E-fuels

Deutsche Physikalische Gesellschaft, Arbeitskreis Energie
Frühjahrssitzung Bad Honnef, 12. April 2024
Dr. Ireneusz Pyc

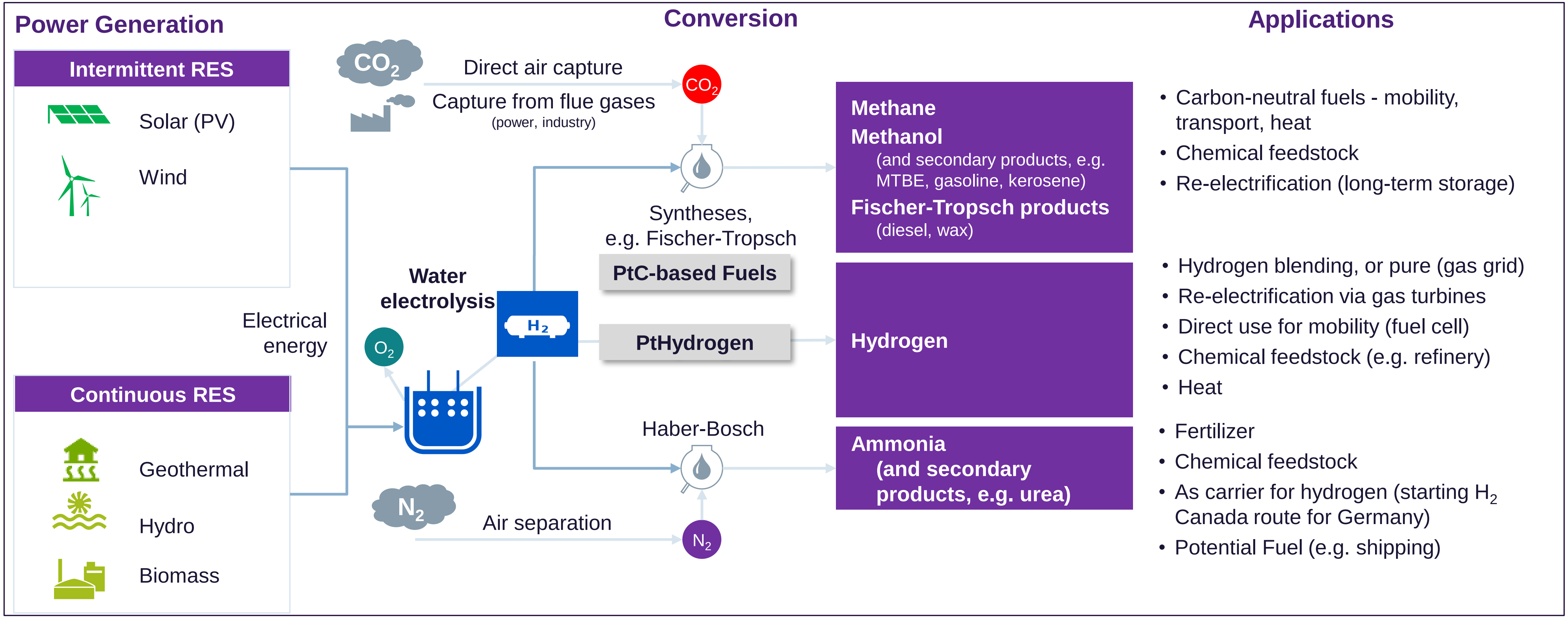
Agenda

1. (Green) Hydrogen as a basic molecule for e-fuels
2. E-fuels: why e-Methanol ?
3. Technologies, efficiency
4. Use-cases in mobility, transportation, power- and heat sector
5. Techno-economics, e-fuels for Europe
6. Siemens Energy engagement
7. Synthetic energy carriers, dead-end or still good perspectives?

1

Power-to-Hydrogen
Multiple hydrogen-routes provide variety of final products

Hydrogen is multi-functional, provides fuels, storage, it connects Energy, Mobility and Industry



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Application of synthetic e-fuels means different energy conversion processes resulting in nearly closed loops

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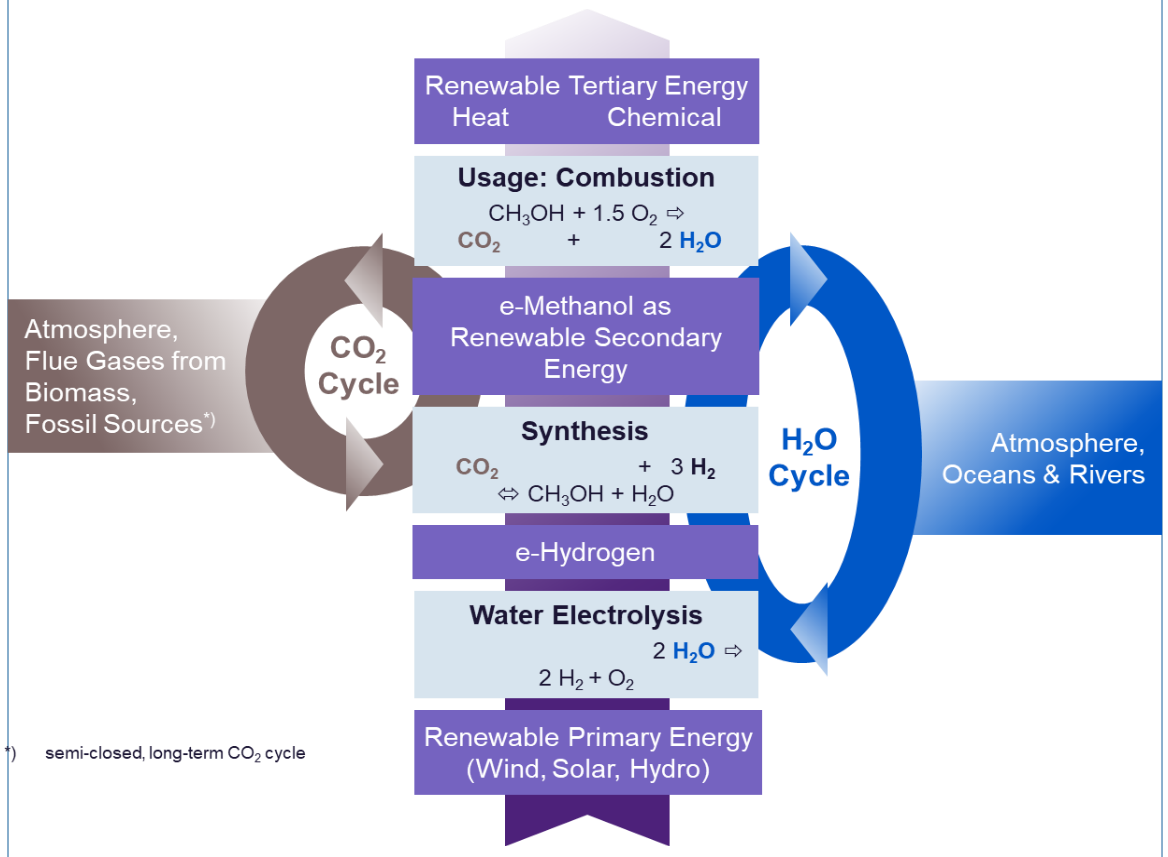
Important for the synthetic fuel classification and cycle understanding: what is carbon neutral, what is carbon free?

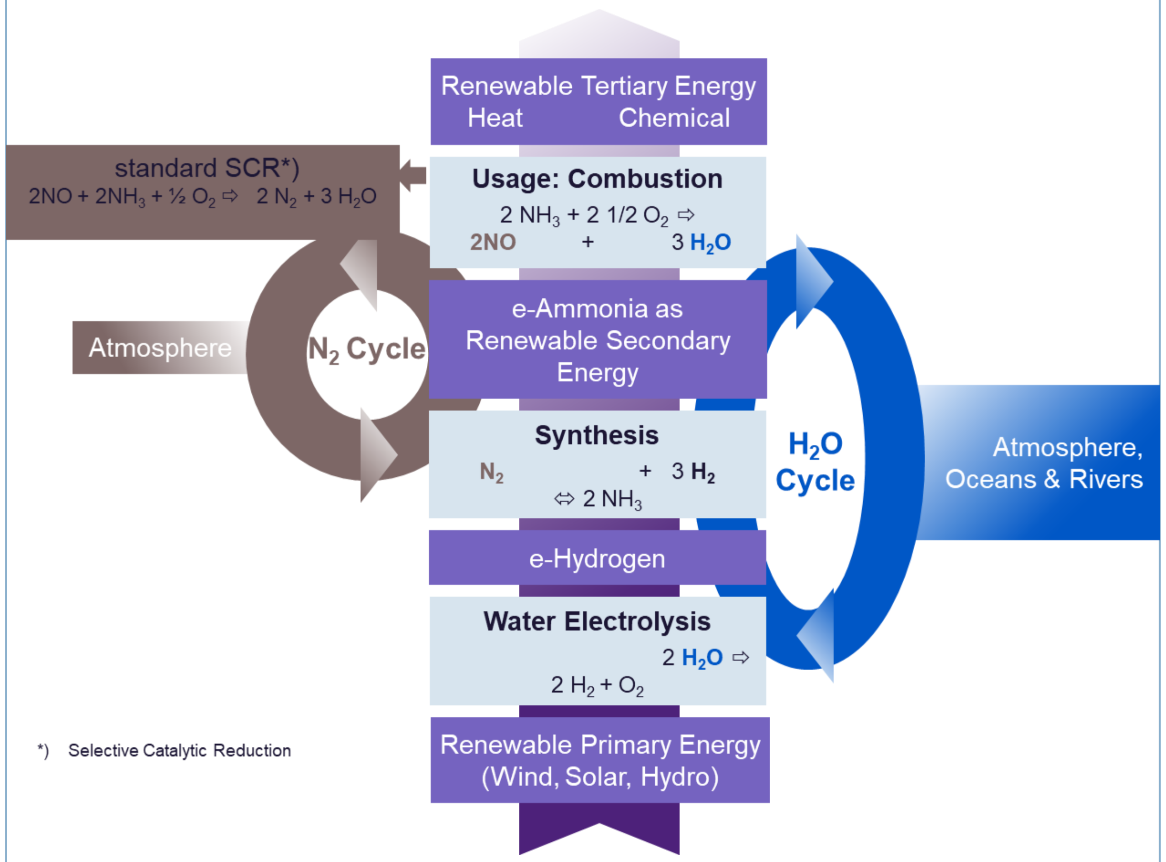
Carbon neutral, example methanol

Similar for other synthetic hydrocarbons



*) semi-closed, long-term CO_2 cycle

Carbon free, example ammonia



*) Selective Catalytic Reduction

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Few words on carbon dioxide - sourcing
Still ongoing discussion on relevance for the climate impact

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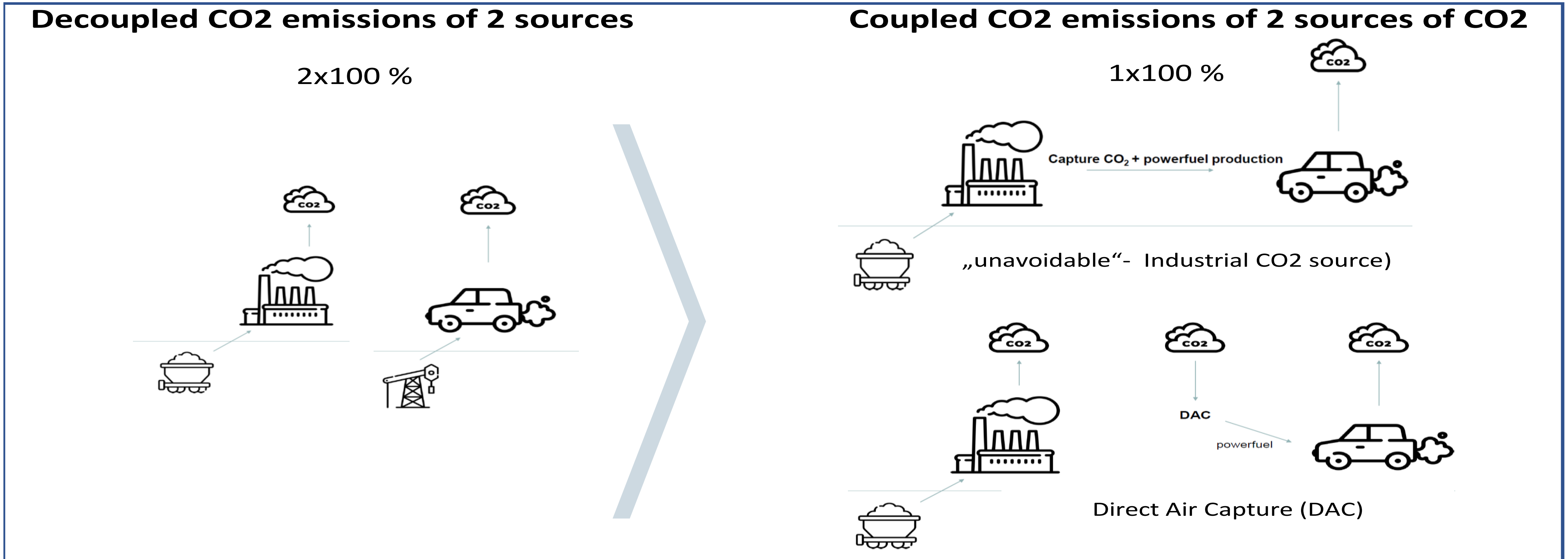
Net savings of CO_2 emissions via synthetic fuels based on recycled CO_2 are independent of the CO_2 source: either industrial (low-cost)- or direct air capture (expansive)- source of CO_2 have the same net impact on



Illustrative: based on pictures from IRENA

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There are different applications for green hydrogen in Industry, Mobility and Energy (power and heat)

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Segment	Application	Description
Industry		**Onsite H_2 production from renewable energy** replacing steam methane reforming (SMR) or coal gasification or substitute trailers for industries like the chemical industry or industrial processes such as:
	Ammonia production	H_2 for Haber-Bosch process
	Hydrocarbon production	H_2 for Fischer-Tropsch Process
1	**Petroleum refinement**	**Hydrocracking and hydrotreating of hydrocarbons, fuel blending, gasoline additives**
	Metal production	H_2 as the main reductant
	Food & Beverage	e.g., Margarine production by fat hardening by means of O_2
Mobility	**Alternative fuel**	Using hydrogen as **fuel** for **fuel cell electric vehicles** for long distance in parallel to battery electric vehicles for short to medium distance; **Reduction of CO_2 footprint** for individual, public and commercial transport
2	**Green e-fuels**	Using hydrogen to create **green fuels** (hydrocarbon mixtures) **substituting or adding to fossil sources**
Energy	Hydrogen blending (gas grid)	**Substitute up to 20% methane/natural gas**[1] in the gas grid by feeding in hydrogen
3	**Re-electrification** **Heat production**	**Provide energy by re-electrification** of green H_2 (supplied by pipeline, trailer or produced onsite) in gas turbines and of green ammonia in coal fired, steam power plants **Heat generation, industrial and home applications**
Add-on	Grid services	Using **electrolysis as load** to provide primary and secondary **control power**
	Energy storage	**Absorb peak production** by storing renewable energy as H_2 **instead of curtailment**
	Energy export	**Export** renewable energy as liquid H_2, ammonia or other hydrogen carrier (e.g., LOHC[2])

1 Source: https://www.dvgw.de/medien/dvgw/leistungen/forschung/berichte/1510nitschke.pdf p. 24 | **2** Liquid Organic Hydrogen Carrier and own SE estimates

1

Hydrogen from renewable energy sources lowers CO_2 footprint from petroleum refining process, directly or via e-fuels

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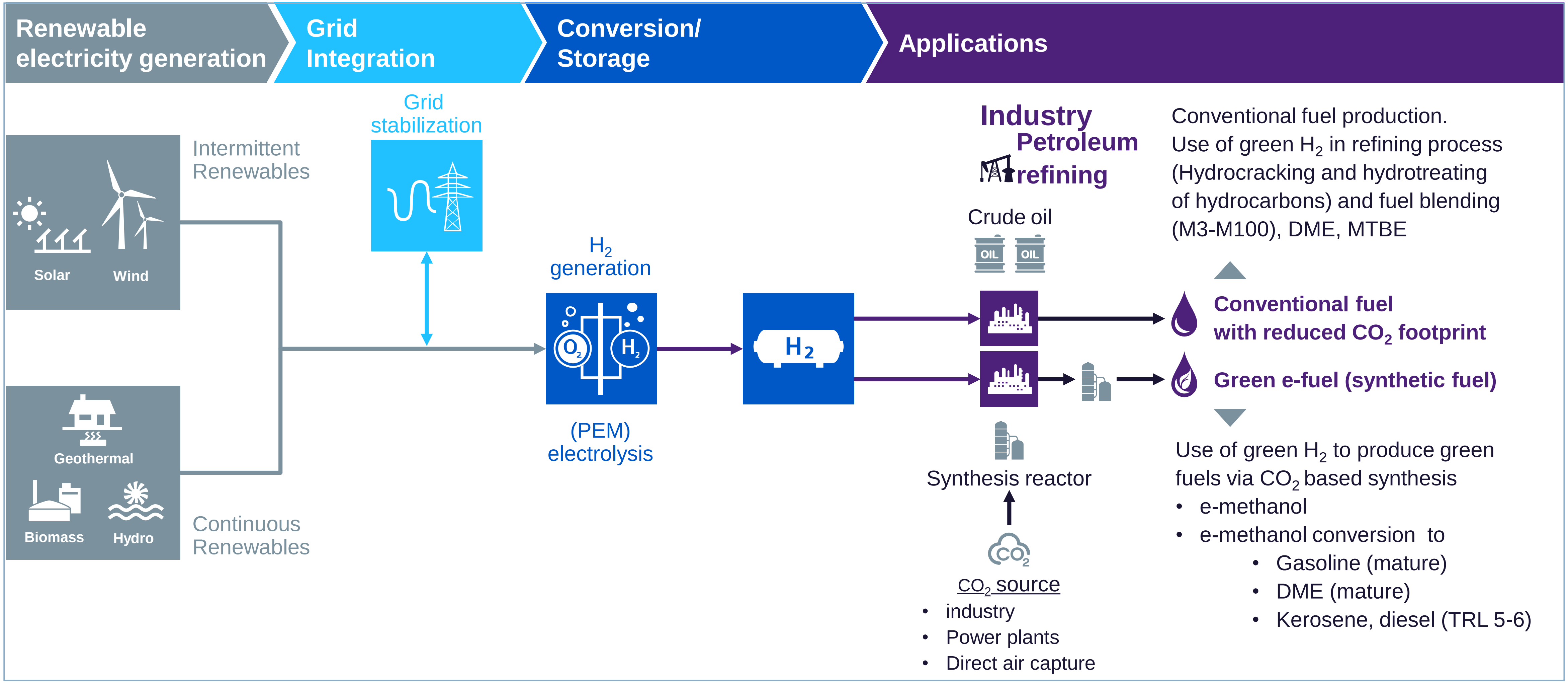

Principle technologies for e-fuel production

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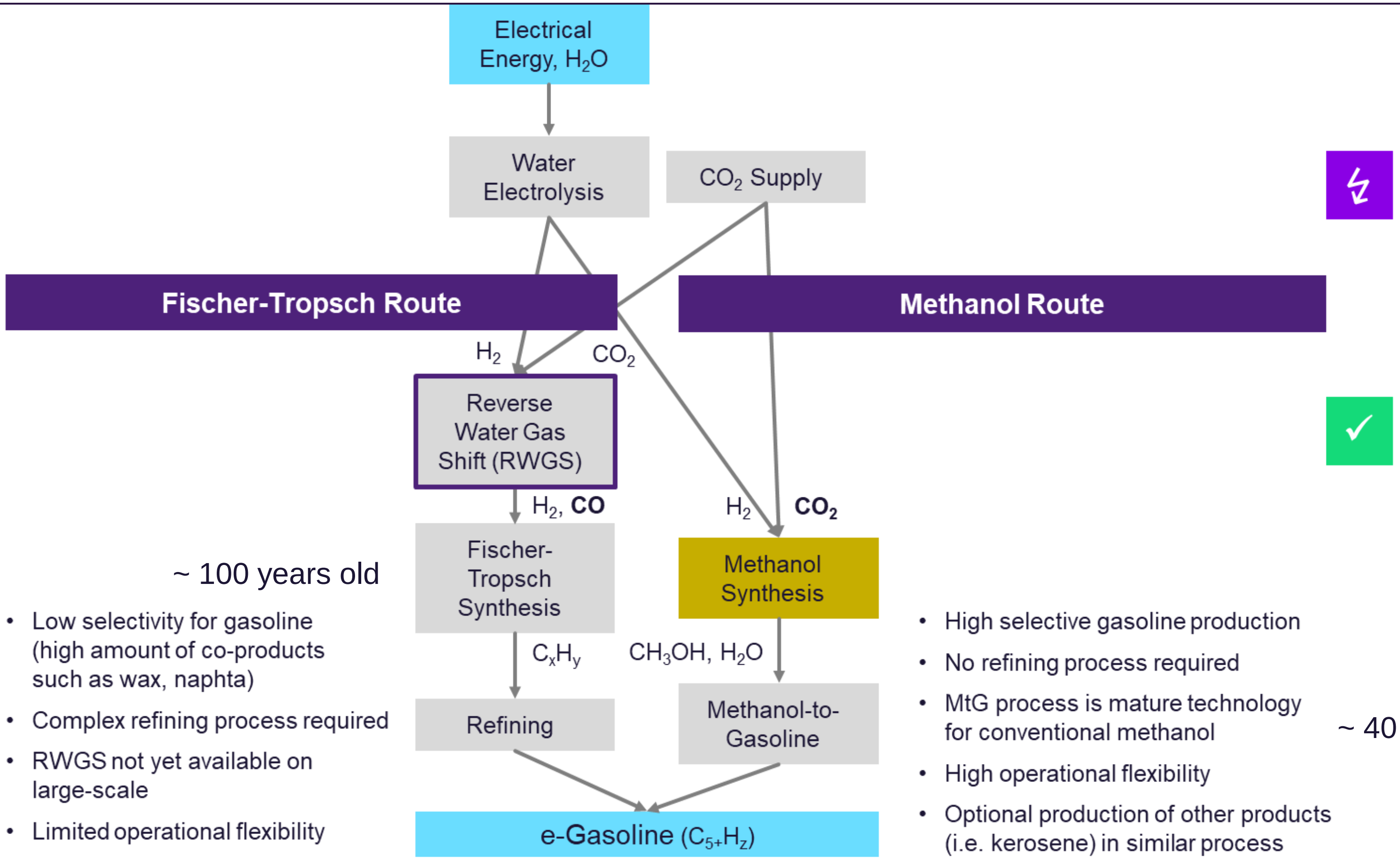
Two alternative, but proven routes for gasoline production: Fischer-Tropsch (F-T) and methanol to gasoline (MtG)



~ 100 years old

- Low selectivity for gasoline (high amount of co-products such as wax, naphta)
- Complex refining process required
- RWGS not yet available on large-scale
- Limited operational flexibility

~ 40 years old

- High selective gasoline production
- No refining process required
- MtG process is mature technology for conventional methanol
- High operational flexibility
- Optional production of other products (i.e. kerosene) in similar process

Efficiency of electricity conversion into e-fuels. The way from electricity to molecules means efficiency losses…

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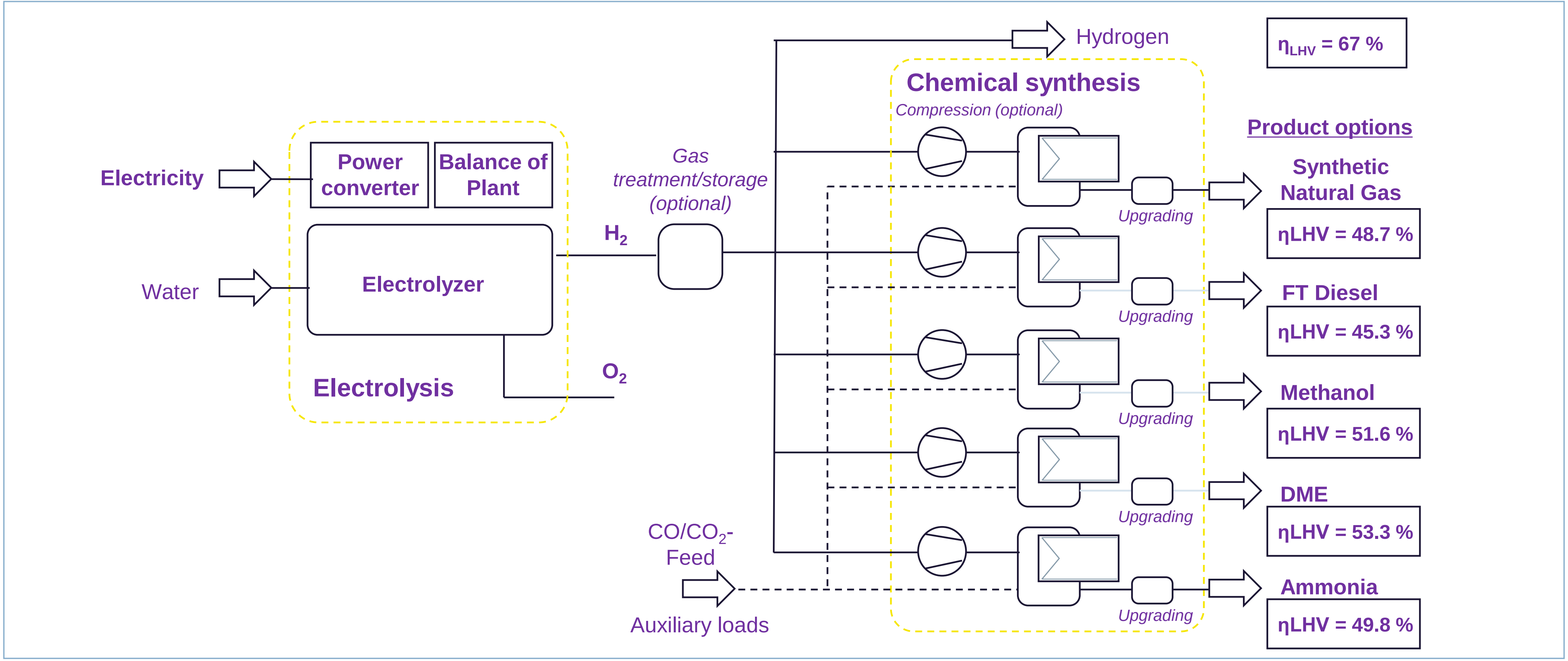
… but is the overall process efficiency the single decisive factor against PtX applications?



Different types of e-fuels are available. Green e-Methanol as a basic chemical and energy carrier provides multiple advantages

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- Lowest alcohol, easy to produce from H_2 and CO/CO_2. Already established market of (black) methanopl > 100 mio t/year
- Liquid fuel, compatible with existing conversion and propulsion technologies, i.e. reciprocating engines, gas turbines, fuel cells
- C/H Energy density half of gasoline, but high energy density compared to H_2 (4x the energy density of compressed 350 bar H_2)
- Easy adoption of existing methanol and conventional fuels infrastructure, i.e. pipelines, tanks, pumps, fueling stations
- Immediate use possible: blending of 1-3% (M3) (EU), 15% (M15) in Italy, Israel, Denmark, M15-M100 in China, intro in India
- Proven processes of conversion of methanol to DME, gasoline and other chemicals and fuels
- Lower water demand for production compared to biofuels
- Sector coupling by multi-functionality with connection between electrical energy, existing mobility & industry sectors
- To the air: Low emissions of CO, NO_x, particulates from combustion. Lowest C/H ratio among all liquid fuels leads to low CO_2 emissions

Green, „electricity“-based

! Low investment risk due to low and stable OPEX, smooth shift from “black”-fossil to “green” e-Methanol

Good macro-economical perspective due to low societal costs for infrastructure → especially relevant for developing countries

Promising micro-economic indicators due to attractive business cases at many sites across the globe

Use cases transportation. Liquid, but low carbon footprint - fuels needed even for a long-term future

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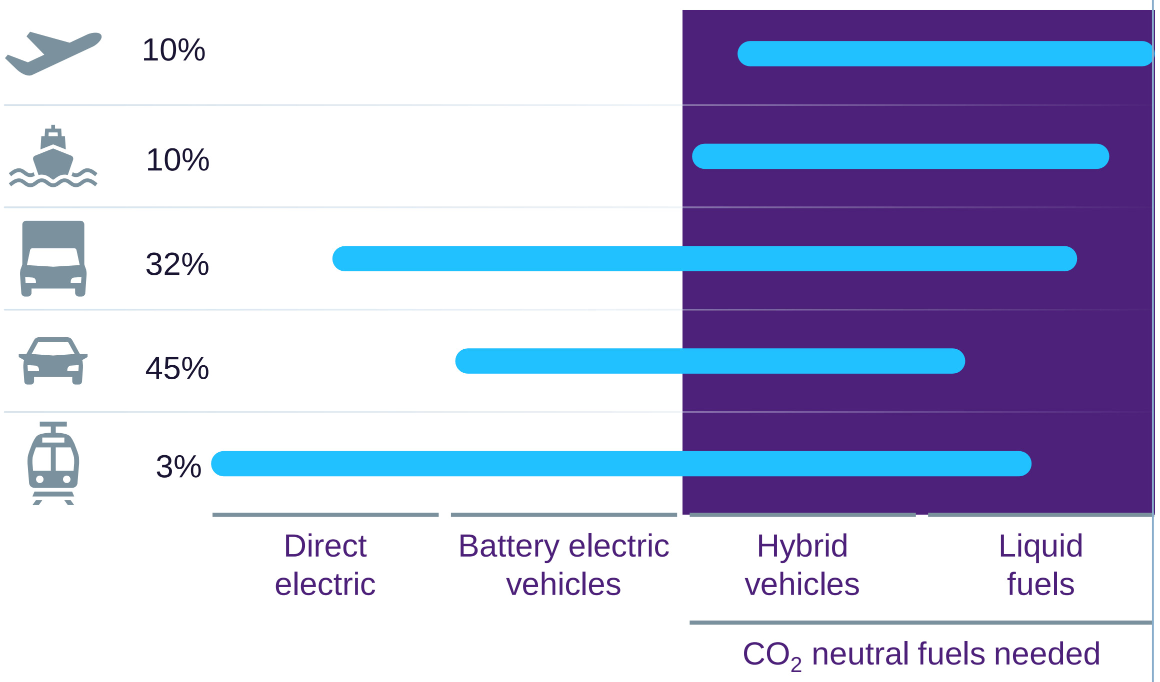
The de-fossilization of long distance, heavy weight and marine transport, aviation requires CO_2 neutral fuels with high energy density

Pathways for de-fossilization

Global CO2 emissions, 2022 (~7,9 Mrd toe)



1 IEA, CO2 emissions in 2022

Reasoning

- Transport and mobility sector is responsible for ~ 20% of global energy related CO_2 emissions (36,8 Gt in 2022), GHG:~41 Gt
- To achieve a substantial de-fossilization, the entry of “green” e-H_2 and e-fuels into the fuel market for transportation (…and heating) is necessary
- Electric cars are preferred for individual mobility– but require an establishment of new and costly infrastructure. Recently a rethinking process o the e-route within buyers and energy policy
- Use of de-fossilized e-fuels, which are compatible with existing conventional fuel infrastructure can achieve immediate CO_2 savings in regions, where combustion engines are being used for longer time
- Japanese and some European car producers recognize advantages of e-fuels in their car strategy
- Liquid fuels stay still as the dominating source of transportation energy in Europe

Aviation: Two alternative routes for kerosene production. Political game for quotas and first demo projects starting

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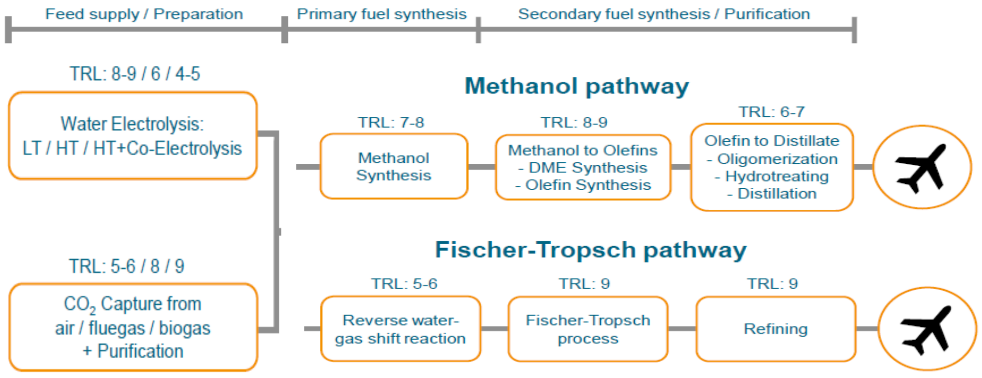
Example: use of de-fossilized jet fuel leads to ticket price increase of 10-20% (+40-80USD) for a 6,500 km economy class flight [5)]

Synthetic pathways to jet fuel (SAF[1)])



Source: Power-to-X, Energy solutions for climate-neutrality, Brussels, January 2021VDMA, 2021

Shares of SAF[1)] in the fuel mix for air transport EU

Shares in the fuel mix (in %)	2025	2030	2035	2040	2045	2050
SAF ramp-up out of which:	**2**	**5**	**20**	**32**	**38**	**63**
Sub-mandate - advanced biofuel (incl. waste lipids)	2	4.3	15	24	27	35
Sub-mandate – green synthetic fuels	-	0.7	5	8	11	28

Source: Power-to-X, Energy solutions for climate-neutrality, Brussels, January 2021, VDMA, 2021, drafted 2021, recently the procentages from 2030 onwards have been increased, ending with 70% in 2050

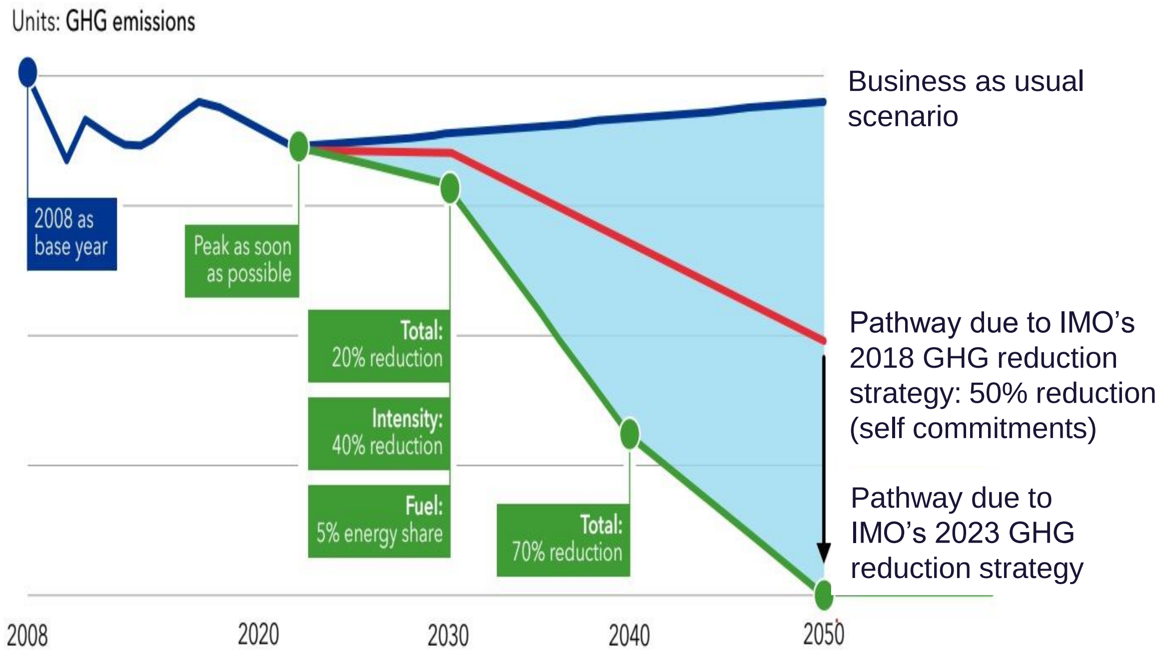
- F-T[2)] and MtK[3)] have achieved comparable TRL-levels.
- MtG processes (main output: C5 chains), currently do not enable production of kerosene/jet fuel (C9-C14)
- Adoption of MtG process for production of kerosene ongoing. More than 100 publicly announced SAF projects early 2023
- While in F-T RWGS[4)]- process for CO_2/CO conversion is required, for MtK CO and CO_2 are both suitable feedstocks
- MtK process-selectivity and -activity profile depend on specific parameters (catalyst, temperature, pressure and contact time)
- MtK process allows higher dynamics, which makes it more suitable for applications with volatile renewable power
- Alcohol-to-Jet and Fischer and F-T are both approved by the ASTM for a 50% blend.
- Proposed EU quotas for e-kerosene are too low to ramp up a carbon-neutral e-kerosene.

1) SAF: Sustainable Aviation Fuels
2) F-T: Fischer-Tropsch
3) MtK: Methanol to Kerosene
4) RWGS, Reverse Water Gas Shift: complex and technically challenging process step to generate CO from CO_2 and H_2 from H_2O
5) Mission possible, reaching net zero carbon emissions from harder to abate sectors by mid century, energy transition, 2018

Shipping: GHG- (mainly CO_2) emission reduction in shipping is based on industry self-commitments

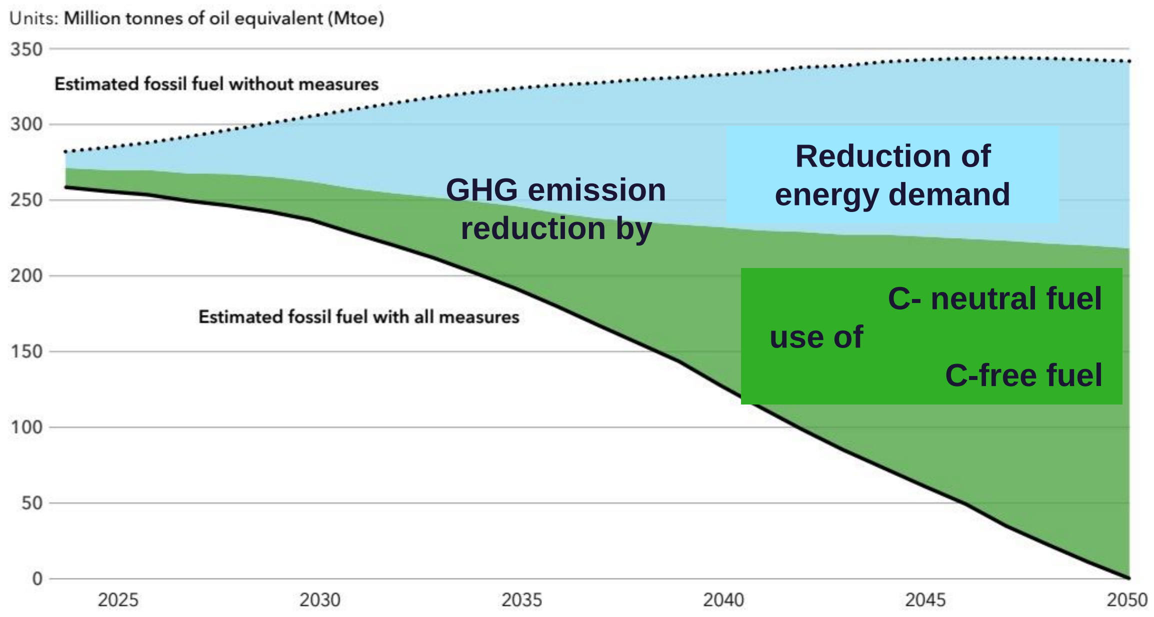
Due to the International Maritime Organization (IMO): Shift to low carbon fuels is increasingly in focus of planned actions

Indicative checkpoints in the 2023 IMO's GHG strategy signed by 175 countries



Source: DNV 2023 based on IMO

Simulated results for the demand of carbon neutral/free fuels in shipping



Measures for GHG reduction:

1. Increase efficiency of drives, logistics, implementation of new wind assisted propulsion, reduction of transportation velocity and..
2. Change of fuel/drive: conversion to carbon-neutral/carbon-free fuels: (e-) LNG, methanol, ammonia, hydrogen, biomass fuels

(Green) methanol develops into a state-of-the art maritime fuel 2024: more than 100 ships in operation or under construction

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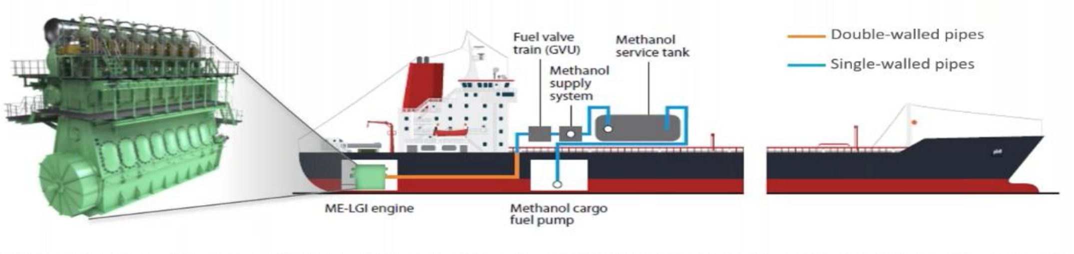

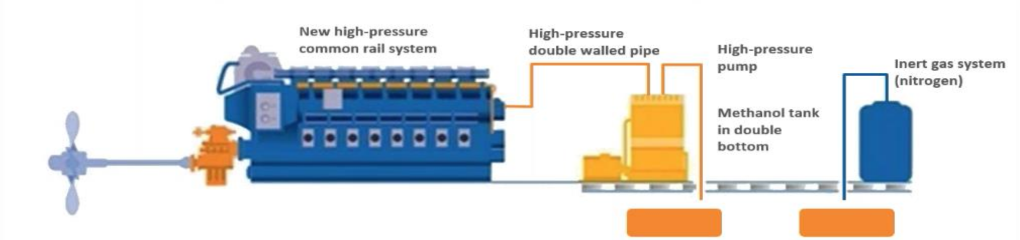

Technology: new ships and repowering

- Only minor modification/cost requirements for ship engine (dual fuel option with diesel); slightly higher efficiency
- Pipes, pumps, valves, tanks and detection to be adopted to methanol requirements
- Green methanol is already certified by ISCC due to the EU‘s renewable energy directive

1. Generation methanol fueled ships

Stena Germanica Ferry, 2015

Methanex

Methanol transporting ship

2019

2. Generation methanol fueled ships

“Laura Maersk” (2,1 tsd TEU), the world’s first methanol fuel-enabled container ship, 2023

Future 17000 TEU ship being able to operate on green methanol, Comm operation: I quarter 2024

Economics:

Example: the vessel fuel-switch from fossil to green fuels (MDO-to green fuels) causes an increases the price of jeans transported from Asia to Europe by ~ 0.3 USD, 1)

Container shipping in a leading position

Maersk has already 25 methanol-enabled vessels on order.12 of them are 16 tsd. TEU, 6 are 17 tsd. TEU-ships. Ane Maersk, 1 time Hamburg in March, 2024 Together with other container lines >100 methanol ships are currently under construction

1) Mission possible, reaching net zero carbon emissions from harder to abate sectors by mid century, energy transition com. London, Nov.2018, TEU: twenty-foot Equivalent Unit)

4

Power generation in steam power plants: Ammonia as de-fossilized fuel for continued operation of coal fired plants

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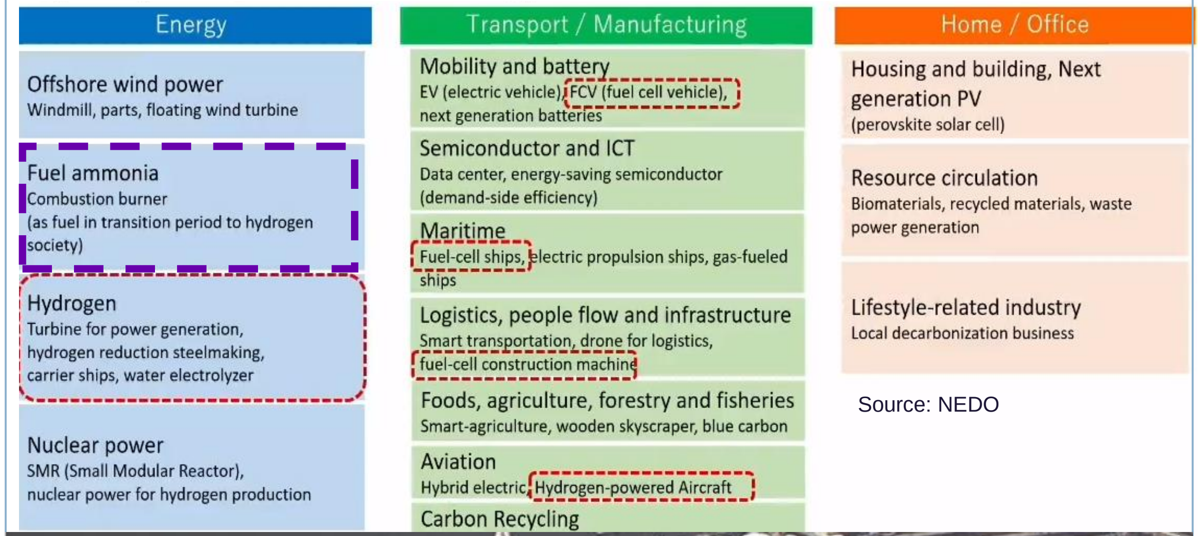
Japanese "Green growth strategy towards 2050-carbon neutrality

JERA to start trial of co-firing ammonia at coal power plant in March 2024



Source: NEDO

Source: Power, Nov. 2020

JERA's 4.1-GW Hekinan Thermal Power Station

Ammonia:

- Japan's CO_2 emissions from the power sector are similar to Germany (~400 mio t/a).
- The CO_2 reduction strategy from power sector is different.
- Instead of closing all coal plants, only those with lowest efficiency will be closed. Remaining plants will be co-fired by green ammonia imported from Australia
- Ammonia based power generation should amount to
  - 20% co-firing for 2030 leads to 10% CO_2 reduction → NH_3 demand: 20 mio t/a.
  - Full ammonia firing, which would be able to reduce the CO_2 emissions by 200 mio t/a from the power sector planned for 2040 → NH_3 demand: 100 mio t/a
- Only relatively small additional investment for adoption of the burner and extension of existing DeNOx plants

Source: financial times

Source: S.Muraki

SIP Energy cariers, Nov.1 2018

Power generation in gas-turbines and combined cycle power plants fired by hydrogen

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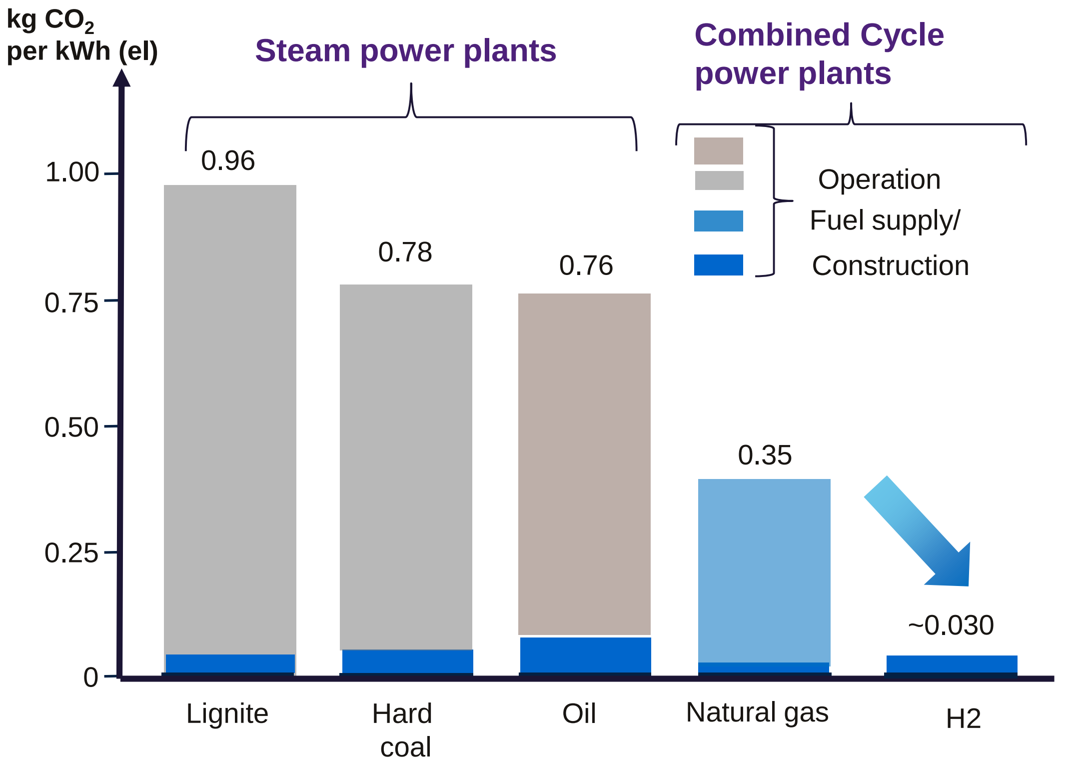
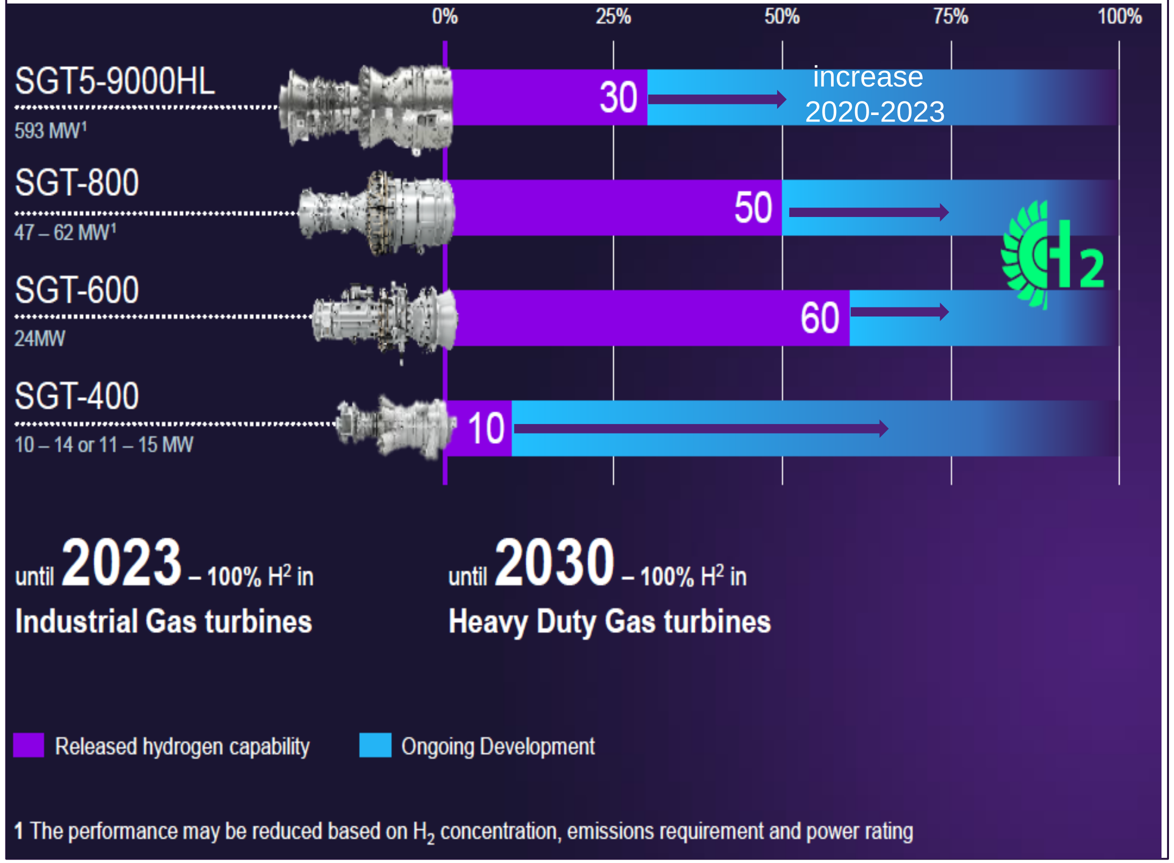
H_2 fired gas turbines in back-up and grid control function will "save" last CO_2 emissions from the power sector

Specific CO_2-emissions of power plants



Capability of Siemens Energy H_2 – burning gas turbines



Potentielle Möglichkeiten der Nutzung von e-Methanol im Wärmesektor. Deutschland: Ausgangslage und Motivation

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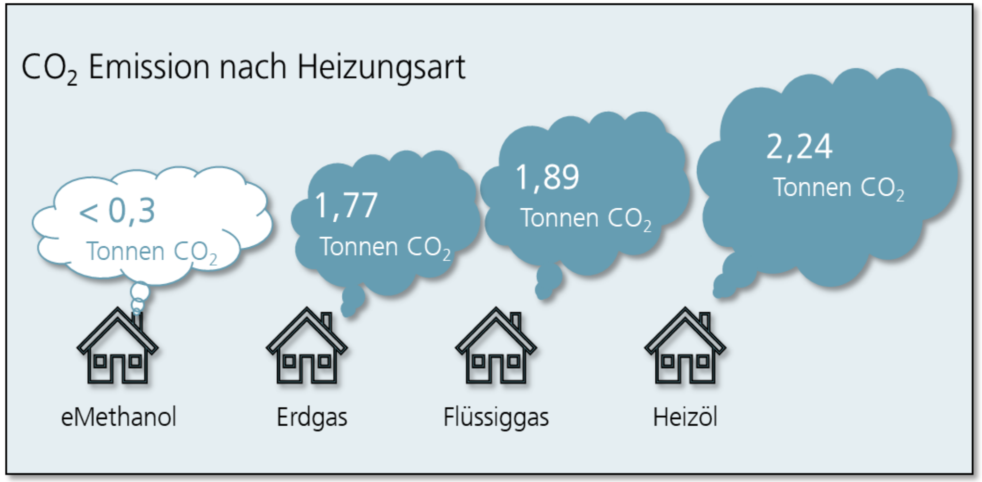
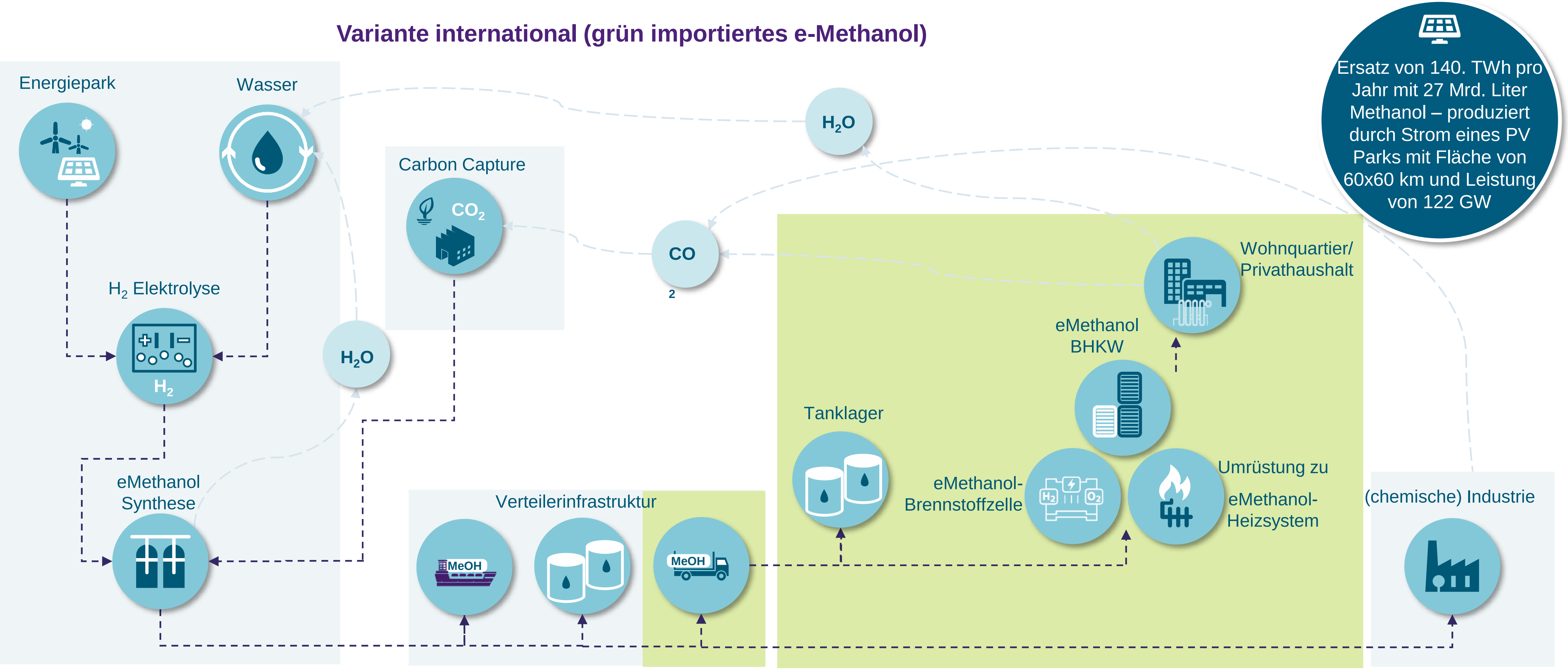


Quelle: Fraunhofer IFF, Magdeburg, I. Pyc, Siemens Energy, 2022

- In Deutschland werden etwa 30 % der Gesamtenergie in privaten Haushalten verbraucht.
- 90 Mio. Tonnen CO_2 werden allein dadurch pro Jahr ausgestoßen, davon sind 70% auf die Erzeugung von Raumwärme zurückzuführen.
- in ca. 10 Mio. deutschen Haushalten (ca. 4 Mio. Heizungen) wird mit Heizöl geheizt - Ölheizungen, zählen nach wie vor zu den durchschnittlich günstigsten Anlagen.
- Die Emissionswerte von Heizöl sind mit einem CO_2-Äquivalent von 319 g/kWh, nach Kohle mit 680 g/kWh hoch. In Anbetracht der Forderungen nach einer Reduktion des CO_2-Austoßes in die Atmosphäre „auf Null", durch die Umstellung auf CO_2-neutrale oder freie Kreisläufe.
- Die Gesetzgebung fordert zeitnahe Verringerung der GHG-Emissionen und der Abhängigkeit vom Import fossiler Brennstoffe, wie Öl, Gas (LNG).
- Die Lösung hierfür: die Verwendung von „grünem e-Methanol", hergestellt aus (klimaneutralen) CO_2, Wasser und grünem Strom, gefahrarm speicherbar, sicher transportierbar und als Energieträger für Wohngebäude einsetzbar.
- Das Projekt „MetHeat" könnte als Leuchtturm für die nachhaltige und klimaneutrale Erzeugung von Raumwärme mit grünem Methanol in Wohnquartieren/Privathaushalten sichtbar werden und durch Wärme-Dekarbonisierung einen Betrag zur CO_2 Reduktion in der Atmosphäre nachweisen.

Konzeptidee Projekt MetHeat

Variante international (grün importiertes e-Methanol)



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Affordability of e-methanol, simulation of economics of selected production sites

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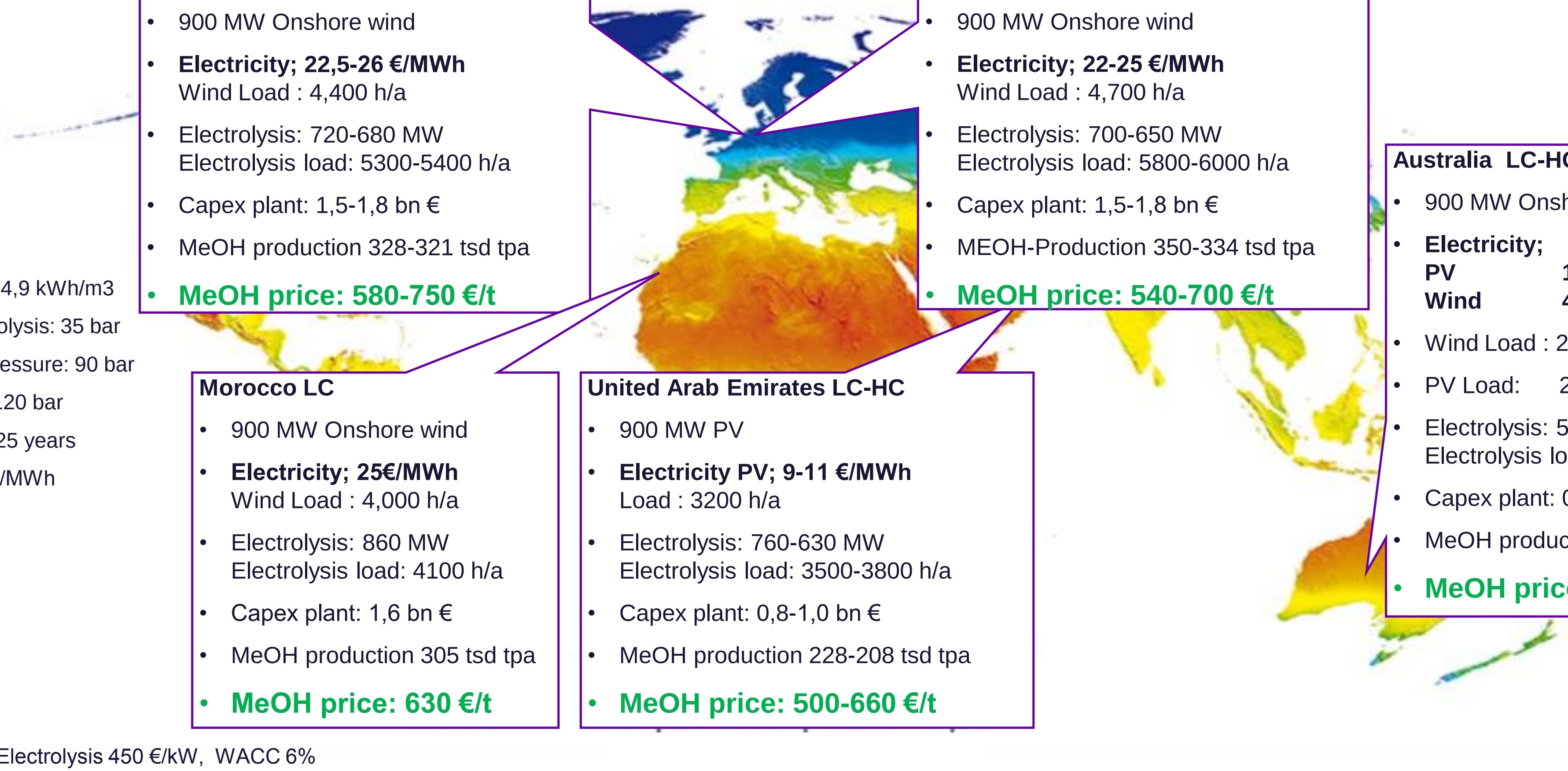
In a foreseeable future methanol production costs of 500-800 €/t (10-15 ct/kWh) are achievable. The increasing CO_2 price in Europe [1)] will lead to an equivalence between the price of imported black methanol and production cost of e-methanol around 2030.



Netherlands LC-HC
- 900 MW Onshore wind
- **Electricity; 22,5-26 €/MWh**
  Wind Load : 4,400 h/a
- Electrolysis: 720-680 MW
  Electrolysis load: 5300-5400 h/a
- Capex plant: 1,5-1,8 bn €
- MeOH production 328-321 tsd tpa
- **MeOH price: 580-750 €/t**

Germany/ Brunsbüttel LC-HC
- 900 MW Onshore wind
- **Electricity; 22-25 €/MWh**
  Wind Load : 4,700 h/a
- Electrolysis: 700-650 MW
  Electrolysis load: 5800-6000 h/a
- Capex plant: 1,5-1,8 bn €
- MEOH-Production 350-334 tsd tpa
- **MeOH price: 540-700 €/t**

Australia LC-HC
- 900 MW Onshore PV+Wind
- **Electricity;**
  PV 12-14 €/MWh
  Wind 41-48 €/MWh
- Wind Load : 2400 h/a
- PV Load: 2500 h/a
- Electrolysis: 560-680 MW
  Electrolysis load: 3700-3900 h/a
- Capex plant: 0.9-1,0 bn €
- MeOH production 180-176 tsd tpa
- **MeOH price: 580-790 €/t**

Morocco LC
- 900 MW Onshore wind
- **Electricity; 25€/MWh**
  Wind Load : 4,000 h/a
- Electrolysis: 860 MW
  Electrolysis load: 4100 h/a
- Capex plant: 1,6 bn €
- MeOH production 305 tsd tpa
- **MeOH price: 630 €/t**

United Arab Emirates LC-HC
- 900 MW PV
- **Electricity PV; 9-11 €/MWh**
  Load : 3200 h/a
- Electrolysis: 760-630 MW
  Electrolysis load: 3500-3800 h/a
- Capex plant: 0,8-1,0 bn €
- MeOH production 228-208 tsd tpa
- **MeOH price: 500-660 €/t**

Selected assumptions
- Electrolysis efficiency 4,9 kWh/m3
- Outlet pressure electrolysis: 35 bar
- Methanol synthesis pressure: 90 bar
- Hydrogen storage at 120 bar
- Lifetime/depreciation 25 years
- Back-up power: 100 €/MWh
- CO2 price: 80 € /t

$$Ct/kWh = \frac{€/t}{55}$$

Scenarios

Low case (**LC**): Capex Electrolysis 450 €/kW, WACC 6%
High case (**HC**) Capex Electrolysis, full scope incl. civil works, 850 €/kW, WACC 8%

1) Starting with 30 €/t CO_2 in 2023, assuming 10%-30% yearly increase, CO_2 price achieves values of 60-190 €/t CO_2 in 2030

Scenario: costs of e-fuels in a foreseeable future.
Not 4-5 €/l, but 1-2 €/l synthetic fuel

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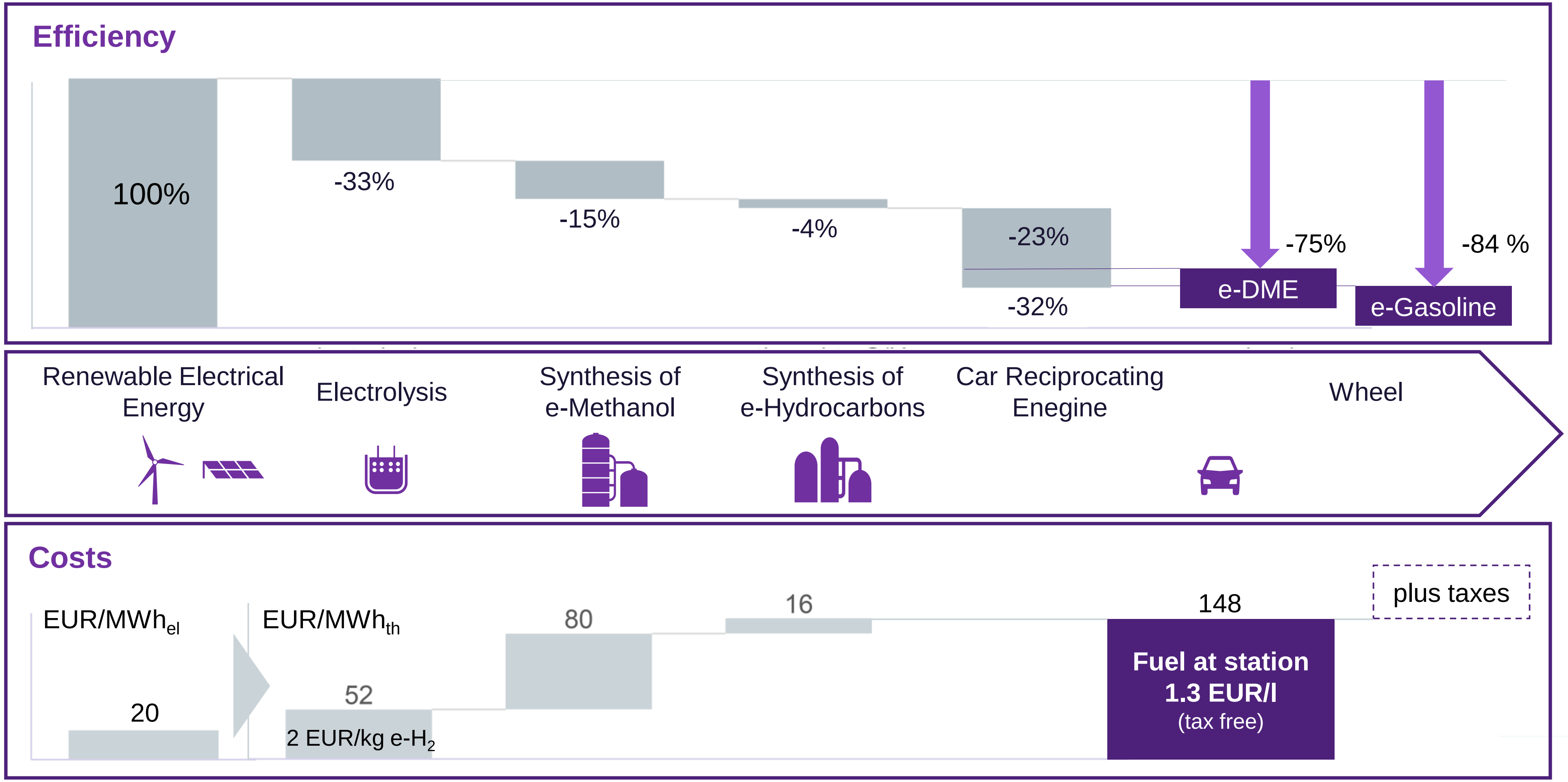

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With their favorable solar- and/or wind-conditions many regions demonstrate the economical potential for e-Fuels production

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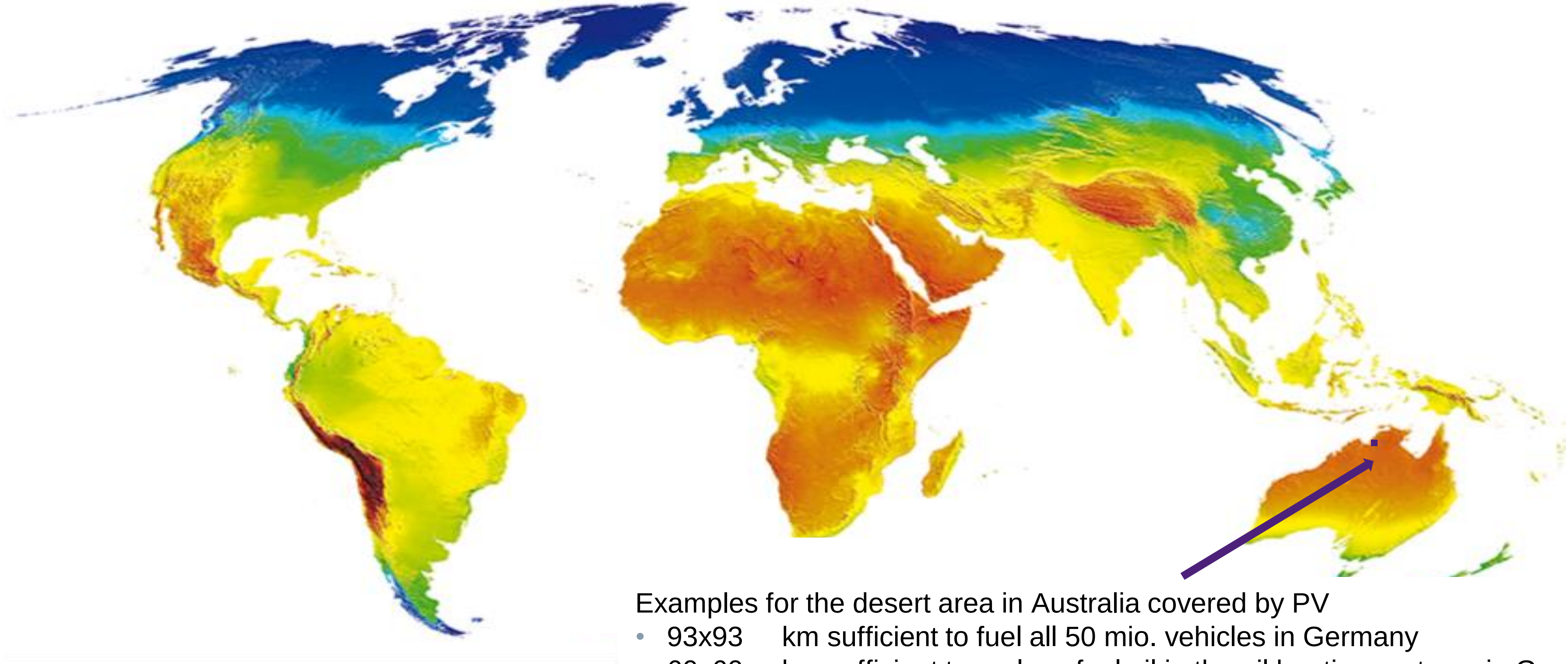
Use of 30 % of the free surface of Australia for PV is sufficient to cover the entire world primary energy demand (617 EJ 2019)
Even for 50% more energy demand until 2050, there are no global surface constraints for use of PV and wind energy



Examples for the desert area in Australia covered by PV
- 93x93 km sufficient to fuel all 50 mio. vehicles in Germany
- 60x60 km sufficient to replace fuel oil in the oil heating systems in Germany
- 270x270 km sufficient to fuel the ship fleet worldwide

Projects completed or in implementation based on Silyzer 300

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6 MW

H2Future Linz

- Green hydrogen for the steel making process
- Our partners: VERBUND, voestalpine, Austrian Power Grid (APG), TNO, K1-MET

8.5 MW

Wunsiedel

- Green hydrogen for industry, grid services and mobility
- Our partners: Siemens AG, WUNH2, SWW Wunsiedel GmbH

up to 20 MW

Oberhausen

- Green hydrogen for Air Liquide pipeline infrastructure
- Our partner: Air Liquide

50 MW

e-Methanol Kassø

- Green hydrogen for CO_2-neutral shipping (Maersk)
- Powered by largest PV park in Scandinavia
- Partner: European Energy
- Start of operation 2023

70 MW

FlagshipONE Örnsköldsvik

- Green hydrogen for CO_2-neutral shipping at large-scale
- Partner: Ørsted
- 50.000 tones from 2025
- 10 more plants by 2030

50 MW

Chemical company

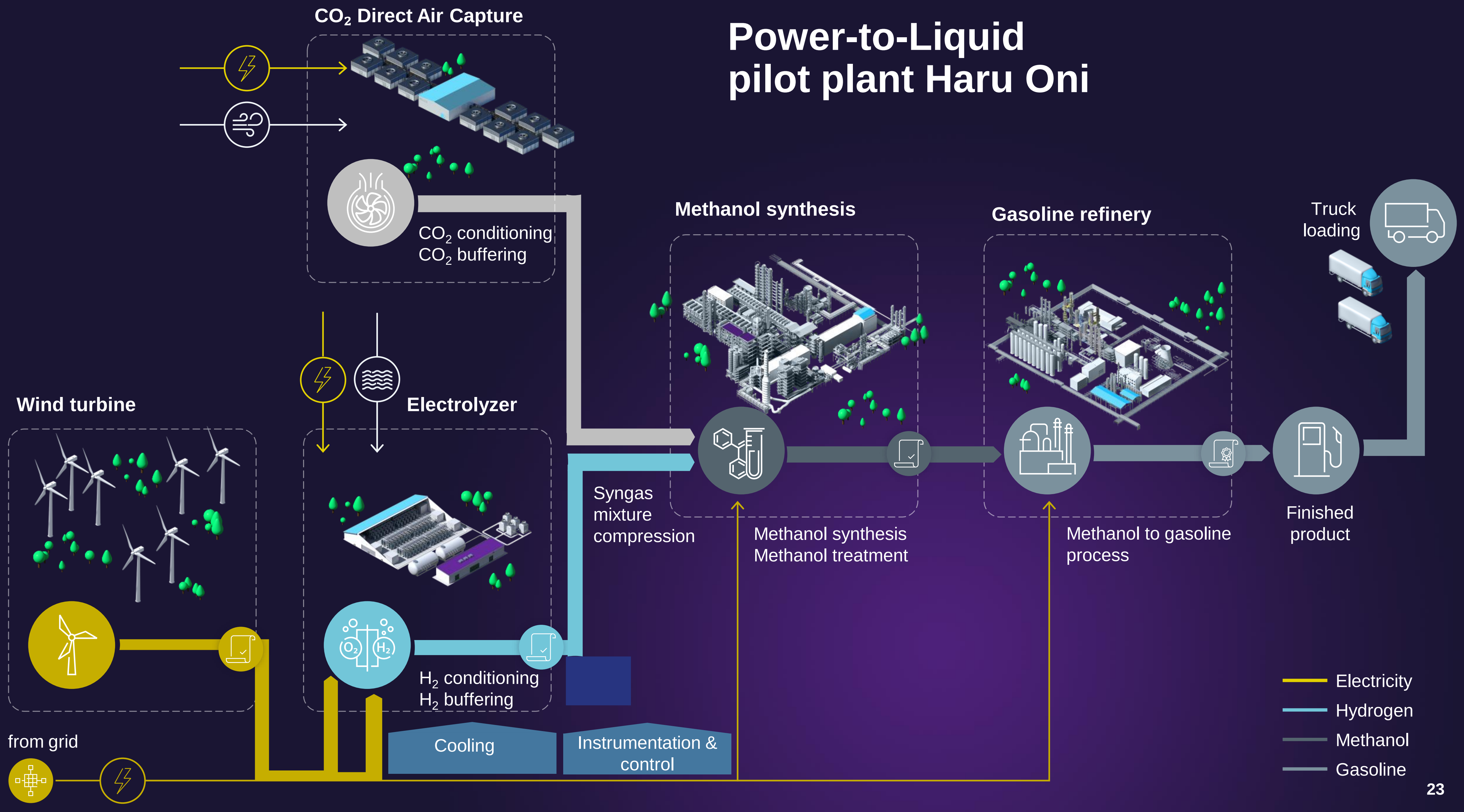
- Hydrogen for chemical site

200 MW

NormandHy

- Renewable electricity
- Engineering and Long Lead Started
- Our Partner: Air Liquide

Power-to-Liquid pilot plant Haru Oni



HARU ONI PILOT PROJECT

First integrated plant for climate-neutral e-fuel production from wind and water

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750,000 liters

of e-methanol per year from 2023 (130,000 liters of e-gasoline)

>55 m liters

e-fuel per year planned from 2025

>550 m liters

e-fuel per year planned from 2027

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

YYYY-MM-DD

Project

Customer:	HIF (Highly Innovative Fuels)
Country:	Chile, Patagonia
Installation:	2022
Product:	Power-to-methanol solution based on Siemens Energy PEM electrolysis
Off-taker:	Porsche AG. First commercial delivery to UK in Nov. 2023

Use cases

- E-Fuel (gasoline) for Porsche cars
- Potential for adding Kerosene or Diesel production in future phases
- Methanol for ships
- Methanol for chemicals

Challenge

- Huge wind energy potential in Magallanes
- Existing natural gas and methanol industry, as well as port infrastructure (Punts Arenas)

→ Perfect conditions to export green energy from Chile to the world

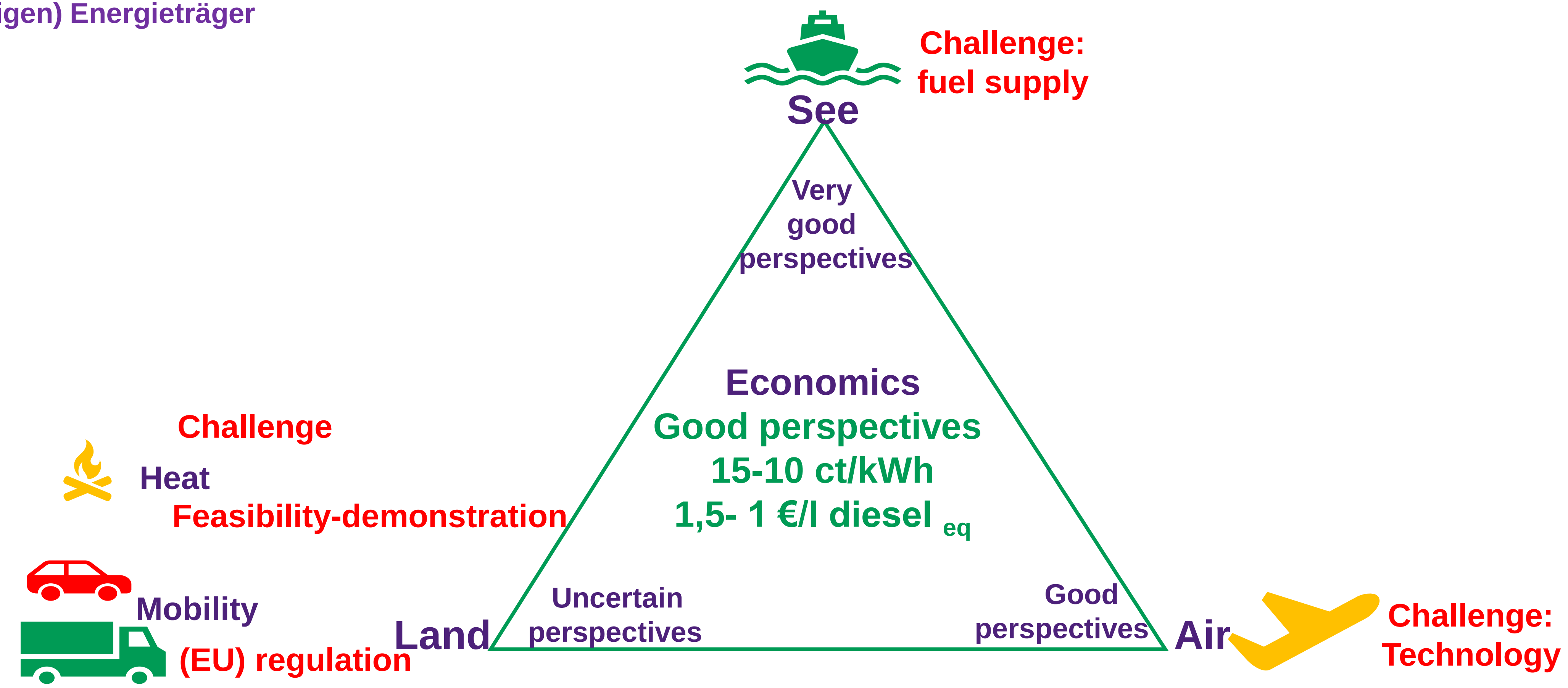
Solutions

- Production of e-gasoline and e-methanol at one of the best spots worldwide for wind energy
- Co-developer Siemens Energy realizing the system integration from wind energy to e-fuel production
- International Partners like Porsche, HIF Global

Synthetische Energieträger
Sackgasse, oder immer noch gute Perspektiven?

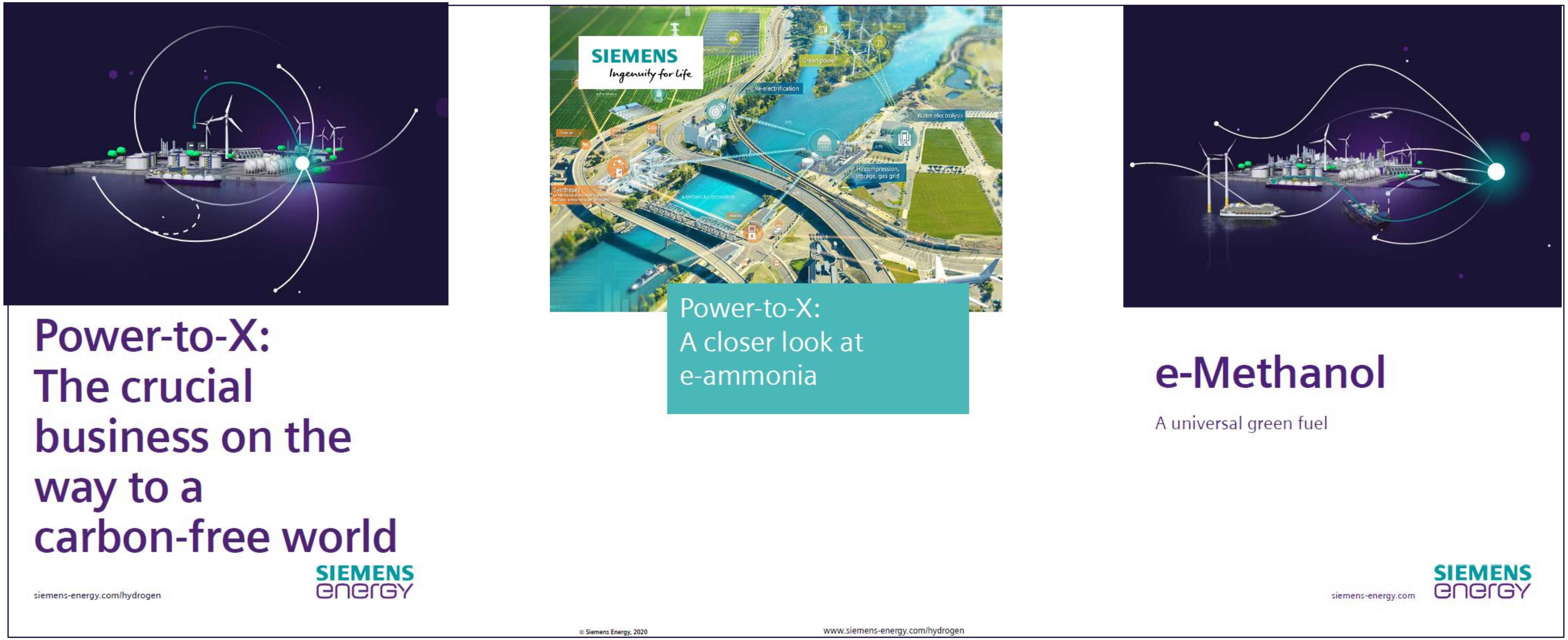
SIEMENS energy

Die neue, auf erneuerbarem Strom basierende weltweite Energieversorgung macht den Einsatz leicht handhabbaren und sicheren Energieträgern und Speichermedien erforderlich. Das sind die mit den existierenden Infrastrukturen kompatiblen synthetischen, (flüssigen) Energieträger



Remark: Additional sector, not considered here is the chemical industry based on methanol –
examples: Formaldehyde, Acetic acid, Olefins, Methylamines, … or ammonia with multiple fertilizer applications

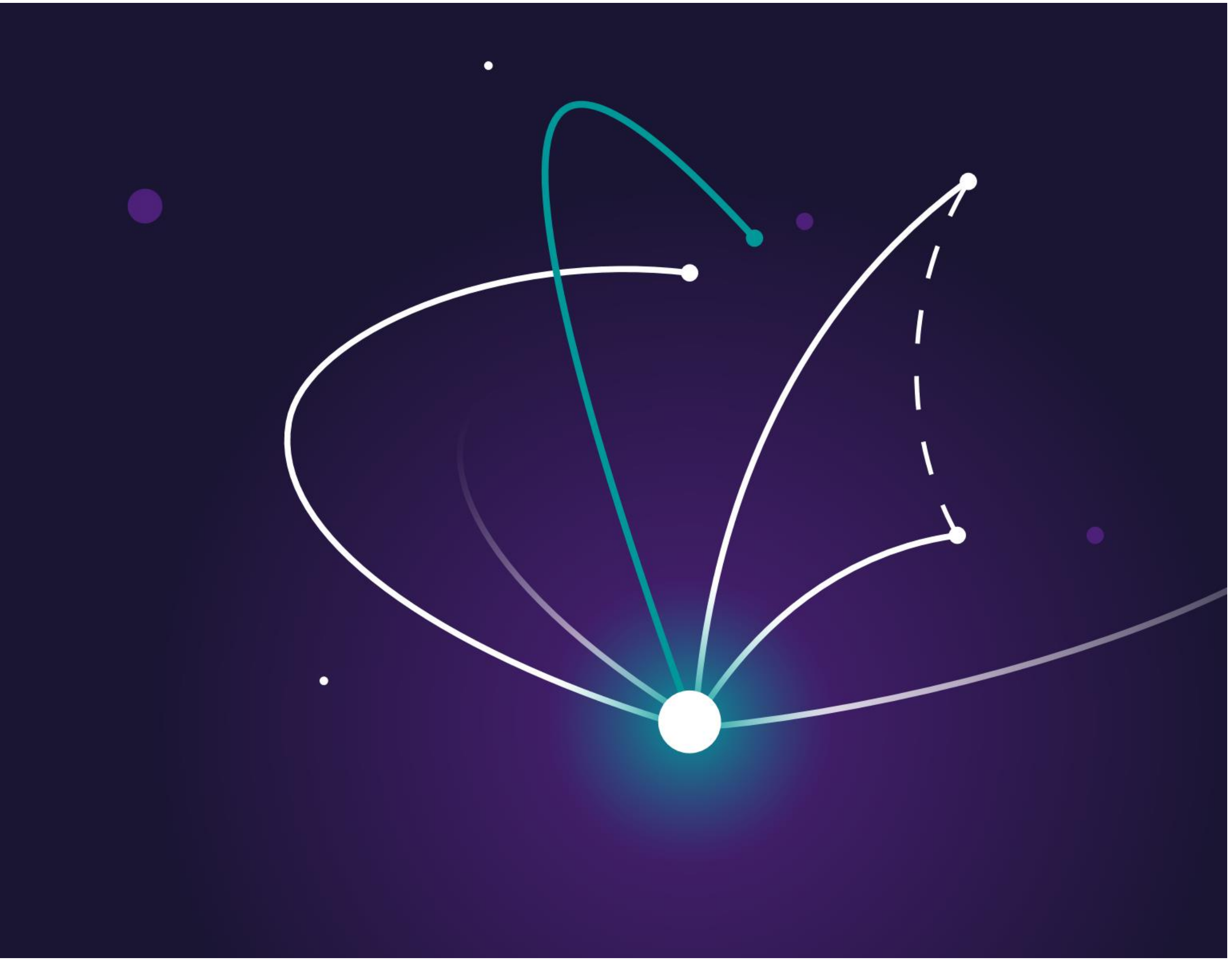
Thanks for your attention
Do you need more details? Please have look



https://www.siemens-energy.com/global/en/offerings/renewable-energy/hydrogen-solutions.html_

https://www.siemens-energy.com/global/en/news/magazine/2020/fuel-from-wind-and-sun.html_

Danke für Ihre Aufmerksamkeit
Kontakt



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