Sector Coupling for Germany

Process and Systems Analysis Group

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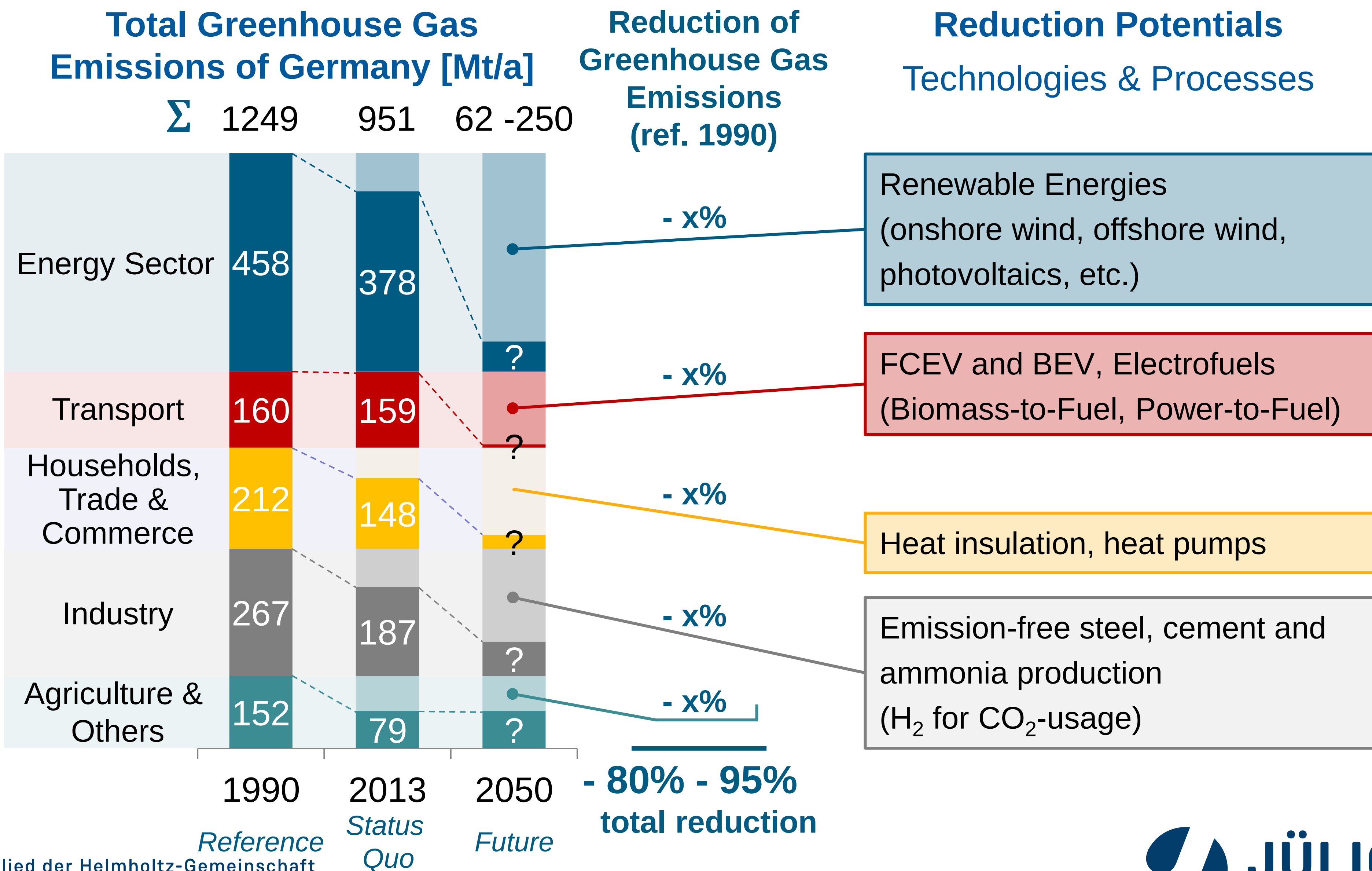
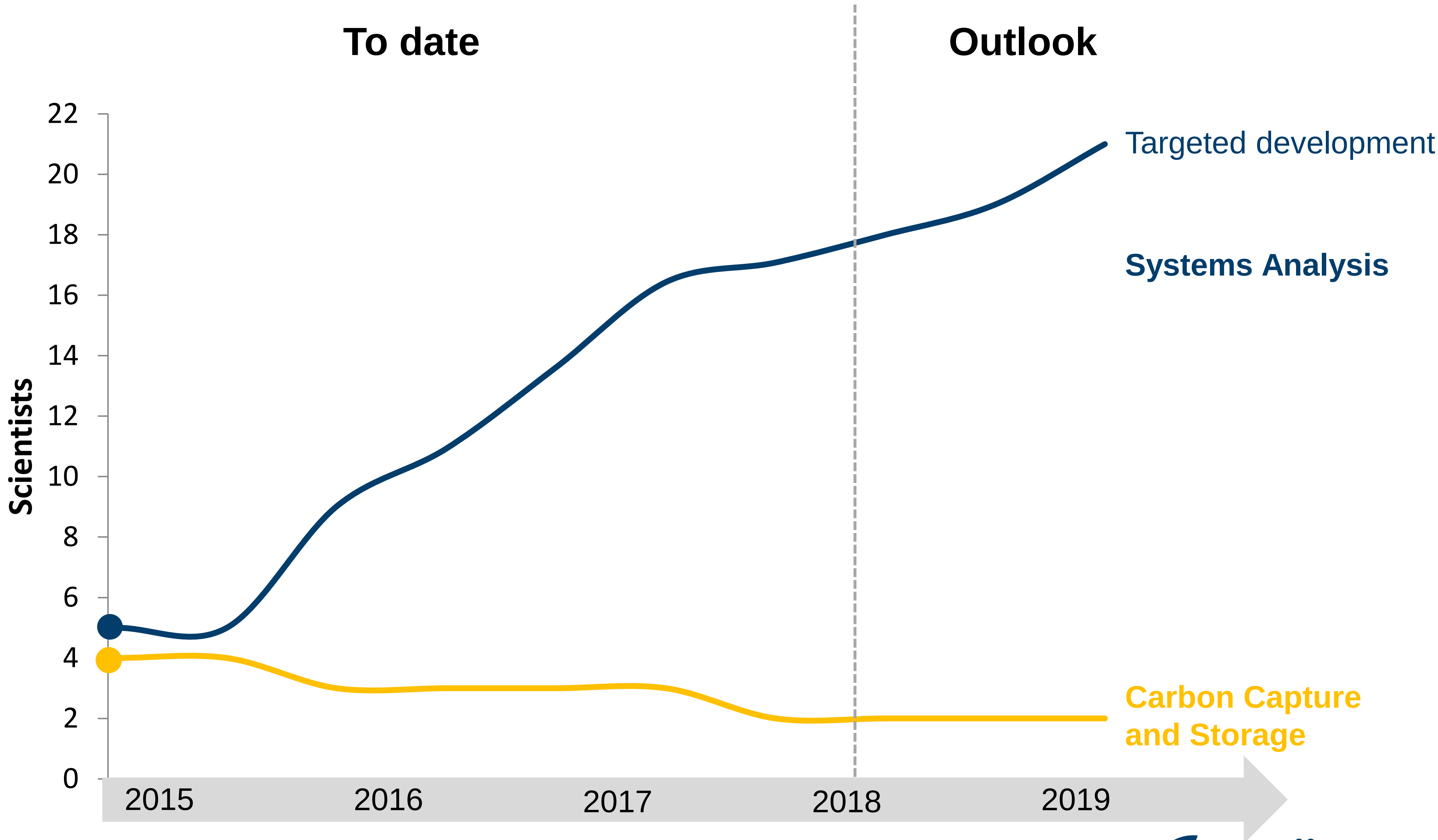
Institute of Energy and Climate Research
IEK-3: Electrochemical Process Engineering
Process and Systems Analysis Group

Overview Research Group

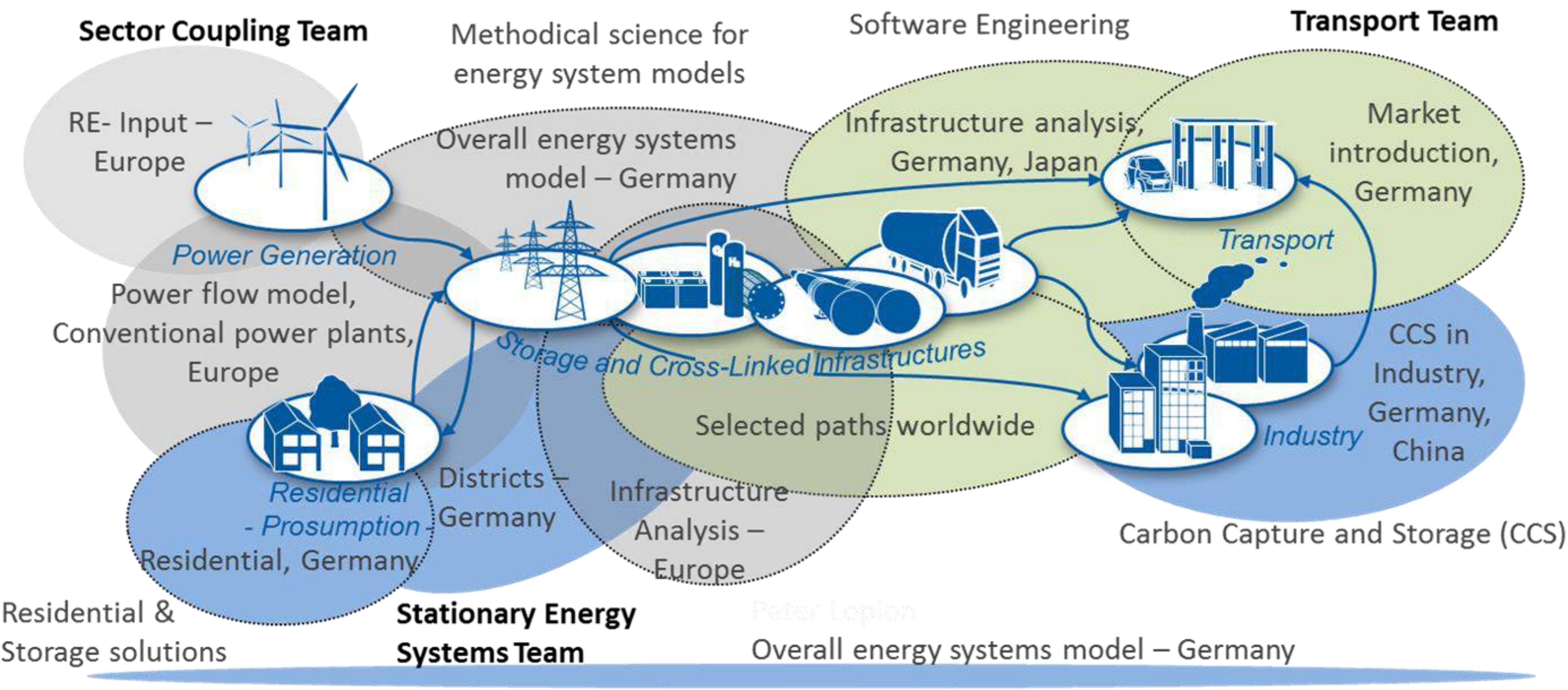
Expected Results



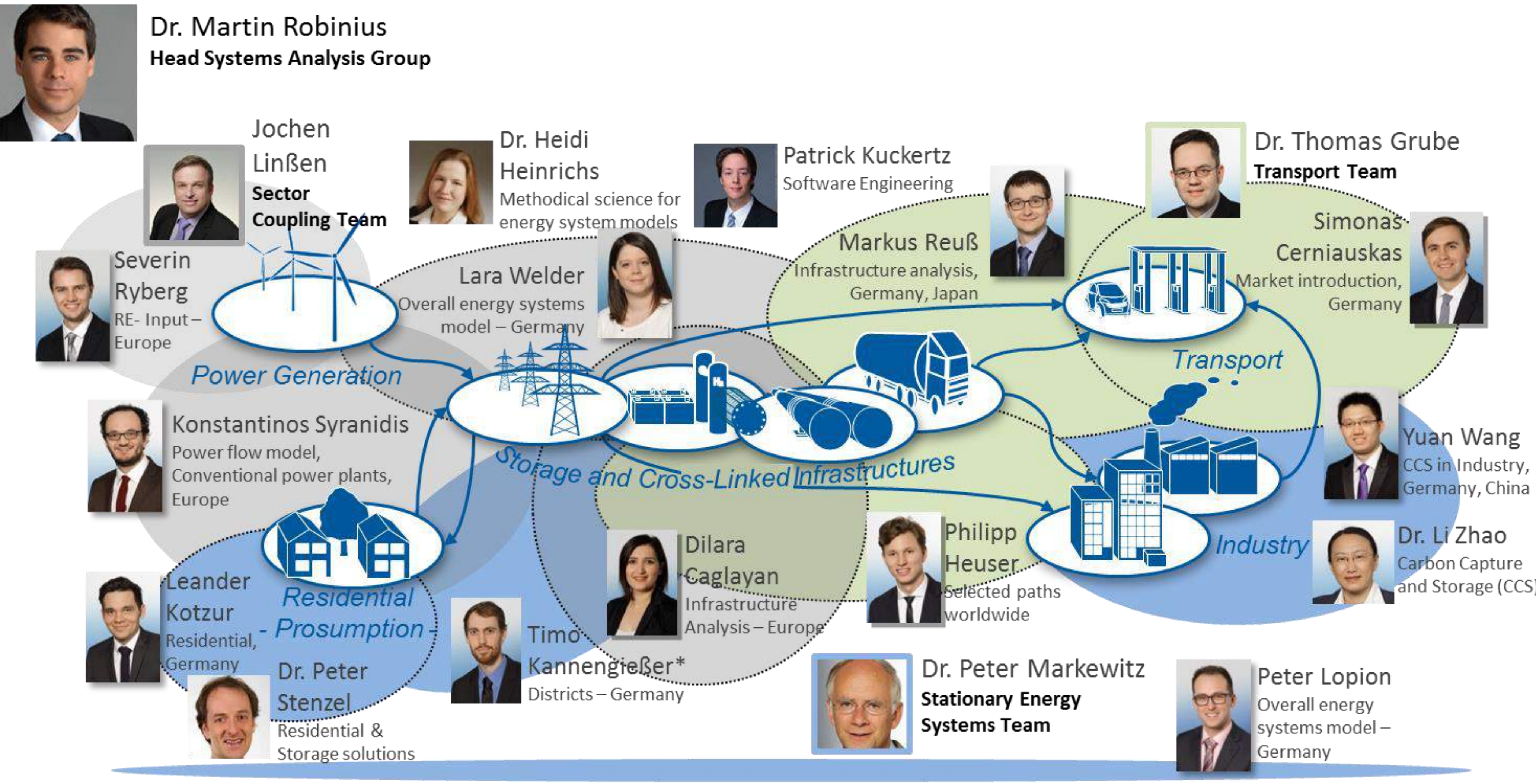
Development Process and Systems Analysis Group



Research Topics within the Process and Systems Analysis Group



Research Topics within the Process and Systems Analysis Group



Motivation

Climate Targets

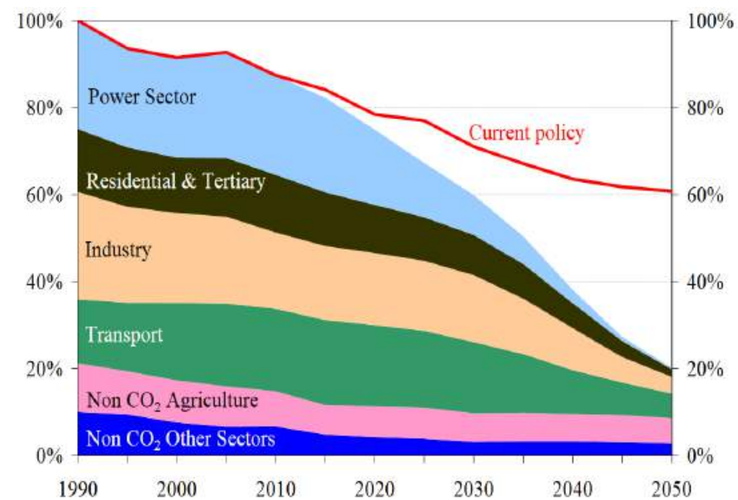
COP21 agreement [1]:

- Limiting **global warming** below 2°C above pre-industrial levels and aim to limit the increasing to 1.5 °C
- Set **global emissions** to peak as soon as possible
- **Reduction of emission** in accordance with the best available science
- **Developing countries** shall get support for adaption to the targets
- **Specific climate actions** are developed in Parties

→ 175 Parties have ratified of 197 Parties to the COP21 agreement

EU Climate Action [2]:

- **EU-28:** 2015 4,4518 MTCO_2 Eq. [3]
- At least 20% (2020), 40% (2030) and 80% (2050) cut in **greenhouse gas emissions** compared to 1990
- At least 20% (2020), 27% (2030) of total energy consumption from **renewable energy**
- At least 20% (2020), 27% (2030) increase in **energy efficiency**



EU Emissions from areas [1]

[1] United Nations, “Paris Agreement”, 2015
[2] EU climate action, https://ec.europa.eu/clima/policies/strategies_en
[3] Eurostat, “Greenhouse gas emission statistics - emission inventories”, 2017

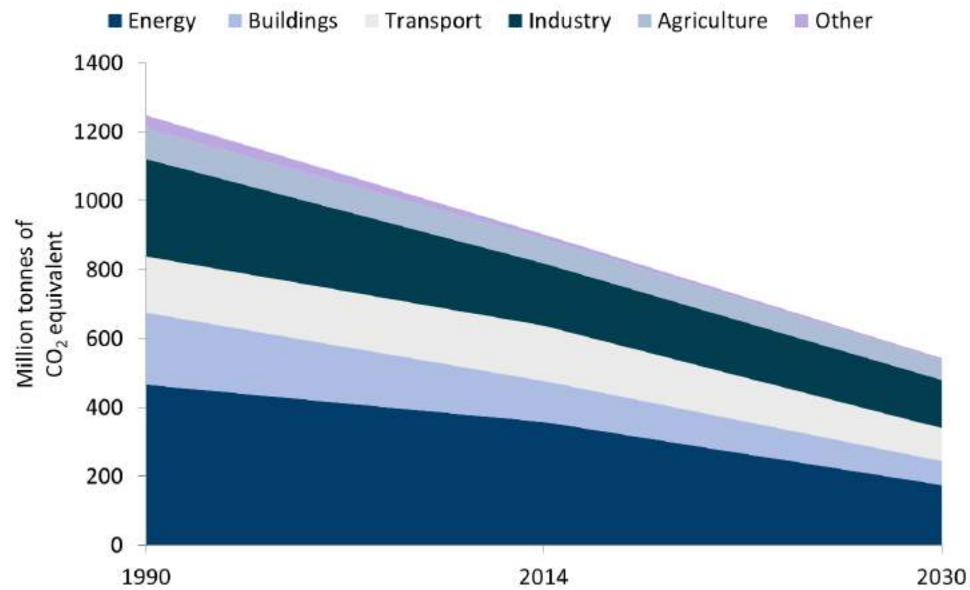
Climate Action Plan Germany

Climate Action Plan 2050 [1]:

	1990 $MTCO_2$ Eq.	2014 $MTCO_2$ Eq.	2014 vs. 1990	Goals 2030 $MTCO_2$ Eq.	Goals 2030 vs. 1990
Germany	1248	902	- 27.7%	543- 562	55-56%

Goals for 2030 (reference 1990) :

- **Energy**:
  GHG - 61-62% | 175-183 $MTCO_2$ Eq.
- **Transport:**
  GHG - 40-42% | 95-98 $MTCO_2$ Eq.
- **Industry:**
  GHG - 49-51% | 140-143 $MTCO_2$ Eq.
- **Buildings:**
  GHG - 66-67% | 70-72 $MTCO_2$ Eq.
- **Agriculture:**
  GHG - 31-34% | 58-61 $MTCO_2$ Eq.



Emissions from areas based on Climate Action Plan 2050 [1]

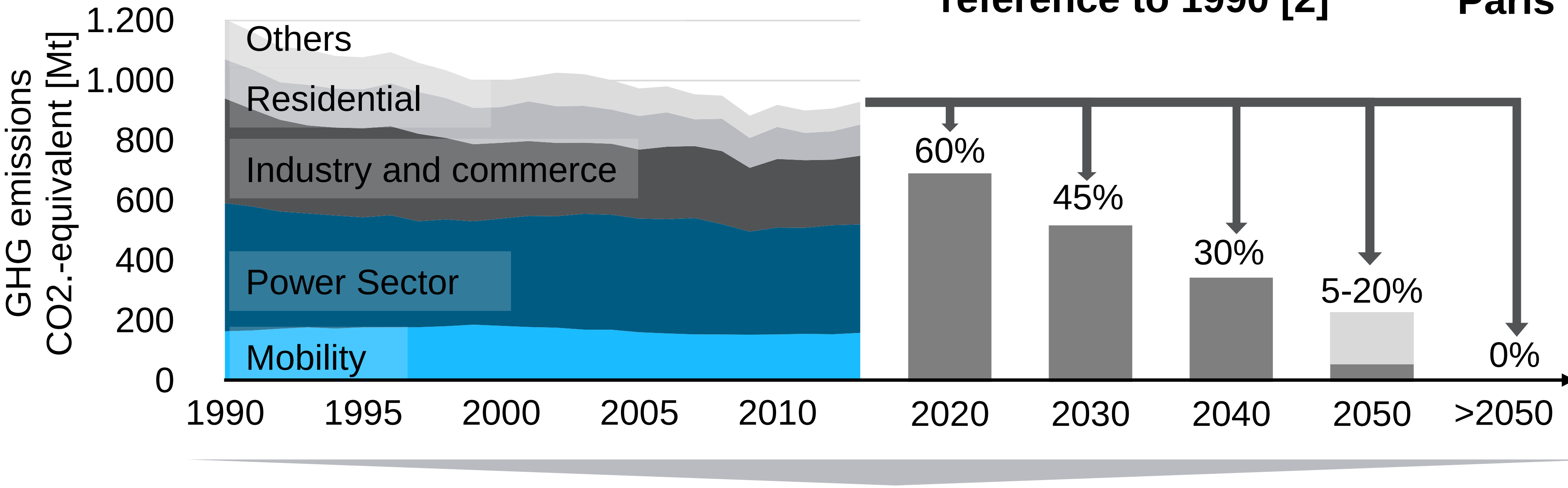
[1] Climate Action Plan 2050; Federal Gouvernement

The overall GHG emission goals of Germany require a holistic transformation of all sectors

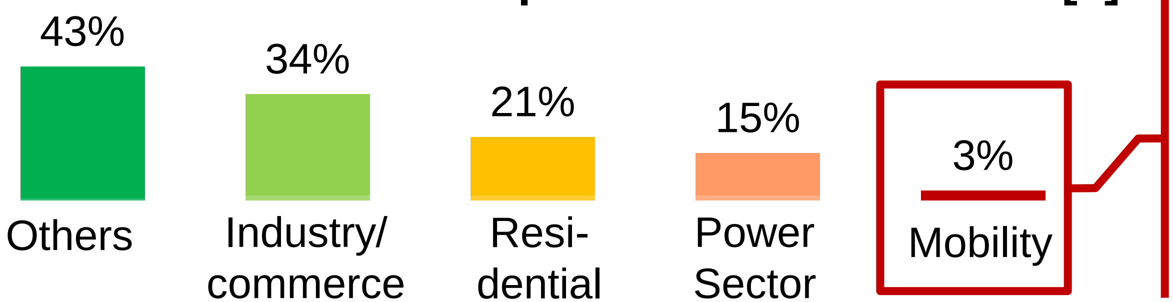
GHG Emissions in Germany since 1990 [1]

Goals of the BRD in reference to 1990 [2]

COP21 Paris [3]



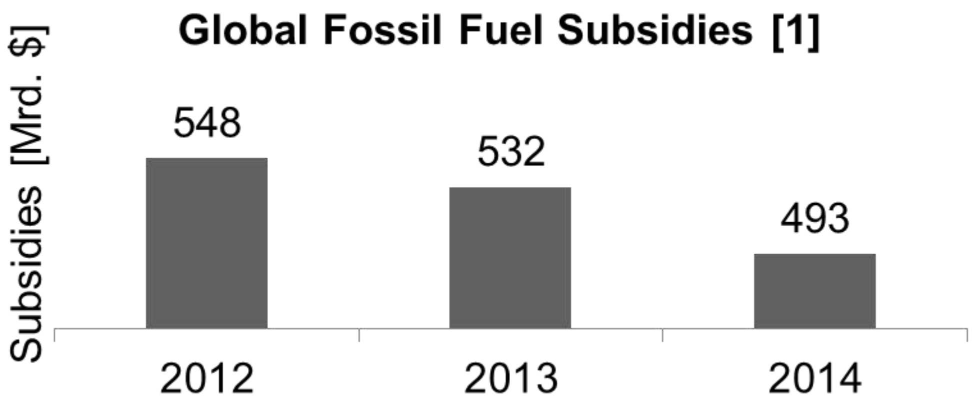
GHG emission reduction per sector 1990 to 2013 [1]

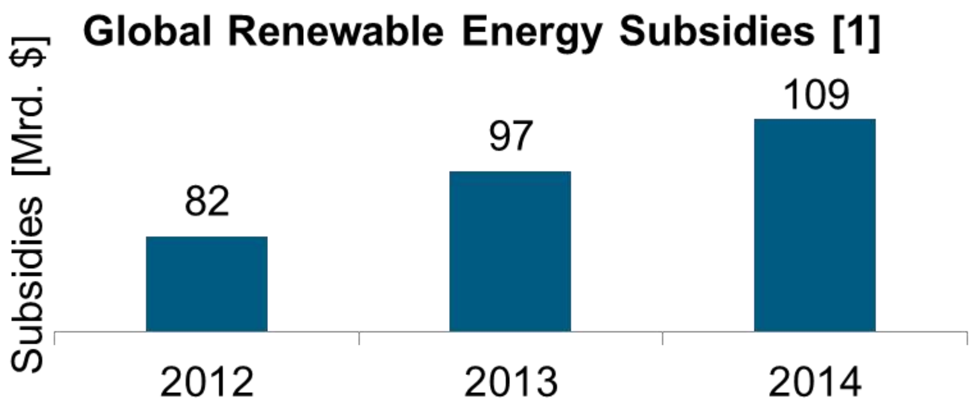


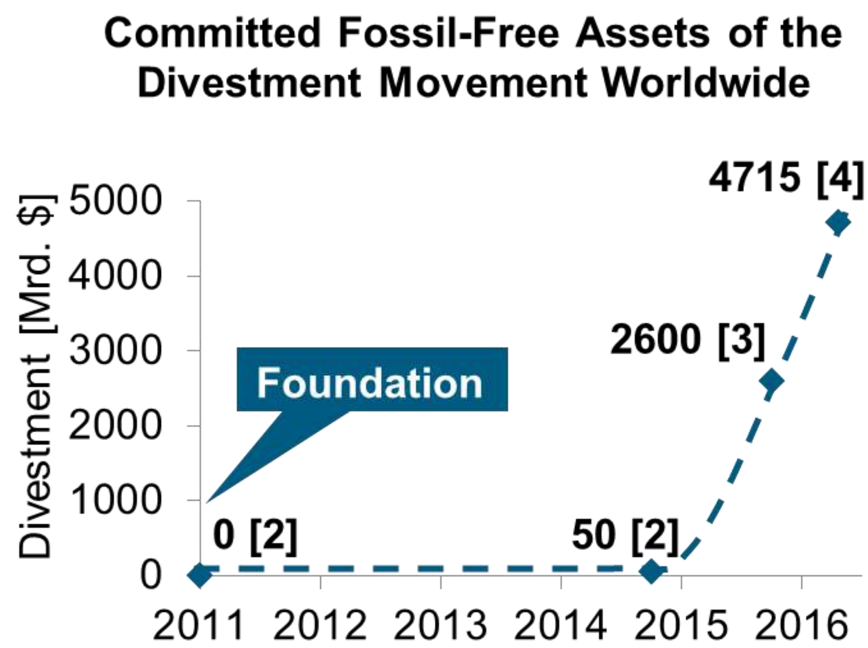
The mobility sector lags behind in comparison to the achieved emission reductions of the other sectors.

[1] BMWi, *Zahlen und Fakten Energiedaten - Nationale und Internationale Entwicklung*. 2016, 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.

Transition of Financial Interests from Fossil Energies towards Renewable Energies







'Energy Giant Peabody Enters Bankruptcy'

\- Wall Street Journal (13/04/2016)

[1] International Energy Agency, *World Energy Investment Outlook*, 2014,
URL: https://www.iea.org/publications/freepublications/publication/WEIO2014.pdf
[2] Arabella Advisors, *Measuring the Global Divestment Movement*, 2014,
URL: http://www.arabellaadvisors.com/wp-content/uploads/2014/09/Measuring-the-Global-Divestment-Movement.pdf
[3] Arabella Advisors, *Measuring the Growth of the Divestment Movement*, 2015,
URL: http://www.arabellaadvisors.com/wp-content/uploads/2015/09/Measuring-the-Growth-of-the-Divestment-Movement.pdf
[4] DivestInvest, URL: http://divestinvest.org/individual/ (access date: 19/04/2016, 4:30 pm)

Consequences of Climate Change

European Union: costs related to climate change [1]

- From 2020: 20 billion Euro/year
- From 2050: 90-150 billion Euro/year
- From 2080 : 600-2,500 billion Euro/year

Germany: costs related to climate change for the year 2100

Human Health: (based on IPCC-Scenario A1B) [2]

- Additional mortality of 5000 persons/year by heat and cold
- Increasing health costs of 220 Mio. Euro related to hospital stay
- + 490 Mio. Euro/year additional cost for public budget (based on +2°C temp) [3]

Transport:

- + 1.2 billion Euro/year additional costs for public budget (based on +2°C temp) [3]

Buildings and Building Industry:

- + 2 billion Euro/year additional costs for public budget (based on +2°C temp) [3]

Water Management :

- + 0.1 billion Euro/year additional costs for public budget (based on +2°C temp) [3]

Coastal Protection:

- + 100 Mio. Euro/year additional cost for public budget (based on +2°C temp) [3]

[1] EU-Project Climate Cost : http://www.climatecost.cc
[2] Hübler et al.; “Kosten des Klimawandels: Die Wirkung steigender Temperaturen auf Gesundheit und Leistungsfähigkeit“, 2007
[3] Ecologic, Infras: “Klimawandel: Welche Belastungen entstehen für die Tragfähigkeit der Öffentlichen Finanzen?”, 2009

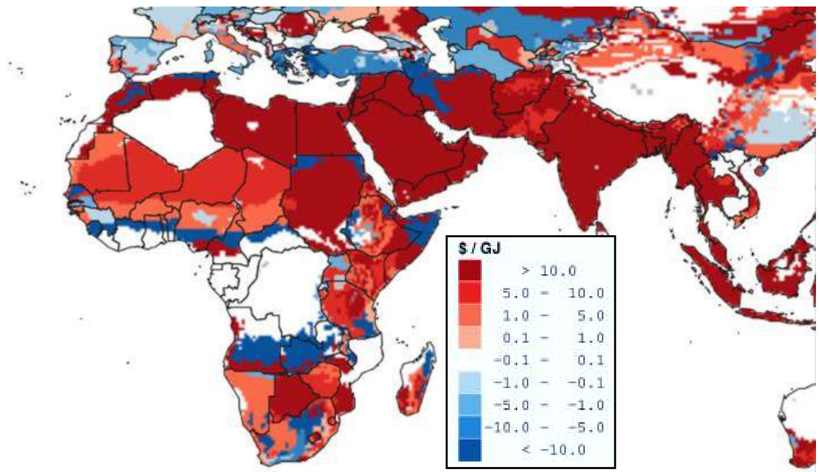
Consequences of Climate Change

Middle East and North Africa, South Asia, and Sub-Saharan Africa:

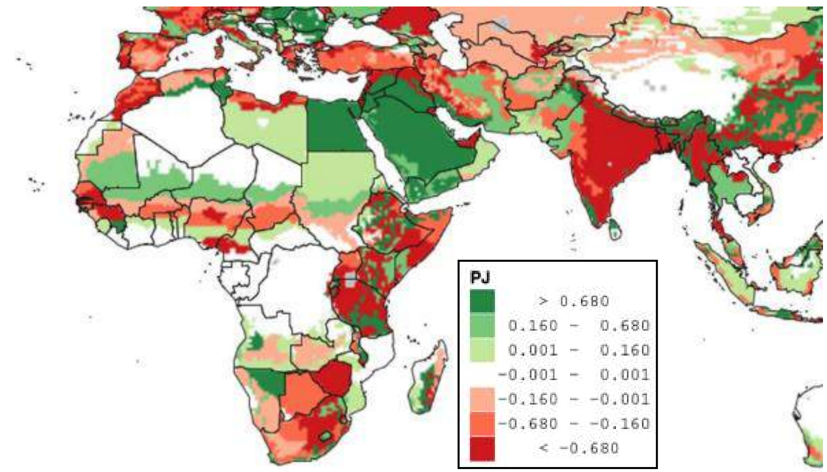
Food Costs (based on RCP8.5 for 2080):

- + 140%*/ 765%** in **Middle East and North Africa**
  - fully utilized agriculture land and limited options to import food
- + 35%*/ 44%** in **South Asia**
  - expansion of agriculture land and changes in trade flows
- + 4%*/ 6%** in **Sub-Saharan Africa**
  - increasing agriculture land and import foods

* prosperity scenario
** poverty scenario



Average different costs of Food for 2080 for RCP8.5 and poverty scenario [1]



Average different production of food crops for 2080 for RCP8.5 and poverty scenario [1]

[1] Biewald et al. "The Impact of Climate Change on Costs of Food and People exposed to Hunger at Subnationnal Scale", 2015

Timeline for Energy Research and Development in Order to Achieve the 2050 Goals

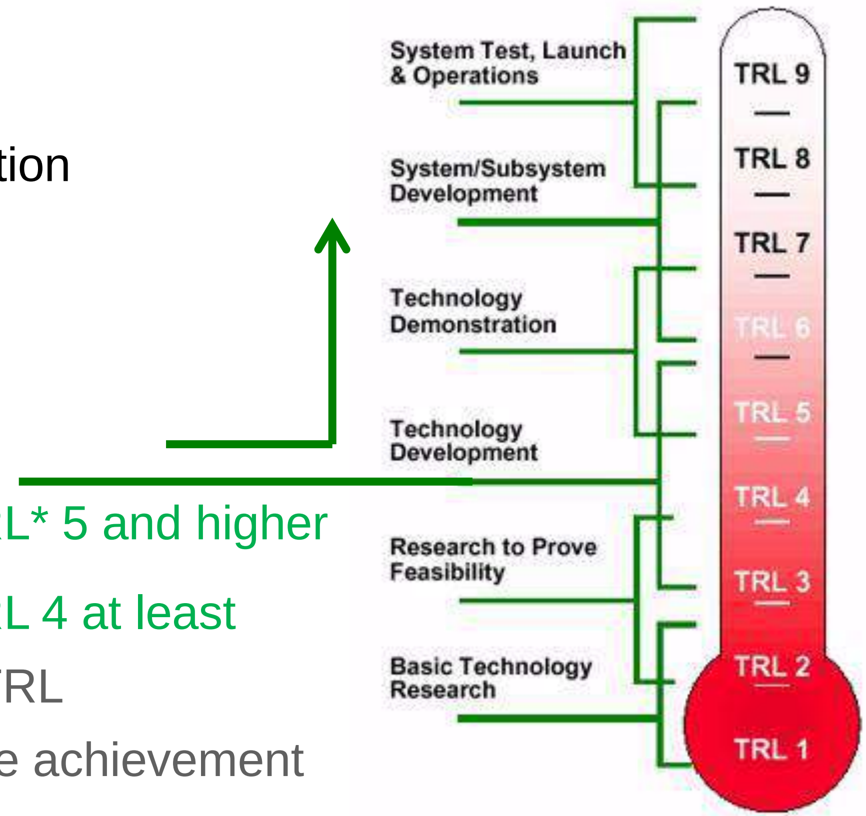
- **2050:** Reduction by 80 % fully achieved
- **2040:** Start of market penetration
- **2030:** Completion of research for first generation technologies

Period of development: till 2040

Period of reasearch: till 2030

⇒ 16 years for more research => TRL* 5 and higher

TRL 4 at least



This does not mean that research with a lower TRL is not reasonable; it is not only contributing to the achievement of the goals of the year 2050.

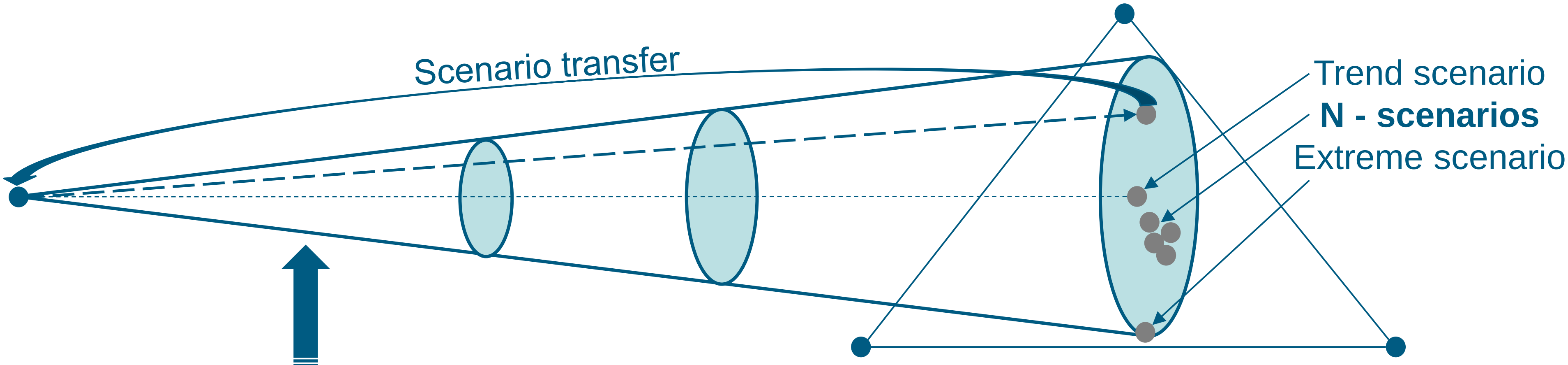
*TRL: Technology Readiness Level

The Future is Uncertain yet Predictable

Most popular Method of System Analysis: Scenario technics

Present — Development — Solution area for the year 2050

Security of supply
Unaltered



Disruptive technologies
Historic exmaple: steam engine

Enviroment protection [1] (Acceptance)

- Greenhouse gas emissions (-80 % to – 95 % towards 1990)
  - Renewable Energies
  - Efficiency
  - Building stock
  - Transport sector
- Phase-out nuclear energy till 2022

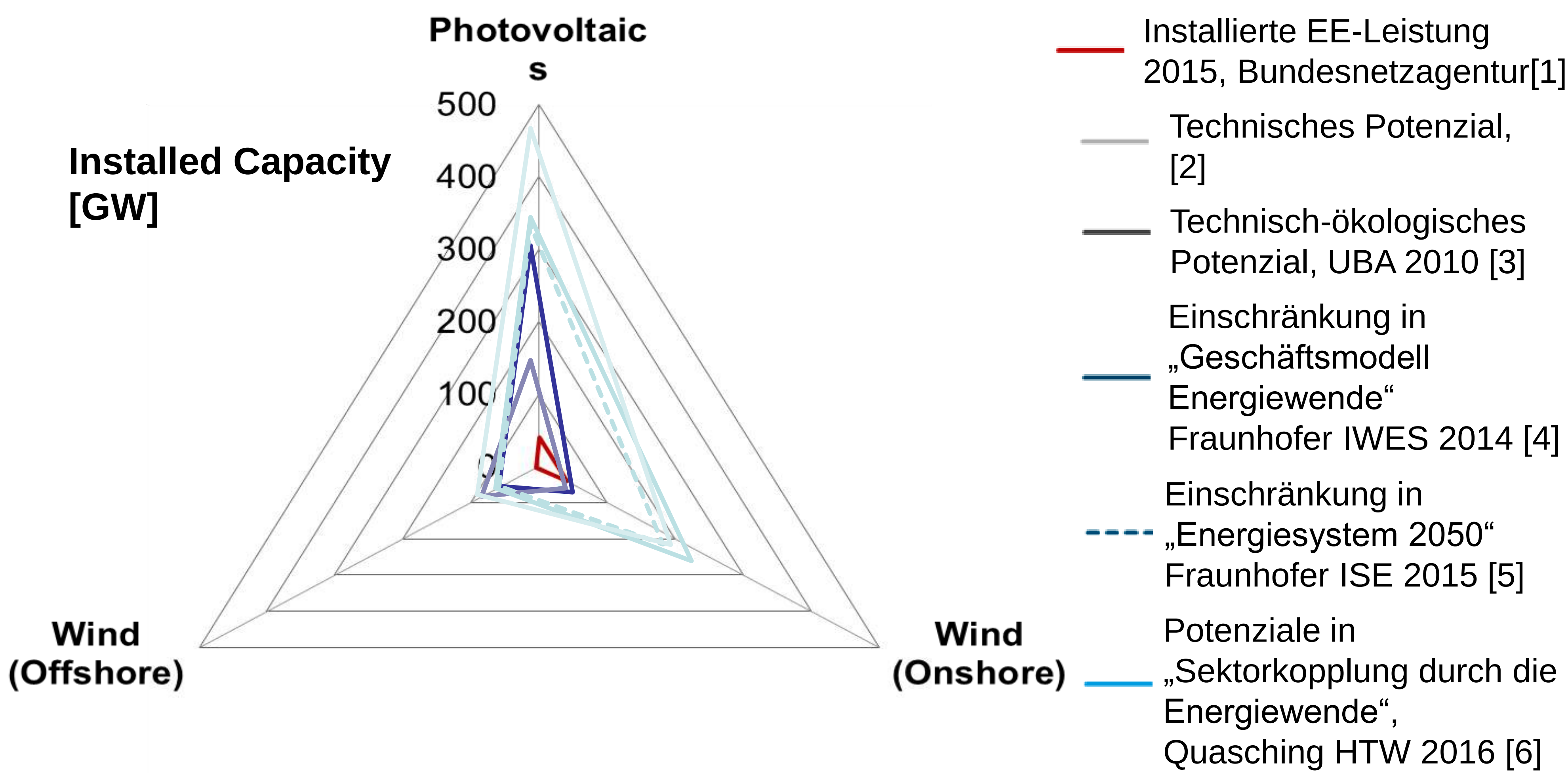
Cost-effectiveness
Unaltered

+/- Variety of developments are considered
- Scenario-transfer often not implemented [3]
- Specific recommendations for action?

Further aspects[4]

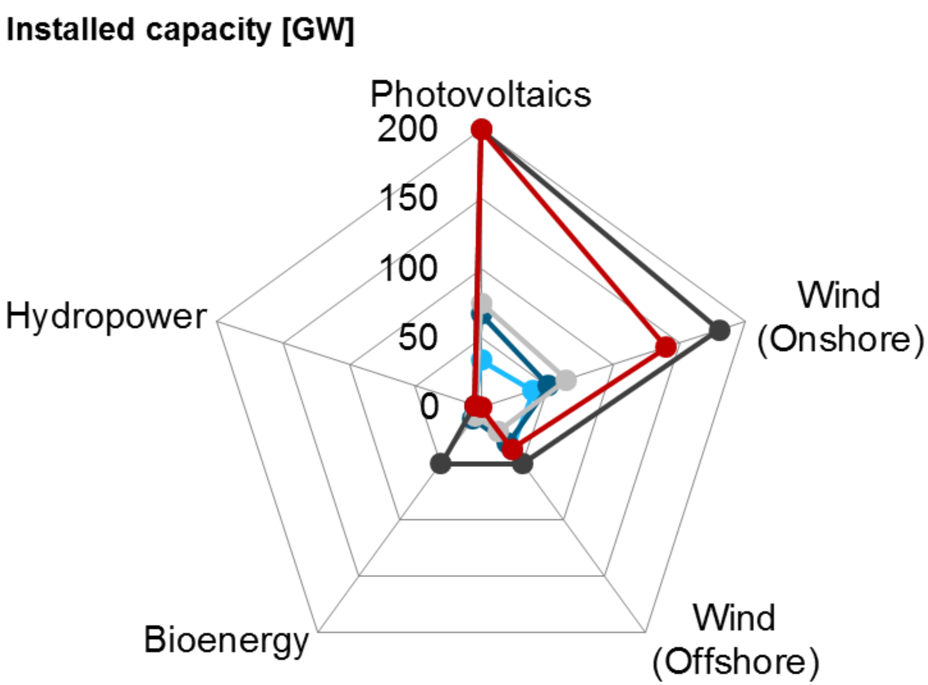
Quellen: [1] Umweltbundesamt (2014): Ziele der Energiewende. URL: http://www.umweltbundesamt.de/daten/energiebereitstellung-verbrauch/ziele-der-energiewende [17.02.2016] [2] Reibnitz, U. (2013): Szenario-Technik für die unternehmerische und persönliche Erfolgsplanung
[3] IZT (2008): Methoden der Zukunfts- und Szenarioanalyse. Überblick, Bewertung und Auswahlkriterien
[4] Mitzner, D. (2010): Strategische Vorausschau und Szenarioanalysen: Methodenevaluation und neue Ansätze, ab S. 156

The Future is Uncertain yet Predictable

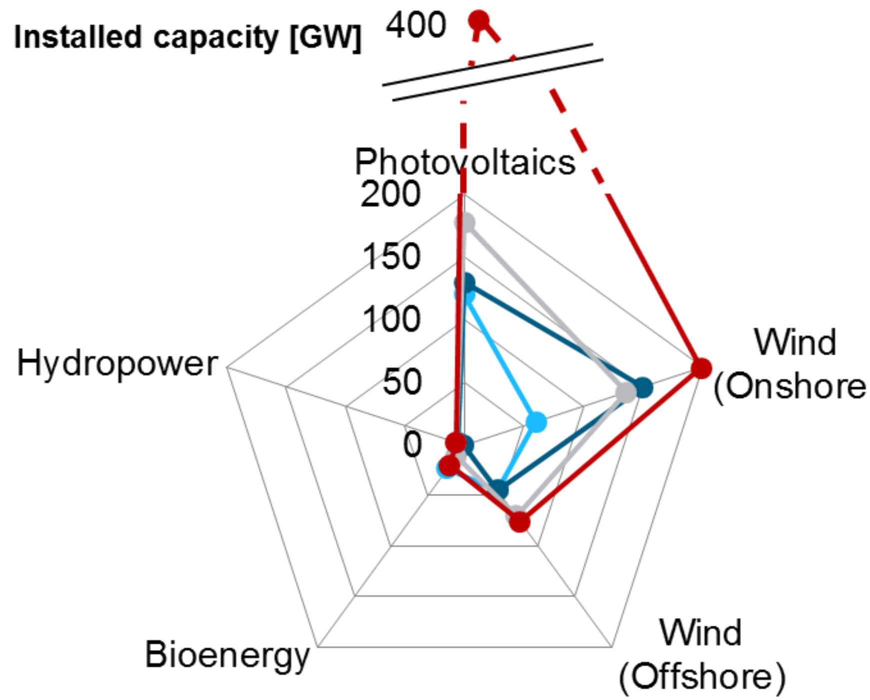


About which World we Discuss is Important

The 80% CO_2-reduction world look different then the > 80%

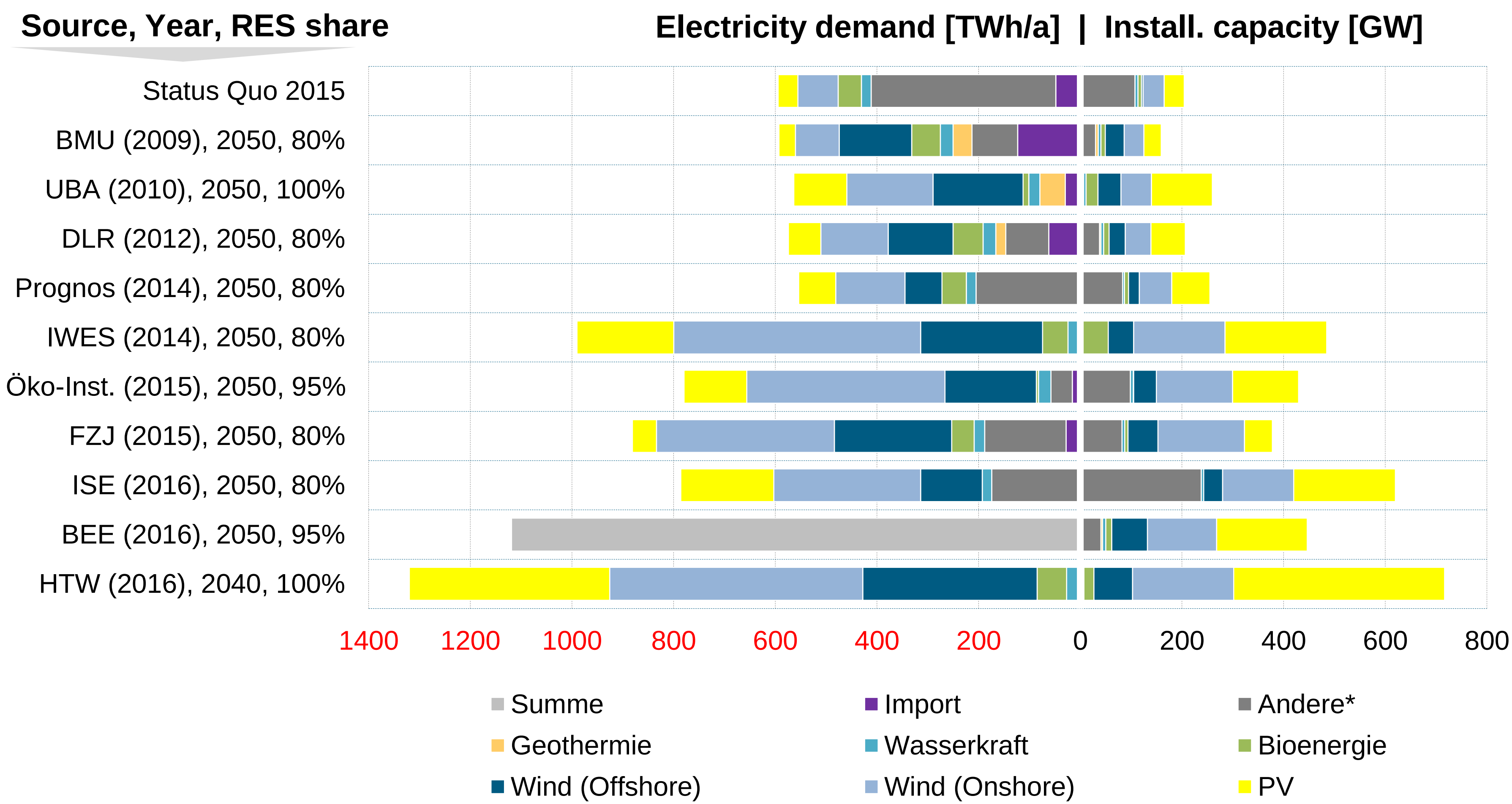


- Leitszenario 2009, BMU (2050, 80% RE) - Published 2009
- Szenario 2011 A, Energy Trans / DLR (2050, 80% RE) - Published 2012
- Trendszenario 2050, Prognos (2050, 80% RE) - Published 2014
- Geschäftsmodell EW*, Fraunhofer IWES (2050, 80% RE) - Published 2014
- Energiesystem 2050, Fraunhofer ISE (2050, 80% RE) - Published 2016



- Energieziel 2050, UBA (2050, 100% RE) - Published 2010
- Klimaschutzszenario 2050, Öko-Institut (2050, 95% RE) - Published 2015
- SZEN-16 KLIMA 2050, BEE eV. (2050, 95% RE) - Published 2016
- Sektorkopplung, HTW Berlin (2040, 100% RE) - Published 2016

Sector Coupling changes the Energy System

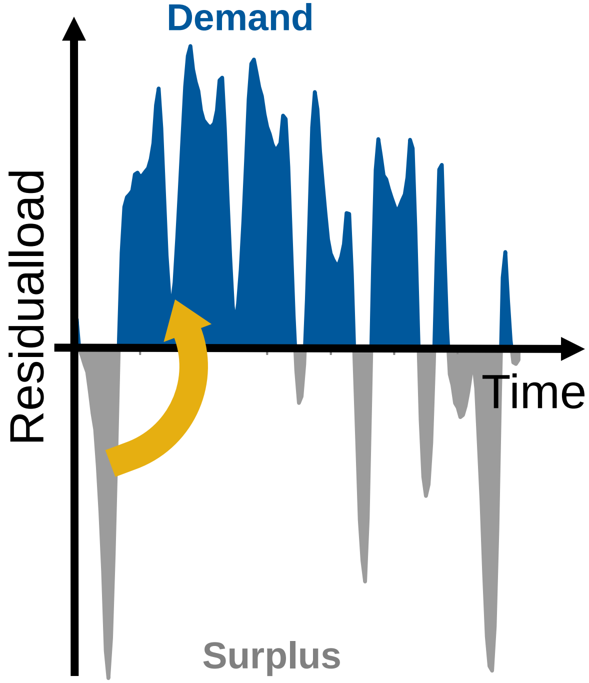


Higher electricity demand due to P2X technologies which will be served throw Renewable Energy Sources

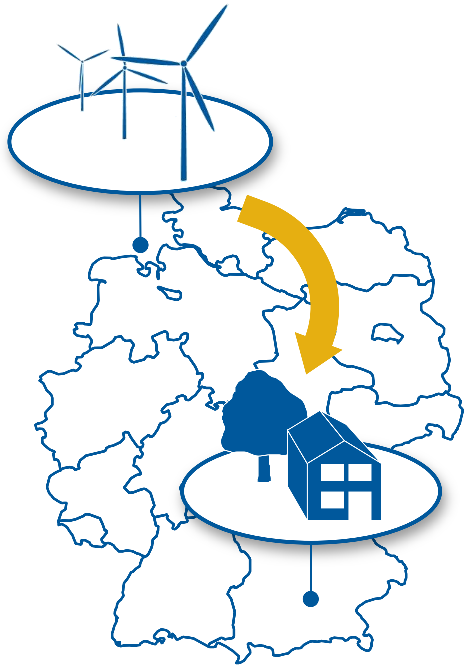
The Task of Sector Coupling

The challenge is the connection of demand and supply

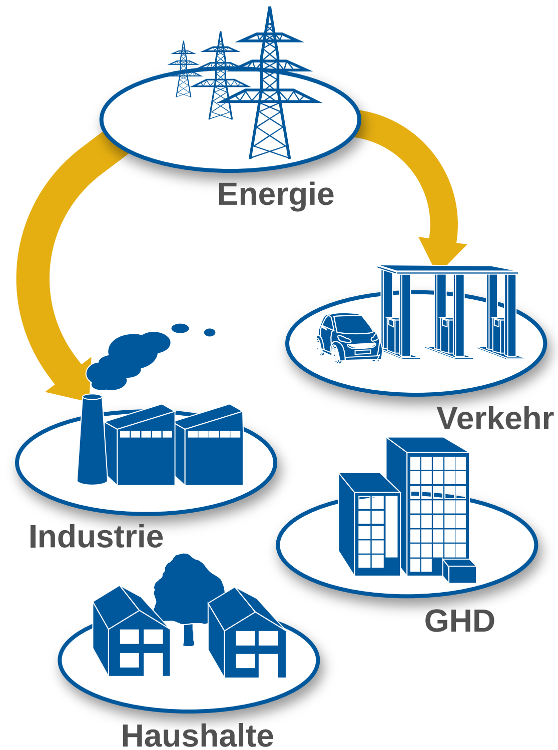
Temporal



Spatial



Sectors



Sector Coupling allows the use of flexibility options (P2X)

Sector Coupling

Sector Coupling

- Different ideas about sector
  - Households, Transport, Industry and Trade, Energy
  - Power, Mobility, Heat…

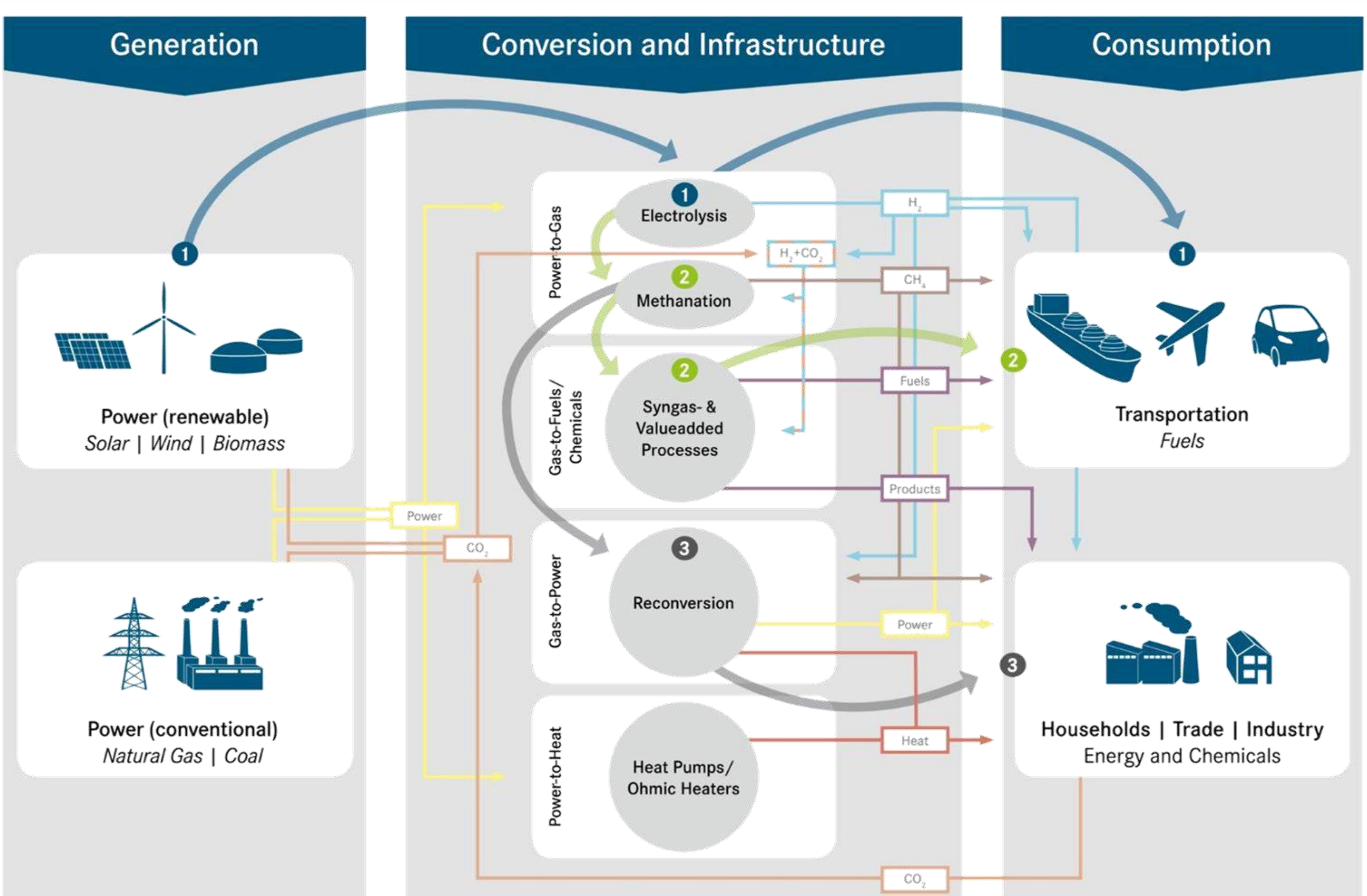
- Sectors all the time coupled:
  - CHP (Heat and Power or Energy and Industry/Households)
  - Natural gas (Households, Industry, Transport)

Many definitions in Germany:

  - „the energy engineering and energy economy of the connection of electricity, heat, mobility and industrial processes, as well as their infrastructures, with the aim of decarbonization, while simulataneously increasing the flexibility of energy use in the sectors of industry and commercial/trade, households and transport under the premises of profitability, sustainability and security of supply" [1].

[1] BDEW. Positionspapier—10 Thesen zur Sektorkopplung. 2017. Available online: https://www.bdew.de/internet.nsf/id/3cc78be7f576bf4ec1258110004b1212/$file/bdew%20positionspapier_10%20thesen%20zur%20sektorkopplung_o%20a.pdf (accessed on 12 June 2017). (In German)

Power-to-X



Robinius, M., et al., *Linking the Power and Transport Sectors—Part 1: The Principle of Sector Coupling.* Energies, 2017. 10(7): p. 956.

Individual and Total Efficiencies of Passenger Cars with Different Powertrain Concepts based on Renewable Electricity

Battery electric vehicle (BEV)

Renewable electricity 100%

Transmission (95%) *(92%)*
(no storage considered)

Battery usage (90%)
→ 86%

Electric motor (85%)
Mechanical system (95%)
Powertrain(78 %)

69% **Total** **72%**

Fuel cell electric vehicle (FCEV)

Renewable electricity 100%

Transmission (95%) *(-)*
Electrolysis (70%) *(70%)*

Hydrogen
→ 67%

Compression/
Transmission (80%) *(75-93%)*
(including storage)

32% **Fuel cell (60%)**

Electric motor (85%)
Mechanical system (95%)
Powertrain 50%

26% **Total** **26-33%**

Internal combustion engine vehicle (ICEV)

Renewable electricity 100%

Transmission (95%)
Electrolysis (70%)

Hydrogen
→ 67%

Power-to-Liquid (70%)
Long-distance transmission (95%)

44% **Liquid fuel**

Combustion engine (30%)
Mechanical system (95%)

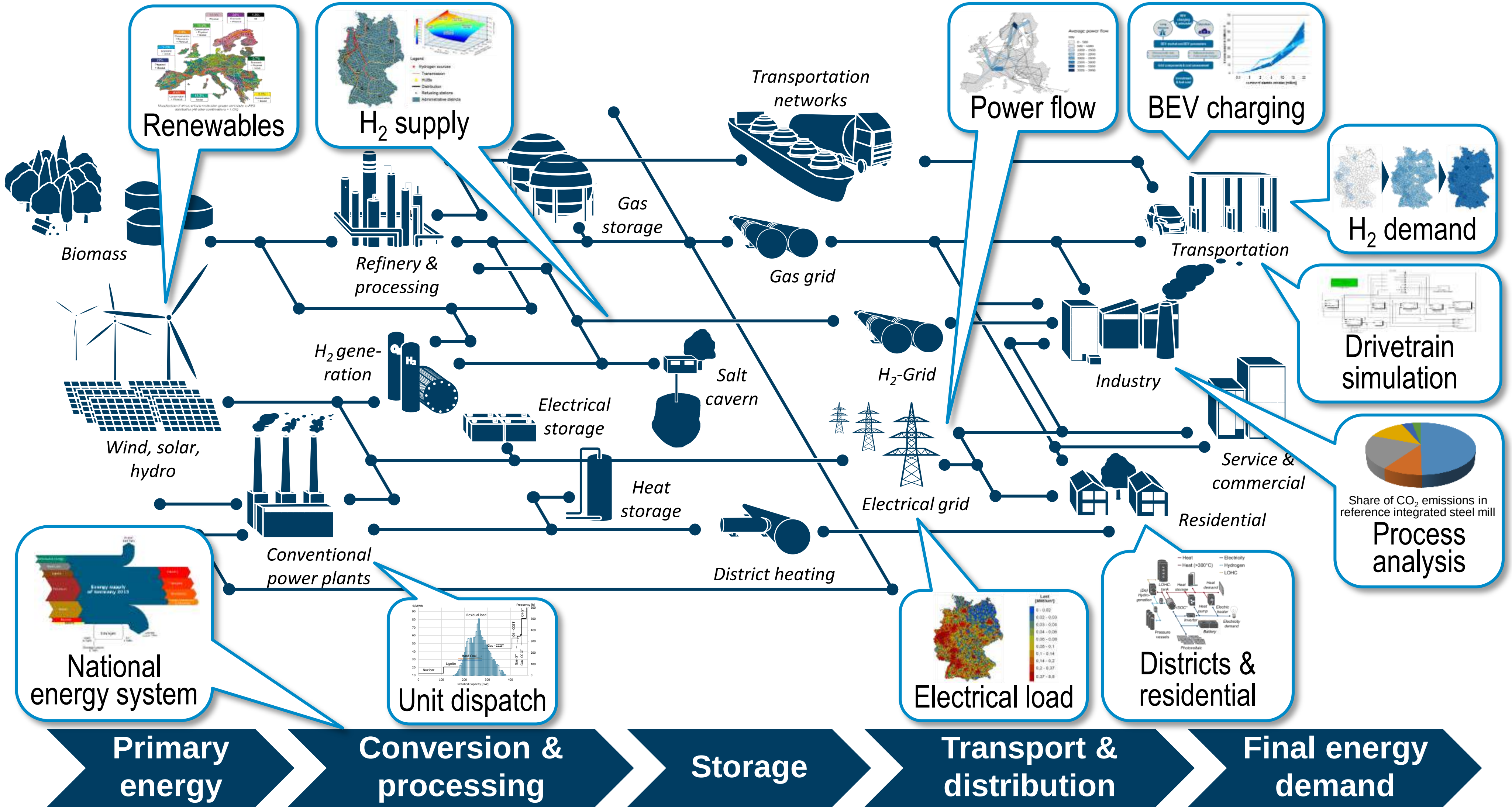
13% **Total**

Please note: Individual efficiencies in parentheses. The cumulated total efficiencies in the boxes result from multiplying the individual efficiencies.

Quelle: Agora Verkehrswende: Die zukünftigen Kosten strombasierter Brennstoffe, IEK-3

Multiscale Toolbox
for
Energy Systems Modeling

Multiscale Toolbox for Energy Systems Modeling



Flexible Computational Infrastructure

User interface

User input

GIS visualization

"The Glue"

- Simulation manager
- Job assignment
- Data transfer
- Web interface

python

C/C++

Procedural algorithms

SQL

Data management

GUROBI OPTIMIZATION

SCIP • SoPlex • GCG • UG • ZIMPL – The SCIP Optimization Suite

Optimization solvers

GitHub

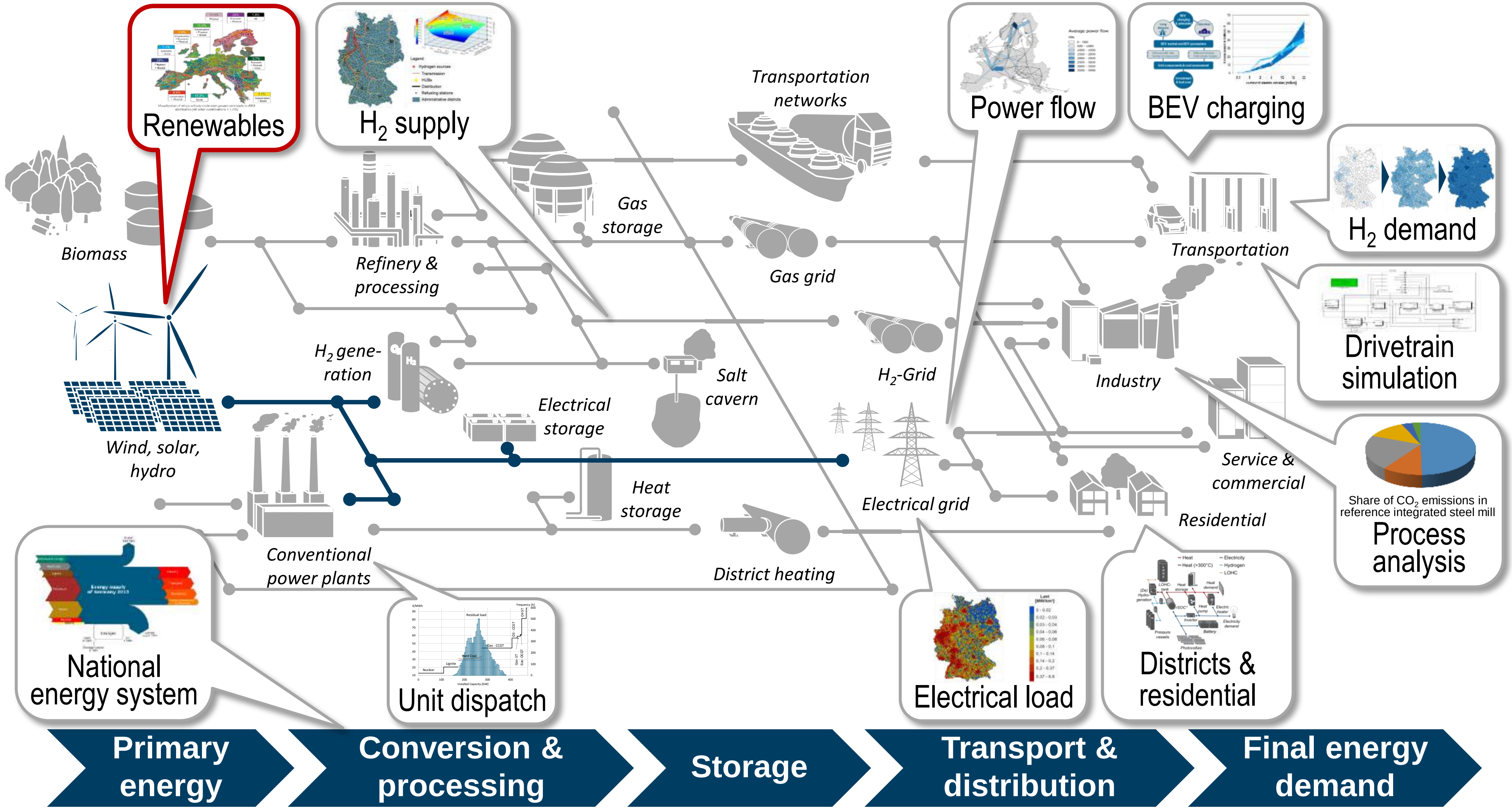
Collaborative software development

Cluster

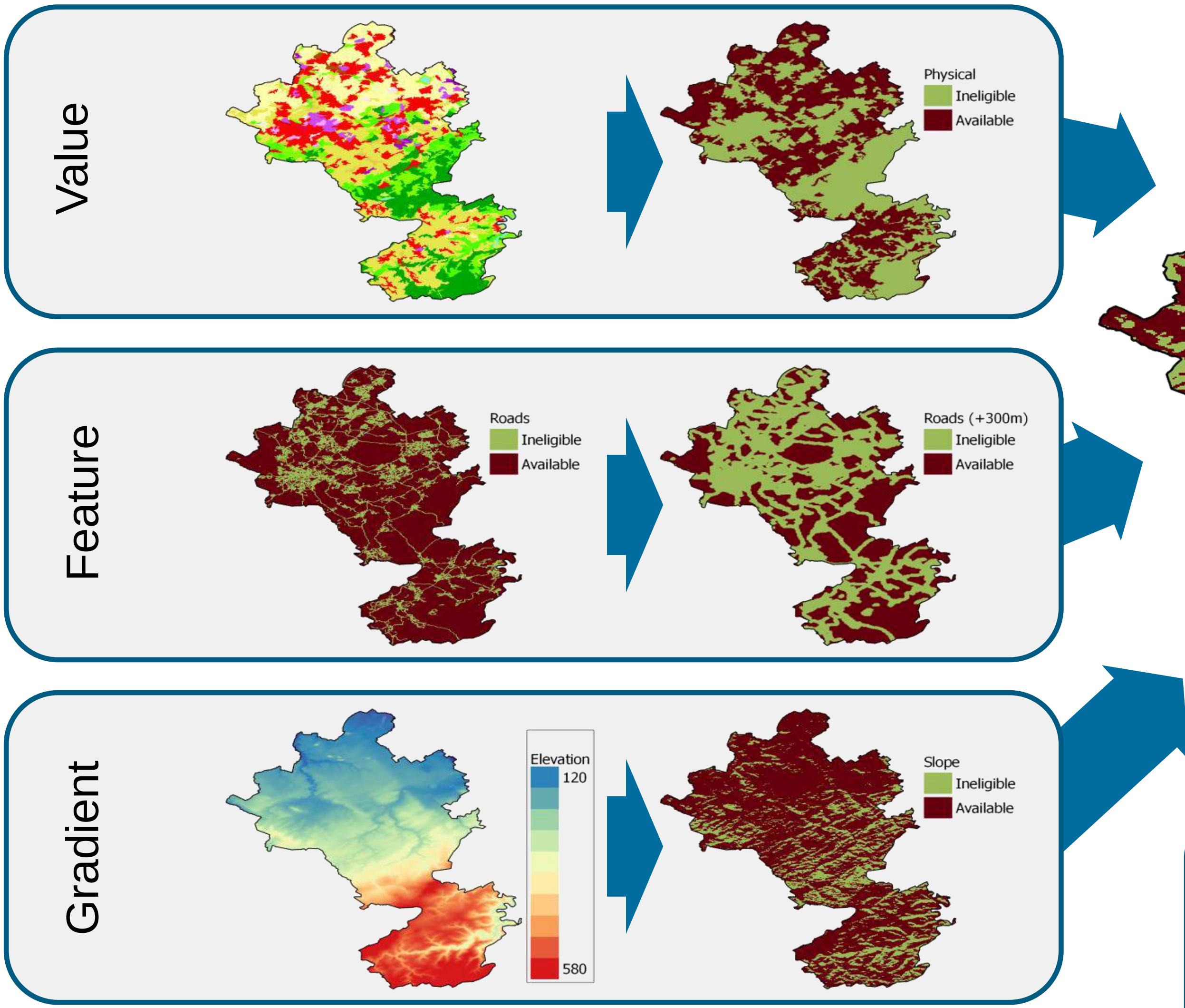
Towards high performance computing

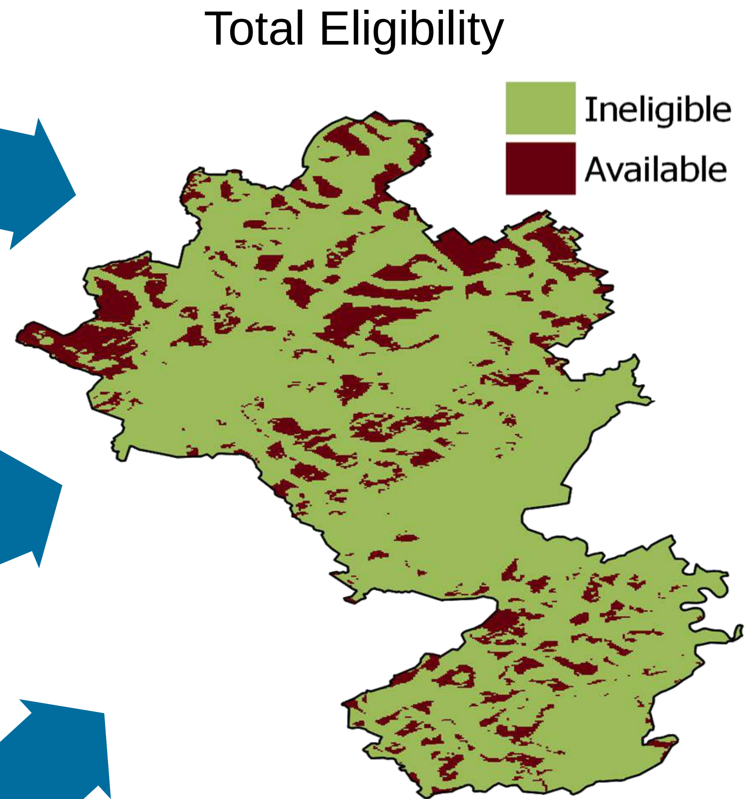
Modeling of Renewable Energies
Example: Wind

Role in the Toolbox



Land Eligibility



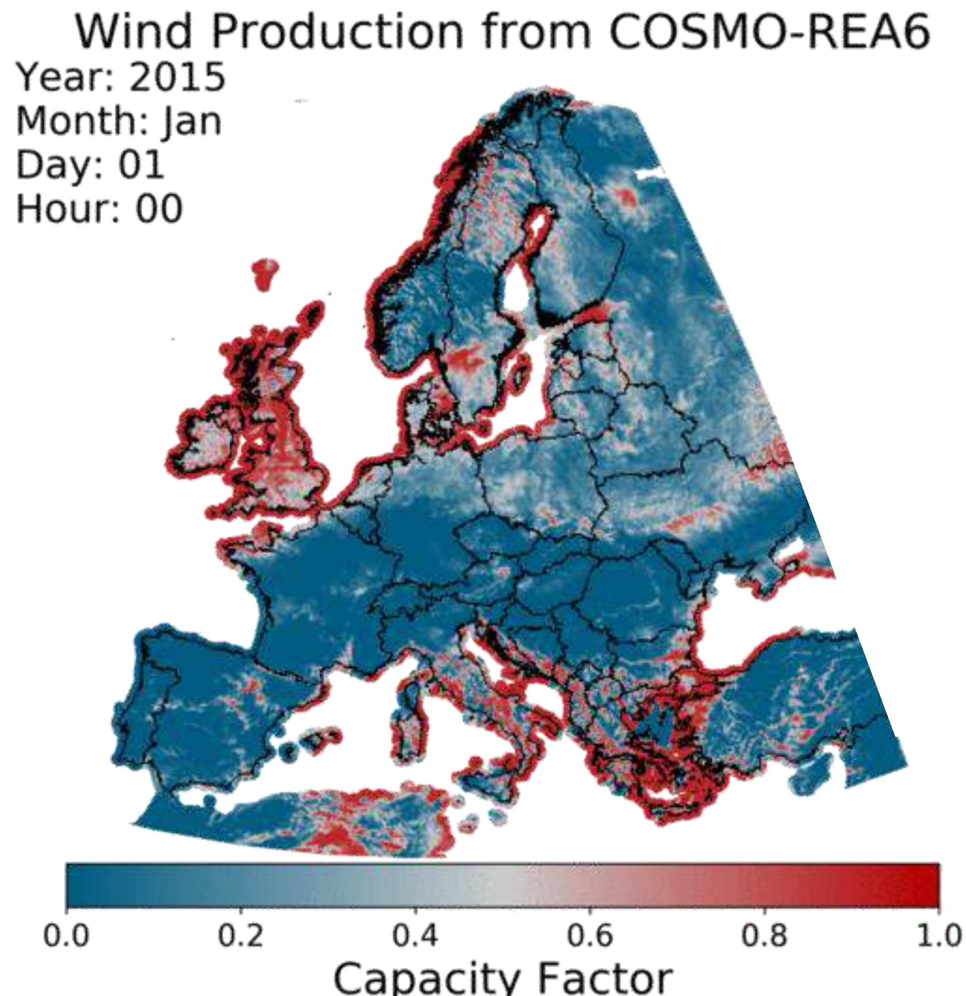


GLAES[1] model standardizes this approach for any technology in any region

1: **G**eospatial **L**and **A**vailability for **E**nergy **S**ystems (https://github.com/FZJ-IEK3-VSA/glaes)

Production Modeling

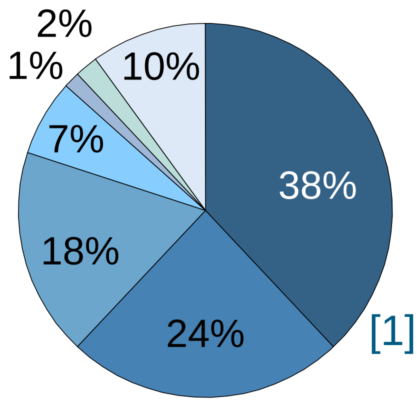
- Climate model data used as input
  - **MERRA** dataset allows for the modeling years **between 1980 and 2016**
  - **CORDEX** datasets allow for modeling **future scenarios until 2100**
  - Other datasets also available: (ERA5, COSMO-REA6, …)
- **Each location** resulting from a land eligibility analysis is **simulated**
  - Aggregation of turbine output constitutes regional production
- Strengths of approach:
  - **Hourly agreement** with measurements
  - **Flexible** to any region definition
  - **Responsive** to land eligibility and sociotechnical development scenarios
  - Follows advances in climate science
- Challenges of approach:
  - **Necessitates highly efficient data processing** techniques that are not built into other models



Sector Coupling
with
Hydrogen
Examples

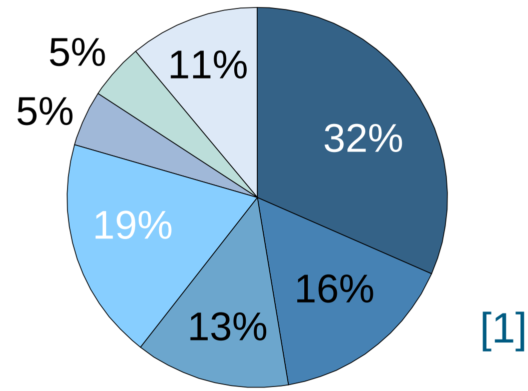
Hydrogen Production and Consumption

World H_2 production



≈ 500 billion m^3_{STP}/a

German H_2 production

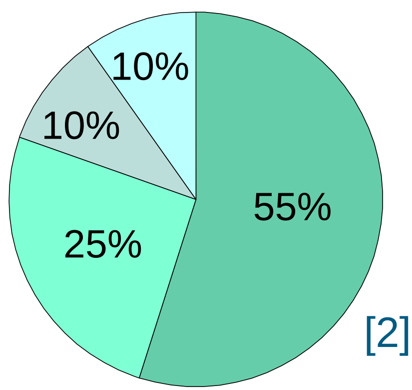


≈ 19 billion m^3_{STP}/a

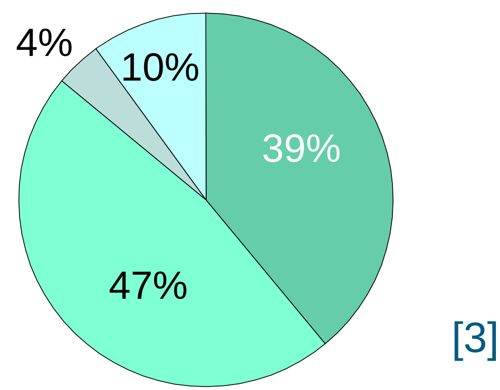
- Steam reforming of natural gas or naphtha
- Partial oxidation of heavy oil
- Gasoline reformation
- Ethylene production
- Other chemical industry
- Chlor alkali electrolysis
- Coal gasification

Captive: 90 %
Merchant: 10 %

World H_2 use



German H_2 use



- Ammonia production
- Refinery
- Methanol production
- Other use

[1] Hydrogeit: *Herstellung von Wasserstoff*. http://www.hydrogeit.de/wasserstoff.htm, Access: 27.01.2015
[2] Decarboni: *Industrial hydrogen and synfuel production and use*. http://decarboni.se, Access: 27.01.2015
[3] Arno A. Evers FAIR-PR: *Consumption of Hydrogen by End Use – 2006*. http://www.hydrogenambassadors.com, Acsess: 27.01.2015

Sector Coupling

Linking the Power and Transport Sectors

Robinius, M., et al., *Linking the Power and Transport Sectors—Part 1: The Principle of Sector Coupling.* Energies, 2017. **10**(7): p. 956.
Robinius, M., et al., *Linking the Power and Transport Sectors—Part 2: Modelling a Sector Coupling Scenario for Germany.* Energies, 2017. **10**(7): p. 957.
Robinius, M., et al., *Power-to-Gas: Electrolyzers as an alternative to network expansion – An example from a distribution system operator.* Applied Energy, 2018. **210**: p. 182-197.

The Year 2050 – Energy Concept 2.0

Assessment based on municipal level and an hourly resolution of grid load and RES feed-in

Power-Sector

RES power [GW **| TWh]:** onshore: 170 | **350**; offshore: 59 | **231**; PV: 55 | **47**; hydro: 6 | **21**; bio: 7 | **44**

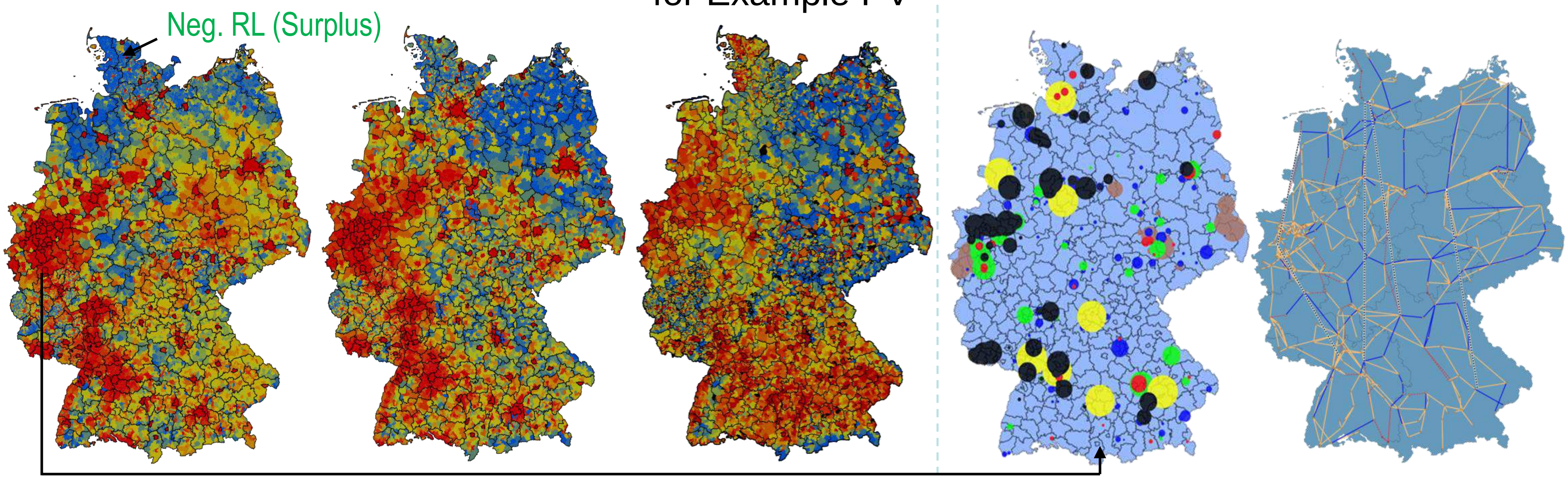
Further assumptions: grid electricity: **528 TWh**; imports: 28 TWh; exports: 45 TWh; pos. residual: natural gas

„Copper plate“ & 40 GWh pumped hydro: **191 TWh (→ 4.0 million t_{H2})**

Grid capacity constraints considered: **293 TWh (→ 6.2 million t_{H2})**

RES: Renewable Energy Sources

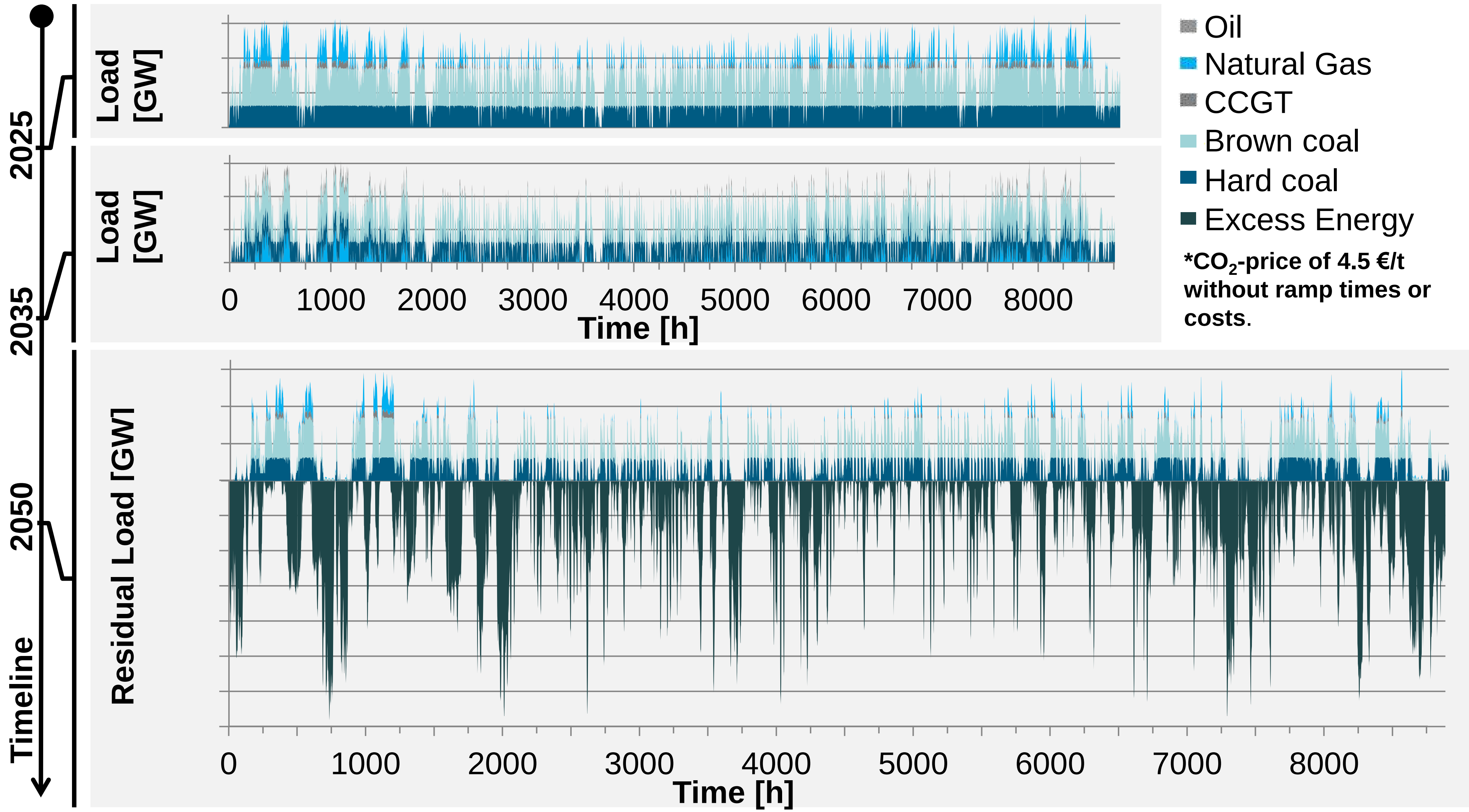
Residual load = Load - RES for Example PV | Conventional Power Plants | Electrical Grid 380 and 220 kV



Positive residual load

All values after Robinius, M. (2016): Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff. Dissertation RWTH Aachen University, ISBN: 978-3-95806-110-1

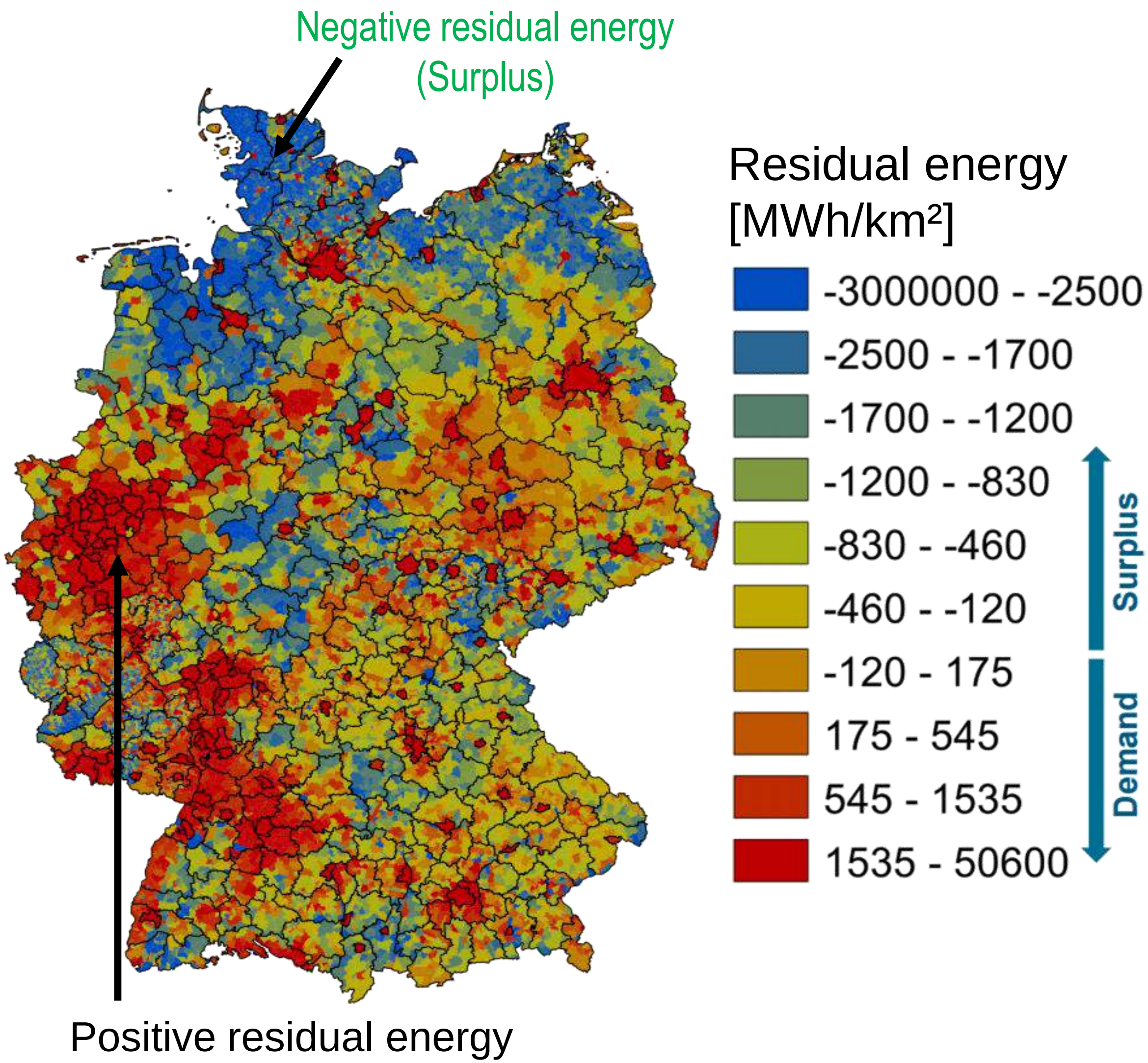
Effect of a Renewable Energy Scenario on the Operation of Conventional Power Plants*

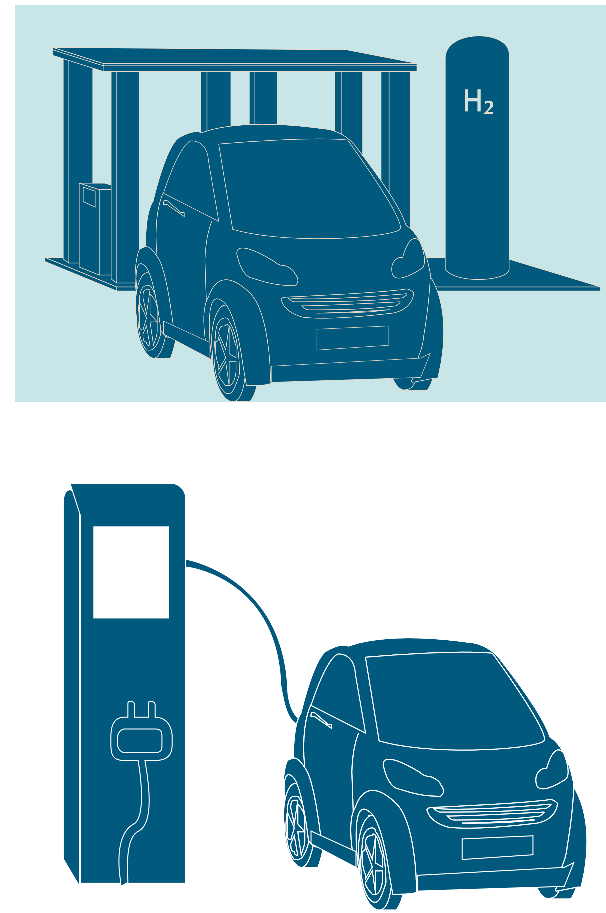


***CO_2-price of 4.5 €/t without ramp times or costs**.

Installed capacity regarding to [1] Übertragungsnetzbetreiber (2015): Netzentwicklungsplan Strom 2025
[2] Bartels, S (2016): Simulationsmodell regional aufgelöster Residuallasten in Deutschland, Masterthesis
[3] Robinius, M. (2016): Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff.

Linking the Power and Transport Sector





First Fuel Cell Vehicles Ready for Market
Intro

1994 MB NECAR 1 (H_2)

1999 Honda FCX V1 (H_2)

2002 Honda FCX-V4: 1st FCV commercially certified *

2004 Clean Energy Partnership (D)

2013–16 **Small commercial series production**

Hyundai ix35 FCEV (2013) | Toyota Mirai (2015) | Honda Clarity (2016)

Fuel cell APUs for passenger cars**,** then for **trucks**, train, ships & **airplanes**

60s 70s 80s 90s 2000s 2010s

1966 **First FCV** GM Electrovan (H_2, AFC)

2001 MB NECAR 5.2, methanol reformer

GM Chevrolet S-10 gasoline reformer

2001 Cold start at -20°C (GM)

2006 HT-PEM (Volkswagen)

2008-2009 **Small series for demonstration projects**

MB B-Class F-Cell | GM HydroGen4 | Honda FCX Clarity

Aromatic membrane -30…95 °C

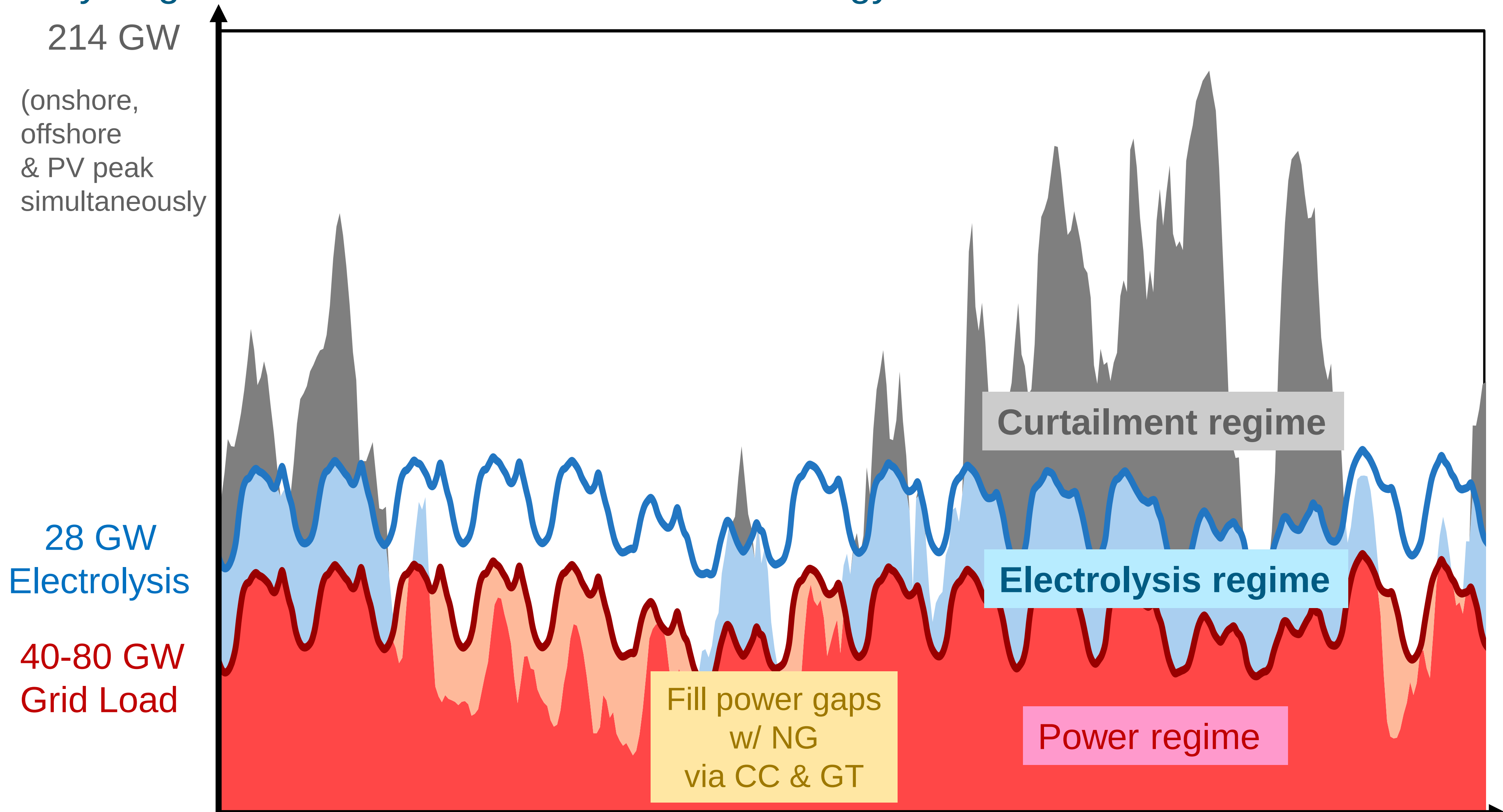
* First fuel-cell vehicle certified by the U.S. EPA and California Air Resources Board (CARB) for commercial use

MB: Mercedes-Benz; GM: General Motors

All cars with PEFC except GM Electrovan with AFC; APUs with SOFC, PEM or HT-PEM

Principle of a Renewable Energy Scenario with Hydrogen

Hydrogen as an Enabler for Renewable Energy

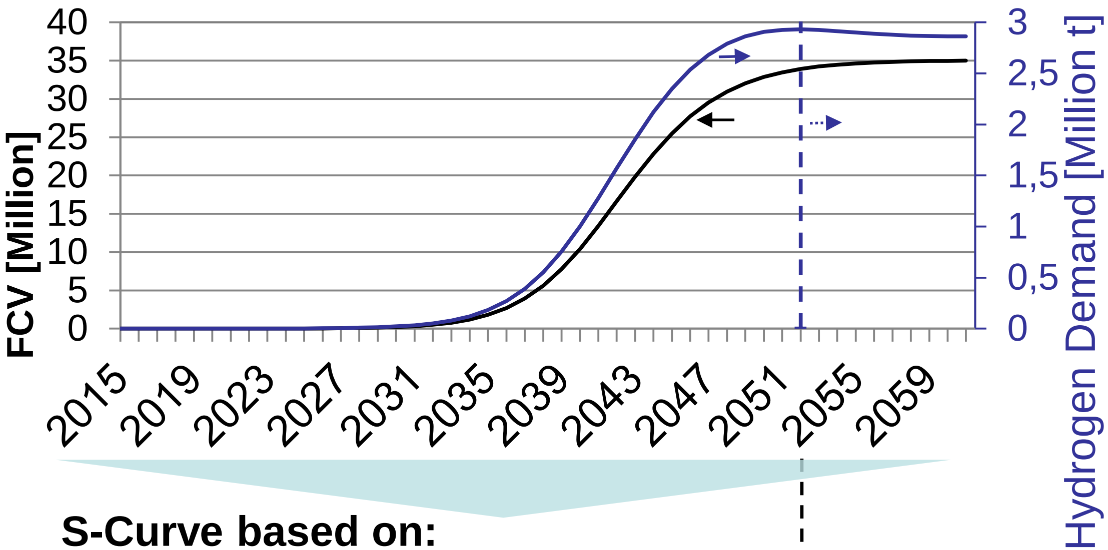


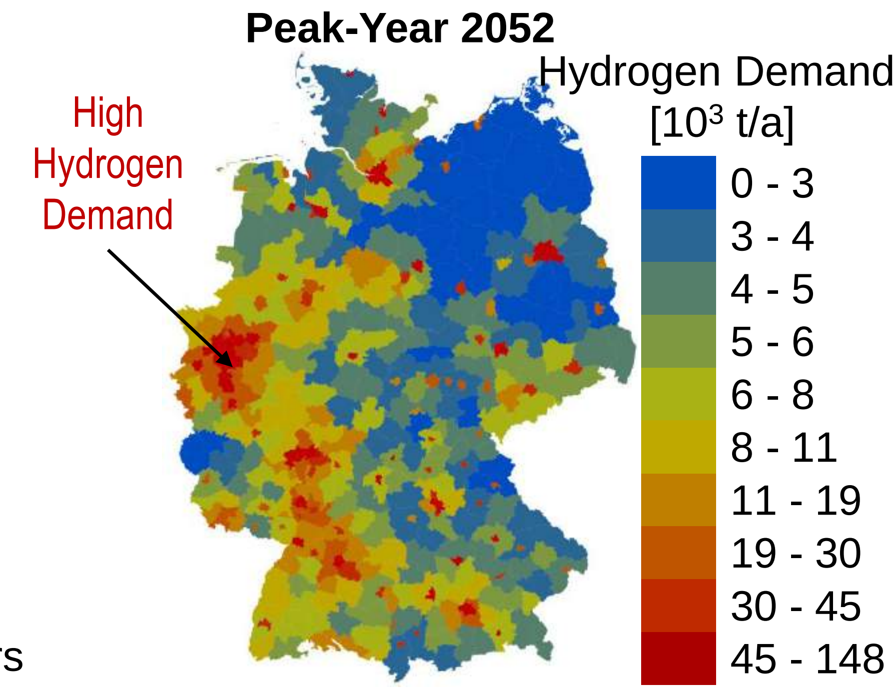
* based on Robinius, M. (2016): Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff. PhD thesis

Energy Concept 2.0

Assessment based on counties level

H_2 Demand/a		
	FCV [kg/100 km]:	**0.92** (2010) → **0.58** (2050) [1], linear decrease
	FCV fleet:	curve fit; until 2033 according to [2]; maximum share in 2050: 75 % of German fleet
	Further assumptions:	**14,000** km annual mileage **12 years** lifetime; total vehicle stock: **44 million cars**
	Peak annual H_2 demand:	**2.93 million t_{H2} (2052)** **(Surplus 2050 Copper plate scenario → 4.0 million t_{H2})**





S-Curve based on:

- Target is 75 % of total passenger cars are FCV
  → 32.9 million FCV in 2050
- Reference points are based on H2Mobility

 # based on:

Number of cars

Population density

Useable income of private households …

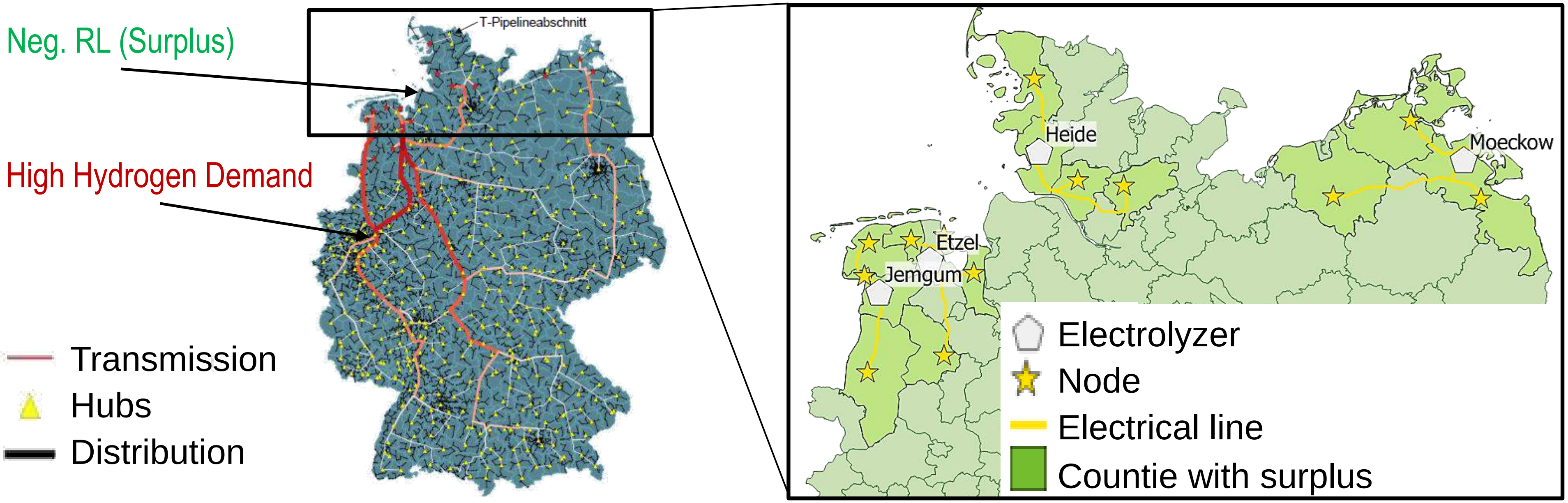
All values after Robinius, M. (2016): Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff and Tietze, V.: Techno-ökonomische Bewertung von pipelinebasierten Wasserstoffversorgungssystemen für den deutschen Straßenverkehr, to be published except: [1] GermanHy (2009), Scenario "Moderat" [2] H2-Mobility, time scale shifted 2 years into the future [3] Krieg, D. (2012), Konzept und Kosten eines Pipelinesystems zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff.

Energy Concept 2.0

Assessment based on counties level

Results

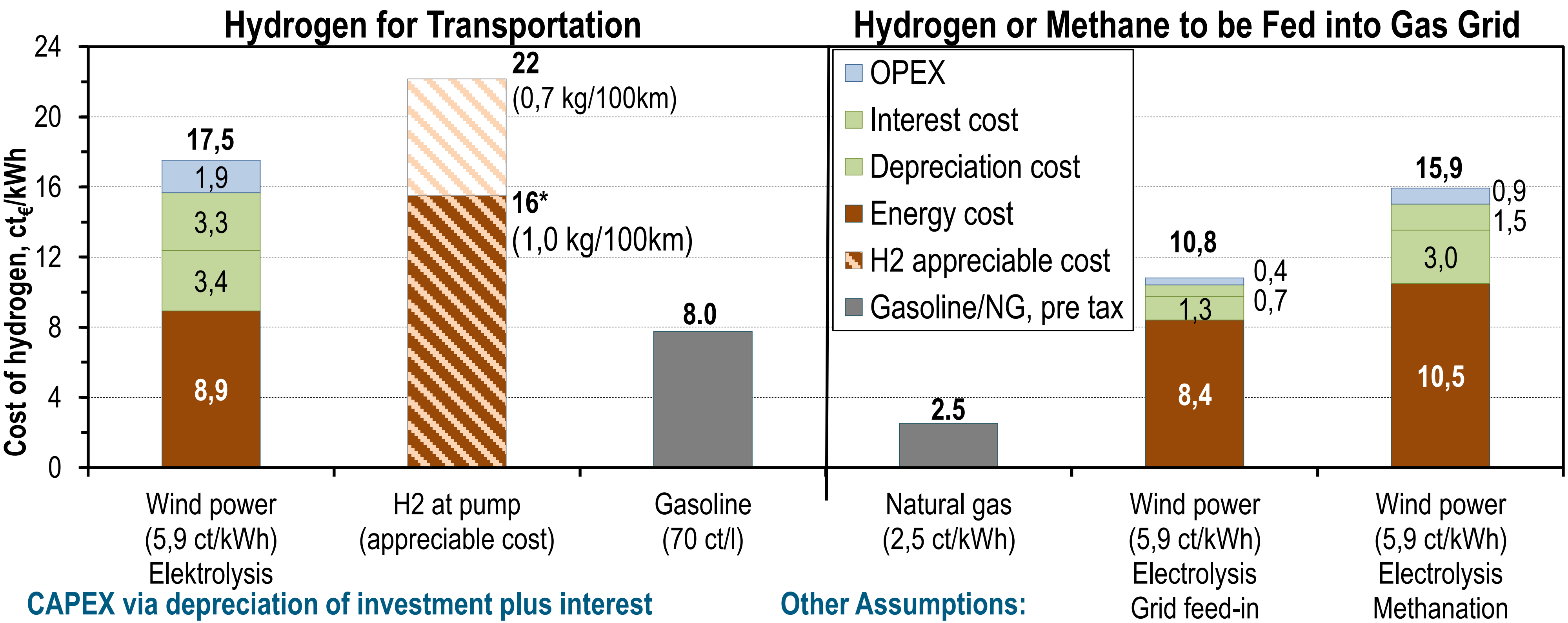
H_2 sources:	**28 GW** electrolysis power in 15 districts in Northern Germany, **15 billion €**
H_2 sinks:	**9,968 refueling stations** with averaged sales of 803 kg/d, **20 billion €**
H_2 storage:	**48 TWh** (incl. 60 day reserve), **8 billion €**
Pipeline invest [3]:	**6.7 billion €** (12,104 km transmission grid); **12 billion €** (29,671 km distribution grid)
Electricity cost:	LCOE Onshore: **5.8 ct/kWh**;
Total H_2 cost (pre-tax):	**17.5 ct/kWh** WACC: 8 %



All values after Robinius, M. (2016): Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff. Dissertation RWTH Aachen University, ISBN: 978-3-95806-110-1; except: [3] Krieg, D. (2012), Konzept und Kosten eines Pipelinesystems zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff. Forschungszentrum Jülich IEK-3
[4] Tietze, V.: Techno-ökonomische Bewertung von pipelinebasierten Wasserstoffversorgungssystemen für den deutschen Straßenverkehr, to be published

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:

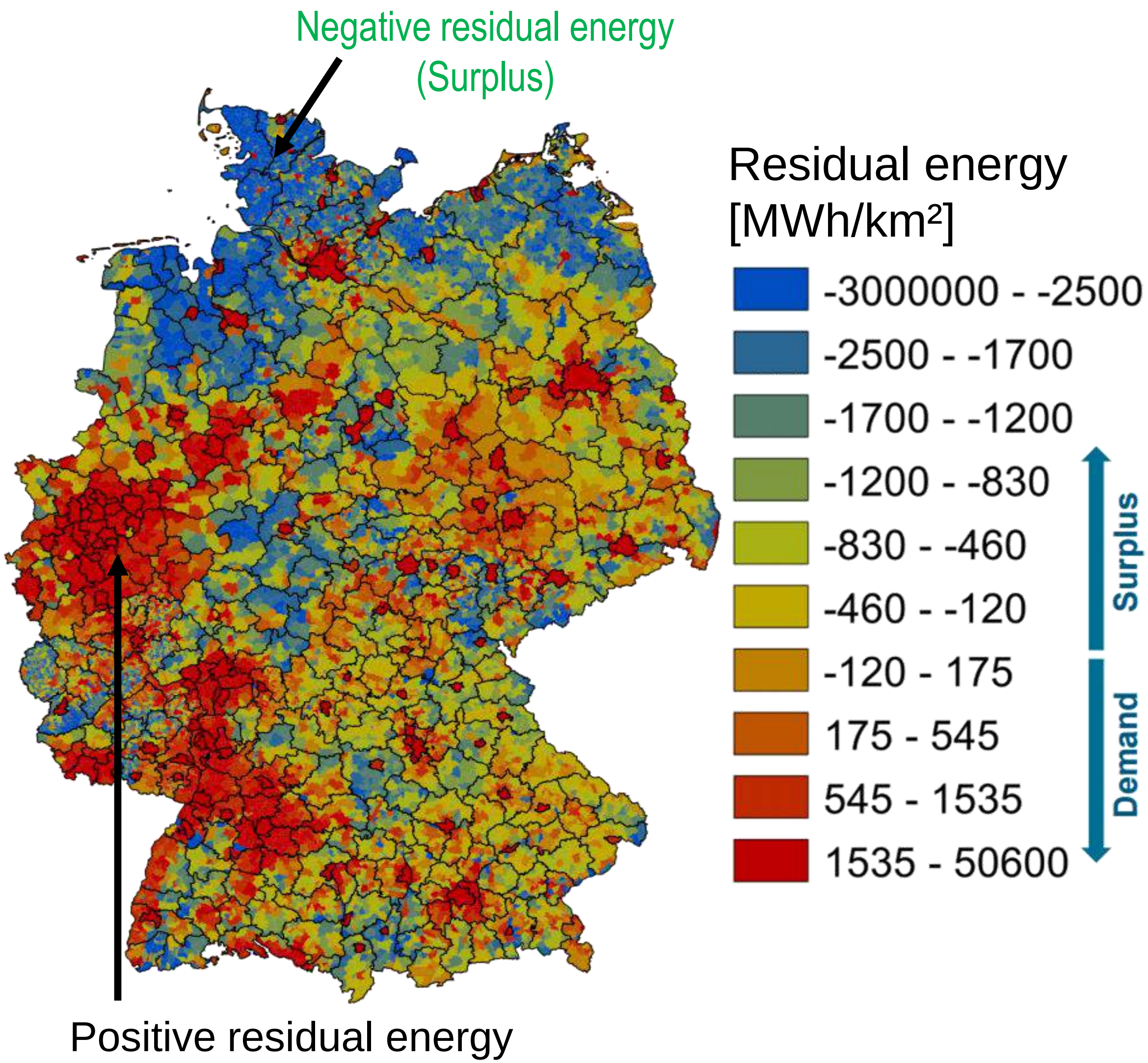
- 2.9 million t_{H2}/a from renewable power via electrolysis
- Electrolysis: η = 70 $\%_{LHV}$, 28 GW; investment cost 500 €/kW
- Methanation: η = 80 $\%_{LHV}$

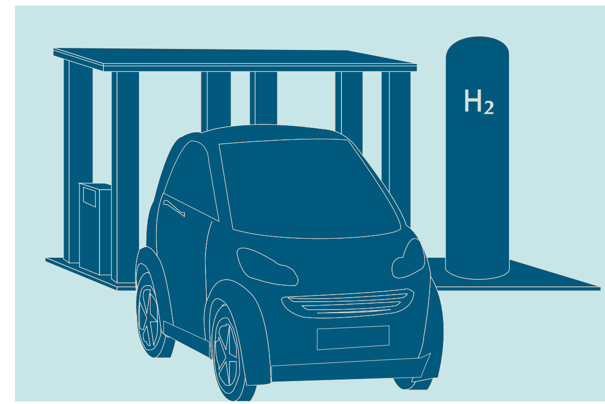
- Appreciable cost @ half the specific fuel consumption

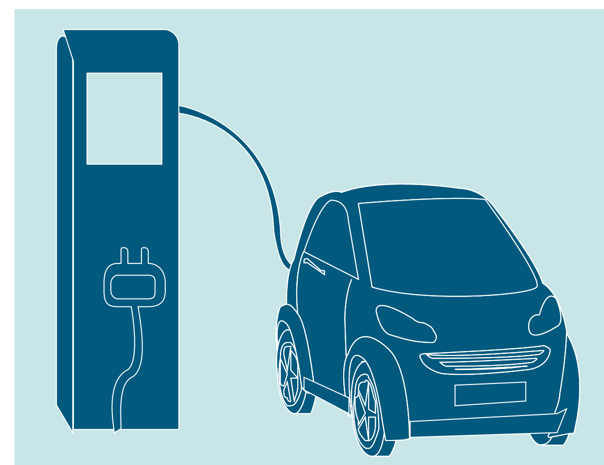
[1] Energy Concept 2.0

Comparative Analysis of Infrastructures

Linking the Power and Transport Sector

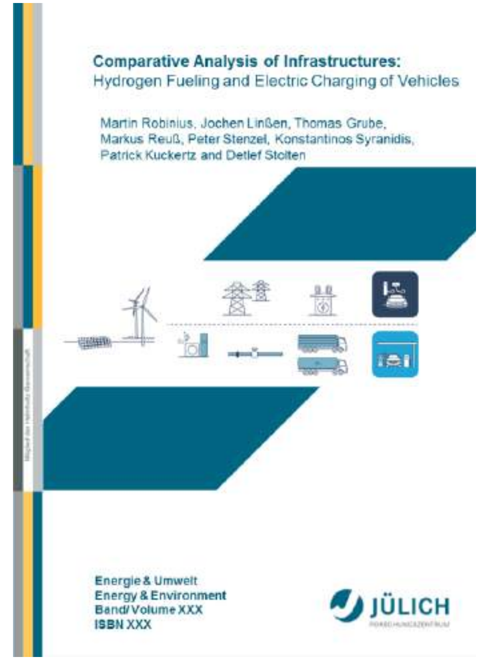






Full report available:

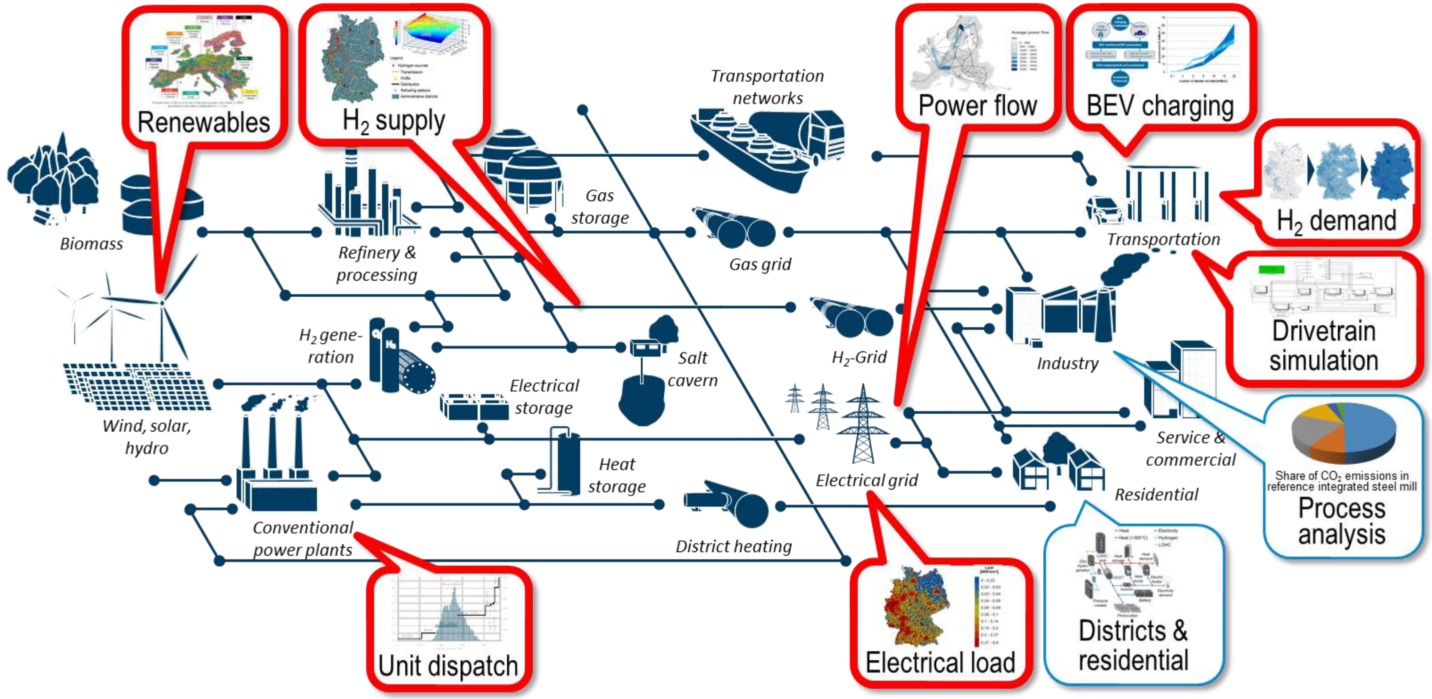
http://www.fz-juelich.de/iek/iek-3/



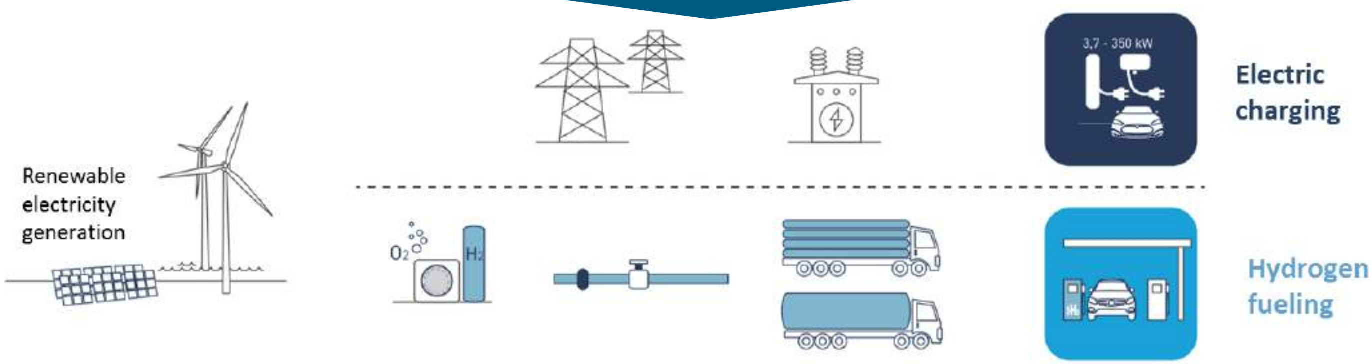
Project team:

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

Applied Model Portfolio



Concerted application



Approach

Meta-analysis of existing infrastructure scenario studies

↓

In depth scenario analysis of infrastructure designs

↓

Consistent scenario framework with different vehicle penetration

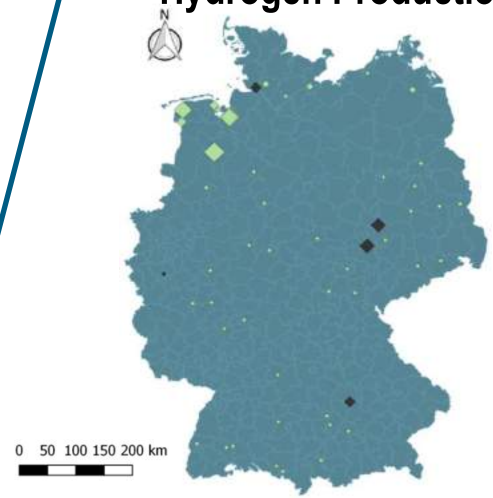
↓

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

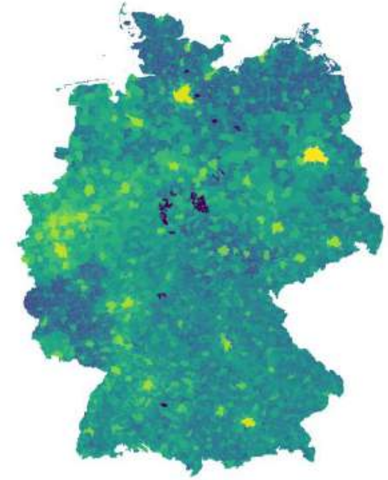
↓

Analysis of investment, costs, efficiencies and emissions

Hydrogen Production

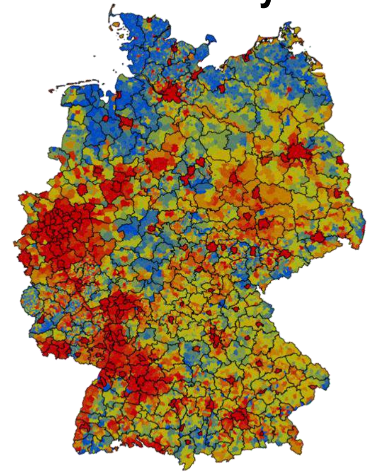


Electric Vehicle stock

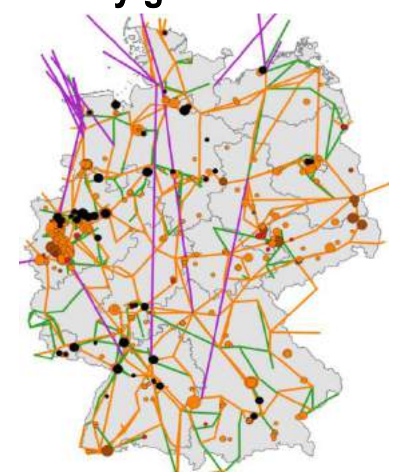


Number of [vehicles] in million	0.1	1	3	5	10	20
Market penetration scenario	Ramp up					Mass market

Renewable electricity and demand



Electricity generation and grid



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 (by 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

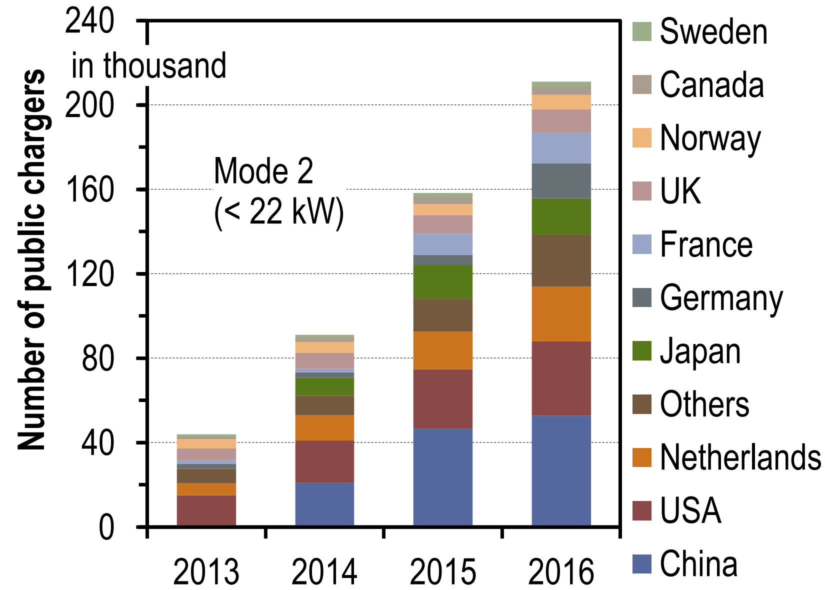
Sources: [9], [10], [14], [15]

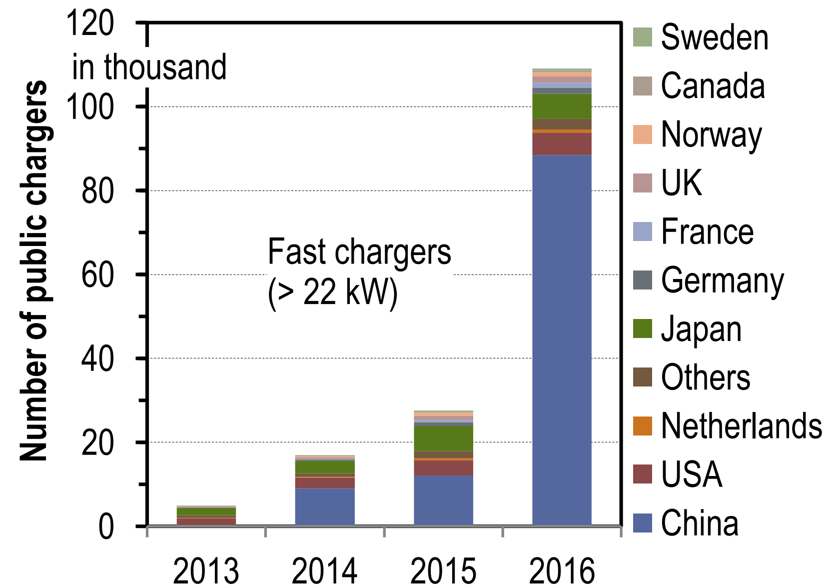
Roadmap for hydrogen refueling stations in Germany [12]

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]

Meta Analysis

Selection criteria of scenario studies

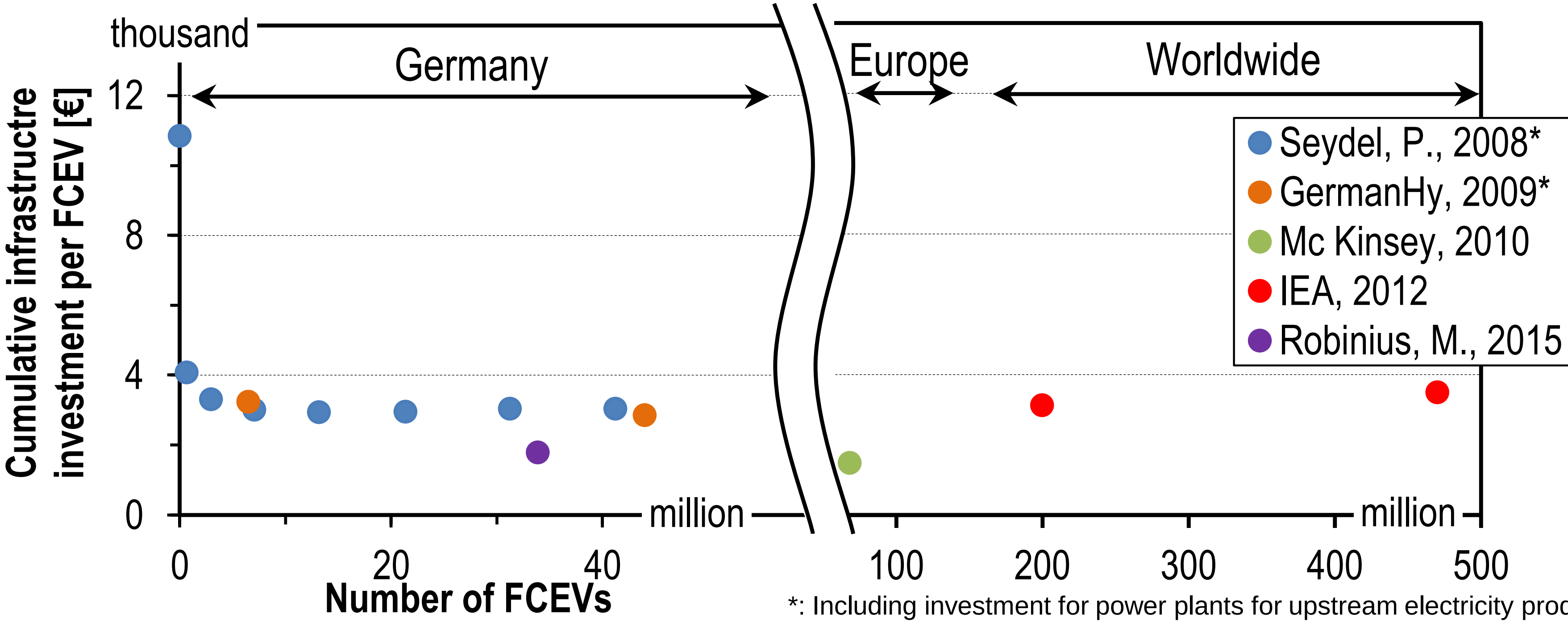
- Focus on Germany (broader context studies for EU, worldwide) and quantitative results; parameters: number of hydrogen fueling stations and charging points, cumulative investment for infrastructure set-up
- Total number of scanned literature sources: 79
- Selected studies for meta analysis: 25 (12 hydrogen and 13 electric charging)

Lessons learned of the meta analysis

- Mostly aggregated results and, in many cases without provision of techno-economic assumptions
- Lack of information in literature of important infrastructure parameters, e.g., hydrogen pipeline length, number of trucks for hydrogen transport → no meta-analysis possible
- Regarding electric charging studies: lack of studies concerning high xEV penetration scenarios, investment for infrastructure build-up, demand for fast-charging and impacts on the distribution grid

Meta Analysis

Hydrogen Fueling Infrastructure – Vehicle Specific Cumulative Investment



*: Including investment for power plants for upstream electricity production
McKinsey – EU&CH&NO, IEA - worldwide

- Cumulative investment differs significantly due to different assumptions e.g. consideration of power plant investment or number of fueling stations
- Specific cumulative investment per FCEV in the range of € 2,000 to 4,000 per FCEV
- Expected decreasing specific investment per FCEV with increasing FCEV stock (due to learning curve and economy of scale) is not observed

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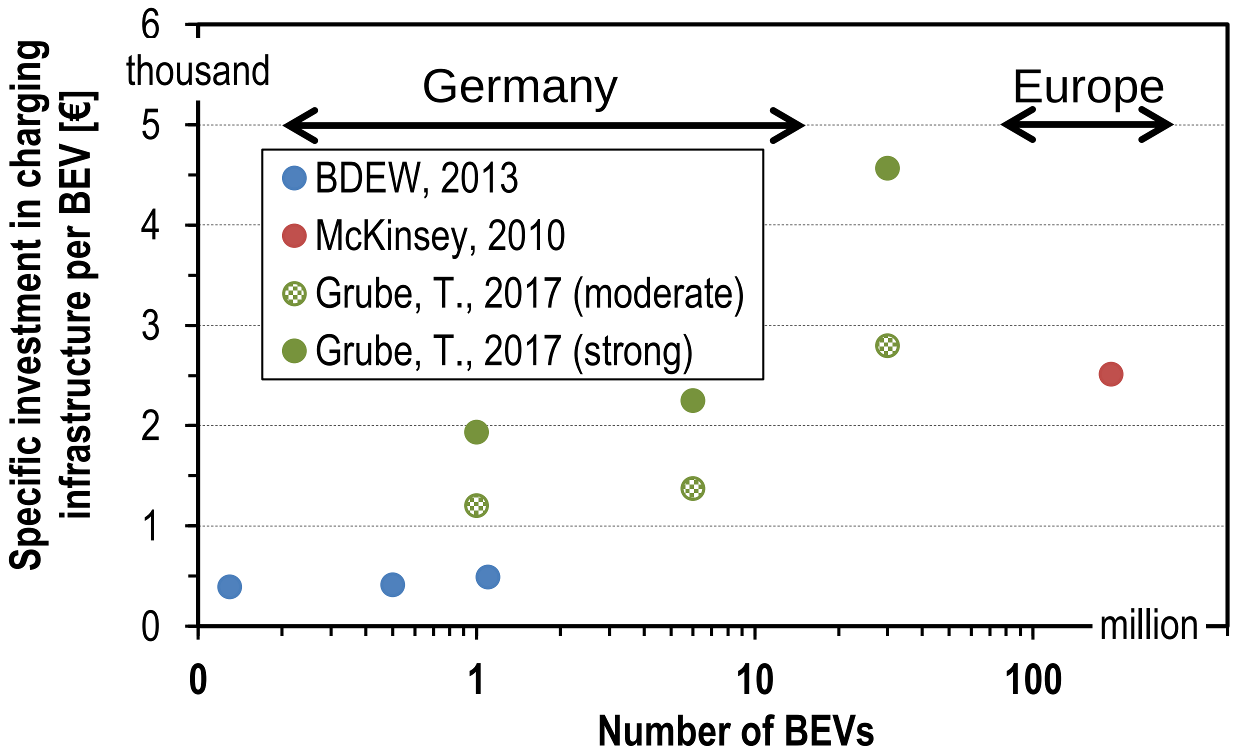
Meta Analysis

Electric Charging Infrastructure – Vehicle Specific Cumulative Investment



investment for public/semipublic normal & fast charging, private charging not included

- According to specific cumulative infrastructure investment per BEV is approx. € 500 per BEV stable for small BEV stocks
- Highest specific investment per BEV occur in the 30 million BEV scenario by Grube et al. => investment for additional grid reinforcements considered and high number of charging points (on-street and additional fast charging)

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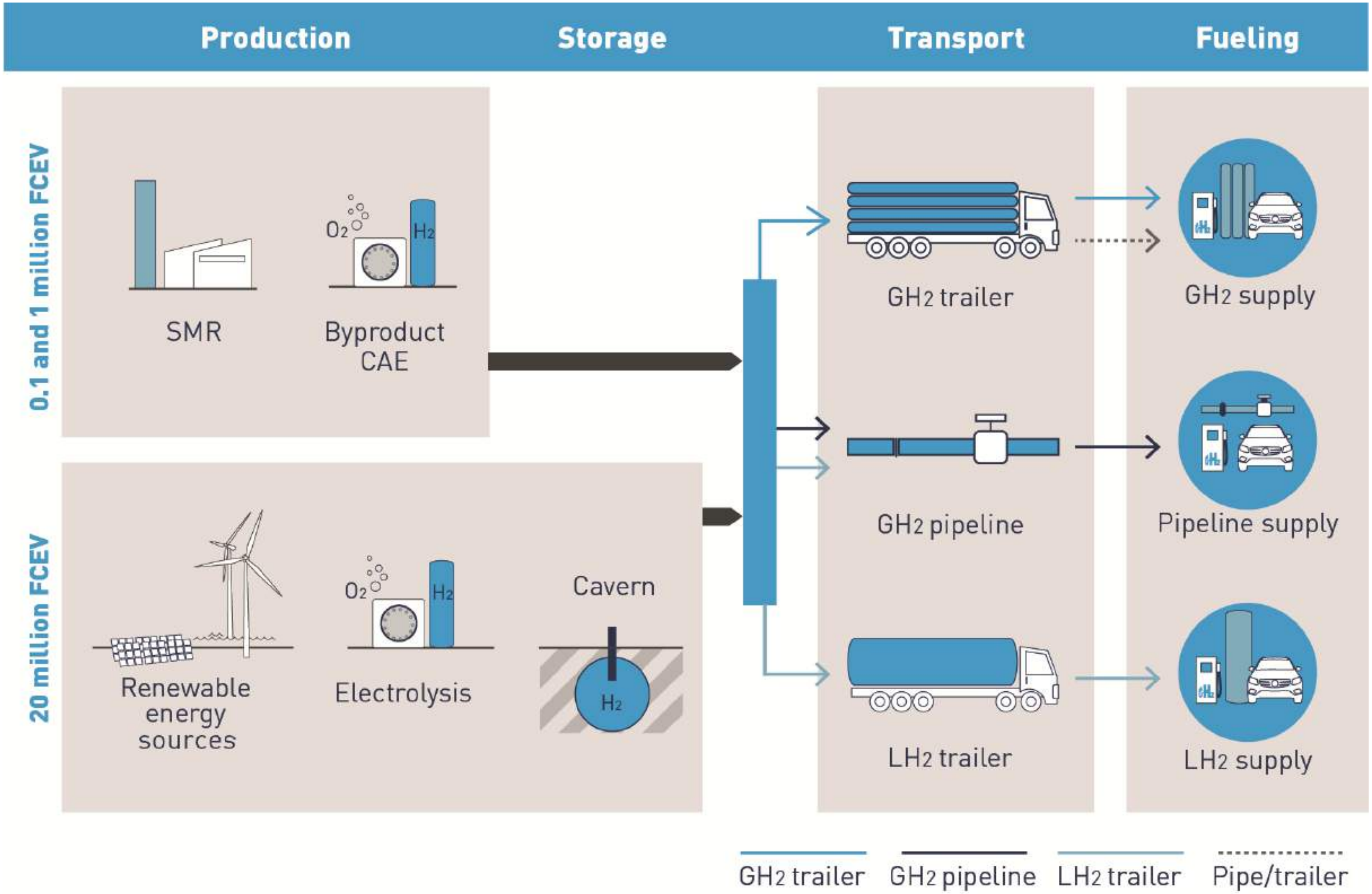
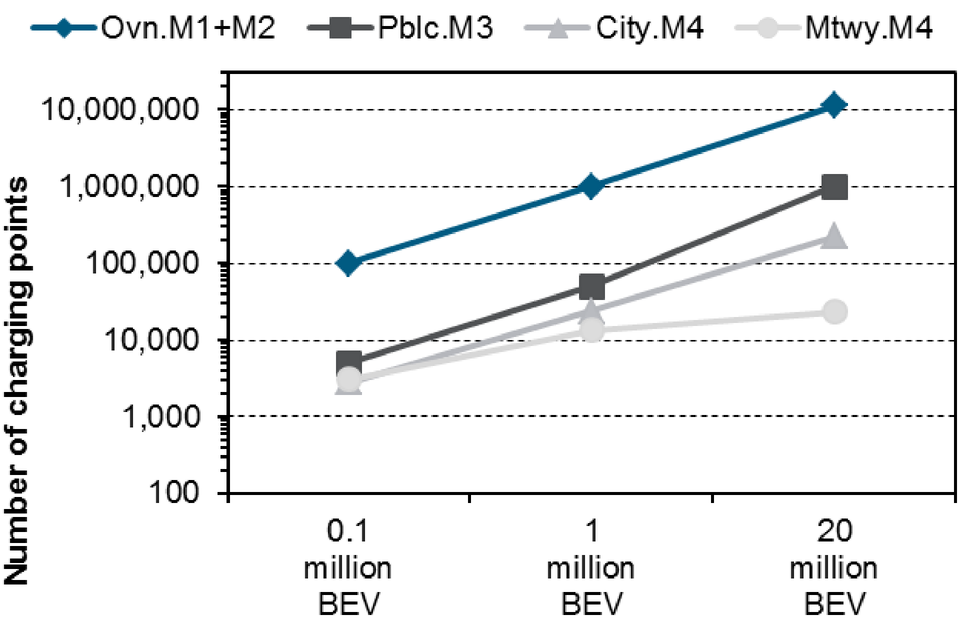
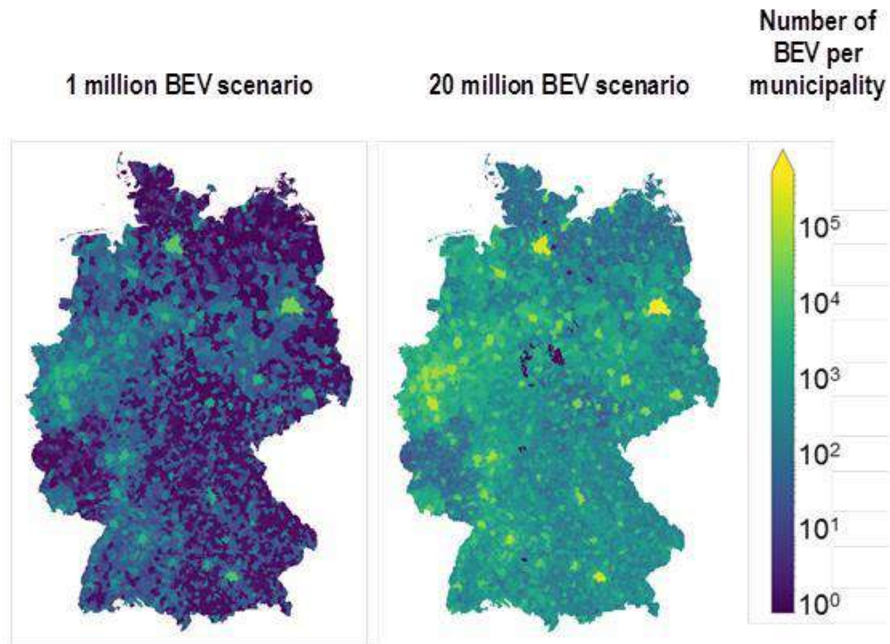
Hydrogen Supply Pathways



Number of BEV and Charging Points





OvN.M1+M2: Home and on-street chargers (Mode 1 and 2); Publc.M3: Public convenience chargers (Mode 3); City.M4: quick chargers in cities (Mode 4); Mtwy.M4: Quick chargers along motorways (Mode 4)

- Number of overnight chargers (Mode 1 & 2) increases with BEV number but with decreasing ratio:
  - 1 by 1 in the first two scenarios (all BEV have an overnight charging option)
  - 1 by 2 in the last scenario (only 58 % of all BEV have an overnight charging option)
- The ratio of BEV per Mode 4 charger increase due to decreasing charging frequency caused by higher driving range (battery capacity)

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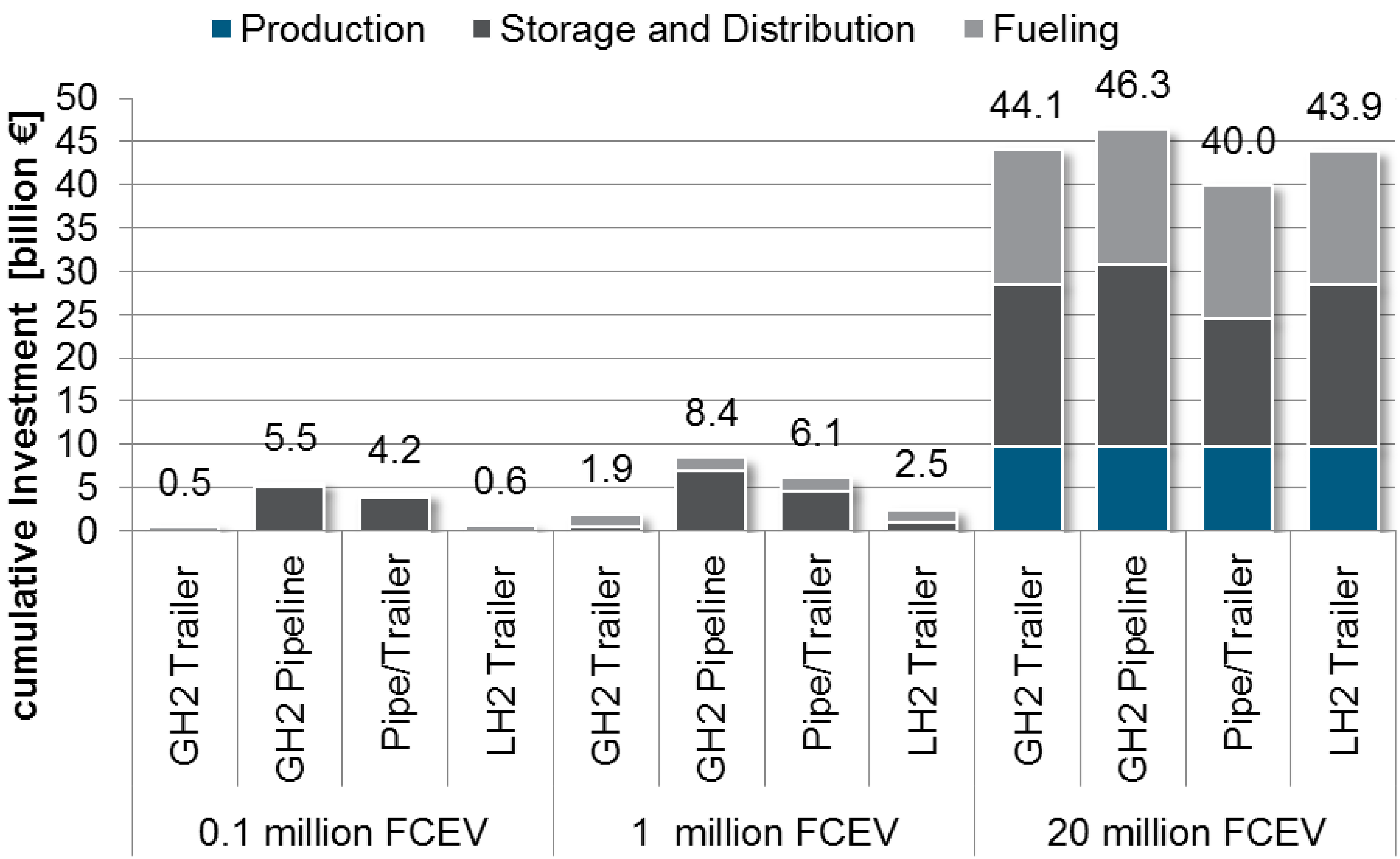
Infrastructure Designs

	Ramp up	Mass market		
	0.1 million	3 million	10 million	20 million
cable length		1,800 km	28,000 km	183,000 km
transformer		6,100	55,000	187,000
slow chargers	100,000 @ 3.7 kW	2.8 million	6.5 million	11 million @ 22 kW
fast chargers	6,000 @ 150 kW	81,000	175,000	245,000 @ 350 kW
storage capacity		2 TWh	5 TWh	10 TWh
electrolysis		3 GW	10 GW	19 GW
truck trailer	42	730	1,500	3,000
pipeline		12,000 km	12,000 km	12,000 km
fueling	400	1,500	3,800	7,000

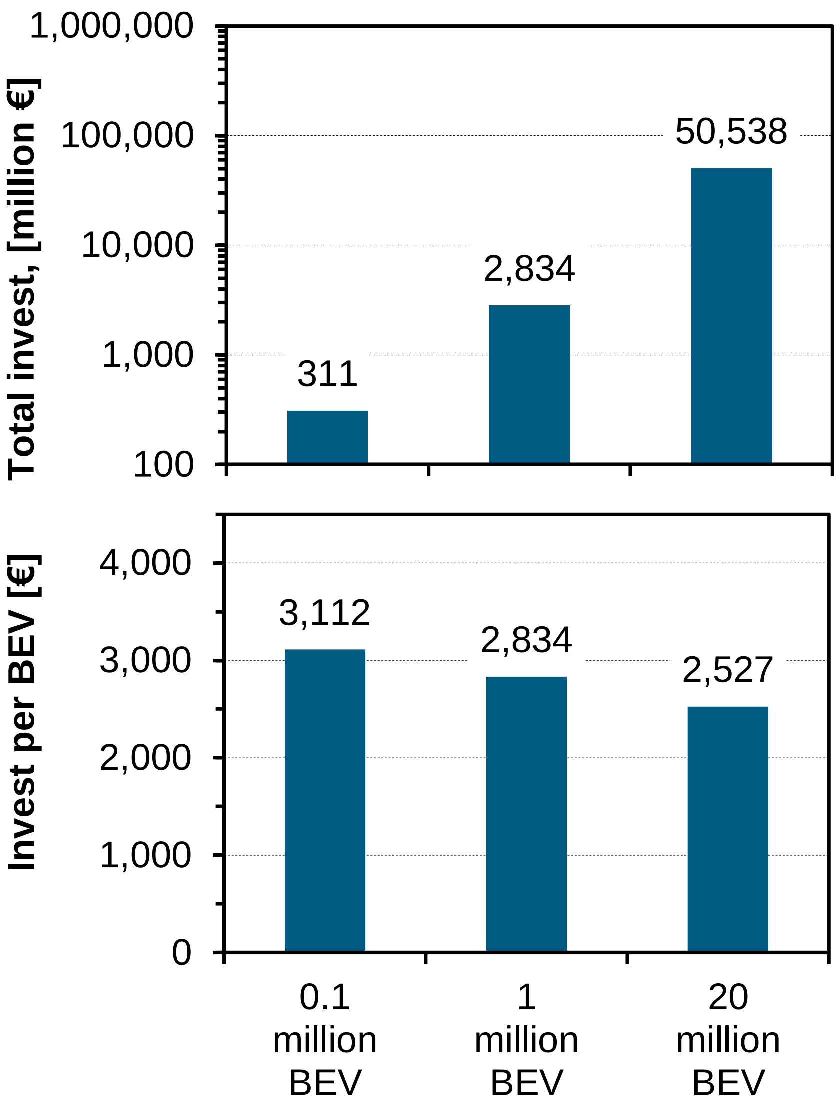
Total Cumulative Investment

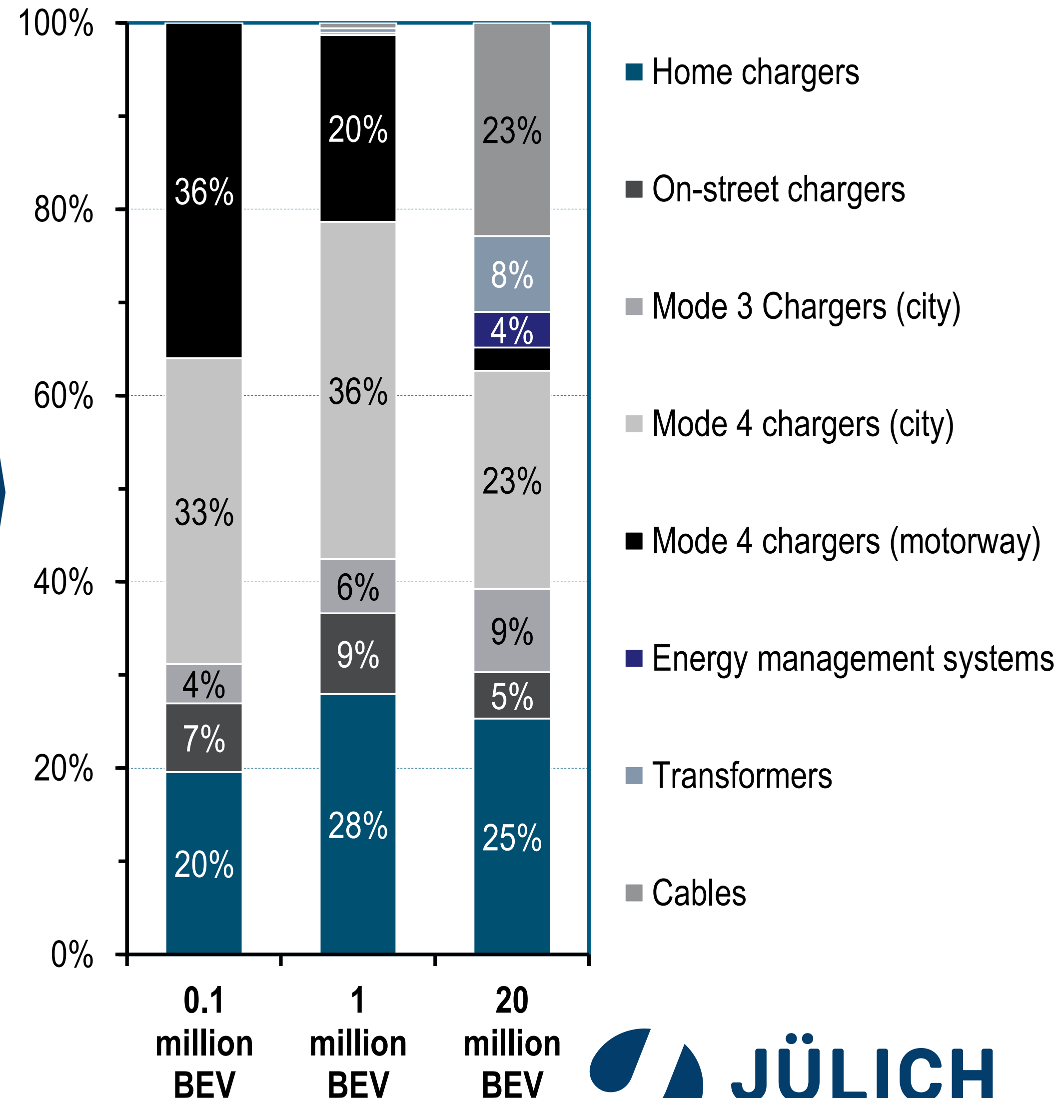
Hydrogen Infrastructure



Total and Specific Investment

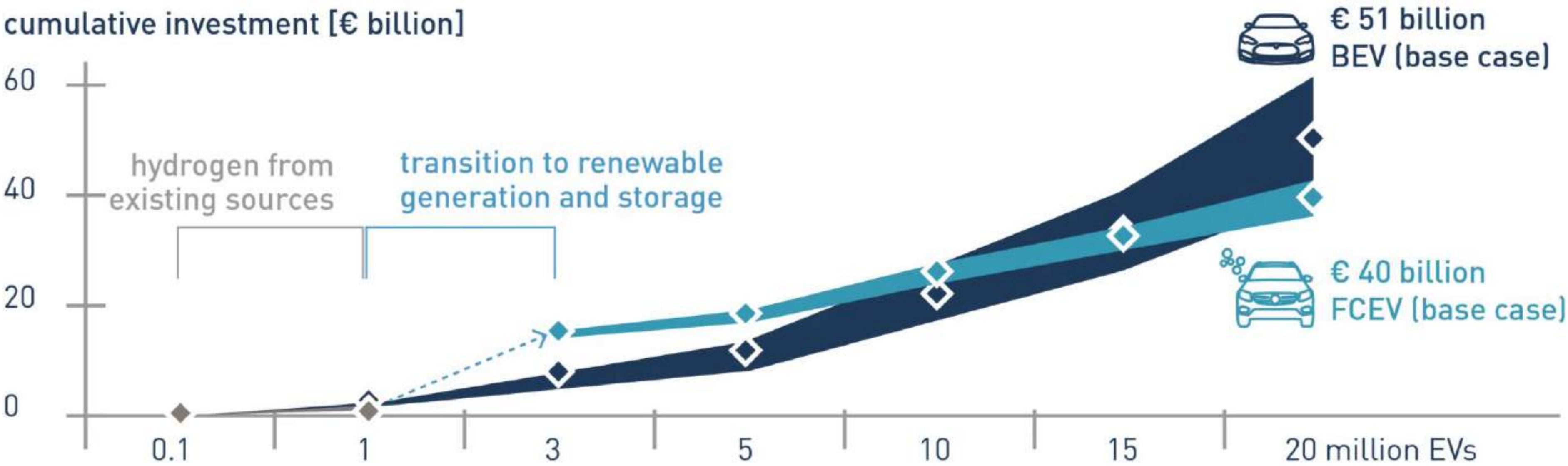
Charging Infrastructure





Cumulative Investment

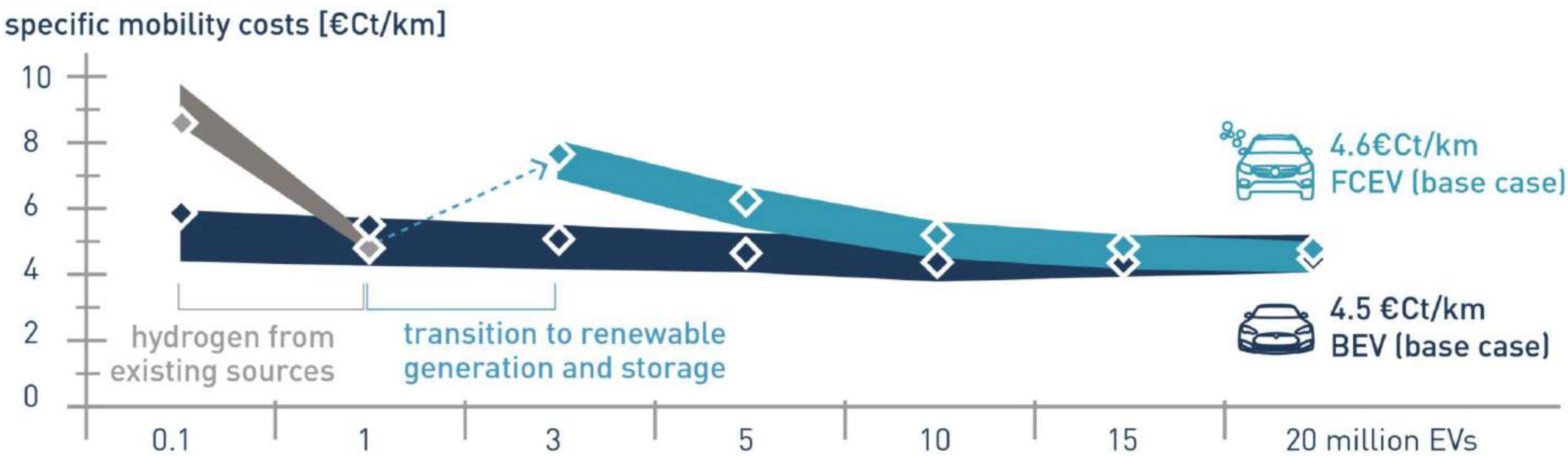
Infrastructure Roll-Out



- 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

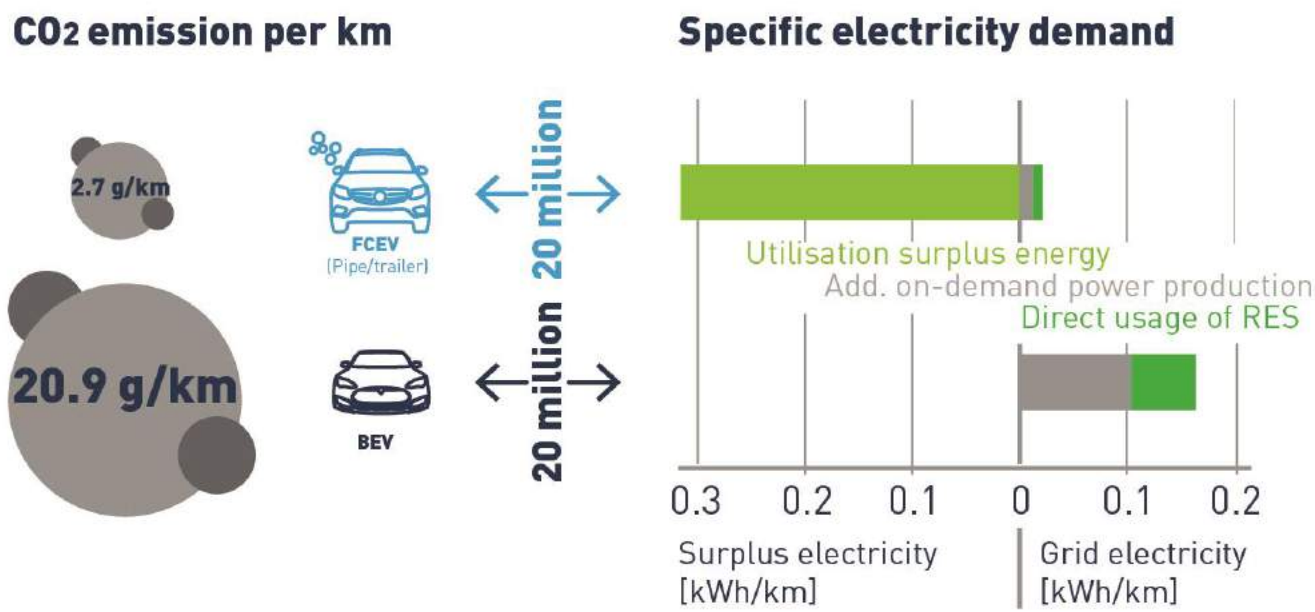
Comparison of Mobility Costs



vehicle purchase and operation costs excluded

- For small vehicle fleets, i.e. 0.1 million cars, BEV fuel costs are significantly lower compared to FCEVs.
- Increase for hydrogen between 1 and 3 million cars results of switching to exclusive utilization of renewable energy for hydrogen production via electrolysis
- Mobility costs per kilometer are roughly same in the high market penetration scenario at 4.5 €ct/km for electric charging and 4.6 €ct/km → the lower efficiency of the hydrogen pathway is offset by lower surplus electricity costs.

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

Conclusions

- Hydrogen and controlled charging key to integration of renewable electricity in transportation
- Complementary development of both infrastructures maximize energy efficiency, optimize the use of renewable energy and minimize CO2 emissions
- Hydrogen infrastructure roll-out for transportation sector enables further large-scale applications in other sectors

Need for further research

- Integrated analysis of infrastructures and energy systems to identify win-win situations
- Modeling of BEV charging require in depth analysis: high uncertainties regarding number of chargers, siting and impact of fast charging on electric distribution grid
- Analyze the impact of new mobility and vehicle ownership concepts as well as autonomous driving on future transport supply concepts

Hydrogen Infrastructure Assessment
The Stranded Investment:
Natural Gas Grid

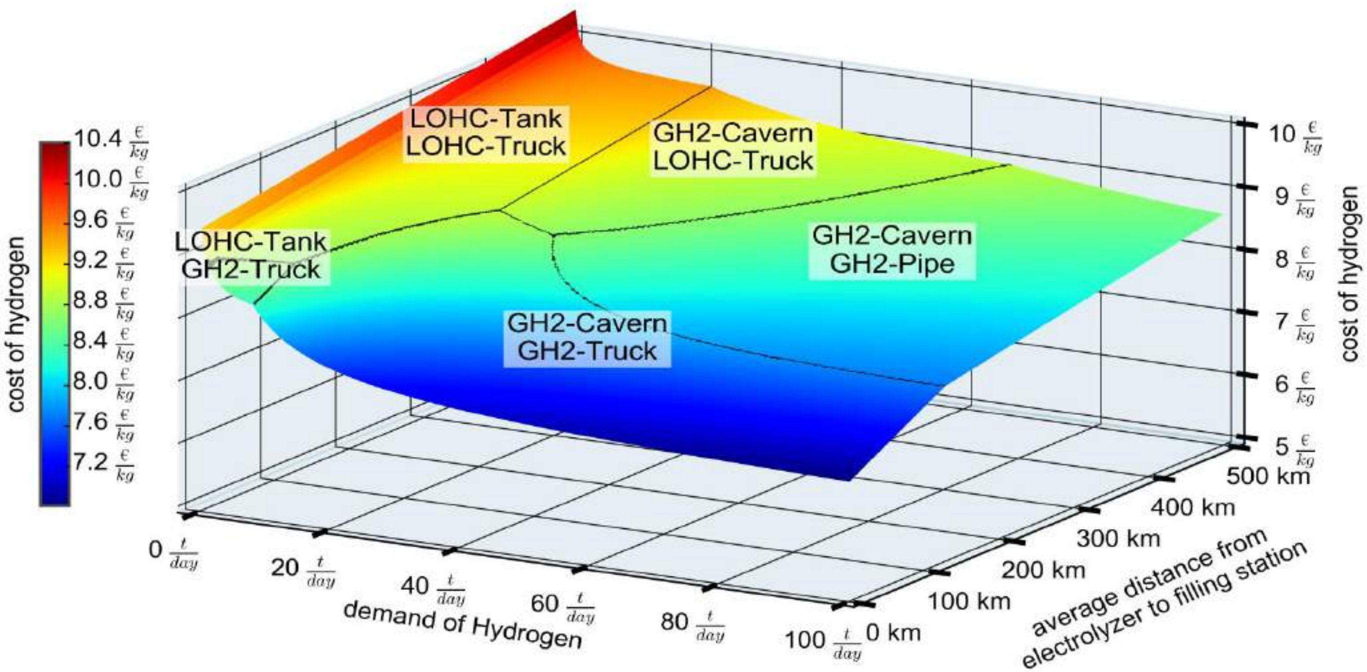
Status Quo

Applied Energy

Volume 200, 15 August 2017, Pages 290–302

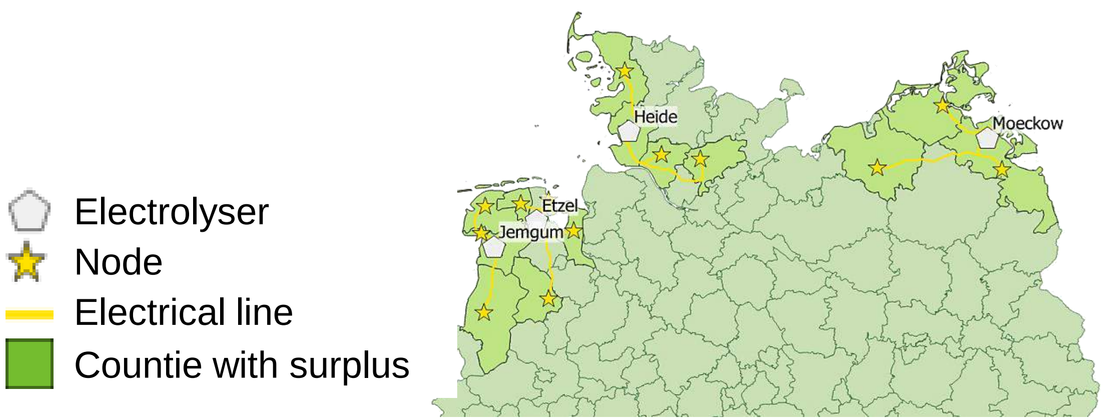
Seasonal storage and alternative carriers: A flexible hydrogen supply chain model

M. Reuß[a], T. Grube[a], M. Robinius[a], P. Preuster[c], P. Wasserscheid[c, d], D. Stolten[a, b]

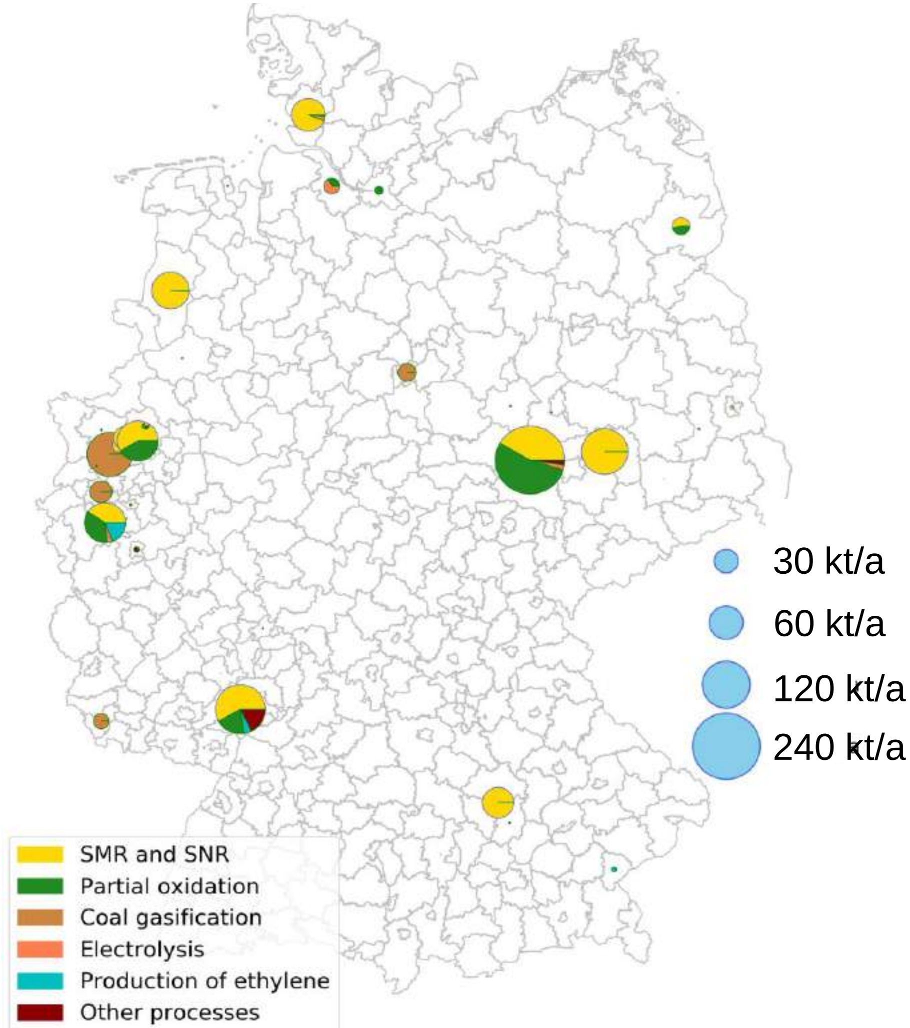


GEO-Spatial Localization of Hydrogen Sources

- 15 districts with significant power oversupply according to IEK Energy Scenario 2.0
- Up to **96 kt p.a.** industrial excess capacity (5 % of today's output) [1]
- No industrial hydrogen capacity growth
- SMR does not require any significant storage
- **Substitution up to 25 %** of total supply is enabled to sustain green hydrogen (green hydrogen certificates [3])

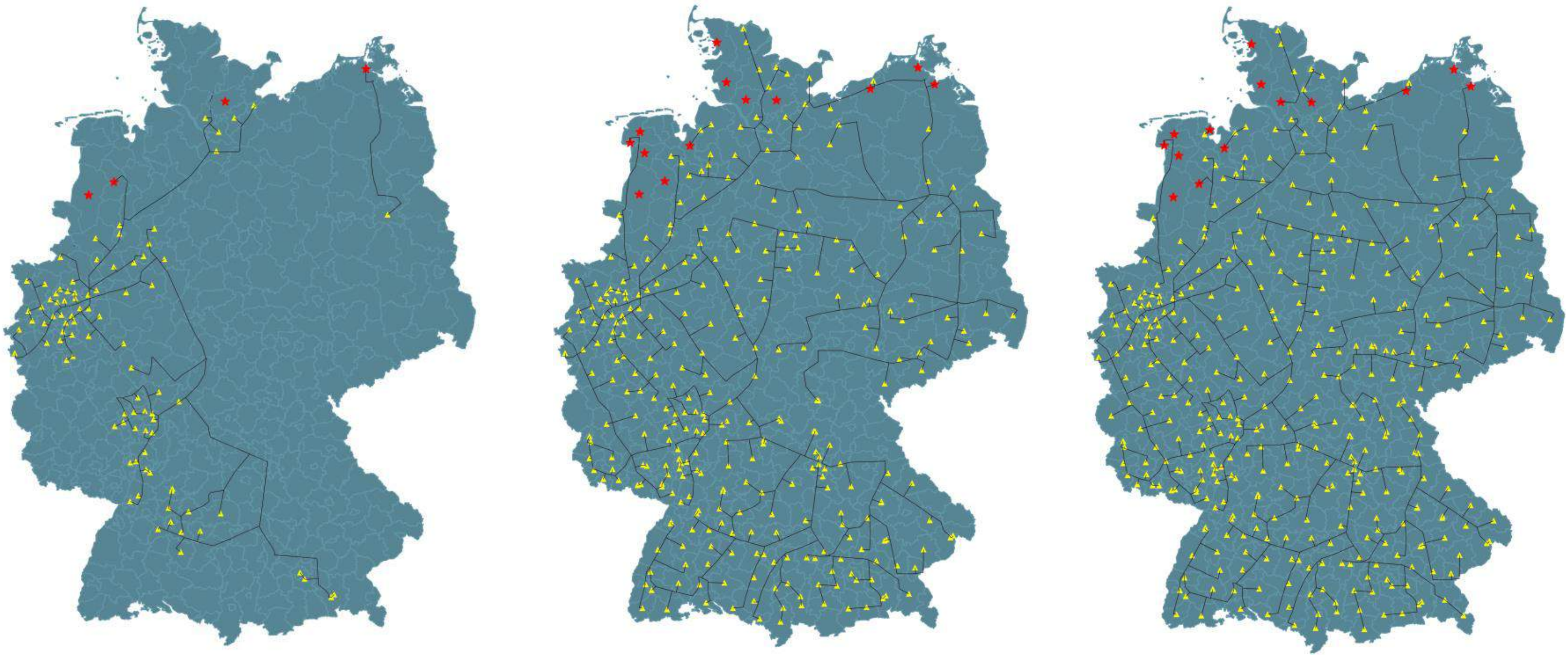


Industrial Hydrogen Demand [kt/a]



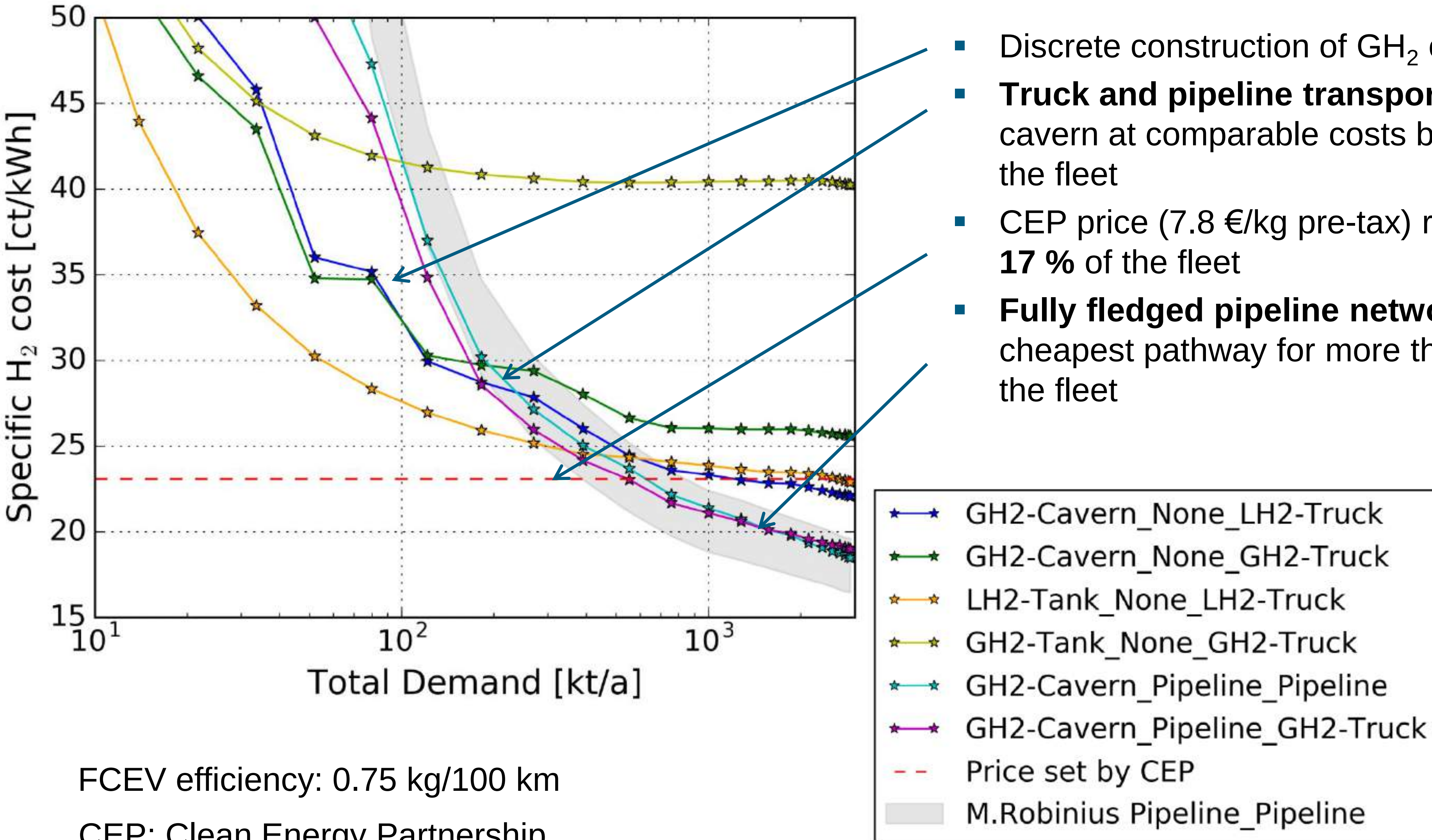
GEO-Spatial Infrastructure Development

2020 2025 2030



0.3 kt/a 2.3 kt/a 22 kt/a

Demand Analysis: Example for Hydrogen in Transport



- Discrete construction of GH_2 caverns
- **Truck and pipeline transport** with salt cavern at comparable costs by **7 %** of the fleet
- CEP price (7.8 €/kg pre-tax) reached by **17 %** of the fleet
- **Fully fledged pipeline network** is the cheapest pathway for more than **40 %** of the fleet

FCEV efficiency: 0.75 kg/100 km

CEP: Clean Energy Partnership

Conclusion for Infrastructure Deployment

- Infrastructure introduction phase can be defined for an interval of up to 50 - 200 kt/a
- Main aspects for cost reduction:
  - *Pipeline cost optimization → **Natural gas pipeline conversion***
  - *Infrastructure utilization → Demand sectors: mobility, industry*
  - *Hydrogen source location → Electrolyzer placement*
  - *Regional cost disaggregation*
  - *Storage time and technology*

European and Worldwide Pathways

Europe Wide Power Flow and Surplus Analysis

Residual load input:

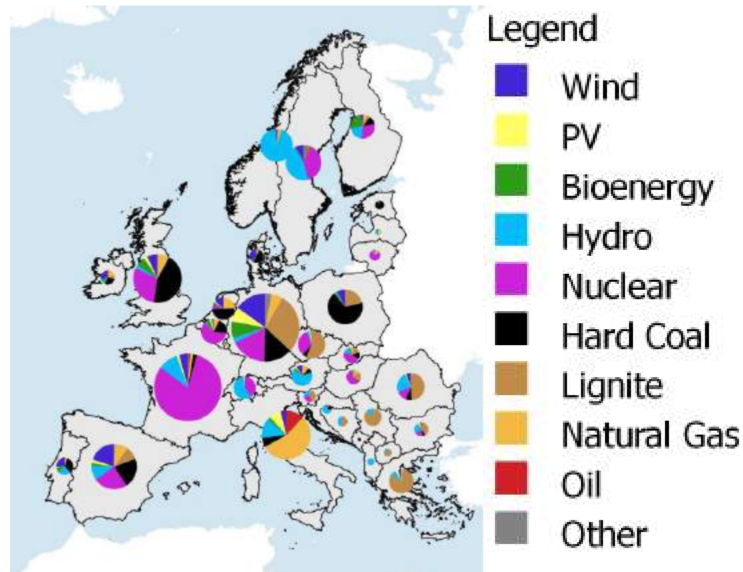
- Residual Load = Load - RES
  - Positive: storage or conventional power plants
  - Negative: surplus for Power-to-X pathways
  - Social and political directives

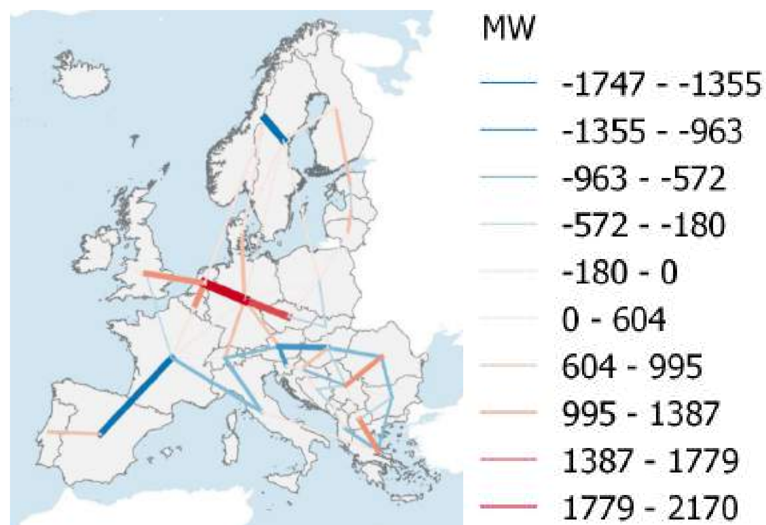
Approach:

- RES: One of the detailed spatial and timely resolved models
- Conventional power plants:
- Power-Flow-Model: open source tool PyPSA [1]

Result:

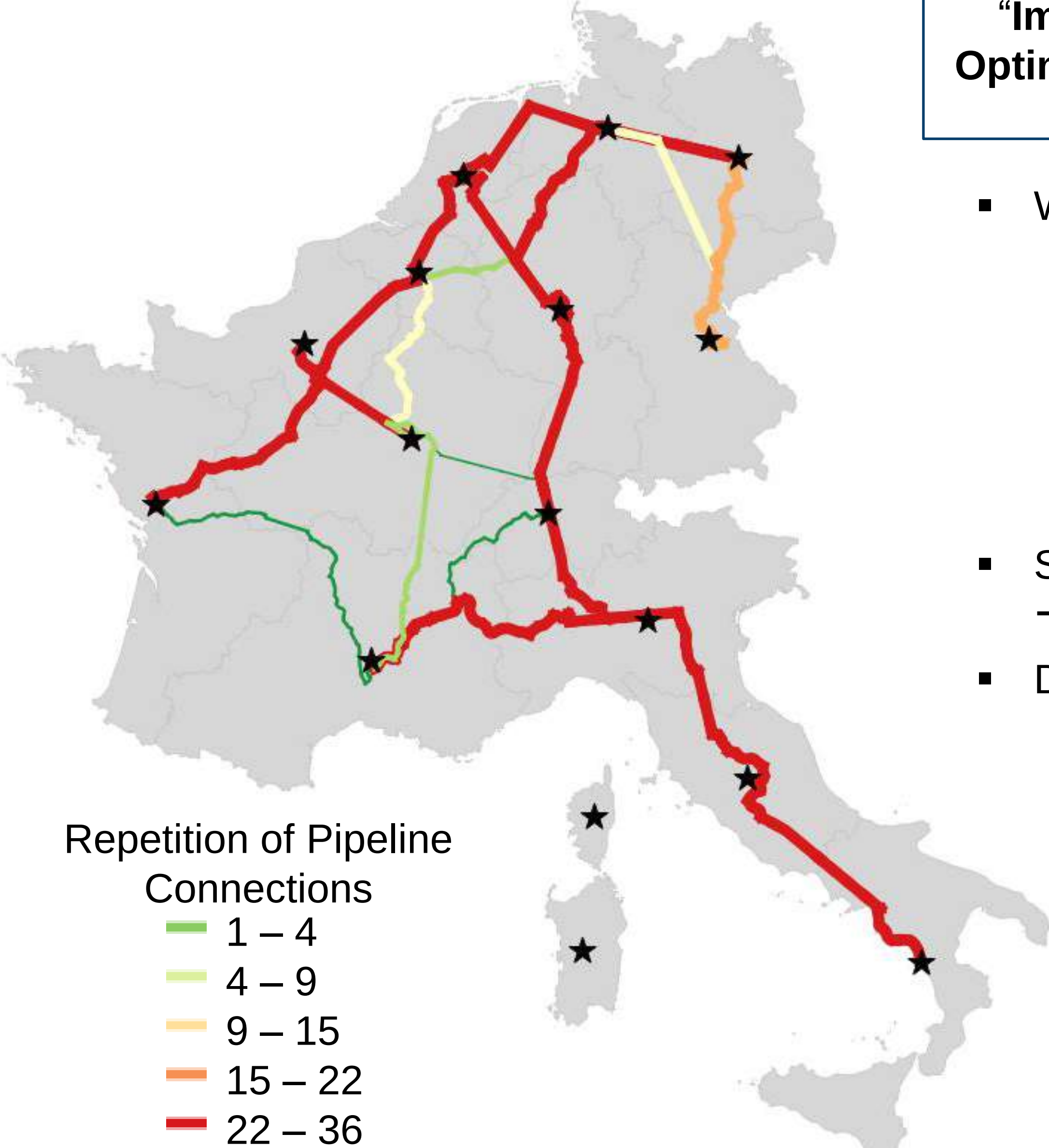
- Detailed Power Flow ananlysis for different implemented scenarios
- Potential surplus locations for Power-to-X pathways
- Zonal or nodal electricity prices for cost calculations





[1] https://github.com/PyPSA/PyPSA

Current Status : Impact of Wind Year Selection



"Impact of Wind Year Selection on the Design of Optimized Energy Systems with Variable Renewable Energy Sources"

- Wind power production between 1980-2015
  - MERRA & Global Wind Atlas for wind speeds
  - CLC for roughness length
  - 4% loss & power curve convolution (Vestas V136-3.45 MW, hub height = 82 m Onshore; Senvion 6200M152 6.2MW; hub height = 80 m)
- Salt cavern storage
  → **Existing natural gas salt cavern potentials**
- Demand & techno-economical are kept **constant**
  - Demand: Hydrogen for mobility (75% market penetration)

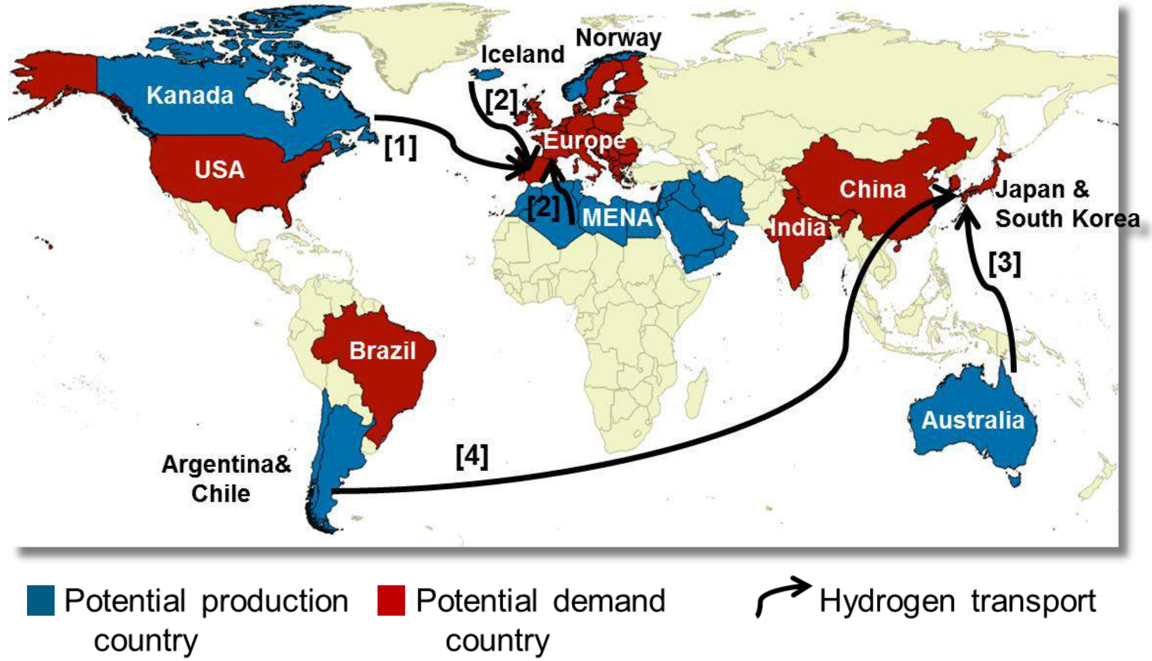
Motivation and Research Question

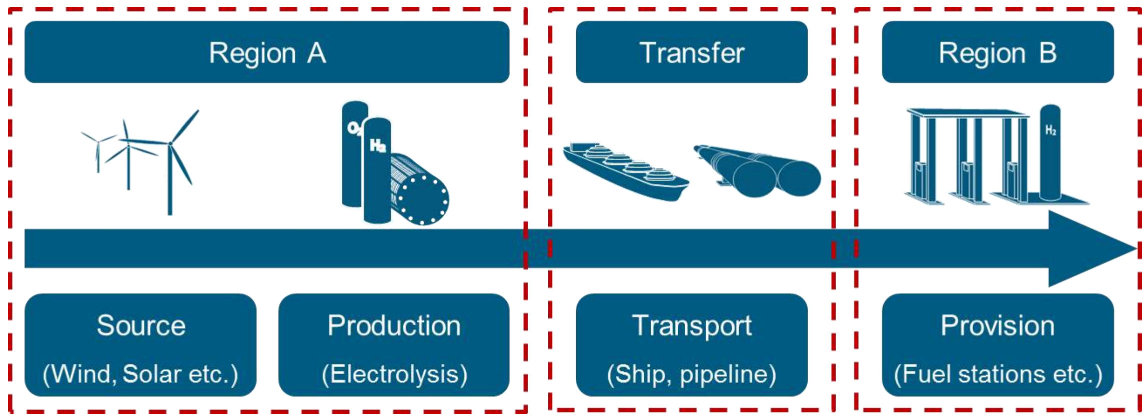
Research Question

„What could a worldwide provision scheme for H_2 from wind and solar power look like?“

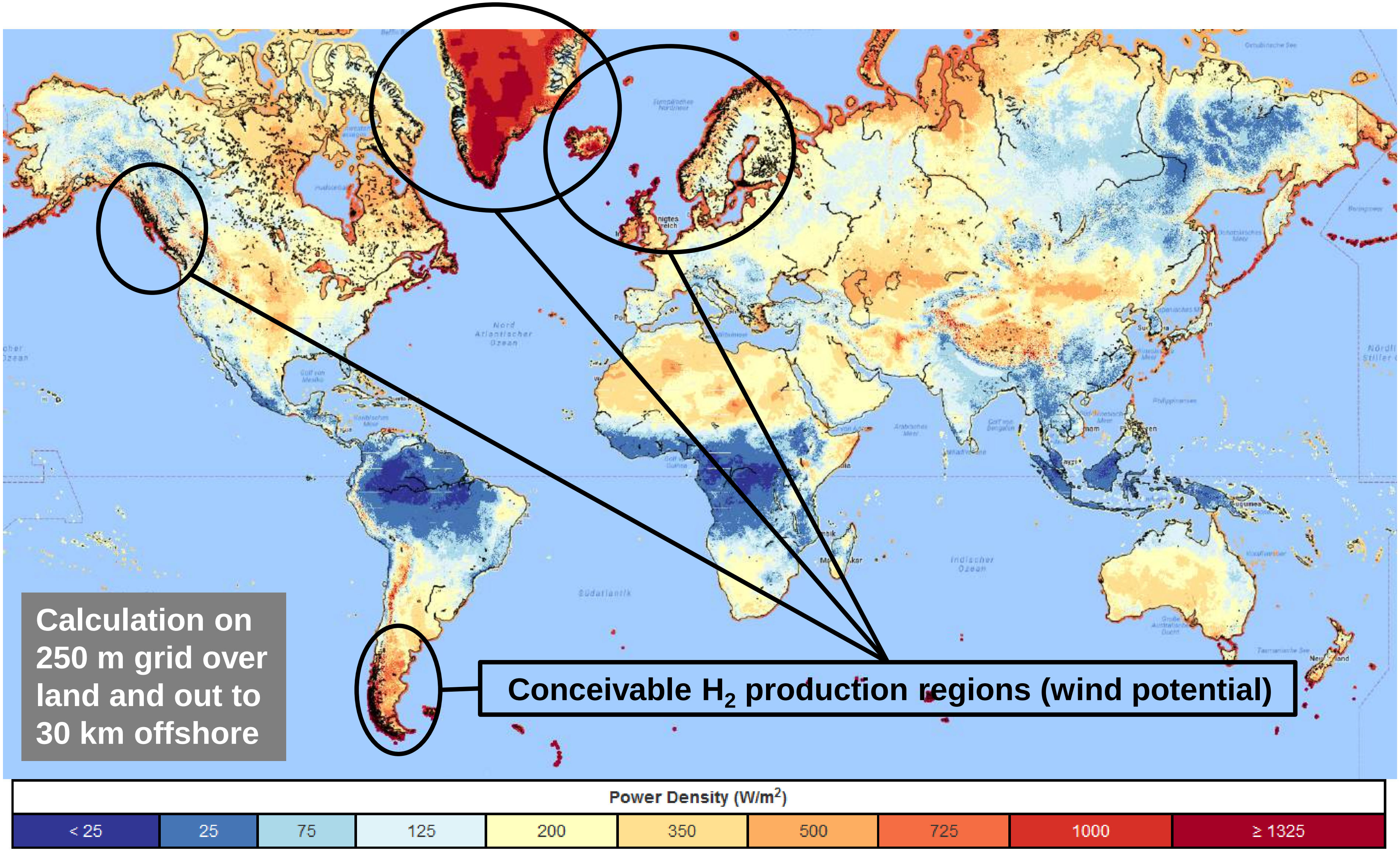
Research tasks

1. Determination of techno-economic RES potential on global scale
2. Model-based design of hydrogen supply chains
3. Derivation of scenario-based cost curves for hydrogen trading connections
4. Comparison of long distance oversea transport (LH2 vs. LOHC)
5. Evaluation of trading connection pool considering market and environmental principles





Global Wind Power Density (Aggregated Mean at 100m Height) [1]



[1] Global Wind Atlas. DTU Wind Energy. URL: http://globalwindatlas.com/map.html

Spatial Orientation – Patagonia – Santa Cruz

[1] Google Satellite Map 2017
[2] GADM database 2015. URL: www.gadm.org

Land Egilibility Using the Example of Santa Cruz

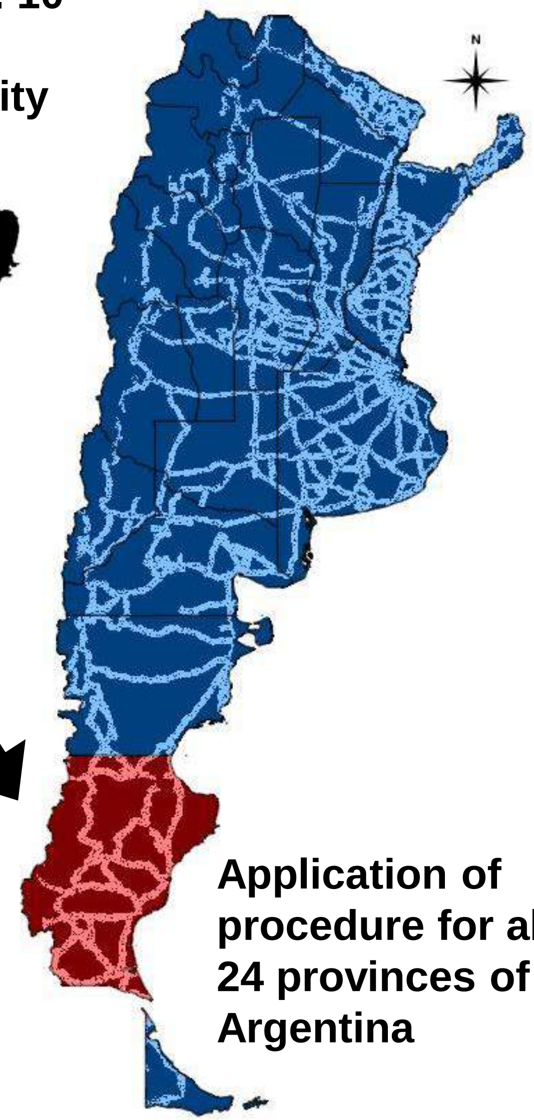
Eligible land in Santa Cruz

+

Road network in Santa Cruz

→

Eligible land max. 10 km from roads to ensure accessibility



Areas of land to be excluded:

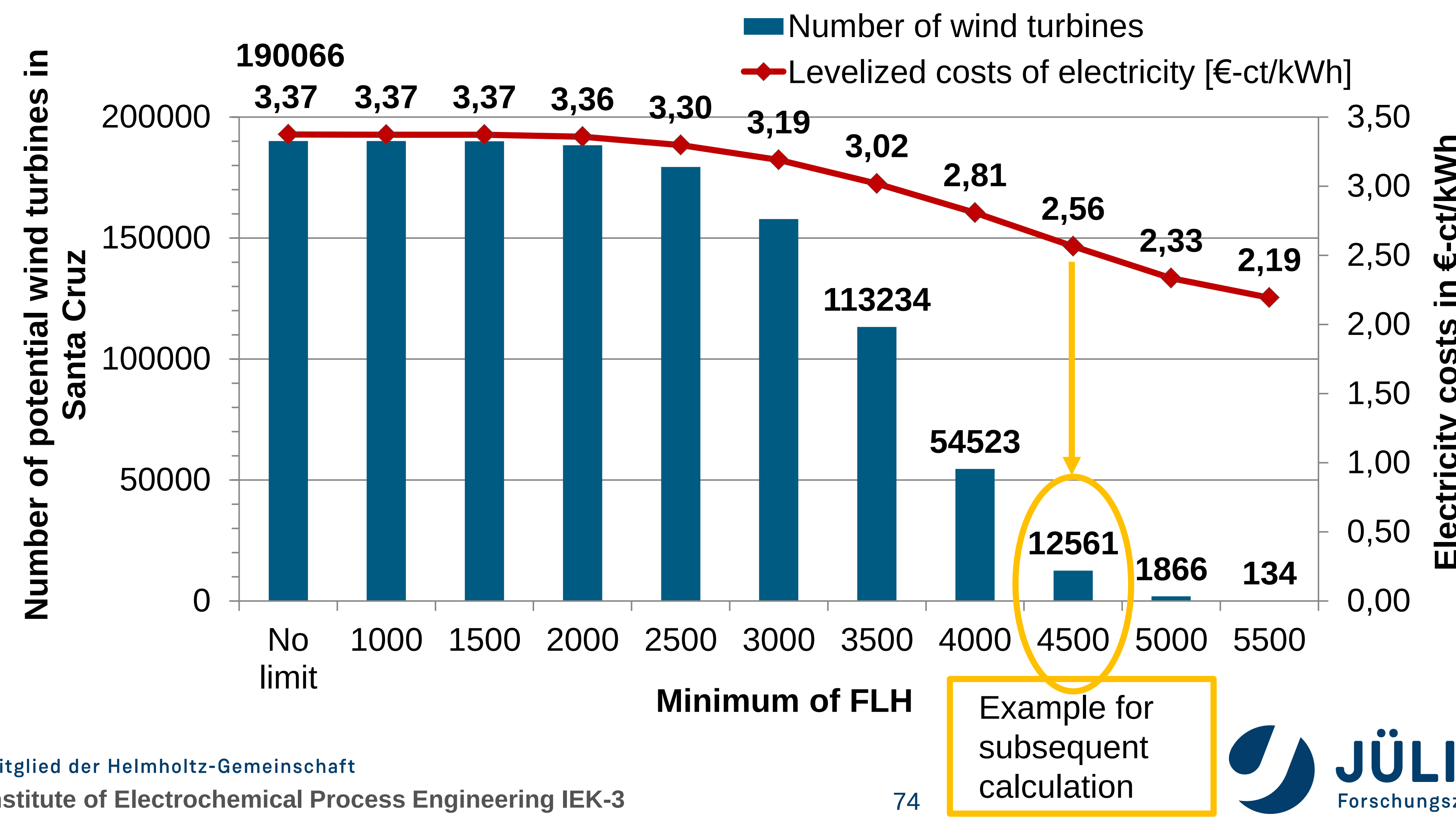
1. Physical restrictions
2. Protected areas
3. Elevations above 1,500 m and slopes above 20°
4. Residential restrictions and infrastructure

	Eligible land [km²]	Total land area [km²]	Share [%]
Santa Cruz	66,097	243,943	27
Argentina	703,818	2,780,100	25

Application of procedure for all 24 provinces of Argentina

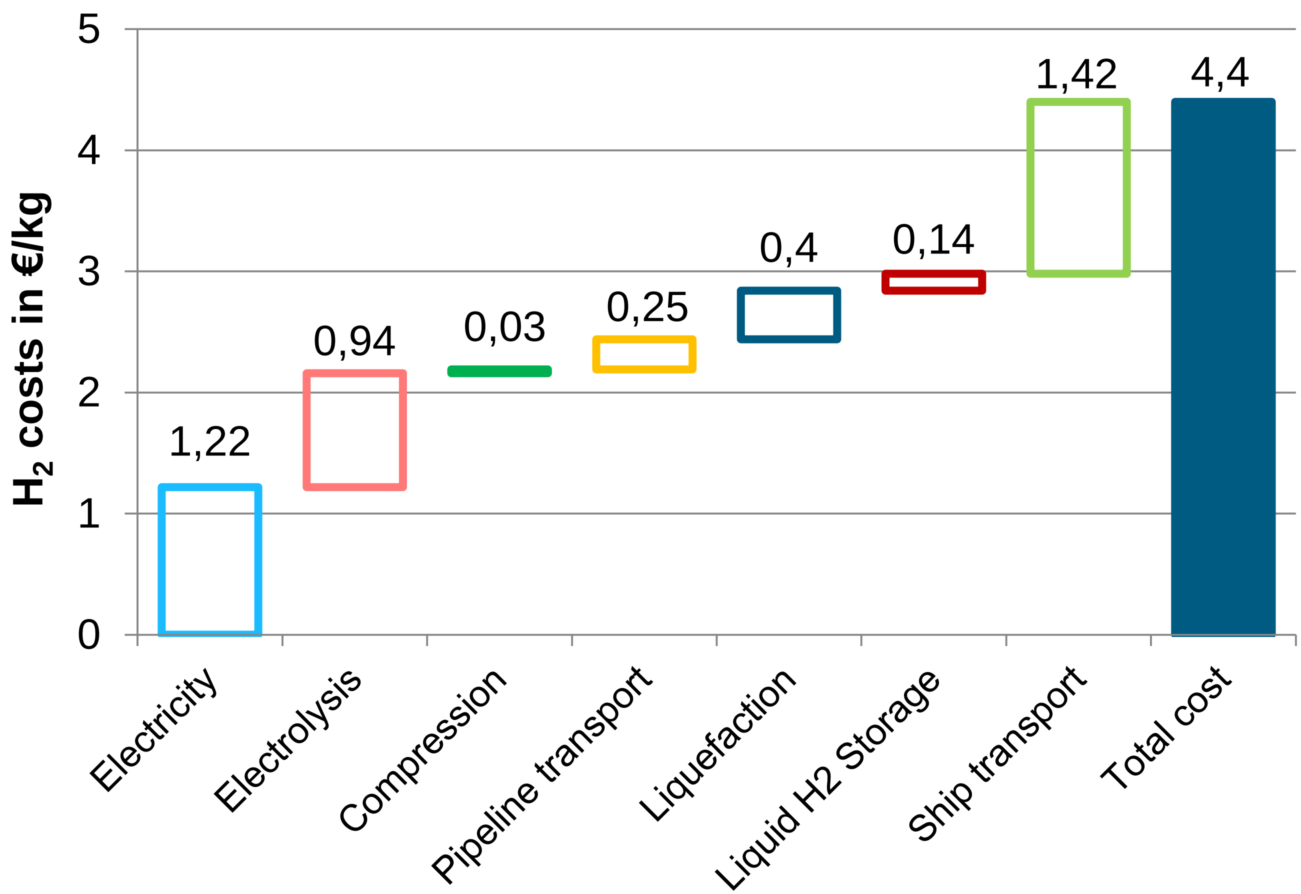
Location Results for Wind Turbines in Santa Cruz

- 190,066 locations for wind turbines (Enercon E-102 E2) are available in Santa Cruz
- Average number of full-load hours: 3613 (varies from 586 – 5805)
- Assumption: Capital cost for wind turbine = 1000 €/kW [1], [2]

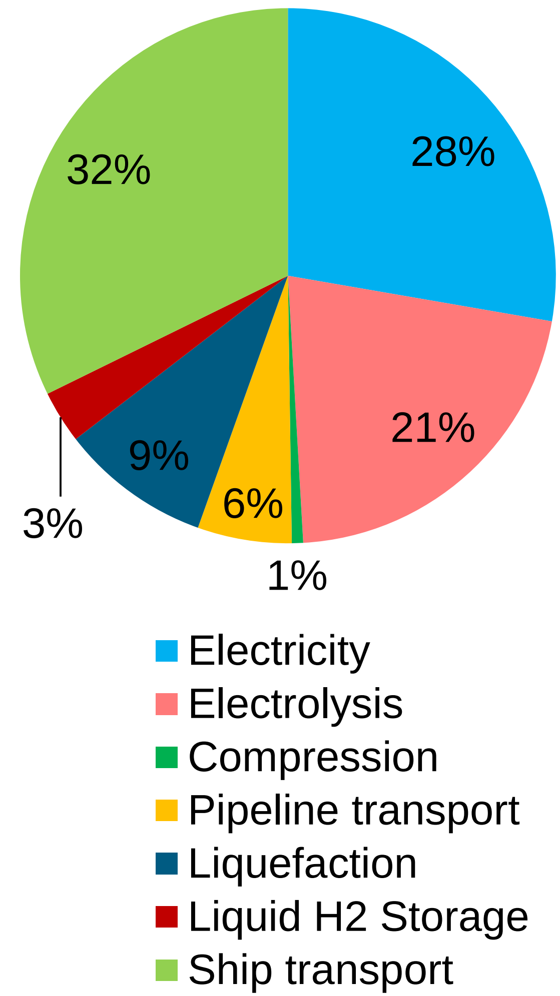


Cost Results for H_2 Provision – Patagonia to Japan

- H_2 Production of 8.8 Mt/a in Patagonia (use of wind energy)
- Domestic transport via Pipeline (8,360 km)
- Liquefaction and storage in domestic harbor (Cap.: 113,600 tons)
- International transport via ship (Patagonia to Yokohama: 21,400 km)



Cost distribution



Important Networks

Networks to Consider

Hydrogen Infrastructure

Netzwerk Brennstoffzelle und Wasserstoff, Elektromobilität

http://www.energieagentur.nrw/netzwerk/brennstoffzelle-wasserstoff-elektromobilitaet/

Brennstoffzelle und Wasserstoff Projekte NRW

http://www.energieagentur.nrw/netzwerk/brennstoffzelle-wasserstoff-elektromobilitaet/projekte?s=Brennstoffzelle&mm=Projekte-in-NRW#ts

Kompetenzatlas

http://www.energieagentur.nrw/tool/kompetenzatlas-brennstoffzelle/index_neu.php

Thank you for your attention

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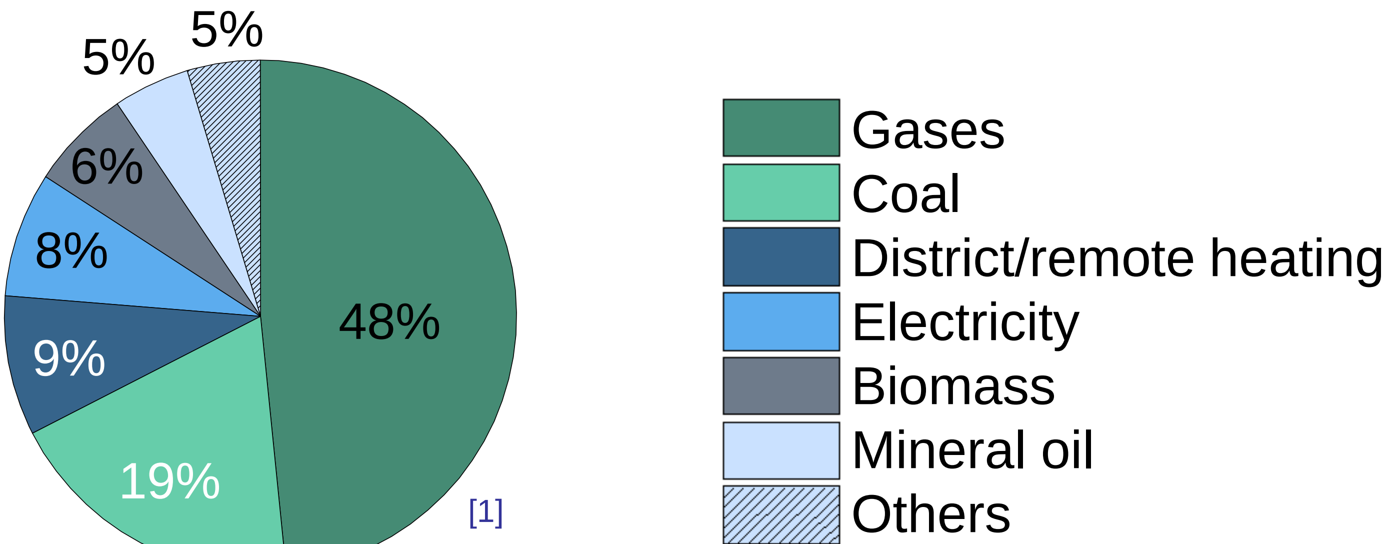
Sector Coupling

Linking the Power and Industry Sectors

Heat Demand in Industry in 2012



*incl. biomass share in waste

Energy use TWh:

Fuels:	492
Electricity:	42
	534

CO_2 emissions in industry[1]
Related to heat provision**: 159 million t**

[1] Datenbasis: Studie für die Arbeitsgemeinschaft Energiebilanzen e.V. (AGEB): Erstellung von Anwendungsbilanzen für das Jahr 2012 für das verarbeitende Gewerbe mit Aktualisierungen für das Jahr 2009-2011, Karlsruhe 2013.

Selection of Alternative Technologies

Heat generation technologies

- Criterion: option of fossil free operation

  - ➢ Heat pumps
  - ➢ Electrode boilers

Alternative fuels

- Criterion: transport via existing infrastructure

  - ➢ Bio-methane
  - ➢ Methane hydrogen blends in the gas grid
  - ➢ Synthetic methane

Technologies for waste heat utilization

- Criterion: high rate of utilization in desired temperature range

  - ➢ ORC plants
  - ➢ Plants for supplying remote heat from waste heat

Current Potential of “Green” Hydrogen

	Conventional	„Green“ hydrogen	Potential for substitution
Ammonia	Natural gas and air[1]: $3CH_4 + 3O_2 + 2N_2 \rightarrow 4NH_3 + 3CO_2$	Pure N_2 and H_2[1]: $N_2 + 3H_2 \rightarrow 2NH_3$	100 %
Methanol	Natural gas and pure oxygen[2]: $CH_4 + 0{,}5O_2 \rightarrow H_3COH$	Pure CO_2 and H_2[3]: $CO_2 + 3H_2 \rightarrow H_3COH + H_2O$	100 %
Refinery	≈ 60 % of the consumed hydrogen is a byproduct (catalytic reformer)[4] ≈ 40 % additionally produced	Additional demand of H_2 can be substituted	40 %
Other	Numerous hydrogenation and reduction reactions in chemical, food, metal industry without change of reactions		100 %

Current accumulated potential for “green” hydrogen

World: 375 billion m^3_{STP}/a   Germany: 13,6 billion m^3_{STP}/a

[1] Appl, M., *Ammonia*, in *Ullmann's Encyclopedia of Industrial Chemistry*, 2000, Wiley-VCH Verlag GmbH & Co. KGaA, ISBN: 9783527306732
[2] Ott, J., V. Gronemann, and F. Potzen, *Methanol*, in *Ullman´s Encyclopedia of Industrial Chemistry*, 2012, Wiley-VCH Verlag : Weinheim, ISBN: 9783527306732
[3] Pontzen, F., et al., *CO_2-based methanol and DME - Efficient technologies for industrial scale production.* Catal. Today, 2011, 171 p. 242-250
[4] Aitani, A.M., *Processes to enhance refinery-hydrogen production.* International Journal of Hydrogen Energy, 1996. 21(4): p. 267-271.