Batteries and Fuel Cells as an Opportunity for Zero Emission Transportation

MAY 22, 2019 | PROF. DETLEF STOLTEN

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d.stolten@fz-juelich.de

IEK-3: Institute of Electrochemical Process Engineering

Setting the Scene

Basic Requirements for a Future Energy System

- According to **COP21** requirements as for 2050 global temperature rise shall be curbed to +1.5 to 2°C, translating into **CO_2 emissions reductions of 80-95 %** based on 1990
- After the transition period energy should **no**t 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 to achieve these goals**
- Teratogenic, carcinogenic and poisonous substances shall be avoided
- Nuclear hazards and extremely high cost of new nuclear plants to be considered
- Radiative forcing to be considered (e.g. methane > 20) for new energy pathways

Introductory Remarks

- 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)

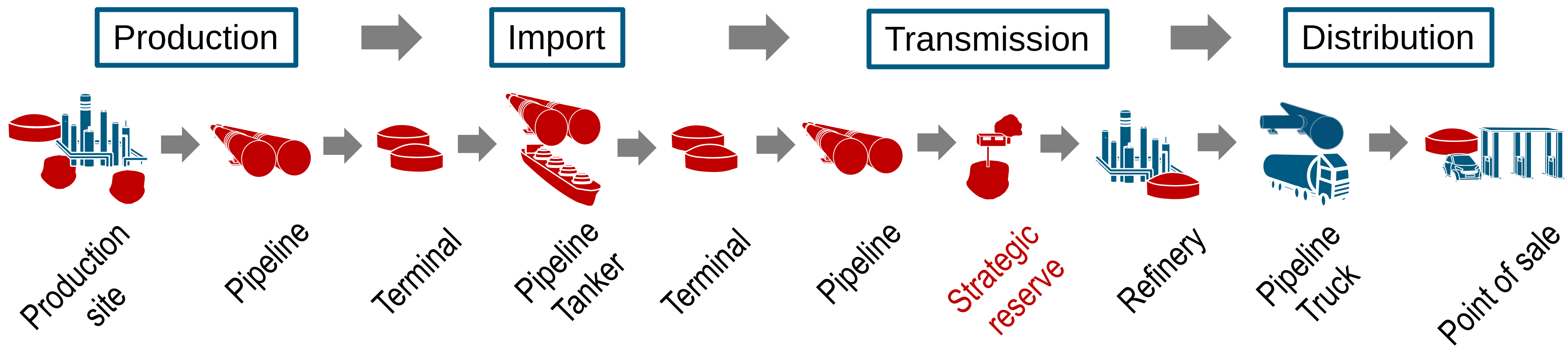
Methane storage

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 large amounts of storage – as we have implemented today**

Storage Elements in the Supply Chain of Crude Oil Products

- Fossil fuel supply chain developed as resilient system to handle possible supply security risks
  - Strategic reserve storage (**90 days** eq. **24.5 million tons** for Germany) to handle market risks [1,2]
  - System immanent chemical storage at each step of the supply chain for supply stability (e.g.: **110,000** liters of oil at each fueling station or **50,800,000** liters at typical tanker [3])



➢ **Highly stable and secure system requires necessary inertia through stockholding and storage** [4]

[1] Minimum Stockholding Obligation and Compliance, (2017). International Energy Agency (IEA).
[2] Ölkrisenvorsorge und -management, (2018). Bundesministerium für Wirtschaft und Energie (BMWi).
[3] Lemieux, S. (2013). Energy Understanding Our Oil Supply Chain, American Petroleum Institute (API).
[4] The role of gas storage in internal market and in ensuring security of supply, (2015). European Commission.

Timeline for CO_2-Reduction and the Implication of TRL Levels

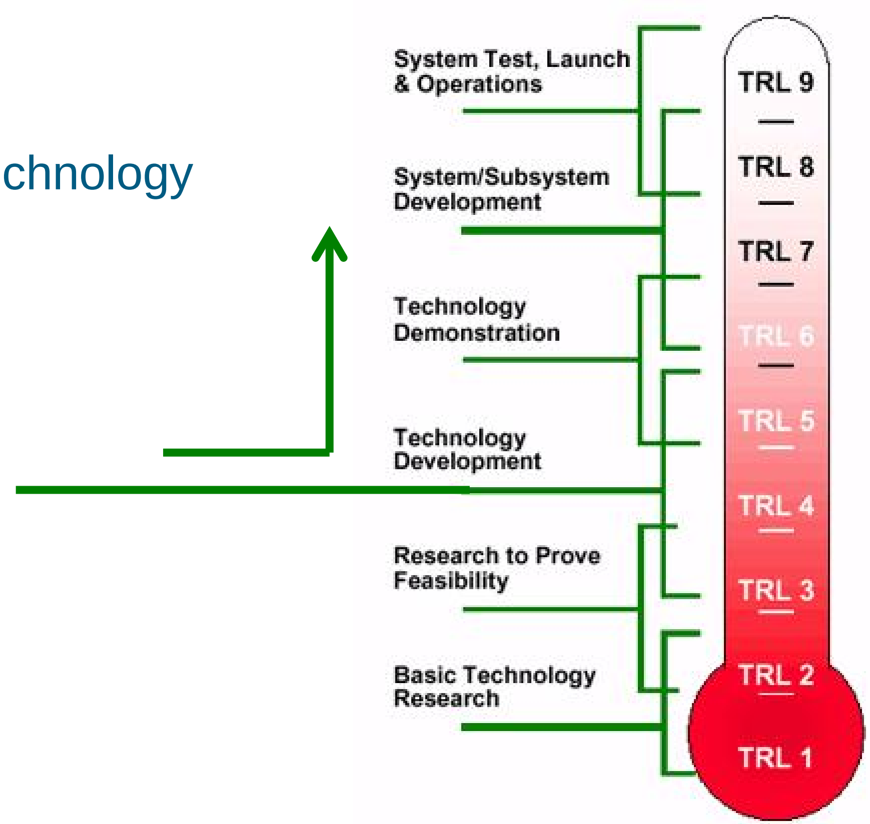
- **2050:** 80% reduction goal fully achieved
- **2040:** start of market penetration
- **2030:** research finalized for 1st generation technology

Development period: unil 2040

Research period: until 2030

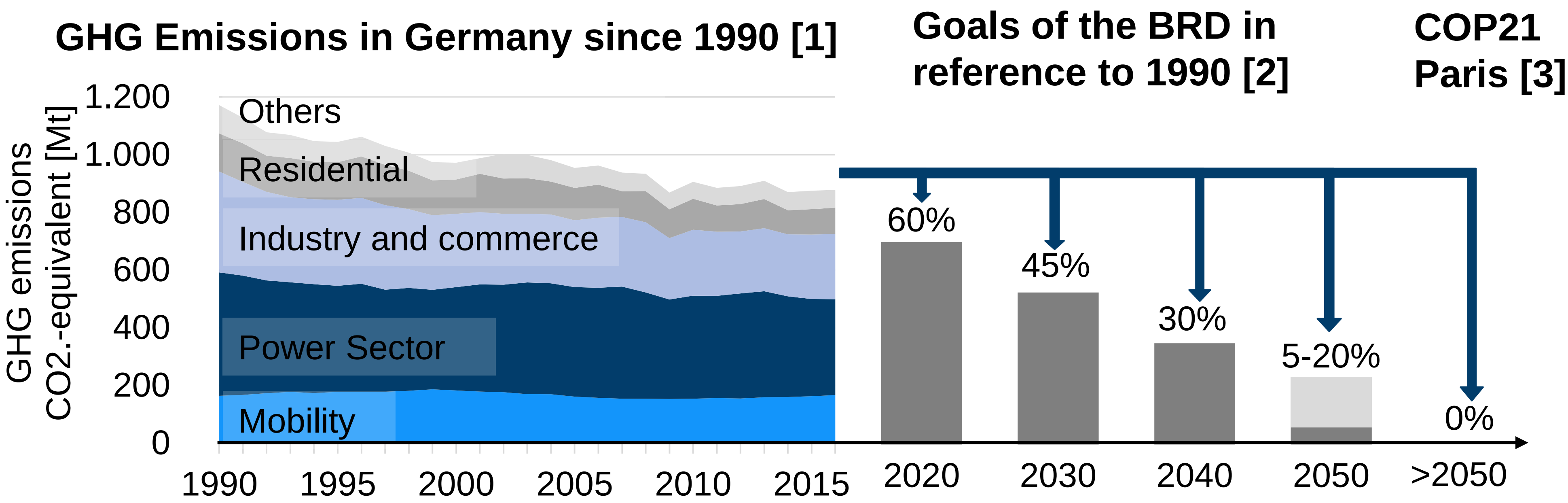
⇒ 11 years left for 1st generationresearch

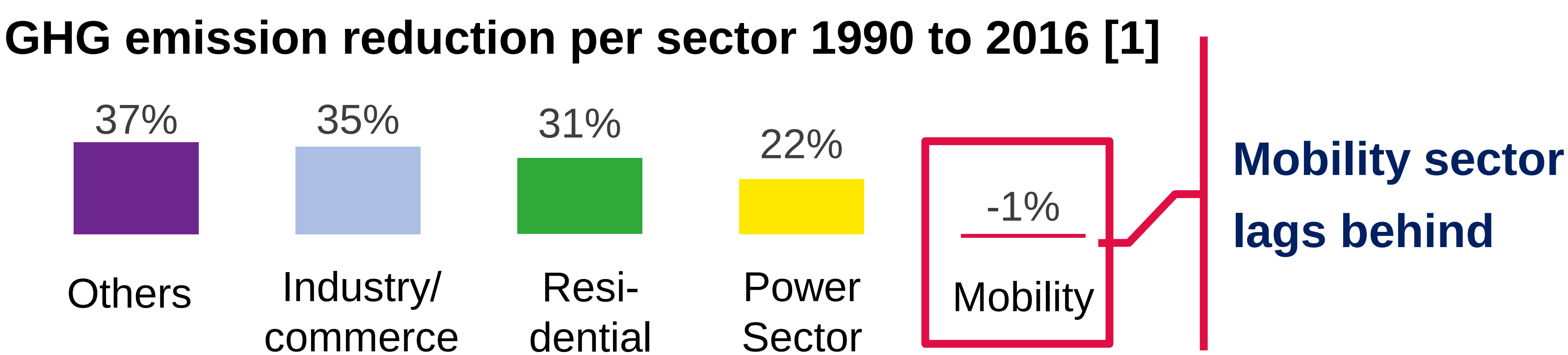
⇒ TRL 5 and higher or TRL 4 at least required



This is not to say research at lower TRL levels is not useful,
it will just not contribute to the 2050 goal

GHG Emission Goals of Germany Require Transformation of All Sectors





[1] BMWi, *Zahlen und Fakten Energiedaten - Nationale und Internationale Entwicklung*. 2018, Bundesministerium für Wirtschaft und Energie: Berlin.
[2] BRD, *Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung*, Bundeskabinett. 2010: Berlin.
[3] UN, *Paris Agreement - COP21*, United Nations Framework Convention on Climate Change 2015: Paris.

Comparison of Battery and Fuel Cell Vehicles

Approach

Meta-analysis of existing infrastructure scenario studies

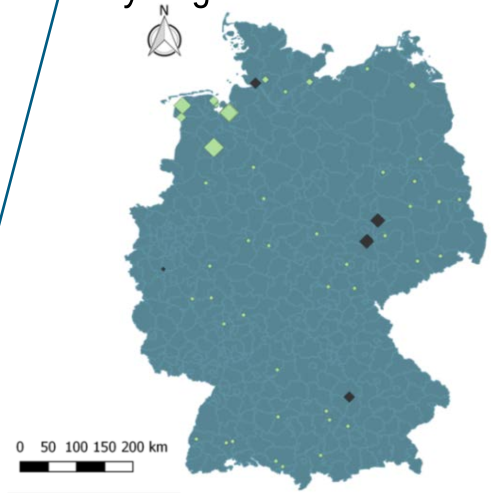
In depth scenario analysis of infrastructure designs, Case Study for Germany

Consistent scenario framework with different vehicle penetration

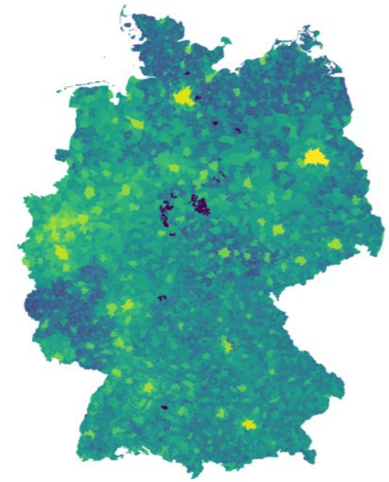
Spatially and temporally resolved models for generation, conversion, transport and distribution

Analysis of investment, costs, efficiencies and emissions

Hydrogen Production

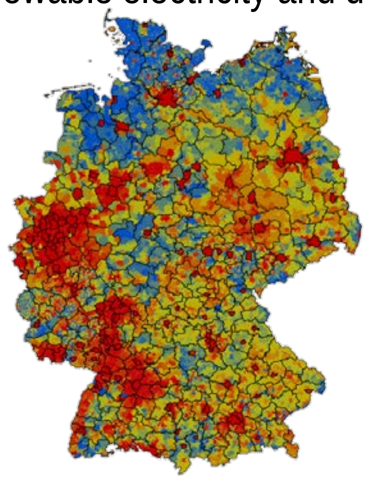


Electric Vehicle Penetration

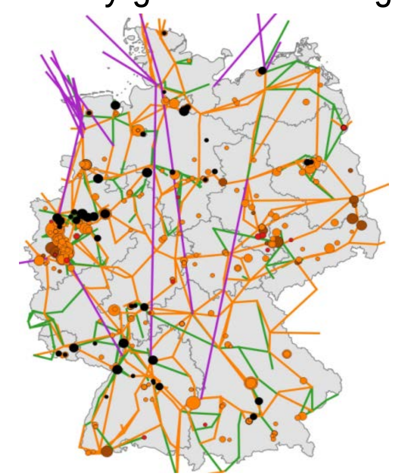


Number of in million	0.1	1	3	5	10	20
Market penetration scenario	**Ramp up**			**Mass market**		

Renewable electricity and demand



Electricity generation and grid



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Status Quo of Infrastructure

- Hydrogen Fueling
  - Approx. 2,500 FCEV in operation worldwide
  - **Worldwide:** 213 public Hydrogen Fueling Station (HRS) in operation by end of 2016: Japan (44%), USA (17%), Germany (13%)
  - **Germany:** network with 30 HRS (06/2017); at present, 27 HRS under construction or planned in Germany,
    → target: 400 HRS before 2023
  - Pipeline systems for hydrogen transport concentrated for chemical uses of hydrogen

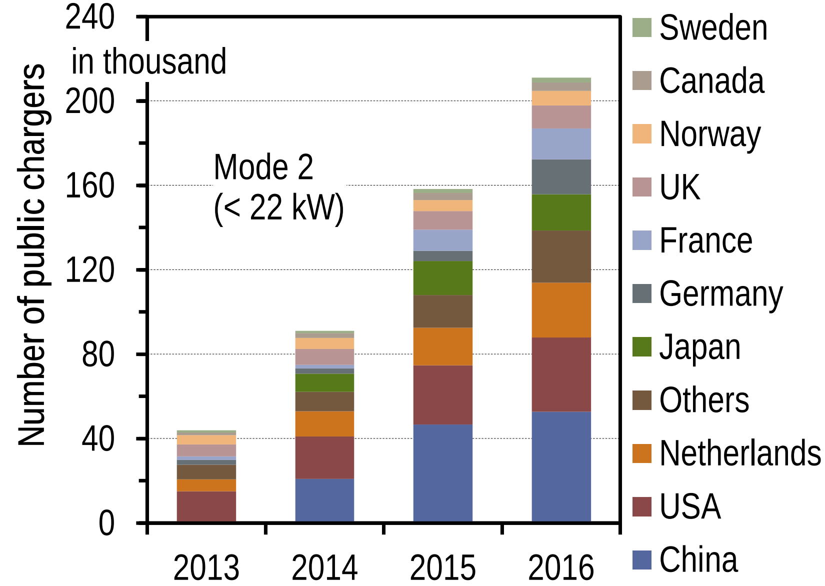
Existing Hydrogen Pipelines (as of 2017-05)	
The USA	2,608 km
Europe	1,598 km
of which in Germany	340 km
Rest of world	337 km
World total	4,542 km

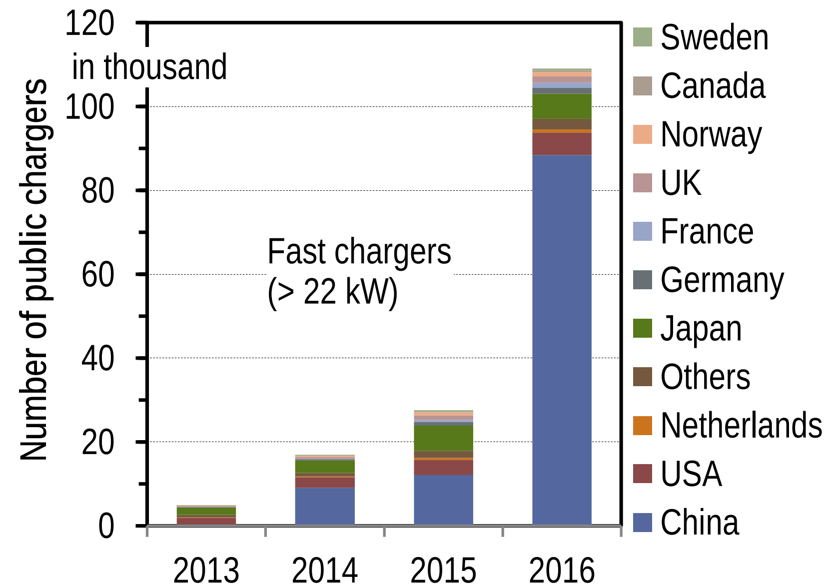
Sources: [9], [10], [14], [15]

Roadmap for hydrogen refueling stations in Germany [12]

Status Quo of Infrastructure

- Electric Charging
  - In 2016, total BEV and PHEV stock was about 2 million worldwide, largely concentrated in China (32 %), followed by the United States (28 %) [16]
  - Dynamic rollout of slow and fast charging worldwide
  - Leading countries by end of 2016 China, the United States and the Netherlands
  - For fast charging options (Modes 3 and 4) highest dynamic and absolute number in China





Sources: [16]

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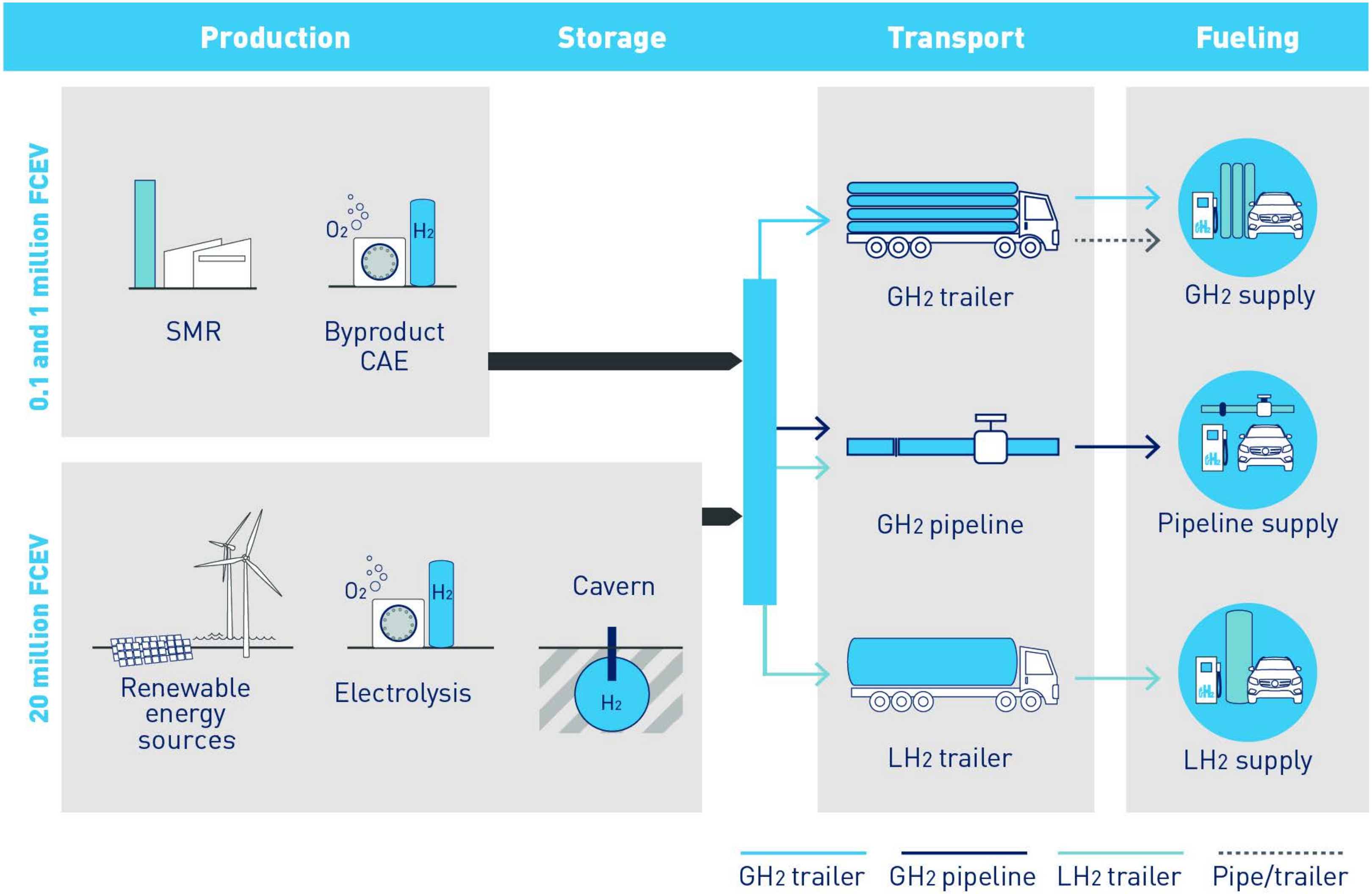
Hydrogen Supply Pathways



Hydrogen Infrastructure Model

- Number of FCEV
- Number of fueling stations
- Investigated pathways

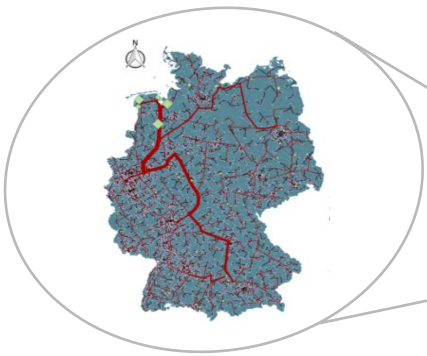
Scenario selection

Preprocessing geospatial data

- Hydrogen production
- Hydrogen demand
- Candidate grid
- (Highway grid)
- Fueling station locations

Geospatial database

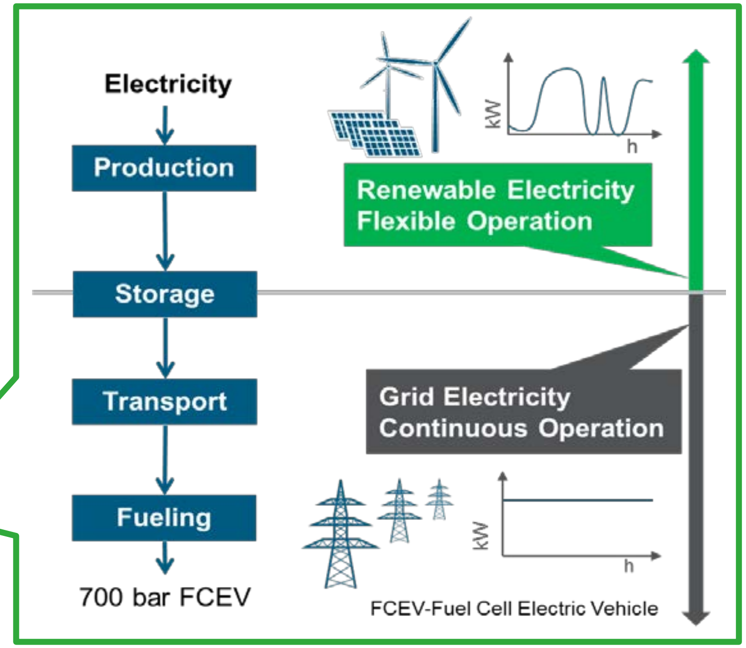
Selection of fueling stations



Optimize grid/route network

Technology database

Hydrogen supply chain model

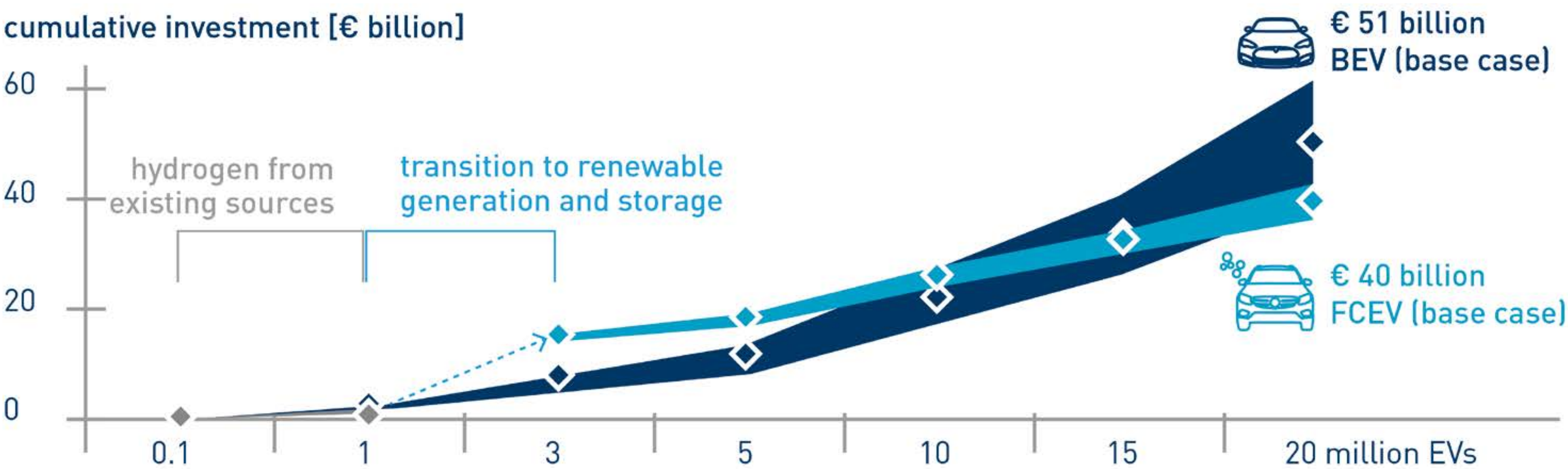


Derive results

- Hydrogen costs
- Energy demand

Cumulative Investment

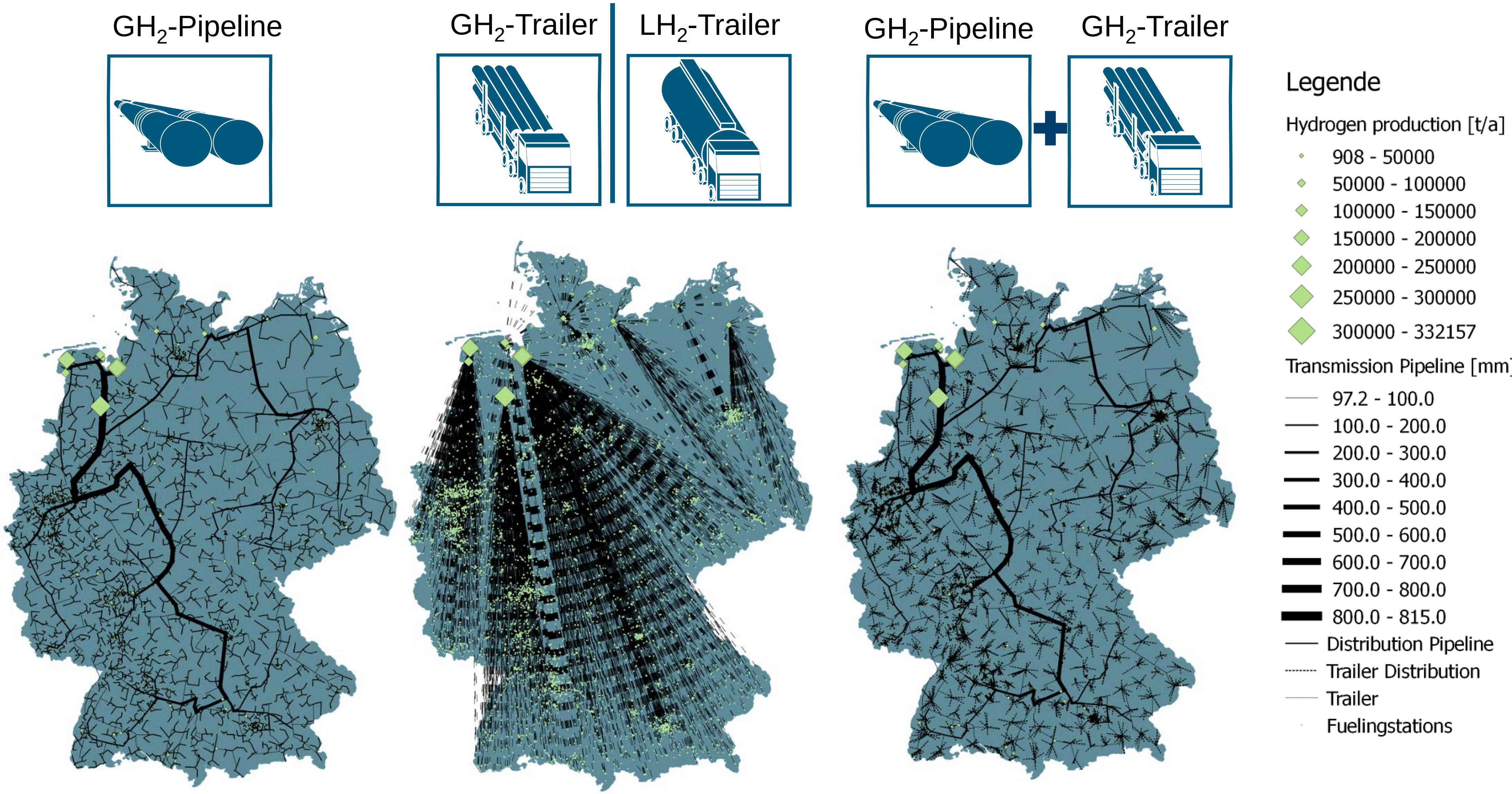
Infrastructure Roll-Out



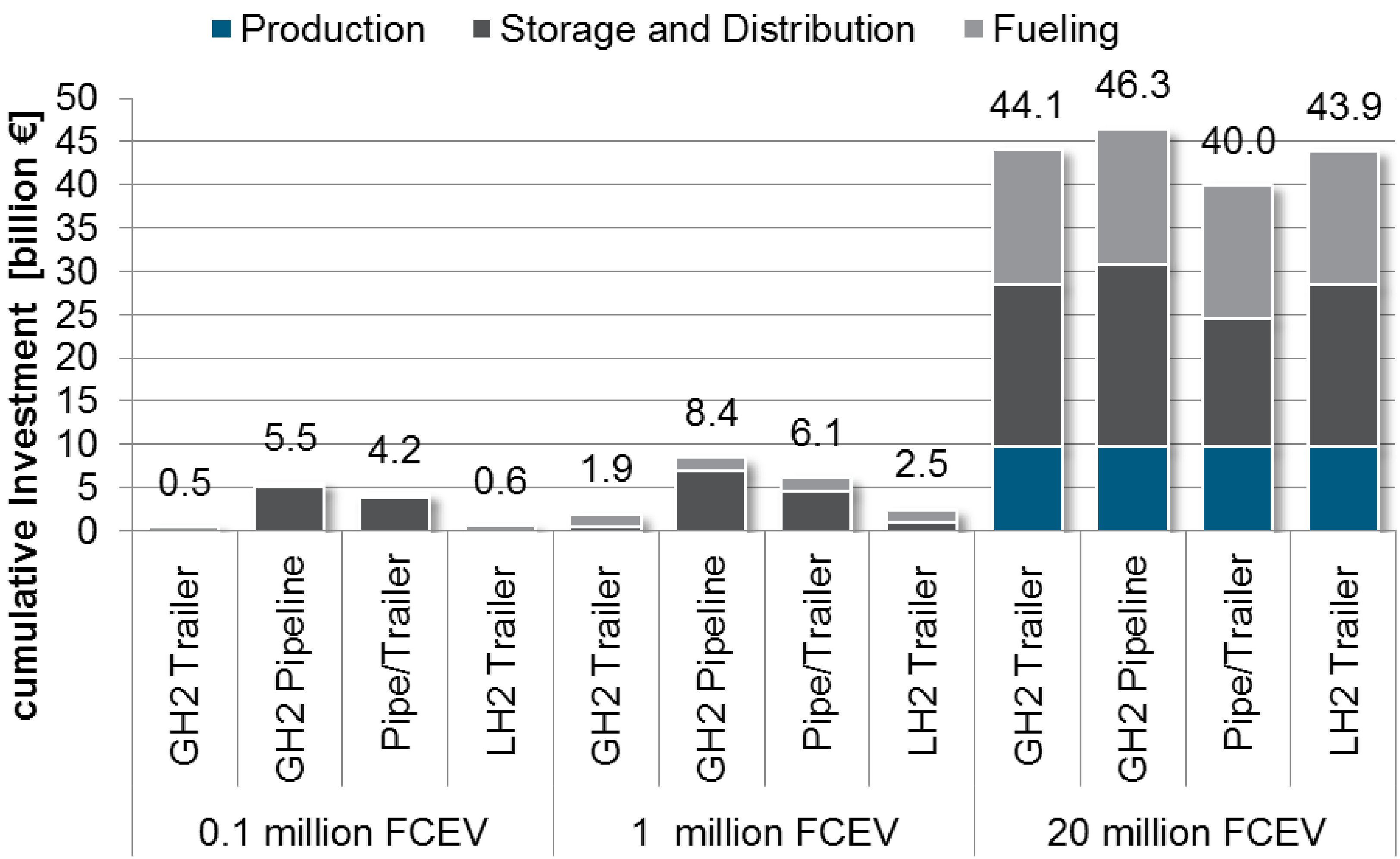
- Hydrogen more expensive during the transition period to renewable electricity-based generation
- High market penetration: battery charging needs more investment than hydrogen fueling
- For both infrastructures investment low compared to other infrastructures

	Investment [€ billion]
Renewable electricity generation scenario	374
Electric grid enhancement plan 2030	34
Federal transport infrastructure plan 2030	265
Hydrogen fueling infrastructure	40
Electric charging infrastructure	51

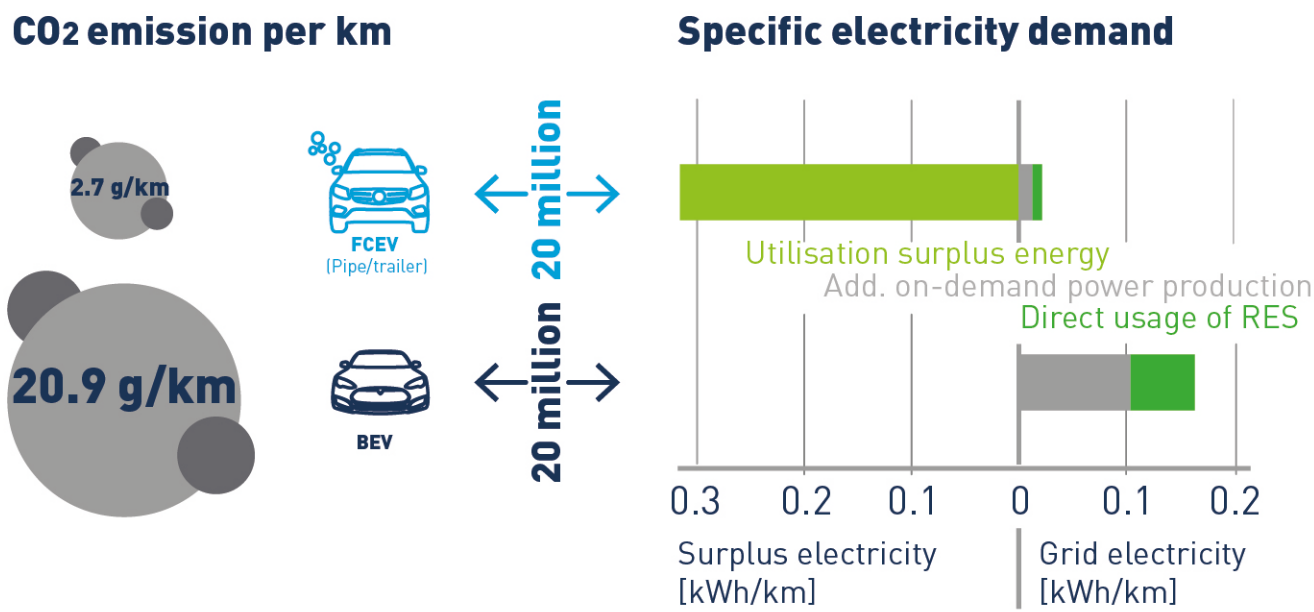
Final Geospatial Results: Scenario for 20 million FCV



Total Cumulative Investment for a Hydrogen Infrastructure



CO_2 Emissions & Electricity Demand



- Efficiency of charging infrastructure is higher, but limited in flexibility and use of surplus electricity
- Fueling infrastructure for hydrogen with inherent seasonal storage option
- Low specific CO2 emissions for both options in high penetration scenarios with advantage for hydrogen, well below the EU emission target after 2020: 95 g_{CO2}/km

THE SPEED OF THE REFUELLING PROCESS DRIVES THE ECONOMIES OF SCALE FOR HYDROGEN

H₂ MOBILITY

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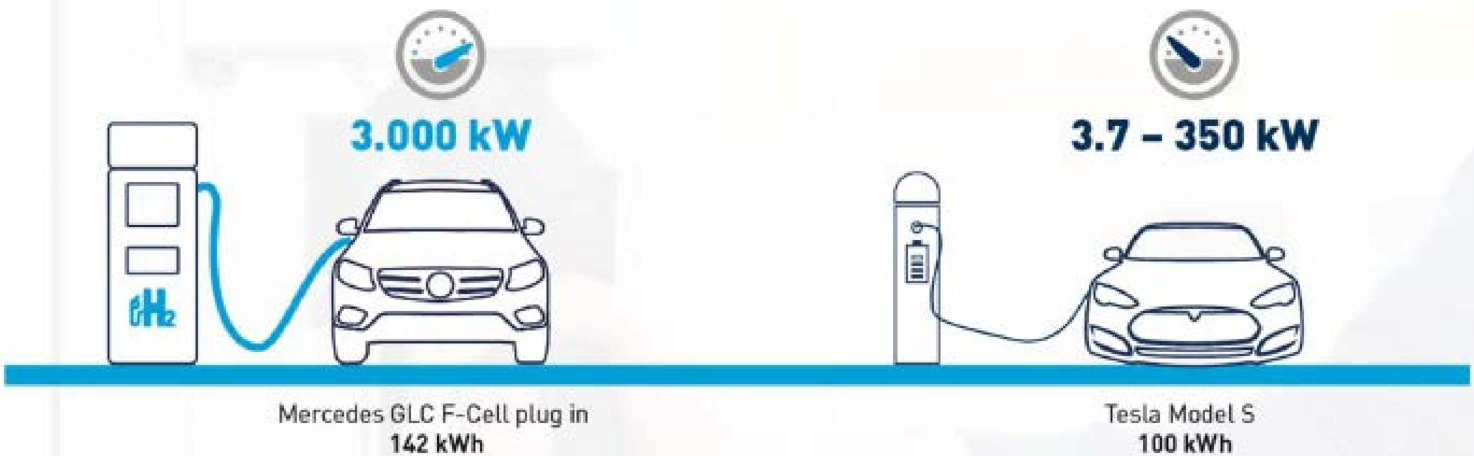
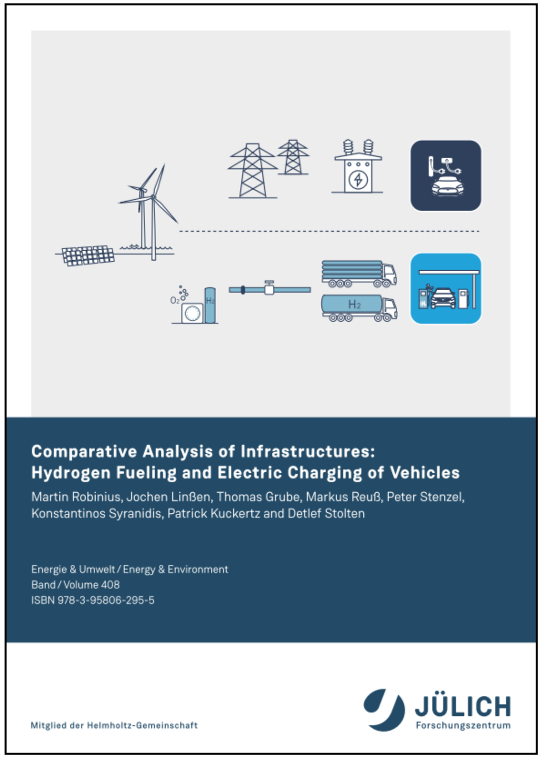


The ultra-fast refuelling process drives the efficient use of the asset:

- ✓ Time efficiency: more efficient use of production and refuelling assets
- ✓ Economics: greater turnover per time unit

Full Report Available

http://hdl.handle.net/2128/16709



Project team:

Martin Robinius, Jochen Linßen, Thomas Grube, Markus Reuß, Peter Stenzel, Konstantinos Syranidis, Patrick Kuckertz and Detlef Stolten

Funded by

H2 MOBILITY
FUELLING HYDROGEN

Do Electro-fuels Provide an Alternative?

Efficiency is Crucial w/ Renewable Power: Hydrogen Delivers on W2W Efficiency

Battery vehicle (renewable electricity)

Efficiency: 80 % x 85 % = 68 %
(W2T) (T2W)

Vehicle cost: ⊖⊖

Fuel production: ⊕

Storage & distrib.: ⊖⊖⊖

Operating range: low

Resources: sufficient

Soot/NOx emissions: none

Fuel cell vehicle (renewable electricity)

Efficiency: 63 % x 60 % = 38 %
(W2T) (T2W)

Vehicle cost: ⊖⊖

Fuel production: ○

Storage & distrib.: ⊕

Operating range: medium

Resources: sufficient

Soot/NOx emissions: none

Combustion engine (CO_2-based fuels)

Efficiency: 70 % x 50 % x 25 % = 9 %
(H_2) (plant) (T2W)

Vehicle cost: ⊖

Fuel production: ⊖⊖

Storage & distrib.: ⊕⊕

Operating range: high

Resources: sufficient

Soot/NOx emissions: medium

Combustion engine (bio-fuels)

Efficiency: 50 % x 25 % = 13 %
(W2T) (T2W)

Vehicle cost: ⊖

Fuel production: ⊖⊖

Storage & distrib.: ⊕⊕

Operating range: high

Resources: limited

Soot/NOx emissions: medium

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

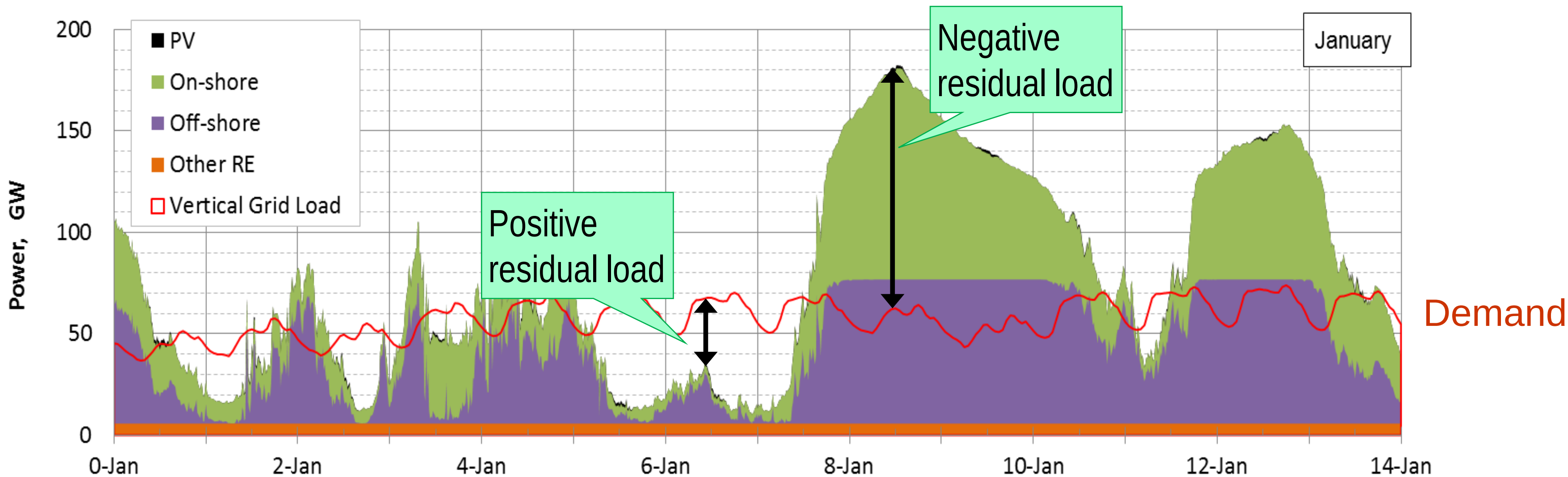
T2W: tank-to-wheel
W2T: well-to-tank
W2W: well-to-Wheel
W2W = total efficincy

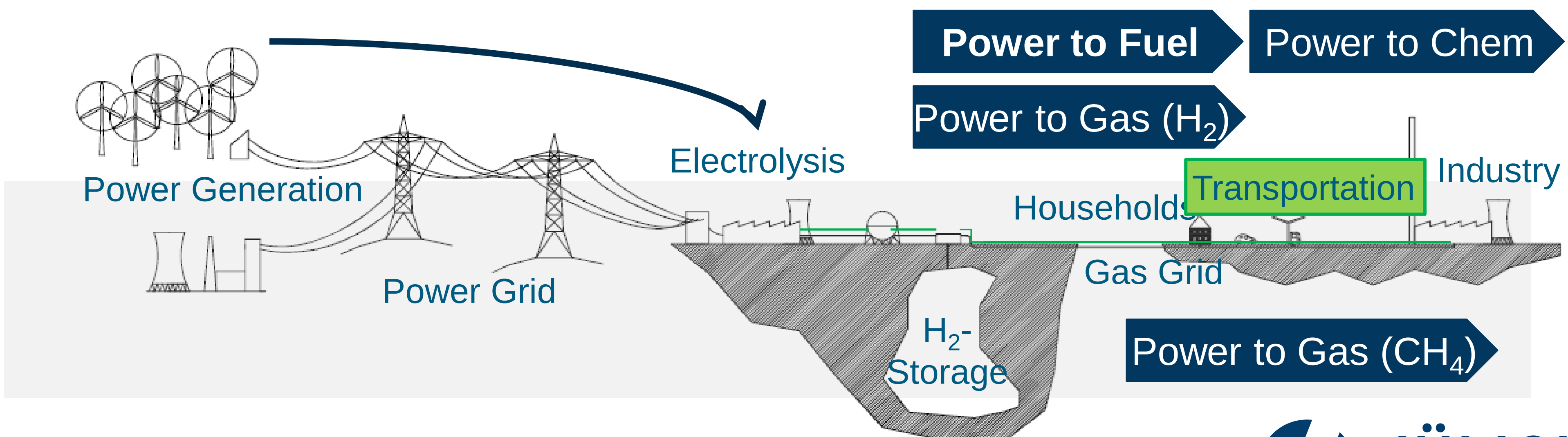
Hydrogen Provision

Excess Energy

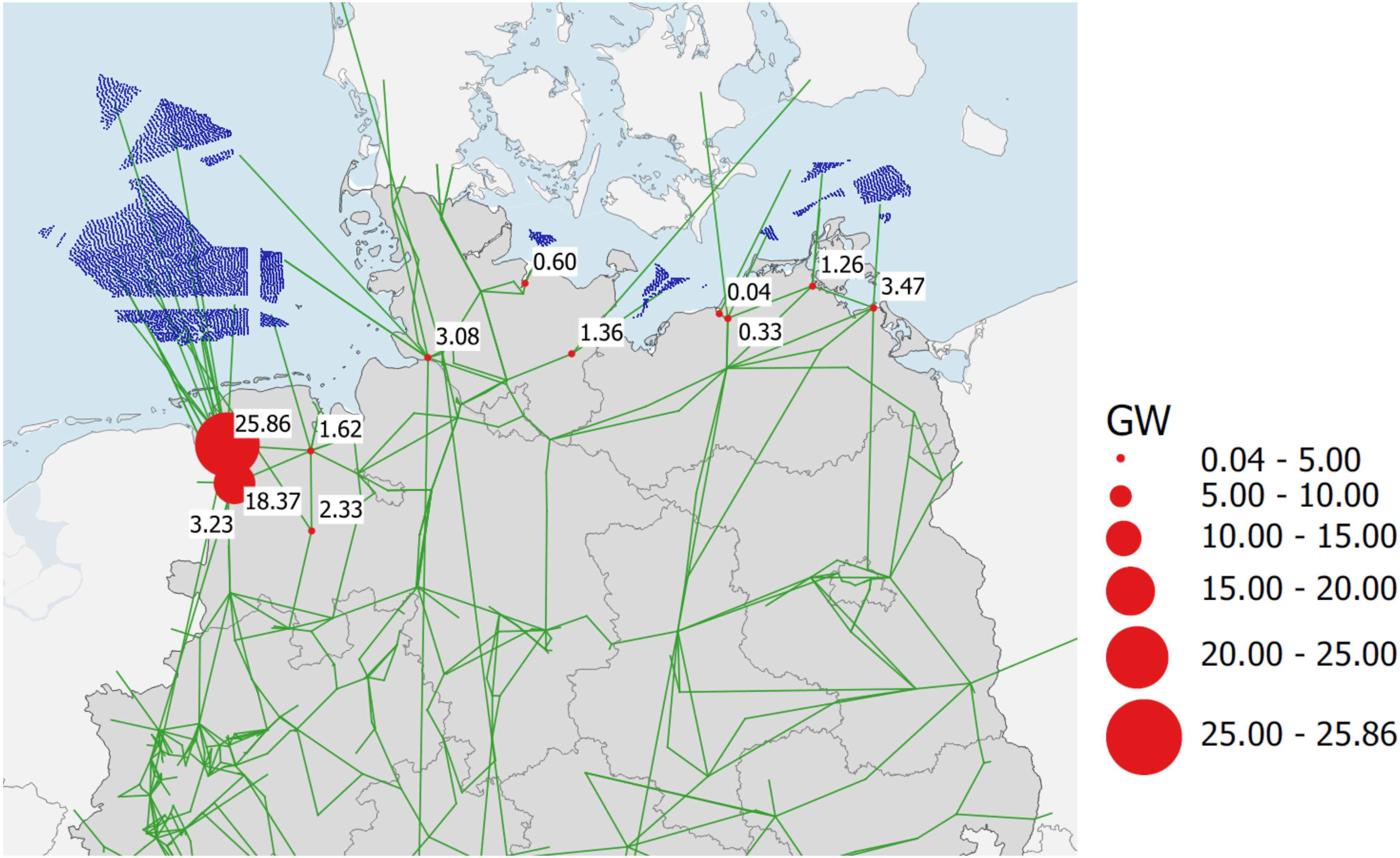
Dedicated RE Installations in Remote Areas

Excess Power is Inherent to Renewable Power Generation

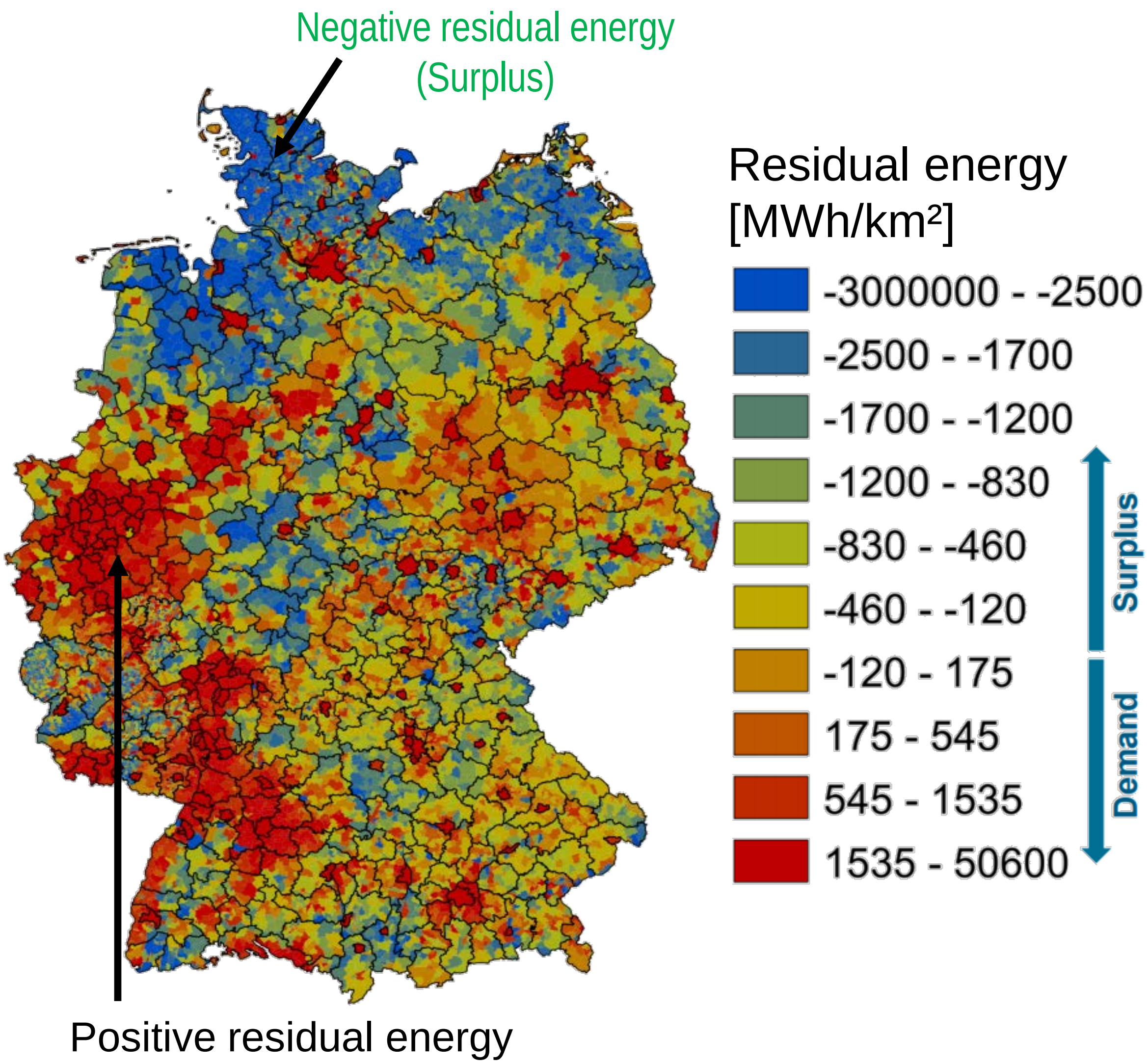


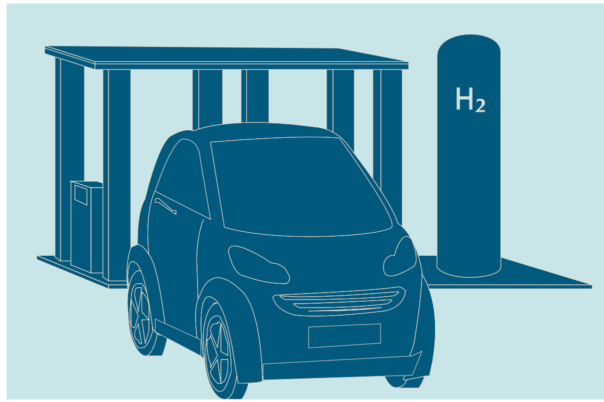


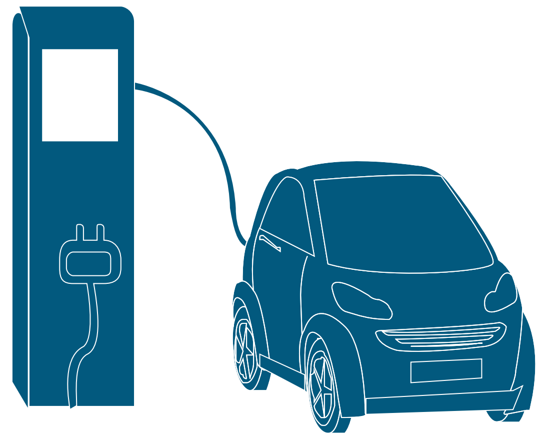
Projected Input of Off-shore Power into the German Power Grid



Linking the Power and the Transport Sector







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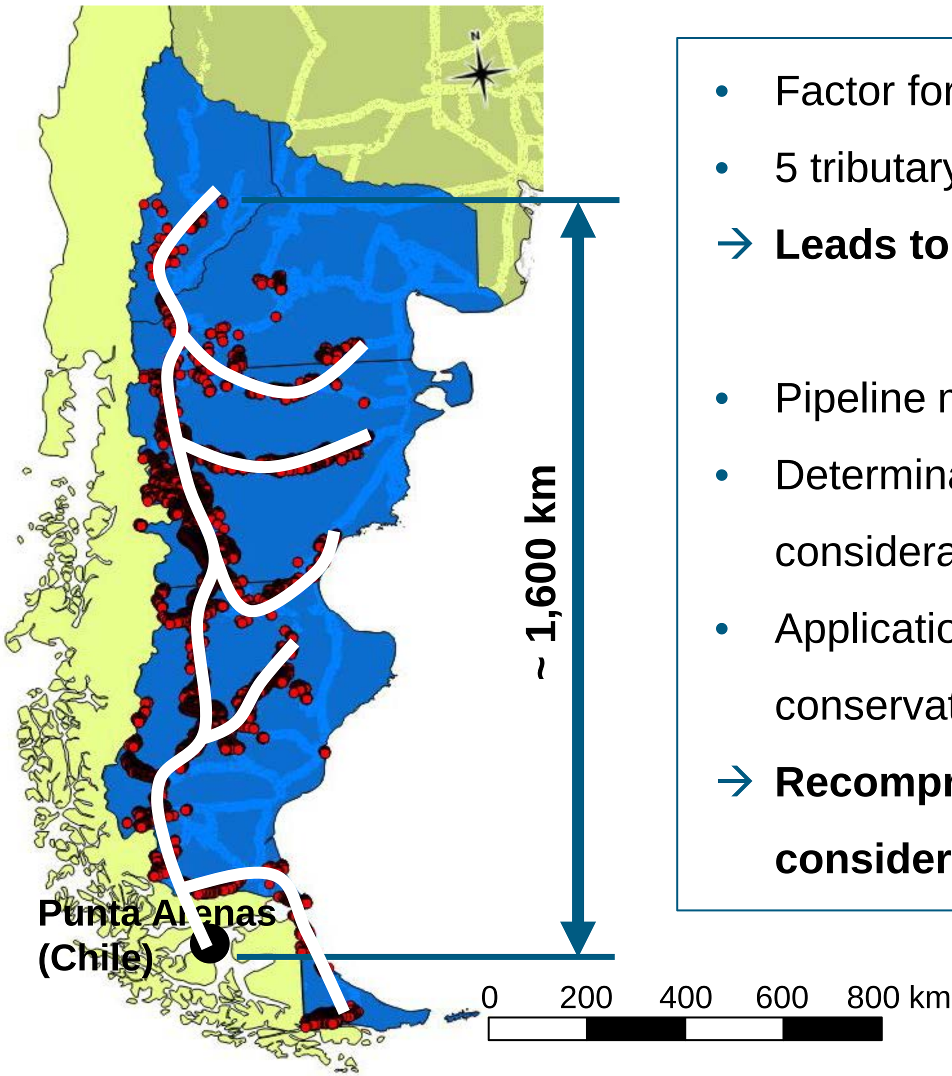
Pipeline through Patagonia to Punta Arenas (simplified)



- Factor for indirect route of 1.2 is considered
- 5 tributary pipelines, 500 km each

→ **Leads to pipeline length of about 4,500 km**

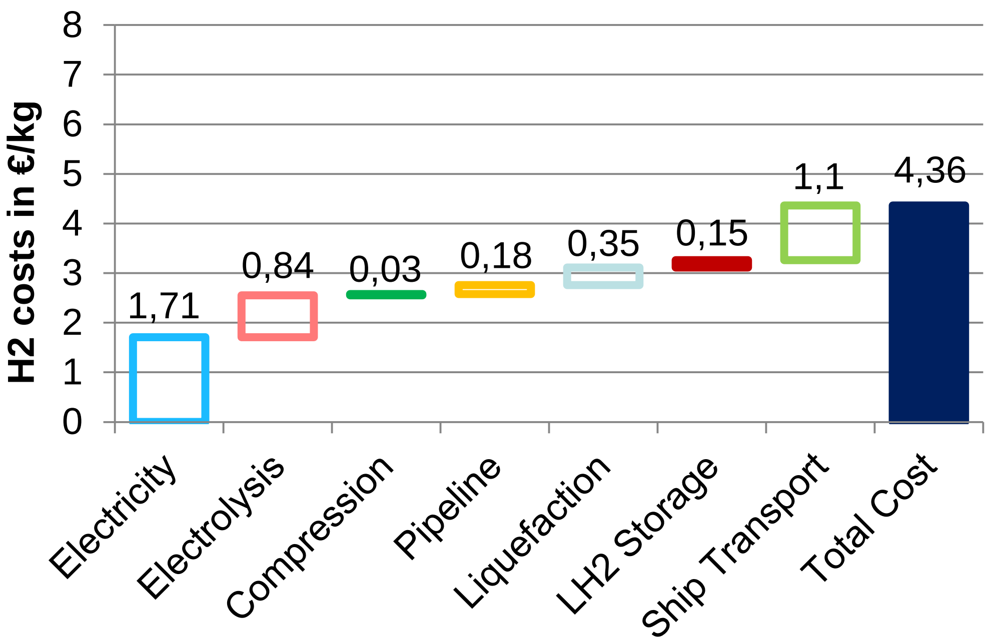
- Pipeline model from V. Tietze, cost data from D. Krieg [1]
- Determination of pipeline quantity and diameter without consideration of recompression
- Application of Krieg‘s cost data (published) leads to more conservative cost estimation

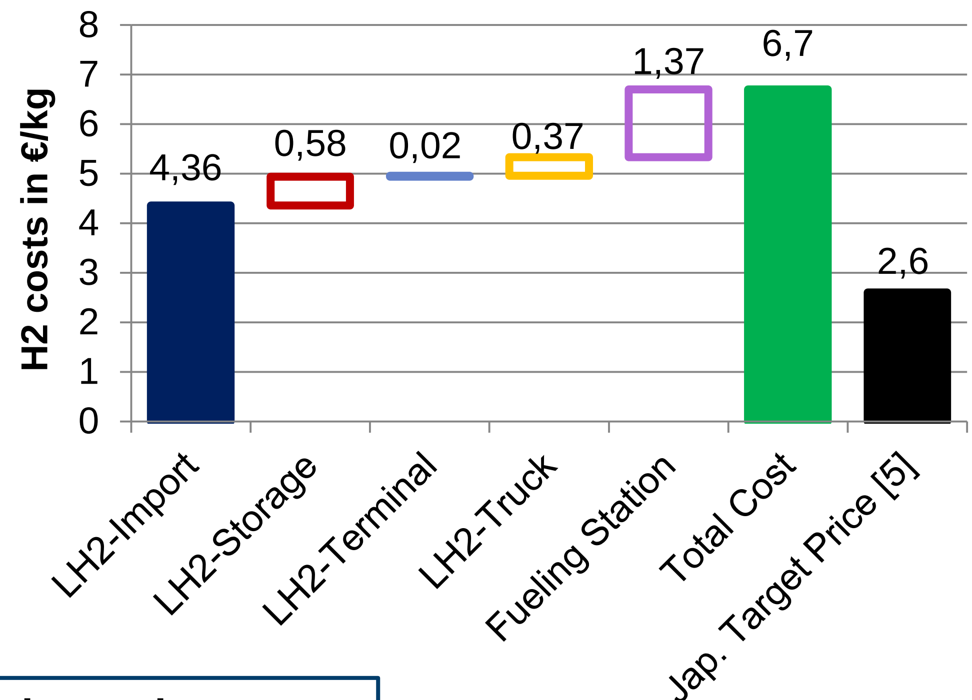
→ **Recompression and associated costs are to be considered in prospective analysis**

[1] Krieg, D. (2012). Konzept und Kosten eines Pipelinesystems zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff.RWTH Aachen University.

Global Energy Supply Systems

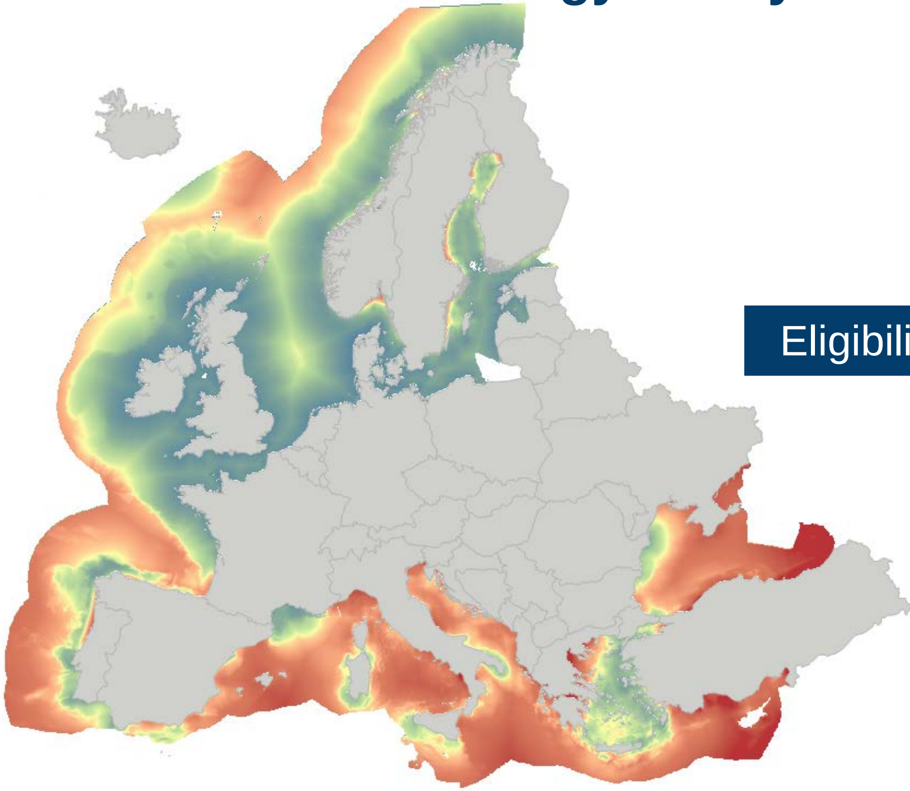
- **Wind potenial in Patagonia sufficient to provide Japan with hydrogen**
  - *Potential of 18 Mt/a of hydrogen for assumed demand of 1.85 Mt/a for 2050 (only mobility)*
  - *Biggest shares in LCOH by **electricity**, **electrolysis**, **ship transport, and fueling stations***
- **LCOH** for provision **at the fueling stations: 6.70 €/kg$_{H2}$ / 7.84 \$/kg$_{H2}$**
  (20.1 €-ct/kWh / 23.52 \$-c/kWh, gasoline: 6.3 €-ct/kWh / 7.37 \$-c/kWh)



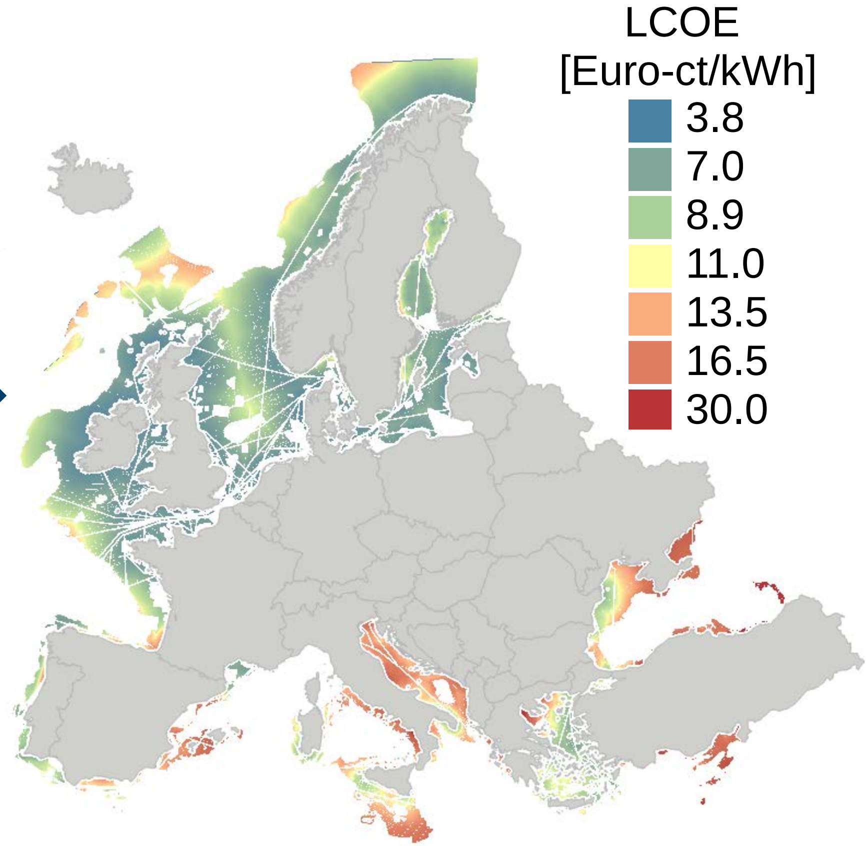


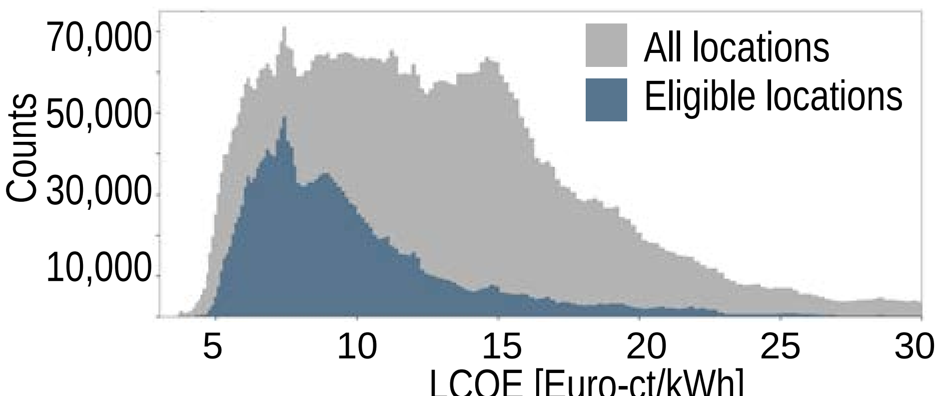
- **Wind-generated hydrogen from Patagonia can be economically competitive to conventional fuels in Japan (with reference to pretax costs)**

Offshore Wind Energy: Analysis



Eligibility Applied

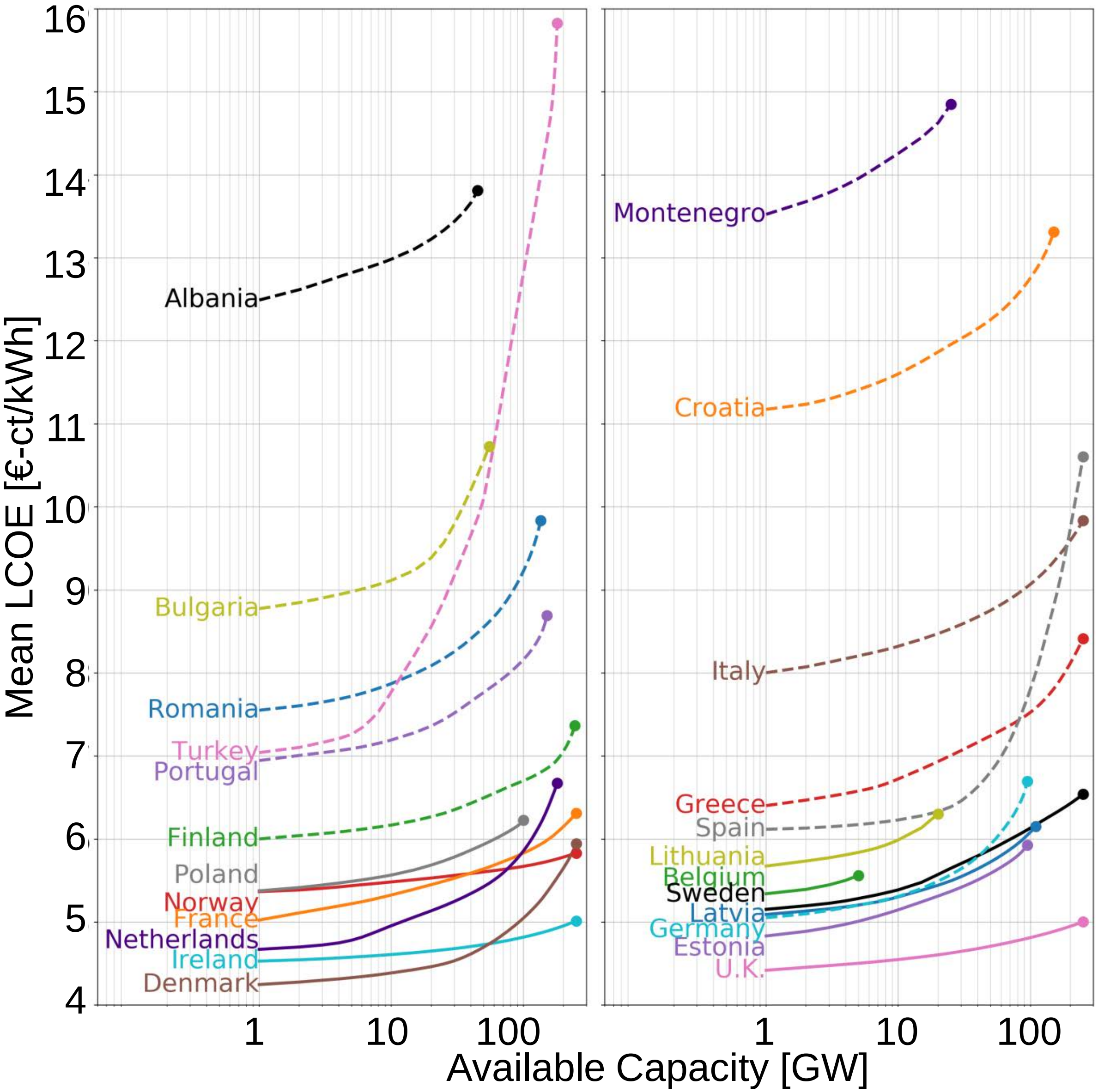




When the results are combined with eligibility:

- **Many** locations with LCOE < 5 Euro-ct/kWh are eliminated by eligibility (distance to shore > 15 km)
- North Sea and Baltic Sea have the cheapest locations

Offshore Wind Energy: Cost over Potentially Available Capacity



Resulting mean LCOE with respect to the available capacity (sorted by lowest LCOE)

Technical potential is **10.7 TW** across Europe

- 2.79 TW Norway
- 2.21 TW Great Britain
- 1.23 TW Ireland

} Countries with highest capacities

Countries where cheap options are available:

- Denmark, U.K., Ireland, Netherlands, Estonia (<5 €-ct/kWh)

All the countries have some technical potential for offshore when economical restrictions are **not** taken into account…

Selected Solar Locations of Saudi Arabia

Analyzed PV potential in Saudi Arabia

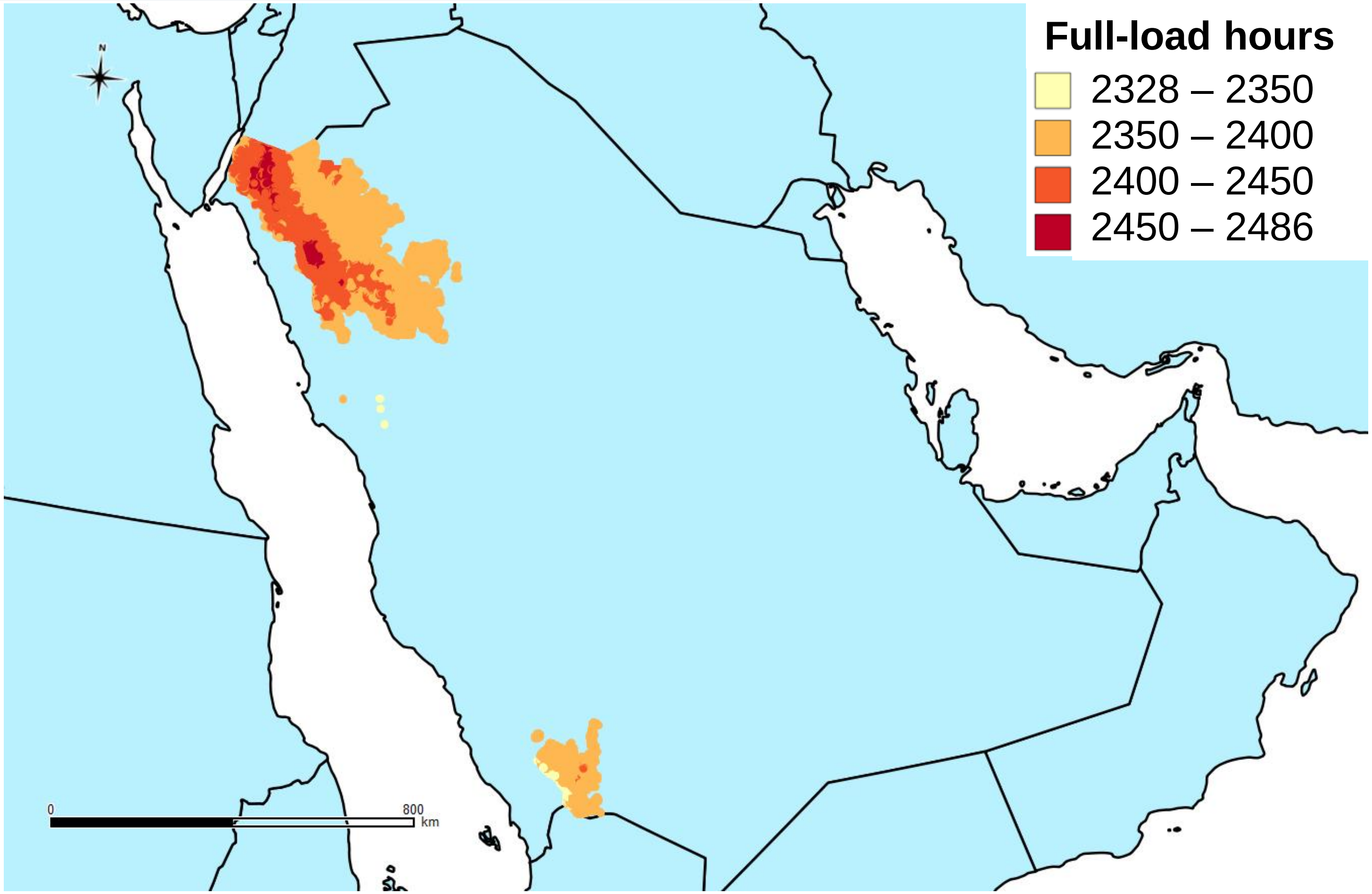
~ 70,100 km² eligible land

~ 76,720 PV locations

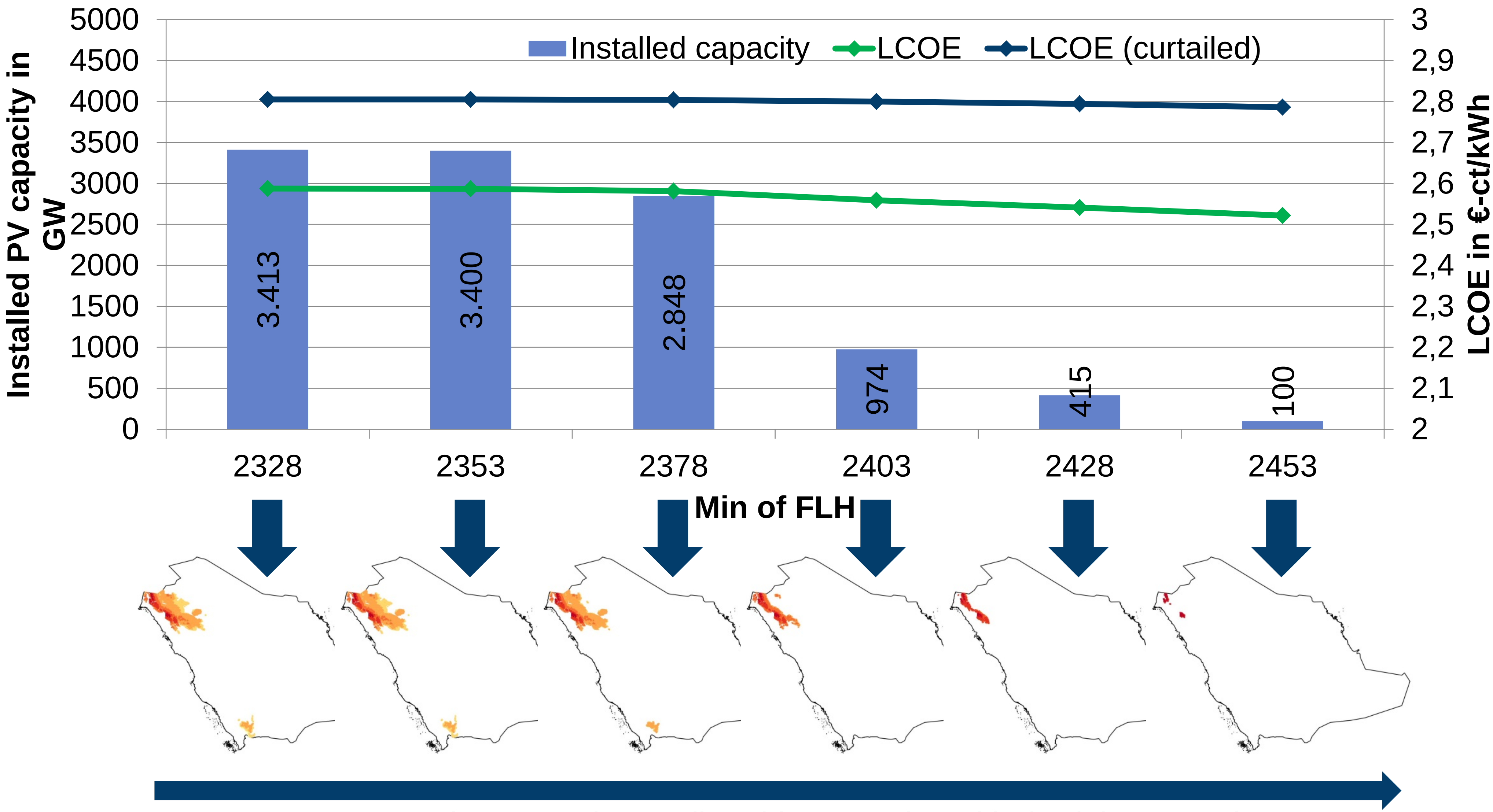
~ 3,505 GW capacity

Additional restrictions:

- Best 5% of all possible locations
- Minimum of full-load hours = 1900

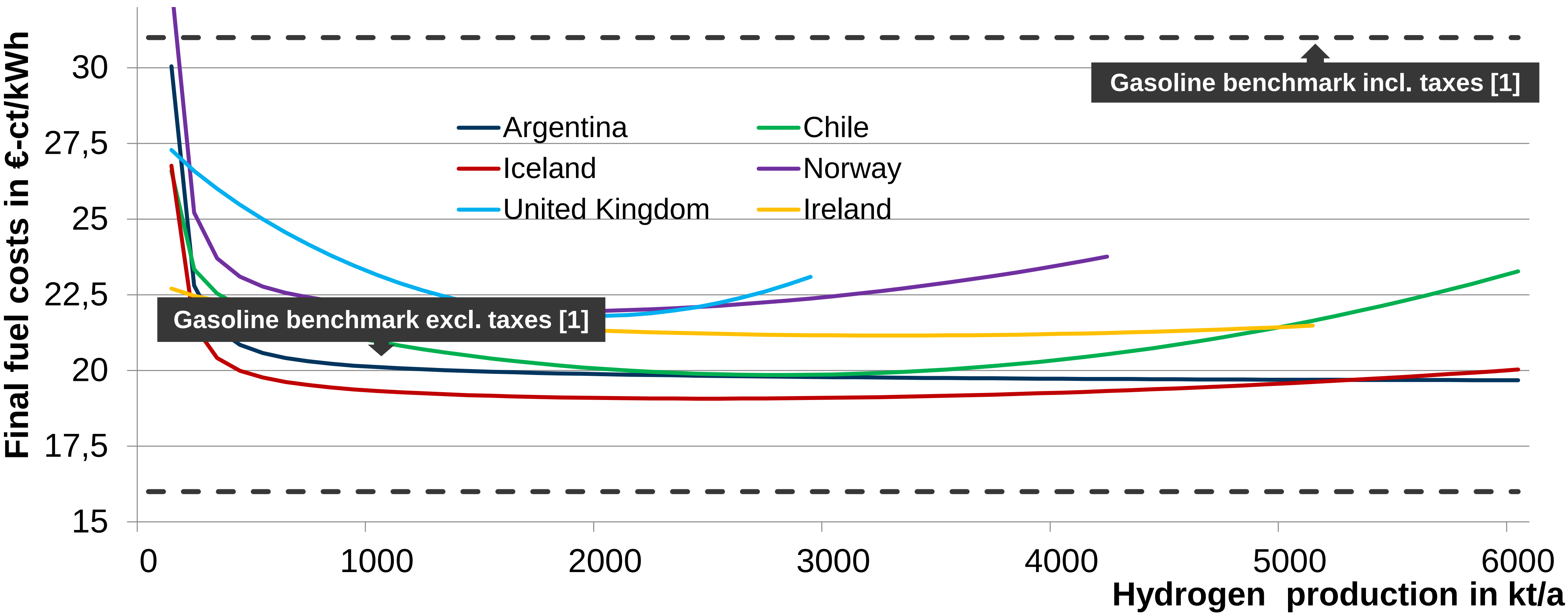


Exemplary Results for Saudi Arabia



Expansion states in Saudi Arabia scenarios with declining capacity

Options for Hydrogen Import from Strong Wind Regions



*** LDV / HDV:** Light / Heavy Duty Vehicle

The Saga of Rising Fuel Prices

If the Energy Transition is successful in some major countries

- **Conventional fuel prices will drop** toward their marginal production cost util a new price level is established; US$5/barrel can be assumed the lowest marginal cost (Saudi Arabia)
- **Finally** that price level will decide over new **explorations** which might **taper off**
- Only **then oil prices might skyrocket**

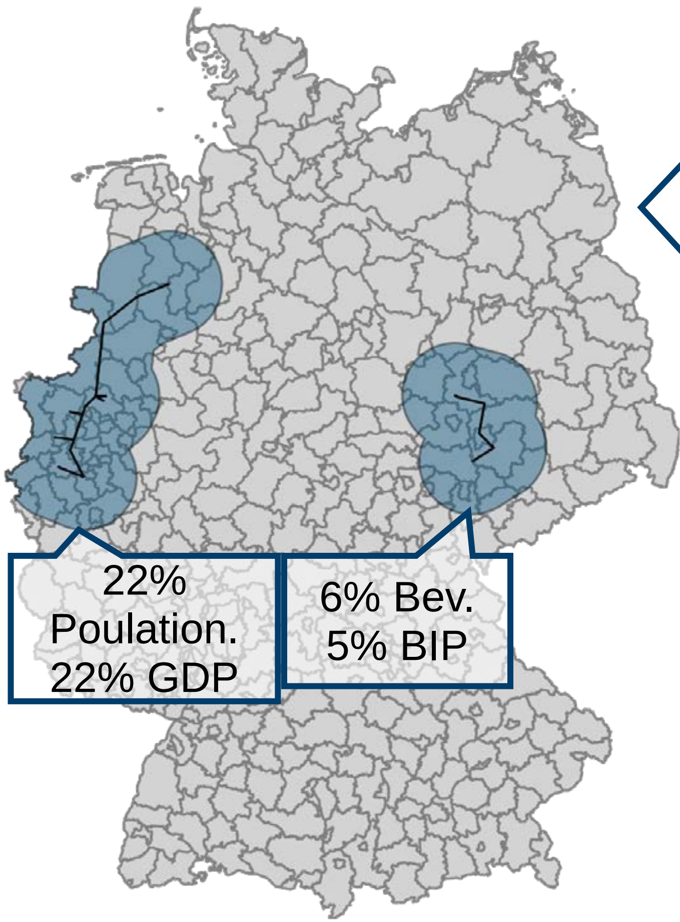
- => **high incumbent market forces to be expected if no counter measures taken**

Example of NG Pipeline Reassignment Potential for Germany

Only Multiple Tube Pipelines Considered

Distance: ~420 km

2020-2025

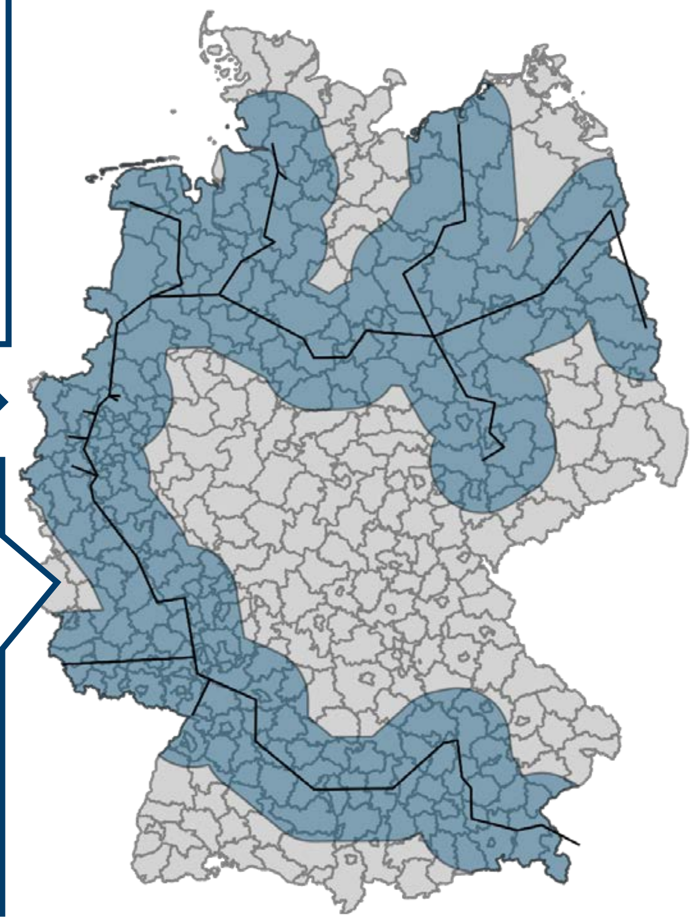


Markpotenzial (Umkreis 50km):
Bevölkerung (2017): ~23,5 Mio. (~28%)
BIP (2017): ~800 Mrd. € (~27%)
Abnahmepotenzial: X kt_{H2}/a
CO_2-Vermeidungspotenzial: X Mt_{CO2}/a

Markpotenzial (Umkreis 50km):
Bevölkerung (2017) [1]: ~67 Mio. (~81%)
BIP (2017) [2]: ~2.500 Mrd. € (~83%)
Abnahmepotenzial: X kt_{H2}/a
CO_2-Vermeidungspotenzial: X Mt_{CO2}/a

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.

Hydrogen Transport

H_2 Pipeline

Property	Today[1]	Future[2]
Capacity t_{H2}/h	2,4	245
CAPEX €/m	500	3400

TRL: 8-9

Advantages:
High throughput capactiy
Low space demand
Low specific cost

Disadvantages:
High upfront cost

Projects:
Leuna (DE)
Texas (US)

Gaseous H_2 Trailer

Property	Today[3]	Future[4]
Capacity kg_{H2}	400	1100
CAPEX €/kg_{H2}	500	600

TRL[3]: 9

Advantages:
No liquefaction required
Low investment cost
Established technology[3]

Disadvantages:
Low transport capacity

Projects:
London (UK)
Oslo (NOR)

Liquid H_2 Trailer

Property	Today	Future
Capacity kg_{H2}	4300	4300
CAPEX €/kg_{H2}	200	200

TRL: 9

Advantages:
Low investment cost
High transport capactiy
Established technology

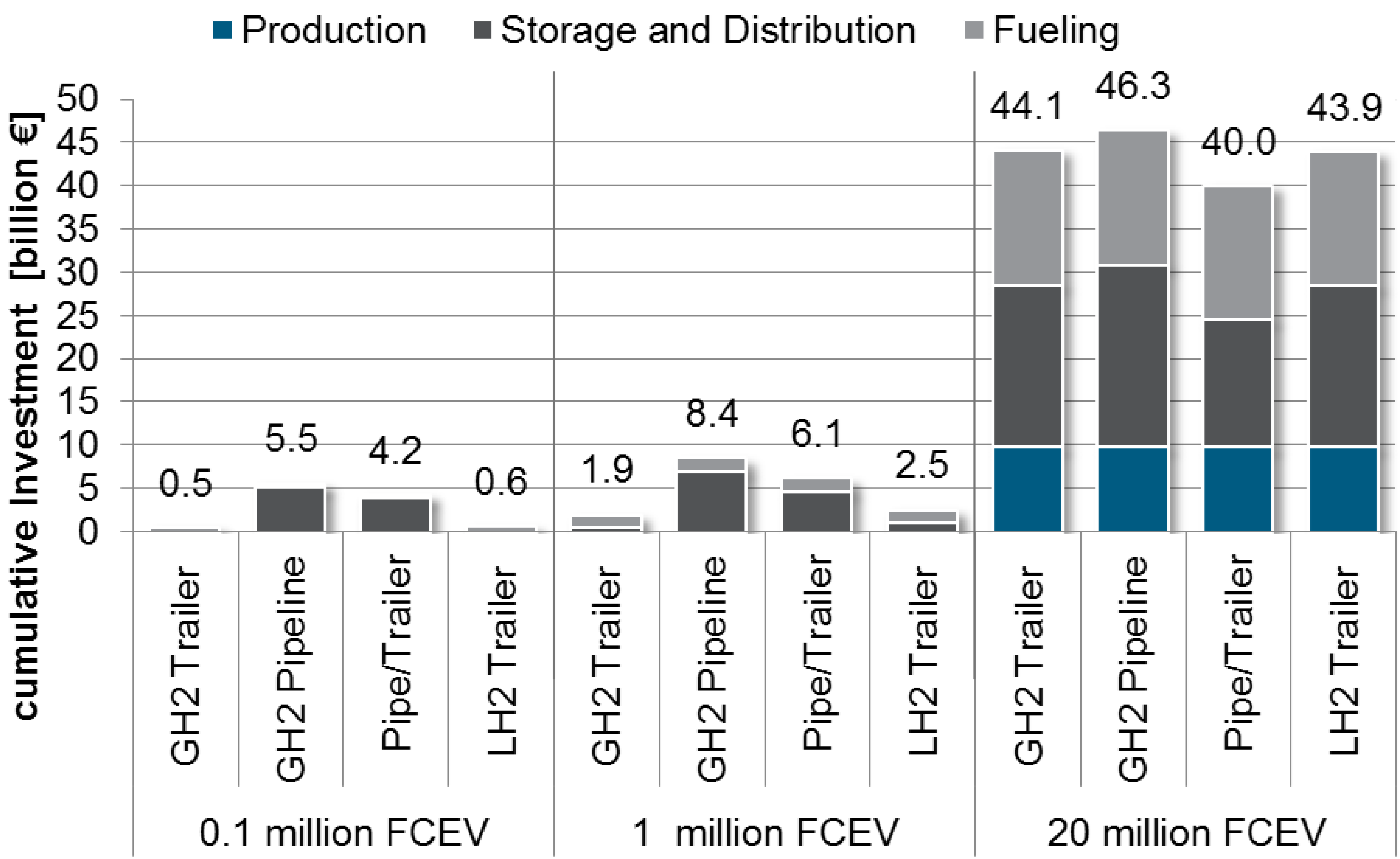
Disadvantages:
Requires liquefaction

Projects:
Vancouver (CAN)
London (UK)

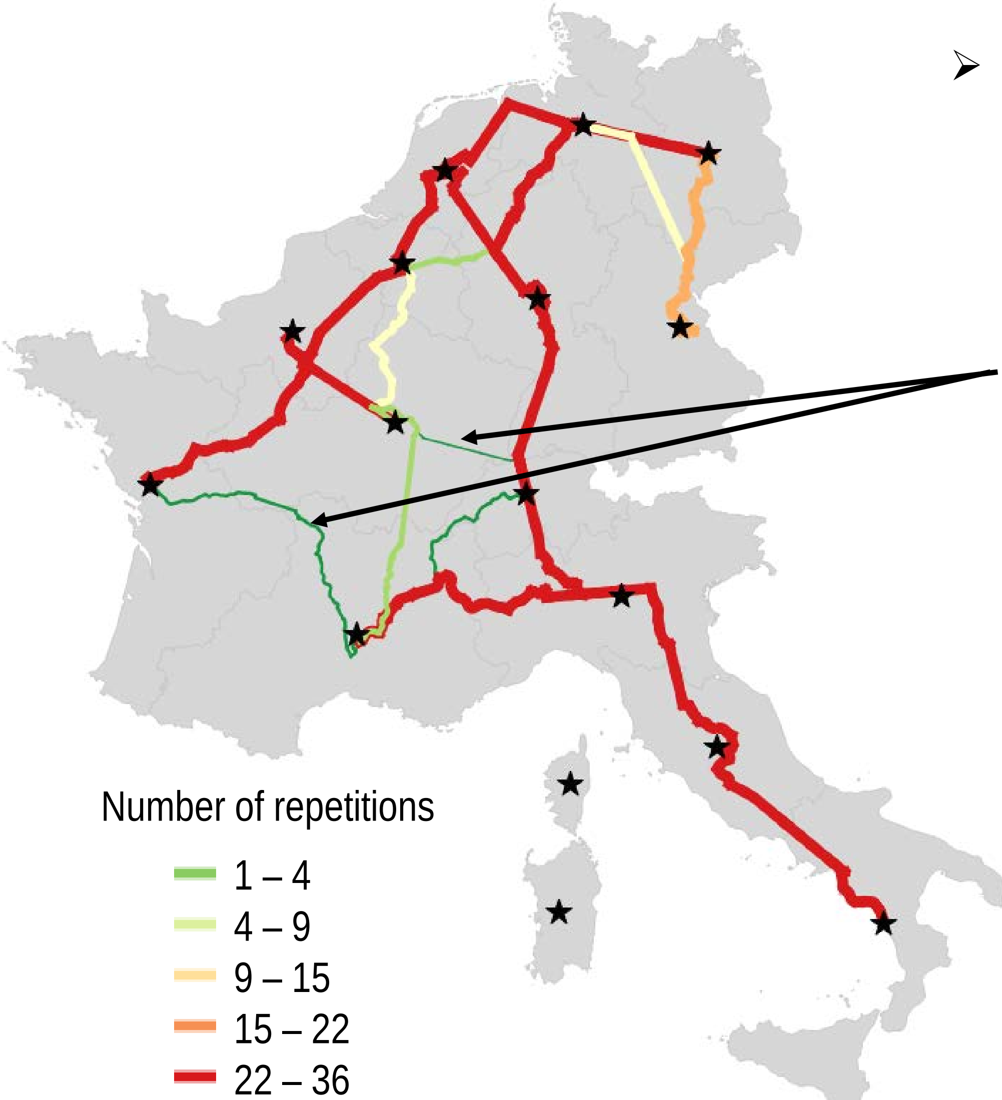
TRL: Technology Readiness Level
CAPEX: Capital Expenditure

1: Pipeline diameter = 100 mm
2: Pipeline diameter = 1000 mm
3: Trailer pressure = 200 bar
4: Trailer pressure = 500 bar

Total Investment



Results – Hydrogen Pipeline Connections



Repetition of pipeline connections as a result of optimization

- Pipeline connections that are built in each wind year as a result of the optimization (red lines)

Occasionally connected regions:

- Regions in which wind turbines are installed changes within France due to full load hour variation in each wind year

Perpetual pipeline connections can be seen (red lines)

A robust pipeline design can be attained for crucial connections

Hydrogen Safety

Safety-relevant Physical Properties of Select Fuels




Property	Unit	H_2 [1]	CH_4 [1]	NH_3 [1]	Gasoline [1]
Density (ambient conditions)	kg m^{-3}	0.09	0.72	0.72	730-780
Ignition limits in air (293 K)	vol. %	4-77	4-17	15-33	1-8
Minimal ignition energy	mJ	0.02	0.29	14	0.24
Auto-ignition temperature	°C	560	595	651	230-450
Laminar flame velocity	cm s^{-1}	346	43	90	40
Lower heating value (grav.)	MJ kg^{-1}	120	50	19	42
Lower heating value (vol.)	MJ m^{-3}	11	36	13	32
MAK (TWA value)	ppm	-	-	20	1 (benzene)

- Outdoors, H_2 disperses quickly to incombustible concentrations (high diffusion rate/low density)
- Less explosive energy compared to other fuels due to low volumetric energy density;
  Energy content [GJ]: gasoline trailer: 1000, H_2 trailer: 132 (500 bar) to 500 (LH_2)
- H_2 flames are not visible in the daylight & produce only little heat radiation
- H_2 safety is "engineereable": e.g. H_2 cylinders [2] & hydrogen refueling [3] are state-of-the art

H_2 safety benefits from high diffusion rate and low volumetric energy density

- **[1]** Safety data sheets: hydrogen (compressed), methane (compressed), ammonia (anhydrous), gasoline (E5), benzene; **[2]** ISO11119-2 AMD1:2014-08; **[3]** SAE J2601;

Measures to be Taken on Fire Incidents

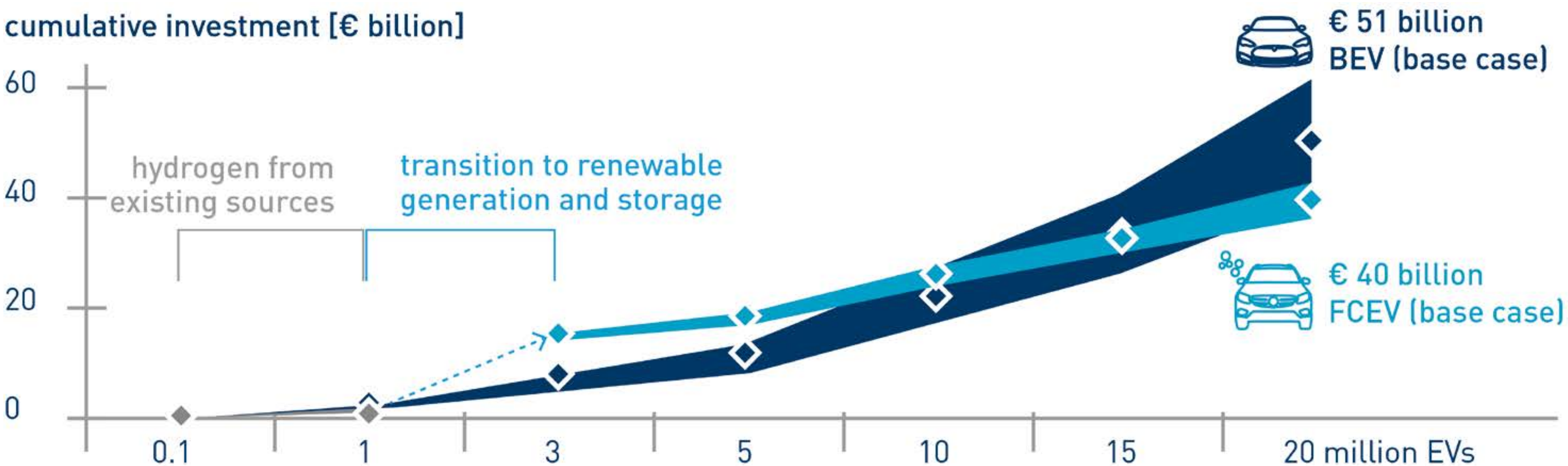
Advice for firefighters [1]	
Hydrogen and methane	Ammonia
▪ Water-spray cooling of receptacles ▪ Standard protective equipment including – flame retardant coat, helmet with face shield – Gloves, rubber boots – In enclosed spaces, self-contained breathing apparatus.	▪ Chemically protective clothing and self-contained breathing apparatus with full face-piece operated in positive pressure mode ▪ Contaminated firewater to be contained and prevented from being discharged to any waterway, sewer or drain

In case of fire incidents, hydrogen or natural gas require only standard firefighting procedures and protective equipment.

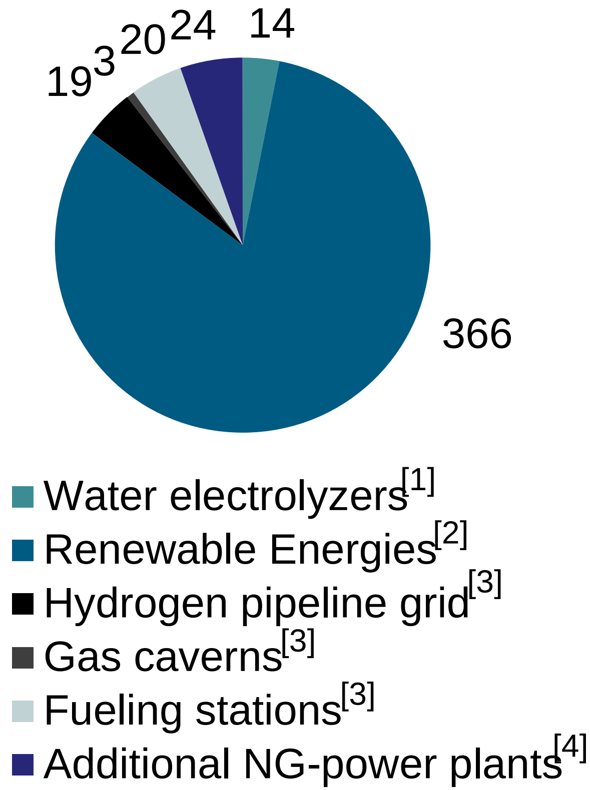
[1] Safety data sheets: Hydrogen (pressurized), Methane (pressurized), Ammonia (anhydrous)

Hydrogen Infrastructure

Results of a Study on Hydrogen Infrastructure for Passenger Cars in Germany



Infrastructure Cost Distribution



Infrastructure of Energy Concept 2.0
Cost Aanalysis [Bn €]

Electrolyzer assumed with 500€/kW
Incl. installation

Less than **15%** is due for a **hydrogen infrastructure** for 75% of German cars (30mn)
(power grid reinforcement neglected)

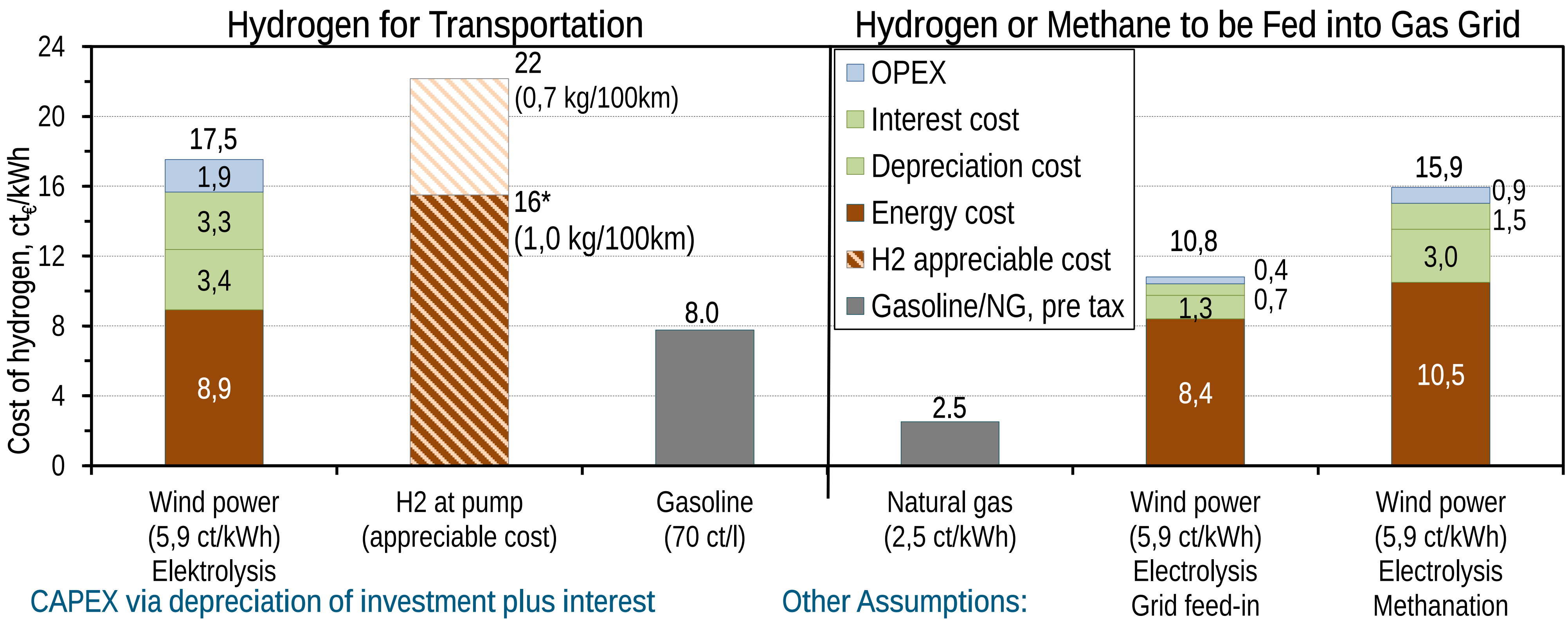
85% is for **renewable power**

[1] Electrolyzer @ 500 €/kW
[2] PV @ 1000 €/kW; wind onshore @ 1400 €/kW; offshore @ 3000/kW; Installed capacities after **[3]** Robinius, M. (2016): Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff. Dissertation RWTH Aachen **[4]** 42 GW GT + comb. Cycles, 23 GW already in place **[5]** Zeitreihen zur Entwicklung Erneuerbarer Energien, BMWi, August 2016 [6] Netzentwicklungsplan NEP 2025, BNA

Hydrogen Cost

Cost Comparison of Power to Gas Options – Pre-tax

Hydrogen for Transportation with a Dedicated Hydrogen Infrastructure is Economically Reasonable



CAPEX via depreciation of investment plus interest

- 10 a for electrolysers and other production devices
- 40 a for transmission grid
- 20 a for distribution grid and refueling stations
- Interest rate 8.0 % p.a.

Other Assumptions:

- 2.9 million t_{H2}/a from renewable power via electrolysis
- **Electrolysis: η = 70 %$_{LHV}$**, 28 GW; investment cost 500 €/kW
- **Methanation: η = 80 %$_{LHV}$**

- Appreciable cost @ half the specific fuel consumption

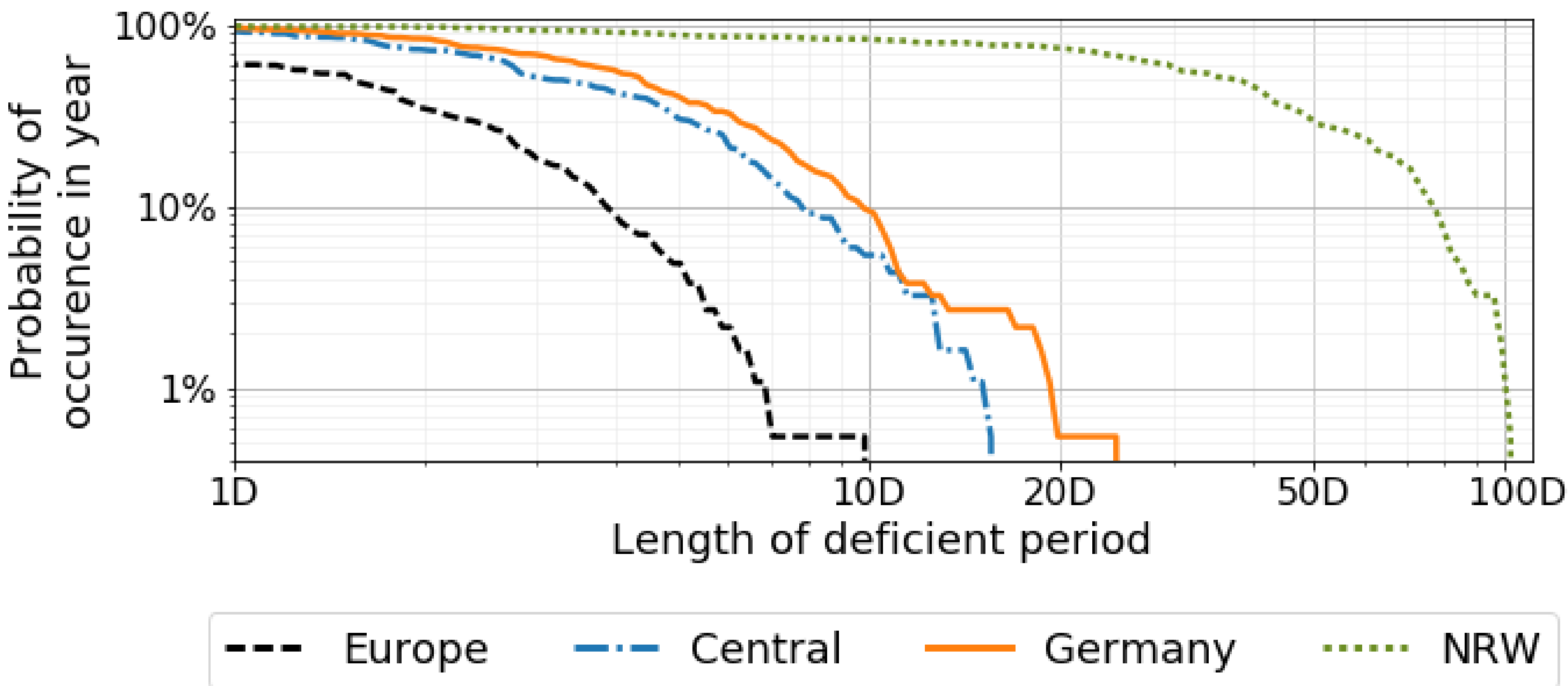
[1] Energy Concept 2.0

Energy Security Considering RE Input Lulls

Annual Probability of Lull Occurrence Depending on the Size of the Region

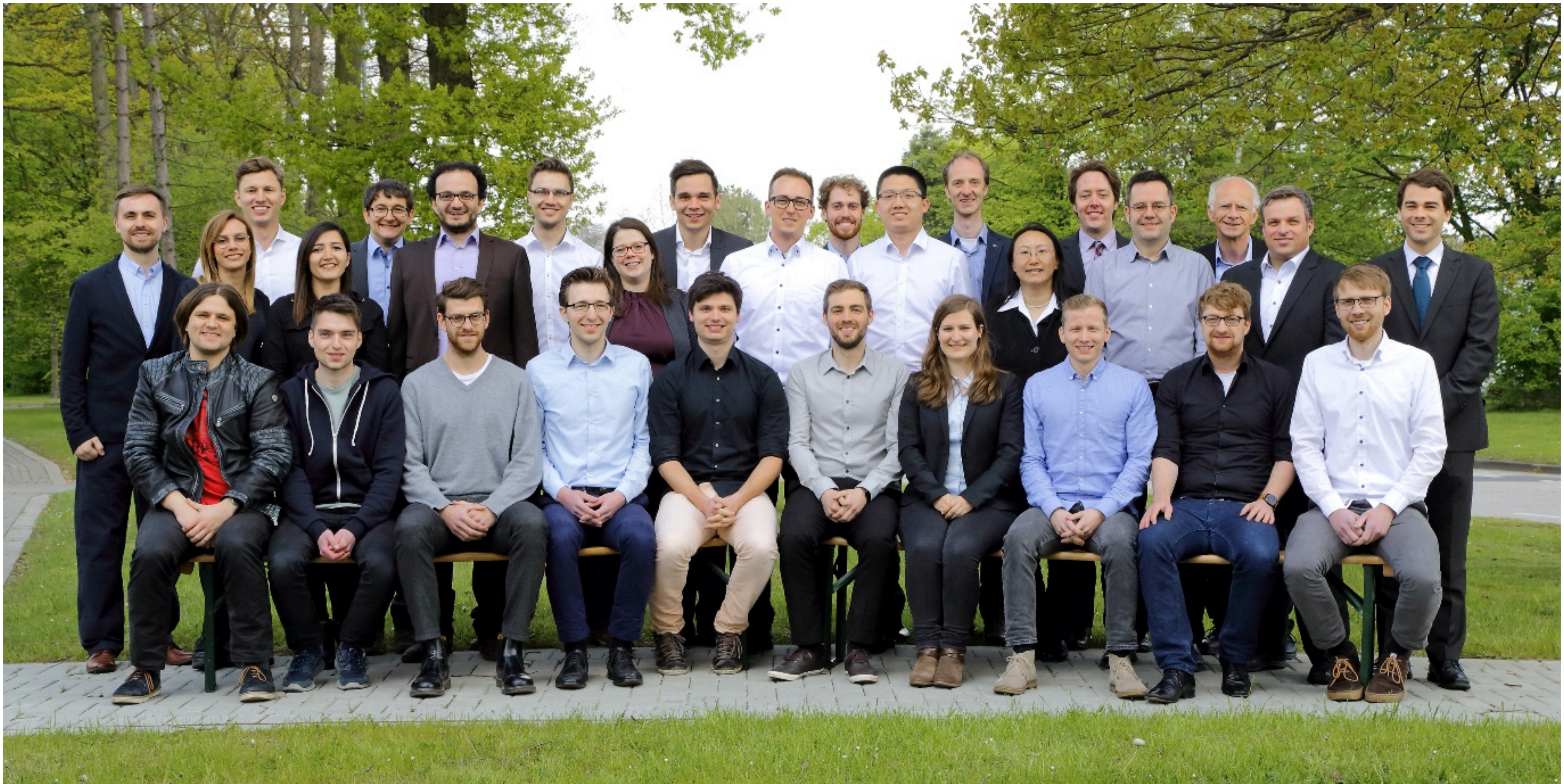
Constraints:

- Lull means a time period where electricity generation from wind, PV, biomass, hydro, and imports cannot offset internal electricity demand and electricity exports
- Power flow across Europe (including within regions) is considered



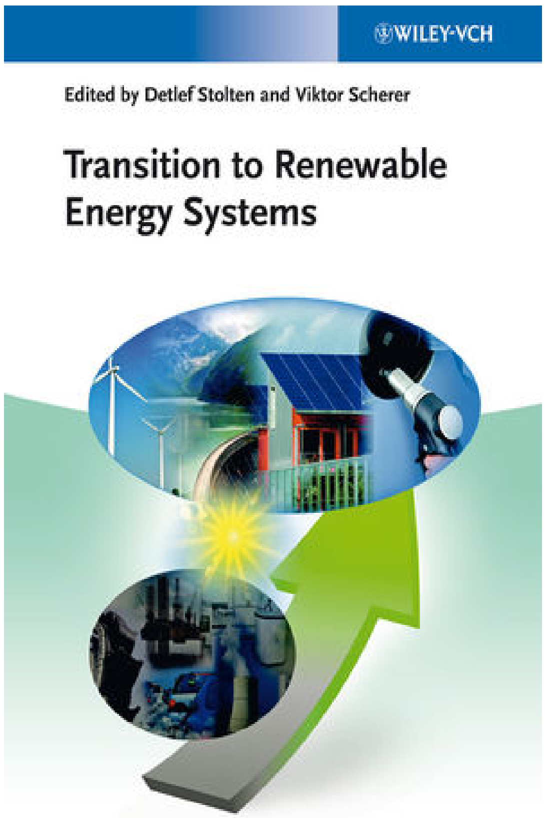
► **Bulk Storage of Renewable Energy (via Gas) is Needed**

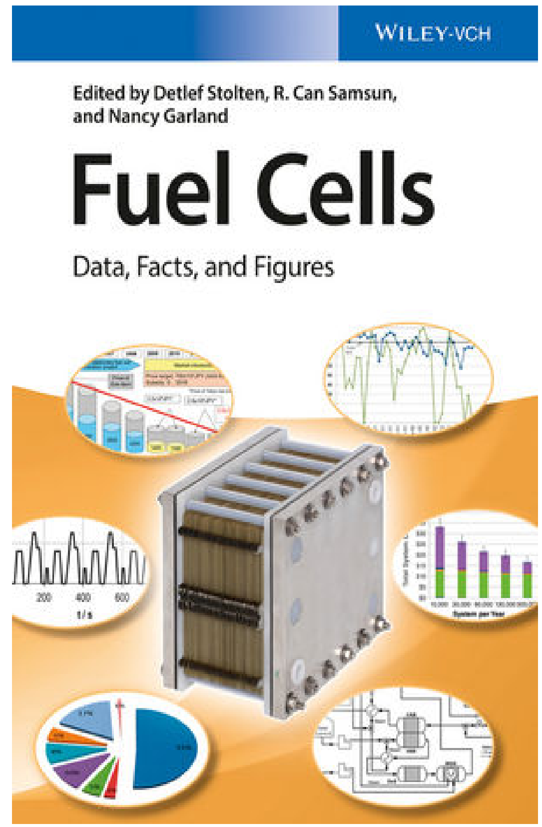
Acknowlwdgement to the Systems Analysis Team



Thank You for Your Attention!

d.stolten@fz-juelich.de





Ramifications of the Energy Transition

- After the transition period energy should **no**t be **more expensive** than today
- **Limited emissions** shall be reduced
- Electricity, fuels and heat must be available at **high reliability**
- **All energy sectors** need **to be addressed to achieve these goals**
- **Hydrogen is required** for **sector coupling**
- Teratogenic, carcinogenic and poisonous substances shall be avoided
- Radiative forcing to be considered (e.g. methane > 20) for new energy pathways
- **Spatial restrictions** in installing renewable energy compel high efficiency of energy pathways
- Dichotomy between a **very distributed** (e.g. household PV) vs. **very centralized** system (off-shore wind farms and coastal on-shore wind power generation)
- Long-term storage for providing
  - Energy security
    - Back-up for sustained low energy input, i.e. **RE input lulls** of >14days
    - **“90 day” or so energy reserve** for critical areas, e.g. transportation
  - Shifting seasonal energy overproduction