Die Energietransformation aus systemanalytischer Sicht

07.10.2020 | PROF. DETLEF STOLTEN

DHV-Symposium "Was nun? Die Herausforderungen des Klimawandels im Spiegel der Wissenschaft"

Bonn

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IEK-3: Techno-Economic Systems Analysis

Setting the Scene

Climate Change Mitigation Drives Green Hydrogen

Climate change → CO_2 equivalent

- Rising sea levels are posing a menace to the world economy
- Storms increase in intensity, size, duration and water load
- Extreme weather events like flooding and droughts increase
- Harvests are going to decline (at the same time when the world population is expanding)

Local emissions

- PM2: small particulate matter reduces life quality, can reduce lifetime and cause cancer
- NOx

Business opportunities

- Harnessing business opportunities through new and more efficient products
- Legal and regulatory support is necessary since the system is tailored to the encumbents

The energy transition triggers great business opportunities

Observation:

If climate change gets tackled appropriately other issues are solved “by default“

Basic Requirements for a Future Energy System

- In 2050 **CO_2 emissions** based on 1990 shall **be reduced** by **80-95 % in line w/ COP21**
- After the transition period energy should **not** be **more expensive** than today
- **Limited emissions** shall be reduced
- Electricity, fuels and heat must be available with **high reliability**
- **All energy sectors** need **to be addressed**
- Teratogenic, carcinogenic and poisonous substances shall be avoided
- Nuclear hazards to be considered
- Radiative forcing to be considered (e.g. slip of methane w/ rf = 30) for new energy pathways

Paramount Topics

- Storage
  - Short term: **grid stabilization** (pumped hydro, batteries, gas storage etc)
  - Long term: **compensate for** sustainedly **low power generation** (only gas storage feasible)
- **Transportation** (from generation to consumption; connecting regions of different climate)
- Compensation of fluctuating renewable input
- **Spatial restrictions**
- Handling dichotomy between a **very distributed** (e.g. household PV) vs. **very centralized** system (off-shore wind farms and coastal on-shore wind power generation)
- Sector coupling

Energy Pathways at a Glance

An Approach of Ranking Renewable Energy Pathways

- The simplest applicable energy pathways will in most cases turn out to be the most efficient, effective and cost effective

Direct use of power

Storage in batteries (grid stabilization)

Hydrogen storage (long-term storage, seasonal storage, trade of RE)

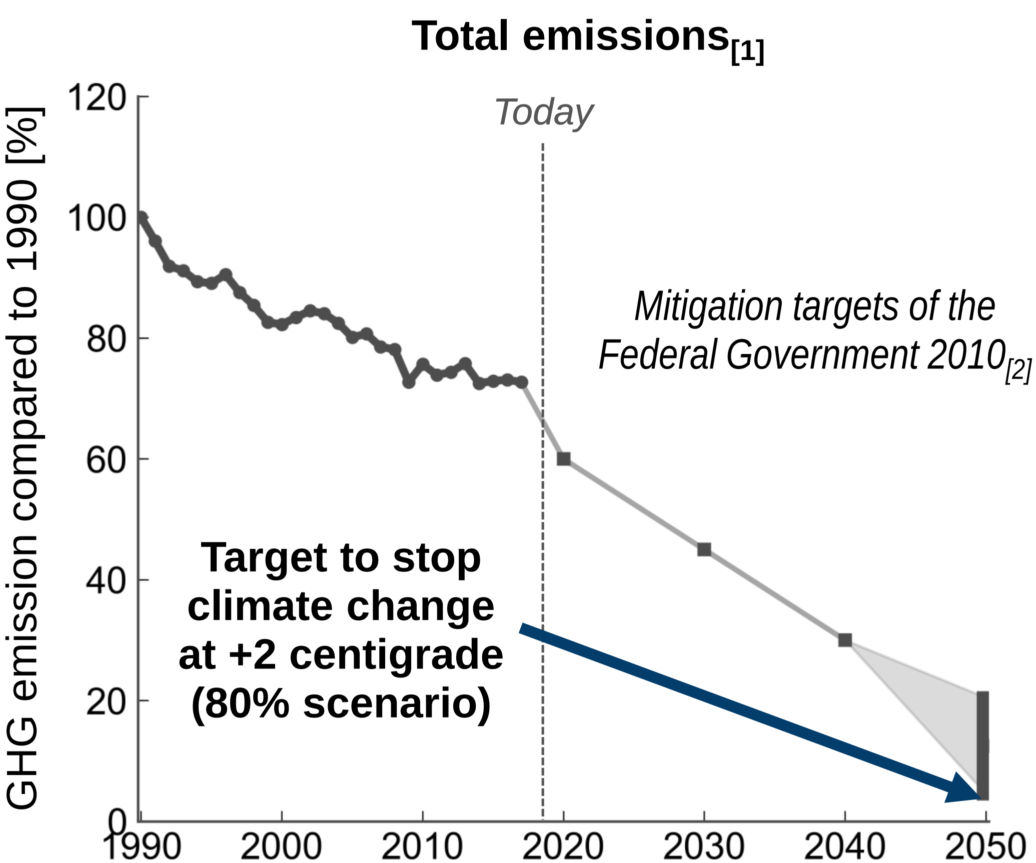
Methane storage

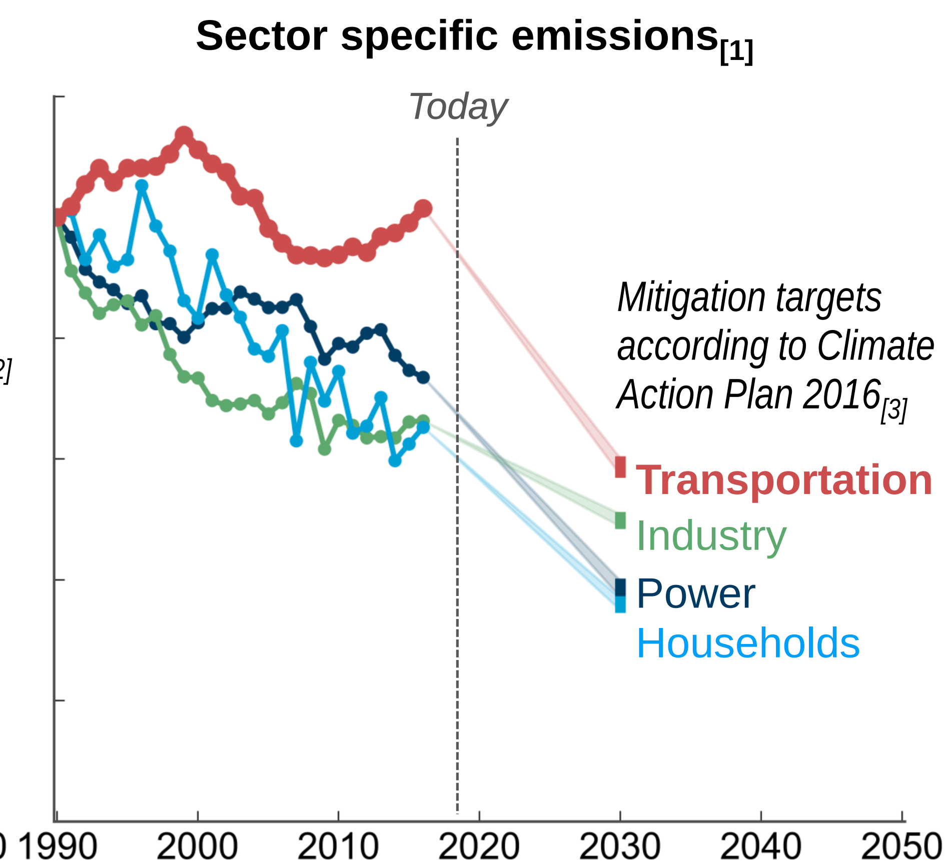
Liquid fuel production

- Power to chem comes in parallel
- Quantitative storage requirements will probably be much higher than we anticipate today
- All of the above mentioned storage options will be needed, owing to the limited applicability of the easier ones (e.g. liquid jet fuel for aviation)
- The complete energy chain needs to be considered for future decisions
- **Energy security requires substantial storage capacities – as implemented today**

The German Energy System

Greenhouse Gas (GHG) Emissions in Germany Since 1990

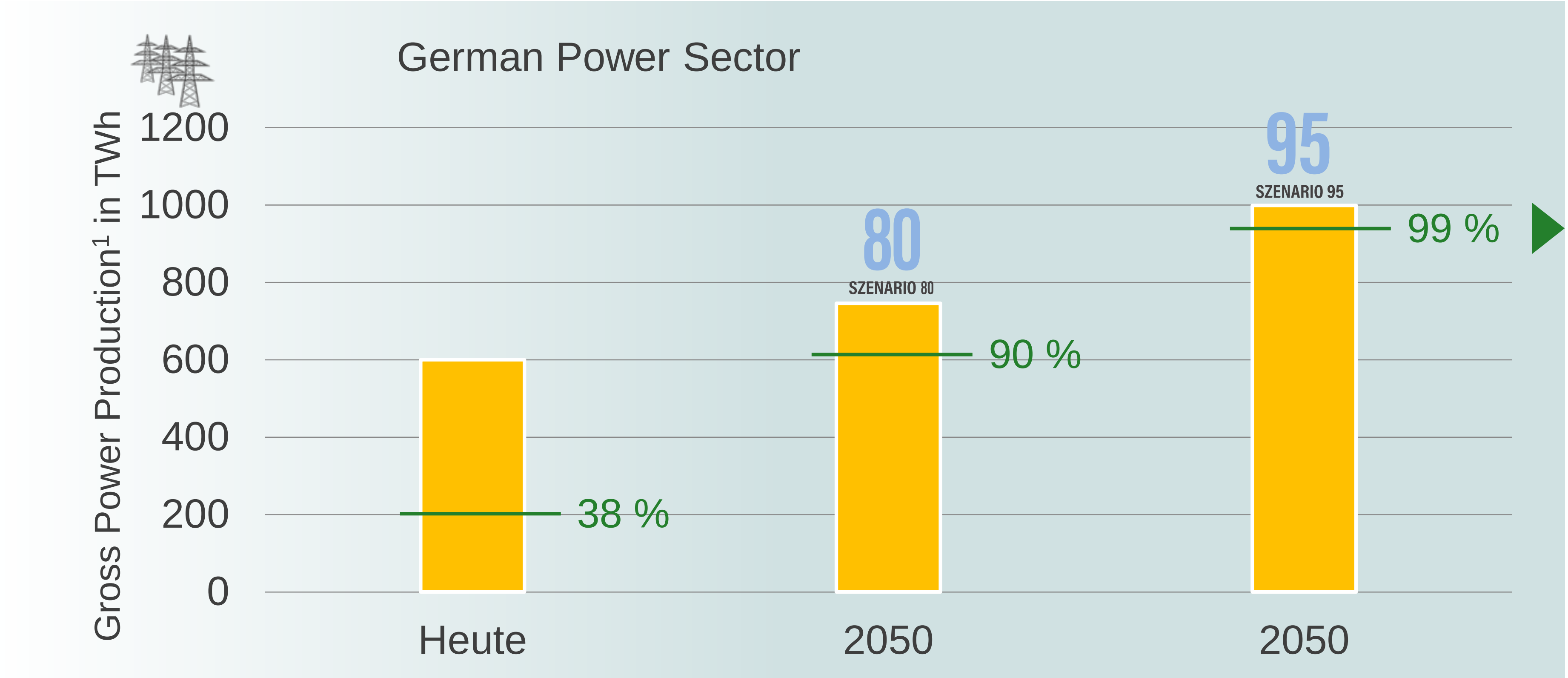




- **Achieving mitigation targets requires contributions from all sectors**
- **No GHG palpable CO_2 reduction in the transportation sector since 1990**

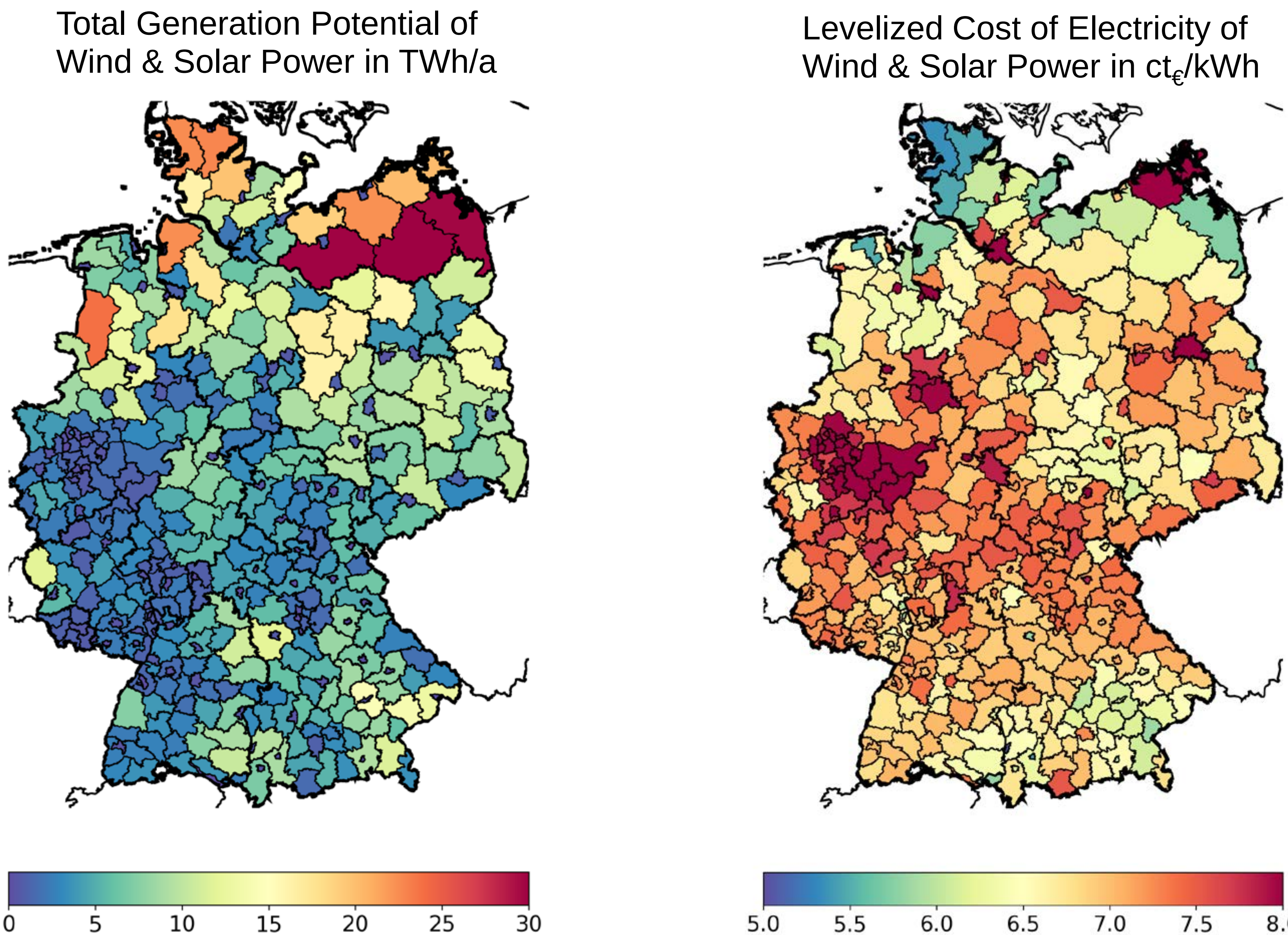
[1] BMWi, *Zahlen und Fakten Energiedaten - Nationale und Internationale Entwicklung*. 2018: Berlin.
[2] BRD, *Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung*. 2010: Berlin.
[3] BMU, *Klimaschutzplan 2050 - Klimaschutzpolitische Grundsätze und Ziele der Bundesregierung*. 2016: Berlin.

Substitution of Fossil Energy Leads to Increased Power Demand

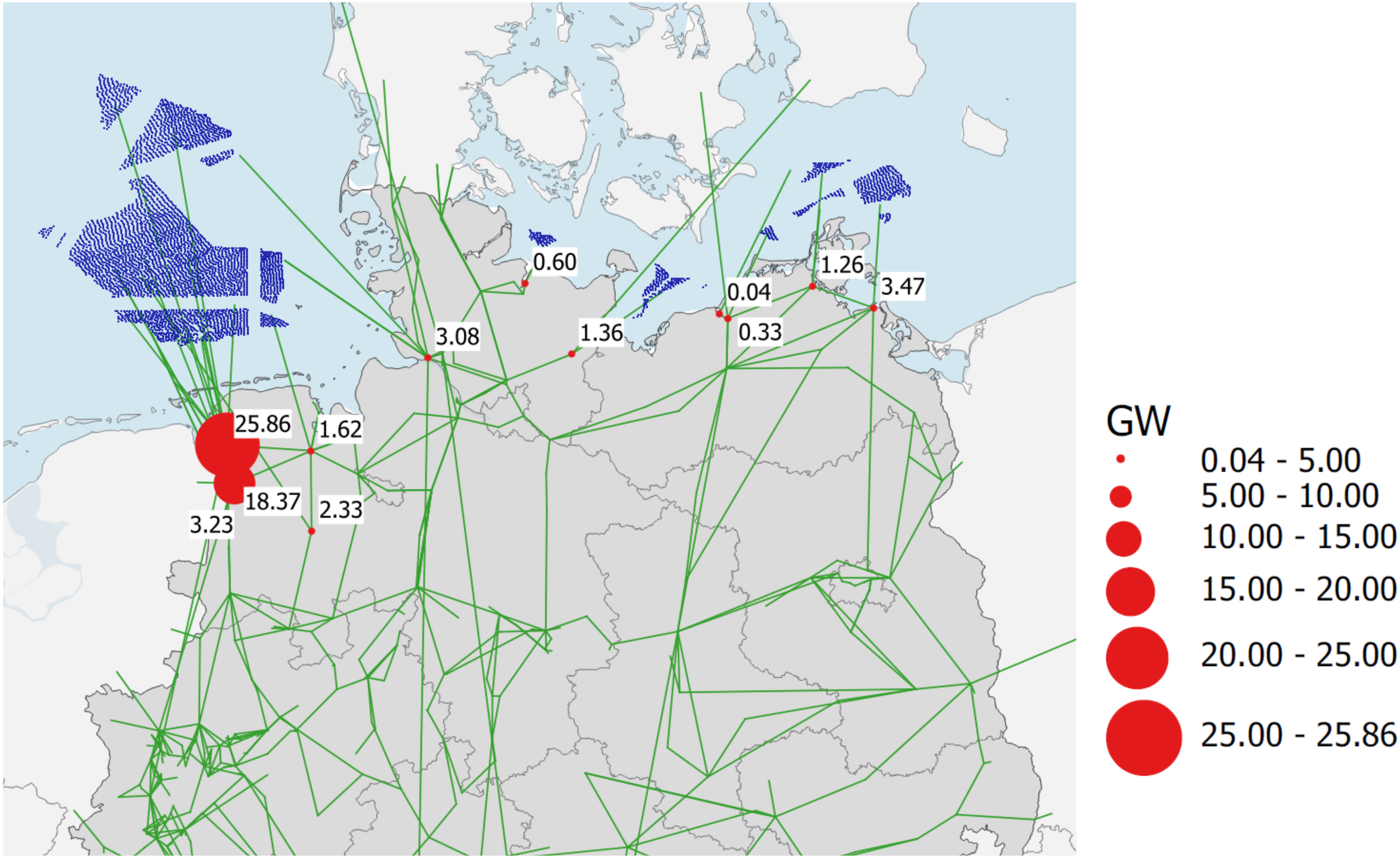


[1] excluding import and export

Energy Transportation from North to South is Inherent for Renewables in DE



Projected Input of Off-shore Power into the German Power Grid



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Energy Transportation and Distrubution is Essential

Expansion of the power transportation grid crucial

– National grid expansion plan until 2030 first step in the right direction
– DC-DC power lines from north to south desriable

Transformation of the natural gas transport grid to hydrogen bears a great opportunity

– Large quanties can be transported
– Wide coverage possible w/o interrrupting the NG gas grid
– Short lead time e.g. 5 years for conversion otjher 0-20 years for building new power lines
– Low cost, since pipelines exist

The distribution grids will be strained most

- Additional electrical load from
    - Passenger vehicles
    - Heat pumps
    - Direct electrical heating

ES 2050 Study*

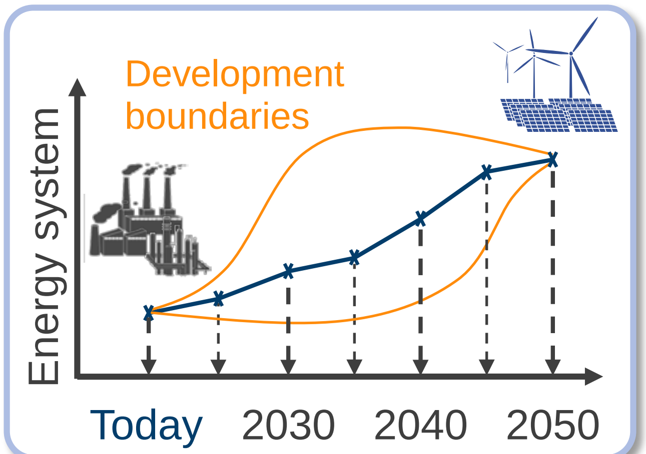
ES 2050 kurz

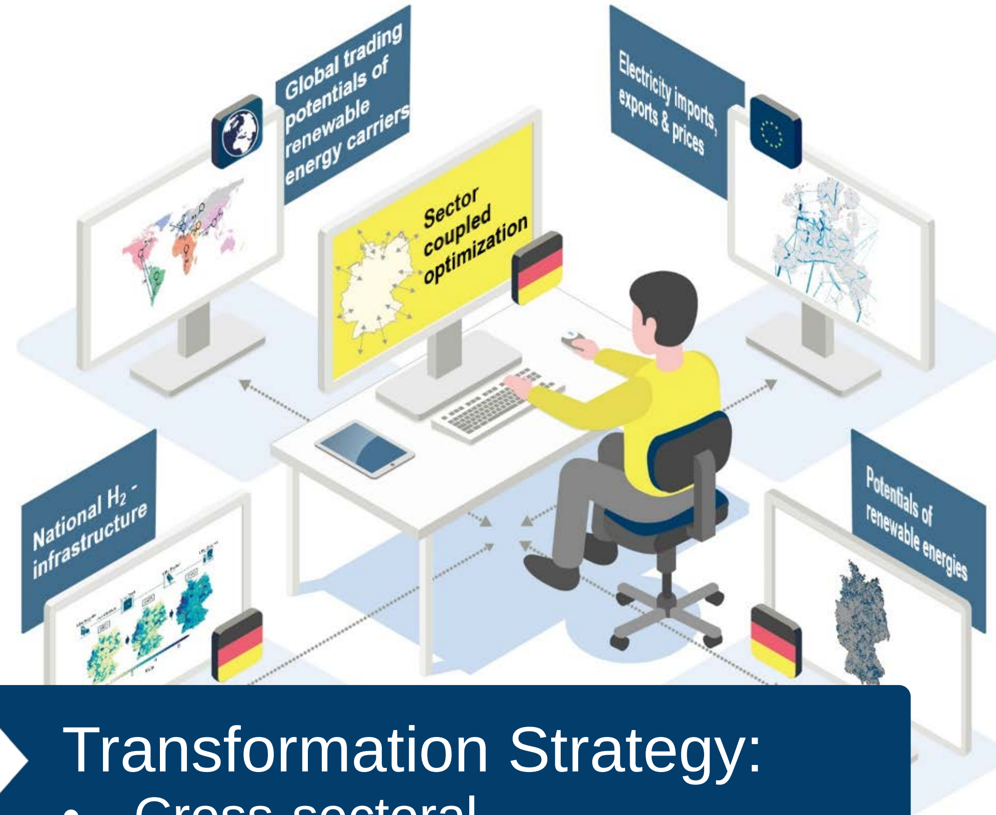
ES 2050 lang

Wege für die Energiewende – Kosteneffiziente und klimagerechte Transformationsstrategien für das deutsche Energiesystem bis zum Jahr 2050. Schriften des Forschungszentrums Jülich, Reihe Energie & Umwelt/Energy & Environment, Band/Volume 499; Robinius M., Markewitz P., Lopion P., Kullmann F., Heuser P.-M., Syranidis K., Cerniauskas S., Schöb T., Reuß M., Ryberg S., Kotzur L., Caglayan D., Welder L., Linßen J., Grube T., Heinrichs H., Stenzel P., Stolten D.: https://juser.fz-juelich.de/record/877960/files/Energie_Umwelt_499.pdf

Approach: Cross-sectoral Cost-optimization of the Entire Energy System under CO_2-Emission Constraints from Today through 2050

over 2000 interrelations





→ **Transformation Strategy:**

- Cross-sectoral
- Cost-optimal
- Technologically unbiased

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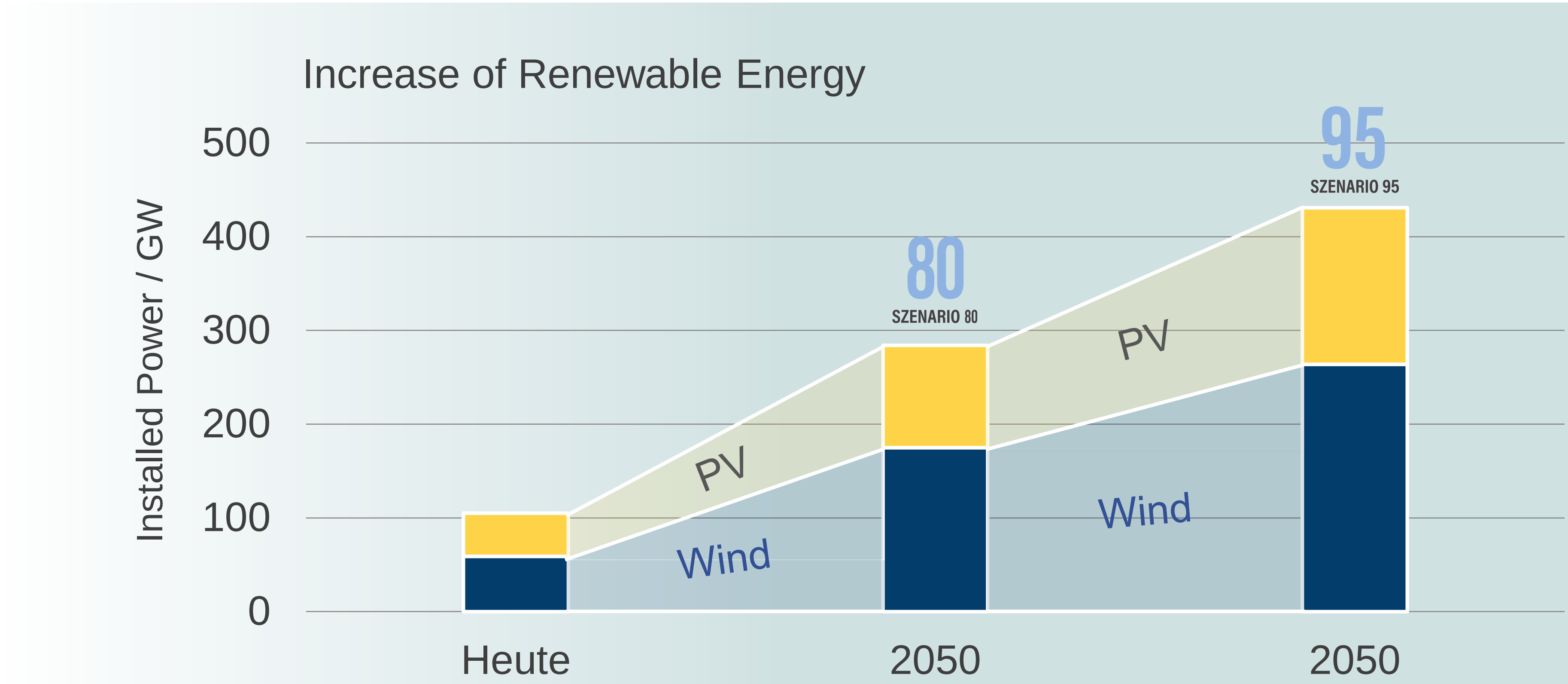
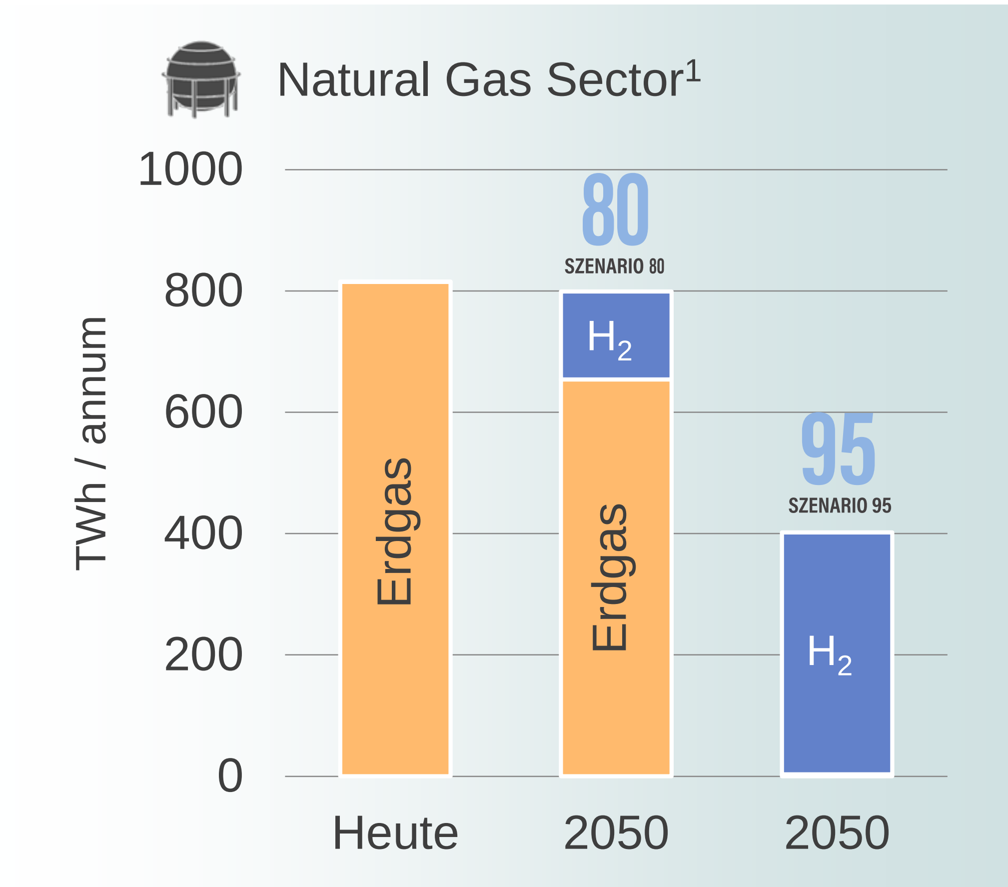
Swift Action in Installing Renewable Energy Devices is Required



CO2 Abatement Strategies for 80% and 95% @ 2050 Differ Notably



[1] electricity demand

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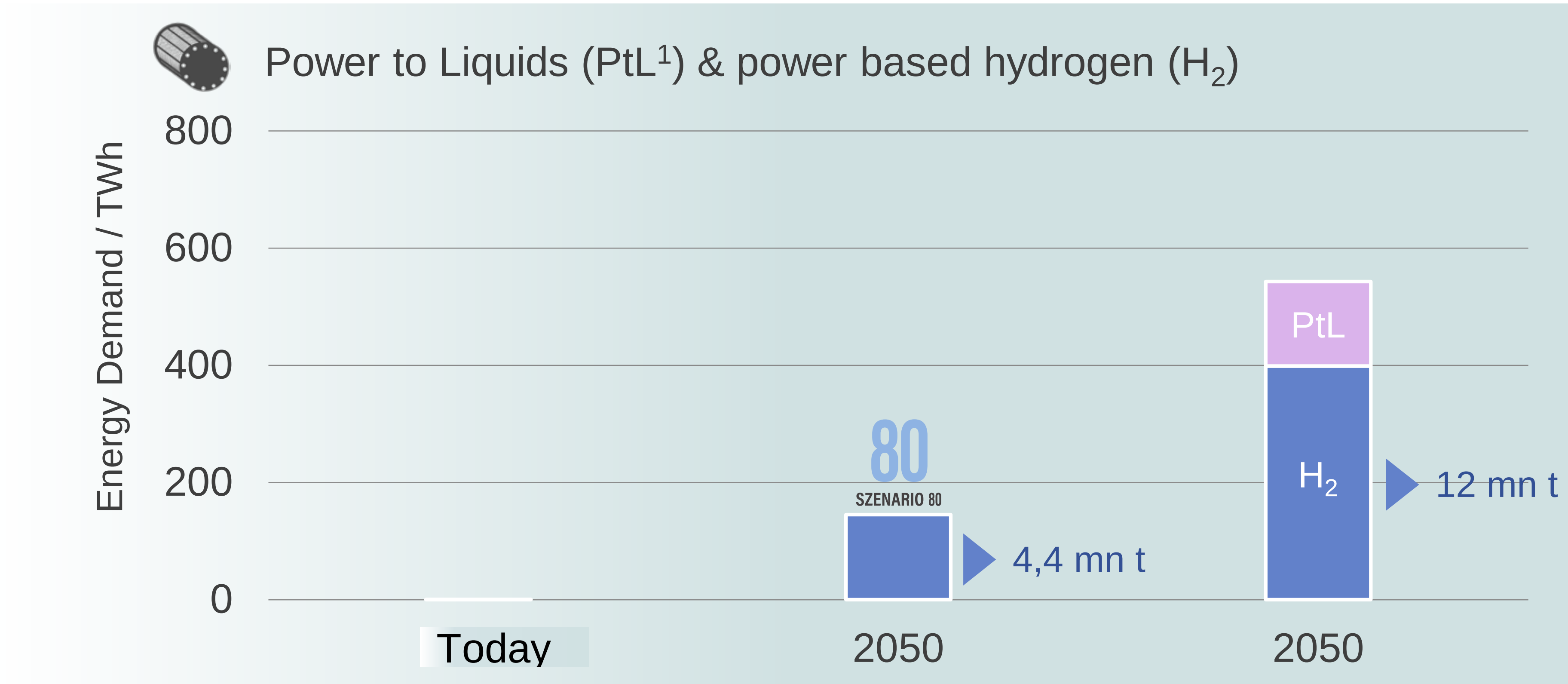
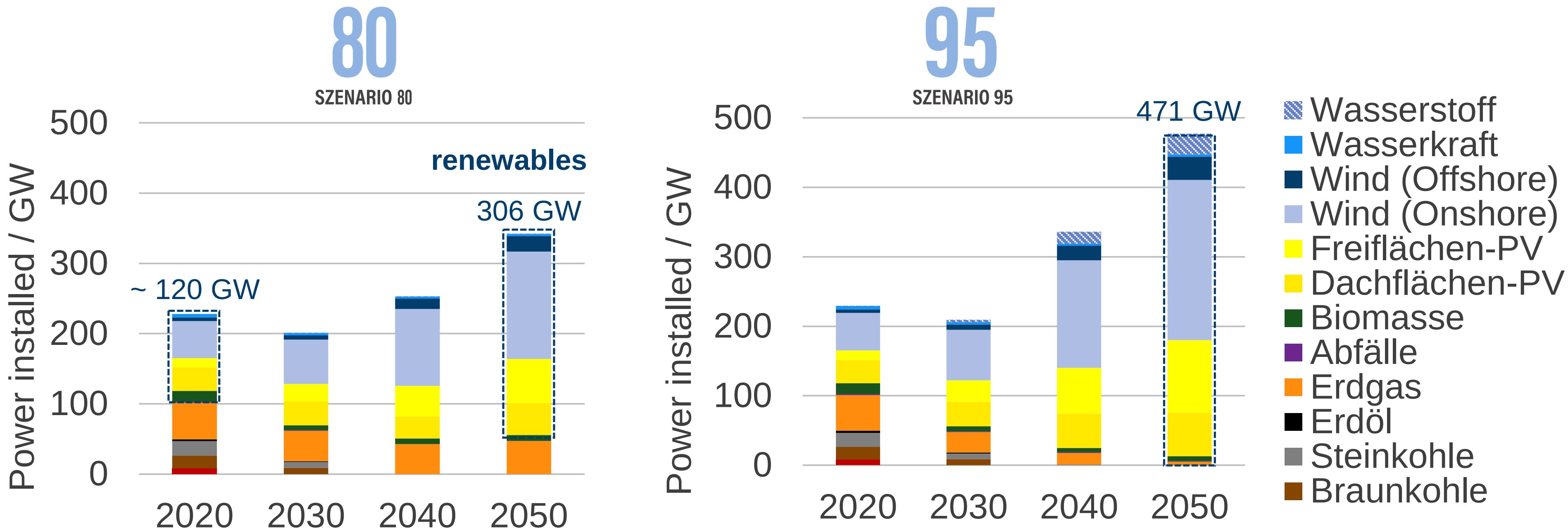
Power to X Technology Represents the Basis for Sector Coupling



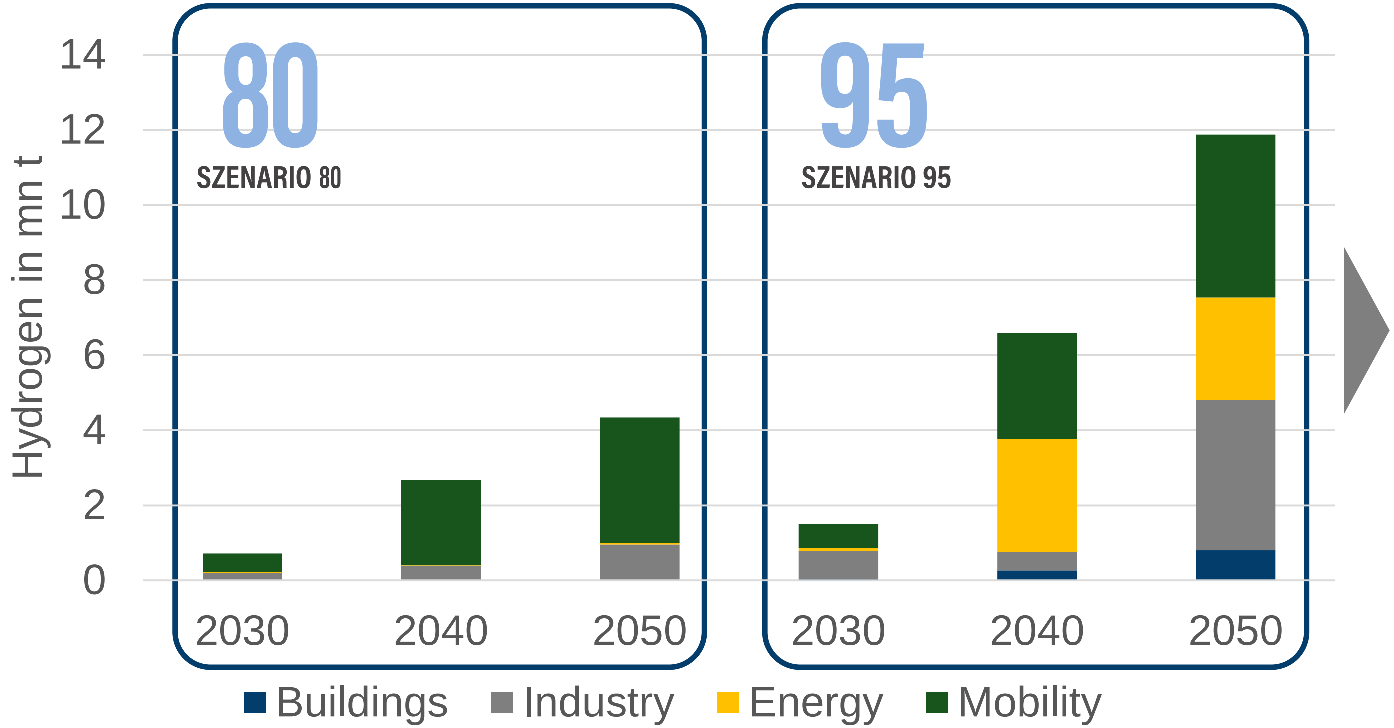
[1] Power-to-Liquid-Fuels (syn. Diesel, Benzin, Kerosin)

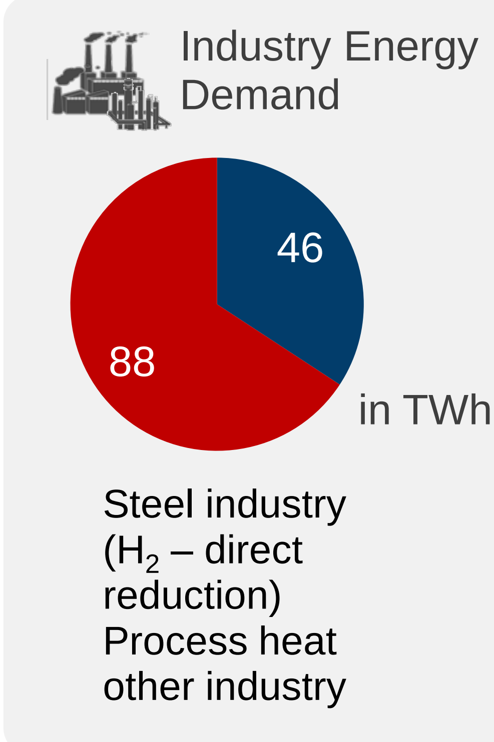
Energy Sector: Projected Installed Power in Germany



[1] https://www.windbranche.de/windenergie-ausbau/deutschland

Hydrogen Demand Triples for the 95% Scenario (no industry feedstock considered)





- Scenario 80: Hydrogen demand of 4 mn t (mostly transport and industry)
- Scenario 95: Hydrogen demand of 12 mn t across all sectors (incl. process heat)

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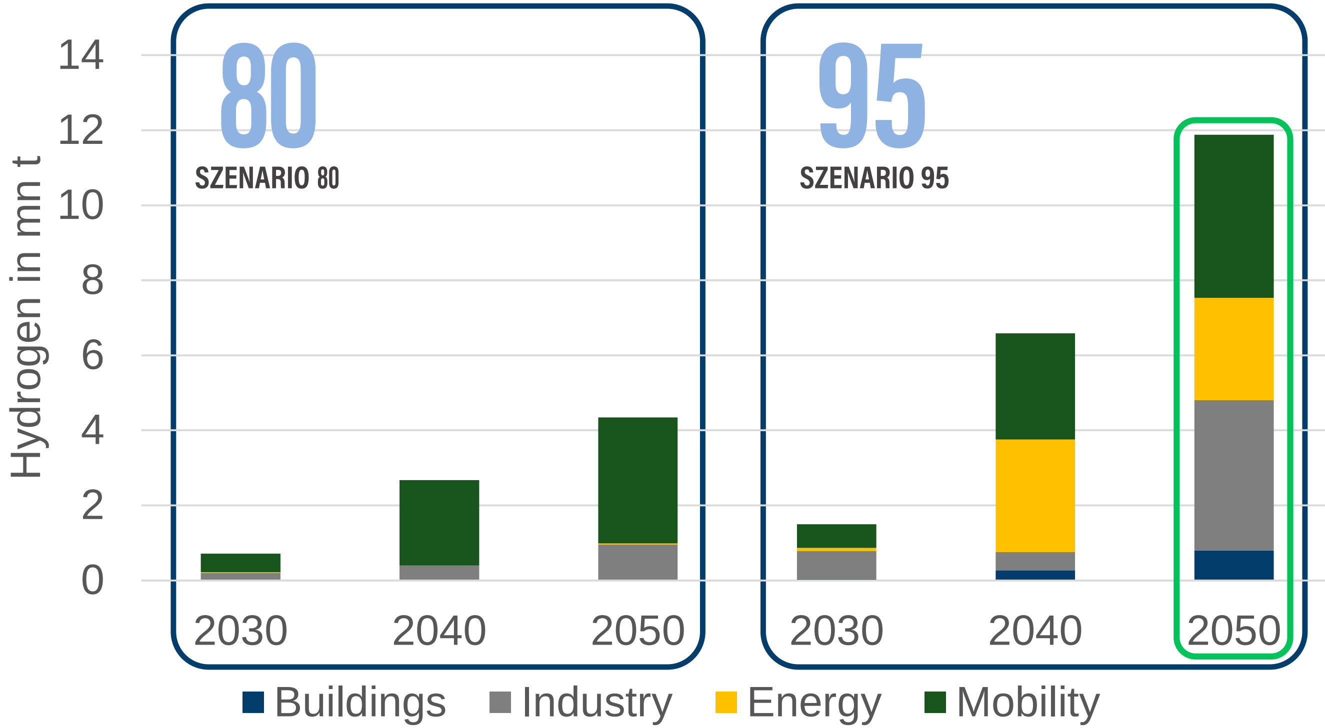
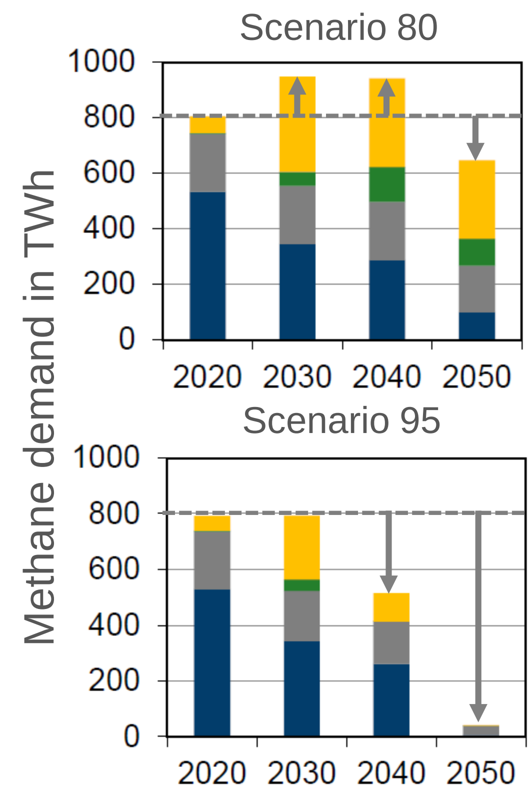
Hydrogen and Methane Demand





- Scenario 80: Hydrogen occurs in mobility and industry only,
  NG demand rises in between before dropping in 2050
- Scenario 95: H_2 in all sectors ➔ infrastructure development & supply chain analysis needed

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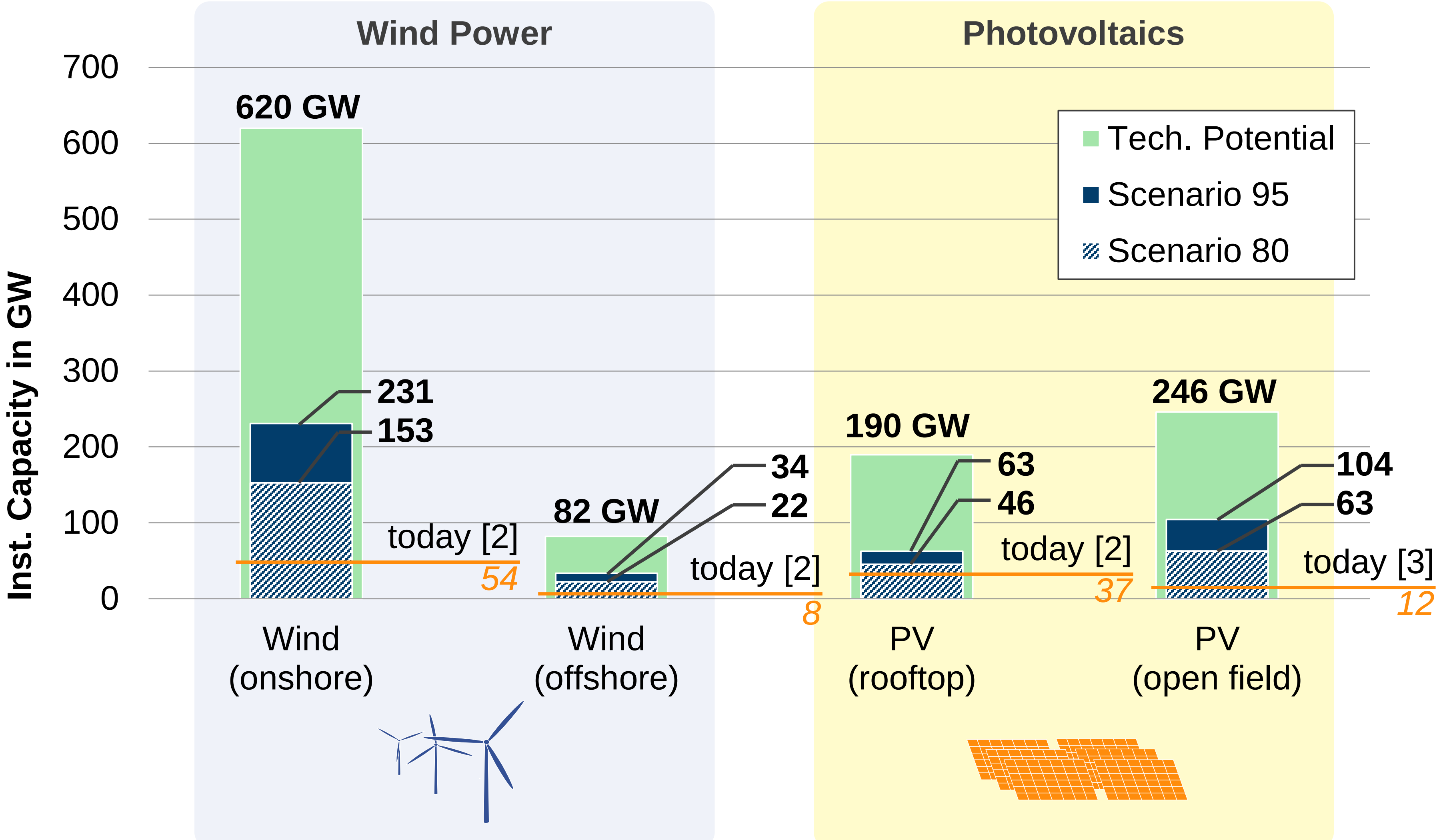
Renewable Energies: Installed Capacities & Tech. Potentials [1]



[1] Robinius, M., Markewitz, P., Lopion, P. et al. (2019): Kosteneffiziente und klimagerechte Transformationsstrategien für das deutsche Energiesystem bis zum Jahr 2050. (Kurzfassung) Forschungszentrum Jülich GmbH

[2] Fraunhofer ISE: https://energy-charts.de/power_inst_de.htm

[3] Bundesnetzagentur: EEG-Anlagenstammdaten (https://www.marktstammdatenregister.de/MaStRApiDokumentation/)

Sector Coupling

Sector Coupling: What is to be Coupled?

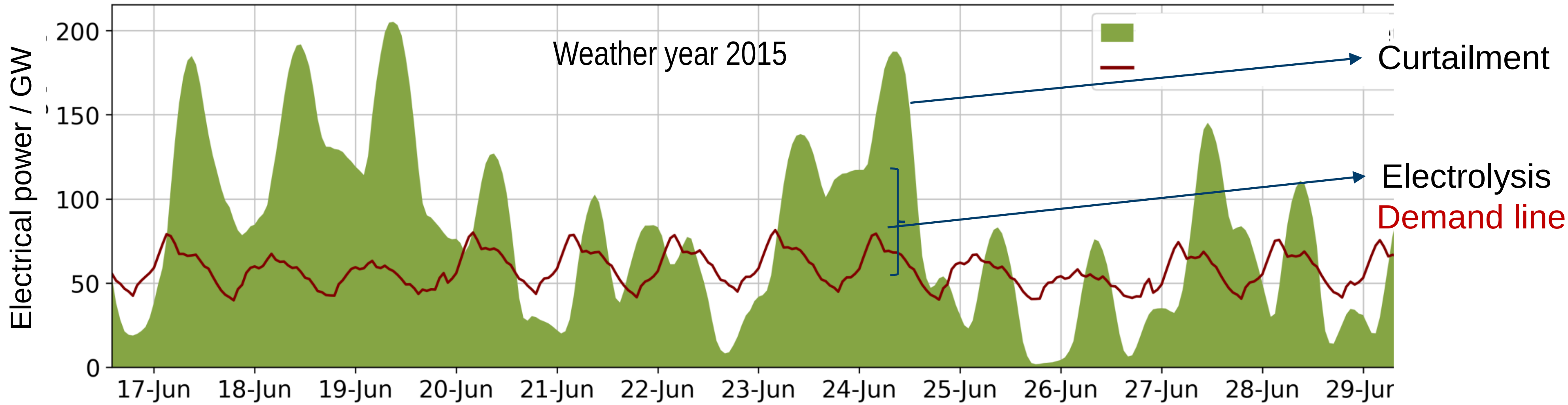
Energy sectors

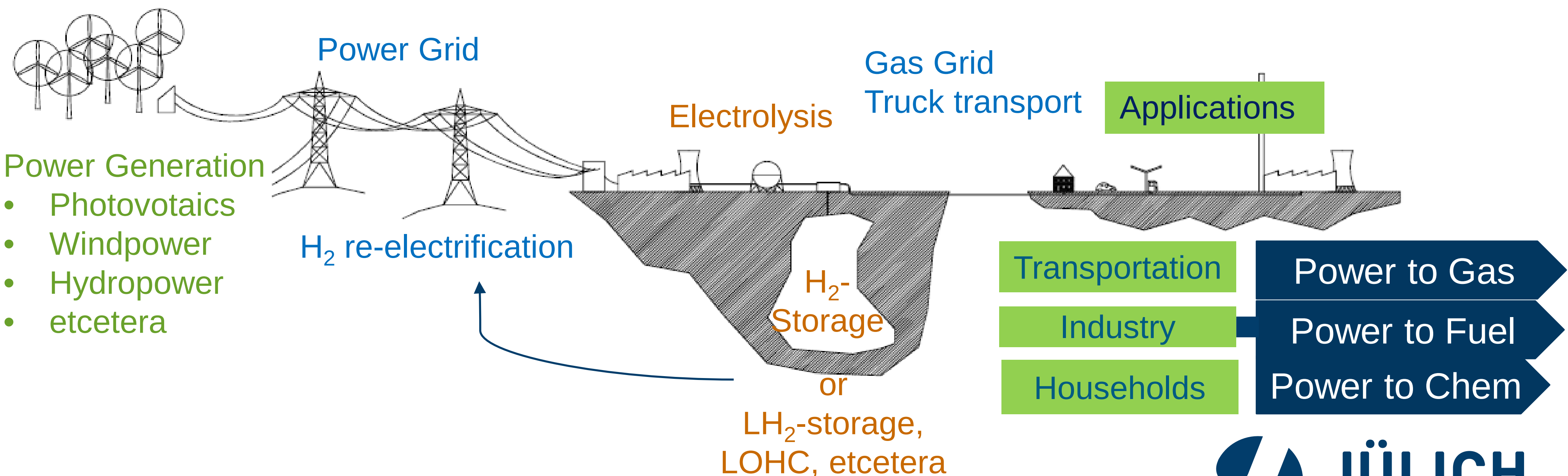
- Public power
- Transportation
- Industry
- Residential

To be coupled

- Public power to transport (direct via overhaead lines, batteries or indirect via hydrogen or PtL)
- Public power to industry energy demand (via Ac-AC; AC-gas; substituting proprietary power generation of industry, coal, oil and natural gas)
- Public power to industry matter demand (substituting coal, oil and natural gas incl. reformed hydrogen; another 450 TWh)
- Residental (via heat heat pumps or power via power based fuels for heating)

Green Electricity Fluctuates / Hydrogen Generation Serves for Storage & Sector Coupling





Electrolytic Water Splitting to Generate Hydrogen

$H_2O \rightarrow H_2 + \frac{1}{2} O_2 \uparrow + \Delta h_{el}$ Efficiency of $70\%_{LHV}$ can be attained

Electrical energy is used to split the water molecule into hydrogen and oxygen

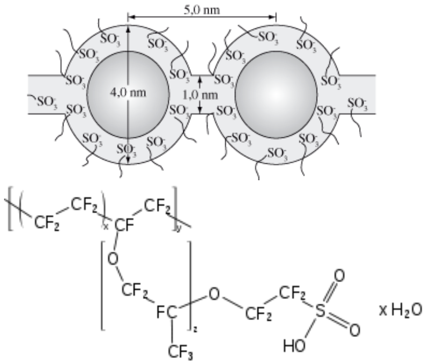
The hydrogen is stored; the oxygen is generally vented

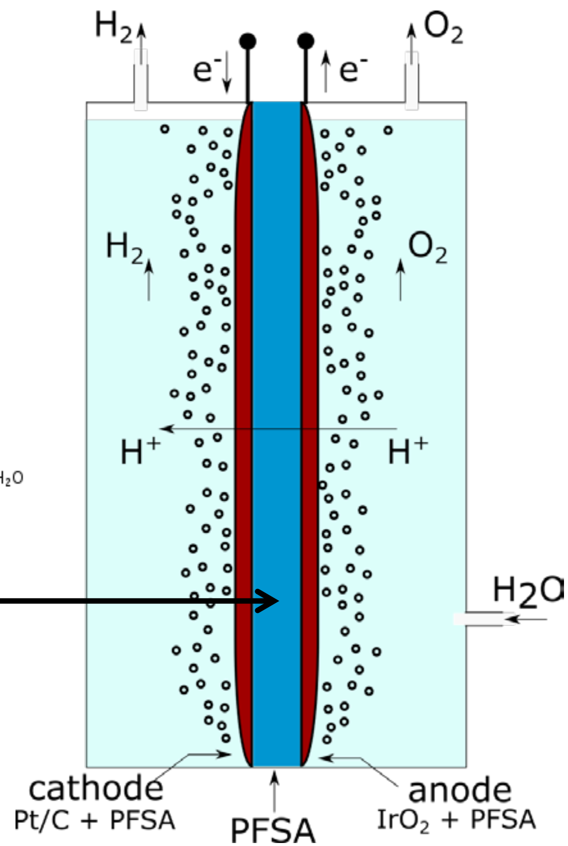
Two major technologies:

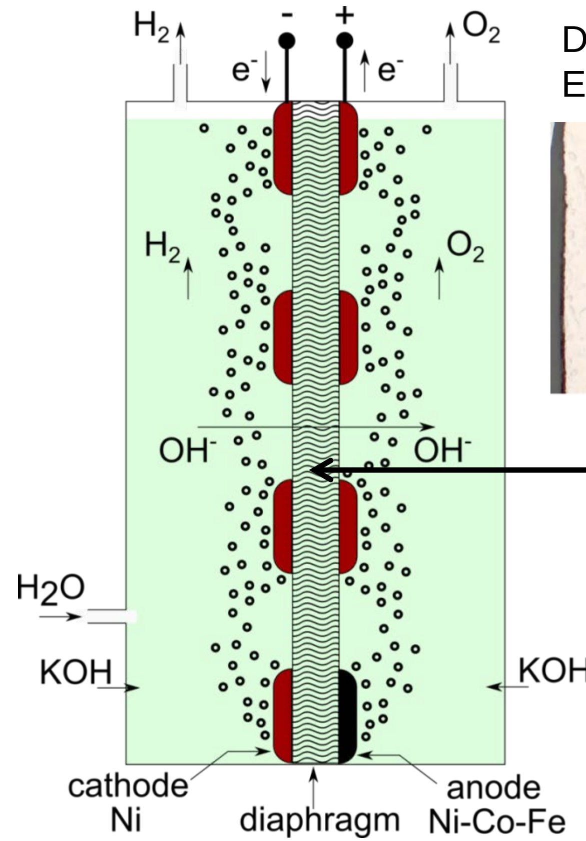
- Alkaline electrolysis
  - Proven: > 100MW
  - Cheaper
  - Less flexible
  - Bulkier
  - No precious metals
- Polymer Electrolyte Membrane (PEM) Electrolysis
  - Up to 10 MW currently
  - main developement strain currently

PEM and Alkaline Electrolysis in Detail

PFSA membranes:
Ex. Nafion





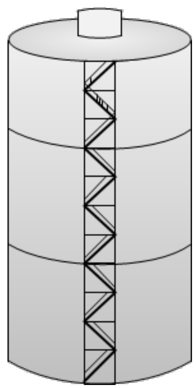
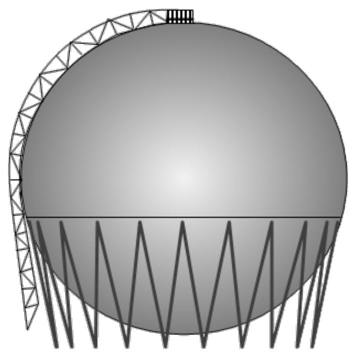
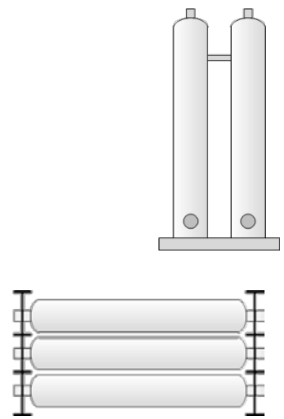
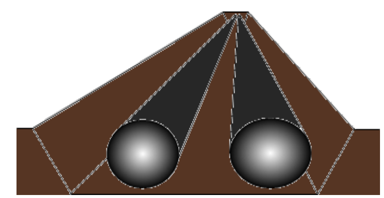


Diaphragms:
Ex. Zirfon

	Acid (Nafion)	Alkaline (KOH)
Anode	$2H_2O \rightarrow 4H^+ + O_2 + 4e^-$	$2OH- \rightarrow 1/2O_2 + H_2O + 2e^-$
Cathode	$4H^+ + 4e^- \rightarrow 2H_2$	$2H_2O + 2e^- \rightarrow 2OH^- + H_2$

Near-Surface Gas Storage Facilities

	Gas holders	Spherical gas vessels	Ground storage assemblies	Pipe storage facilities
Maximum pressure [bar]	1.01 - 1.5	5 - 20	40 - 1000	20 - 100
Storage capacity [scm]	$< 6 \times 10^4$	$< 3 \times 10^5$	$< 1 \times 10^4$	$< 9 \times 10^5$
Invest/ storage capacity ‡ [€/scm]	?	20 - 50	50 - 180	20 - 50

Gaseous Hydrogen: Geologic Gas Storage Facilities

	Depleted oil / gas fields	Aquifers	Salt caverns	Rock caverns / abandoned mines
Working volume [scm]	10^{10}	10^{8}	10^{7}	10^{6}
Cushion gas	50 %	up to 80 %	20 - 30 %	20 - 30 %
Gas quality	reaction and **contamination** with gases present, microorganism and minerals		saturation with water vapor	
Annual cycling cap.	only seasonal		seasonal & frequent	

Investment in rock salt caverns: approx. 40 ct/kWh installed capacity

Liquid Hydrogen

Great mass storage option, if

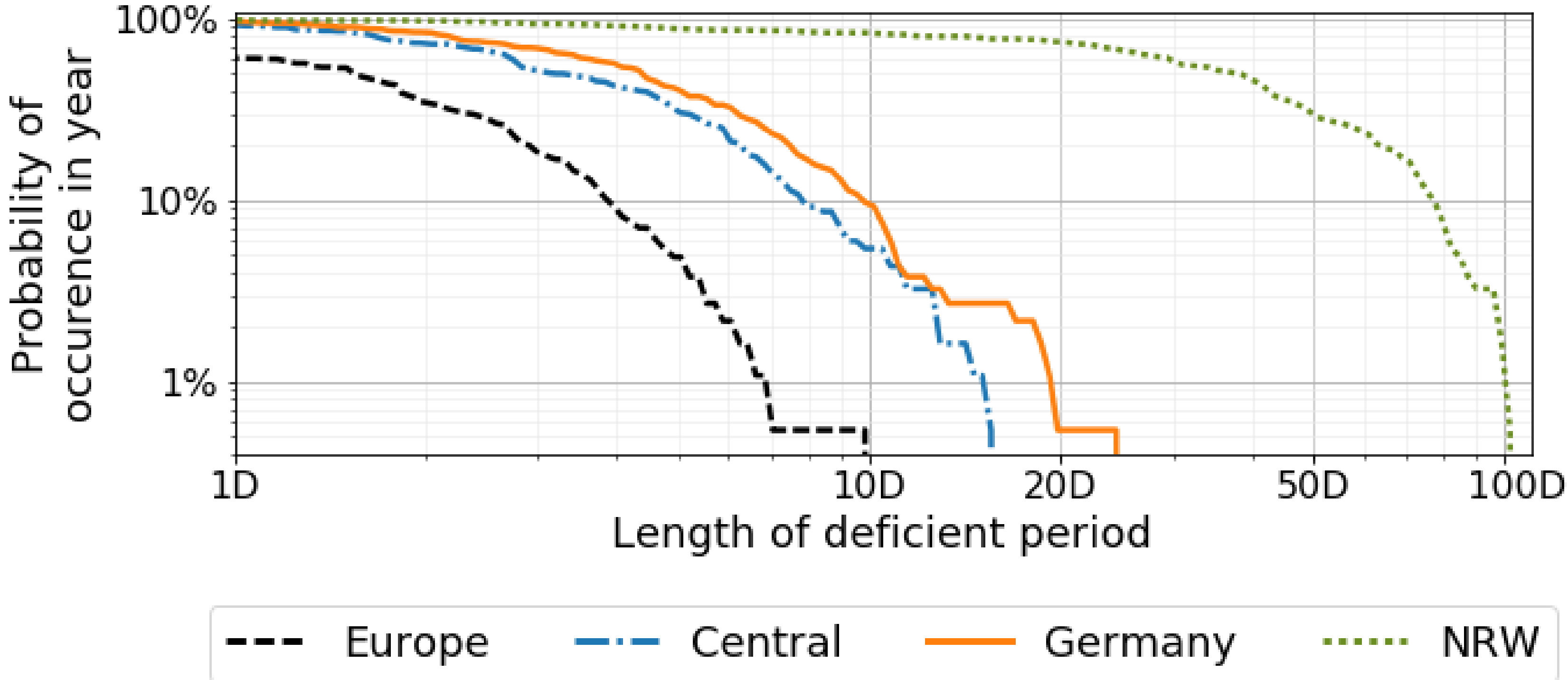
- LH_2 can easily be transported by truck, train or ship

Liquefaction

- Current energy loss of liquefaction >30% of hydrogen energy content
- Future systems have a **potential of 7 kWh/kg or 21% loss**
- Current plants 150 l/h – 20000l/h (up to 47 MW)
- Specific evaporation low for large storage tanks
- Evaporated H_2 can be used and is not lost in most cases
- Current plants amount to at most 40 MW H2
- Hence, **current H_2 liquefaction is NOT being done centrally** in the sense of energy systems

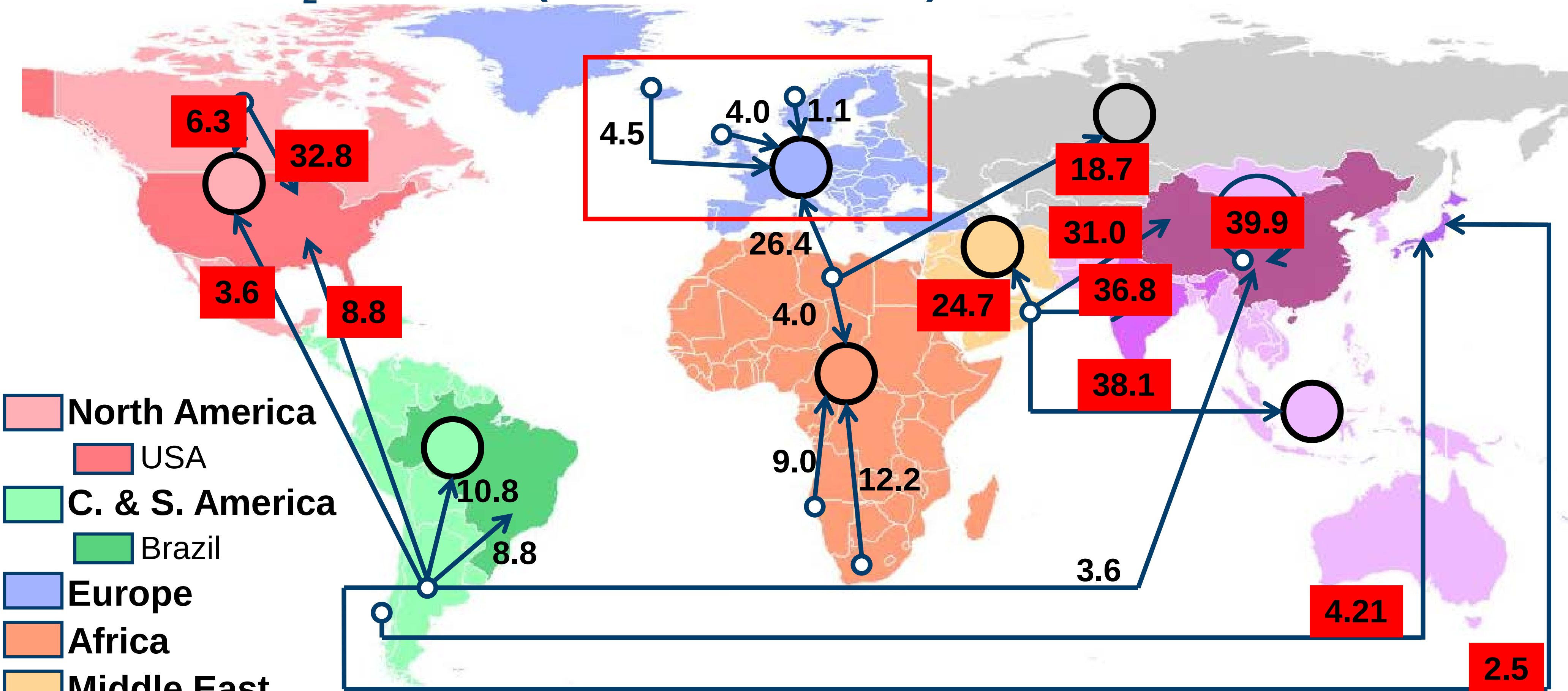
Lulls of 2- 3 Weeks are to be Expected in Central Europe

- European electricity grid considered



Hydrogen Storage has the Potential to Furnish the Energy Demand during Lulls

Worldwide H_2 Allocation (Reference Scenario) - Flows in million tons



	Germany	Japan	Europe	USA	China	India	Southeast Asia
Demand in Mt/a	4.57	6.7	31.4	41.7	70.9	36.8	38.1
Import cost in €/kg	3.61	3.83	3.86	3.68	4.05	3.84	3.99

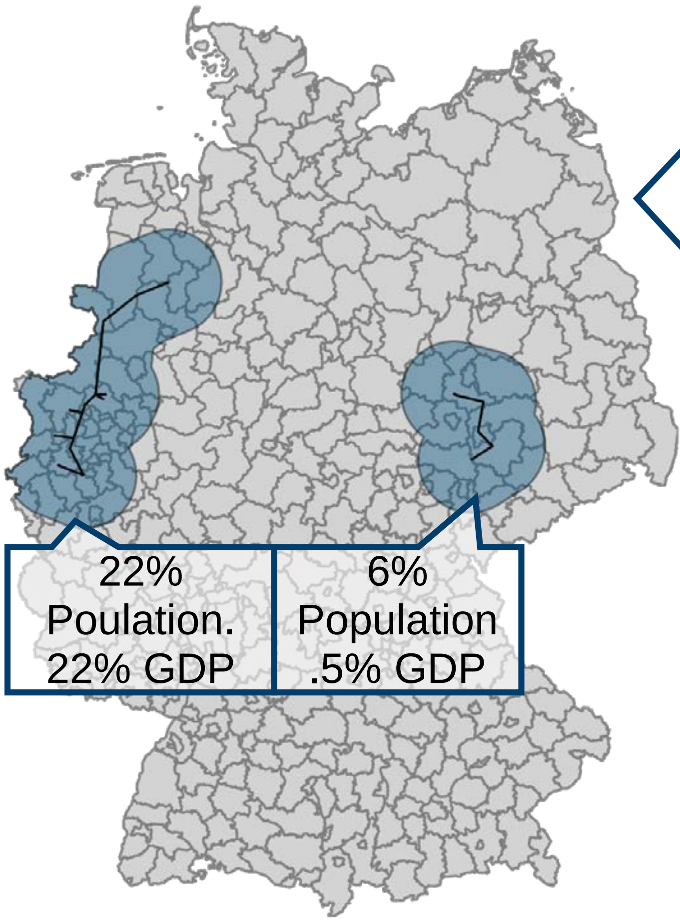
H_2 flows in Mt

Example of NG Pipeline Reassignment Potential for Germany

Multiple Tube Pipelines Considered Only w/ a single tube (NG distribution not interupted)

Distance: ~420 km

2020-2025

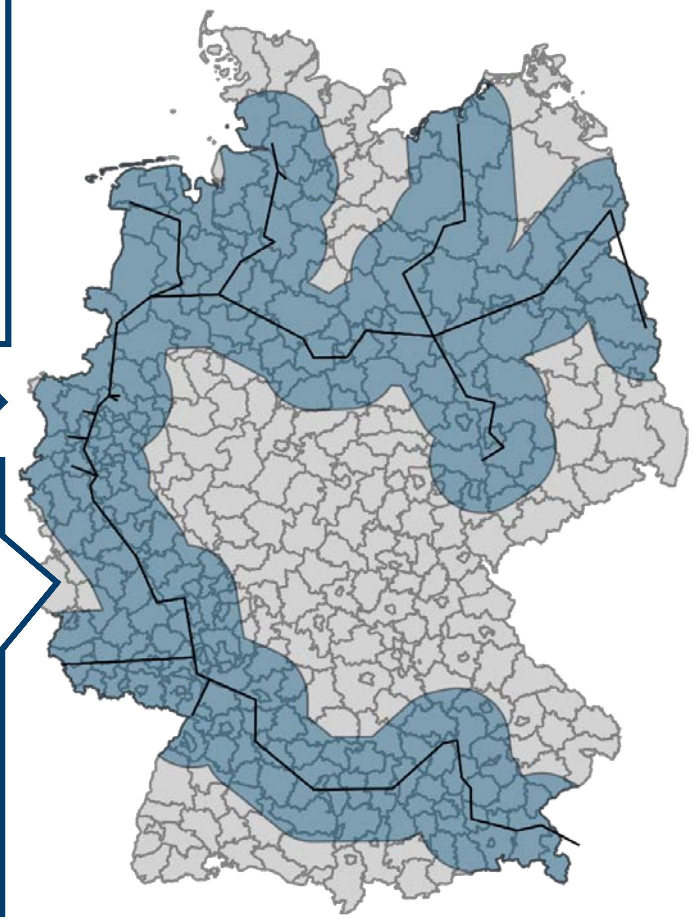


Market Potential
(Perimeter 50km):
Population (2017):
~23,5 mn (~28%)
GDP (2017):
~800 bn € (~27%)

Market Potential
(Perimeter 50km):
Population (2017) [1]:
~67 mn (~81%)
GDP (2017) [2]:
~2.500 bn € (~83%)

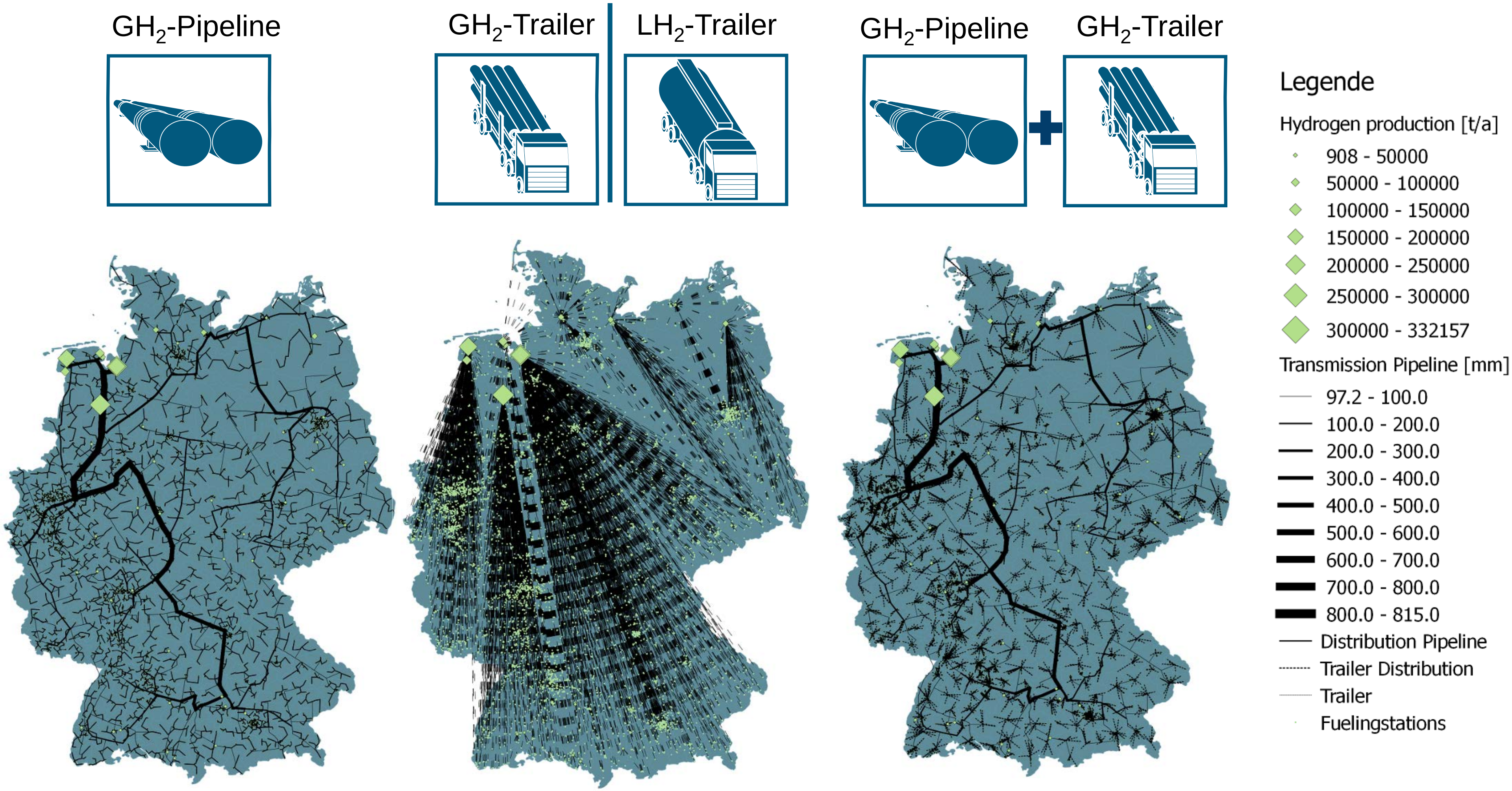
Distance: ~2600 km

2035-2040



[1] Eurostat (2018). Bevölkerung am 1. Januar nach Altersgruppen, Geschlecht und NUTS 3 Regionen.
[2] Eurostat (2018). Bruttoinlandsprodukt (BIP) zu laufenden Marktpreisen nach NUTS-3-Regionen.

Final Geospatial Results: Scenario for 20 million FCV



Transportation Application as an Example (numbers for passenger vehicles)

Battery vehicle (renewable electricity)	Fuel cell vehicle (renewable electricity)
Efficiency: 80 % x 85 % = 68 % (W2T) (T2W)	Efficiency: 63 % x 60 % = 38 % (W2T) (T2W)
Combustion engine (CO_2-based fuels)	**Combustion engine (bio-fuels)**
Efficiency: 70 % x 50 % x 25 % = 9 % (H_2) (plant) (T2W)	Efficiency: 50 % x 25 % = 13 % (W2T) (T2W)

Today's W2W Effciency ≈18% w/ combustion engines

T2W: tank-to-wheel
W2T: well-to-tank
W2W: well-to-Wheel
W2W = total efficincy

Furthermore:
Trucks (from LDV to HDV)
Local Trains (cruising range 600 to 1000 km)

Fuel Cells are on the Market

- Emission-free transportartion from paasenger vehicles via trains to long haul trucks

750 km cruising range

600 km cruising range

327 passengers

400 km cruising range

34 t truck

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Thank You for Your Attention!

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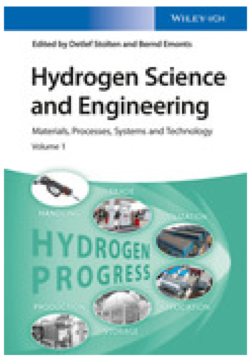

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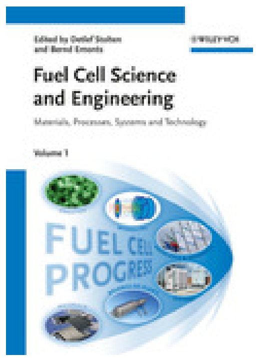

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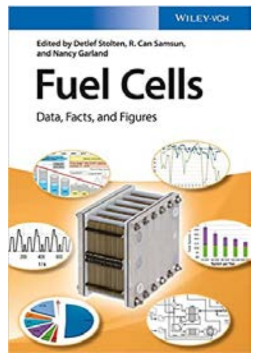

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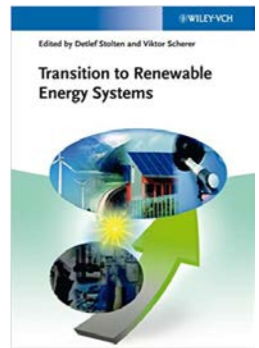

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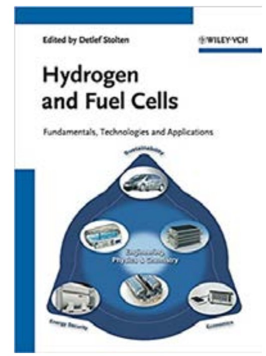

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