



## **Grüner Wasserstoff soll Realität werden – Verheißung, Potenzial und Perspektive**

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**Prof. Dr. Christopher Hebling  
Director Division Hydrogen Technologies  
Fraunhofer-Institute for Solar Energy Systems, Freiburg, Germany**

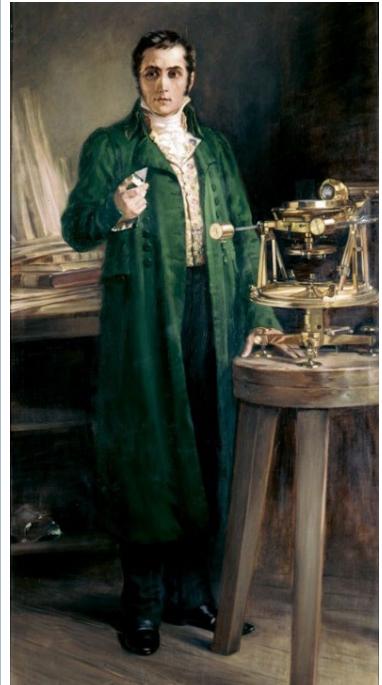
**Klima- und Energiedialog, Heilbronn, 10<sup>th</sup> March 2023**



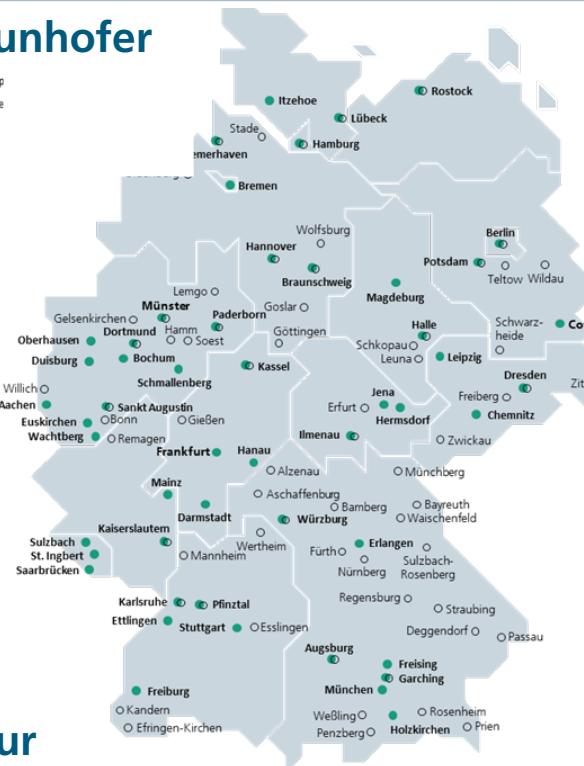
# Fraunhofer-Society (est. in 1949)

76 Institutes – 30.000 staff – € 3 billion revenue – 2 new patents per day

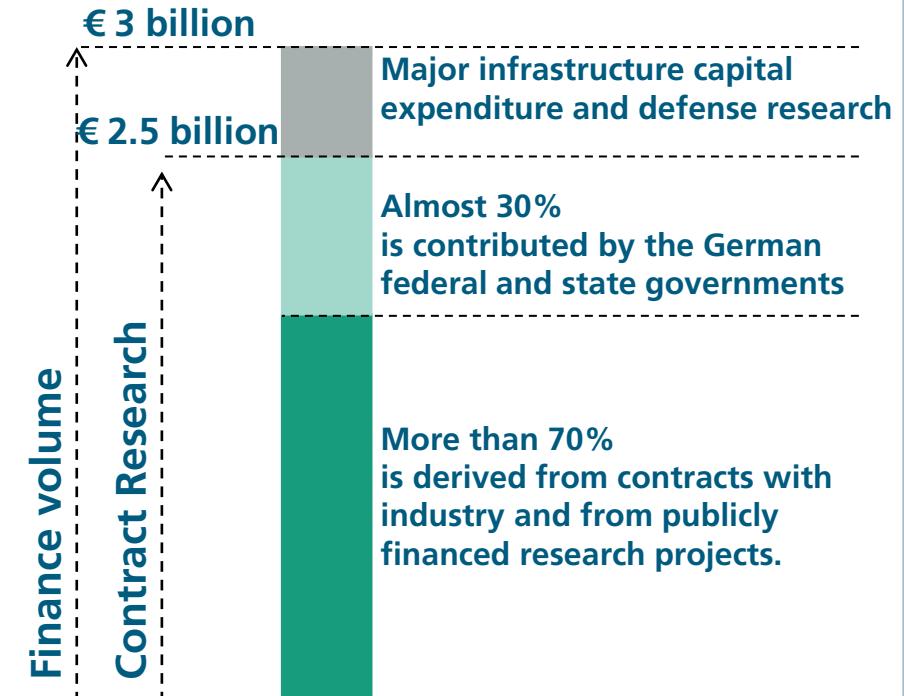
World's leading applied research organization prioritizing key future-relevant technologies and commercializing its findings in business and industry. A trailblazer and trendsetter in innovations and research excellence.



**Joseph von Fraunhofer**  
**1787-1826**



**Researcher - Inventor - Entrepreneur**



# Division Hydrogen Technologies H2T @ Fraunhofer ISE

Defossilization of Transport, Chemicals and Process Heat

150 Scientists and engineers, 15 Mio€ annual budget through contract research



## Sustainable Mobility

Fuel cell cars at the solar hydrogen filling station at Fraunhofer ISE



## Synthetic Fuels and chemicals

Development of catalysts and processes incl. LCA analyses for Power-to-Liquid processes



## Power-to-X Technologies

Water electrolysis as basic technology for renewable fuels;  
Power-to-Gas simulations

# Thermochemical Processes, Sustainable Catalytic Materials

Competence in Methanol Synthesis since 2012

## Test Rigs

Design & construction and operation of test rigs for methanol and DME synthesis

Measurement & control (LabView)

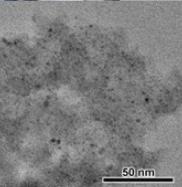
Flexible operation (24/7, etc.)



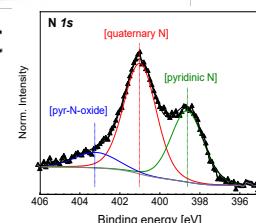
Methanol/DME miniplant with loop, 2013



Catalyst synthesis & characterisation



## Catalyst



Carbon2Chem® methanol miniplant with loop, 2017

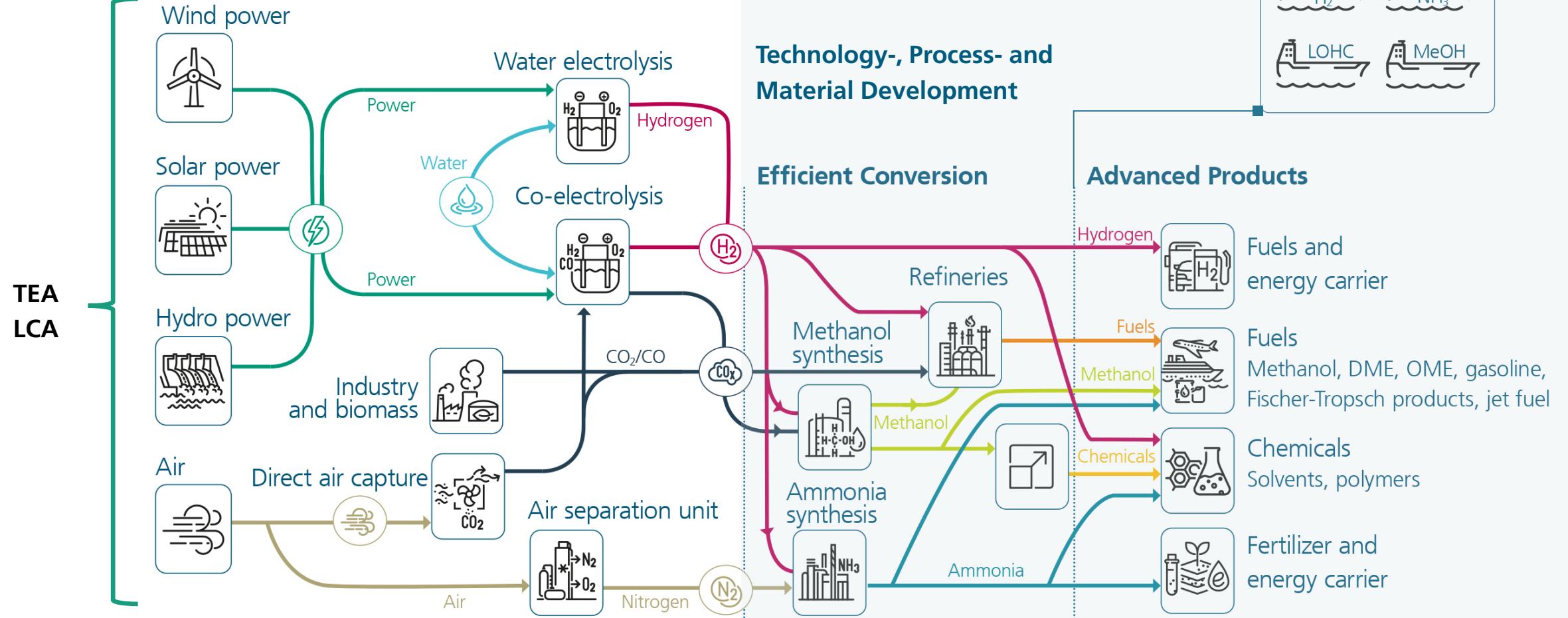


Scale-down test rig for methanol synthesis, 2019



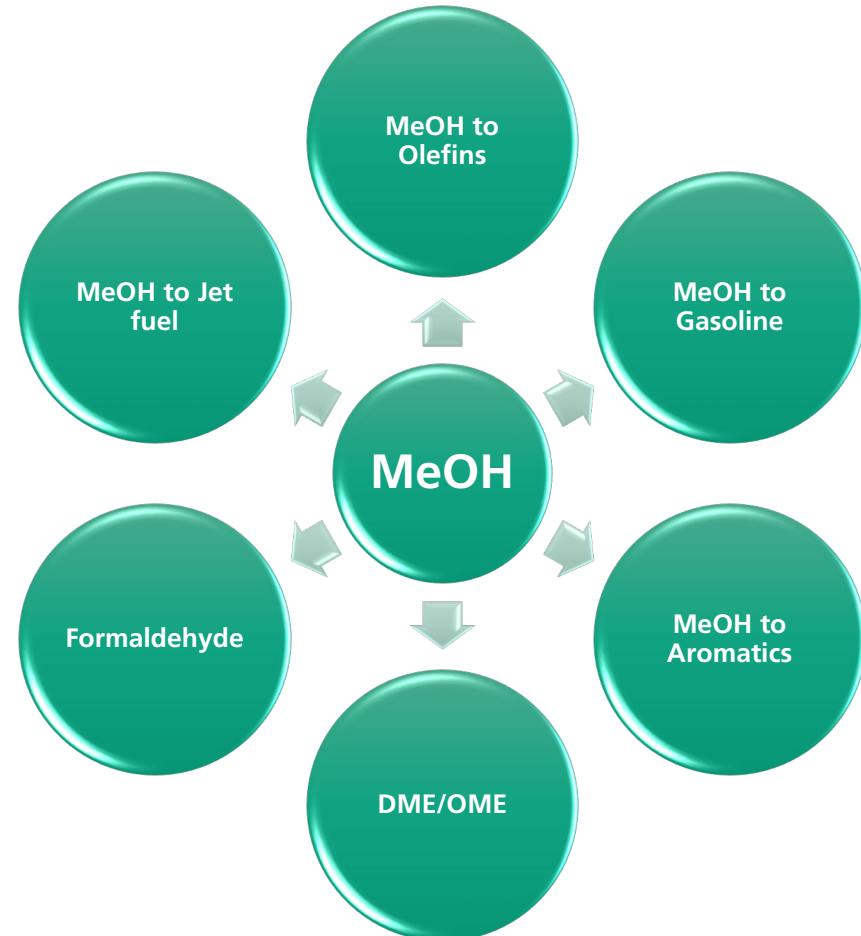
©Chunyip Wong - iStock

# Sustainable Energy Carriers, Fuels and Base Molecules



# Promising Perspective for Methanol

Methanol as Feedstock for Chemical Industry and for all Modes of Transport



## Methanol as a Building Block

- > 100 mio annual tons worldwide production capacity
- Feedstock for Otto & diesel engines and gas turbines
- Feedstock for the chemical industry

# Maersk – Worlds Largest Integrated Logistics Company

Methanol and Ammonia as Preferred Shipping Fuels, Net-Zero by 2040

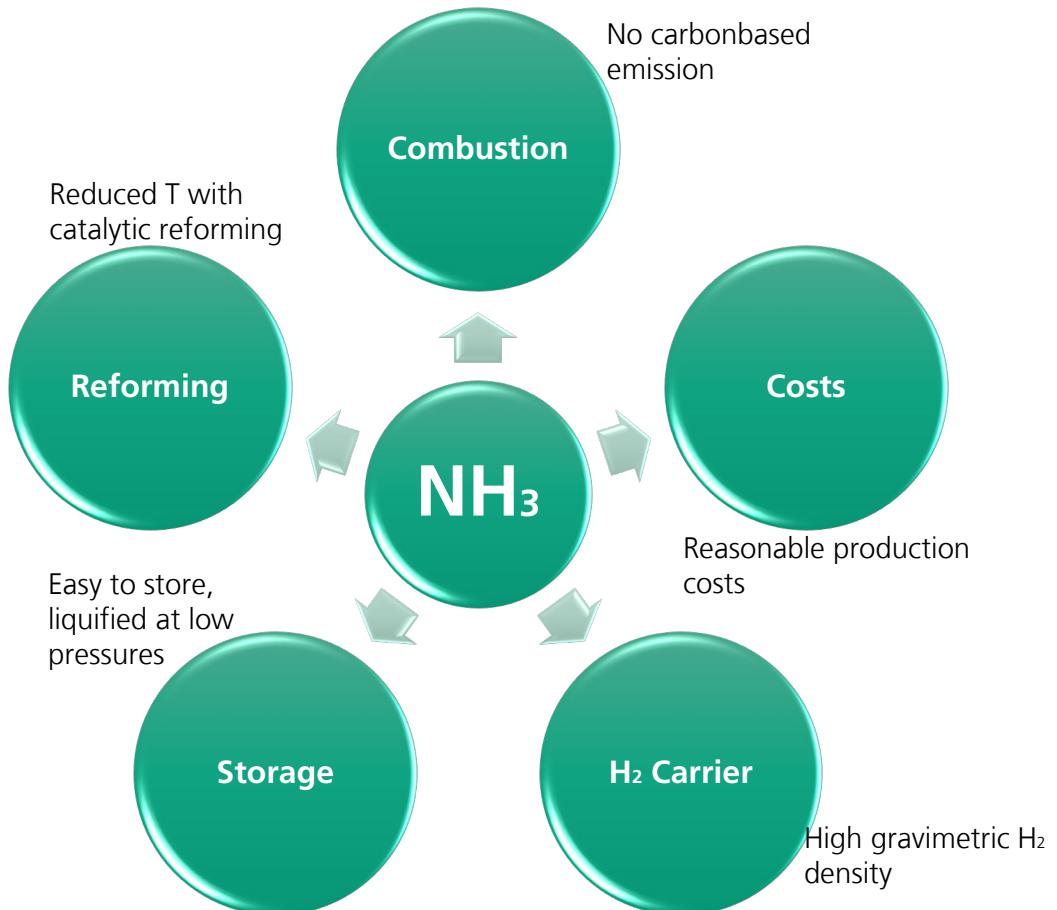
## 19 Green Methanol-Enabled Vessels on Order

- Maersk 3.5 bn t/a direct CO2-emissions
  - »Continued research on priority future fuels (biodiesel, methanol, ligning fuels and ammonia) confirming that net-zero technologies are available.
  - Maersk will not use transition fuels (such as LNG) but leapfrog to fully net-zero fuels.«
- LNG as short-term solution; danger of stranded assets
- »... our first carbon neutral vessel on the water by 2023
  - ... This vessel will be running on carbon neutral methanol
  - ... We consider green ammonia as a promising option for marine fuels and a dual fuel engine for ammonia is under development.«



[1] <https://www.maersk.com/news/articles/2021/02/23/maersk-backs-plan-to-build-europe-largest-green-ammonia-facility> Maersk – leading container shipping company

# Promising Perspective for Ammonia



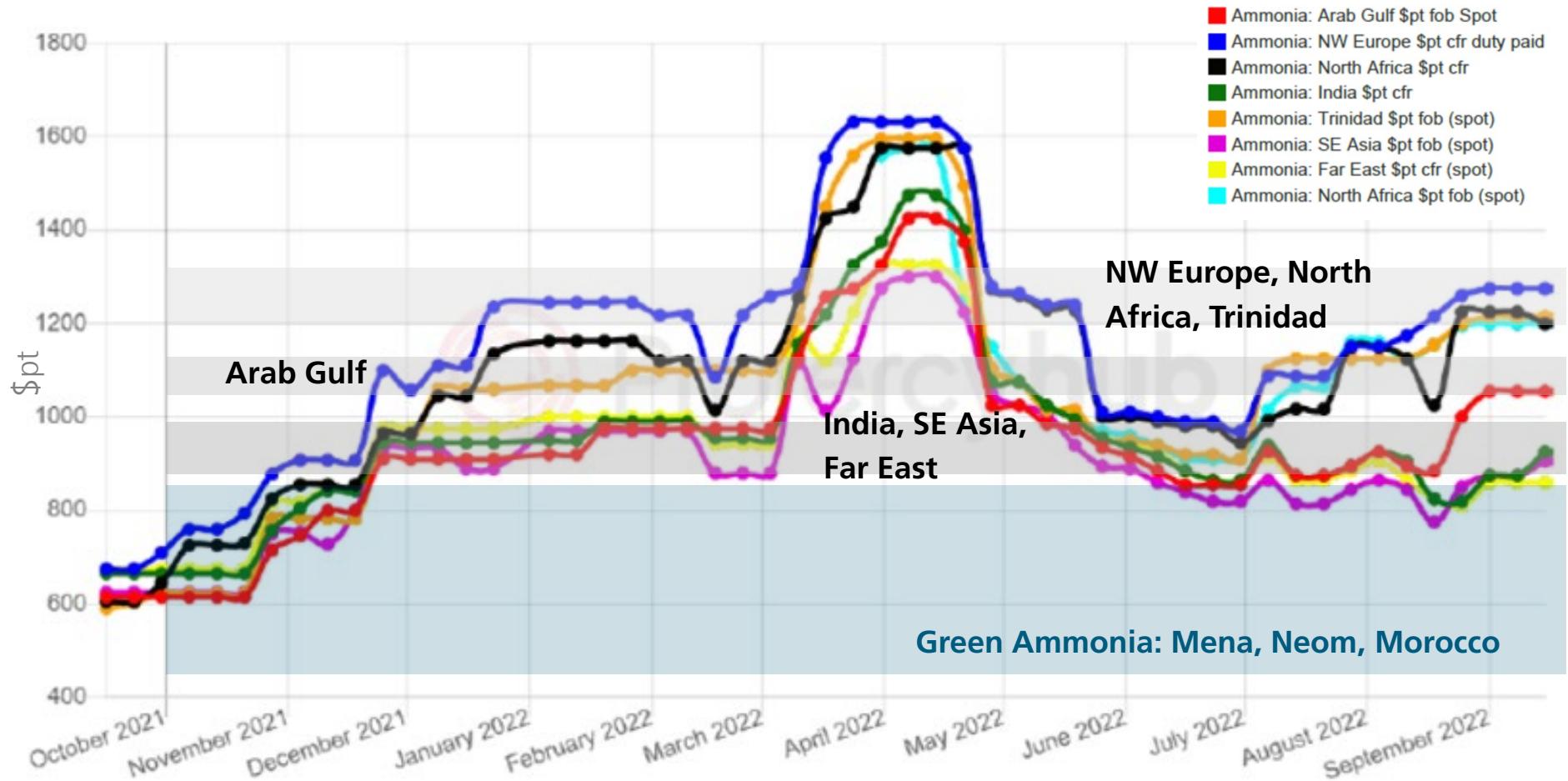
## Increasing Global Ammonia Demand

- Important bulk chemical
- > 160 mio annual tons worldwide production capacity
- Existing infrastructure
- Easy to liquify/store
- High specific energy density 5.18 kWh/kg  
(Gasoline ~ 12 kWh/kg)
- Established pathways to urea, etc.
- No need for CO<sub>2</sub>
- Many ongoing projects worldwide

# Global Ammonia Price

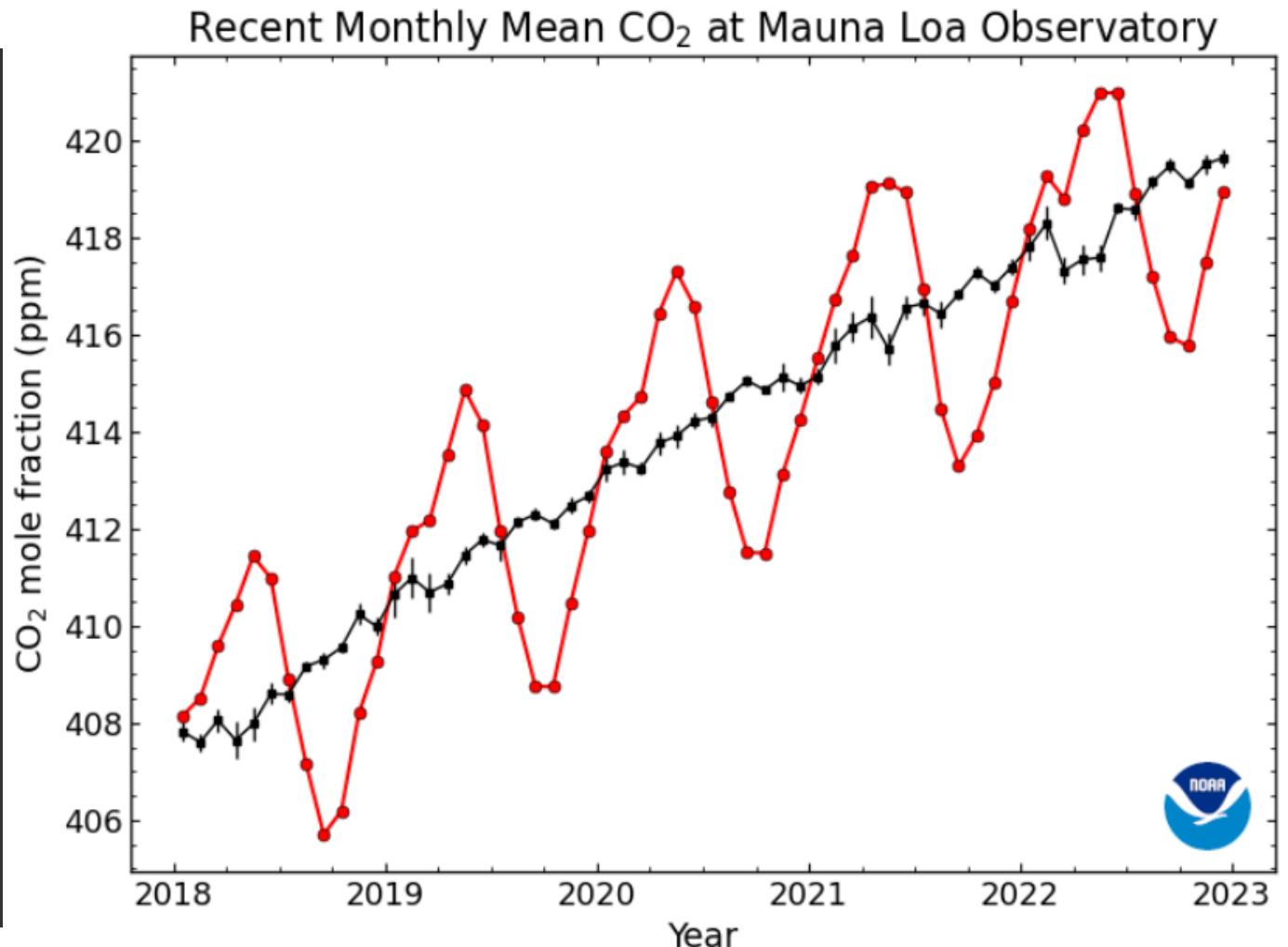
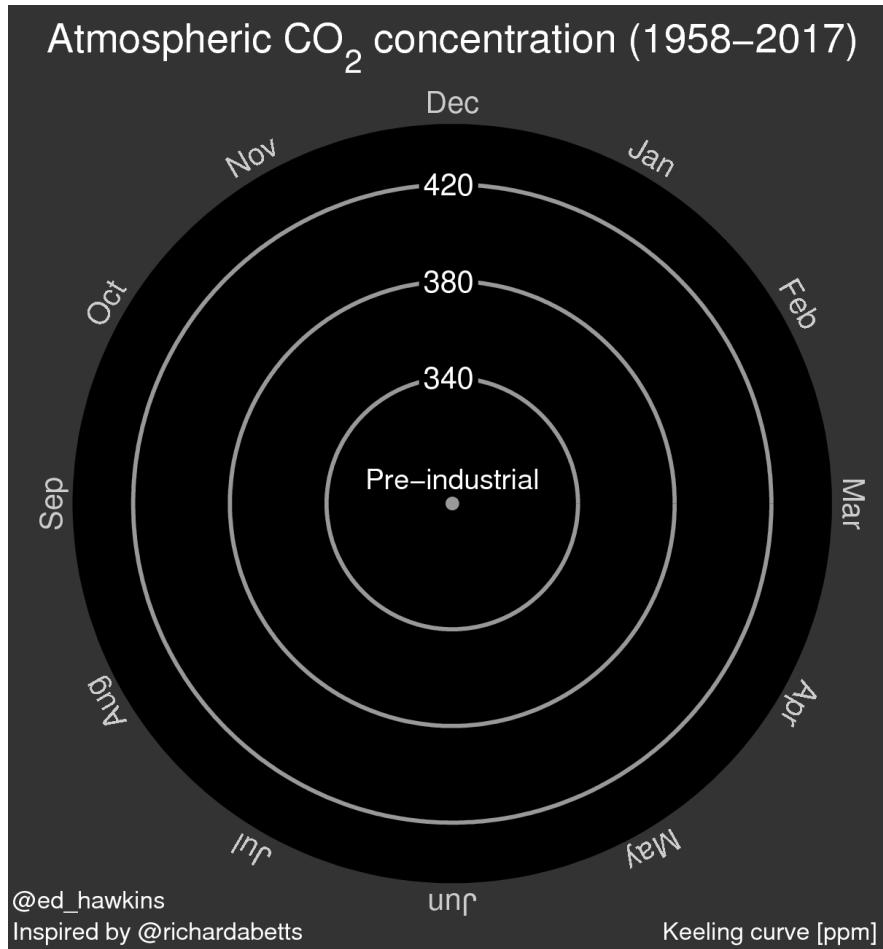
Green Ammonia currently cheaper than conventional Ammonia

Green ammonia in  
MENA from  
**\$ 350/ton** in Neom to  
**\$ 500-700** in Morocco  
and  
**\$ 600-800** in Egypt

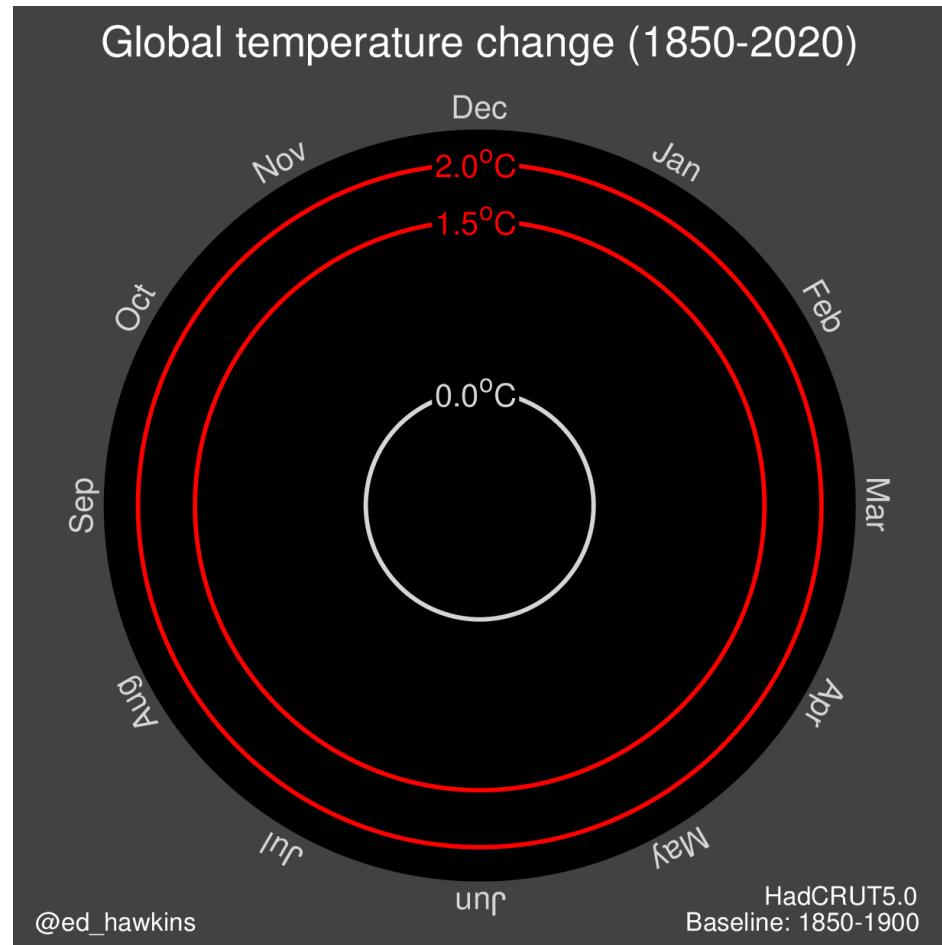
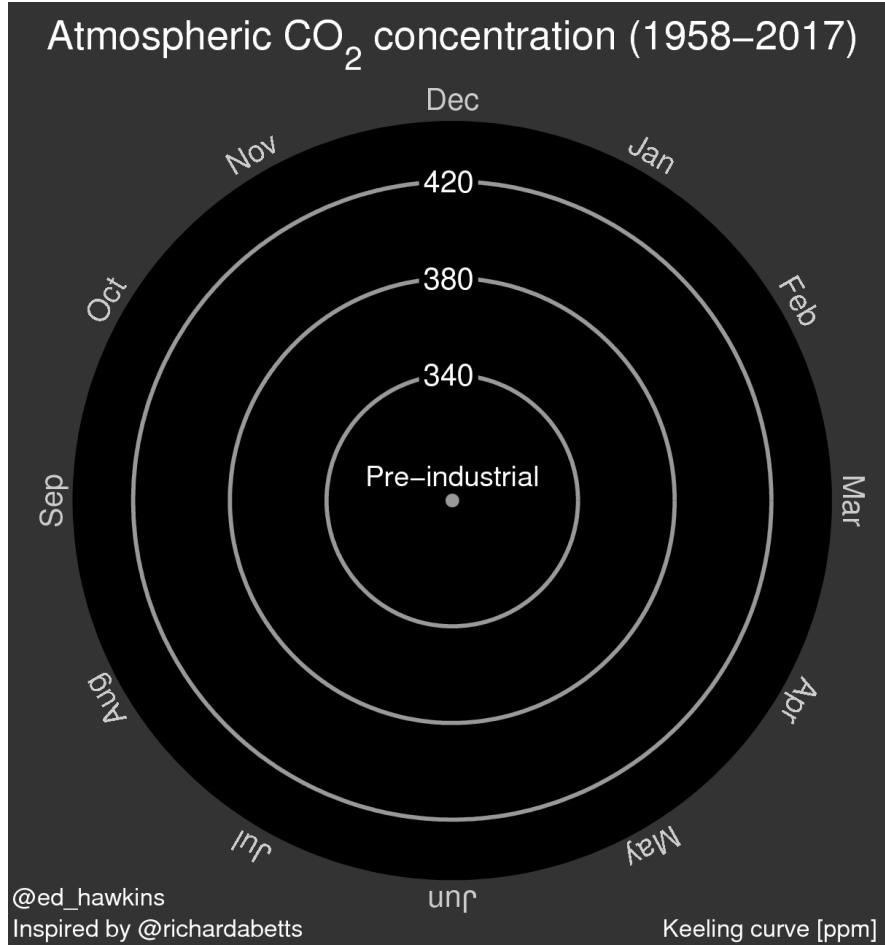


<https://www.profercy.com/2022/09/potential-resumption-of-russian-ammonia-exports-sends-shockwave-through-global-market/ammonia-prices-16-sept-2022/>

# CO<sub>2</sub> Increase and the Resulting Rise of the Temperature



# CO<sub>2</sub> Increase and the Resulting Rise of the Temperature



# Germany's Natural Gas Supply

2021-2022

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# Electricity from Renewables Became Cheaper - Nuclear and Coal did not

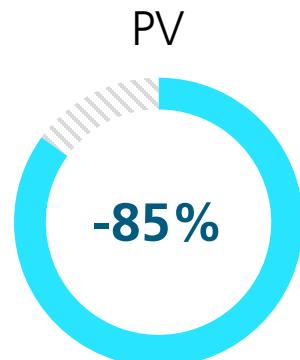
## The global weighted-average LCOE from 2010-2020

Onshore Wind

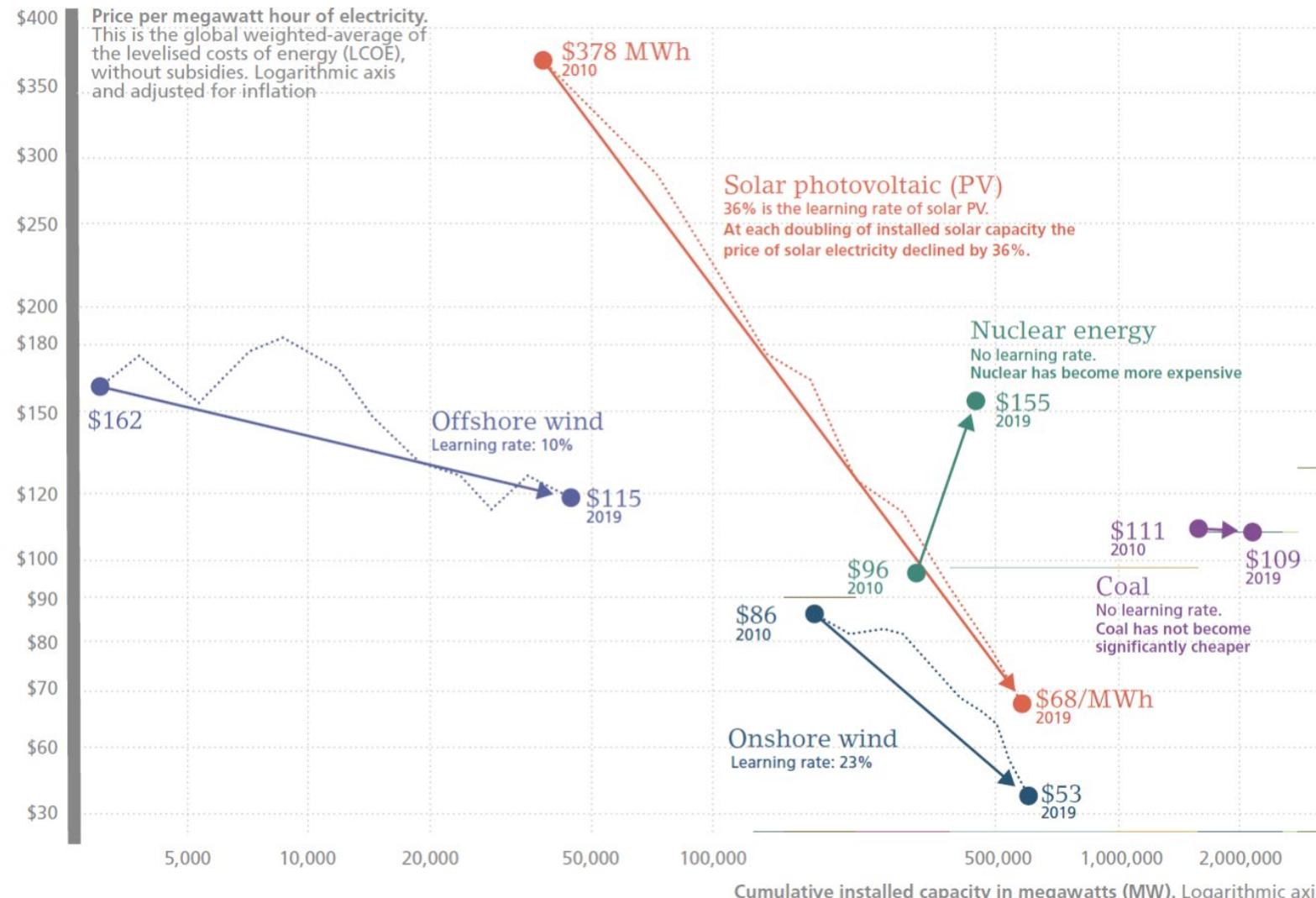


Price fell from  
0.089 to 0.039  
USD/kWh

PV

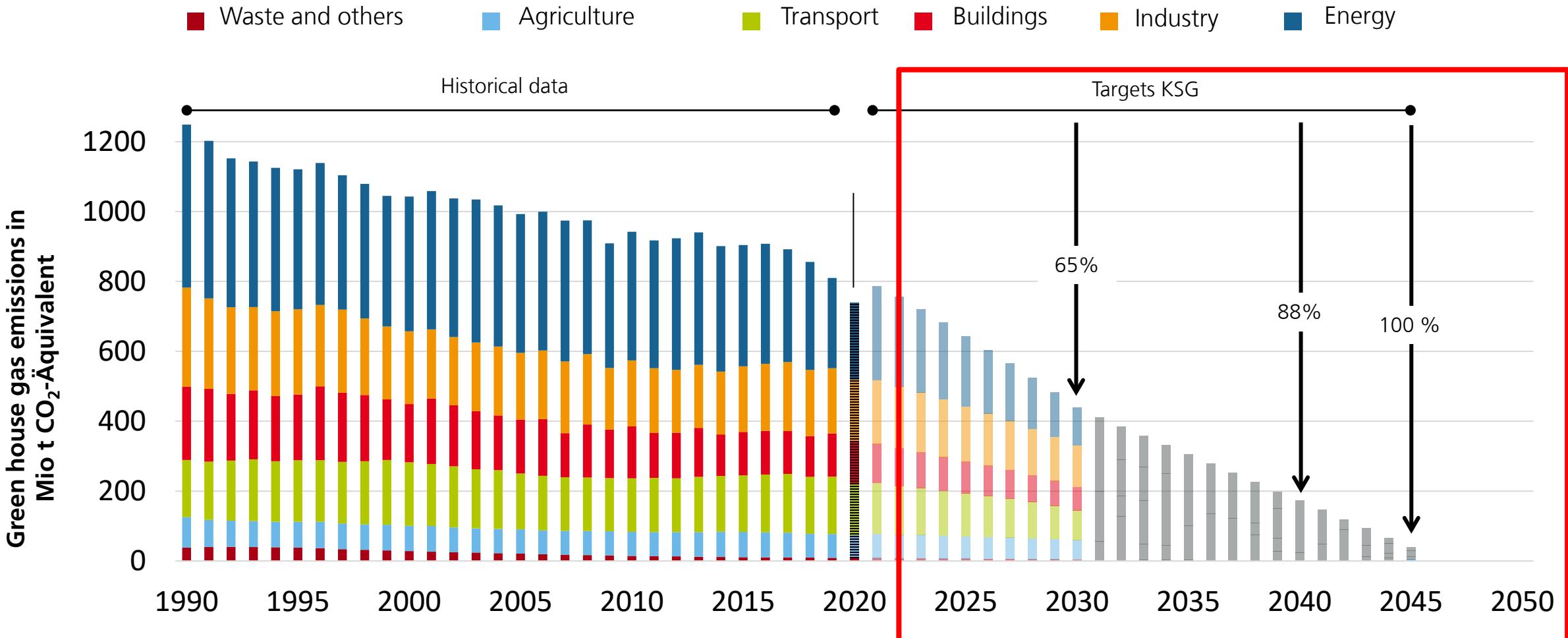


Price fell from  
0.38 to 0.06  
USD/kWh



# Scope of the analysis and its model

## Emission path to climate neutrality in Germany



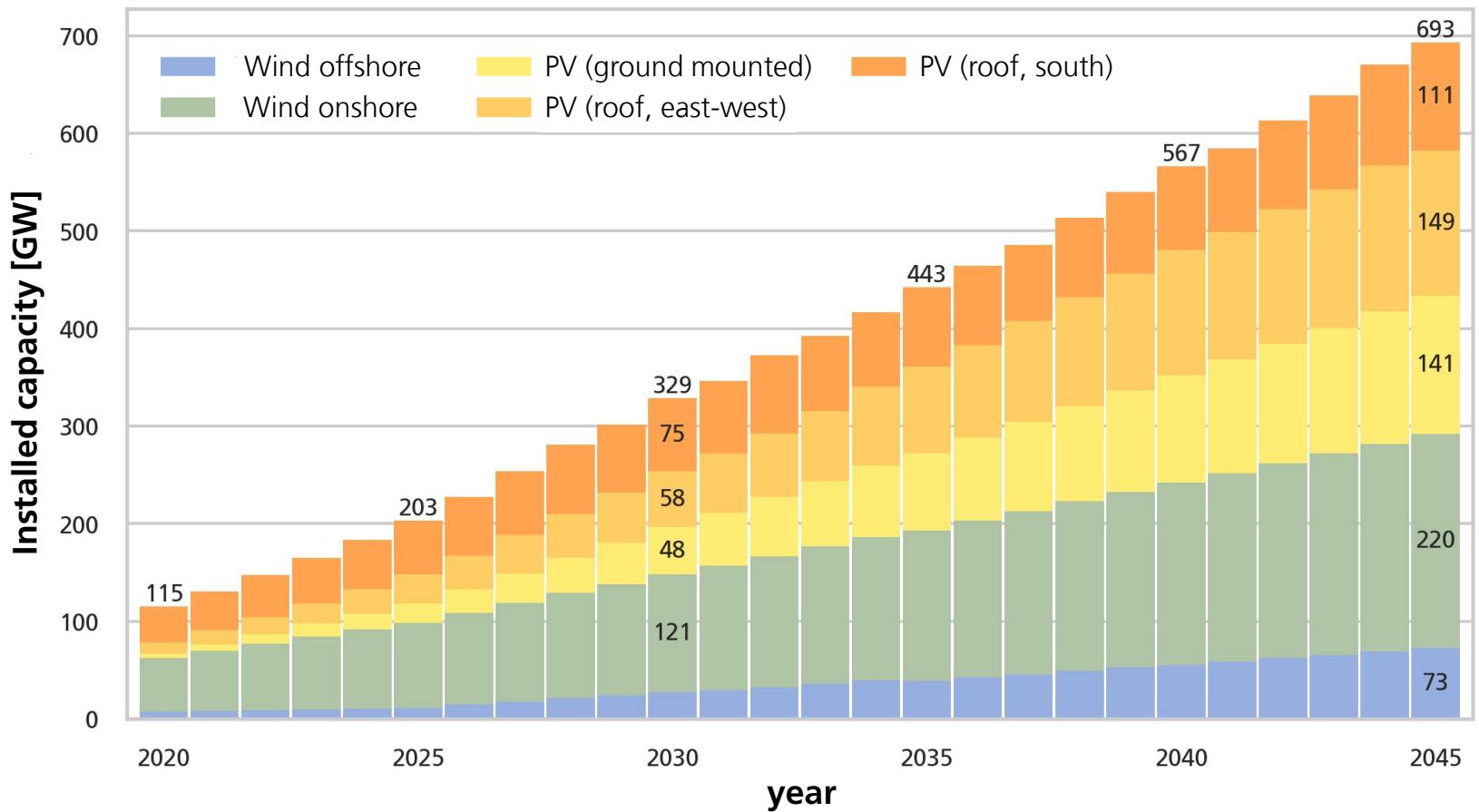
Historische Daten und VJS: Vorjahreschätzung (VJS) der deutschen Treibhausgas-Emissionen für das Jahr 2020. Umweltbundesamt, 15.3.2021

FHG-SK: ISE-INTERNAL

# Energy System Analysis – Results

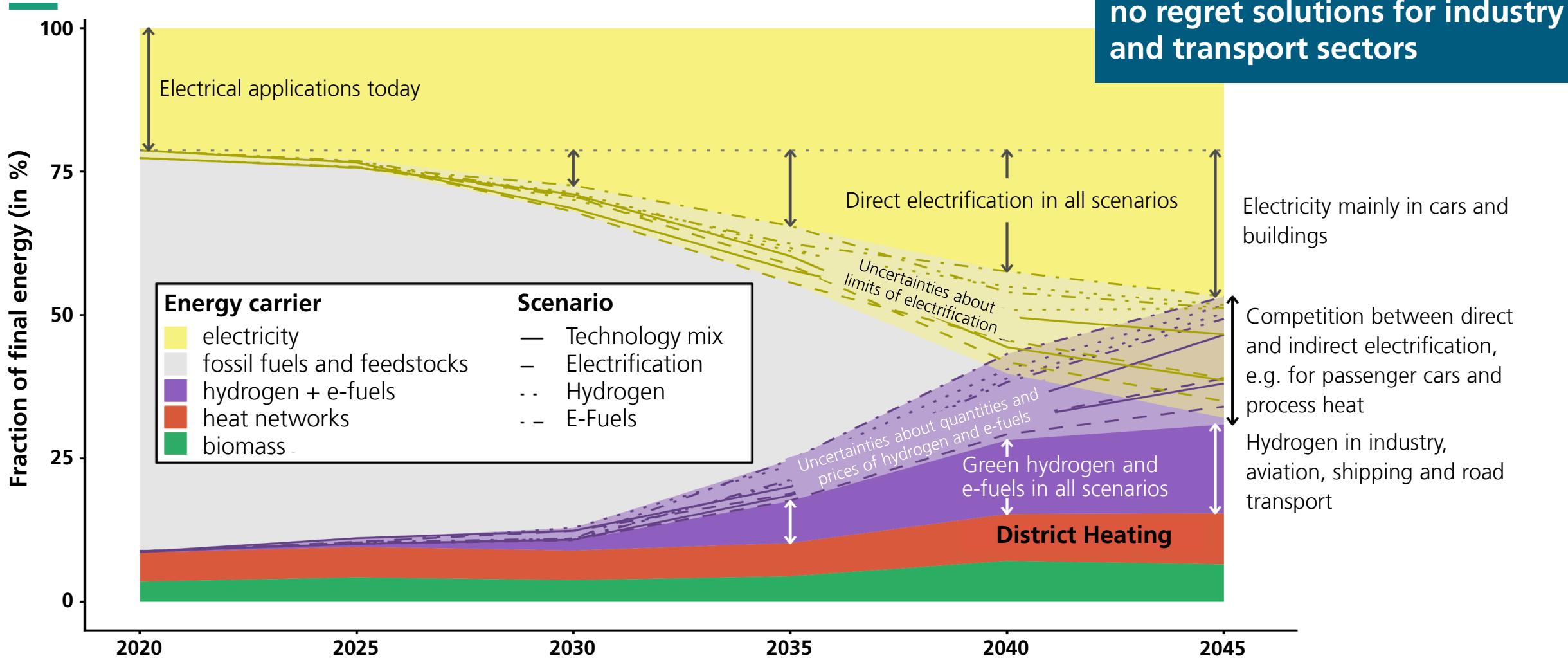
## Installed Capacity of Wind Energy and Photovoltaic Systems in Germany by 2045

- **Solar and Wind** become the pillars for energy supply
- **Strong expansion necessary** to meet rising electricity demand and reduce consumption of fossil fuels
- **Installed power 2030:**
  - 181 GW photovoltaics
  - 121 GW wind onshore
  - 27 GW wind offshore



# Energy System Analysis for Germany

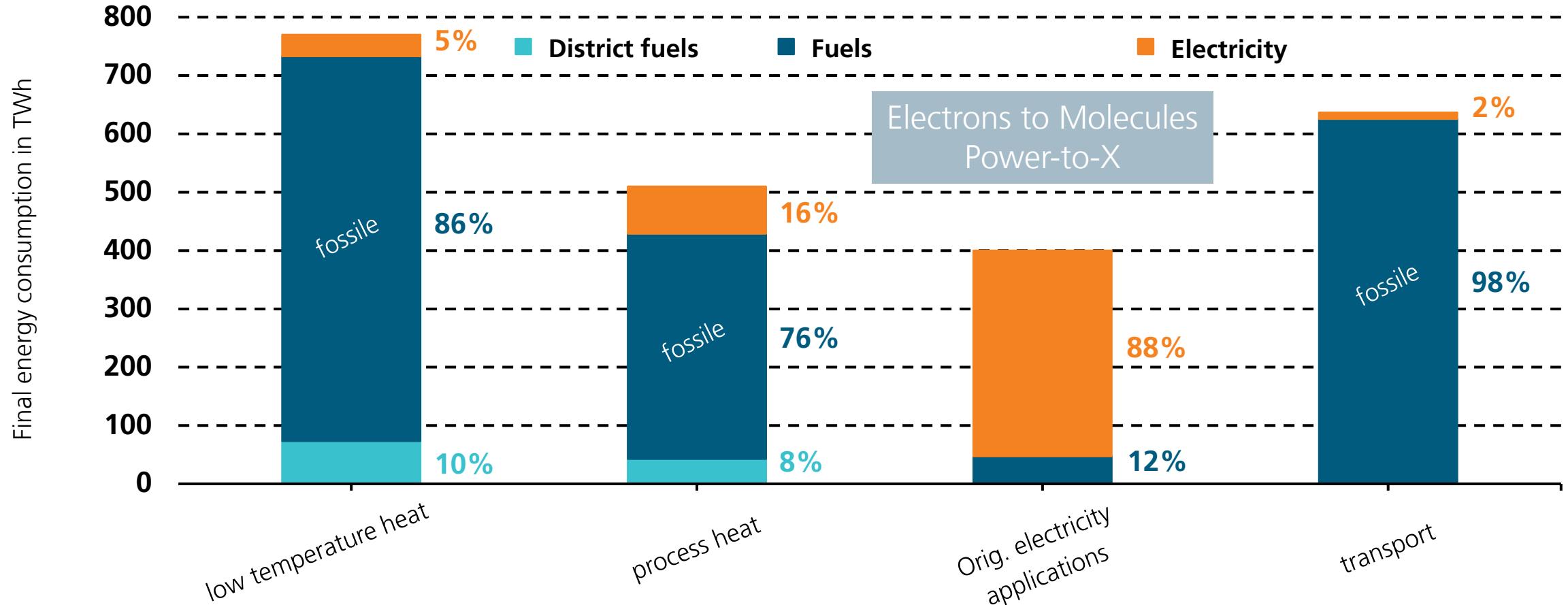
Final energy: Direct vs. Indirect Electrification



<https://ariadneprojekt.de/publikation/eckpunkte-einer-anpassungsfähigen-wasserstoffstrategie/>

# Energy System Analysis for Germany

## »Sector Coupling« - The Next Phase of the Energy System Transformation

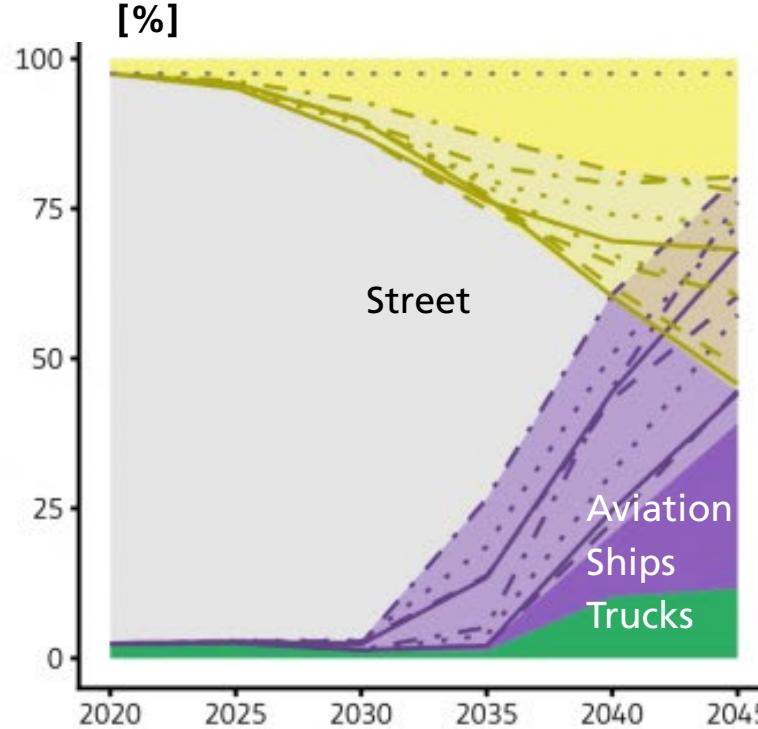


# The Role of Hydrogen

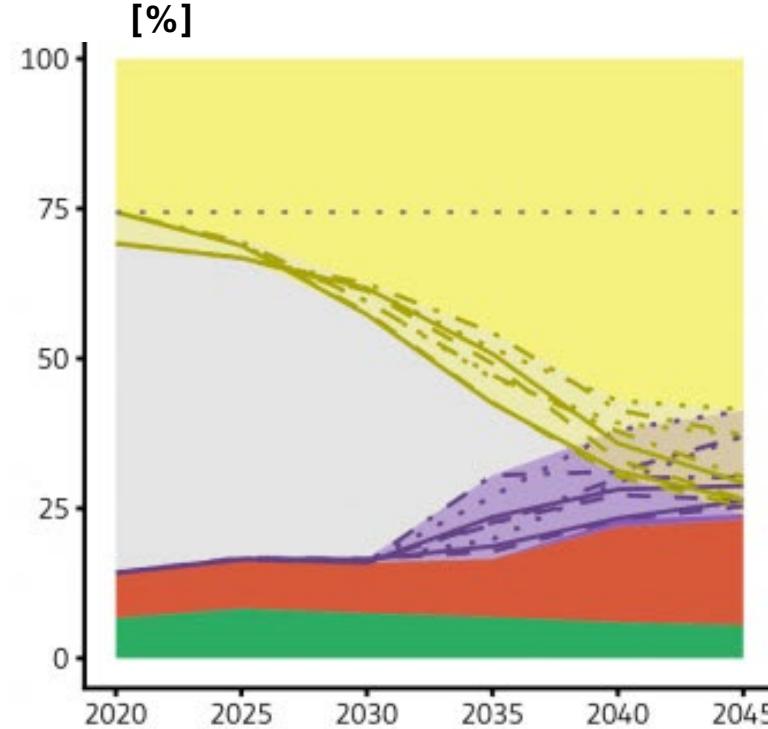
Share of Hydrogen in the End Energy in Various Sectors in %

Energy carrier	Scenario
electricity	— Technology mix
fossil fuels and feedstocks	- Electrification
hydrogen + e-fuels	.. Hydrogen
heat networks	-- E-Fuels
biomass	

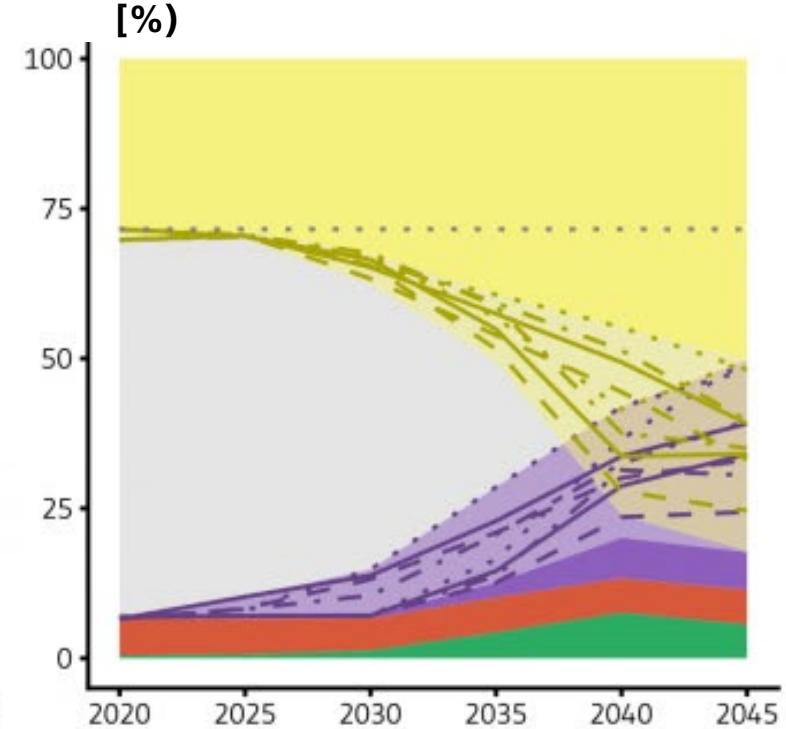
Traffic



Buildings



Industry



Uncertainty about the role of hydrogen in process heat and heavy-duty traffic

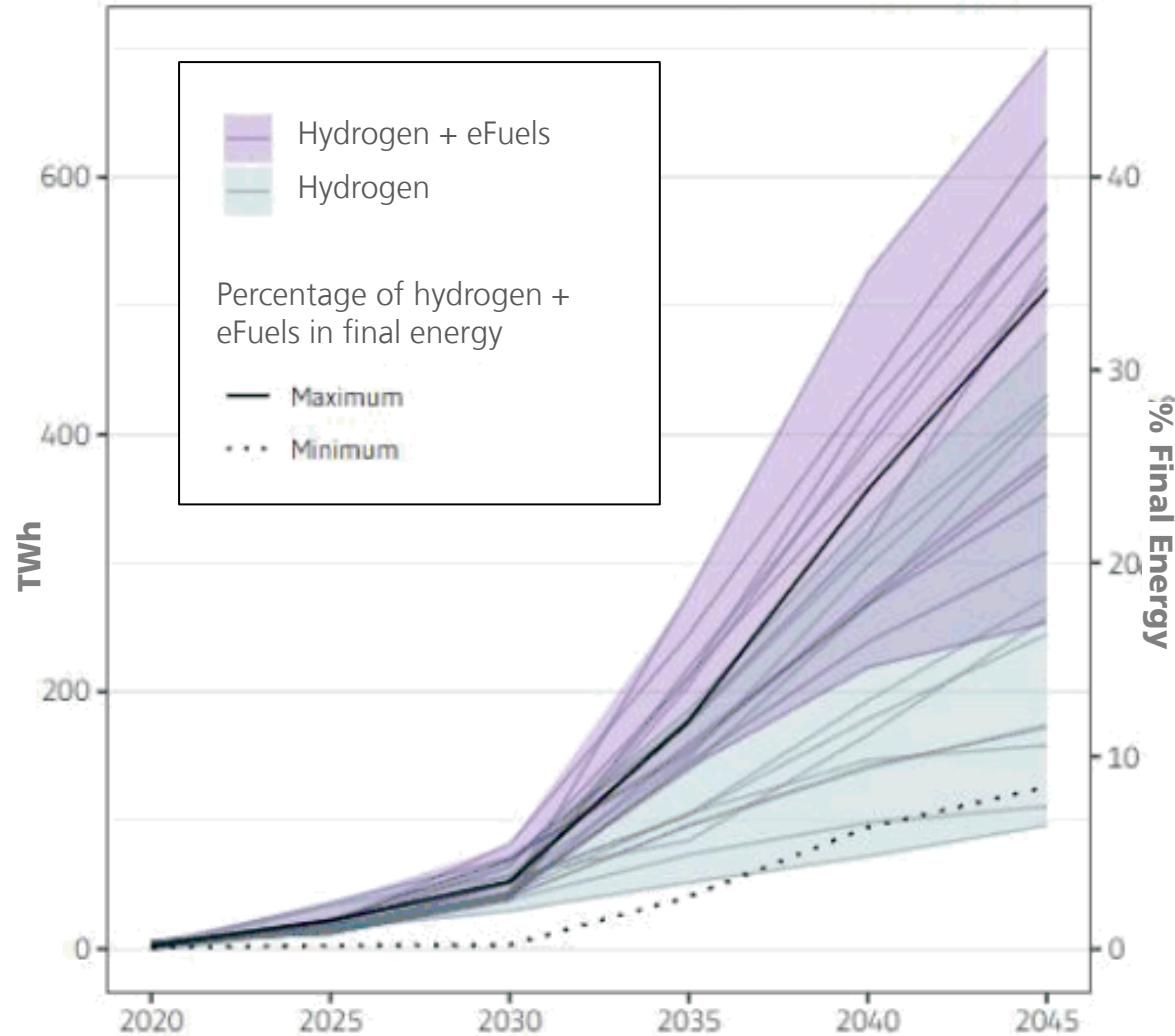
Quelle: F. Ueckert et al., Positionspapier Wasserstoff, Ariadne 10/2021

# Demand for Hydrogen and eFuels in Germany

## Results Systems Analysis (Ariadne Project)

- Demand of hydrogen and eFuels in Germany ranges between **250 and 700 TWh in 2045**
- The scenario-analysis of Ariadne project illustrates:
  - Until 2030, the use of H<sub>2</sub> and eFuels still limited
  - Role of hydrogen and eFuels may vary heavily depending on the future climate strategy and the extend of electrification measures.
- **“No-regret”- Options for almost all scenarios are the energetic and material use of H<sub>2</sub> and eFuels in the industry (steel, ammonia, petro-chemicals), aviation, shipping and trucks.**

Demand for H<sub>2</sub> and eFuels in Ariadne-Scenarios

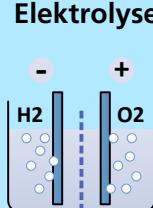
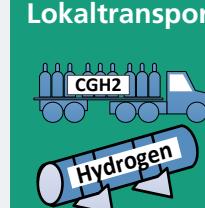
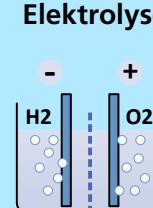
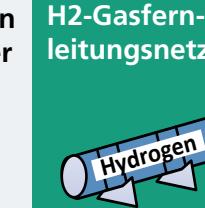
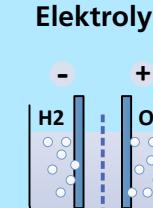
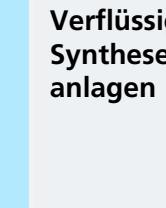


# 40 National Hydrogen Roadmaps, Strategy Papers and R&D Programms (2023)

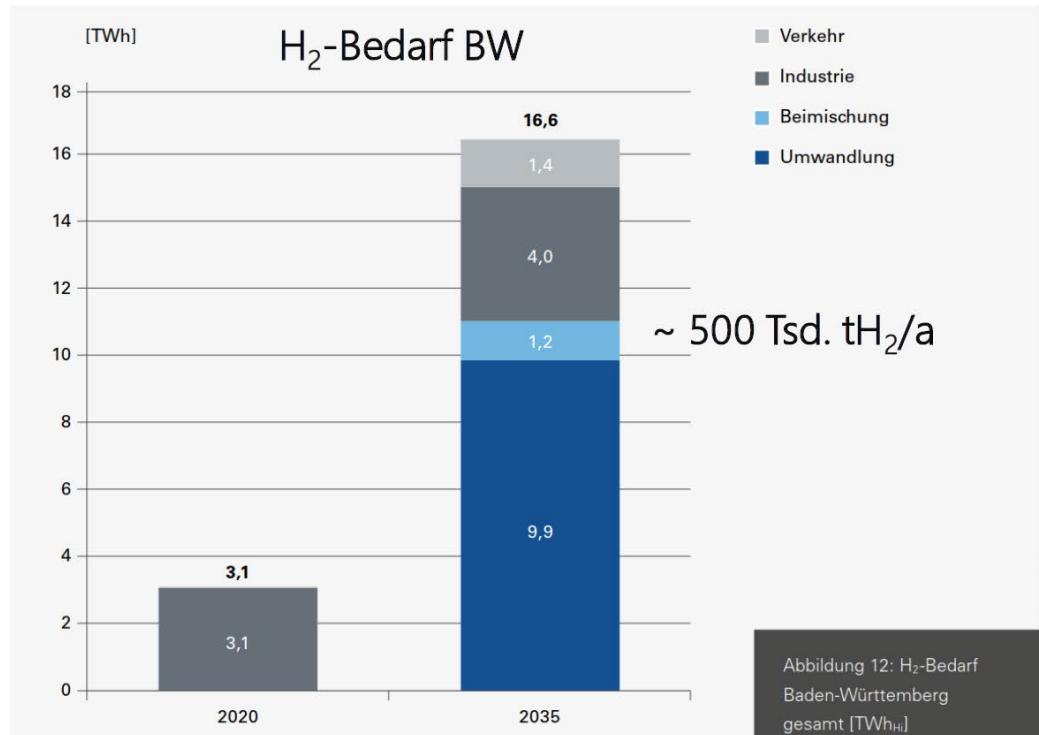


[https://de.wikipedia.org/wiki/Datei:BlankMap-World\\_gray.svg](https://de.wikipedia.org/wiki/Datei:BlankMap-World_gray.svg)

# Time Scale – Availability of H2

	Das regionale H2-Ökosystem			Nationale H2-Wirtschaft			INTERnationaler H2-Import		
Technologie	Elektrolyse 	Lokale Gasspeicher 	Lokaltransport 	Elektrolyse 	Netzgebundener Gasspeicher 	H2-Gasfernleitungsnetz 	Elektrolyse 	Verflüssiger / Syntheseanlagen 	Internationale Verschiffung 
Typische Größe	2 – 30 MW	1 – 2 Tage Vorrat	Verteilnetz	50 - 500 MW	Saisonaler Speicher	Innerdeutsche Transfernetz	> 1000 MW	Große Chemieanlage	Bspw. 5000 t pro Schiff
Geschätzte Bauzeit	2 - 3 Jahre	< 1 Jahr	< 1 Jahr bis wenige Jahre	< 5 Jahre	Neubau 10 Jahre	Wenige Jahre	< 5 Jahre	tbd	Weniger Jahre
Offene techn. Fragen	Keine offenen Fragen	Keine offenen Fragen	Keine offenen Fragen	Scale-Up noch nicht durchgeführt	Keine offenen Fragen	Gasreinheit Ausspeisung unklar	Scale-Up noch nicht durchgeführt	Scale-Up noch nicht durchgeführt	Keine Energieimporte vor 2030. (siehe Folgefolie)
Umsetzungserfahrung	Diverse Umsetzungen	Diverse Umsetzungen	Stand der Technik	Förderung für Projekte sind ausgelobt	Erste Demo bewilligt, sonst aktuell nur Visionen!	Erste Demo bewilligt, sonst aktuell nur Visionen!	Erste Demo über H2Global (Ca. 1 Mia. Fördergeld)	Erste Demo über H2Global (Ca. 1 Mia. Fördergeld)	Erste Demo über H2Global (Ammoniak?)

# H<sub>2</sub>-Demand in Baden-Württemberg



Elektrolyseleistung  
58 MW  
(geplant und in Betrieb)

9.100 MW  
(benötigt)

Quelle: Plattform H2BW; Analyse der aktuellen Situation des H<sub>2</sub>-Bedarfs und -Erzeugungspotenzials in Baden-Württemberg; 28.04.2022



# Criteria for H<sub>2</sub>-Utilization

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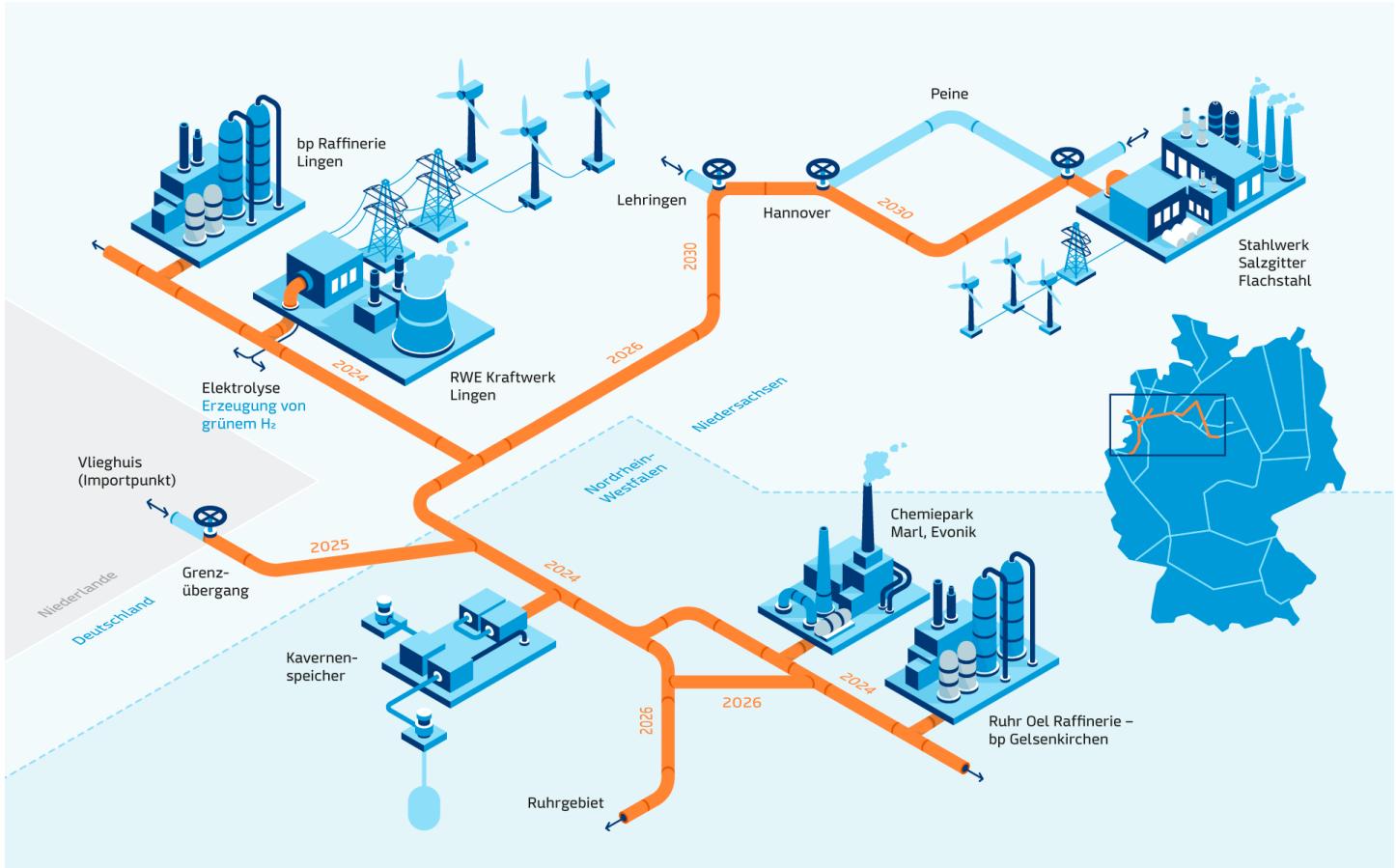
- CO<sub>2</sub>-Vermeidungseffizienz – Merit Order ( $t_{CO_2}/MWh_{H_2}$  und  $MWh_{elEE}$ )
- CO<sub>2</sub>-Vermeidungskosten – Merit Order ( $t_{CO_2}/\epsilon_{Invest}$  und  $t_{CO_2}/\epsilon_{OPEX+CAPEX}$ )
- CO<sub>2</sub>-Vermeidungspotential (absolut) - Marktgröße / Hebel
- CO<sub>2</sub>-Vermeidungspotential (Produktionsstandort)
- Geschwindigkeit (Beitrag zum schnellen H<sub>2</sub>-Hochlauf)
- Nachhaltigkeit Dekarbonisierungs-Pfad
- Alternativlosigkeit des Wasserstoffs
- Sektorkopplungsfunktion / Systemdienlichkeit
- Bedeutung für Wirtschaftsstandort
- ....

# Hydrogen Infrastructure

How does an integrated hydrogen economy look like?

## Grüner Wasserstoff in der Zukunft:

- Überregionale Wasserstoff-Netze
- Vernetzung über Landesgrenzen hinweg
- Import grüner Wasserstoff
- Große und sehr kostengünstige saisonale Speicherung (Kavernen)
- Große (und kleine) Verbraucher



Quelle der Abbildung: GetH2-Initiative; <https://www.get-h2.de/umsetzung/>; abgerufen am 03.05.2022

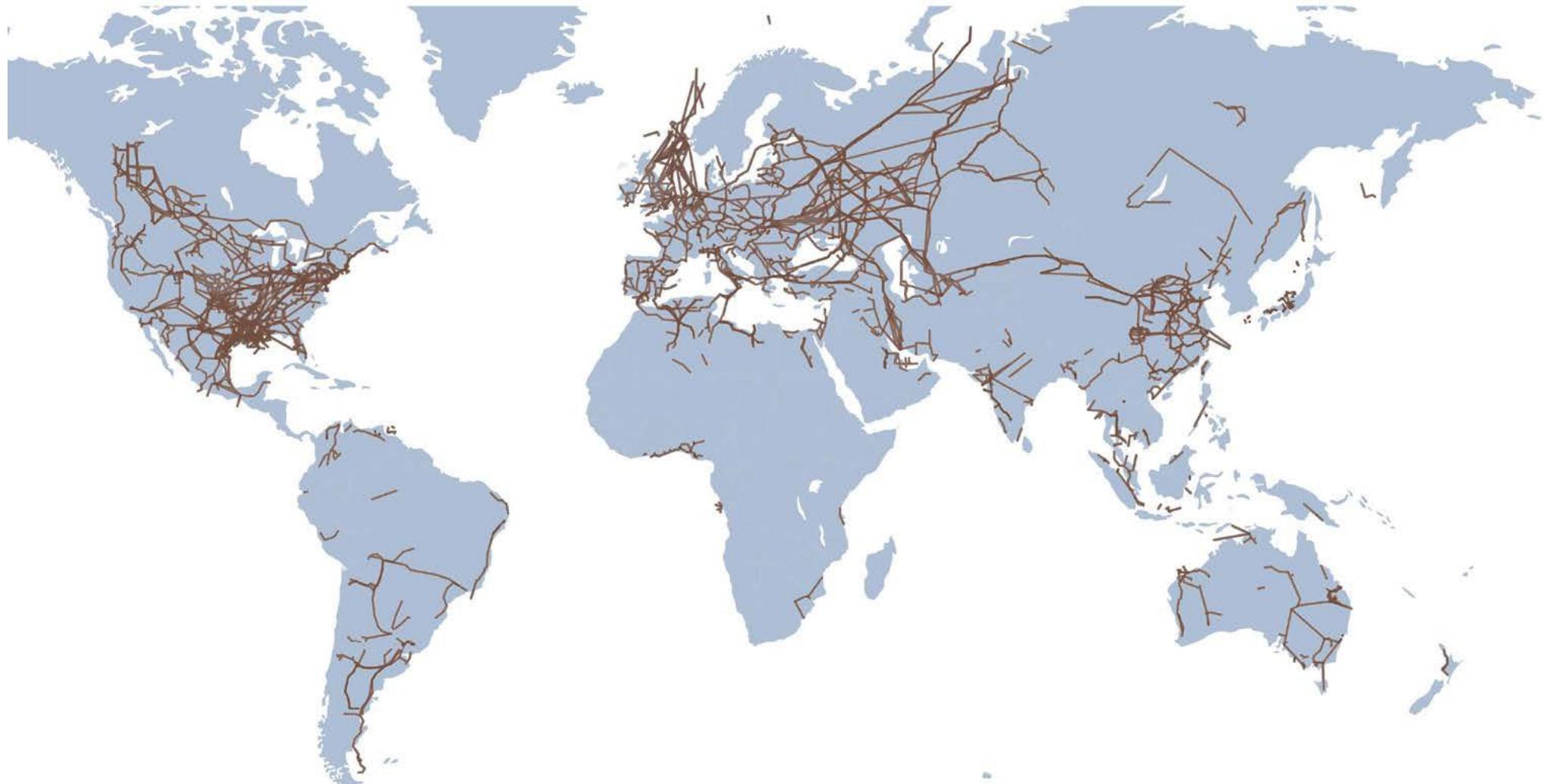
# Sustainable Energy Carriers

## An Expanding Network of Hydrogen Trade Routes, Plans and Agreements

- EU "Fit for 55", **RePowerEU**
- **Inflation Reduction Act**, USA
- **Reforming carbon markets & pricing**
  - Emission Trading System, ETS
  - Energy Taxation Directive, ETD
  - Carbon Contracts for Difference, CCD
- **H2Global Foundation** - fostering production and use of green hydrogen
- Trackable, tradeable, transparent and trustworthy **guarantees of origin** (GO)
- **Energy sovereignty** and **system resilience** become central fields for energy strategy

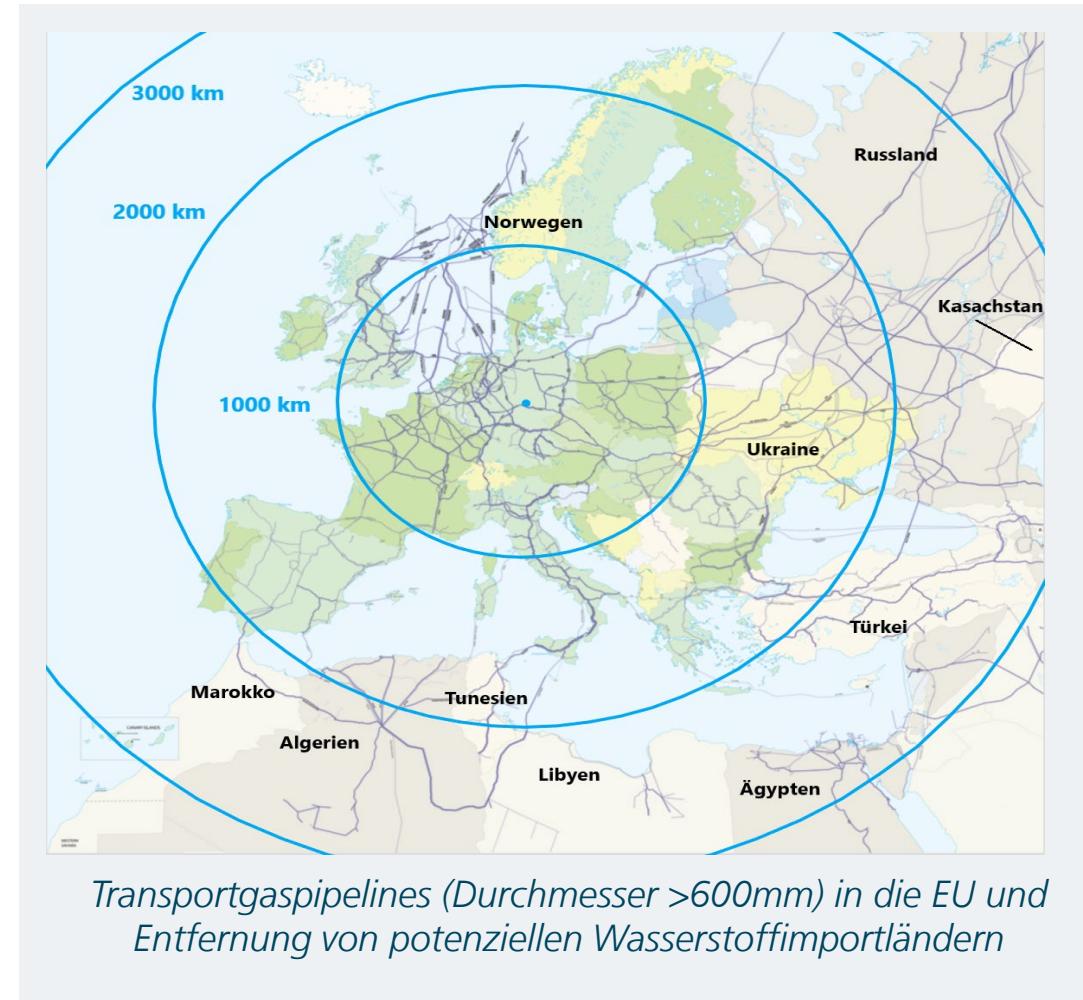


# Global Map of Natural Gas Transmission Pipelines



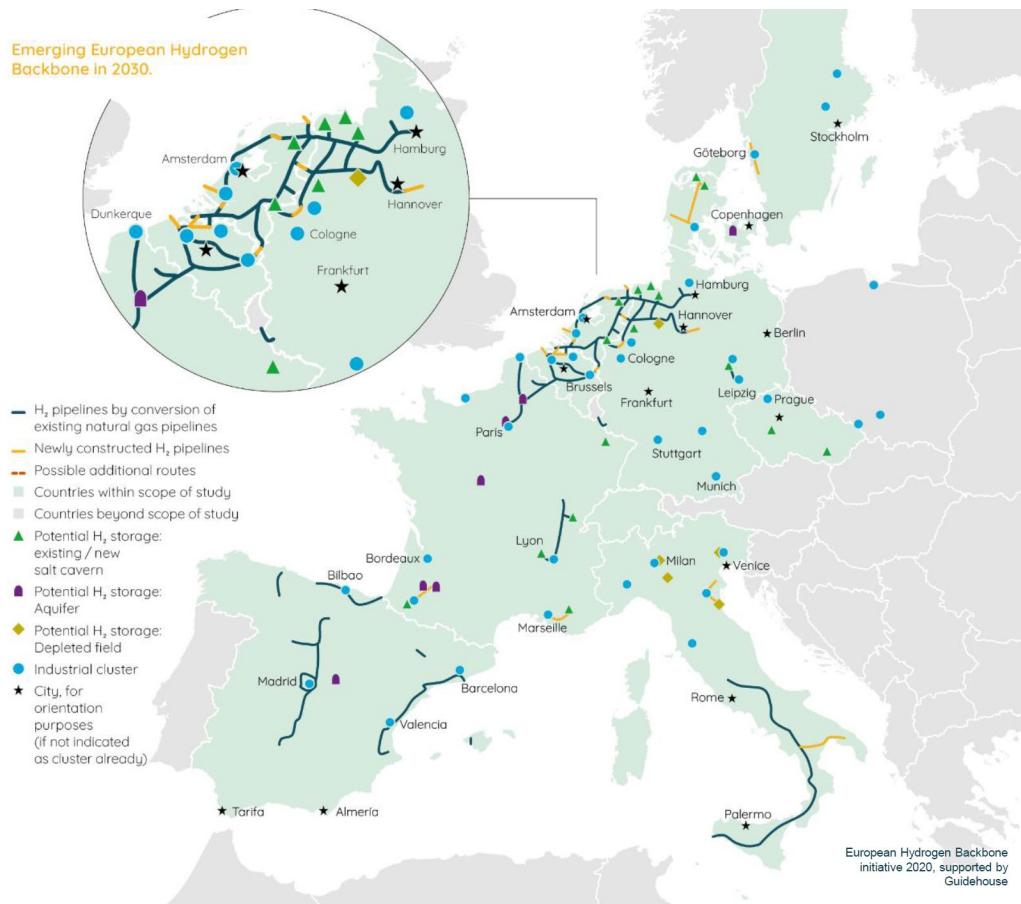
# Diversified Hydrogen Supply by Partner Countries in Different Regions

- Pipeline supply (1000-3000km):
- Russia: large potentials but not useable for long time
- North Africa and MENA region
  - **Positive:** Technical availability, within reach to EU, pipelines available
  - **Critical:** political reliability, values, sustainability
- **Diversification** of supply countries increases import costs, but decreases economic risks due to dependencies

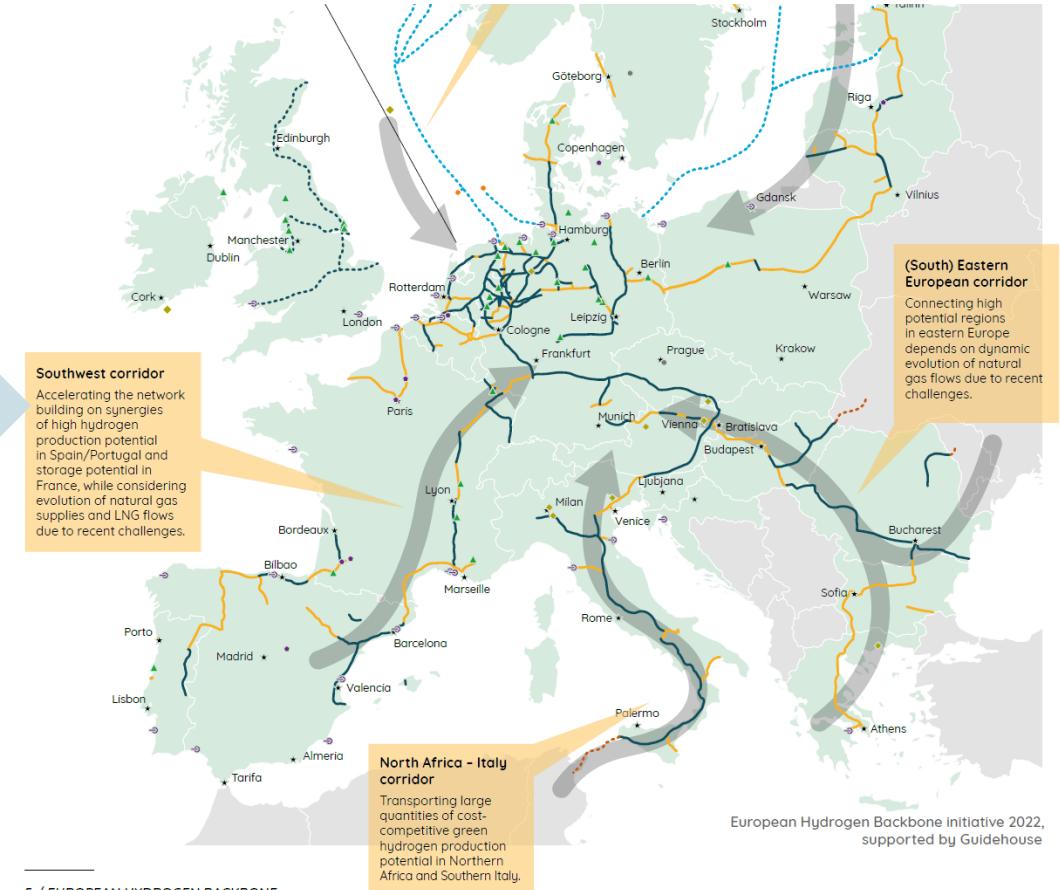


# Time Scale

## Hydrogen Backbone 2020 and 2022



2020 → 2022



Quelle: European Hydrogen Backbone Initiative – beide Darstellungen skizzieren die VISION für 2030

# Where are the Best Locations for PtX Production?

Geographic Information System (GIS) Analysis: Site-Specific Assessment

## Power Grid

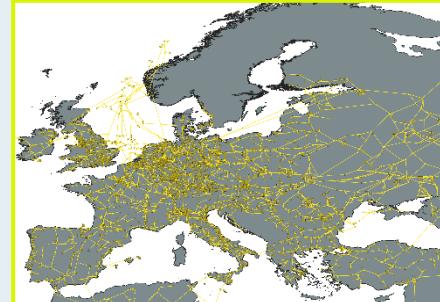
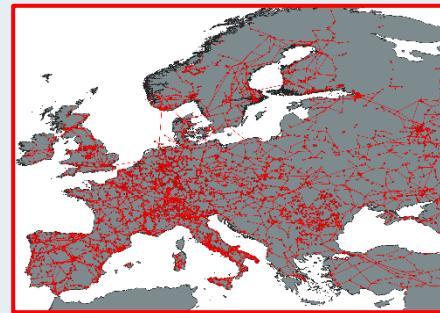
- Power Buses
- Power Lines
- Transformers
- Power Plants

## Gas Grid

- Pipelines & Storages
- Retrofitability
- Compressors
- Producers
- Consumers
- LNG

## Water

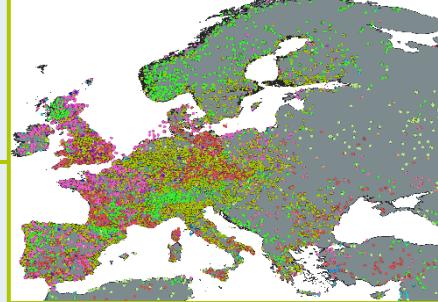
- Desalination Plants
- Reservoirs and Lakes
- Rivers
- Pipelines
- Wastewater Plants



**Economy, Ecology & Politics**  
Markets, Staff Availability, Political Stability,  
Social Acceptance, Regulatory

**GIS-based Location Analysis and Site Suitability Assessment**

**Renewable Energies**  
Production Time Series and Potentials  
Renewable Energy Plants



Railways  
Roads  
Waterways  
Ports  
Airports

Industrial Areas  
CO<sub>2</sub> Sources  
Waste Heat  
Oxygen Consumers

Geological Storages  
Elevation  
Slope & Aspect  
Land Use  
Available Areas  
Protected Areas



# National Hydrogen Strategies in GCC

## Hydrogen Ambitions and Targets

### Saudi Arabia



#### National Strategy

- Completed yet still pending publication as part of the National Circular Carbon Economy Program

#### Announced Hydrogen Targets

- World's leading H<sub>2</sub> Producer and Exporter
- Capture >27 Mt CO<sub>2</sub>e by producing 4 Mt clean H<sub>2</sub>/Year

### Oman



#### National Strategy

- Announced in Feb 2020
- Expected soon

#### Announced Hydrogen Targets

- Establishing a hydrogen centric society by 2040
- Large-scale exporter of green hydrogen or green ammonia

### Kuwait



#### National Strategy

- A formalised H<sub>2</sub> strategy not existant
- White paper in Jan 2021

#### Announced Hydrogen Targets

- Promoting green and blue hydrogen production and domestic use
- Intensified cooperation with other GCC countries



### Bahrain



#### National Strategy

- A formalised H<sub>2</sub> strategy not existant
- Feasibility studies in Nov 2020
- Industrial Strategy 2022–2026 in Jan 22

#### Announced Hydrogen Targets

- Establish a hydrogen Economy

### Qatar



#### National Strategy

- No roadmap is under development

#### Announced Hydrogen Targets

- Keep position as the world's leading exporter of LNG
- Cooperate with blue hydrogen importer

### UAE



#### National Strategy

- Announced at COP26 in Nov 2021
- Expected soon

#### Announced Hydrogen Targets

- Top global producer by 2031
- Capture 25% of key global export markets (e.g. in Europe and Asia)

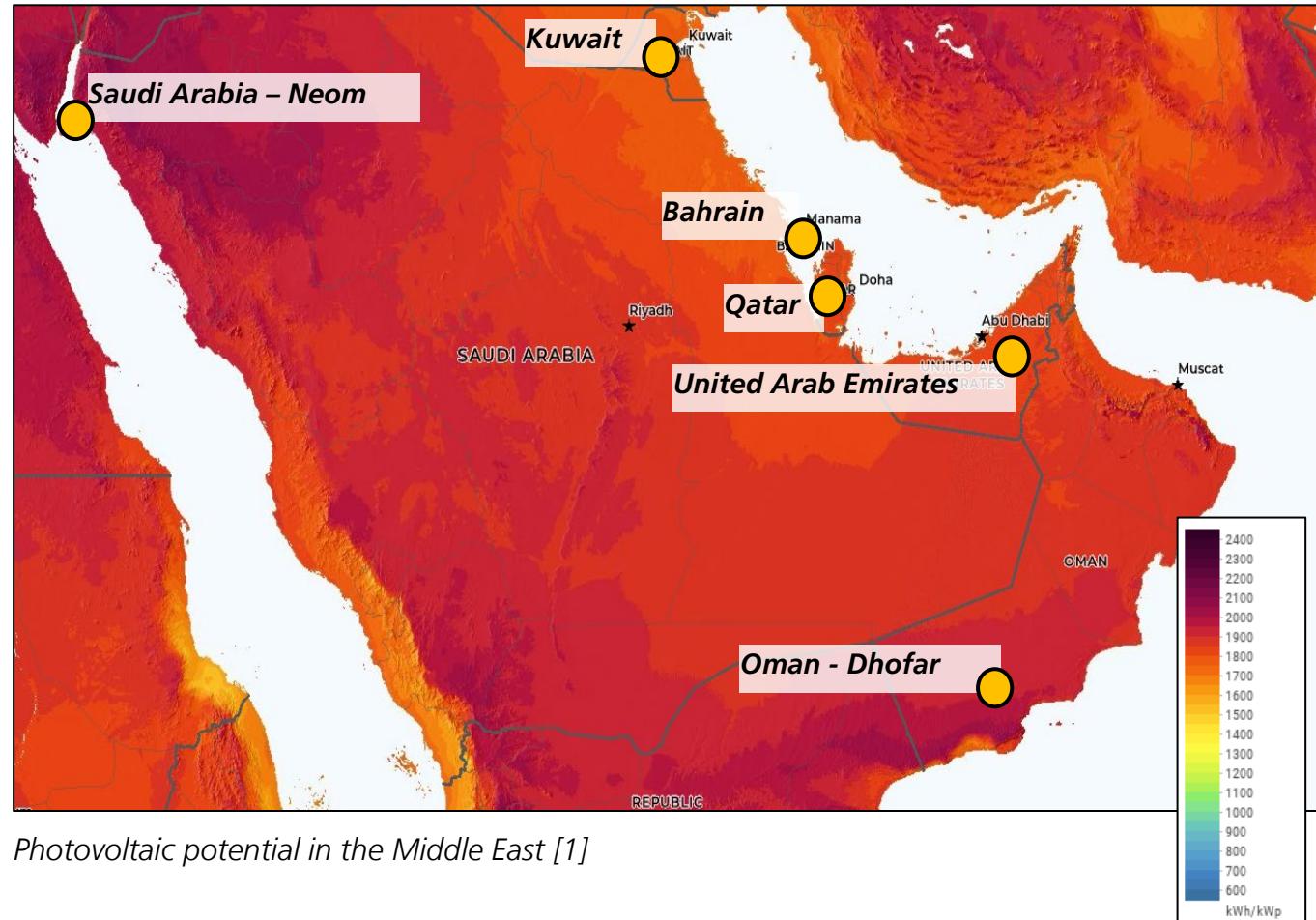
# Gulf Cooperation Council – Examined Locations for Power-to-X Products

## Analyzed Locations

- Saudi Arabia – Neom
- Kuwait
- Bahrain
- Qatar
- United Arab Emirates
- Oman – Dhofar

## Assessed System Boundaries:

- RE production at selected locations with subsequent large-scale H<sub>2</sub> production at PtX Hub, conversion and transport until final delivery at import harbor in Germany



[1] Global Solar Atlas by the World Bank: <https://globalsolaratlas.info/support/about>

# Gulf Cooperation Council - Hydrogen First-Movers

UAE, Saudi-Arabia, Oman, Bahrain, Qatar, Kuwait

- 33% of the world's oil reserves
- 20% of the planet's natural gas reserves
- High solar yields and abundant land availability
- Strong financial backbone, direct and fast decision-making, existing infrastructure

**Hydrogen market will lead the GCC to both,  
an economic and political powerhouse**

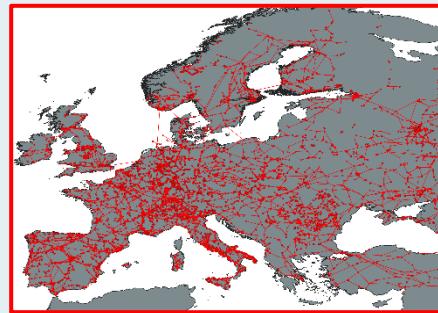


# Where are the Best Locations for PtX Production?

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- Power Plants



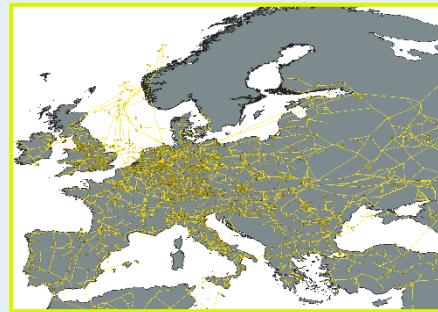
**Economy, Ecology & Politics**  
Markets, Staff Availability, Political Stability,  
Social Acceptance, Regulatory



- Railways
- Roads
- Waterways
- Ports
- Airports

## Gas Grid

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- LNG

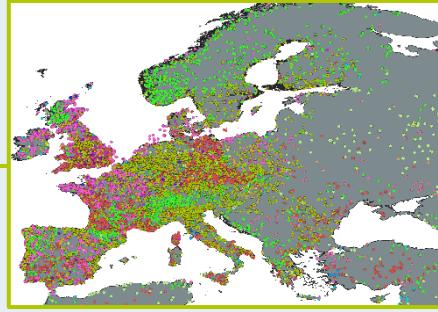


**GIS-based Location Analysis and Site Suitability Assessment**



**Renewable Energies**

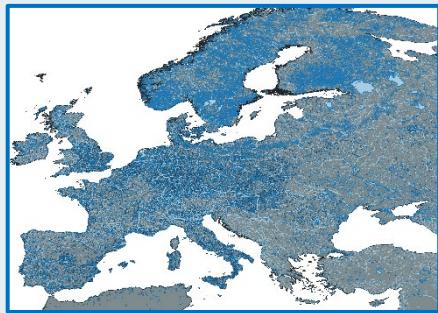
Production Time Series and Potentials  
Renewable Energy Plants



- Industrial Areas
- CO<sub>2</sub> Sources
- Waste Heat
- Oxygen Consumers

## Water

- Desalination Plants
- Reservoirs and Lakes
- Rivers
- Pipelines
- Wastewater Plants

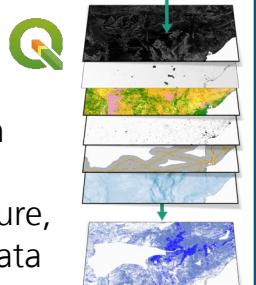


- Geological Storages
- Elevation
- Slope & Aspect
- Land Use
- Available Areas
- Protected Areas

# Methodology for Techno-Economic Assessments of Large-Scale Power-to-X

## Location Analyses for large-scale RE and PtX

**GIS analysis** of countries to identify best suited regions: land use, topology, population density, infrastructure, weather data



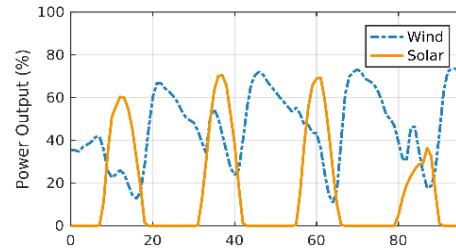
**Location Parameters** (capital + grid power costs)

**Export destination**

**Further requirements** (Desalination, available land)

**Internal Database** for technical and economical parameters for system components (Efficiencies, Capex, Opex, etc.)

**Annual wind and solar timeseries** based on satellite data over the past 10 years (or specific timeseries)



**Transport route analysis** based on real shipping routes



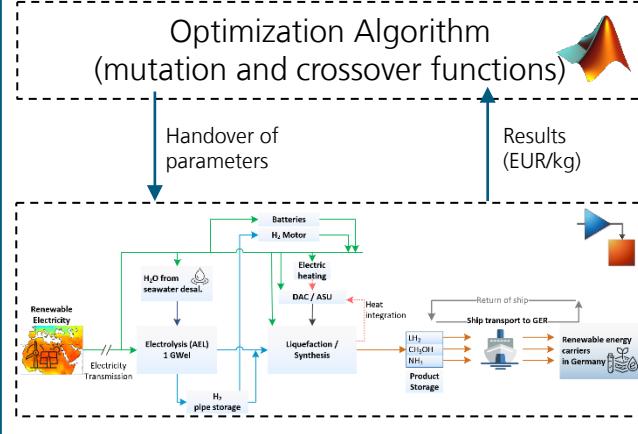
## PtX System Optimization

Holistic **PtX production and supply chains** (RE, electrolysis, H<sub>2</sub>-liquefaction/synthesis)

System optimization using **Genetic Algorithm** to solve complex problems

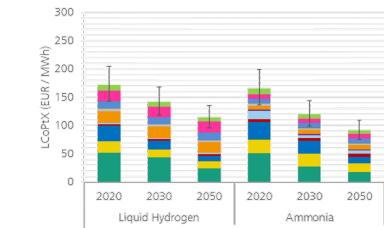
**Dynamic, non-linear modelling** of PtX production plants

**Advanced PtX operation management** taking component behaviors into account, e.g., limited part load operation of synthesis



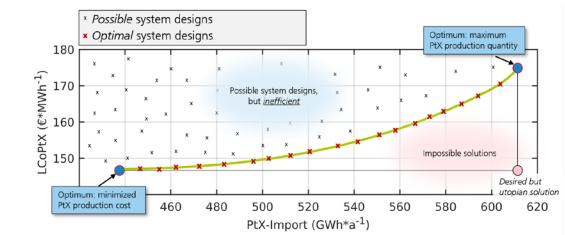
## Results Output

**Key performance indicators:** Levelized costs of product (EUR/MWh; EUR/kg), Total PtX product, investment and operational cost, efficiency, full load hours, water consumption, energy flows, cost structure of products, etc.



**Plant design in the cost optimum**, e.g., optimized ratio of wind/ solar to electrolysis, intermediate hydrogen storage

**Pareto front** of multi objective optimization



# CO<sub>2</sub> - Sources in the United Arabic Emirates

## Specific CO<sub>2</sub> Capture Costs [€/tCO<sub>2</sub>]

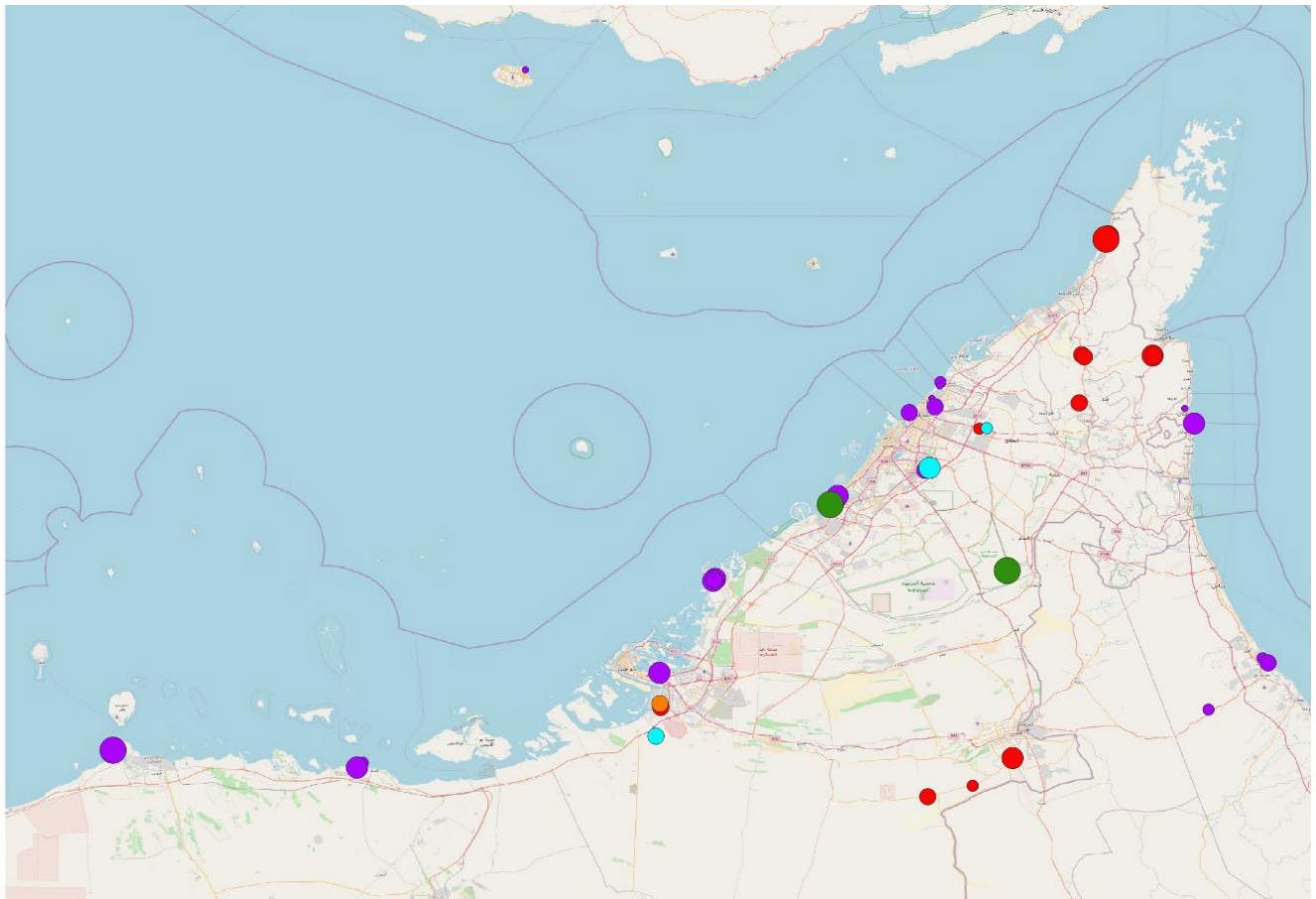
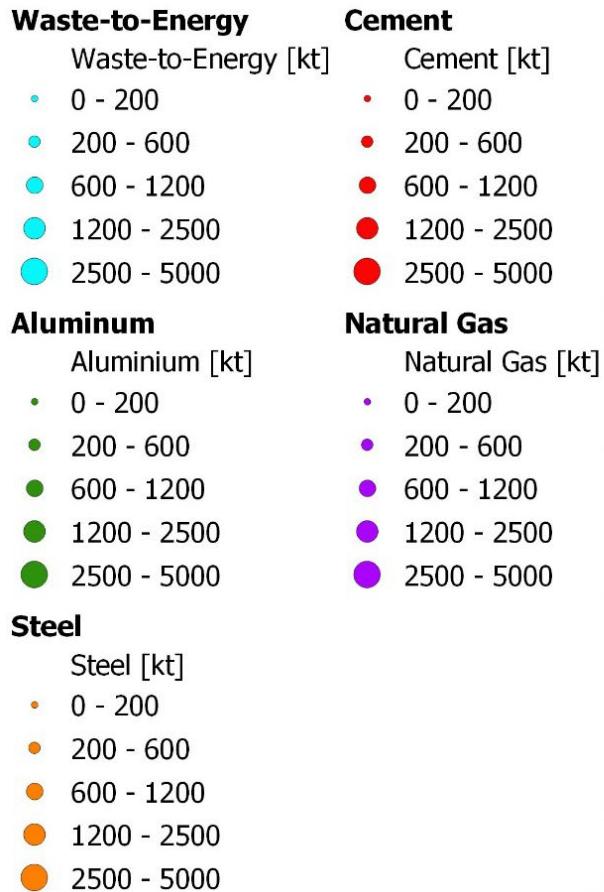
Waste-to-Energy:  
35 – 50 €/tCO<sub>2</sub>

Aluminium:  
10 – 20 €/tCO<sub>2</sub>

Steel:  
25 – 95 €/tCO<sub>2</sub>

Cement:  
35 – 110 €/tCO<sub>2</sub>

Natural Gas:  
45 – 90 €/tCO<sub>2</sub>



# Results: Technoeconomics

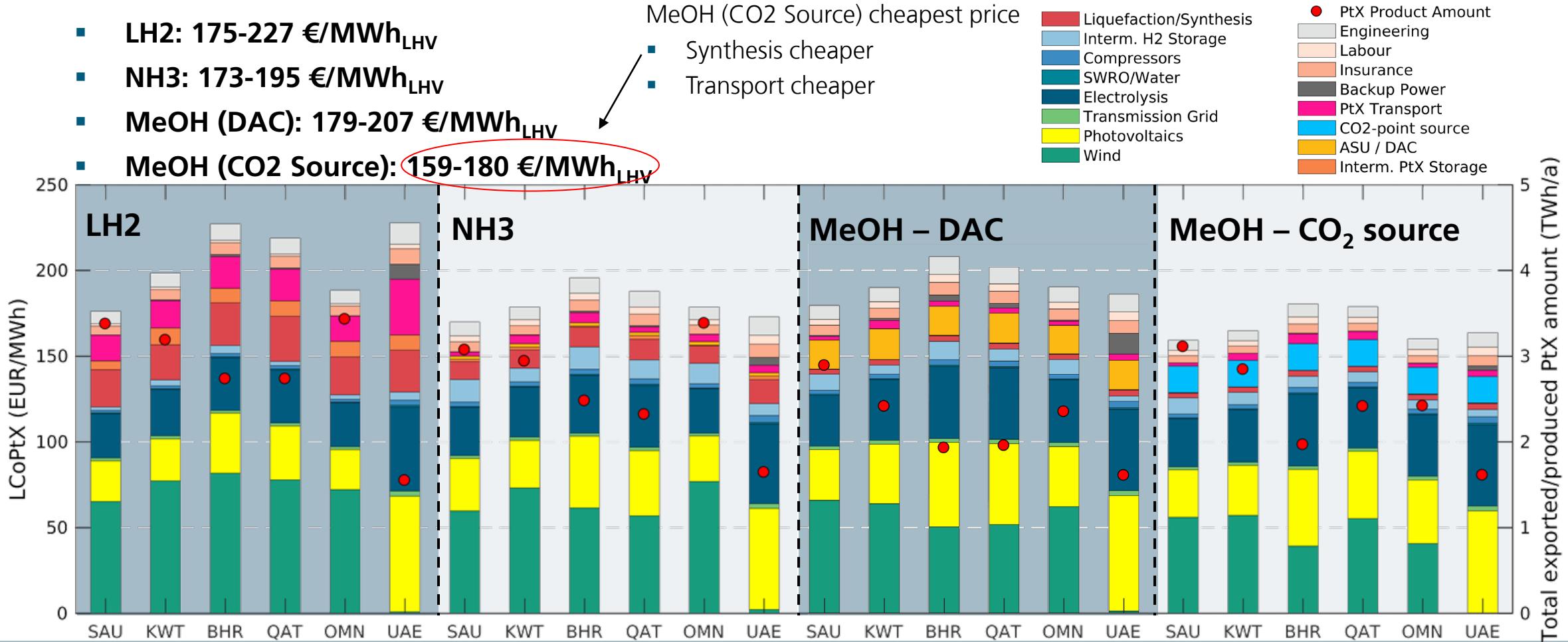
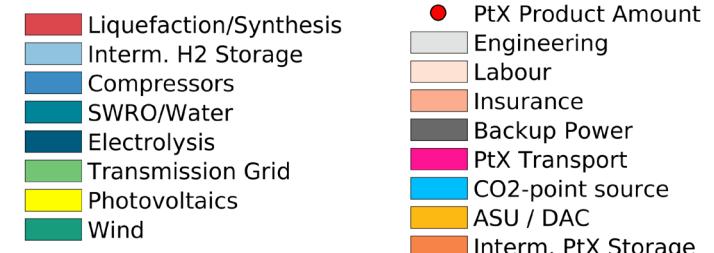
PtX production cost for selected locations in GCC

## PtX supply cost for 2030:

- LH2: 175-227 €/MWh<sub>LHV</sub>
- NH3: 173-195 €/MWh<sub>LHV</sub>
- MeOH (DAC): 179-207 €/MWh<sub>LHV</sub>
- MeOH (CO2 Source): 159-180 €/MWh<sub>LHV</sub>

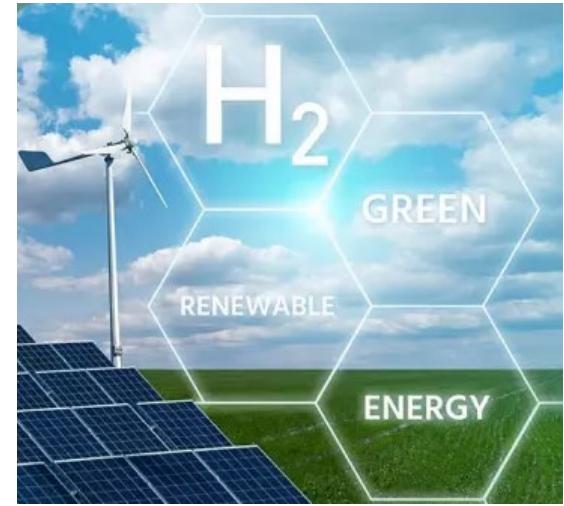
MeOH (CO2 Source) cheapest price

- Synthesis cheaper
- Transport cheaper



# Zusammenfassung der aktuellen Situation

- Energiesouveränität und Systemresilienz werden zu zentralen Handlungsfeldern künftiger Energiestrategischer Überlegungen
- Der Import von Wasserstoff sowie darüber erzeugte Syntheseprodukte durch globale Energiepartnerschaften bildet eine wesentliche Säule der nationalen und der EU-Wasserstoffstrategie.
- Die meisten Studien gehen von künftigen Importanteilen nach Deutschland und in die EU von über 50% aus.
- Aufgrund guter ökonomischer Bedingungen für die Herstellung und die Lieferung sind Staaten wie die MENA-Region, Australien, Westafrika, Algerien, Kanada, Namibia relevante und teils neue Ansprechpartner.
- Die sich verschärfende Klimakrise und der Ukraine-Krieg hat zur Erkenntnis geführt, dass die Umsetzung der Defossilisierung der Energiewirtschaft erheblich beschleunigt werden muss
- Die Fortschreibung der Nationalen Wasserstoffstrategie reflektiert in ihrem Ambitioniertheitsniveau in keiner Weise die energie- und geopolitische Situation
- Die Defossilisierung im (insb. im straßengebundenen) Verkehrssektor kann ohne Wasserstoff nicht gelingen
- Internationale Forschungskooperationen und Energiepartnerschaften sind eine Voraussetzung für schnelleren Fortschritt, langfristige (Handels-)Beziehungen und ein sicheres Investitionsumfeld





Thank you for your attention!

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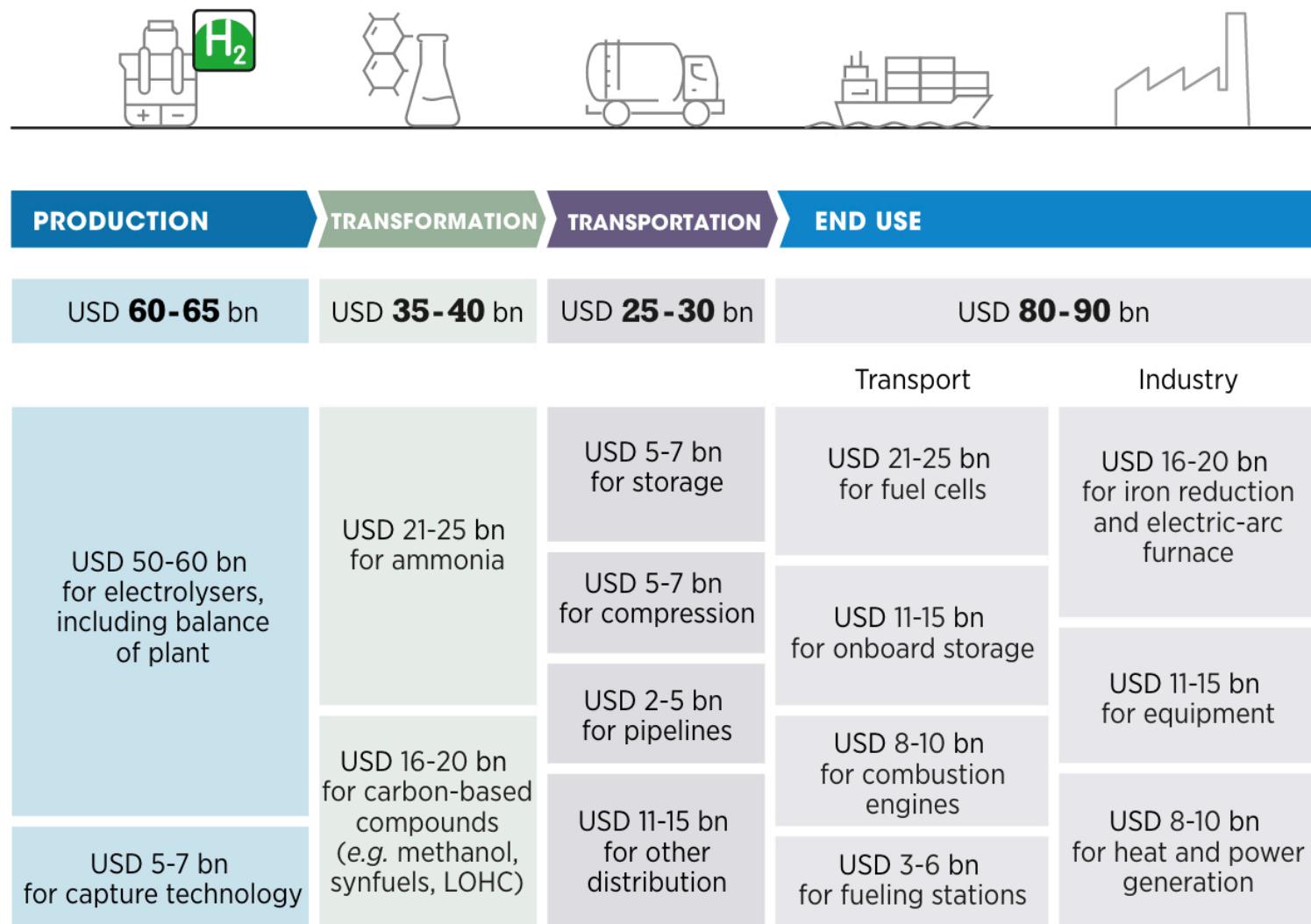
**Prof. Dr. Christopher Hebling**  
[christopher.hebling@ise.fraunhofer.de](mailto:christopher.hebling@ise.fraunhofer.de)



# Value Creation from Production to End Use

## H2 Unknown Unknowns

- **Research and development and innovation** driven hydrogen technologies and applications (along the value chain) are key within the hydrogen economy
- A country (or region's) ability in capturing value in the hydrogen economy will lie in its capacity to produce high **quality, cost-competitive and innovative** hydrogen equipment and components along the value chain.
- This includes a **substantial capacity** in making research and innovation market-ready.



# Hydrogen Production Processes

## The “Colours” of Hydrogen

