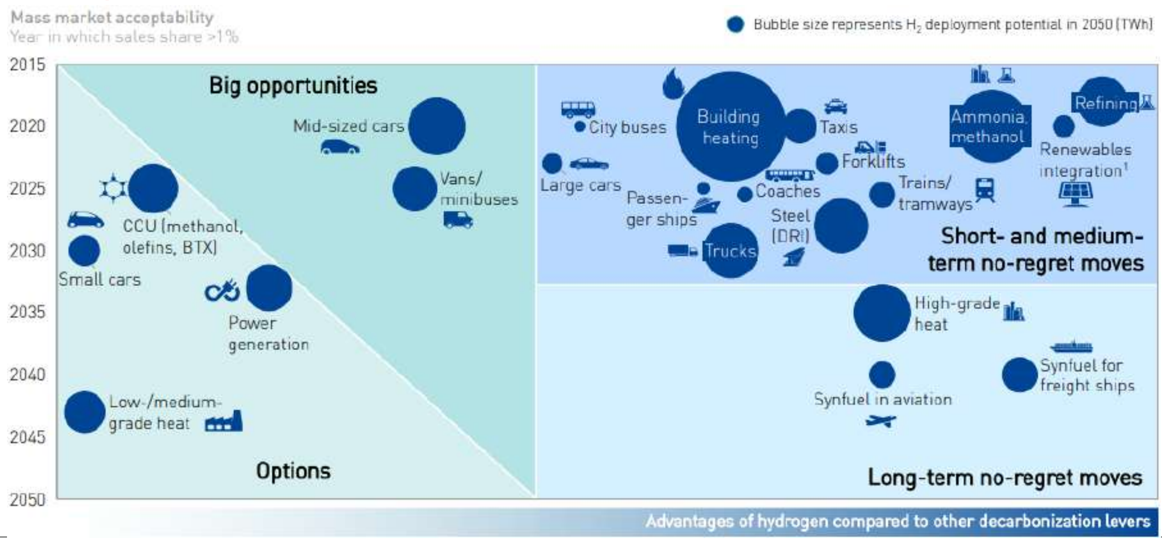
2. Initial Steps to Find and Evaluate your PtX Potential

Step 5: Consider different H2 market options and evaluate them for your country!

Some are quite controversial



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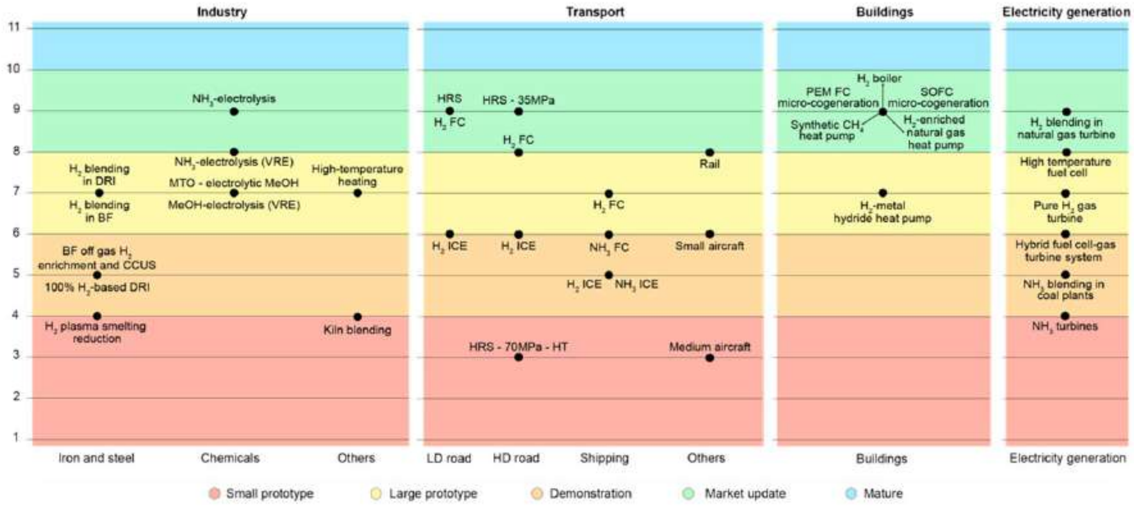
Source: Fuel Cells and Hydrogen, Hydrogen Roadmap Europe, 2019, p.62/exhib.28.

2. Initial Steps to Find and Evaluate your PtX Potential

Step 4: Consider Technology Readiness Levels of Key PtX Production, Storage and Distribution Technologies



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

2. Initial Steps to Find and Evaluate your PtX Potential – Key Take-Aways

- To check your domestic potential for using green hydrogen and renewable PtX, the following steps are recommended:
  - Determine the “Marginal Abatement Cost Curve“ to evaluate see potential CO_2 savings and required CO_2 prices in the sectors of your country
  - Consider the “Clean Hydrogen Ladder“ to get a first impression whether the use cases for H_2 are uncompetitive, which are unavoidable for decarbonisation, and which sit somewhere in the middle
  - Analyze the domestic options to identify “No regret Options“ where green hydrogen is best applicable
  - Consider “Technology readiness levels“ to check status of applicability of green hydrogen or PtX based technologies

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Any questions?

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3. Use Cases for Green Hydrogen and renewable PtX products

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3. Use cases for Green Hydrogen and Renewable PtX

Which use cases are feasible and might push the demand for green hydrogen and renewable PtX?

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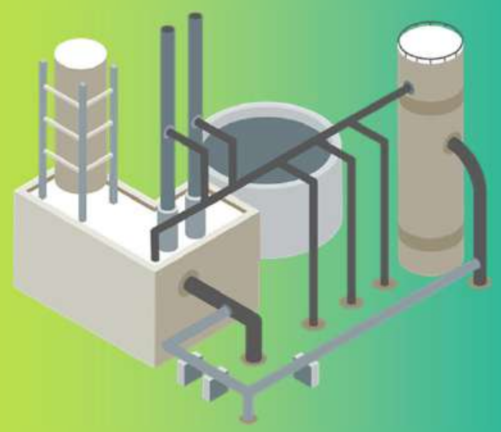

Use case: Green Steel Production

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Use case: Green Steel

Climate challenge for the steel industry – today coal…

New slide added by TS

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Use case: Green Steel

Climate challenge for the steel industry – …and tomorrow green hydrogen?

New slide added by TS

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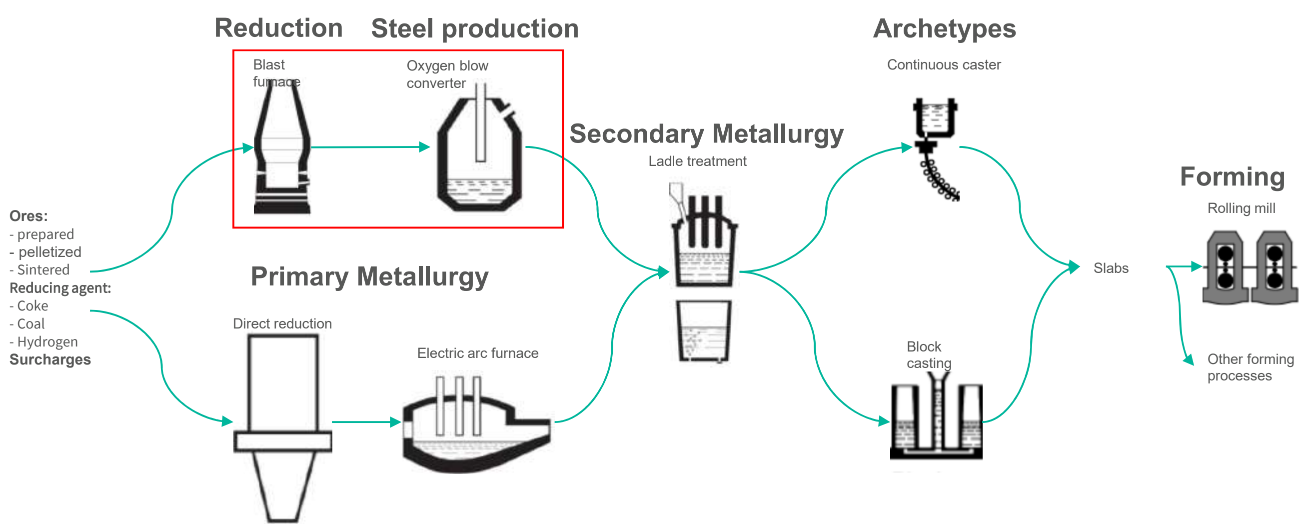
Use case: Green Steel

CO_2 emissited from using coal as fuel (50%) and processs-related CO_2 (50%)



New slide added by TS

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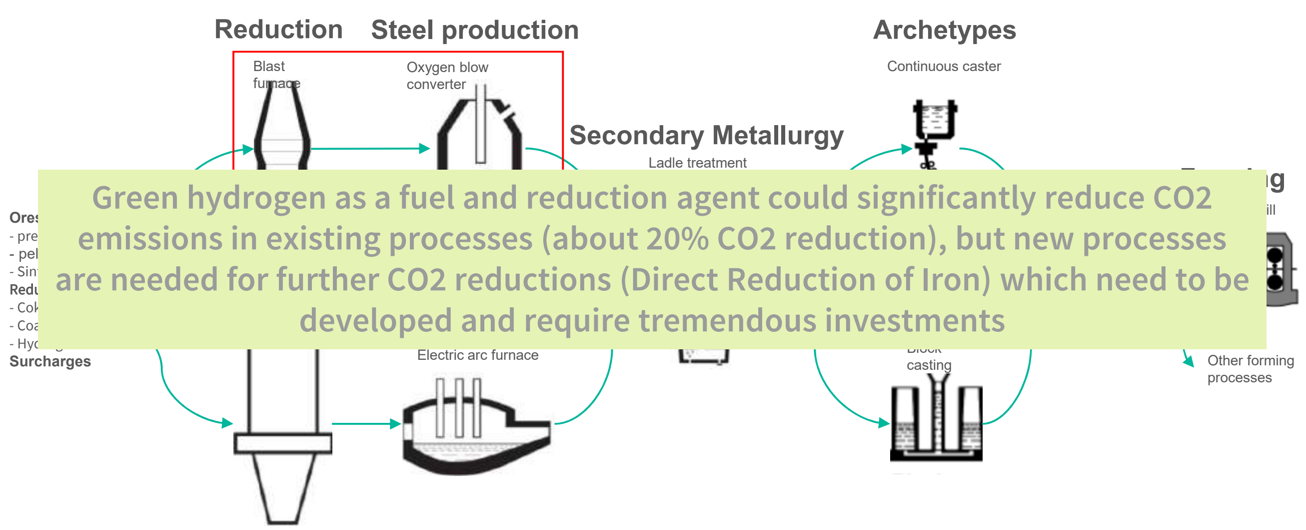
Use case: Green Steel

CO_2 emissited from using coal as fuel (50%) and processs-related CO_2 (50%)



Green hydrogen as a fuel and reduction agent could significantly reduce CO2 emissions in existing processes (about 20% CO2 reduction), but new processes are needed for further CO2 reductions (Direct Reduction of Iron) which need to be developed and require tremendous investments

New slide added by TS

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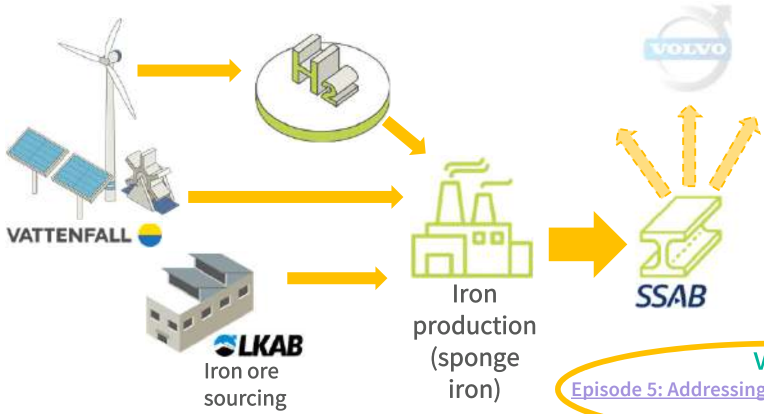
Use Case: Green Steel

Climate Friendly Steel in Sweden

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

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



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

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

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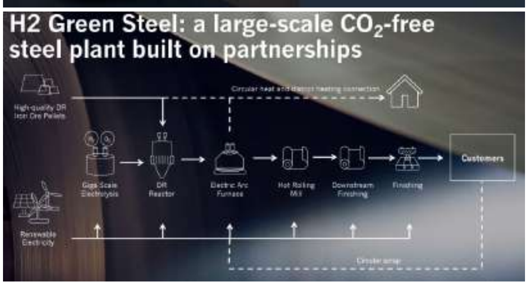
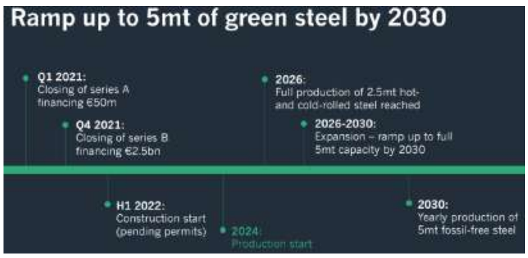
Use Case: Green Steel

Premium Markets for Green Steel





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

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Use Case: Green Steel

Example: Decarbonising the German Steel Industry

Impact of decarbonization on power and production costs

Increase in electricity demand?

- Production cost of **1kg H_2**: 3.6-5.3 €/kg, using **50-55 kWh**
- → **50 kg** of H_2 required to produce **1 t of steel**
- **Germany** (EU's largest steel producer): **100 TWh** of RE needed to fully decarbonise annual production of **42 Mt of steel**
- → This **100 TWh** of additional RE demand → **20 % increase in total electricity demand in Germany!**
- *To compare: Solar park Benban (Egypt): 3800 GWh/year; land use 37.2 km² → that is 3.8% of electricity needed to decarbonise German steel industry*

Increase in steel production costs?

- Price of **1t steel: around €400,** incl. €50 required for the coal used
- @ 3.6 €/kg H_2: Replacing coal with H_2 costs extra 180 €/t steel **→ 1/3 increase of total price**
- @ 1.80 €/kg H_2 (2030): **Price difference would drop approx. 10%**

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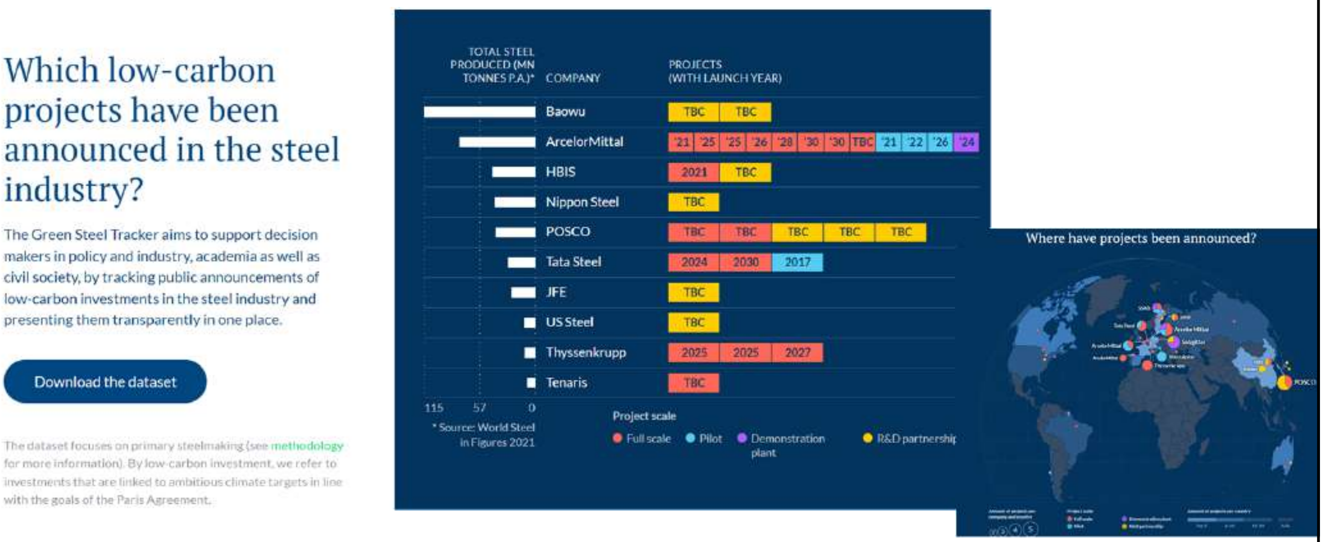
Use Case: Green Steel

Low-carbon steel projects announced

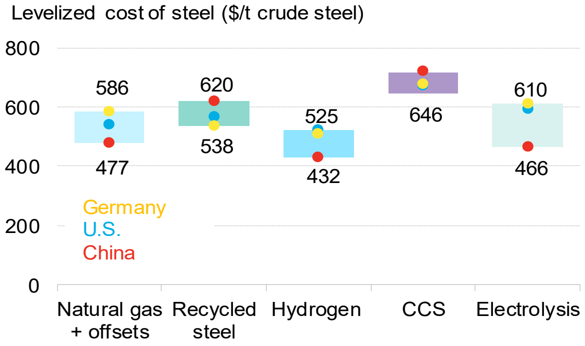


Source: https://www.industrytransition.org/green-steel-tracker/

Use Case: Green Steel

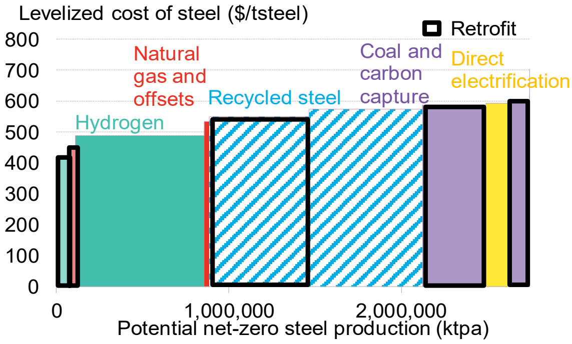
Options to achieve Net-Zero Steel (2050)

Potential supply curve for net-zero steel



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

Cost of net-zero steelmaking routes

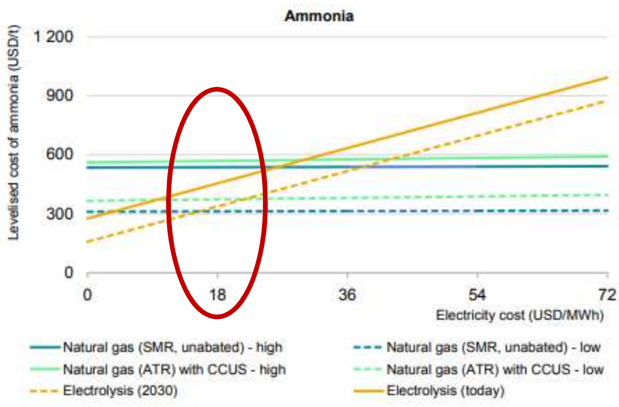


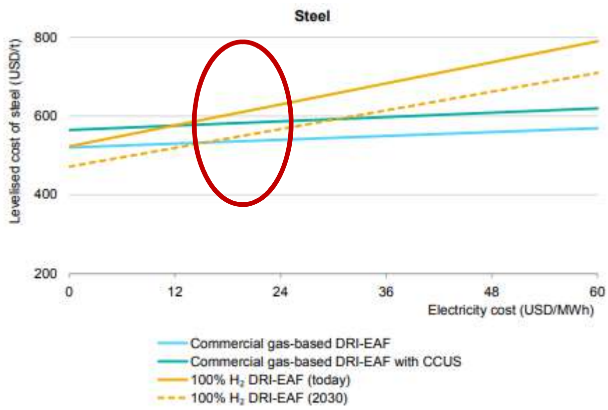
Note: CCS is carbon capture and storage.

Source: BloombergNEF, 2022.

Use Case: Green Steel

Cost Sensitivities for Green Ammonia and Green Steel





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

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

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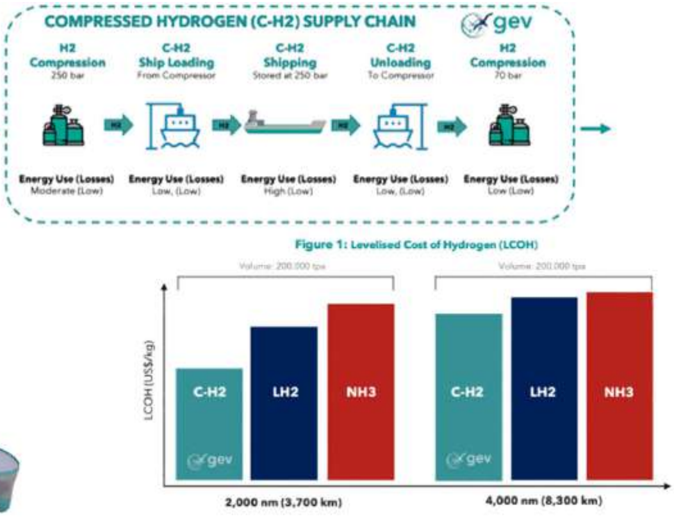
3. Use Case Green Steel

Development of 2.8 GW Green Facility (Australian Hydrogen Ship Maker)



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

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Any questions?

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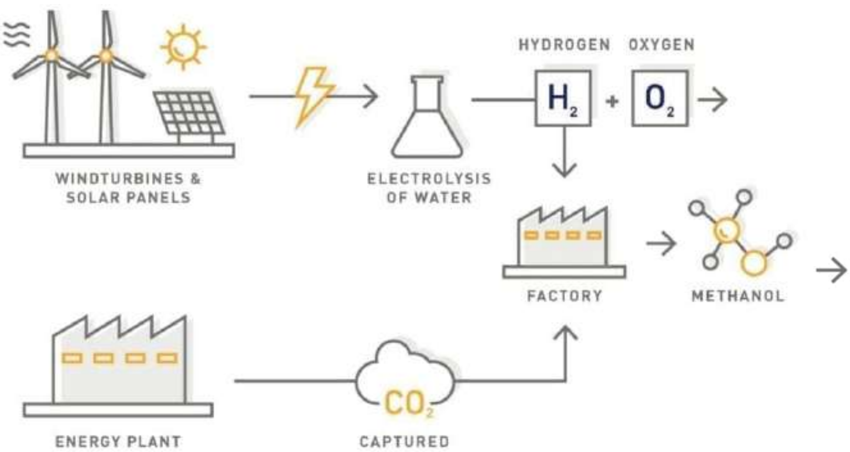
139.5

Use case: Green Methanol in chemical industry

Use case: Chemical Industry

Green Methanol - the universal platform chemical



Chemical:
dyes, resins, adhesives, plastics

Construction:
plywood

Cosmetics:
perfumes

Energy:
fuel cells, biodiesel, DME,
shipping fuel, H2 transport

Pharma:
medication

Textiles:
synthetic fiber

Source: Dorothy Lozowski (2020), New Power to Methanol project, INEOS

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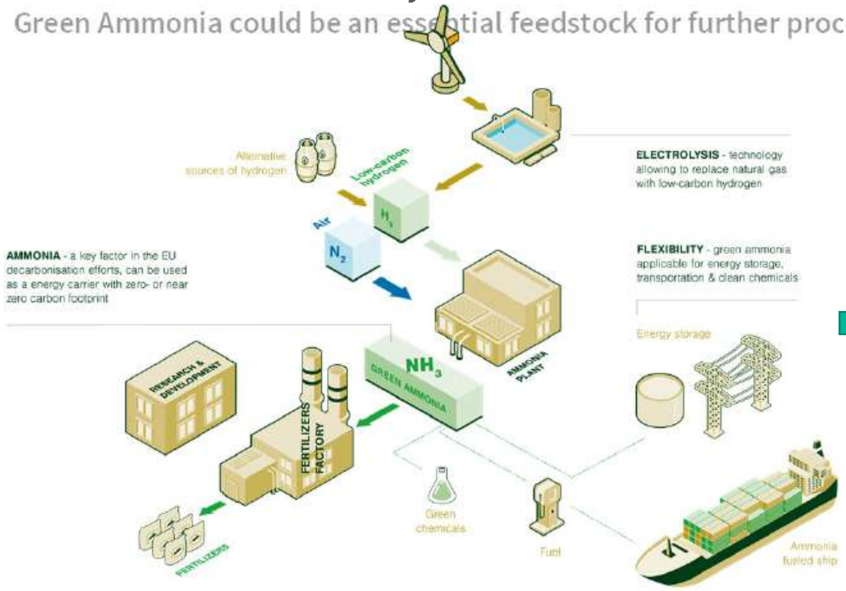
Use case: Chemical Industry

Green Ammonia could be an essential feedstock for further processing



Agriculture:
- fertiliser, pesticides

Chemical:
- dyes, plastics

Energy:
- fuel cells, shipping fuel, H2 transport

Mining:
- Explosives

Textiles:
- synthetic fiber

Source: https://www.euractiv.com/section/energy-environment/opinion/ammonia-the-other-hydrogen/

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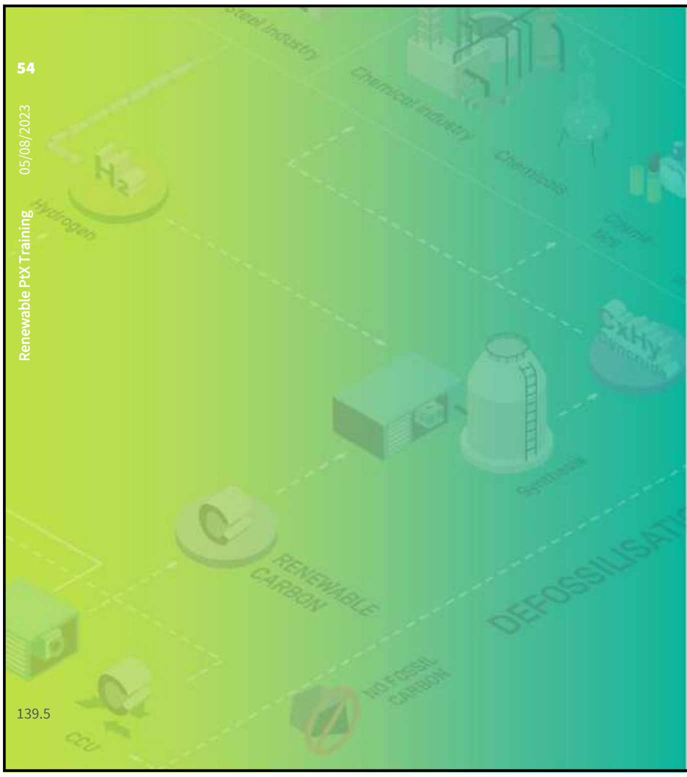

139.5

Use case: Green hydrogen and renewable PtX as fuels

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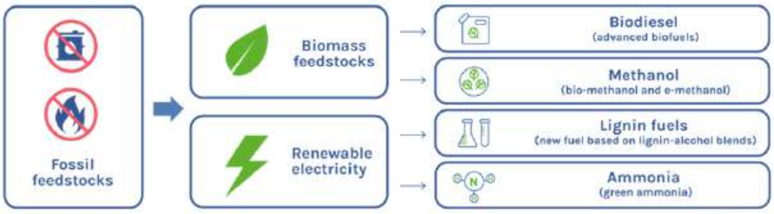
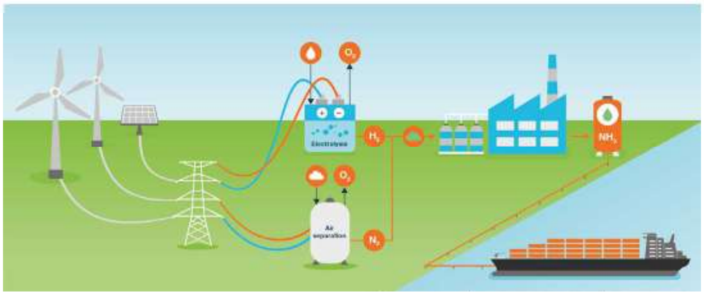
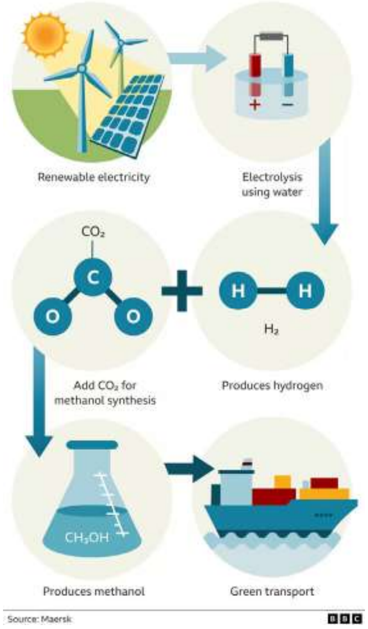
Hydrogen derived fuels
Shipping – the race is on



Methanol



Ammonia



Sources: Global Maritime Forum, MAN Energy Solutions (2022), The need for flexible fuel solutions, MAERSK

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Hydrogen derived fuels
Aviation – drop in fuels

SAF Pathways in the pipeline

- ✓ Virent SAK
- ✓ Shell IH2
- ✓ Global Bioenergies
- ✓ Swedish Biofuel
- ✓ Indian CSIR-IIP
- ✓ Methanol

D4054

Product	Certification	Input	Blending ratio by volume
Jet A-1	D1655		100%
Fischer-Tropsch (FT-SPK)	D7566 Annex 1		50%
Fischer-Tropsch with aromatics (FT-SKA)	D7566 Annex 4		50%
Alcohol to jet (ATJ- SPK)	D7566 Annex 5		50%
Hydroprocessed esters and fatty acids (HEFA)	D7566 Annex 2		50%
Catalytic hydrothermolysis jet fuel (CHJ)	D7566 Annex 6		50%
Hydrocarbon - hydroprocessed esters and fatty acids (HC-HEFA-SPK)	D7566 Annex 7		50%
Synthesized iso-paraffins (SIP)	D7566 Annex 3		10%

Source: ENVReport2022_Art49.pdf (icao.int)

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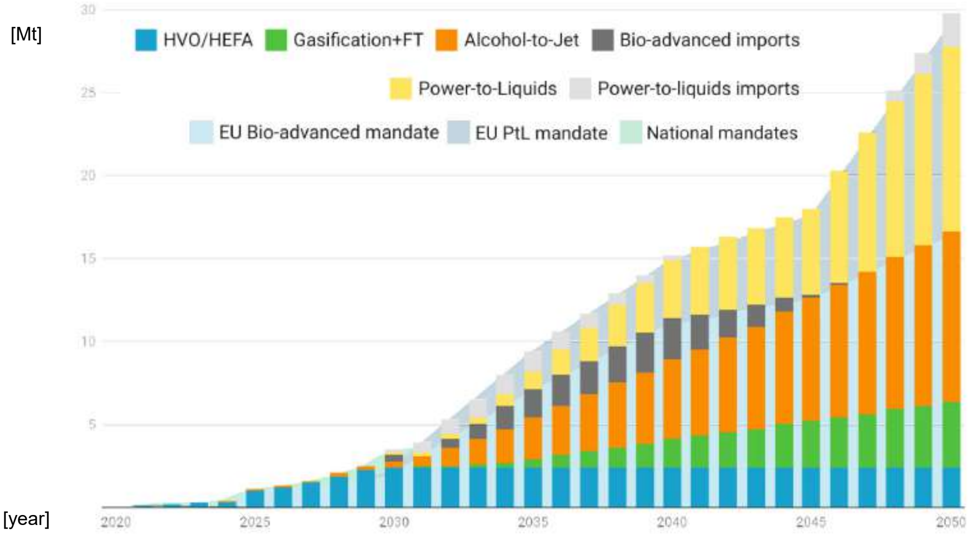
Hydrogen derived fuels
Aviation – European SAF supply outlook up to 2050



Source: SkyNRG, A Market Outlook on Sustainable Aviation Fuel, July 2021

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Hydrogen derived fuels
Aviation – scaling to 40 million tons of SAF per year

	Production plant	Size	Location/ State /Investment	Multiplier*
	ProQR Project plant	365 t/a PtL	Brazil / Planning phase / CAPEX ~40 million EUR	X 109.590
	Nordic Electrofuel	10,000 t/a PtL	Norway / Planning phase / CAPEX ~175 million EUR	X 4.000
	Neste	100,000 t/year HEFA	Finnland/ In operation / CAPEX not available	X 400
	Gevo	158,000 t/year ATJ	USA / Planning phase / CAPEX ~900 million USD	X 253

*** Multiplier = number of projects needed for producing 40 mio tons SAF per year**

the unit „t“ stands for metric tons

Sources: ProQR, Nordic Electrofuel, Gevo Breaks Ground on Net-Zero 1 Site in Lake Preston, SD Porvoo refinery | Neste

Use case: PtL for Aviation

ProQR in Brazil

Use Case: Aviation

ProQR in Brazil

GIZ project together with the Brazilian ministry of Science, Technology and Innovation, and the project partners German Aerospace and the National Agency of Petroleum, Natural Gas and Biofuels

- The project aims to create an internationally applicable reference case for **local production and use of Power-to-Liquid Sustainable Aviation Fuels (PtL SAF)**
- **Small decentralised power plants** that produce fuel for aviation from renewable electricity can already be **economically in many remote locations in Northern Brazil** since the costs of carrying fuels are high
- Involves Renewable Energies and the Fischer Tropsch technology
- **Production is close to the place of fuel consumption**
- ProQR will support the planning, financing, construction and operation of a demonstration plant in Brazil

Source: GIZ (2020): https://www.giz.de/en/worldwide/63299.html

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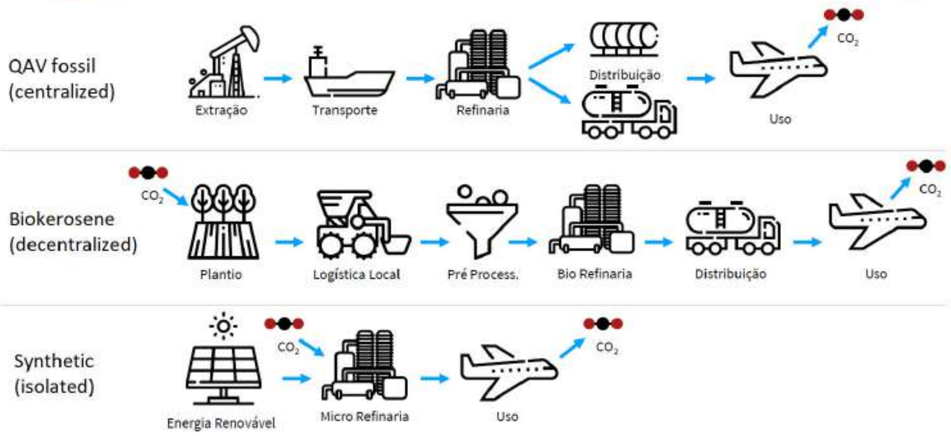
Use Case: Aviation
ProQR in Brazil

Scenarios: centralized – decentralized - isolated



139.3 Source: ProQR (2021): Aviacao limpa para o Brasil. https://ptx-hub.org/wp-content/uploads/2021/06/20210611_Apresentacao-Marcos-Costa-GIZ_Webinar_ProQR.pdf -

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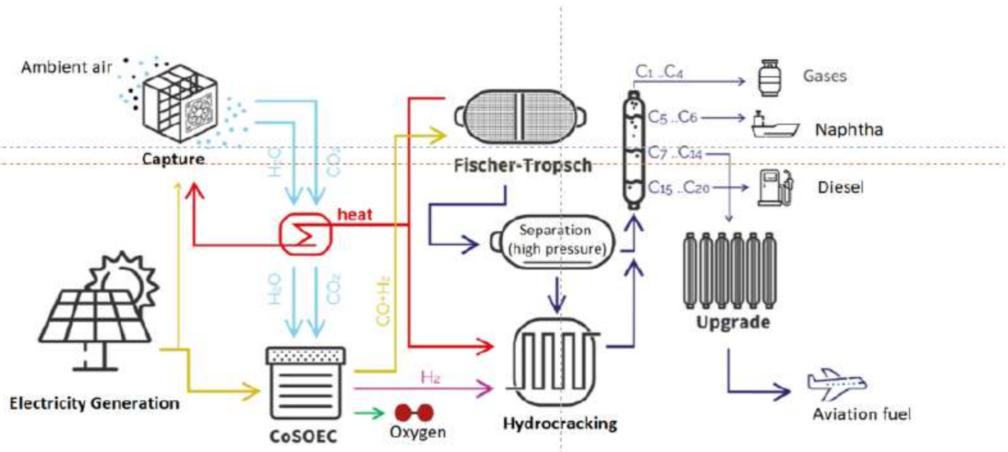
Use Case: Aviation
ProQR in Brazil

Model of the plant



139.4 Source: ProQR (2021): Aviacao limpa para o Brasil. https://ptx-hub.org/wp-content/uploads/2021/06/20210611_Apresentacao-Marcos-Costa-GIZ_Webinar_ProQR.pdf -

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Any questions?

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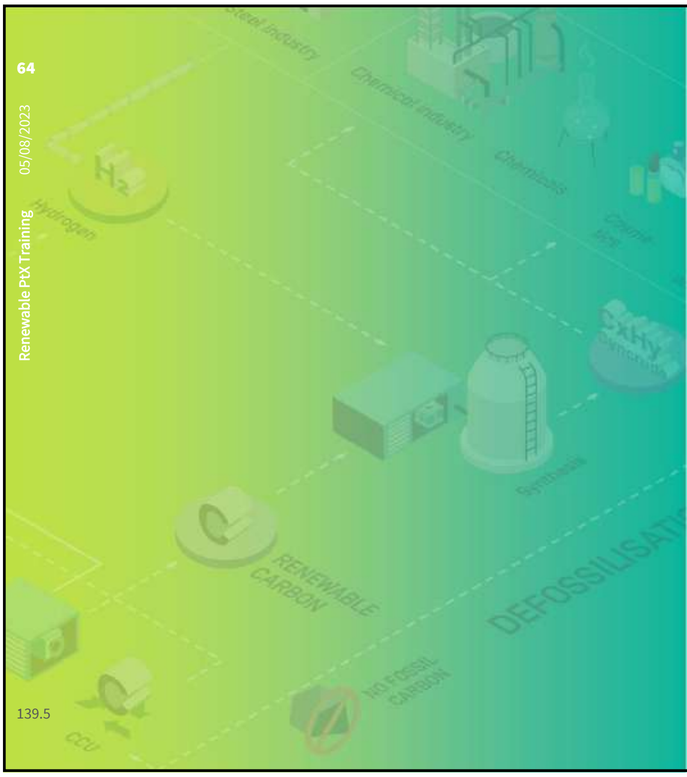

Use case: Off-grid Power Supply Using Hydrogen

CEOG in French Guiana

139.5

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Use case: Offgrid systems

How do photovoltaics-diesel/fuel cell-battery systems work?

The aim: use as much solar power as possible instead of diesel

Concept of using PV as part of the hybrid system has just been initiated.

Offgrid hybrid systems

- Diesel generator supplies an off-grid system with power and provides local grid frequency
- Photovoltaics is added to substitute diesel generation – diesel gen reacts to negative load with reduced output

Grid-connected hybrid systems

- Diesel generator supplies power in case of (frequent) blackout
- Photovoltaics is added to substitute grid electricity and diesel generation

Batteries as short-term storage increase level of usable solar power and diesel savings

Eletrolysis of water allows long-term storage

Fuel cell systems may substitute diesel generator

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Use case: Offgrid power supply

Different stationary and mobile solutions available in the market

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Use case: Offgrid power supply
French Guiana: Large Offgrid power system with hydrogen production and storage

CEOG Renewable Power Plant

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

-**55 MW PV** solar farm
-**16 MW alkaline electrolyser,** 16 bar
-hydrogen storage unit to store 128MWh
-produce approximately 860t/a
-**fuel cells generate 3 MW** of electricity during night
-The project will also include a battery storage system.
The integrated solar and green hydrogen power plant will deliver
-a fixed electrical output of 10MW from 8am to 8pm
-and 3MW from 8pm to 8am
-Supposed to have lower costs than a diesel power plant

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

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CEOG in French Guiana

Joint Venture:

*HDF Energy and its equity partners, the infrastructure fund Meridiam and the petroleum operator SARA announced the start of the construction of **CEOG Renewstable Power Plant** in French Guiana.*

[…]

It is the first time that a renewable energy project supplies a grid through a capacity-based Power Purchase Agreement, usually used for thermal power plants […] This type of electricity offtake contract guarantees the availability and stability of the electricity produced by CEOG. This last characteristic is essential for powering isolated grids or reducing congestion on large networks.

(ESI Africa, 2021)

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

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CEOG in French Guiana

Technology:

The heavy-duty fuel cell systems will incorporate Ballard's proprietary proton exchange membrane (PEM)-based, liquid-cooled, fuel cell stack technology named FCgen®-LCS.

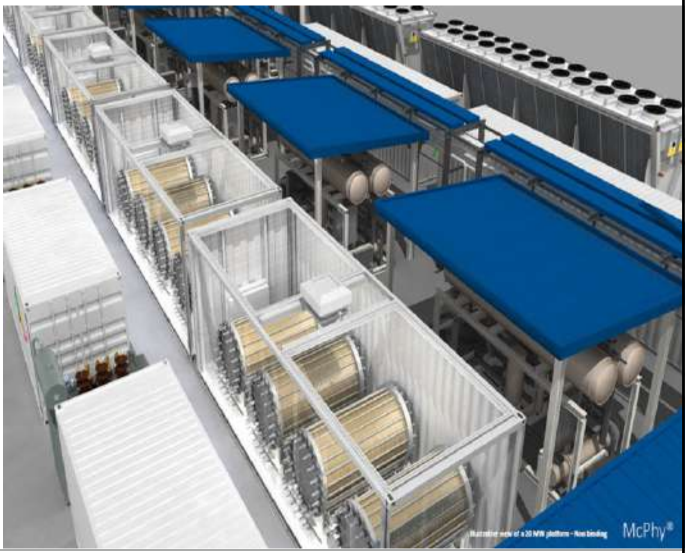
[...]

McPhy Energy, a leading hydrogen production and distribution equipment supplier based in France, is providing its Augmented McLyzer high-pressure alkaline electrolysis technology for the project.

[...]

Operating at a pressure of 30 bar, the 16MW McPhy Augmented McLyzer high-power electrolyser will produce approximately 860t of green hydrogen a year.

(NS Energy, 2021)



Source: NS Energy (2021).: https://www.nsenergybusiness.com/projects/centrale-electrique-de-louest-guyanais-ceog-hydrogen-power-project/
Image: HDF Energy

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Use cases: Key Take-Aways

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3. Use cases – Key Take-Aways

- Over the last years, the need for decarbonization of industry (especially in the UE) has become a driver for future green hydrogen and renewable PtX demand
- This brings up several use cases, to mention some examples
  - Green Steel: substituting coal by green hydrogen and introducing new hydrogen-based processes
  - Green Methanol and Ammonia could become important energy carriers and feedstocks for many chemical products
  - Green Hydrogen is the basis for PTx fuels (PtL, SAF) which are relevant for aviation, shipping or even road transport
  - In offgrid power supply, green hydrogen could be produced and stored for later use, or even be used as local fuel source
- The use cases are being investigated and developed, but may require time for modification of existing plants and processes and new technical developments

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Any questions?

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Conclusions

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MODULE 5: Markets for Renewable PtX - Key Take-Aways

1. Current and Future Demand for Green Hydrogen and Renewable PtX

- Hydrogen is already a common energy carrier and feedstock in industrial process, by 99% based on fossil fuels. In future, demand will be rising up to an estimate of about 500 Mio. tH2/a with industry as a main user.
- Decarbonization is the main driver for the growing global demand of green hydrogen and renewable PtX
- Today, the markets for green hydrogen and renewable PtX are still at the very beginning, but ware expected to develop to a global green hydrogen and renewbale PtX market with new trading flows and partnerhsips emerging all over the globe
- As a result, green hydrogen and renewable PtX are expected to become globally traded commodities

2. Initial Steps to Find and Evaluate your domestic PtX potential

- There are **some sectors** and applications **where hydrogen will be unavoidable, in others, hydrogen will be not competitive** and hence not suitable to start hydrogen economy –
- **For a systematic analysis of the domestic PtX potential:** determine the "Marginal Abatement Cost Curve", **start with "No Regret Options"** and available technologies with a high "Technology Readiness Level"
- But: always remember that direct use of electricity comes first before converting it into green molecules

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MODULE 5: Markets for Renewable PtX - Key Take-Aways

3. Use cases are developing and growing

- Over the last years, the need for decarbonization of industry (especially in the EU) has become a driver for future green hydrogen and renewable PtX demand
- New use cases are being investigated and developed to use green hydrogen and renewable PtX as an energy carrier and feedstock, especially in hard-to-abate industry branches
  - Green Steel, Green Methanol and Ammonia could play a major role in the future
  - Green Hydrogen or PtX-based fuels (PtL, SAF) could help to decabonize aviation, shipping or even road transport
  - In offgrid power supply, green hydrogen could be key to long-term storage

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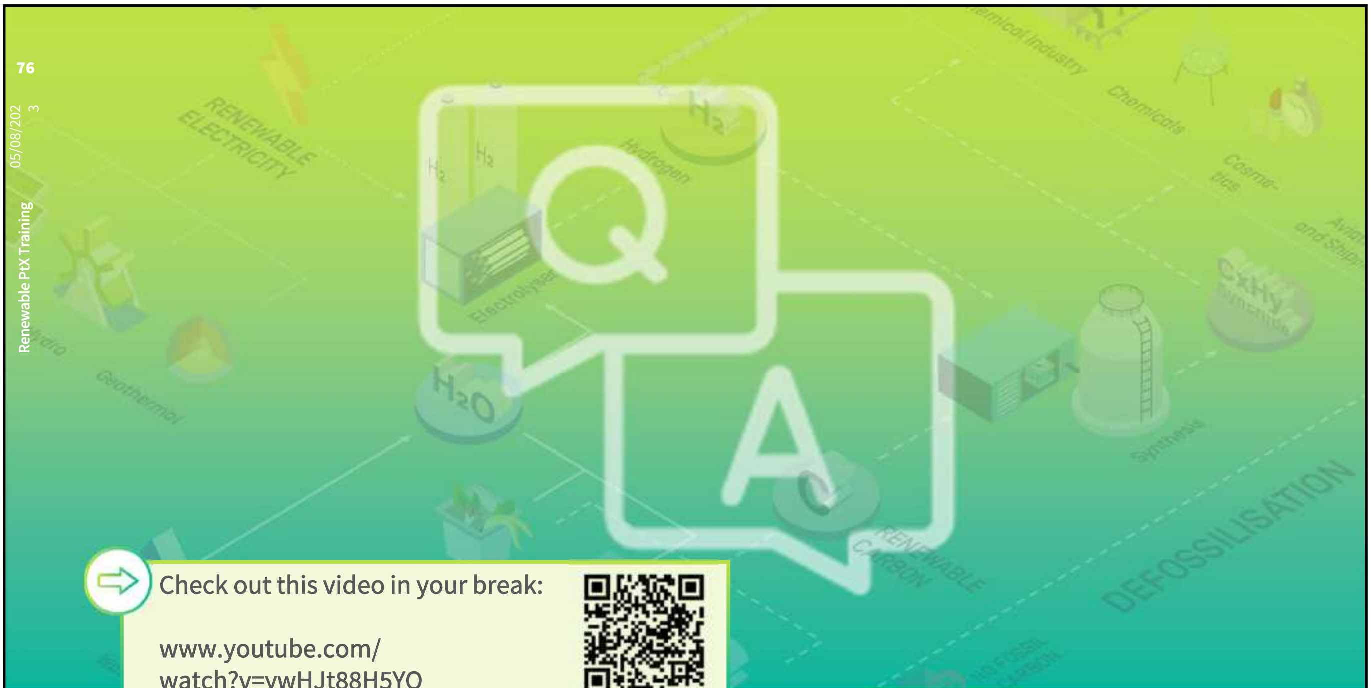

Check out this video in your break:

www.youtube.com/watch?v=ywHJt88H5YQ

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Break out group discussion
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"What could be the role of green hydrogen and PtX in your country?"
"Where do you see market opportunities?"
Grab a coffee & discuss among your group
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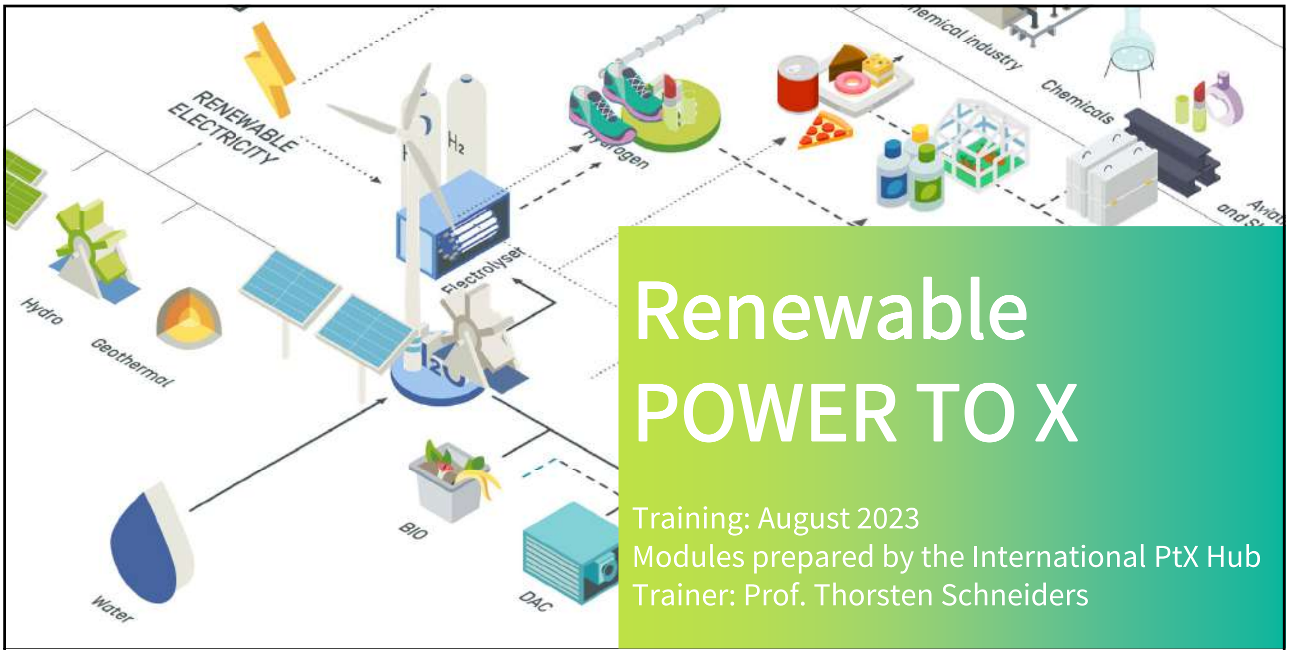
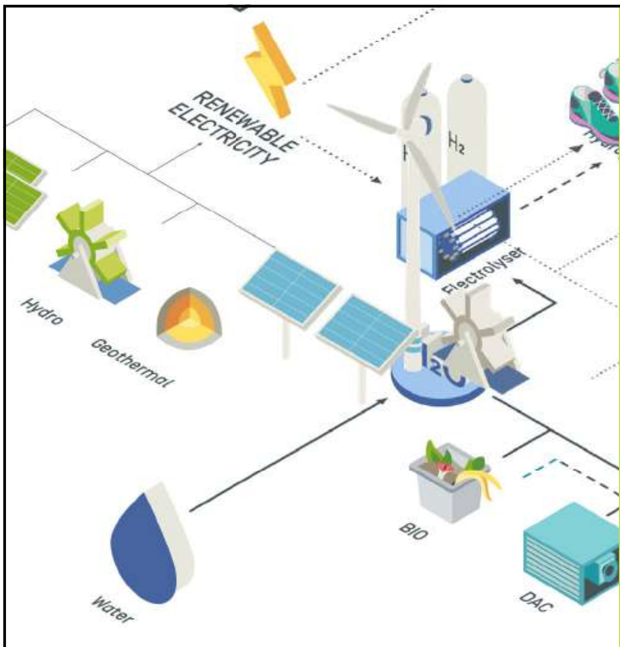


Renewable POWER TO X

Training: August 2023
Modules prepared by the International PtX Hub
Trainer: Prof. Thorsten Schneiders



Renewable POWER TO X

Part 6: Sustainability Criteria for Renewable PtX

Training: August 2023
Modules prepared by the International PtX Hub
Trainer: Prof. Thorsten Schneiders

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The PtX Hub only guarantees the quality of the lecture if the training has been conducted by authorised trainers.

Agenda

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

2 **Production Pathways of Renewable PtX**
What is needed for PtX, incl. green hydrogen

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

4 **PtX Infrastructure**
How to transport and store PtX products (incl. gH_2) best?

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

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

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

List of abbreviations

- **CAPEX:** Capital cost expenditures
- **CCfD:** Carbon contracts for difference
- **CCS:** Carbon Capture and Storage
- **DAC:** Direct Air Capture
- **FLH:** Full-load hours
- **GW:** Gigawatt
- **HVDC:** High voltage, direct current
- **LCOE:** Levelised cost of electricity
- **LOHC:** Liquid organic hydrogen carrier
- **LHV:** Lower heat value

- **OPEX:** Operating cost expenditures
- **PEM:** Proton Exchange Membrane
- **PtX / PtL / PtG:** Power-to-X / -Liquid / -Gas
- **PV:** Photovoltaic
- **RE:** Renewable Energy/ies
- **RES:** Renewable Energy System(s)
- **RWGS:** Reverse Water Gas Shift Reaction
- **SMR:** Steam methane reforming
- **SOEC:** Solid Oxide Electrolyser Cell
- **TWh:** Terawatt hours
- **WACC:** Weighted average cost of capital

Key Conversion Data

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

Conversion kWh and kg H_2:

- 1 kg H_2 = 33.3 kWh H_2 *(heat unit Hu /calorific value)*
- 1 MWh H_2 = 30 t H_2
- 1 Mio t H_2 = 33 TWh H_2

Monetary value per weight or calorific value

- 4.5 ct/kWh H_2 = 45 €/MWh H_2 = 1.5 €/kg H_2
  or: 1€/kg H_2 = 3 ct/kWh H_2
- 100 €/MWh H_2 = 3.33 €/kg H_2
  or: 1€/kg H_2 = 30 €/MWh H_2

Module 6

Sustainability Criteria for Renewable PtX

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Besides its contribution to climate protection, how does PtX fit to the Sustainable Development Goals (SDG)?

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The Paris Agreement

PARIS2015 COP21·CMP11

Limit temperature increase to **1.5° Celsius**

Reduce GHG Emissions to **Net-Zero**

→ the 1.5° challenge

Foto: HvM-22-03-Antwerp

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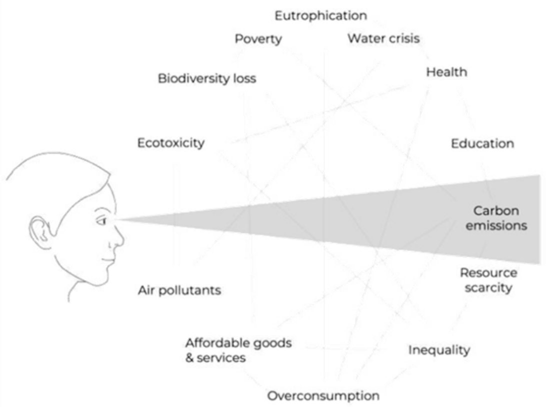
How to get to Paris?
- A broader perspective introducing the Sustainable Development Goals (SDG)



A Carbon Tunnel Vision is not enough!

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How to get to Paris?
- A broader perspective introducing the Sustainable Development Goals

17 SDGs for Planet, People and Prosperity

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1. Development of the EESG Framework
Embedding PtX strategy in SDGs and NDCs

RISKS

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

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

CHANCES

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

Source: UNESCO, 2021.
Source: Nationaler Wasserstoffrat, Nachhaltigkeitskriterien für Importe von erneuerbarem Wasserstoff und PtX-Produkten, 06/2021.
NDC = Nationally determined contributions

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Which sustainability aspects do we need to consider ?

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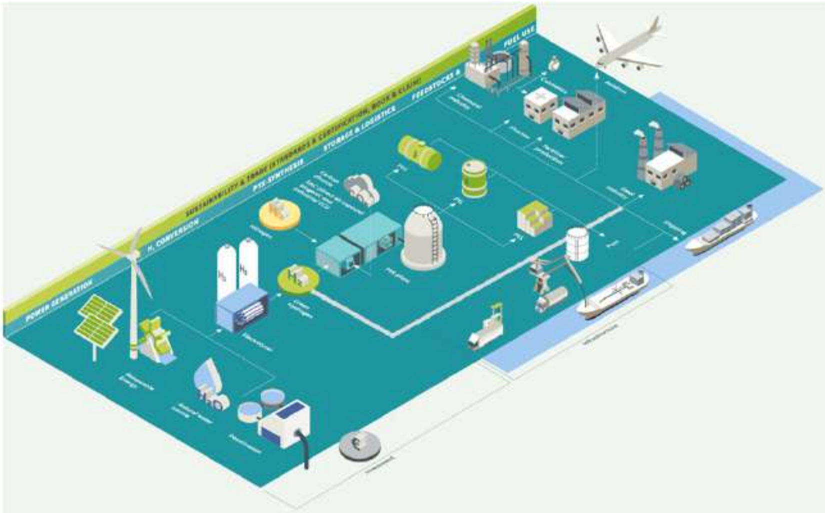
Challenge: Application of sustainability standards
Towards a comprehensive assessment concept



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

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

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1. Development of the EESG Framework
Sustainability concerns must be considered at different assessment levels

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

Tools
- Measuring/Monitoring
- Valuing/Evaluation
- Standards
- Certification
- Due Diligence
- Indicators
  - *data*
  - *thresholds*
  - *timelines*

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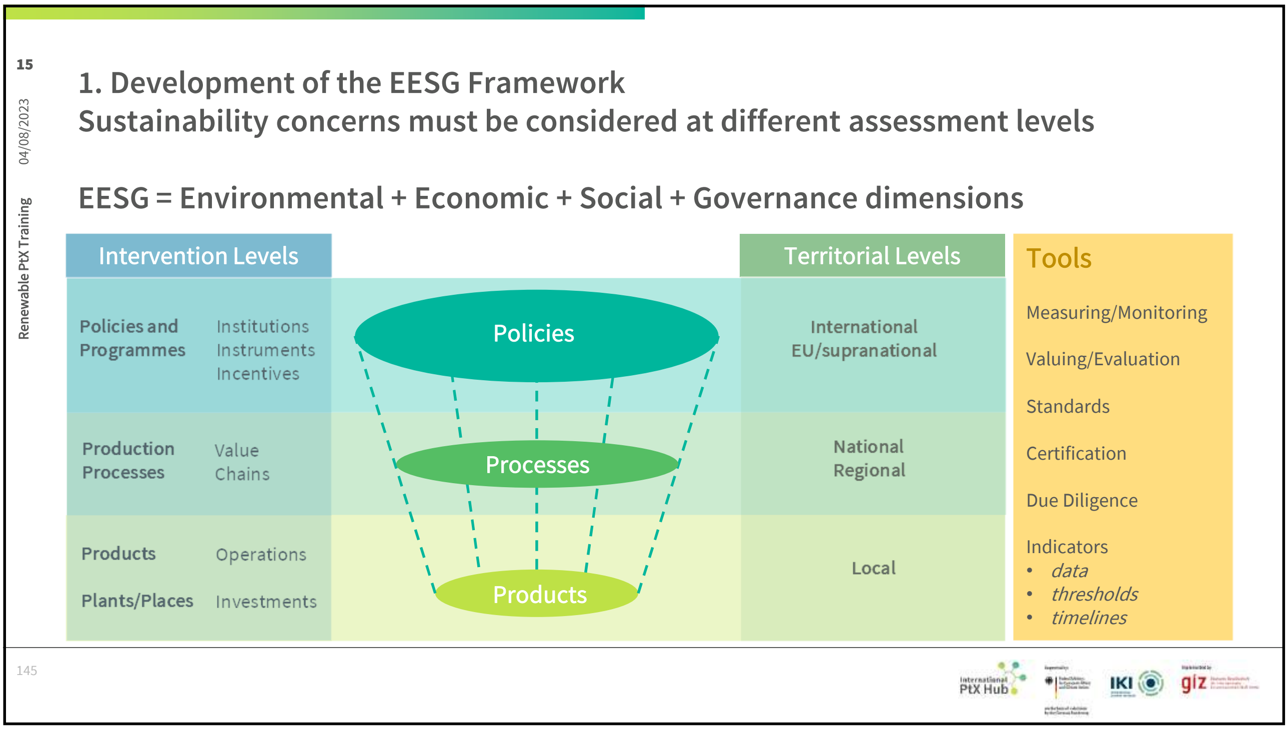
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1. Development of the EESG Framework
Sustainability concerns must be considered at different assessment levels
EESG = Environmental + Economic + Social + Governance dimensions
Intervention Levels
Policies and Programmes
Institutions Instruments Incentives
Production Processes
Value Chains
Products
Operations
Plants/Places
Investments
Policies
Processes
Products
Territorial Levels
International EU/supranational
National Regional
Local
Tools
Measuring/Monitoring
Valuing/Evaluation
Standards
Certification
Due Diligence
Indicators
• data
• thresholds
• timelines
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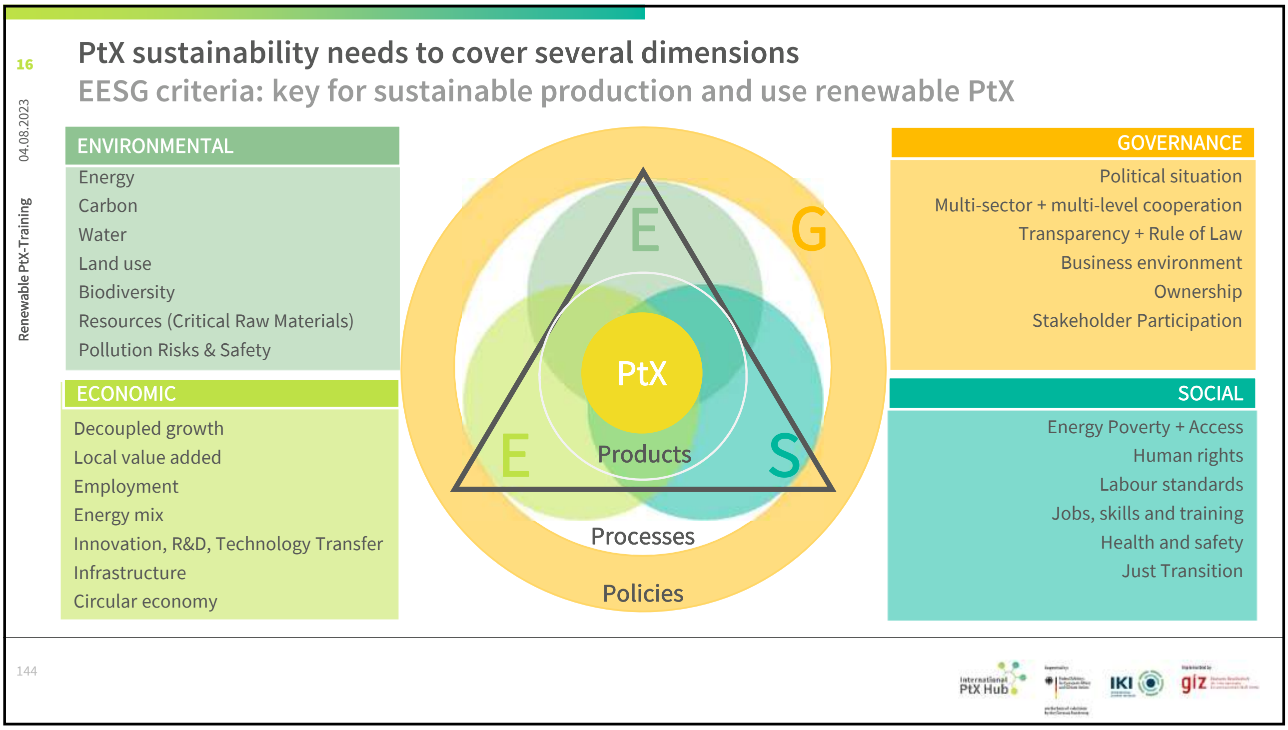
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PtX sustainability needs to cover several dimensions
EESG criteria: key for sustainable production and use renewable PtX
ENVIRONMENTAL
Energy
Carbon
Water
Land use
Biodiversity
Resources (Critical Raw Materials)
Pollution Risks & Safety
ECONOMIC
Decoupled growth
Local value added
Employment
Energy mix
Innovation, R&D, Technology Transfer
Infrastructure
Circular economy
E
G
PtX
E
Products
S
Processes
Policies
GOVERNANCE
Political situation
Multi-sector + multi-level cooperation
Transparency + Rule of Law
Business environment
Ownership
Stakeholder Participation
SOCIAL
Energy Poverty + Access
Human rights
Labour standards
Jobs, skills and training
Health and safety
Just Transition
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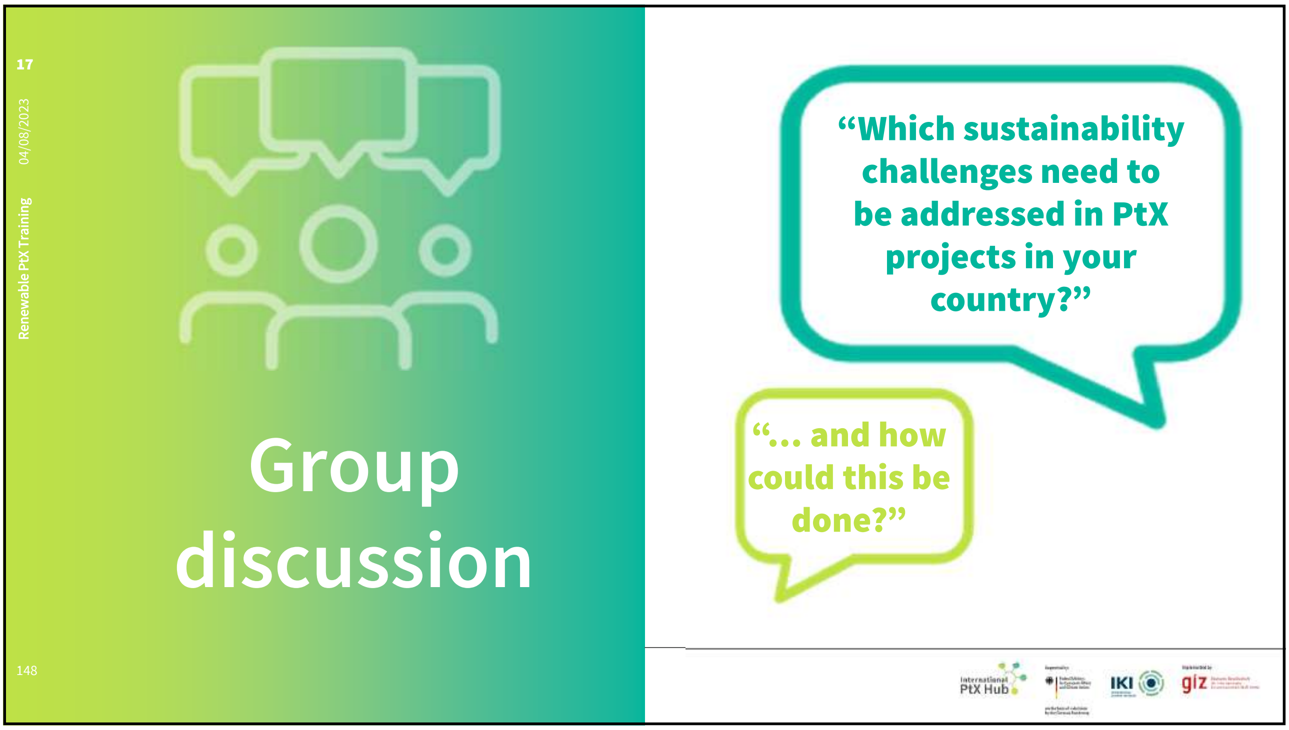
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Group discussion
“Which sustainability challenges need to be addressed in PtX projects in your country?”
“… and how could this be done?”
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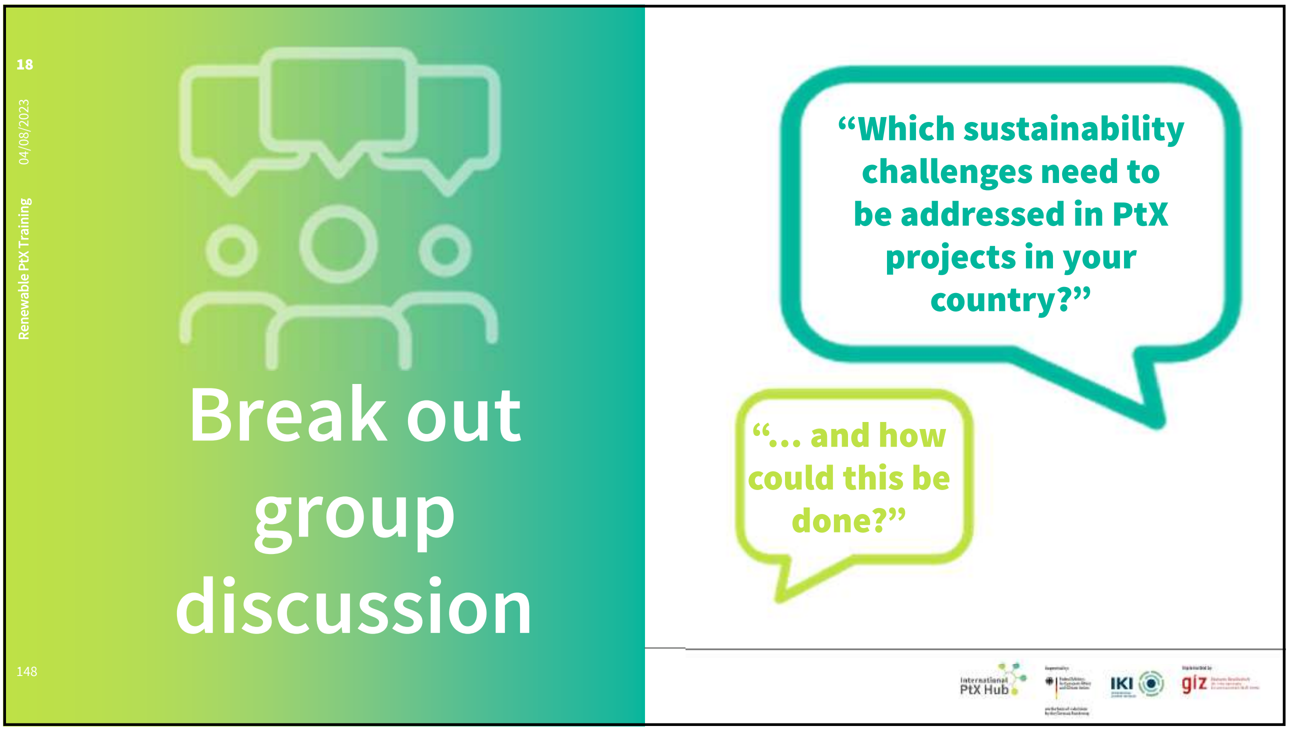
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Break out group discussion
“Which sustainability challenges need to be addressed in PtX projects in your country?”
“… and how could this be done?”
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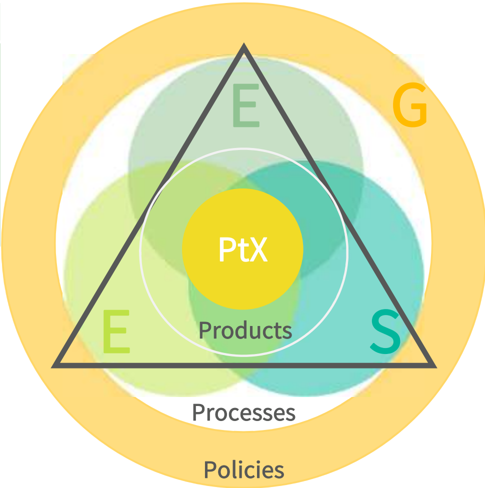
EESG: a closer look at the ENVIRONMENTAL dimensions

ENVIRONMENTAL
- Energy
- Carbon
- Water
- Land use
- Biodiversity
- Resources (Critical Raw Materials)
- Pollution Risks & Safety

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



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

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

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2.1 Environmental Dimensions

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

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What are revelant aspects regarding energy, especially the electricity needed for eletrolysis?

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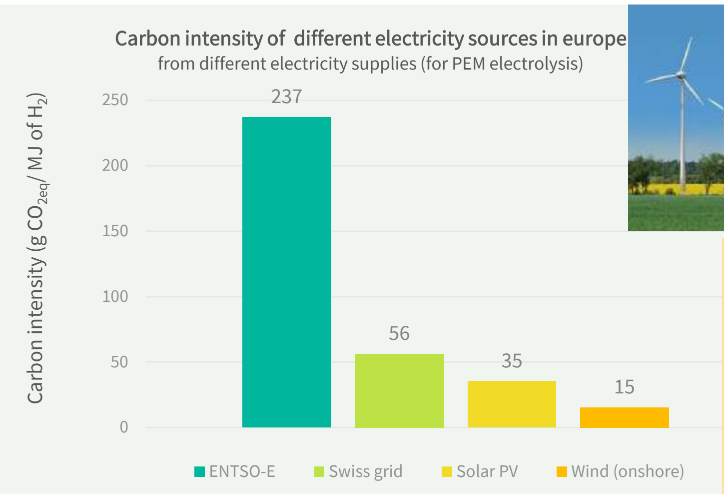
2.1 Environmental Dimensions: Energy

Low carbon intensity of electricity for green hydrogen and PtX production needed

ELECTRICITY

Renewability



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

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

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Source: ENTSO-E and Swiss grid

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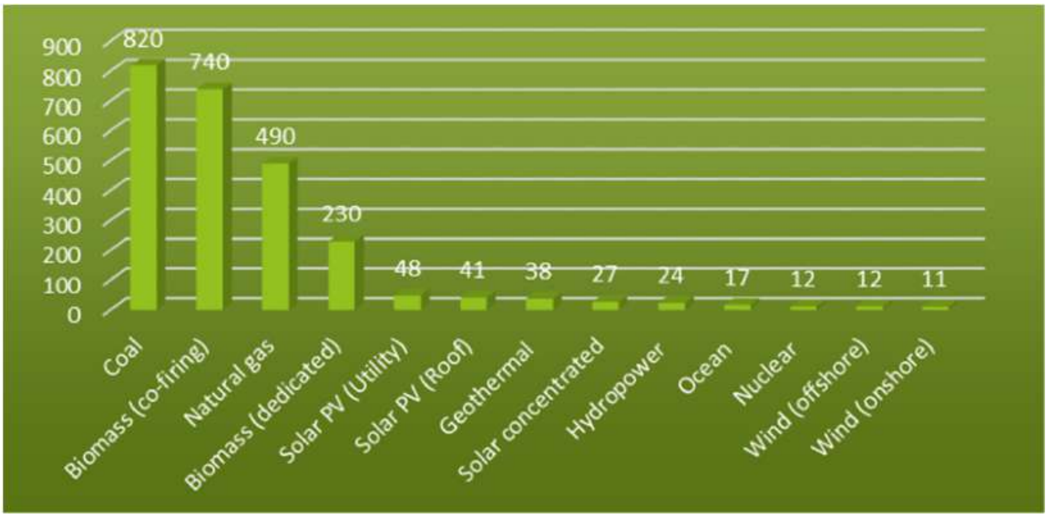
2.1 Environmental Dimensions: Energy
CO_2 emissions per kWh by electricity source in gCO_2 per kWh



8billiontrees (03/2023) Carbon Footprint of Solar Panel 4x More Than Carbon Footprint of Nuclear Power. https://8billiontrees.com/carbon-offsets-credits/carbon-footprint-of-nuclear-power/

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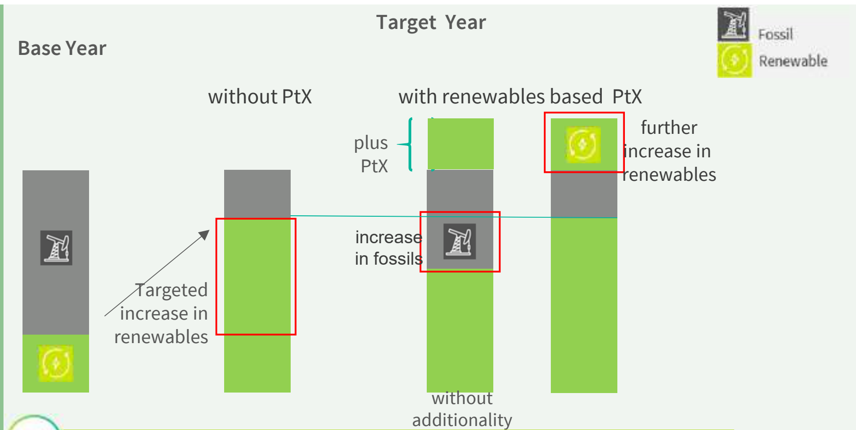
2.1 Environmental Dimensions: Energy
Additional renewables should be installed to supply PtX production

ELECTRICITY

Additionality



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

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

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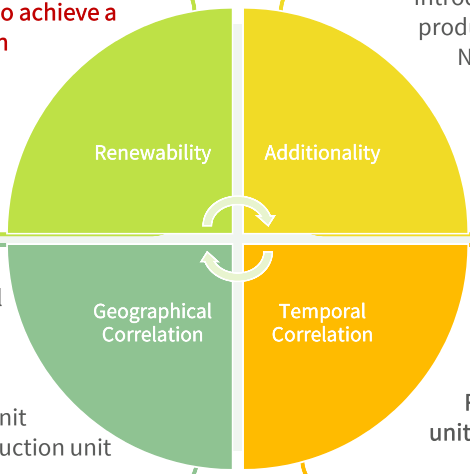
2.1 Environmental Dimensions: Energy

ELECTRICITY

SUMMARY

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

Introduction of PtX production should NOT lead to an increase in fossil use but be based on **additional RE**



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

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

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2.1 Environmental Dimensions: Carbon

Renewable Carbon needed for PtX products

CARBON

Carbon Cycle

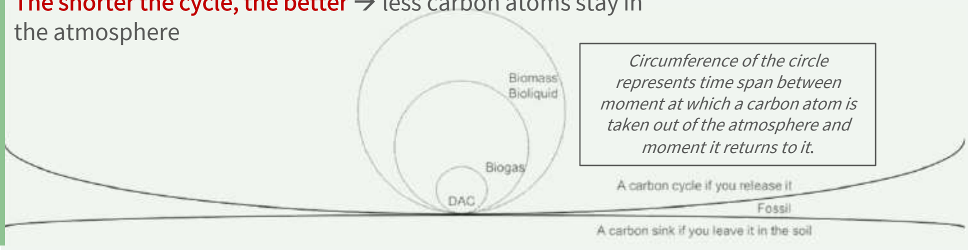
Needed for the production of **hydrocarbons**

Can be obtained from **various sources:**

- ambient air
- biomass sources
- industrial/geological point sources

For PtX products to be **carbon neutral**, a **closed carbon cycle must be in place**

The shorter the cycle, the better → less carbon atoms stay in the atmosphere



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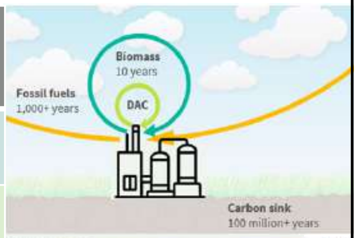
2.1 Environmental Dimensions: Carbon
Evaluation of different carbon sources

CARBON

Carbon Cycle

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



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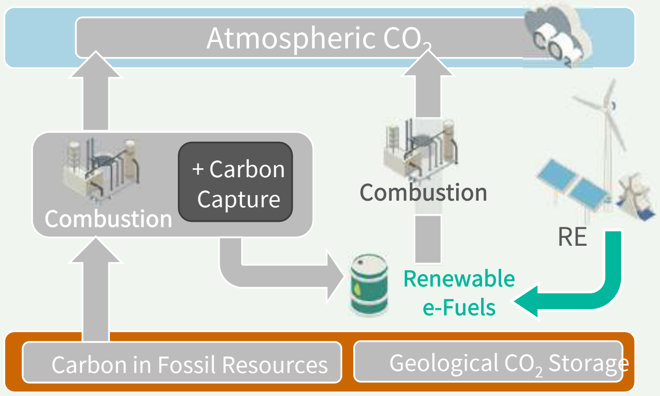
2.1 Environmental Dimensions: Carbon
Industrial Point Sources of Carbon – CO_2 from fossile industrial sources is not renewable

CARBON

Carbon Cycle

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

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



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

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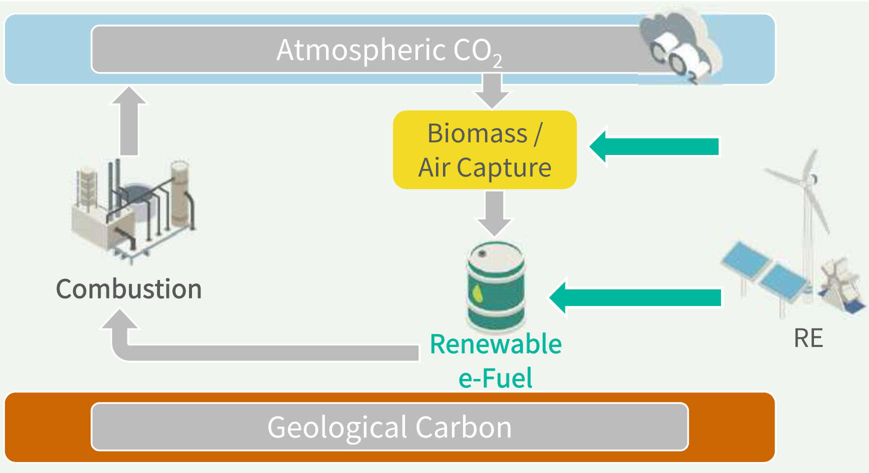
2.1 Environmental Dimensions: Carbon

Renewable Carbon is sourced from biomass or the atmosphere

CARBON

RENEWABLE Carbon Cycle

Cycle with renewable carbon sources is best option



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2.1 Environmental Dimensions: Carbon

Renewable Carbon from Direct Air Capture (DAC)

CARBON

RENEWABLE Carbon Cycle

Direct Air Capture (DAC)

DAC is best option for **long-term** perspective:
- **Closed, immediate carbon cycle**
- Available in **sufficient amounts** and at every potential production site
- But: efficiency is low and costs increase

Requirements:
- Same energy requirements as electrolysers
- Land use management

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

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

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

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

Source: German Environment Agency 2016

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

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2.1 Environmental Dimensions : Carbon

Renewable Carbon from biomass sources

CARBON

Carbon Cycle
Biomass sources

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

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

Requirements:

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

Criticalities:

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

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Any questions?

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What about water for electrolysis?

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2.1 Environmental Dimensions: Water

Water Footprint of H_2 production is lower than water use for fossil energy

WATER

Water Footprint

- 1 kg of H_2 needs 9 kg of H_2O
- Therefore, **2.3 Gt of H_2 requires** 20.5 Gt or **20.5 billion m³ per year** of freshwater → accounts for **only 1.5 ppm of Earth's available freshwater**
- Most of this water can be recovered throughout the different use cases of H2
- In 2014, **251 billion m³** of freshwater were withdrawn for power generation and energy production from **fossil fuels** and **31 billion m³** were consumed as the water was used for **cooling, mining, hydraulic fracturing, and refining**

→ water withdrawn for hydrogen production by electrolysis is still 33% less than the current fossil fuel energy-related uses

Does the Green Hydrogen Economy Have a Water Problem? | ACS Energy Letters

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2.1 Environmental Dimensions: Water

Water Footprint of H_2 production is lower than water use for fossil energy

WATER

Water footprint per litre SAF

Roughly 5 metric tons of pure water a day is required for every megawatt of electrolyser capacity

→An electrolyser of 100 MW capacity consumes roughly 500 tons of water per day (tpd) and produces roughly 50 tpd of hydrogen.

→If the system is water-cooled, the water required will be doubled;
A large hydrogen project, say **30,000 MW, will require at least 150,000 tpd of pure water**. This is approximately the **water demand of a city with a population between 500,000 to one million people**

→But: a **water-cooled 2,000 MW coal-fired power plant consumes around 100,000 tons of water per day.**
If the **coal power plant is closed** and its water offtake rights become available for hydrogen production, there will be **enough water to support at least 18,000 MW of electrolysis**

The importance of water to the hydrogen industry - Advisian

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2.1 Environmental Dimensions: Water

Water use of different Sustainable Aviation Fuels (SAF) based on biomass and electrolysis

WATER

Water footprint per litre SAF

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

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

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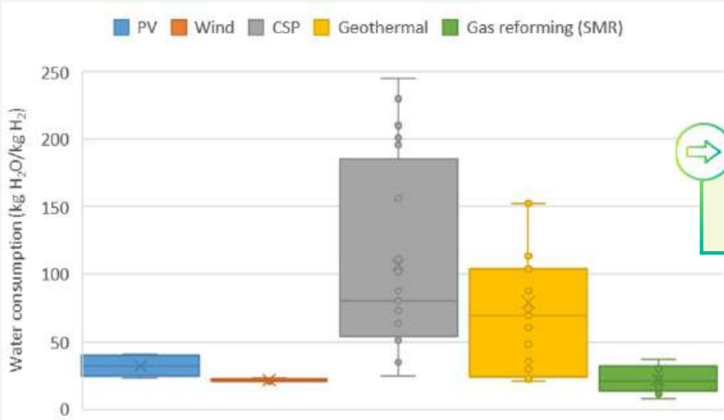
2.1 Environmental Dimensions: Water

Lifecycle water consumption is lowest with renewable energy sources

WATER

Water footprint

Lifecycle water consumption for various hydrogen production pathways



Water footprint can be low when using some RE!

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

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2.1 Environmental Dimensions: Water

Sewater desalination can supply electrolysis and create new local water source

WATER

Water Stress

PtX production could compete with other water uses.

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

Pros ✓
- **Costs** 0.6-1.6 €/m³ in 2030 (**< 2%** of total H_2 production costs)
- Potentially **creates local added value**

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

Aqueduct Water Risk Atlas (wri.org)

164 Source: IRENA, The Geopolitics of the Energy Transformation: The Hydrogen Factor, 01/2022, p.9.
Picture Source: Indiatimes, Solar Desalination Device Will Turn Sea Water Into Fresh Water For 400,000 People, 10/2021.

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2.1 Environmental Dimensions: Water

Sea water desalination with Reverse Osmosis (RO)

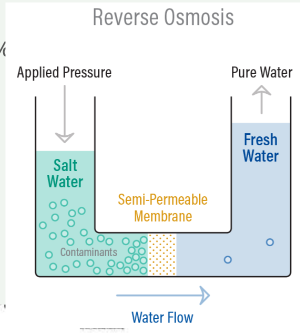
WATER

Reverse Osmosis Water Footprint

- RO requires **3.5–5 kWh of energy for each cubic meter of clean water**
- For a **global hydrogen demand of 2.3 Gt, this yields an additional 0.26–0.37 EJ/a** for RO for water electrolysis
  → i.e., 0.06–0.13% of the minimum energy required to produce the hydrogen by electrochemical water splitting
  → **Economic** viewpoint: desal**ination by RO would add an energy cost of $0.53–1.50 per m³ of clean water** → add no more **than $0.01 to the cost of hydrogen production per kg**

Current state-of-the-art RO plants can achieve **recoveries of up to 50%** (total of **41 billion m³ of seawater** withdrawn annually for hydrogen production) = **around 30 ppb of the world's available supply of seawater each year**

negligible amount compared to the resources available, and the water that cannot be recovered is returned to the same body of water, so that it is not consumed.



ve a Water Problem? | ACS Energy Letters
mosis | Puretec Industrial Water (puretecwater.com)

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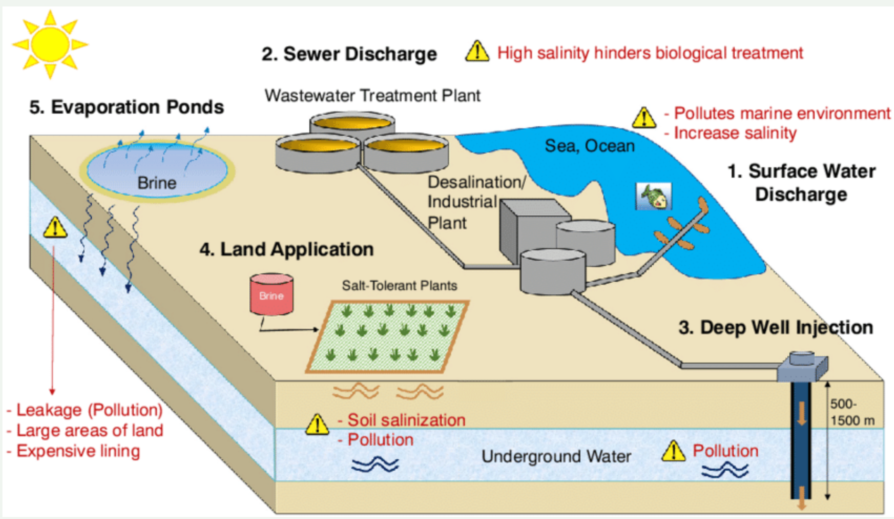
2.1 Environmental Dimensions: Water

Brine from sea water desalination needs to be disposed of properly

WATER

Brine Disposal



environmental-challenges_fig1_351117435

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Any questions?

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Which aspects of land use need to be considered?

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2.1 Environmental Dimensions: Land

Land required for different ways of generating electricity – solar and wind use for different Sustainable Aviation Fuels (SAF)

Land use	Electricity generated *per acre* *over 75 years*	*over 25 years*	Acres per GWh per year[1]	Reclamation options
Solar	**25.00 GWh**	8.33 GWh	3 (*perpetual*)	Remove panels or dual-use[2]
Nuclear (mining)	16.66 GWh	16.66 GWh	0.06 (*only once*)	Very high cost (radioactive)
Coal (mining)	11.11 GWh	11.11 GWh	0.09 (*only once*)	Costly (<15% reclaimed)
Wind	2.90 GWh	0.96 GWh	26 (*perpetual*)	Remove turbines or dual-use[2]
Hydro	2.50 GWh	0.83 GWh	30 (*perpetual*)	Drain dam + restoration
Biomass	0.40 GWh	0.13 GWh	188 (*perpetual*)	Replant trees

Sources at http://fep.link/g104

[1] a GWh is the same as a million kilowatt hours | [2] reclamation may not be necessary because land can be simultaneously used for other purposes
Data was gathered from multiple sources and studies. It was normalized here to be illustrative. Actual project land use varies widely by geography.

Clean Energy (02/2023) Land Use Implications of Energy Choices. https://cleanenergy.org/blog/land-use-implications-of-energy-choices/

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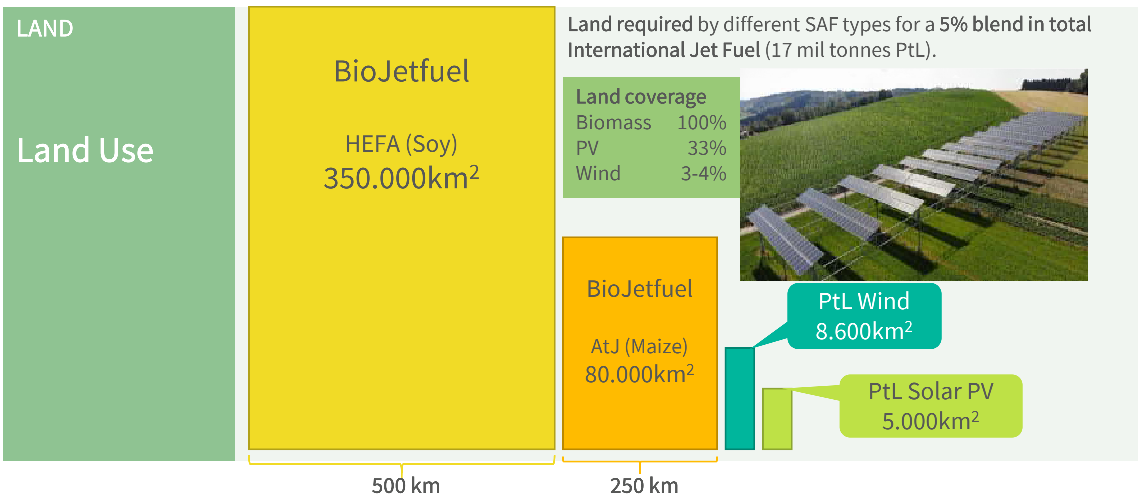
2.1 Environmental Dimensions: Land

Comparison of land use for different Sustainable Aviation Fuels (SAF)



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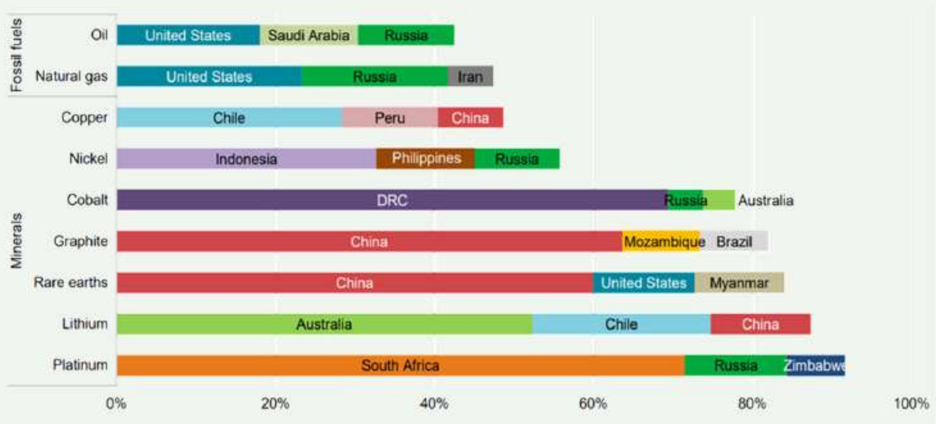
Don´t we need rare earth materials for PtX production, especially for electrolyzers?

2.1 Environmental Dimensions: Resources and Recycling

Critical raw materials and where to find them

CRITICAL RAW MATERIALS (CRM)

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



168.1 Source: IEA, TheRoleofCriticalMineralsinCleanEnergyTransitions. https://iea.blob.core.windows.net/assets/24d5dfbb-a77a-4647-abcc-667867207f74/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf

2.1 Environmental Dimensions: Resources and Recycling

Demand for rare raw materials is increasing

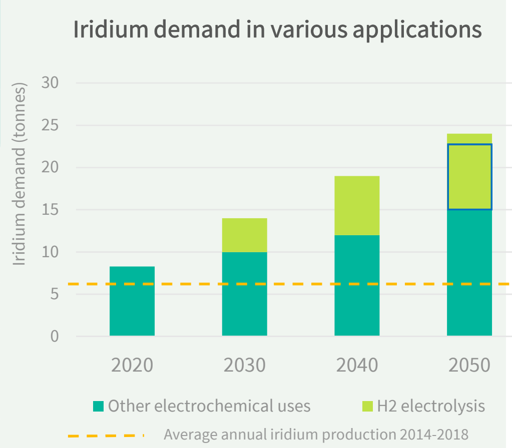
CRITICAL RAW MATERIALS (CRM)

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

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

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

2050 target: European Hydrogen Roadmap



2.1 Environmental Dimensions: Resources and Recycling

Saving strategies to prevent shortage of raw materials

CRITICAL RAW MATERIALS (CRM)

Savings strategies

- prevention
- extention
- recycling

Typ	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	-

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Any questions?

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Test your knowledge

"Which sustainability criteria will be the hardest to meet in your country?"

"Which sustainability criteria for PtX production do you consider important?"

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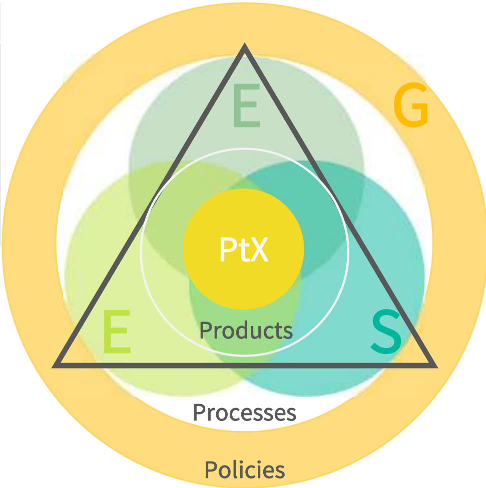
EESG: a closer look at the ECONOMIC dimensions

ENVIRONMENTAL
- Energy
- Carbon
- Water
- Land use
- Biodiversity
- Resources (Critical Raw Materials)
- Pollution Risks & Safety

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



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

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

2.3 Economic Dimensions

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

2.3 Economic Dimensions

Fears and rumours about PtX exports form other coutntries

unsustainable debt

power asymetries

neocolonialism

sun grabbing

marginalisation

resource conflicts

(neo)/ greenextractivism

privatisation

resource curse

degradation

elite capture

Goal: JUST Energy Transition = just green hydrogen transition

A just energy transition is "the transformation of the energy sector from operating mainly with fossil fuel-based sources toward a zero-carbon sector using renewable energy" (1) that ensures "a fair sharing of adjustment benefits and burdens" (2)

Energy Justice in practice: encompasses at least six dimensions (3)

1. **Procedural justice:** involving communities in transparent planning processes of GH2 infrastructure (engagement, consultation, adhering to principle of free, prior + informed consent (FPIC))
2. **Distributive justice:** fair distribution of transition's costs + benefits (fair allocation of generated electricity as well as water)
3. **Relational justice:** preserve sustainable ways of living, minimizing negative socio-ecological effects
4. **Restorative justice:** Recognition of Global North's historical + ecological debts resulting from colonialism + climate change
5. **Recognitional justice:** Respecting identities, cultures, rights, interests, needs and vulnerabilities of all individuals + communities affected
6. **Epistemic justice:** inclusion of diverse knowledge systems in decision-making processes (valuing local and indigenous knowledge) alongside scientific and technical expertise

Source: (1) UNRISD (2022). Evaluating Existing Transformations: The Case for a Just Energy Transition. UNRISD Issue Brief, 14, December 2022, p.1.
(2) IRENA (2022) World Energy Transitions Outlook 2022: 1.5°C Pathway. International Renewable Energy Agency, p.29.
(3) Müller, F., Tunn, J., & Kalt, T. (2022) Hydrogen justice. Environmental Research Letters, 17(11), 115006.

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2.3 Economic Dimensions: Energy Mix and Transformation

Global growth of renewables is triggering supply for renewable PtX

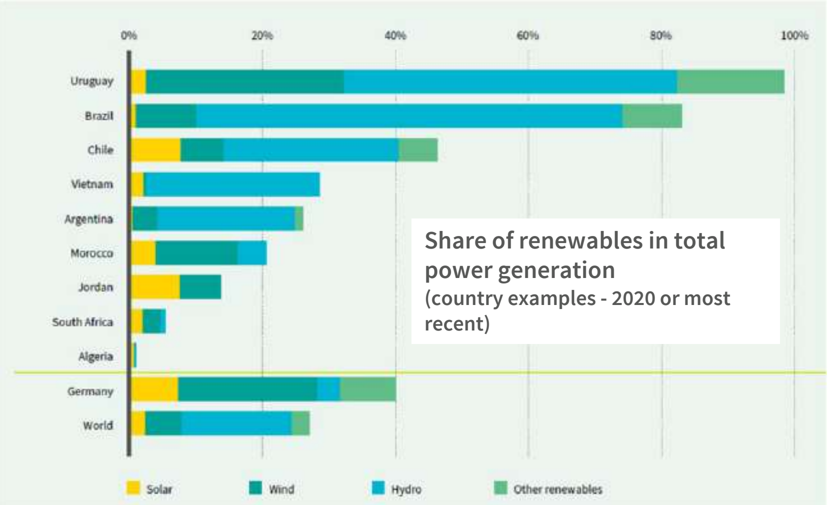
ENERGY MIX AND TRANSFORMATION

Energy Mix
- fossil
- renewables

Energy trends and scenarios

H2 and PtX
- potentials
- actual

Market Design (ETS, CDM etc)



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2.3 Economic Dimensions: Value Added and Decoupled Growth

New projects have to provide local value creation

VALUE ADDED AND DECOUPLED GROWTH

Value Added

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

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

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

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

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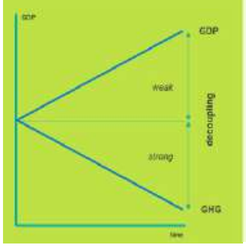
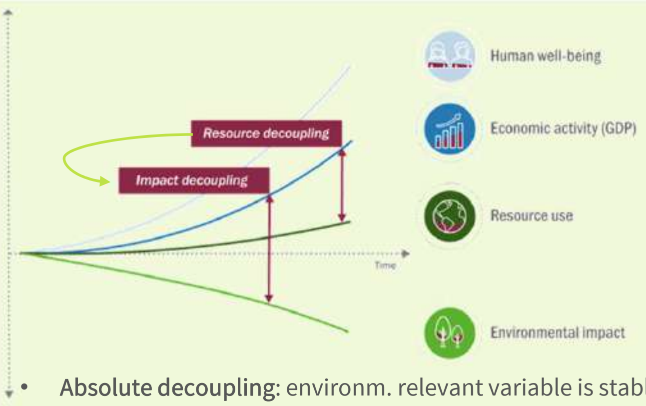
2.3 Economic Dimensions

Value Added and Decoupled Growth

VALUE ADDED AND DECOUPLED GROWTH

Decoupled Growth





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

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

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2.3 Economic Dimensions: Value Added and Decoupled Growth

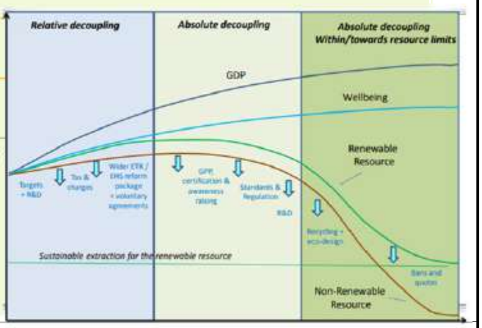
Reneewables and renewables PtX decouple economic growth and environmental impact

VALUE ADDED AND DECOUPLED GROWTH

Decoupled Growth

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

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



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

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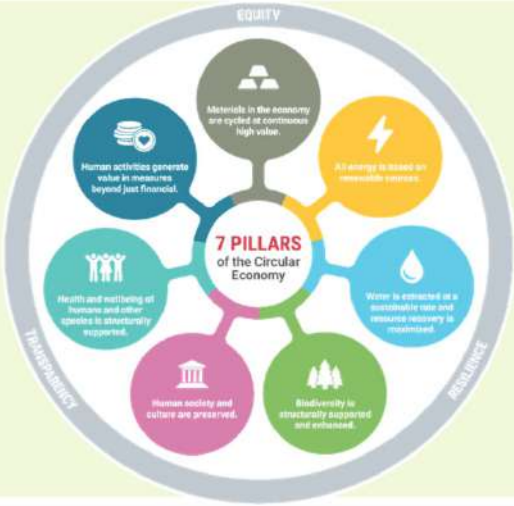
2.3 Economic Dimensions : Value Added and Decoupled Growth

Circular economy to contribute to sustainability

Circular Economy

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



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

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Any questions?

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Break out group discussion
"What are potential positive socio-economic impacts of your projects?"
"How could potential negative impacts be avoided or mitigated?"
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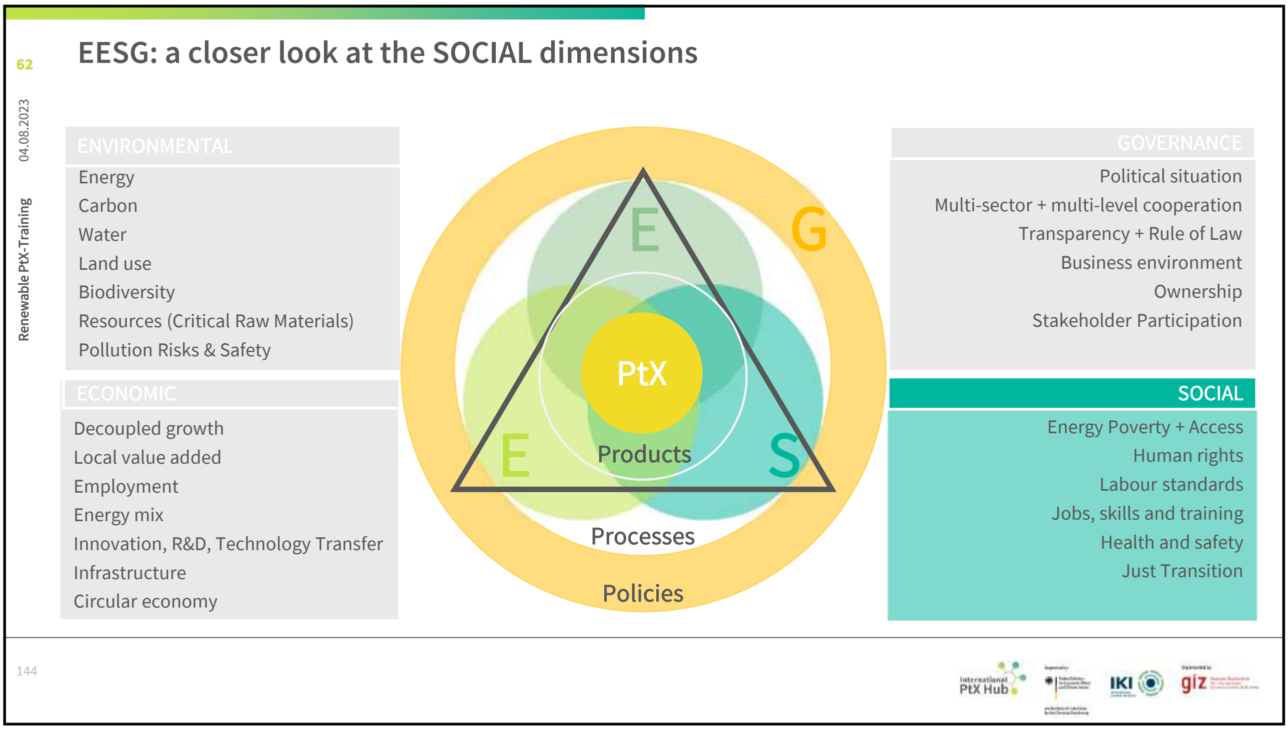
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EESG: a closer look at the SOCIAL dimensions
ENVIRONMENTAL
Energy
Carbon
Water
Land use
Biodiversity
Resources (Critical Raw Materials)
Pollution Risks & Safety
ECONOMIC
Decoupled growth
Local value added
Employment
Energy mix
Innovation, R&D, Technology Transfer
Infrastructure
Circular economy
E
G
E
S
PtX
Products
Processes
Policies
GOVERNANCE
Political situation
Multi-sector + multi-level cooperation
Transparency + Rule of Law
Business environment
Ownership
Stakeholder Participation
SOCIAL
Energy Poverty + Access
Human rights
Labour standards
Jobs, skills and training
Health and safety
Just Transition
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2.2 Social Dimensions

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

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2.2 Social Dimensions

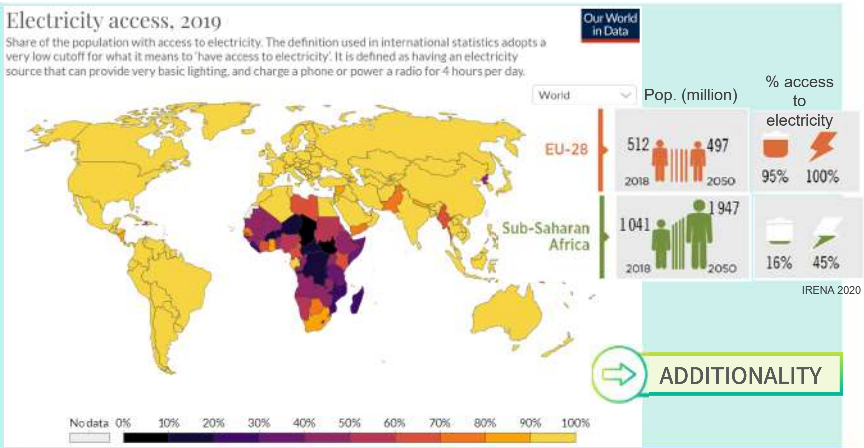
Access to Energy and Resources

ACCESS TO:

1. Energy: connection to electricity (SDG7)

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

3. Land: land use conflicts



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

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

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2.2 Social Dimensions
Human Rights and Labour Standards

LABOUR STANDARDS

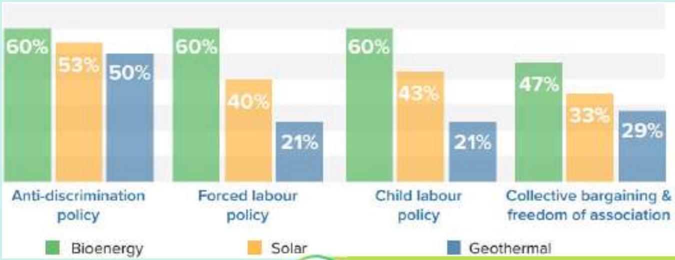
International Labour Organization

Core Labour Standards

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

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

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



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

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

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2.2 Social Dimensions
Human Rights and Labour Standards

LABOUR STANDARDS AND HUMAN RIGHTS

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

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

179 Source: EDP, Human and Labor Rights Policy.

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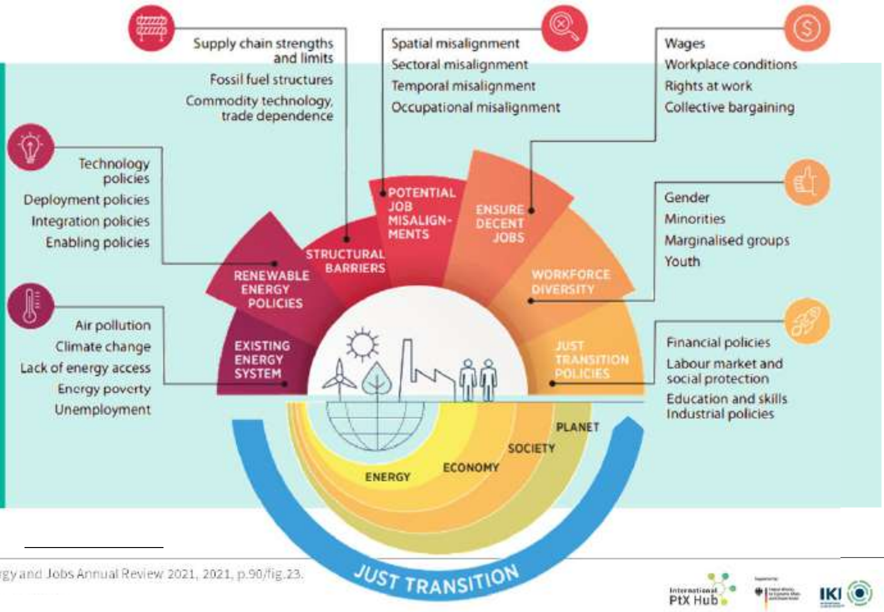
2.2 Social Dimensions

Jobs and Skills

JUST TRANSITION

Jobs in the Just Energy Transition: Challenges and policies



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

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2.2 Social Dimensions

South Africa's Just Transition landscape

- Effects on bio-diversity.
- GHG emissions.
- Air quality.
- Resource use.
- Land use.
- **Research Institutions:** CSIR, SEA, WWF, SANBI, Water research Council, TIPS, Oneworld.

- Economic growth.
- Number and quality of jobs.
- Government spending.
- Economic diversifiation.
- Skills.
- **Research Institutions:** CSIR, TIPS, Greencape, NBI, UCT, Meridian.
- **Stakeholders:** DPME, EDD, NT, IKI, Dtic, IPPO, Exxaro, Eskom, Sasol, EIUG, GIZ, MPG, Mineral Council of SA, Agora, Res4Africa, Labour Unions, World Bank.

- Health impacts.
- Community participation.
- Quality of life.
- Crime.
- Other social pathologies.
- **Research Institutions:** CSIR, YES, NBI, Oneworld, SEA.
- **Stakeholders:** DPME, NPC, DSD, IPPO, UNECA, MPG, Labour Unions.

- Cost of various technologies.
- Impacts on electricity tariffs.
- Grid stability and reliability.
- **Research Institutions:** CSIR, Eskom, UCT, Meridian.
- **Stakeholders:** DPE, NT, NERSA, Sasol, GIZ, MPG, World Bank.

Source: DMRE, TOWARDS A JUST ENERGY TRANSITION FRAMEWORK IN THE MINERALS AND ENERGY SECTORS, 1172021, p.29/fig.6.

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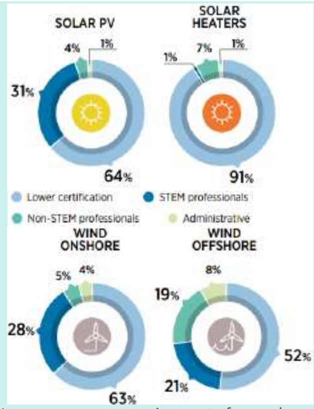
2.2 Social Dimensions
Jobs and Skills

JOBS AND SKILLS

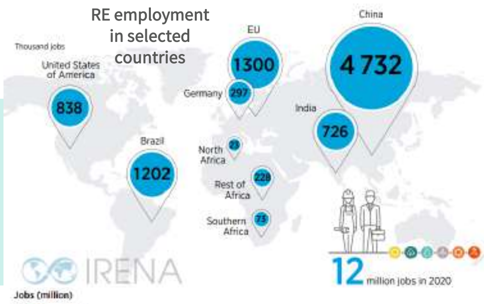
Jobs
- Gains in Renewables
- Losses in Fossils

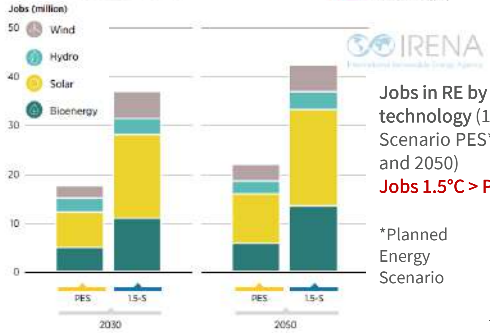
Jobs and Just Transition
- Regional disparities / diversity

Skills and Training
- Qualifications and skills profile



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





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

Jobs 1.5°C > PES

*Planned Energy Scenario

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

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Any questions?

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Test your knowledge

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

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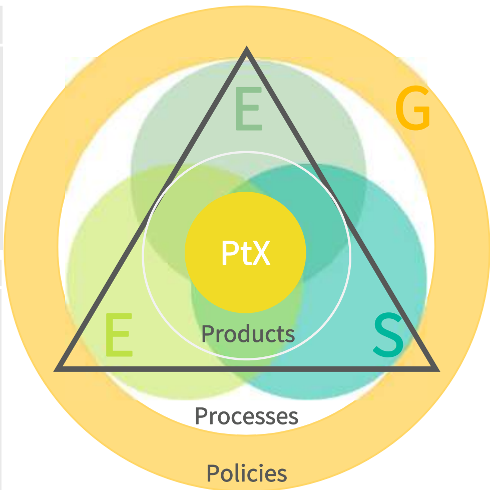
EESG: a closer look at the GOVERNANCE dimensions

ENVIRONMENTAL
- Energy
- Carbon
- Water
- Land use
- Biodiversity
- Resources (Critical Raw Materials)
- Pollution Risks & Safety

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



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

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

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2.4 Governance Dimensions

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

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2.4 Governance Dimensions

Cluster: Policy Committment and Coherence

GOV Concerns
Standards & Certification
Transparency & Participation
Policy Commitment & Coherence
Stability & Rule of Law
...

Some Examples

PA Implementation
(PA: Paris Agreement on GHG)

-- *NDC*
(Nationally Determined Contribution)

-- *Art.6*
(Cooperative Meachanisms)

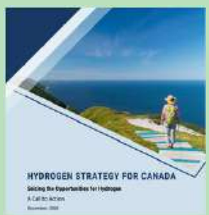
-- Carbon neutrality commitment

-- National H2 Strategy

-- PtX Roadmap

...

https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Chile%20First/Chile%27s_NDC_2020_english.pdf



https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf

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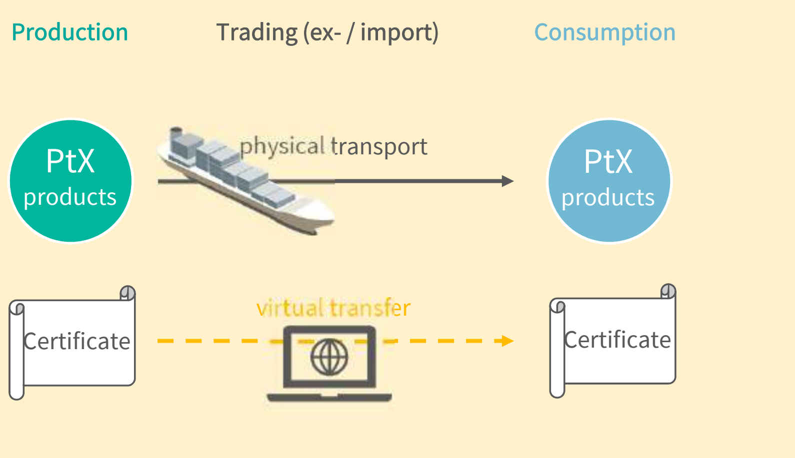
How can we certify, that PtX products are produced in a sustainable, renewable way?

2.4 Governance Dimensions: Standards and Certification

Would we like to trade physical products or certificates?

STANDARDS AND CERTIFICATIONS

Trading products or properties ?



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2.4 Governance Dimensions: Standards and Certifications

Requirements for PtX certifications need to ensure sustainable PtX

STANDARDS AND CERTIFICATIONS

Requirements for PtX Certification

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

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

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

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

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2.4 Governance Dimensions

Standards and Certifications

STANDARDS AND CERTIFICATIONS

Different certification institutions / schemes

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

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2.4 Governance Dimensions - Standards and Certifications

Green hydrogen standards in comparison

STANDARDS AND CERTIFICATIONS

Several green hydrogen standards are in place or under development

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

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Notes: *RFNBO: renewable fuels of non-biological origin. REDII revision proposed to expand this to all end use sectors.
Source: Guidehouse, EU certification frameworks Sustainability criteria for green hydrogen, Knowledge Session Certification of Green Hydrogen, 24.11.2021.

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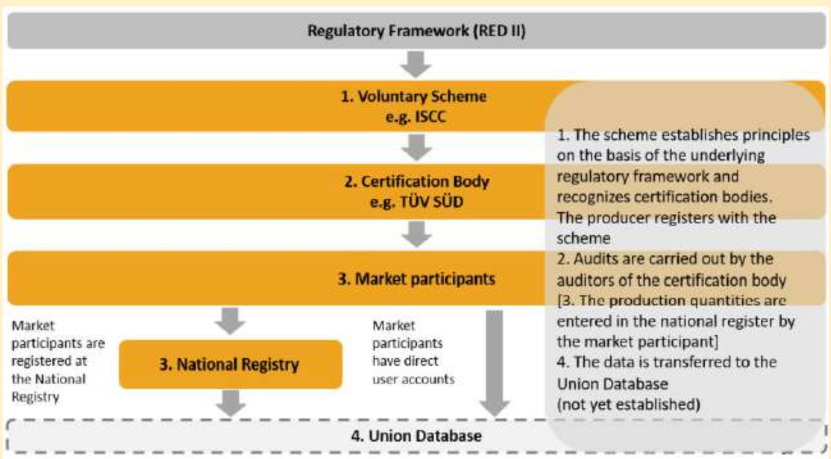
2.4 Governance Dimensions: Standards and Certifications

Certification process in the EU

STANDARDS AND CERTIFICATIONS

Certification process in the EU

Producer reports quantity of RFNBOs placed on market and their associated GHG emissions towards the responsible authority. This can be done by Proofs of Sustainability (PoS), if a national registry is in place.



193.2

Source: World Energy Council, Global Harmonisation of Hydrogen Certification , 01/2022, p.17/figure1.

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GHG reduction targets of schemes

Regulation/ standard	Sector	H2 type	Reduction target	Refernce baseline	Threshold
CertifHy	Transport	H2 from renewable sources	60%	91 gCO2equ/MJ	36.4 gCO2equ/MJ
China Hydrogen Alliance's Standard	-	Low-carbon H2	-	-	14.51 gCO2equ/kgH$_2$
	-	Clean and renewable H2	-	-	4.9 gCO2equ/kgH$_2$
LCFS	Transport	H2 from electrolysis, and bio based H2	20%	94 gCO2equ/MJ	76.1 gCO2equ/MJ3
RED II	Transport	H2 from renewable sources	70%	94 gCO2equ/MJ	28.2 gCO2equ/MJ
RTFO	Transport	H2 (excl. biomass)	60%	83.8 gCO2equ/MJ (petrol + diesel)	33.52 gCO2equ/MJ
TÜV Süd CMS 70	Transport	H2 (excl. electrolysis)	60% Fossil fuel	94 gCO2equ/MJ	37.6 gCO2equ/MJ
	All, except transport	H2 (excl. electrolysis)	60% Grey H2	89.7 gCO2equ/MJ	35.9 gCO2equ/MJ
	All	H2 from electrolysis	75%	Fossil fuel/grey H2 (dep. on application)	23.5 gCO2equ/MJ - 22.42 gCO2equ/MJ

Source: World Energy Council, Global Harmonisation of Hydrogen Certification , 01/2022, p.25/table5.

193.3

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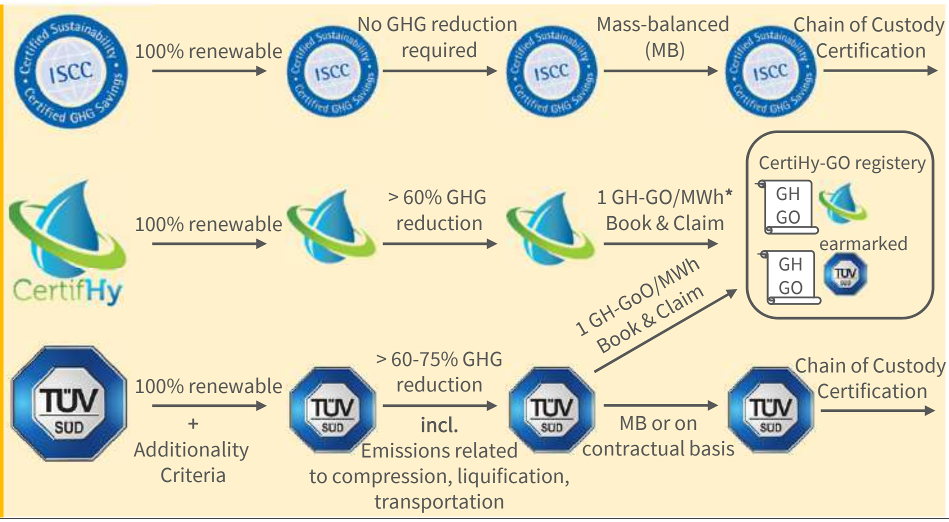
2.4 Governance Dimensions: Standards and Certification

Existing certifications systems are based on different criteria

STANDARDS AND CERTIFICATIONS

Existing certification systems:
- Hydrogen from renewable energy resources ISCC
- CertifHy (only EU)
- TÜV SÜD Green Hydrogen



Source: (adapted) TÜV SÜD, Certification systems on Hydrogen and its relevance for a sustainable future, Knowledge Session Certification of Green Hydrogen, 24.11.2021.
*Trading unit: 1 Green Hydrogen (GH) – Guarantee of Origin (GO) in unit of 1 MWh (based on lower heating value)

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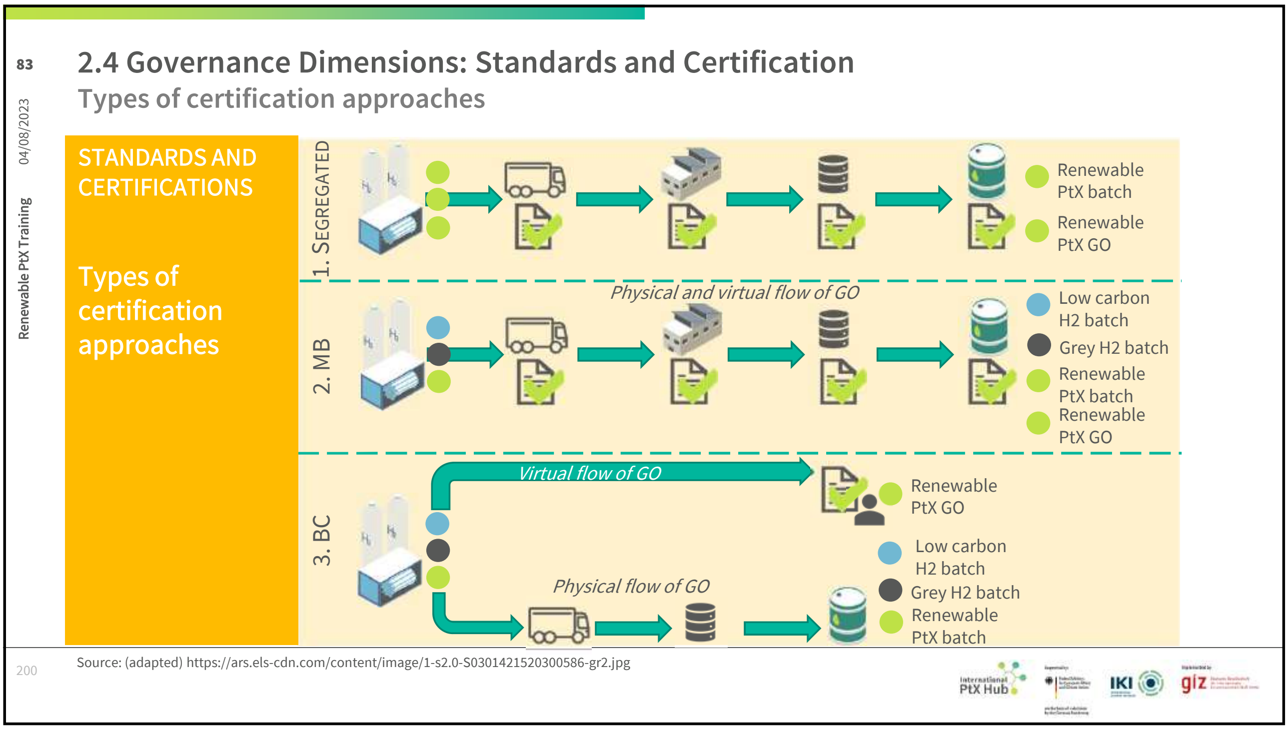
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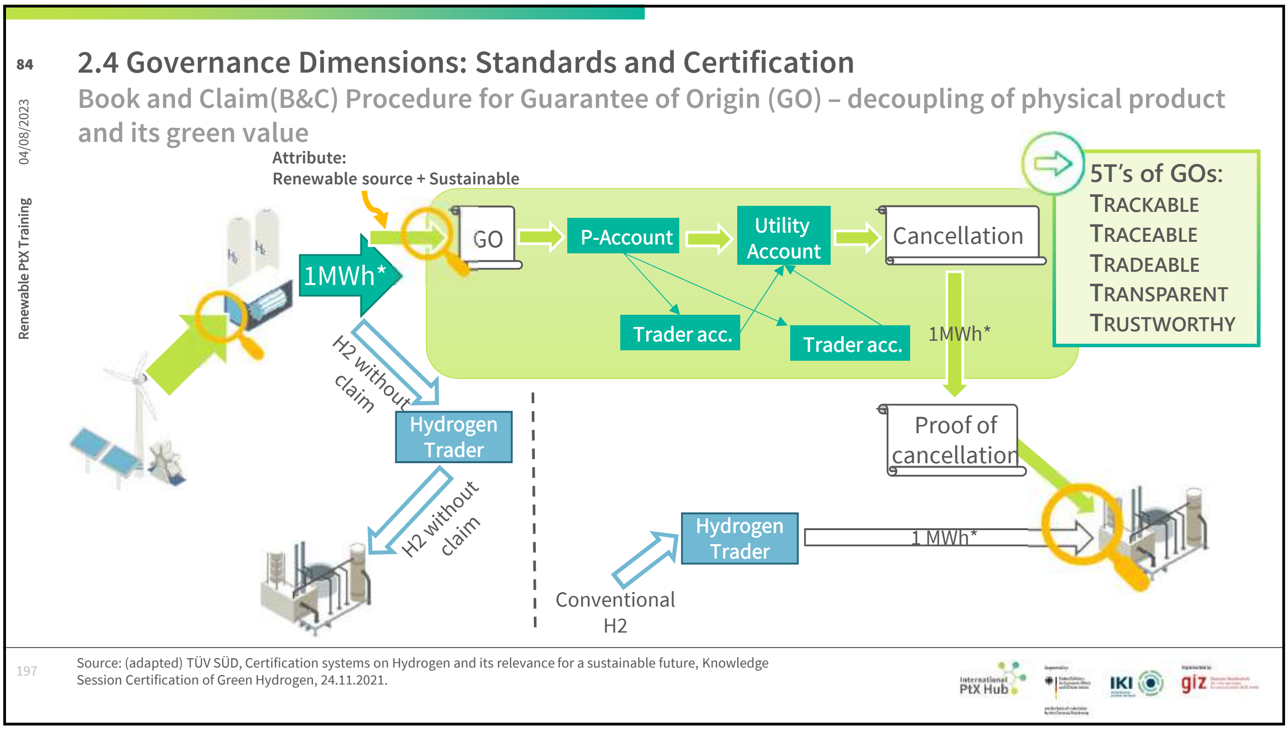
2.4 Governance Dimensions: Standards and Certification
Types of certification approaches
STANDARDS AND CERTIFICATIONS
Types of certification approaches
1. SEGREGATED
Renewable PtX batch
Renewable PtX GO
Physical and virtual flow of GO
2. MB
Low carbon H2 batch
Grey H2 batch
Renewable PtX batch
Renewable PtX GO
3. BC
Virtual flow of GO
Renewable PtX GO
Low carbon H2 batch
Grey H2 batch
Renewable PtX batch
Physical flow of GO
200
Source: (adapted) https://ars.els-cdn.com/content/image/1-s2.0-S0301421520300586-gr2.jpg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2.4 Governance Dimensions: Standards and Certification
Book and Claim(B&C) Procedure for Guarantee of Origin (GO) – decoupling of physical product and its green value
Attribute:
Renewable source + Sustainable
1MWh*
GO
P-Account
Utility Account
Cancellation
Trader acc.
Trader acc.
1MWh*
5T's of GOs:
TRACKABLE
TRACEABLE
TRADEABLE
TRANSPARENT
TRUSTWORTHY
H2 without claim
Hydrogen Trader
H2 without claim
Proof of cancellation
Hydrogen Trader
1 MWh*
Conventional H2
197
Source: (adapted) TÜV SÜD, Certification systems on Hydrogen and its relevance for a sustainable future, Knowledge Session Certification of Green Hydrogen, 24.11.2021.

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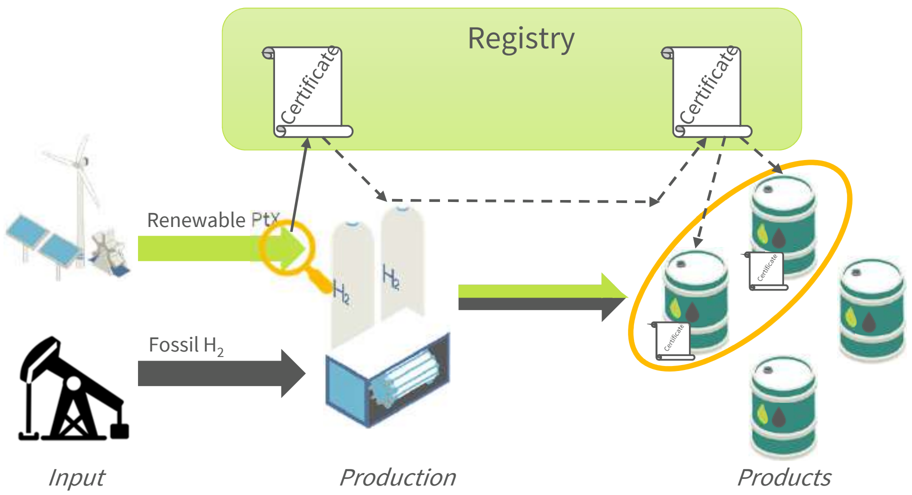
2.4 Governance Dimensions: Standards and Certification

Mass Balance (MB) certifies that the end product consists of green H2 or renewable PtX (share)



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Eligible carbon sources for different regulations/standards for hydrogen/ RFNBOs

Sust. criteria for H2/RFNBOs	Regulations							Funding Programme	Schemes		
Regulation/ Standard	ISCC PLUS	CertifHy	dena – Biogas register	TÜV Süd CMS 70	China H2 Alliance's Standard[1]	Certification Scheme (Japan)[2 3]	Carbon Certification Scheme	H2Global	LCFS	RED II	RTFO
GHG emissions	to- Wheel	V Gate	demand	V Wheel	V Wheel	V Gate	Well-to-Gate	W Wheel	V Wheel	W Wheel	Wheel[5]
Eligible carbon sources											
Fossil-based carbon	+	tbu	+	out of scope	out of scope	n/a	+	+	+	pending Delegated Act	+
Biogenic carbon	+	tbu	+	out of scope	out of scope	n/a	+	+	+	pending DA	+
Carbon from DAC	-	tbu	+	out of scope	out of scrope	n/a	+	tbu	+	pending DA	+
Additional criteria											
Land use	+	-	-	-	-	-	-	+	+	-	-
Water consumption	+/-	-	-	-	-	-	+/-	+/-	+/-	+/-	-
Social impact	+	-	-	-	-	-	-	+	+	-	-

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Any questions?

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Open discussion

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

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Sustainability Indicators to Consider (Fraunhofer‘s PtX Atlas)

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

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

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

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

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

Proximity to Germany
- Logistics infrastructure
- Distance (km)
- Economic relations
- Cultural proximity

MODULE 6 Sustainability: Key Take-Aways

1. Development of the EESG Framework
- To achieve the Paris Agreement, **defossilisation of the economy is needed**, for the economy and the biosphere.
- Green hydrogen and renewable PtX are key for the decarbonization of industry and hard-to abate sectors.
- **PtX sustainability dimensions need to address the entire value chain** and specifically analyse the environmental, economic, social and governance dimension.
- Sustainability concerns must be considered at **different assessment levels.**

2. Sustainability Dimensions of the EESG Framework
- **Economic:** PtX production and trade should contribute to improving **economic prosperity and well-being** as well as environmental wellbeing (decoupled growth). Leap-frogging potentials should be taped.
- **Environmental:** The various environmental dimensions of PtX production are essential to determine the level of **sustainability**. The production of additional **renewable power for hydrogen production is a must.** The use of renewable power for hydrogen production does not impair the overall energy transition and especially the decarbonisation of the power sector.
- **Social:** The transformation of energy systems and introduction of new technologies like PtX always have major social implications, which is why a **"just transition"** must be ensured.
- **Governance:** National and international **standards and certification schemes** must provide proper **regulatory frameworks to ensure the sustainability of the traded products** and for ramping-up PtX markets and trade.

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Any questions?

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Open discussion

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

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

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Thank you for your kind attention!
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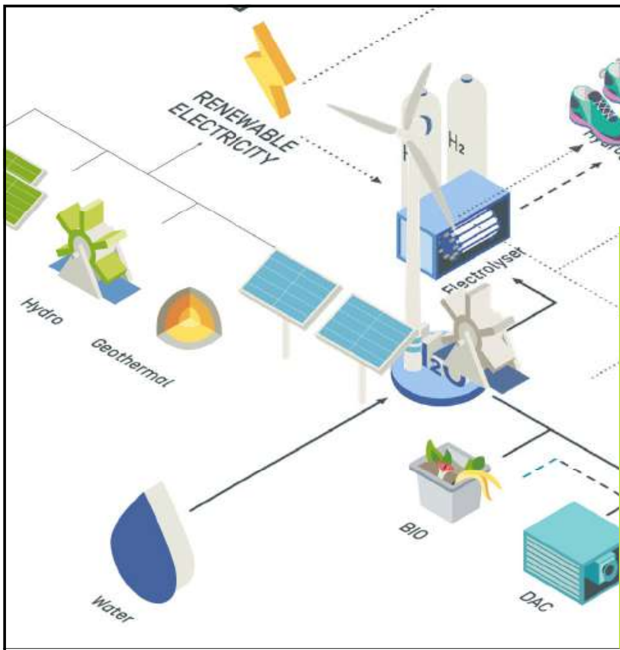
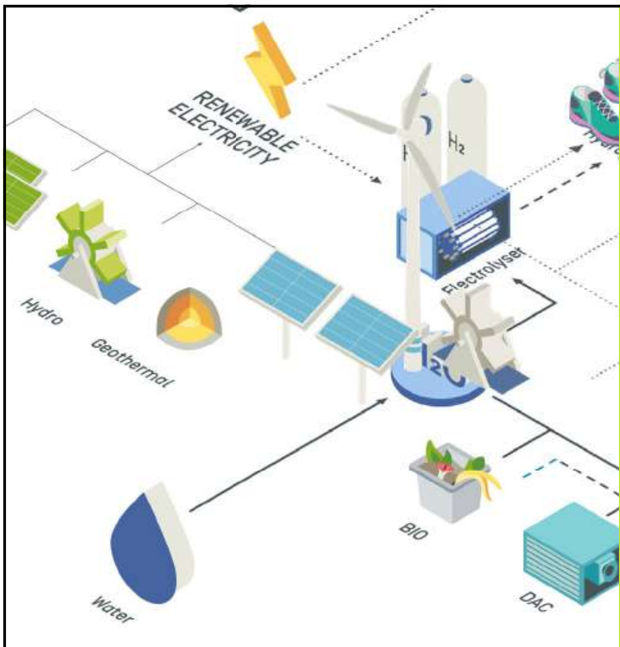


Renewable POWER TO X

Training: August 2023
Modules prepared by the International PtX Hub
Trainer: Prof. Thorsten Schneiders



Renewable POWER TO X

Part 7: Support Policies and Regulations for Renewable PtX

Training: August 2023
Modules prepared by the International PtX Hub
Trainer: Prof. Thorsten Schneiders

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Agenda

List of abbreviations

CAPEX: Capital cost expenditures

CCfD: Carbon contracts for difference

CCS: Carbon Capture and Storage

DAC: Direct Air Capture

FLH: Full-load hours

GW: Gigawatt

HVDC: High voltage, direct current

LCOE: Levelised cost of electricity

LOHC: Liquid organic hydrogen carrier

LHV: Lower heat value

- **OPEX:** Operating cost expenditures
- **PEM:** Proton Exchange Membrane
- **PtX / PtL / PtG:** Power-to-X / -Liquid / -Gas
- **PV:** Photovoltaic
- **RE:** Renewable Energy/ies
- **RES:** Renewable Energy System(s)
- **RWGS:** Reverse Water Gas Shift Reaction
- **SMR:** Steam methane reforming
- **SOEC:** Solid Oxide Electrolyser Cell
- **TWh:** Terawatt hours
- **WACC:** Weighted average cost of capital

Key Conversion Data

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

Conversion kWh and kg H_2:

- 1 kg H_2 = 33.3 kWh H_2 *(heat unit Hu /calorific value)*
- 1 MWh H_2 = 30 t H_2
- 1 Mio t H_2 = 33 TWh H_2

Monetary value per weight or calorific value

- 4.5 ct/kWh H_2 = 45 €/MWh H_2 = 1.5 €/kg H_2
  or: 1€/kg H_2 = 3 ct/kWh H_2
- 100 €/MWh H_2 = 3.33 €/kg H_2
  or: 1€/kg H_2 = 30 €/MWh H_2

Module 7

Support Policies and Regulations for Renewable PtX

1. **Setting Up a Green Hydrogen Economy**
   - Holistic approach
   - Five policy instruments for a market scale-up
2. **Regulatory Architecture and Policy Proposals**
   - Regulatory architecture for a hydrogen economy
     - Supply-side measures
     - Demand-side measures
   - Policy proposals and policy roadmap
3. **Setting Up a National PtX Strategy**
   - Setting up a National Hydrogen Strategy
   - Evolution of national hydrogen strategies
   - Case studies and country examples of national hydrogen strategies and policies

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What is needed to establish a Green Hydrogen economy?

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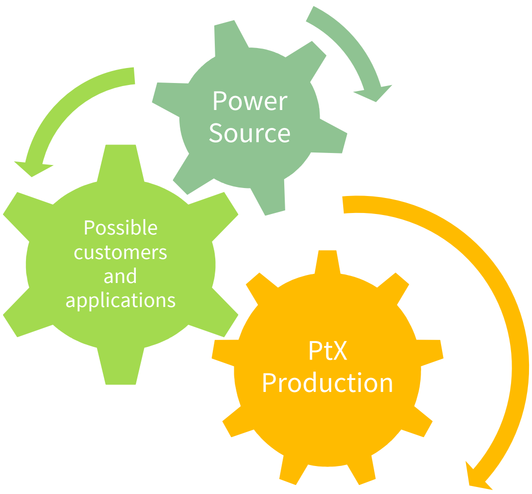
1. Setting Up a Green Hydrogen Economy

Holistic Approach towards a green hydrogen project (lloking into the project developers´ head)



- Formulate **clear goals** and **intermediate steps**
- Be aware that the project might be **economically challenging**
  - → look for **partners**, build alliances
  - → look for **funding**, subsidies etc.
- Find your **story to inspire** creditors
- Think from a **customer's point of view**

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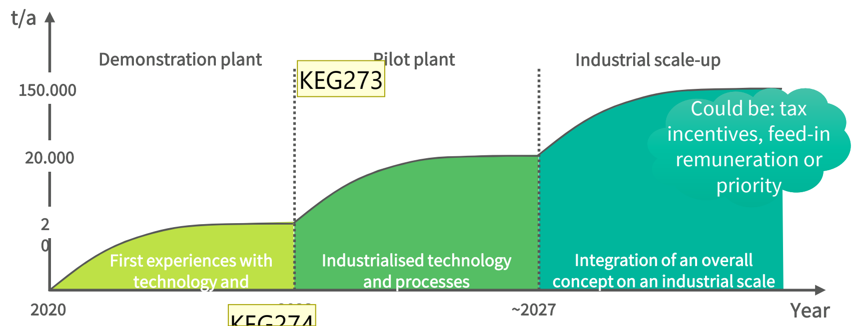
1. Setting Up a Green Hydrogen Economy

Phases of a Market Scale-Up



KEG275

- PtX faces the typical hen-egg-dilemma:
  - **Supply side: investors** claim there is not yet sufficient solvent demand
  - **Demand side: potential customers** complain that there is not yet sufficient stable supply at affordable prices. Exception: Aviation
- For a **breakthrough** and effective transformation **market mechanisms** alone will not be sufficient.
- KEG276 **et kick-start: Policy intervention** providing regulatory frameworks, R&D, financial support **on supply and demand side** and **lost-fund installations** will be required.

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1. Setting Up a Green Hydrogen Economy

Five Policy Instruments for a Market Scale-Up

1 Long-term policy signals

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

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

2 Demand creation

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

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

3 Investment risk mitigation

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

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

4 Removing barriers

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

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

5 R&D + knowledge sharing

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

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

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

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KEG273 Dies ist korrekt, wenn wir von Technologien reden, die TRL 3 - 5 haben. Es gibt jedoch auch PtL-Anlagenkonzepte von EDL, die TRL 8-9 sind und direkt als Industrial scale-up realisiert werden können. Dies ist unabdingbar, um die THG-Minderungsquoten erzielen zu können.
Kriegsmann, Elisabeth GIZ; 30.08.2021

KEG274 Hen egg prob.: my techn. is not ready yet and waiting for regulation and reg. waits for tech. to be available off the shelf to reg. it!
Kriegsmann, Elisabeth GIZ; 29.08.2022

KEG275 Valley of death needs to be overcome.
Venture capital müsste alles ausrollen, Staat müsste erste Anlagen finanzieren (INERATEC jet fuel)
Kriegsmann, Elisabeth GIZ; 29.08.2022

KEG276 on demand side kein problem bei airlines
Kriegsmann, Elisabeth GIZ; 29.08.2022

11

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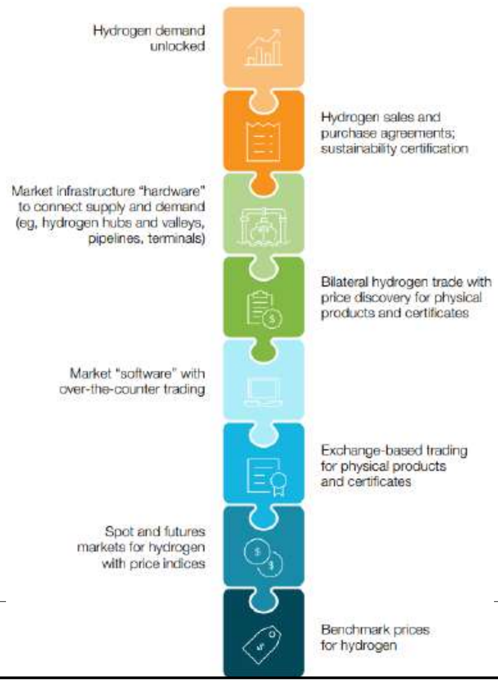

Steps towards a cross-border, global hydrogen commodity market

Market infrastructure to be designed:

- market design
- pricing methodologies
- price indices
- regional benchmark prices
- contractual structures
- trading hubs for hydrogen and its derivatives

Hydrogen Council, McKinsey & Company (10/2022) Global Hydrogen Flows: Hydrogen trade as a key enabler for efficient decarbonization, p.36/exhib.22.

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Any questions?

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Test your knowledge

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

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2. Regulatory Architecture and Policy Proposals

Which regulatory instruments and plicies support the ramp-up of green hydrogen economy?

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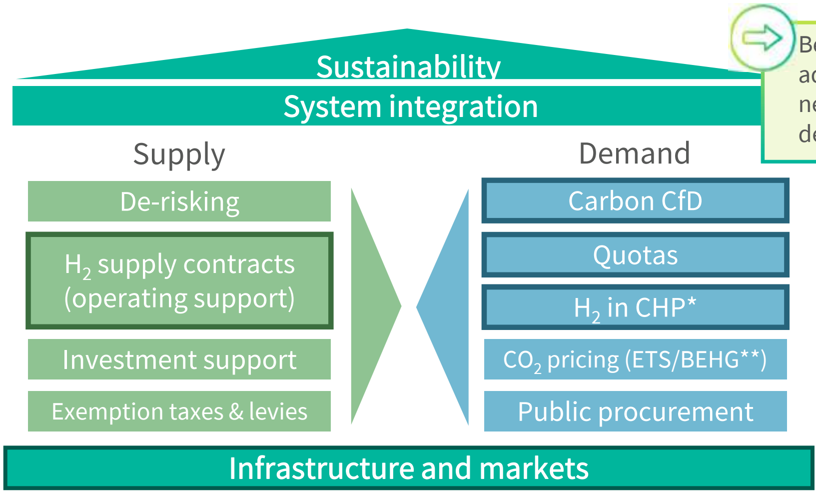
2. Regulatory Architecture and Policy Proposals

Regulatory Architecture for a Hydrogen Economy



Besides **policy instruments**, adequate **support architecture** is needed to scale-up supply and demand for H2.

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*CHP: Central Heating Plant/ Co-generation Heat and Power Plant
**BEHG: *Brennstoffemissionshandelsgesetz*. The German Fuel Emissions Trading Act creates the basis for trading in certificates for emissions from fuels and ensures that these emissions are priced insofar as they are not covered by EU emissions trading.
Source: illustration adapted: Matthias Deutsch (Agora Energiewende) / Matthias Schimmel (Guidehouse), Making renewable hydrogen cost-competitive Policy instruments for supporting green H2. ONLINE EVENT, 08 JULY2021, p.16-21.

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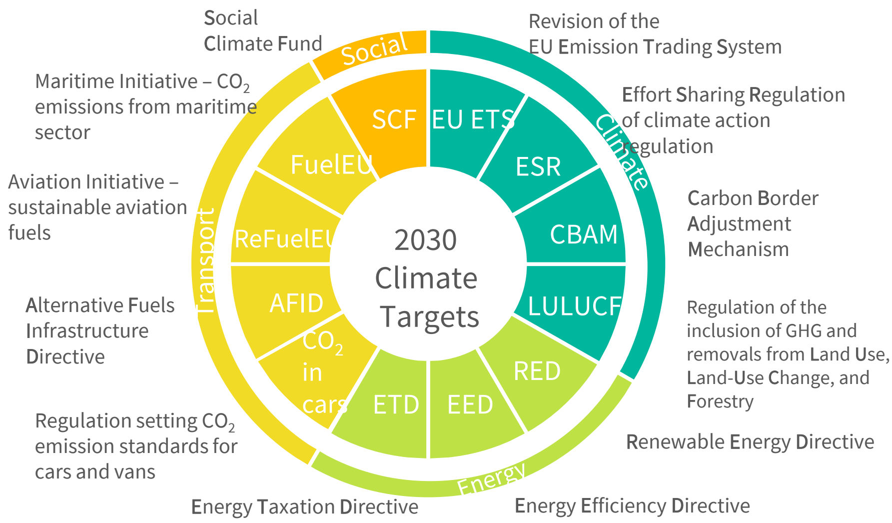
2. Regulatory Architecture and Policy Proposals

EU example: policy mix for green hydrogen

Policy Instruments to Increase Demand and Supply for Green H2 and Minimise Commercial Off-Taker Risk



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2. Regulatory Architecture and Policy Proposals

Important policy instruments: Development and international cooperation

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

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

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

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

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

International agreements
setting up international trade routes

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

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Policy Instrument: Finance and Investment

Financing should follow 4 main directions

- **Public support:** subsidies, adequate carbon pricing, pilot projects, CCfDs
- **R&D and large-scale deployment:** cost reduction of production and utilization
- **Economies of scale:** supply chains, widespread infrastructure
- **Massive investments in additional production** of RE

219.1

Folie 18

CM93 kann hier bleiben als Back up
Christoph Menke; 16.02.2022

CM94

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How to recover costs associated with support policies?

	Public-sector Budget	Power Levies	Climate Surcharge	Usage Obligations	Green Lead Markets
+	• Large sums of money over the short-term • Costs would be automatically distributed in a socially equitable manner, given the progressive nature of the tax regime	• Assured funding (no budget freezes or exhausted funds) • Targets the right consumers	• Incentivises material efficiency and substitution	• Would force obligated parties to cover H_2 costs	• Encouragement of **labelling system** for climate-friendly basic materials → helps communicating the necessity of climate-friendly products
–	• Unfair cost–benefit distribution over the long-term. • Could also result in 'stop and go' funding, e.g. due to budget cuts or freezes	• Harder to implement legally • Disproportionate burdens on lower-income households → negative distributional effects • Energy-intensive industries may need exemptions • Direct electrif.measures disadvantaged due to higher electricity prices	• Represents a completely new instrument with a complex set-up → requiring some time to generate a significant funding stream	• Obligated parties pass along cost increases to end consumers →obligations have greater impact on lower-income individuals→ negative distributional effects • Requires robust standards + transparent, clearly understandable certification	• Relies on the willingness of households + businesses to pay a premium for climate-friendly products

Source: Own illustration based on: Matthias Deutsch (Agora Energiewende) / Matthias Schimmel (Guidehouse), Making renewable hydrogen cost-competitive *Policy instruments for supporting green H2*, 2021, p.51-53.

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2. Regulatory Architecture and Policy Proposals

What are policy instruments to support the supply side or the demand side?

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Folie 19

CM94 als back up lassen
Christoph Menke; 27.01.2022

2. Regulatory Architecture and Policy Proposals

Policy Recommendations: Supply Side Measures

- **Investment aid** could finance **CAPEX** for electrolysers
  At EU level, the Innovation Fund supports innovative low-carbon technologies (such as electrolysers) with revenues from the EU ETS
- **Exemption** of electrolysers **from taxes and levies:** decreases cost of electricity, which is largest component of **OPEX**
- **De-risking instruments** to reduce financing costs: significantly lowers necessary investment outlays
- **H_2 supply contracts:** provide support for both production and demand → could be harnessed to address remaining cost discrepancy

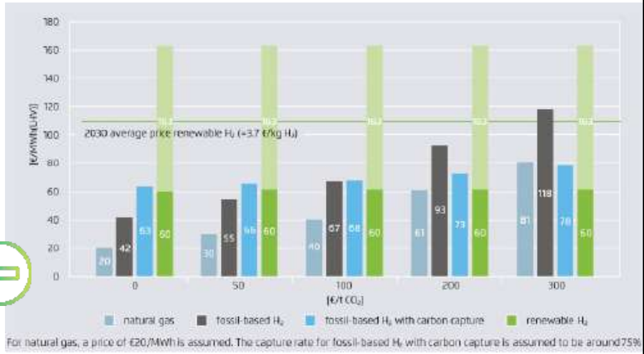
Source: Matthias Deutsch (Agora Energiewende) / Matthias Schimmel (Guidehouse), Making renewable hydrogen cost-competitive
Policy instruments for supporting green H2, 2021, p.46ff.

2. Regulatory Architecture and Policy Proposals

Policy Recommendations: Demand Side Measures

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

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



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

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

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2. Regulatory Architecture and Policy Proposals

Policy Proposals to Connect Supply and Demand Side

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2. Regulatory Architecture and Policy Proposals

Policy Instrument: Carbon Contract for Difference (CCfD)

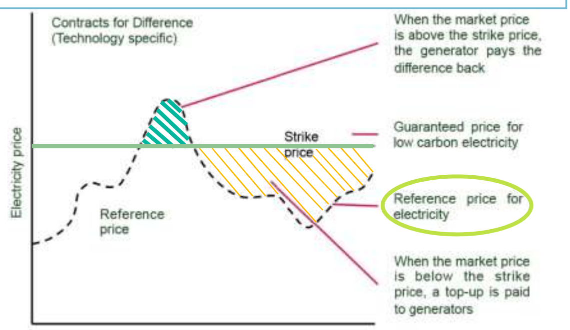
Generator can stabilise its revenues at a pre-agreed level (strike price) via long-term contract with LCCC.

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

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

Also applicable to steel, cement and fertiliser

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



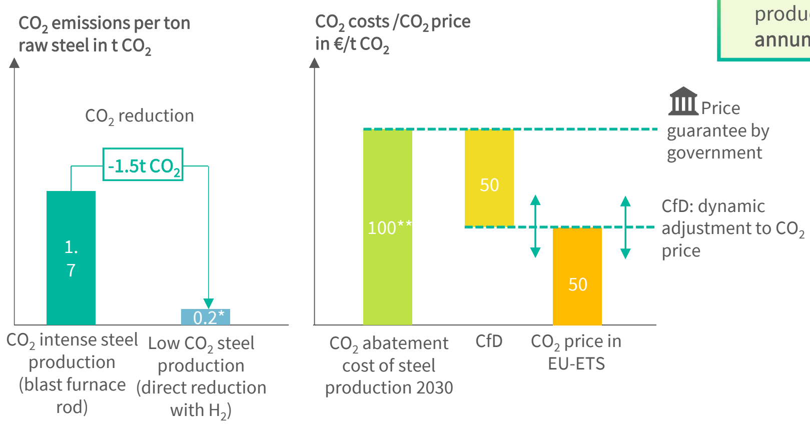
217 Source: Renewable UK, Rebecca Explains It All: The CfD, Sep 17, 2019.

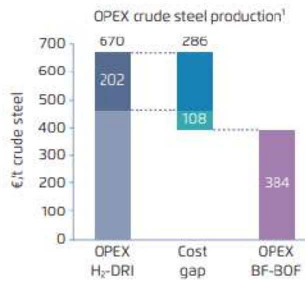
CM91

2. Regulatory Architecture and Policy Proposals

Example: Carbon Contract for Difference (CCfD) in German Steel Production

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





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

CM92

Initial targets of policy framework for renewable hydrogen

Target applications where H_2 is needed and a 'no-regret' option

Support instruments for renewable H_2 - Demand side measures	Billion EUR per year			
	Germany		EU	
	Low	High	Low	High
Option 1: Carbon Contracts for transformation of 33% GER / 50% EU **primary steel production capacity** to H_2-DRI with **current free allocation regime** (2022–2035/2040) *Cost recovery: Climate levy or EU ETS revenues*	1.1*	2.7*	4.1*	10.2*
	* average annual costs of a portfolio of 10 years CfD contracts, ignoring effect of sequential build up and phase out			
Or Option 2: CCfD for transformation of 33% GER / 50% **primary steel production capacity** to H_2-DRI with **effective CO_2-price gradually increasing** from 50€/t (2021) to 90€/t in 2040	0*	1.6*	0*	6.1*
PtL quota aviation (2025-2030: 10% and 2030–2050: increase to 100% by 2050) Setting EU-wide 10% quota in aviation, creates demand for e-kerosene, leading to a ramp-up in renewable H_2 and PtL production and further technological learning *Cost recovery: Additional costs are passed on to end-users (aviation passengers)*	1.4	1.9	10.3	14

Source: (Extract. Adapted) Matthias Deutsch (Agora Energiewende) / Matthias Schimmel (Guidehouse), Making renewable hydrogen cost-competitive *Policy instruments for supporting green H2*, 2021, p.20.

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CM91 back u lassen
Christoph Menke; 27.01.2022

Folie 26

CM92 als Back up drinnen lassen
Christoph Menke; 27.01.2022

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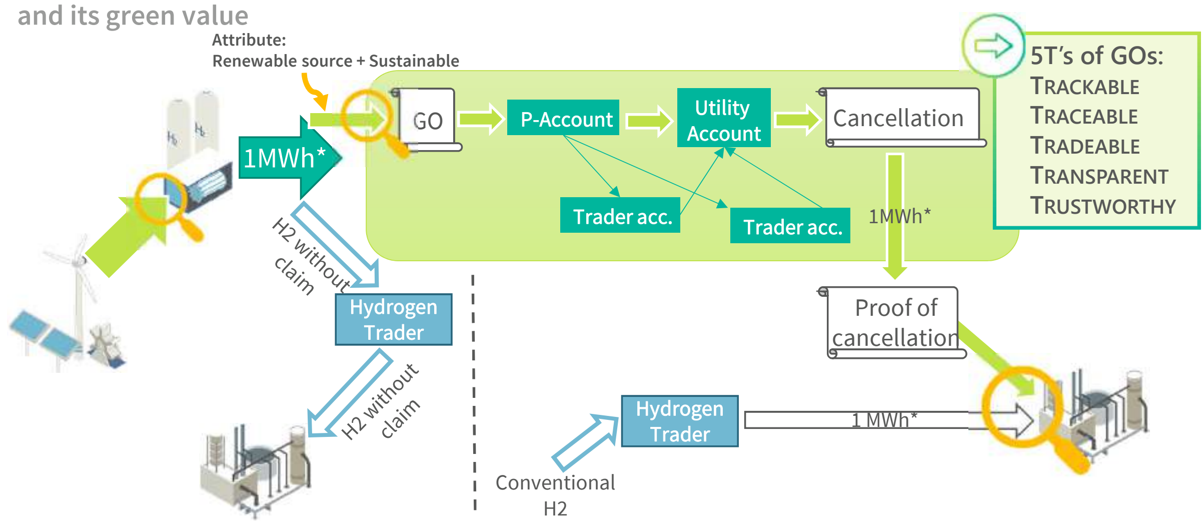
2. Regulatory Architecture and Policy Proposals

Book and Claim(B&C) Procedure for Guarantee of Origin (GO) – decoupling of physical product and its green value



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

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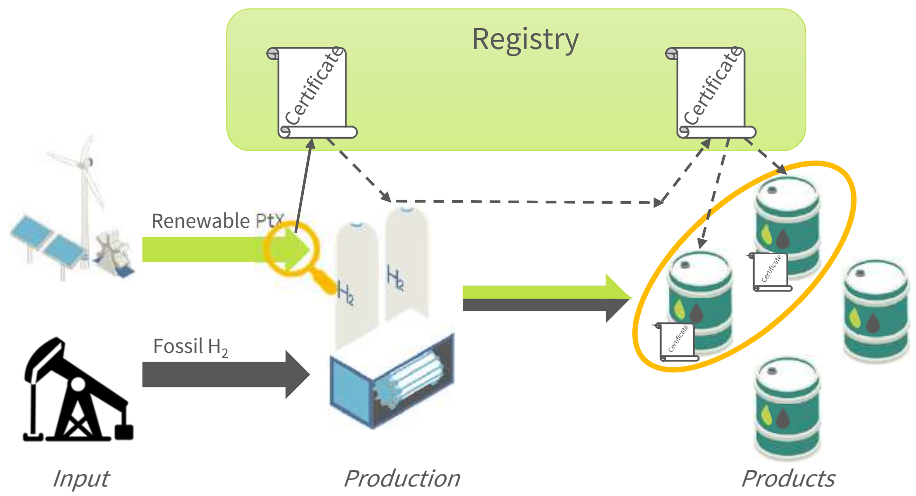
2. Regulatory Architecture and Policy Proposals

Mass Balance (MB) certifies that the end product consists of green H2 or renewable PtX (share)



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Any questions?

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3. Setting Up a National Hydrogen Strategy

Setting up a national hydrogen strategy

International PtX Hub

3. Setting Up a National Strategy

What should be the goals and the content of a National Hydrogen Strategy?

Goals (examples)

- Participate in growing global market for green hydrogen and renewable PtX
- Export abundant domestic renewables ressources to other countries vie green hydrogen and renewbale PtX
- Establish new industry, create jobs and local value
- Attract foreign investments
- Expand own industry based on their competences (e.g. chemcial industry, oil&gas)
- Decarbonize energy, transport and industry sectors
- …

Contents (examples)

- Industry roadmap
- Renewables roadmap
- Energy infrastructure roadmap
- Education and training roadmap
- Targets for green hydrogen in energy, transport, industry etc.
- Set up supportive framework (e.g. funding)
- Support projects (e.g. permitting, provision of project finance)
- Establish partnerships with othe rr countries (importer / exporter)
- …

3. Setting Up a National Hydrogen Strategy

Components of a national Strategy Components

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

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

3. Setting Up a National Strategy

Establishing Policy Priorities

Acceleration of manufacturing capacity and **tackling high investment costs** of electrolysers + enabling infrastructure
- Grants
- Loans
- Tax Credits

Reduction of costs of **renewable electricity** for green H_2 production
- Changes to electricity taxes + grid fees
- CCfDs
- Auctions
- Feed-in tariffs/ premiums

Addressing **sustainability**
- Certification schemes
- Eco-labels
- Additionality measures/ mandates

Enablement of **demand and market entry** for green H_2
- Electrolyser capacity targets
- Green H_2 mix targets
- Green product mandates
- Public procurement schemes
- Carbon taxes
- Quotas

Policies

Where to start?
No regret options first!
- The deployment of green H_2 faces sector specific **barriers**, some universal (**cost barrier**).
- **Political commitment + obligations** (→ sales guarantees) ensure investment security and can be a backbone of a market run-up.

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

3. Setting Up a National Hydrogen Strategy

Evolution of national hydrogen strategies


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3. Setting Up a National Hydrogen Strategy
Since 2017, several countries have formulated and established National Hydrogen Strategies
Finland
Sweden
Denmark
Netherlands
Belgium
Poland
Czech Republic
Germany
Slovakia
Austria
Hungary
France
Portugal
Croatia
Spain
Italy
Norway
Canada
United Kingdom
European Union
Russian Federation
Uzbekistan
China
Japan
Morocco
Egypt
Oman
Republic of Korea
Saudi Arabia
Colombia
Singapore
South Africa published a National hydrogen strategy in 2022
Paraguay
Uruguay
Australia
Chile
New Zealand
222
Source: IRENA, Geopolitics of the Energy Transformation T ydrogen Factor, p.39/fig.3.1.
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3. Setting Up a National Hydrogen Strategy
Since 2017, several countries have formulated and established National Hydrogen Strategies
Finland
Sweden
Denmark
Netherlands
Belgium
Poland
Czech Republic
Germany
Slovakia
Austria
Hungary
France
Portugal
Croatia
Countries with a H2 national strategy often have a specific focus such as:
• Industry and technology exports (Germany and Korea),
• H2 exports (Australia and Chile)
• strong fuel cell development (Japan)
Egypt
Oman
Saudi Arabia
Colombia
Singapore
South Africa published a National hydrogen strategy in 2022
Paraguay
Uruguay
Australia
Chile
New Zealand
222
Source: IRENA, Geopolitics of the Energy Transformation T ydrogen Factor, p.39/fig.3.1.
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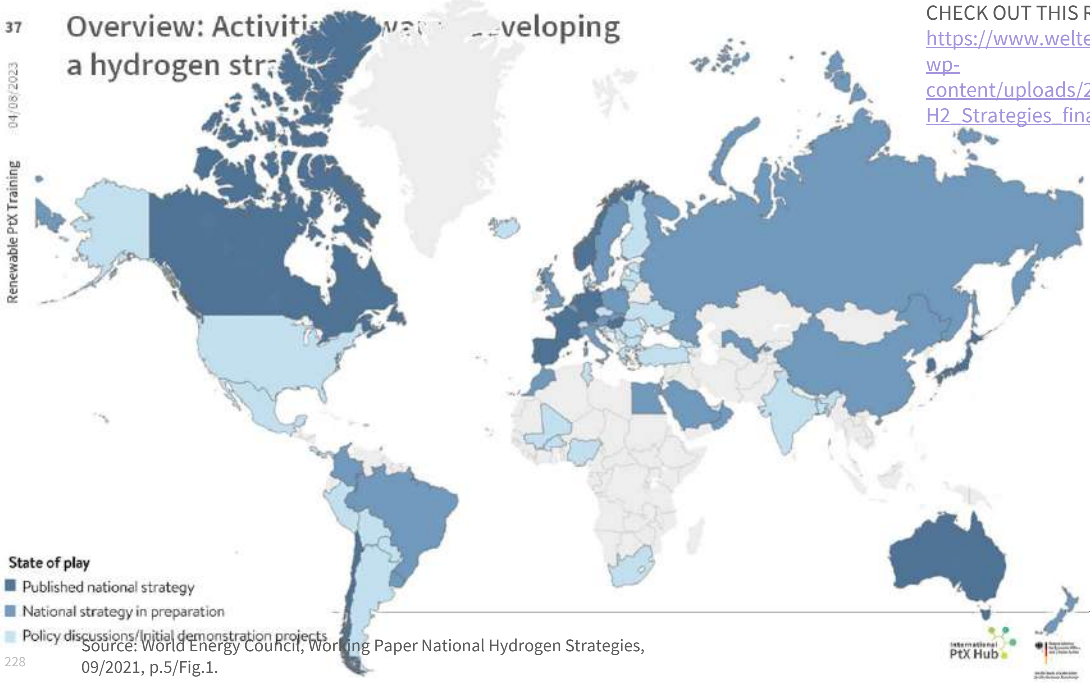
Overview: Activiti… wa… …veloping a hydrogen str…

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



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

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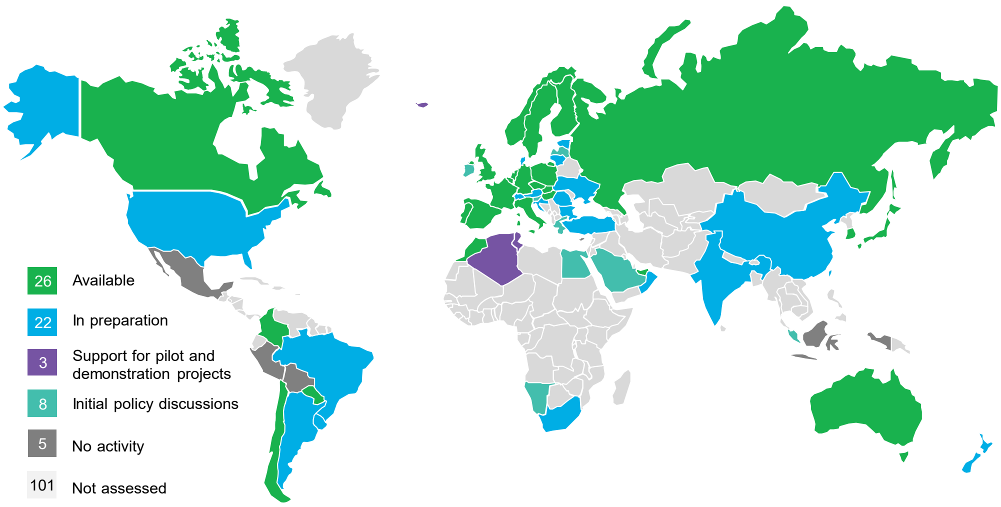
3. Setting Up a National Strategy

National Hydrogen Strategies in January 2

KEG283 KEG284



Source: BloombergNEF

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KEG283 checken, ob man die anschauen kann
Kriegsmann, Elisabeth GIZ; 29.08.2022

KEG284 bei Policy circle nach Kernelemnten der H2 Strategien der Länder fragen!!
Kriegsmann, Elisabeth GIZ; 29.08.2022

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8/2023

3. Setting Up a National Hydrogen Strategy
Comparison of National Hydrogen Strategies

CATEGORY	ASIA Australia	ASIA Japan	ASIA South Korea	EUROPE EU	EUROPE France	EUROPE Germany	EUROPE Hungary	EUROPE Netherlands	EUROPE Norway	EUROPE Portugal	EUROPE Spain	LAC Chile	NORTH AMERICA Canada
Strategy contains timeline for market development with targets	Detailed	Detailed	Detailed	Detailed	Mentioned	Detailed	Mentioned	Mentioned	Not seen	Mentioned	Detailed	Detailed	Detailed
Strategy contains hydrogen cost targets	Mentioned	Detailed	Detailed	Not seen	Not seen	Not seen	Not seen	Not seen	Not seen	Not seen	Not seen	Mentioned	Mentioned
Strategy includes measures to support H2 development													
Direct investments	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed	Not seen	Mentioned	Detailed	Detailed	Mentioned	Mentioned	Mentioned
Other economic and financial mechanisms	Detailed	Mentioned	Detailed	Detailed	Detailed	Detailed	Mentioned	Detailed	Detailed	Detailed	Mentioned	Mentioned	Mentioned
Legislative and regulatory measures	Detailed	Mentioned	Detailed	Detailed	Mentioned	Detailed	Mentioned	Detailed	Mentioned	Detailed	Detailed	Detailed	Mentioned
Standardisation strategy and priorities	Detailed	Detailed	Detailed	Mentioned	Mentioned	Detailed	Mentioned	Mentioned	Detailed	Detailed	Detailed	Mentioned	Detailed
Research & development initiatives	Detailed	Detailed	Detailed	Mentioned	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed	Mentioned	Detailed
International strategy	Detailed	Detailed	Mentioned	Mentioned	Mentioned	Detailed	Detailed	Detailed	Mentioned	Detailed	Detailed	Mentioned	Mentioned
Strategy addresses social issues for H2 development	Detailed	Detailed	Detailed	Not seen	Detailed	Mentioned	Not seen	Mentioned	Mentioned	Detailed	Detailed	Detailed	Detailed
Strategy includes review and update	Mentioned	Not seen	Not seen	Not seen	Not seen	Detailed	Not seen	Not seen	Mentioned	Mentioned	Detailed	Mentioned	Not seen
Strategy's H2 target source by 2030	Clean	Fossil-based with CCS	From natural gas	Low carbon	Low-carbon & fossil based	Carbon-free	Low carbon & carbon free	Blue & Green	Clean	Green	Renewable	Green	Low carbon intensity
Strategy's H2 target source by 2050	Clean	CO_2-free	Eco-friendly CO_2-free	Clean / Renewable	Low carbon	Renewable	Low carbon & carbon free	Green	Clean	Green	Renewable	Green	Low carbon intensity
Import / Self-reliance / Export	Export; Self-reliance	Import	Import; Export (tech)	Depends on Member States	Export	Import; Export (tech)	Self-reliance	Import to export H2 (EU hub)	Self-reliance	Self-reliance; Export	Self-reliance; Export	Self-reliance; Export	Self-reliance; Export

Strategies content: ● Detailed ● Mentioned ○ Not seen

- Asia strategies have a strong cost orientation, EU and its countries not so much
- Only Chile and Portugal have a strategy focusing on “green” H_2 (NL for 2050)
- Other countries focus on CO_2 emissions reduction related to H_2 production from other feedstocks as well
- Countries with abundancy of renewable energy or nuclear energy have an export strategy
- Some countries like South Korea and Germany have a strategy focused on technology exports

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Source: World Energy Council, National Hydrogen Strategies, 2021

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3. Setting Up a National Hydrogen Strategy
Comparison of National Hydrogen Strategies

CATEGORY	ASIA Australia	ASIA Japan	ASIA South Korea	EUROPE EU	EUROPE France	EUROPE Germany	EUROPE Hungary	EUROPE Netherlands	EUROPE Norway	EUROPE Portugal	EUROPE Spain	LAC Chile	NORTH AMERICA Canada
SECTORAL PRIORITIES													
Heating	Immediate	Immediate	Lower	Lower	Lower	Lower	Immediate	Immediate	Lower	Immediate	Lower	Immediate	Immediate
Industry													
Iron and Steel	Long term	Lower	Lower	Long term	Immediate	Immediate	Long term	Immediate	Lower	Immediate	Lower	Not seen	Immediate
Chemical feedstock	Immediate	Lower	Not seen	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate
Refining	Not seen	Lower	Not seen	Immediate	Immediate	Immediate	Immediate	Immediate	Lower	Immediate	Immediate	Immediate	Immediate
Others (cement, etc.)	Not seen	Not seen	Not seen	Not seen	Immediate	Lower	Long term	Lower	Not seen	Immediate	Lower	Not seen	Immediate
Power													
Power generation	Lower	Immediate	Immediate	Lower	Not seen	Not seen	Lower	Lower	Not seen	Lower	Lower	Not seen	Lower
Back-up services	Lower	Lower	Lower	Lower	Not seen	Not seen	Long term	Lower	Not seen	Lower	Lower	Not seen	Lower
Transport													
Passenger vehicles	Lower	Immediate	Immediate	Lower	Lower	Lower	Long term	Immediate	Lower	Lower	Lower	Long term	Immediate
Medium and heavy duty	Immediate	Long term	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Lower	Immediate	Lower	Immediate	Immediate
Buses	Immediate	Long term	Immediate	Immediate	Immediate	Immediate	Immediate	Immediate	Lower	Immediate	Lower	Immediate	Immediate
Rail	Lower	Lower	Lower	Immediate	Immediate	Immediate	Lower	Immediate	Not seen	Immediate	Lower	Not seen	Long term
Maritime	Long term	Lower	Lower	Long term	Lower	Long term	Lower	Lower	Immediate	Long term	Lower	Long term	Long term
Aviation	Lower	Lower	Not seen	Long term	Immediate	Long term	Not seen	Lower	Lower	Long term	Lower	Long term	Long term

- Most of the other countries have a focus on sectors H_2 is already in use (chemical feedstock, refining)
- Asia focuses on energy uses of H_2 for transport and power generation (Ene-Farm in JP –implemented in houses for CHP and water)
- Norway is the only country with an immediate focus on Maritime industry and France in the Aviation industry

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Source: World Energy Council, National Hydrogen Strategies, 2021

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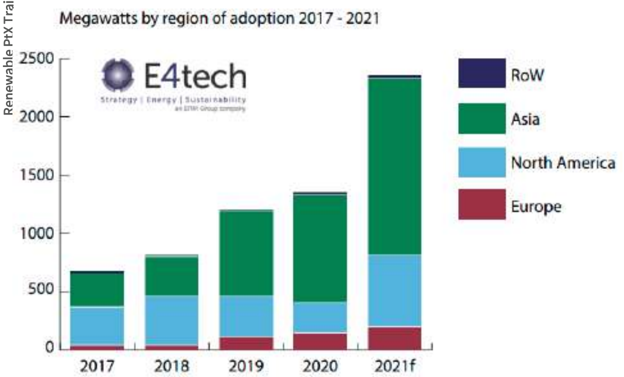
3. Setting Up a National Hydrogen Strategy

Comparison of growth paths in National Hydrogen Strategies



- Asia is the region with most H_2 lead by Japan with stationary systems and fuel cell vehicles (with South Korea)
- China is growing very fast
- North America is the second region, mainly with the USA and California, where there is a great market for FC vehicles due to policies and access to refueling stations

222 Source: World Energy Council, National Hydrogen Strategies, 2021

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Any questions?

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Examples for national hydrogen strategies and policies

CM100 CM101

44 What is happening worldwide in hydrogen/PtX?

Overview on national H_2 policies based on different RE sources

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Figure 17 Strongest potential PtX producer worldwide

226 Source: Frontier Economics/Word Energy Council, International aspects of a Power-to-X Roadmap, 2018, p.43/fig.17.

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CM100 wäre gut update zu haben, zu alt
Christoph Menke; 26.01.2022

CM101 can we get an update?
Christoph Menke; 27.01.2022

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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

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Source: Frontier Economics/Word Energy Council, International aspects of a Power-to-X Roadmap, 2018, p.44/Fig.18.

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

Hinicio

	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 hydrogen 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 hydrogen.
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 organisations for the planning of its National H_2 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 hydrogen consuming technologies. Japan envisions itself as an H2 importer. Chile positions itself as an exporter of hydrogen and its derivatives on its H_2 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 hydrogen required to satisfy the Japanese market.

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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 hydrogen. 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 hydrogen and its derivatives. The aforementioned characteristics allow ports to group multiple hydrogen off takers, while having the potential to produce the required hydrogen in a semi-centralised way. This concept of hydrogen 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 hydrogen equipment.

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3. Setting Up a National Hydrogen Strategy

Comparison of National Hydrogen Strategies - Japan

- Japan has used the Olympic games to showcase its H_2 projects
  - Olympic village was supplied by H_2
- Japan has the second most sold H_2 car, the Toyota Mirai (testing in Brazil now)
- Advanced with ENE-Farm systems: stationary fuel cells for residential use

222 Source: World Energy Council, National Hydrogen Strategies, 2021

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3. Setting Up a National Hydrogen Strategy

Comparison of National Hydrogen Strategies - USA / California and H_2 refueling stations

- Hydrogen refueling stations:
  - Japan 114
  - Germany 101
  - 48 in California, Korea 33, France 26, North America 26 (except California)
- Favorable policies for EVs and fuel cell cars (emissions law)
- Large incentives for innovation and start-ups – Nikola Motors, SimpleFuel, ZeroAvia, Hyzon

222 Source: World Energy Council, National Hydrogen Strategies, 2021

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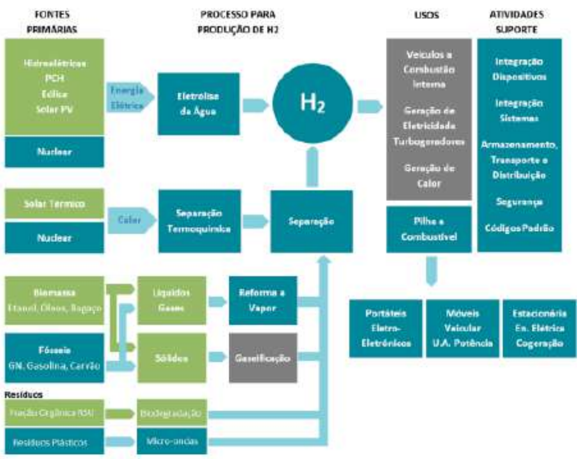
3. Setting Up a National Hydrogen Strategy

Comparison of National Hydrogen Strategies - Brazil



- Programa Nacional do Hidrogênio covers:
- Multi production pathway
  - Utilization of Brazil's a vast energy potential
  - Renewable energy (solar, wind and hydro)
  - Fossil fuels, especially NG with CCS
  - Biofuels and biowaste with CCS (negative emissions)
  - Natural Hydrogen
- Water management control
- Use of existing infrastructure (H_2 blending with NG)
- Use of H_2 in the transport sector
- Use of H_2 in refining

222 https://www.gov.br/mme/pt-br/assuntos/noticias/mme-apresenta-ao-cnpe-proposta-de-diretrizes-para-o-programa-nacional-do-hidrogenio-pnh2/HidrognioRelatriodiretrizes.pdf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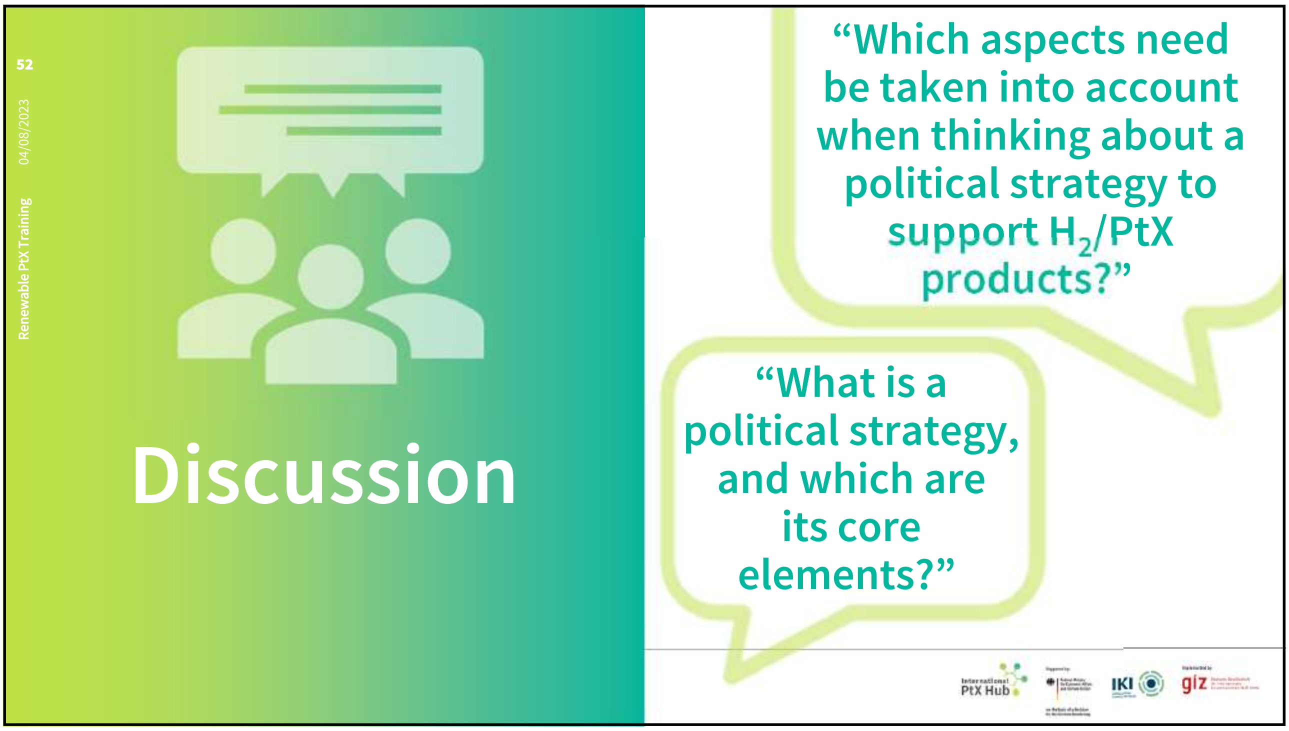
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Discussion
“Which aspects need be taken into account when thinking about a political strategy to support H_2/PtX products?”
“What is a political strategy, and which are its core elements?”
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Case study: Hydrogen Strategy and policy in the European Union (EU)

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EU hydrogen strategy as an element of the Green Deal and energy strategy till 2050

- EU Hydrogen Strategy is part of the **Green Deal** and the **Next Generation EU Development Instrument**
  - **2020 to 2024:** Installation of electrolysers for renewable hydrogen with an electrolysis capacity of at least 6 GW (currently: 1 GW) and production of up to 1 million tonnes of renewable hydrogen.
  - **2025 to 2030:** Hydrogen as an essential component of the integrated energy system, by installing electrolysers for renewable hydrogen with an electrolysis capacity of at least 40 GW and producing up to 10 million tonnes of renewable hydrogen.
  - **2030 to 2050:** Renewable hydrogen technologies mature and be deployed at scale in all sectors where decarbonisation is difficult.
- **Estimated investment volume**: Investments up to 2050 in renewable hydrogen up to 180 - 470 billion € and for low CO_2 fossil hydrogen up to 18 billion €.
- **Funding**: EU ETS Innovation Fund €10 billion by 2030 to promote low-carbon technologies$_2$; Important Projects of Common European Interest (IPCEI) programme

Source: Matthias Deutsch (Agora Energiewende) / Matthias Schimmel (Guidehouse), Making renewable hydrogen cost-competitive - *Policy instruments for supporting green H2*, 2021, p.57f.

Folie 54

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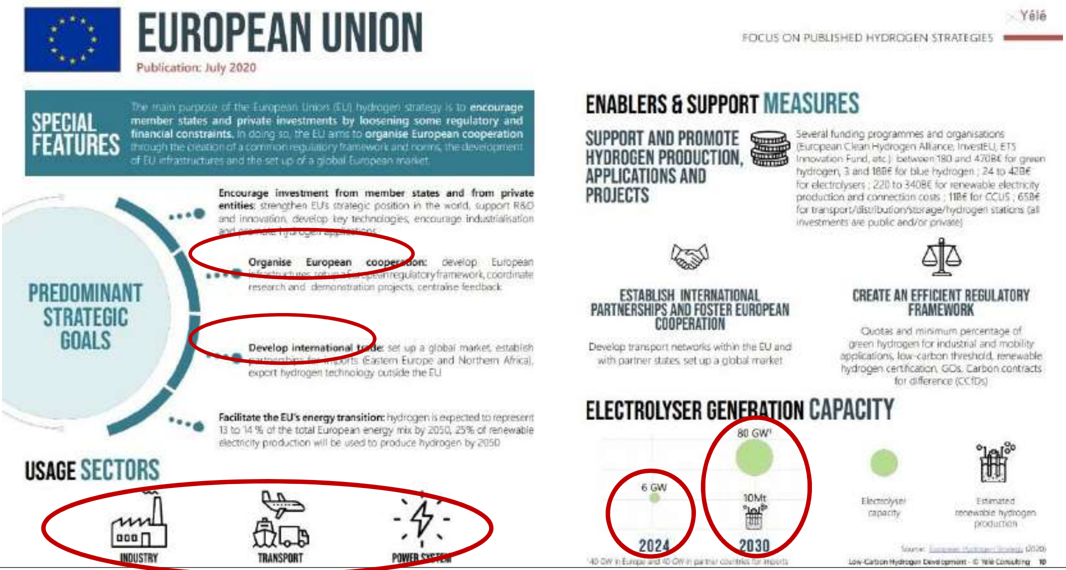
EU Hydrogen Strategy



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Source: Yele, Low-Carbon Hydrogen Development Analysis of Strategies & Roadmaps Around the World, 2020, p.10.

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Ensuring sustainability and system integration

1. Define clear sustainability criteria for climate-neutral PtX processes and products
2. Establish legislation and a certification scheme
3. Develop a roadmap for the adoption of sustainability criteria

PtX needs significant amount of RE → **define criteria for renewables-based electrolysis**

RED II foresees 3 methods for demonstrating the use of RE when electrolyser produces renewable H_2 for transport sector :

i. Electrolyser consumes renewables share of grid mix→ in combination with requirement to save at least 70% GHG emissions, this is only possible in countries with almost fully decarbonised electricity systems (e.g. Norway or Iceland)

ii. Electrolyser operates in ring-fenced system with direct connection to dedicated renewables generation

iii. Electrolyser consumes 100% renewable electricity from grid
→ **additionality, temporal and geographic correlation!**

Source: Matthias Deutsch (Agora Energiewende) / Matthias Schimmel (Guidehouse), Making renewable hydrogen cost-competitive - *Policy instruments for supporting green H2*, 2021, p.57f.

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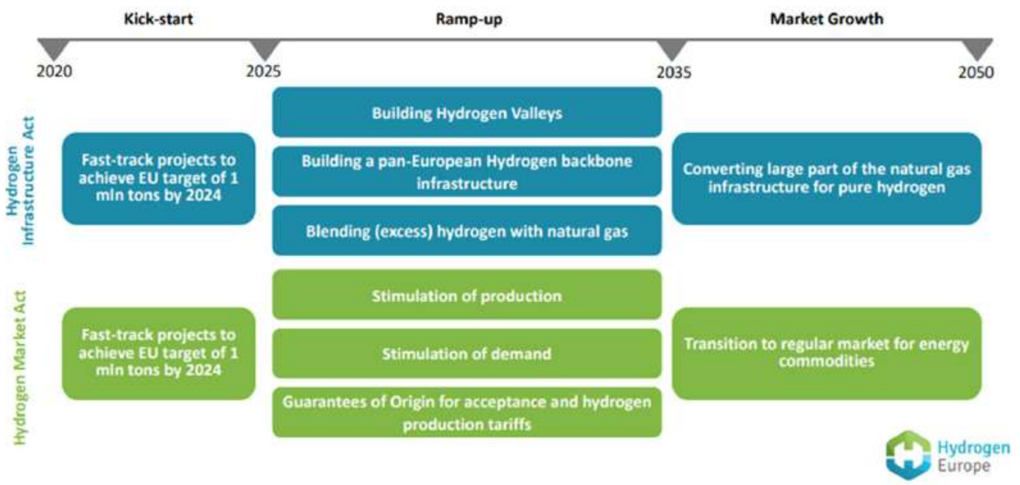
Harmonised approach to regulatory development via H_2 Act



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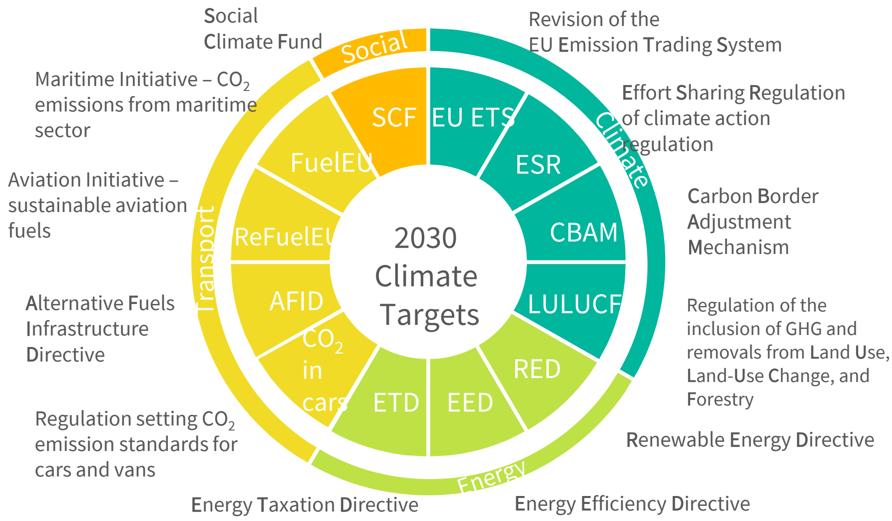
2. Regulatory Architecture and Policy Proposals

EU example

Policy Instruments to Increase Demand and Supply for Green H2 and Minimise Commercial Off-Taker Risk



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3. Setting Up a National Hydrogen Strategy

Case study: Hydrogen Strategy and policy in Germany

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Germany´s National Hydrogen Strategy

In July 2023, targets were doubled!

- German Federal Government published **National Hydrogen Strategy in** June 2020, with the **goals of**
  - Establishing hydrogen technologies as core elements of the energy transition (e.g. for decarbonisation of production processes)
  - Creating conditions for market take-up of hydrogen technologies,
  - Strengthening German companies and their competitiveness through accelerated R&D
- **Funding**: within the framework of the 7th research programme with a total of €7 billion (including the hydrogen technology offensive)
- **Projects**: Energy Transition Labs, Hydrogen Research Network, National Innovation Programme for Hydrogen and Fuel Cell Technologies (NIP)

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KEG282
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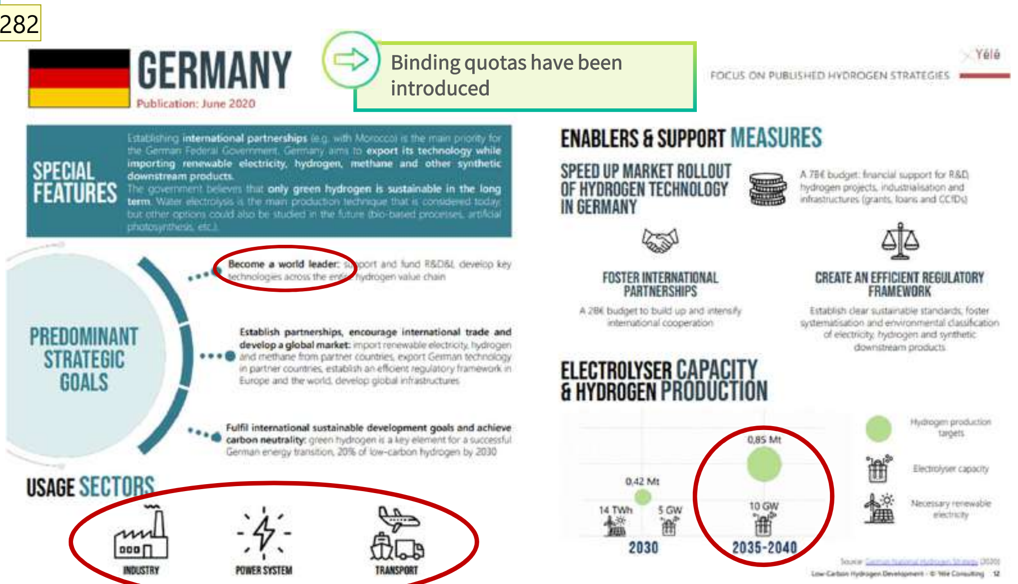
Binding quotas have been introduced



Source: Yele, Low-Carbon Hydrogen Development Analysis of Strategies & Roadmaps Around the World, 2020, p.10.

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CM96
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German funding instruments towards the development of PtX projects worldwide

- H2Global Auction-based promotion of international green hydrogen projects
- National **Funding Guideline** for international hydrogen projects in non-EU countries
- **H2Uppp**: Provision of supporting services to small private-sector projects
- Global as well as bilateral **innovation funds**

Already implemented

Individual project funding:
Grants for projects in Saudi-Arabia and Chile in December 2020

Source: BMWi, 2021

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CM95 does we need to update up?
Christoph Menke; 27.01.2022

KEG282 quotas depend on how strongly politicians push this concept
Kriegsmann, Elisabeth GIZ; 29.08.2022

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Christoph Menke; 27.01.2022

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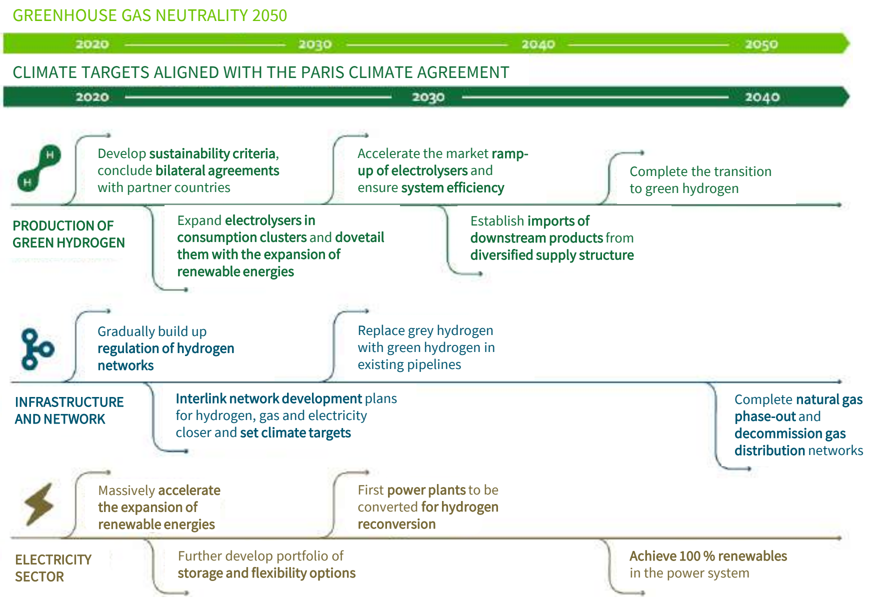
Country Example: Directional decisions for the sustainable use of hydrogen in the context of decarbonisation for Germany



Source: SRU, Wasserstoff im Klimaschutz: Klasse statt Masse, 2021, p.78/Abb.12.

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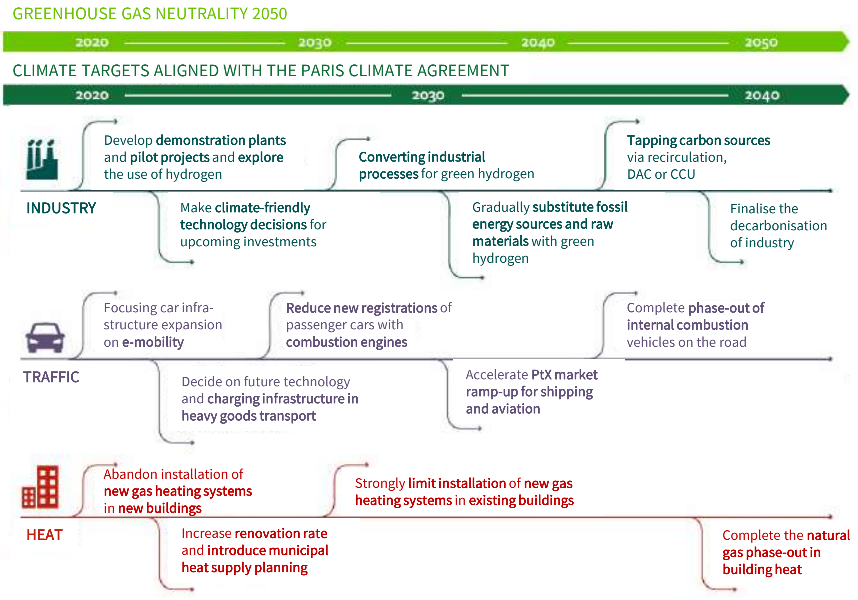
SRU: Directional decisions for the sustainable use of hydrogen in the context of decarbonisation



Source: SRU, Wasserstoff im Klimaschutz: Klasse statt Masse, 2021, p.78/Abb.12.

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CM98 hier als Back up lassen
Christoph Menke; 16.02.2022

Folie 64

CM99 kann hier als Back up lassen
Christoph Menke; 16.02.2022

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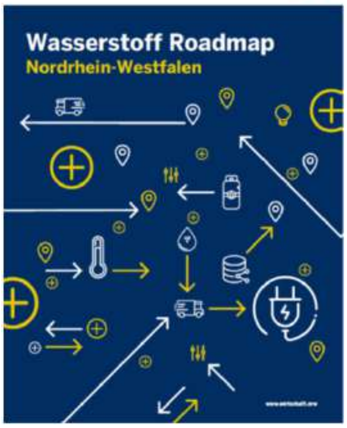
Regional Hydrogen Strategy: North-Rhine Westphalia

Industrial region requires green hydrogen and PtX for decarbonization of steel and chemical industry



- **Hydrogen roadmap of** the **NRW state government** (11/2020):
  - Making **industrial processes** in NRW almost climate-neutral by 2050 using hydrogen
  - **By 2025:** first large-scale plants in operation, 100 kilometers of H_2 pipeline network installed, 400 fuel cell trucks, 80 H_2 filling stations, and 500 hydrogen buses.
  - **By 2030:** 240 km of H_2 lines, 11,000 fuel cell trucks, 200 H_2 filling stations, 1,000 fuel cell waste collectors and 3,800 fuel cell buses, up to 3 GW electrolysis
- **Structural change in the Rhenish mining area** offers implementation
  - Municipalities currently planning numerous H_2 projects
- **Funding** via national instruments, but also separate structural aid funding and state funding (ERDF, Progres)

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Any questions?

Case study: Successful development of a hydrogen market in Chile

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3. Setting Up a National Strategy

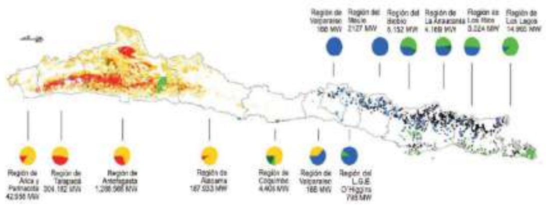
Country Example: PtX in Chile SWOTs

Green Hydrogen in Chile

Strengths
- One of the **world best solar and wind potentials** with high plant factors (solar: >35%; Wind: >60% ➡ 100% green H_2).

Challenges
- **Water shortage** in the north (=> sea water desalination).
- **Long distance** from consumer markets (Export H_2).

Opportunities
- Opportunities for **fully integrated projects** (=> sector-coupling).
- Possible **conversion of coal-fired power plants** into green H_2 production plants, or **H_2 fired plants (Gas/H_2)**.



Potential for renewables in Chile:
➔ **>1,865 GW**
➔ **>5,000 TWh/y** (≈70 TWh/y demand)

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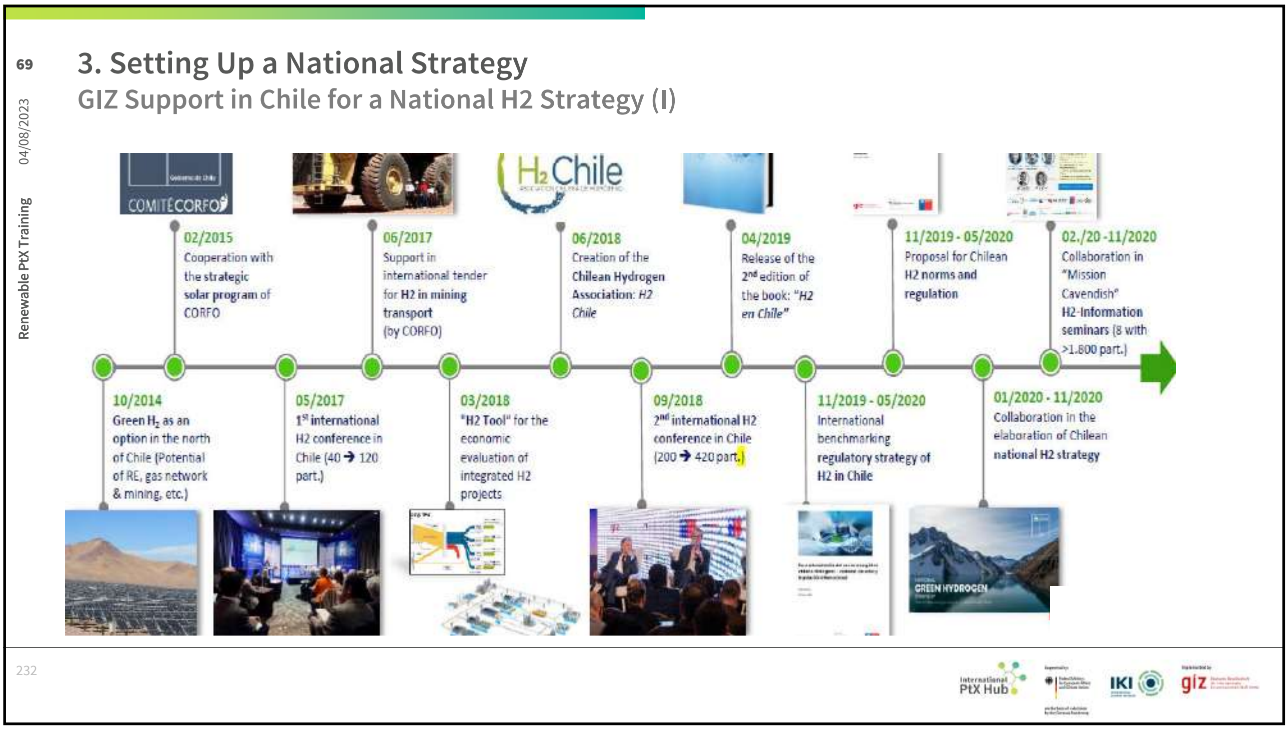
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GIZ Support in Chile for a National H2 Strategy (I)
COMITÉCORFO
H2Chile
02/2015
Cooperation with the strategic solar program of CORFO
06/2017
Support in international tender for H2 in mining transport (by CORFO)
06/2018
Creation of the Chilean Hydrogen Association: H2 Chile
04/2019
Release of the 2nd edition of the book: "H2 en Chile"
11/2019 - 05/2020
Proposal for Chilean H2 norms and regulation
02./20 -11/2020
Collaboration in "Mission Cavendish" H2-Information seminars (8 with >1.800 part.)
10/2014
Green H2 as an option in the north of Chile (Potential of RE, gas network & mining, etc.)
05/2017
1st international H2 conference in Chile (40 → 120 part.)
03/2018
"H2 Tool" for the economic evaluation of integrated H2 projects
09/2018
2nd international H2 conference in Chile (200 → 420 part.)
11/2019 - 05/2020
International benchmarking regulatory strategy of H2 in Chile
01/2020 - 11/2020
Collaboration in the elaboration of Chilean national H2 strategy
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GIZ Support in Chile for a National H2 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
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3. Setting Up a National Strategy
GIZ Support in Chile for a National H2 Strategy (III)
11/2020
Initiation of green H2 platform for America Latina and the Caribbean
11/20 – 03/2021
Analysis of the "state of the art" of Carbon Capture and Utilization and potentials in Chile
11/2020 – today
Technical assistance for selected hydrogen projects in Chile (feasibility studies, consulting, etc.)
3. and 4. 11.2020
3rd International H2 conference in Chile: "Green H2 Summit" (>5.700 participants!)
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)
02/2
Analy
requi
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3 y 4 de noviembre
CHILE 2020
GREEN HYDROGEN SUMMIT
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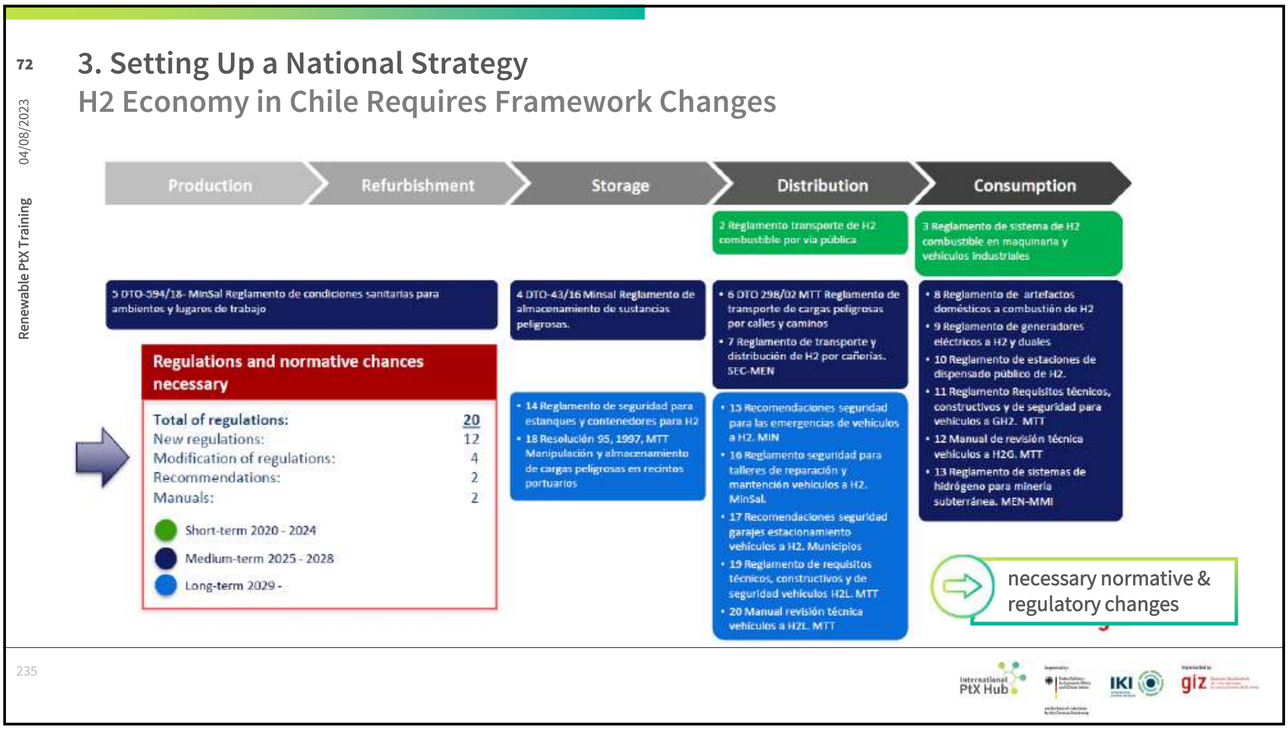
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3. Setting Up a National Strategy
H2 Economy in Chile Requires Framework Changes
Production
Refurbishment
Storage
Distribution
Consumption
2 Reglamento transporte de H2 combustible por vía pública
3 Reglamento de sistema de H2 combustible en maquinaria 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 cañerias. 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
necessary normative & regulatory changes
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Any questions?

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Policy Recommendations

- To be **sustainable, hydrogen (H2) must come from additional renewable electricity**
  → If not, it undermines the overall **powershift towards renewables** (→ additionality)
- By going **the extra mile beyond H2 towards PtX, use options and added value creation rise significantly**
- PtX requires more than only H2, but also C, N2 and others. These should all come from sustainable sources!
  - Renewable carbon is vital: biogenic residues, DAC, recycled carbon from waste or CCU (from industries which will still exist in a defossilised future)
- PtX can provide **carbon-neutral feedstocks and fuels for industry: chemicals and fertilisers, steel, cement or glass as well as fuel for aviation and shipping**
- **Countries should** identify their respective PtX profiles and PtX solution that fit their needs and long-term ambitions.
  (1) **undertake a SWOT analysis**
  (2) **develop a national H_2/PtX strategy**
  (3) **design a PtX Road Map** with measurable targets and clear timelines
- Measures should be aligned with country's **SDG Agenda and Paris Agreement NDCs**
- **National PtX policy** should be driven by **national opportunities, priorities and needs**
- **International co-operation** and partnerships **help speeding-up knowledge and technology transfer**, generating mutual benefits, trade and much needed revenue

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Is the Renewable PtX Really Kicking Off Now? Hype or Reality?

Seven signposts of Scale-Up towards a Renewable PtX Economy

1. **Net-zero climate targets are legislated** – Necessity to decarbonise hard-to-abate sectors
2. **Harmonising of standards + Removing regulatory barriers** – Clears or minimises obstructions to PtX projects
3. **Targets with investment mechanism** – Provides a revenue stream for producers, increases competition, builds capacity + experience
4. **Stringent heavy transport emissions standards** – Incentive for *manufactures to produce*, and *users to buy*, fuel cell trucks and NH_3-powered ships
5. **Mandates and markets for low-emission products** – Incentive for manufacturers to produce low-emission goods (e.g. steel, cement, fertilisers, plastics)
6. **Industrial decarbonisation policies and incentives** – Helps to coordinate infrastructure investment, scale efficient use of and provides incentives for PtX use
7. **PtX-ready equipment becomes commonplace** – Enables and reduces the cost of fuel switching to PtX products

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

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Conclusions

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MODULE 7: Key Take-Aways

1. Setting Up a Green Hydrogen Project

- PtX faces the typical **hen-egg-dilemma: technologically ready** for take-off, but **economically** the rocket is not yet flying. The market alone will not overcome this challenge.
- To over come this challenge **interventions by governments are required on both side, demand and supply** side. There are **five different areas** for policy interventions:
  - long- term policy signals
  - demand creation
  - investment risk mitigation
  - removing barriers
  - R&D + knowledge sharing

2. Regulatory Architecture and Policy Proposals

- Besides policy instruments, adequate **regulatory architecture** is needed that considers the supply and the demand side, the infrastructure development such as pipelines, and cluster development to ensure system integration.
- Policy example: The **EU's global auctioning system** combined with carbon contracts for difference ensures that the **supply side can invest** in the production of **green hydrogen** in the long term and that the **demand side for green hydrogen** has the **certainty that the purchase price is capped** by a maximum price that follows the development of the carbon price. This ensures that the use of green hydrogen does not lead to higher production costs than the use of fossil fuels.

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MODULE 7: Key Take-Aways

3. Setting Up a National Strategy

- Since 2017, several countries have set up National Hydrogen Strategies to plan for the future development of a green hydrogen economy and industry, with different motivations:
  - Create new industry and participate in growing green hydrogen market
  - Develop and export hydrogen technologies
  - Export abundant domestic renewables sources via green hydrogen and PtX products
- Four steps lead to a national strategy: Develop an **adequate R&D programme** adopted to needs of your country. Parallel to this the **vision document** is necessary to raise the visibility of the national hydrogen strategy, while the **roadmap and strategy** define details of the approach.
- A national hydrogen strategy in combination with a strategy to ramp up additional renewables capacities is an important step towards participating in the currently emerging, future global market for green hydrogen and renewable PtX.

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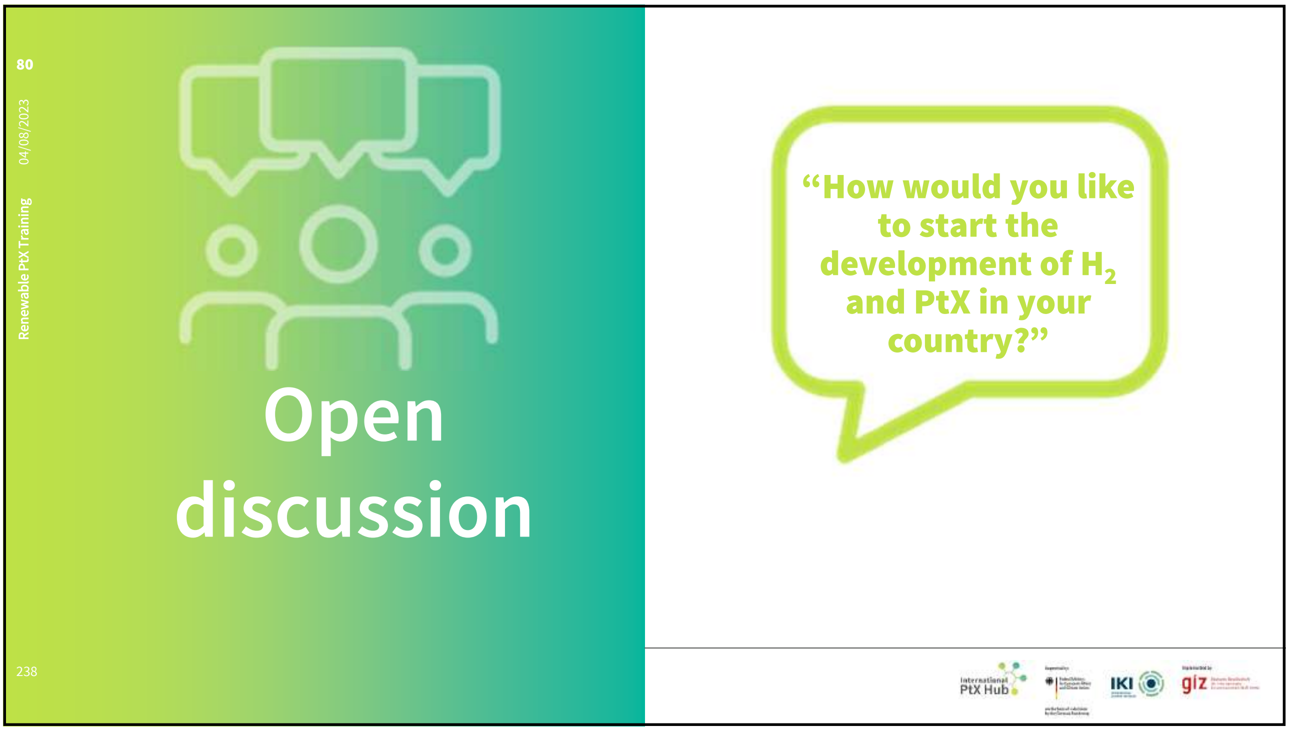
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Open discussion
"How would you like to start the development of H2 and PtX in your country?"
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Your opinion is important to us!

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

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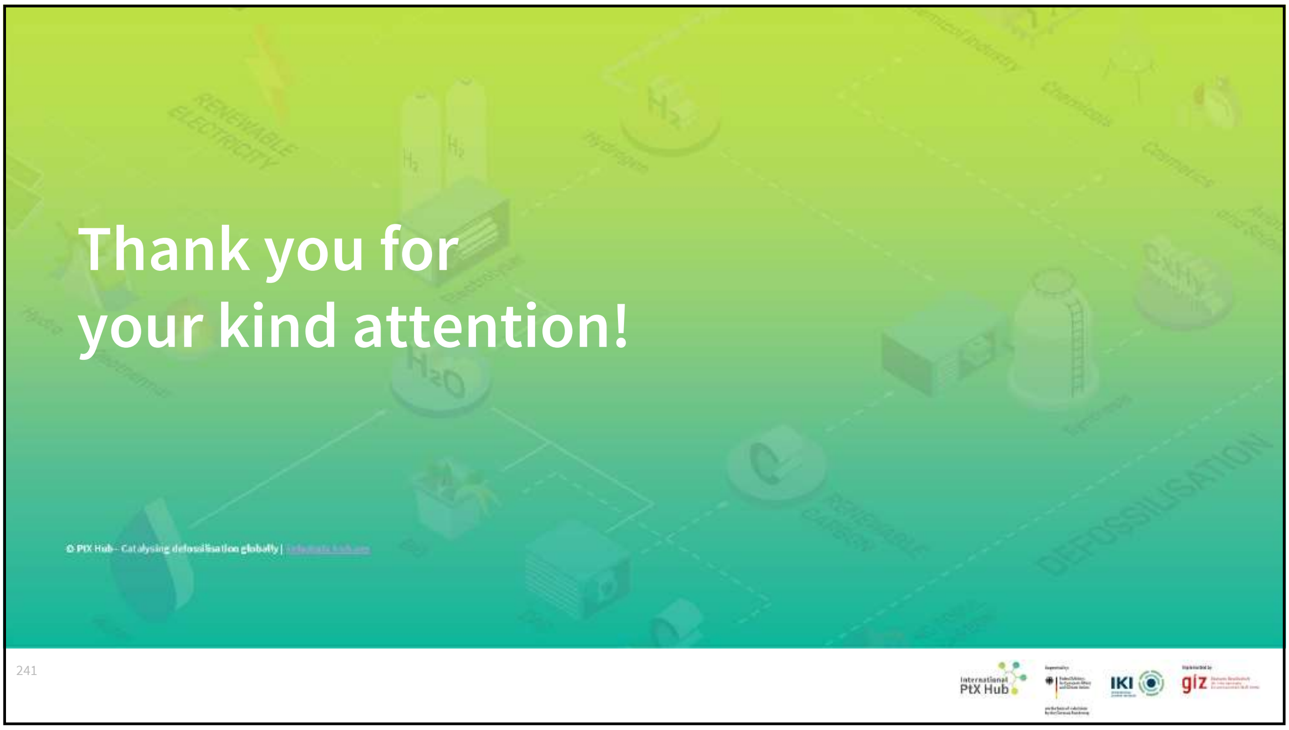

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