# Infrastruktur – Analyse zur Sektorenkopplung Strom und Verkehr

21. MÄRZ 2019| MARTIN ROBINIUS, DETLEF STOLTEN ET AL.

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IEK-3: Institute of Electrochemical Process Engineering



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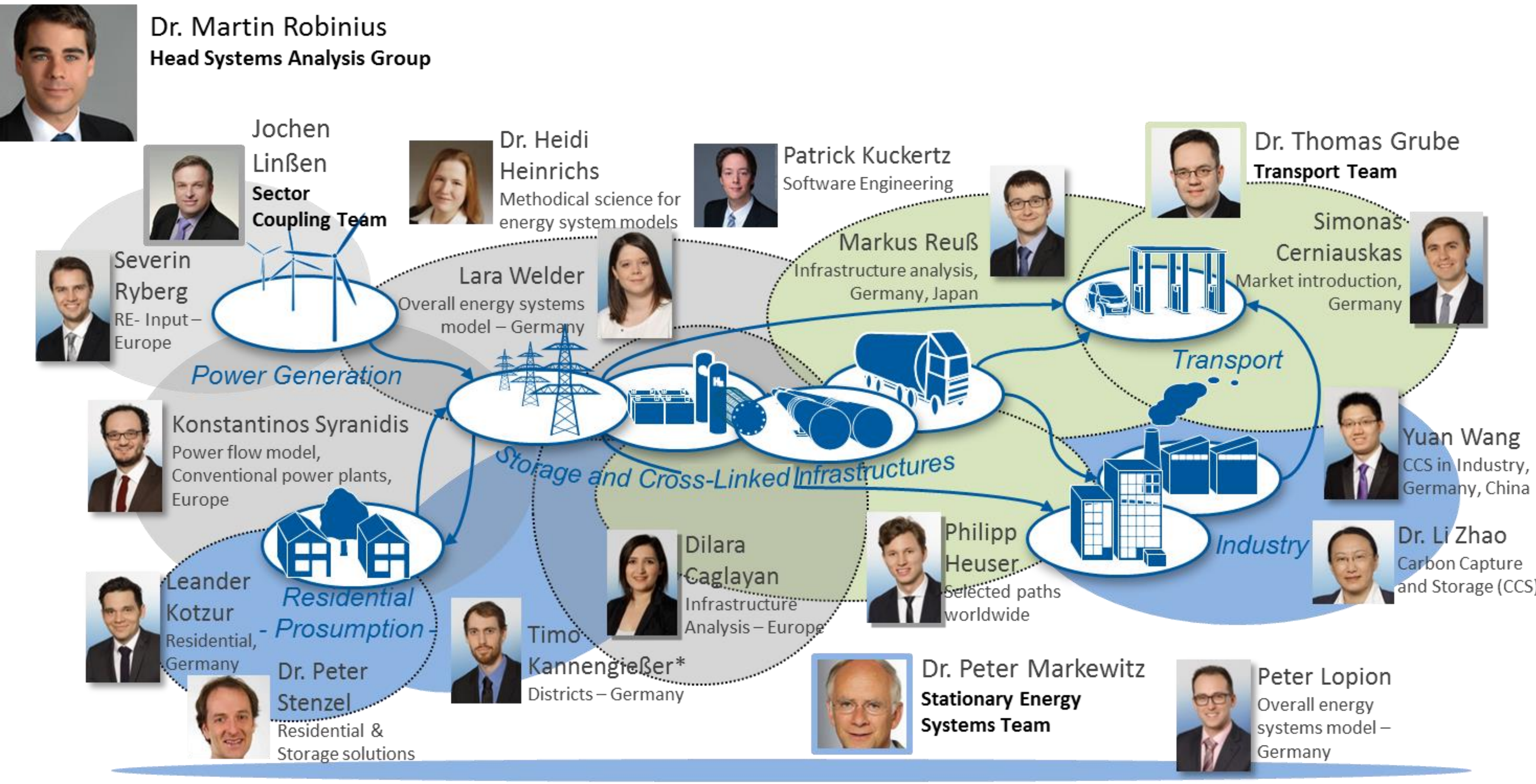
# Research Topics within the Process and Systems Analysis Group



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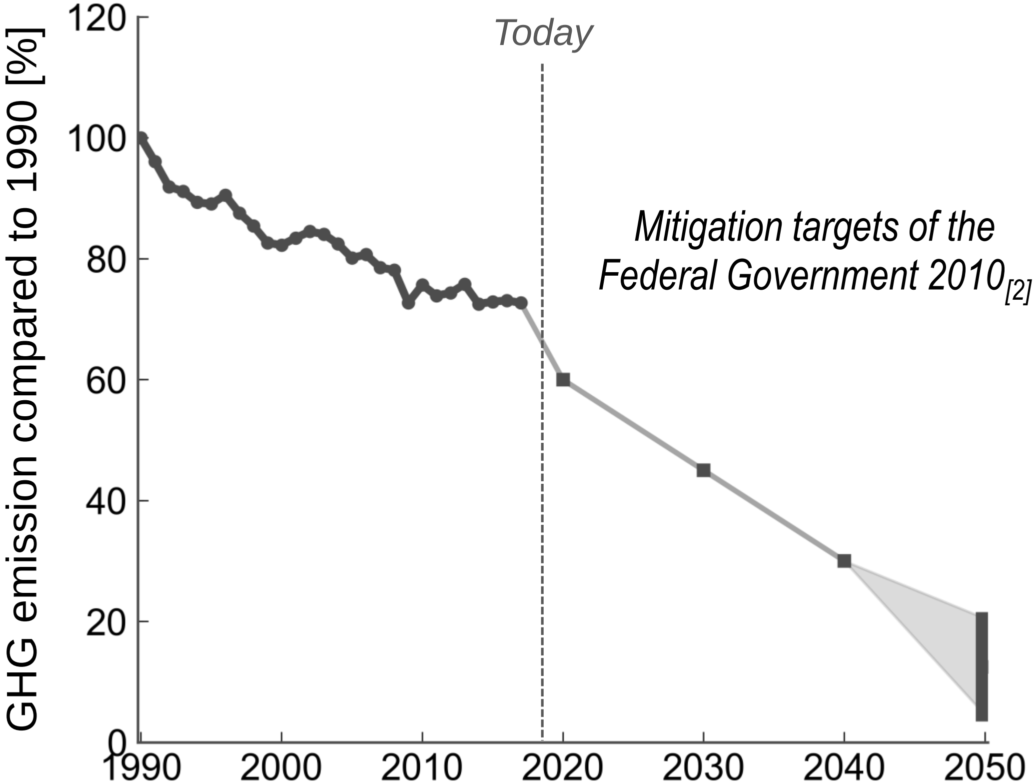
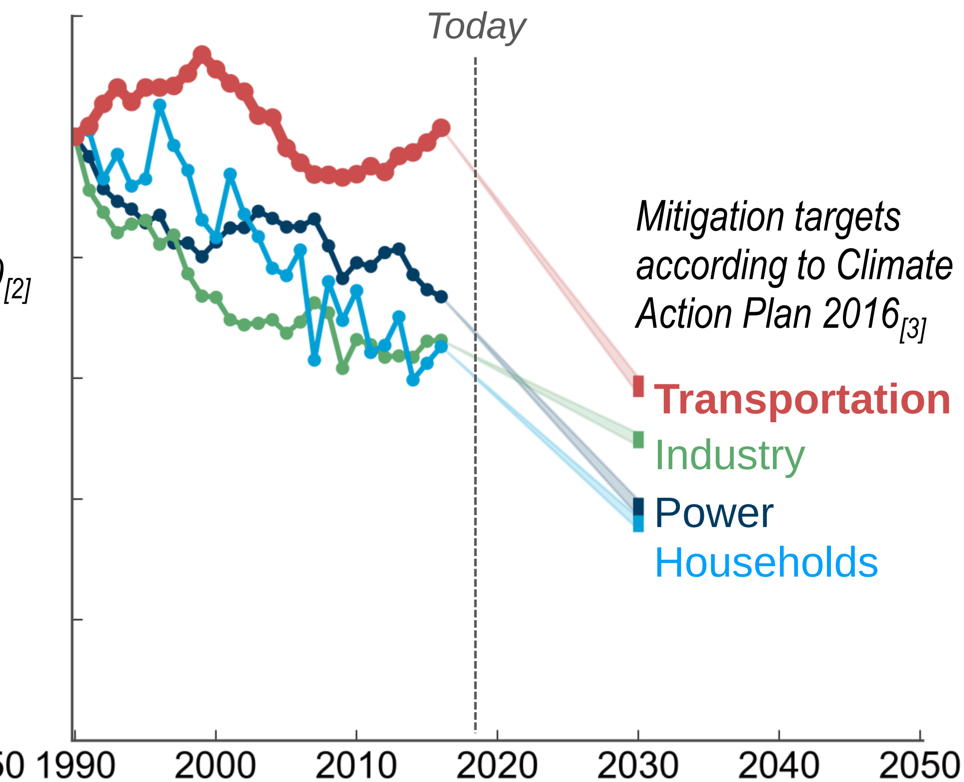
# Greenhouse Gas (GHG) Emissions in Germany Since 1990

**Total emissions[1]**




**Sector specific emissions[1]**




► No GHG reductions in the transportation sector since 1990

► Achieving mitigation targets requires contributions from all sectors

[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.

# Sector Coupling – Definitions

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

- Sectors coupled all the time:
  - 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)
[2] Robinius, M., et al., Linking the Power and Transport Sectors—Part 1: The Principle of Sector Coupling. Energies, 2017. 10(7): p. 956.
**Best Paper Award 2017**

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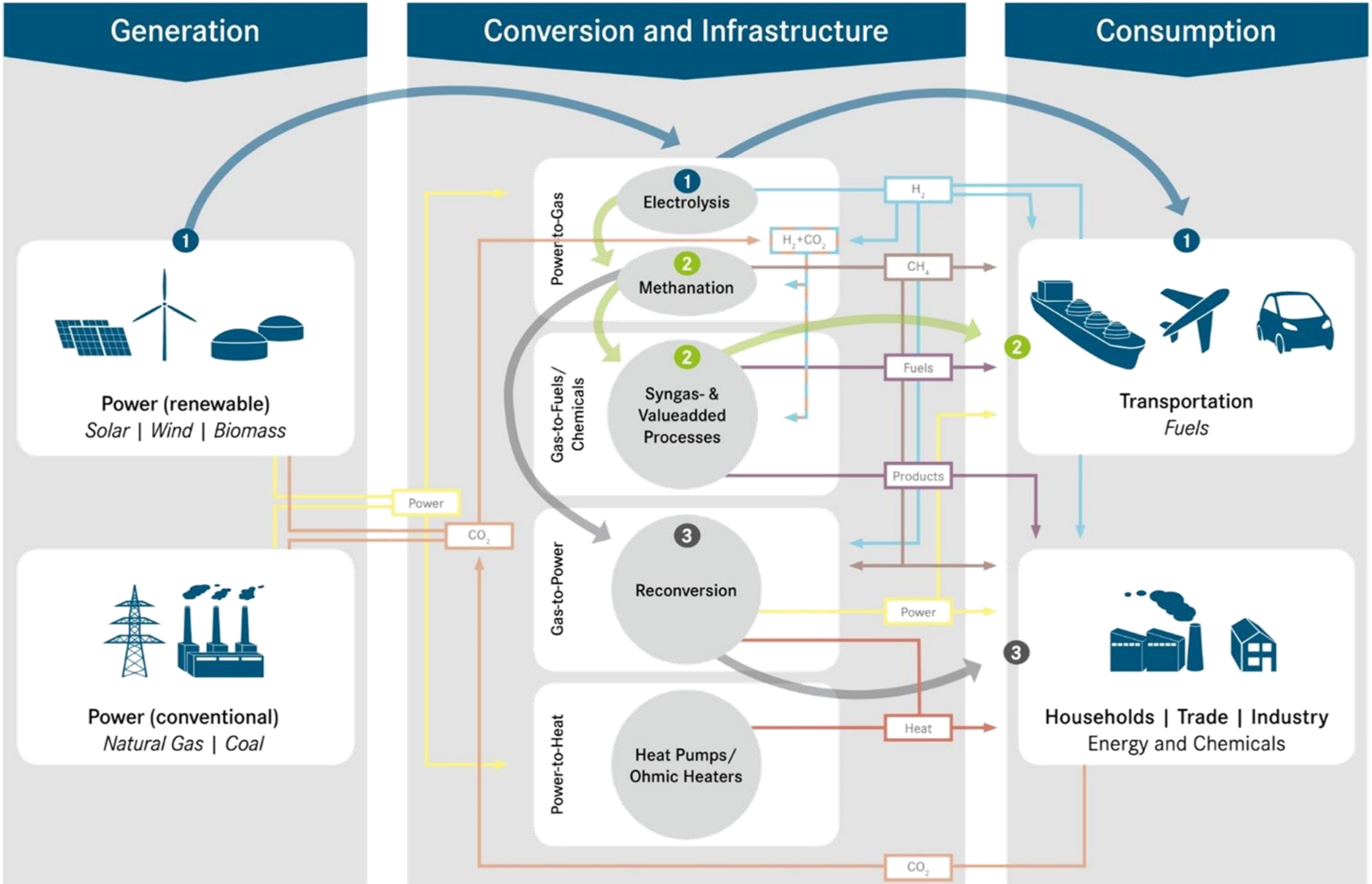
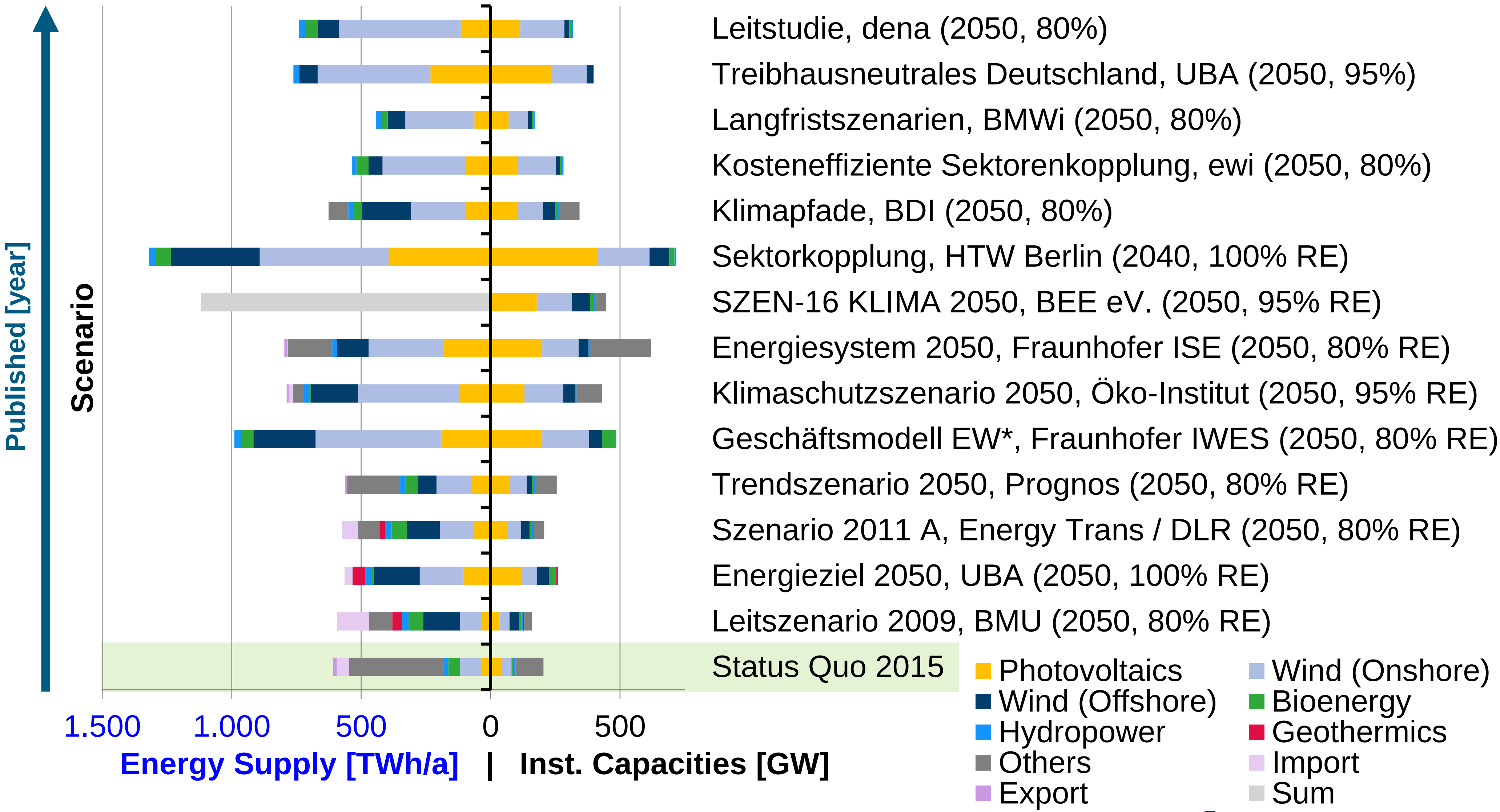
# Principle of Sector Coupling




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

# Installed Capacities and Electricity Supply of Renewable Energies [1-15]



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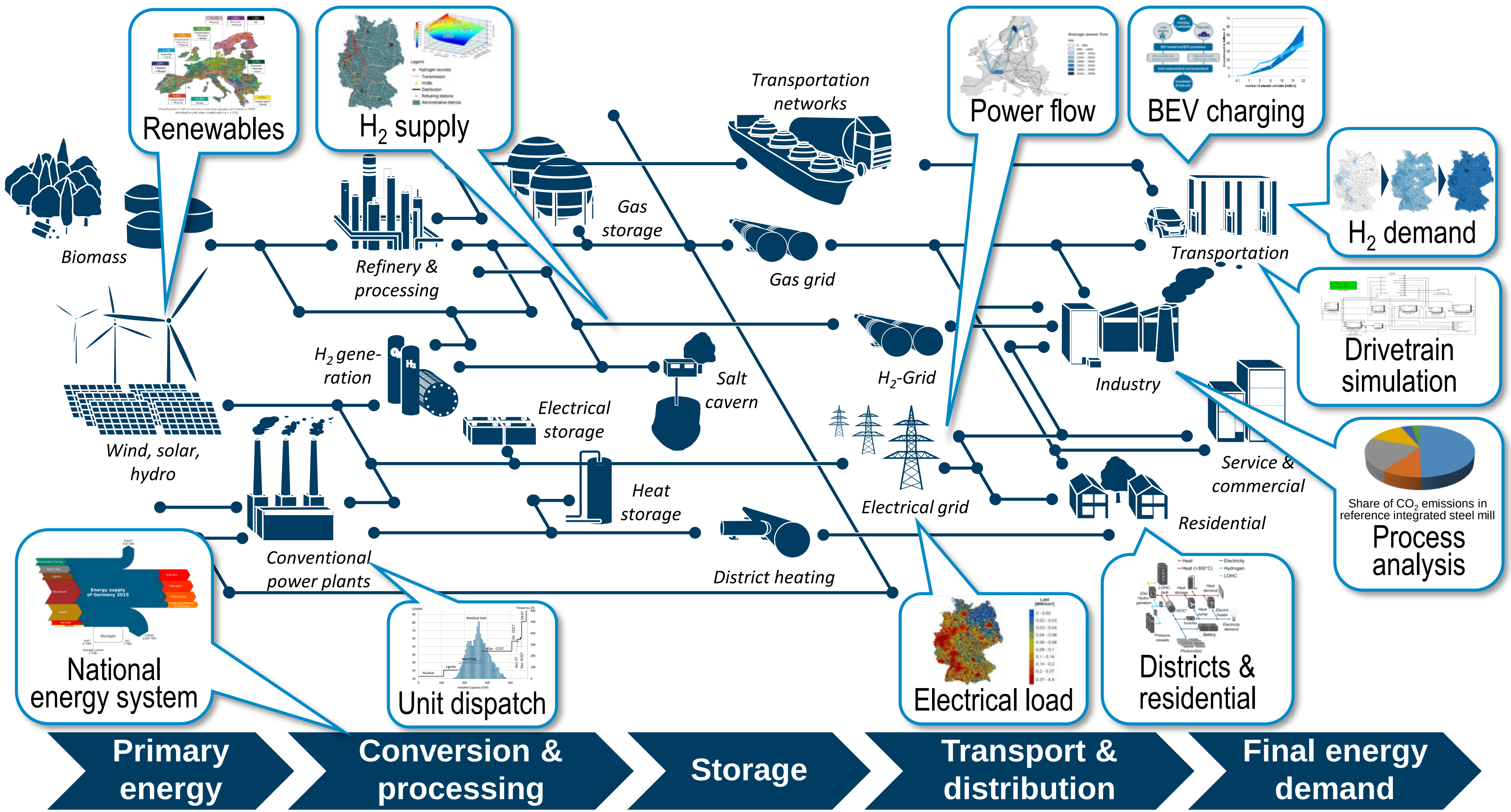
# Multiscale Toolbox for Energy Systems Modeling



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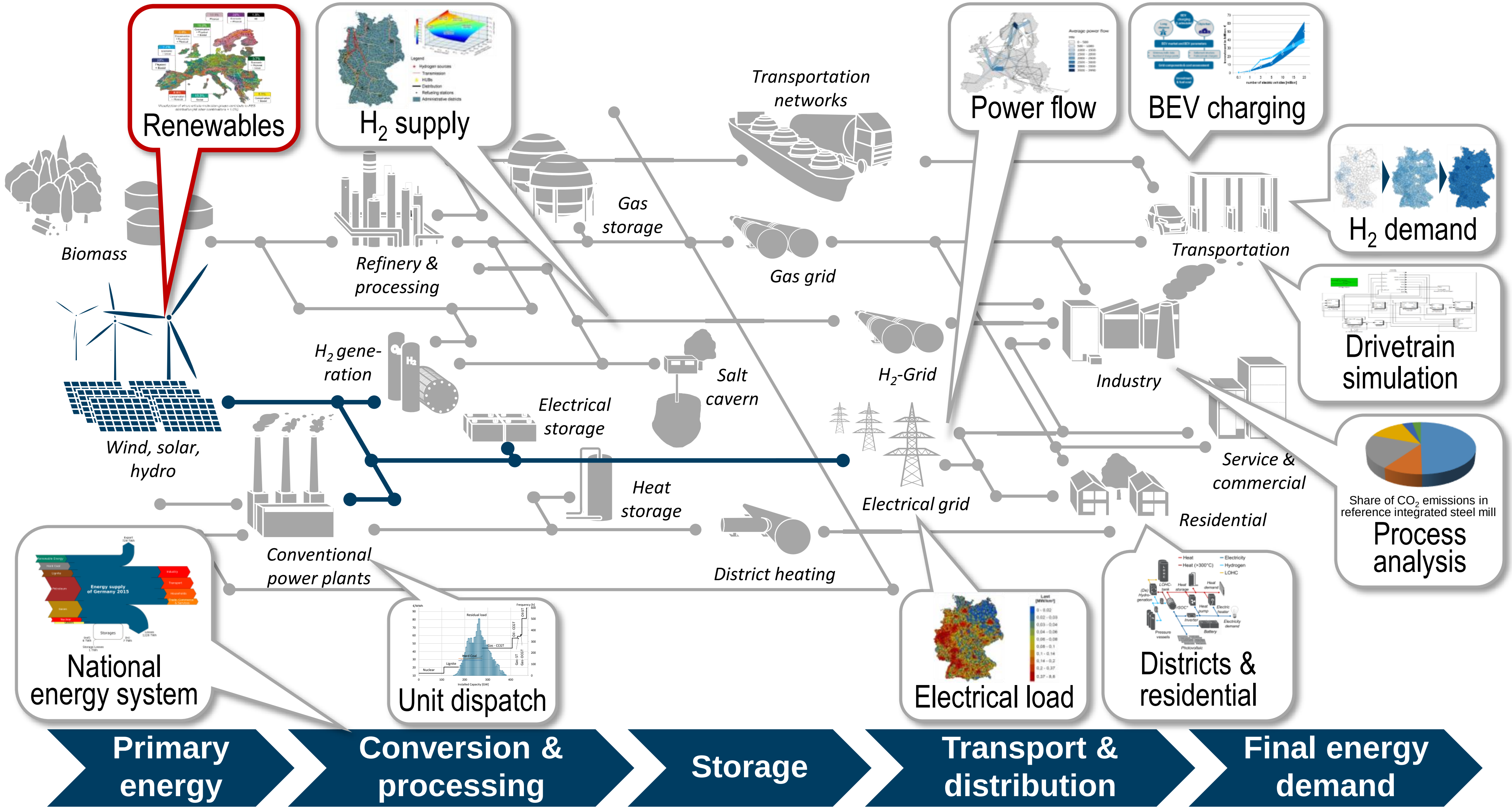
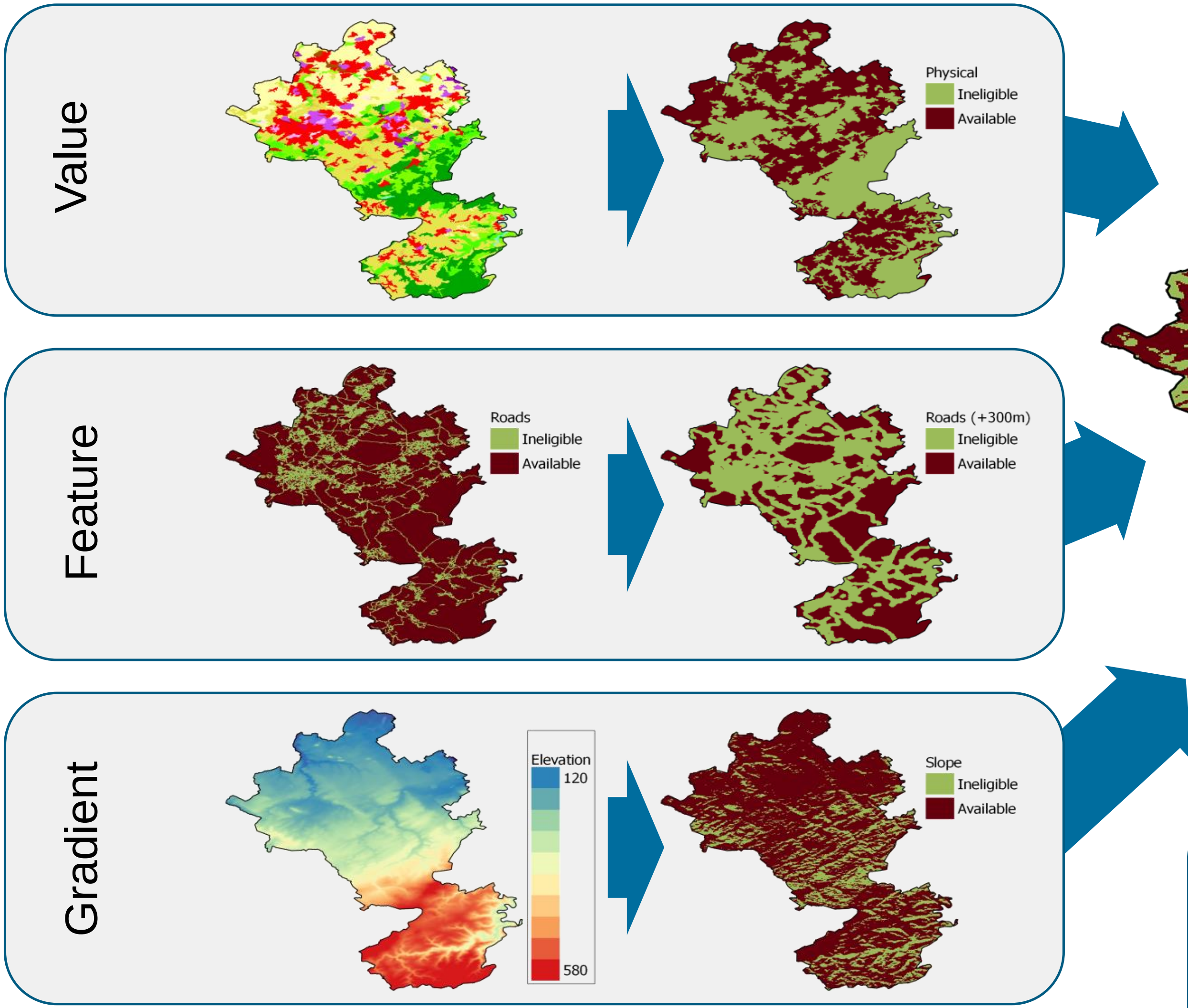
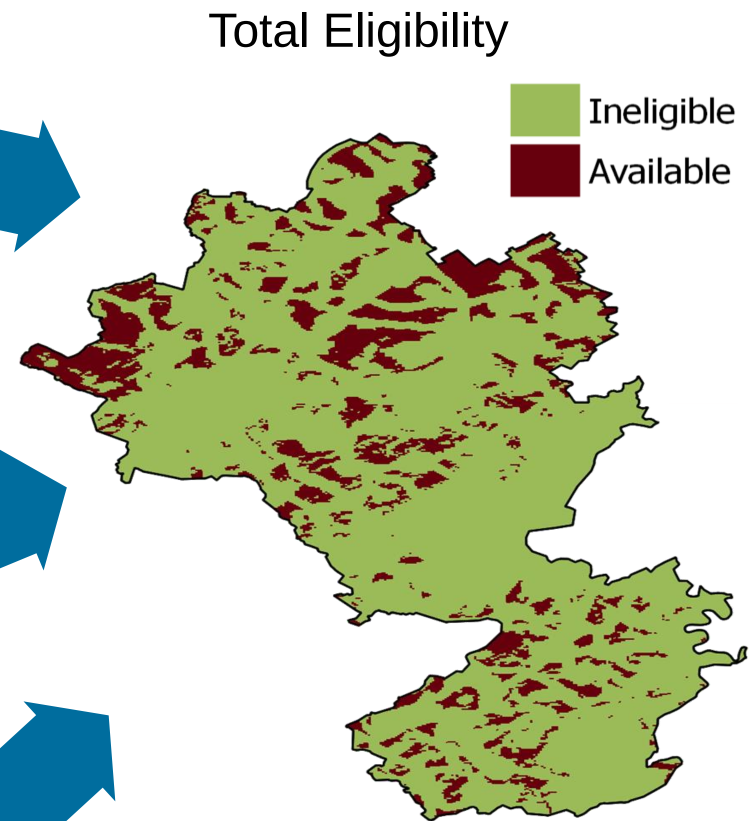
# Role in the Toolbox



# Land Eligibility



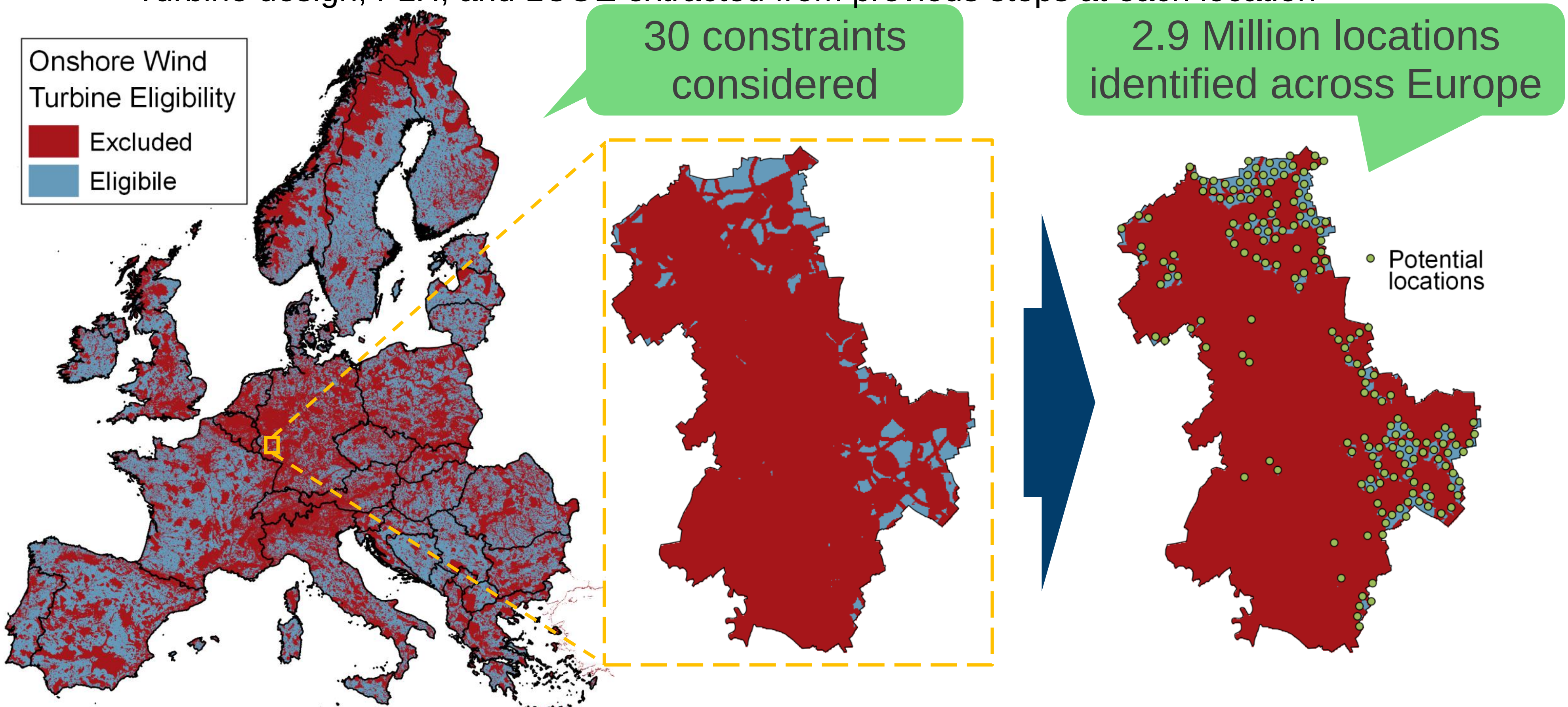

**GLAES[1] model standardizes this approach for any technology in any region**

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

Ryberg, D., M. Robinius, and D. Stolten, *Evaluating Land Eligibility Constraints of Renewable Energy Sources in Europe.* Energies, 2018. **11**(5): p. 1246.

# Restricting Turbine Distribution

- **Land eligibility** model (GLAES [1]) used to define available areas subject to 30 sociotechical constraints
- **Placement algorithm*** finds maximal number of turbines with **850 m separation**
- Turbine design, FLH, and LCOE extracted from previous steps at each location





[1] Geospatial Land Eligibility for Energy Systems (GLAES). https://github.com/FZJ-IEK3-VSA/glaes. 2017
* Inspired by: Robinius, Martin, et al. "Linking the power and transport sectors—Part 2: Modelling a sector coupling scenario for Germany." *Energies* 10.7 (2017):

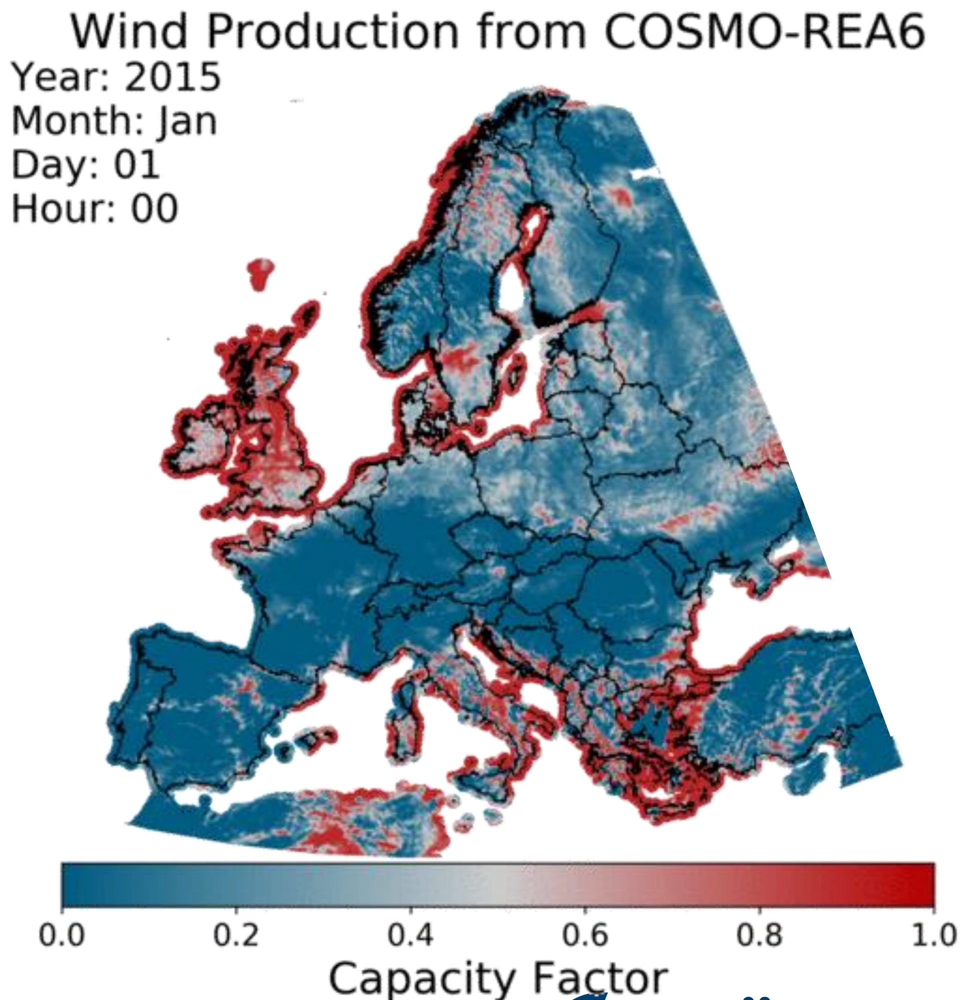
# Production Modeling

- Climate model data used as input
  - **MERRA** dataset allows for the modeling years **between 1980 and 2016**
  - **CORDEX** datasets allow for modeling of **future scenarios until 2100**
  - Other datasets also available: (ERA5, COSMO-REA6, …)

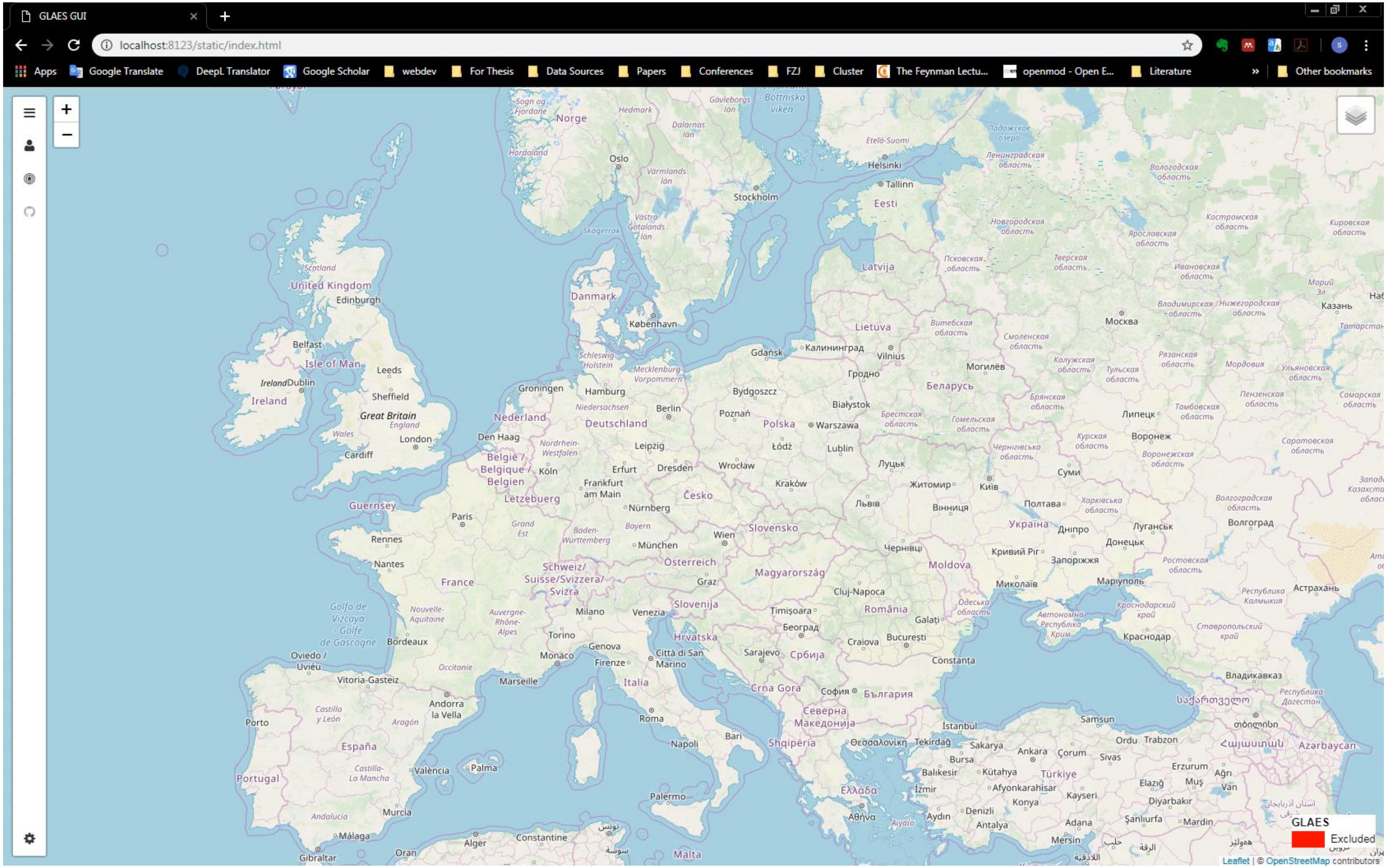
- **Each location** resulting from a land eligibility analysis is **simulated**
  - Aggregation of turbine output constitutes regional production

- Strengths of the 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 the approach:
  - **Necessitates highly efficient data processing** techniques that are not built into other models



# Work in progress (Open Source Tool)



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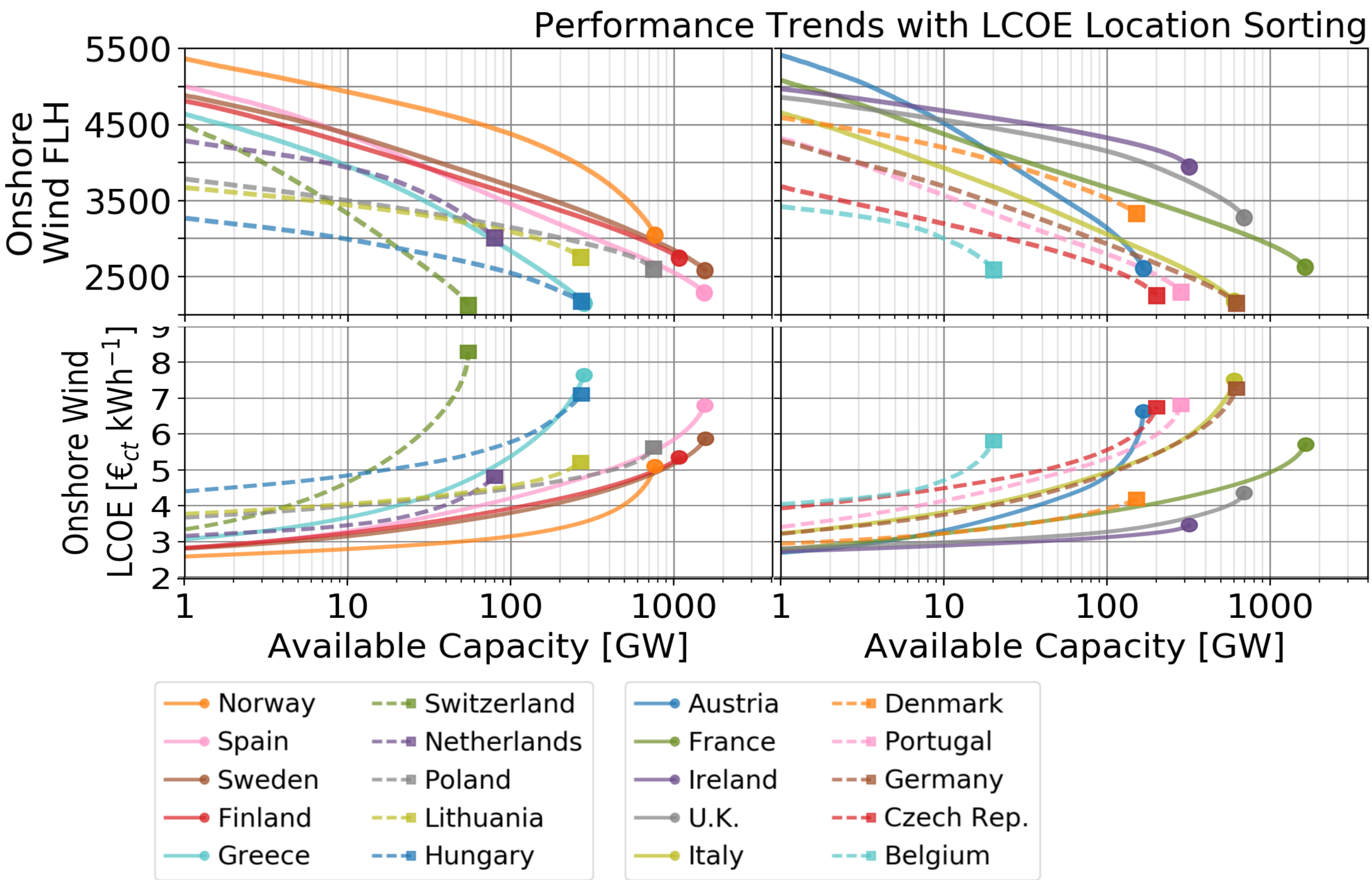
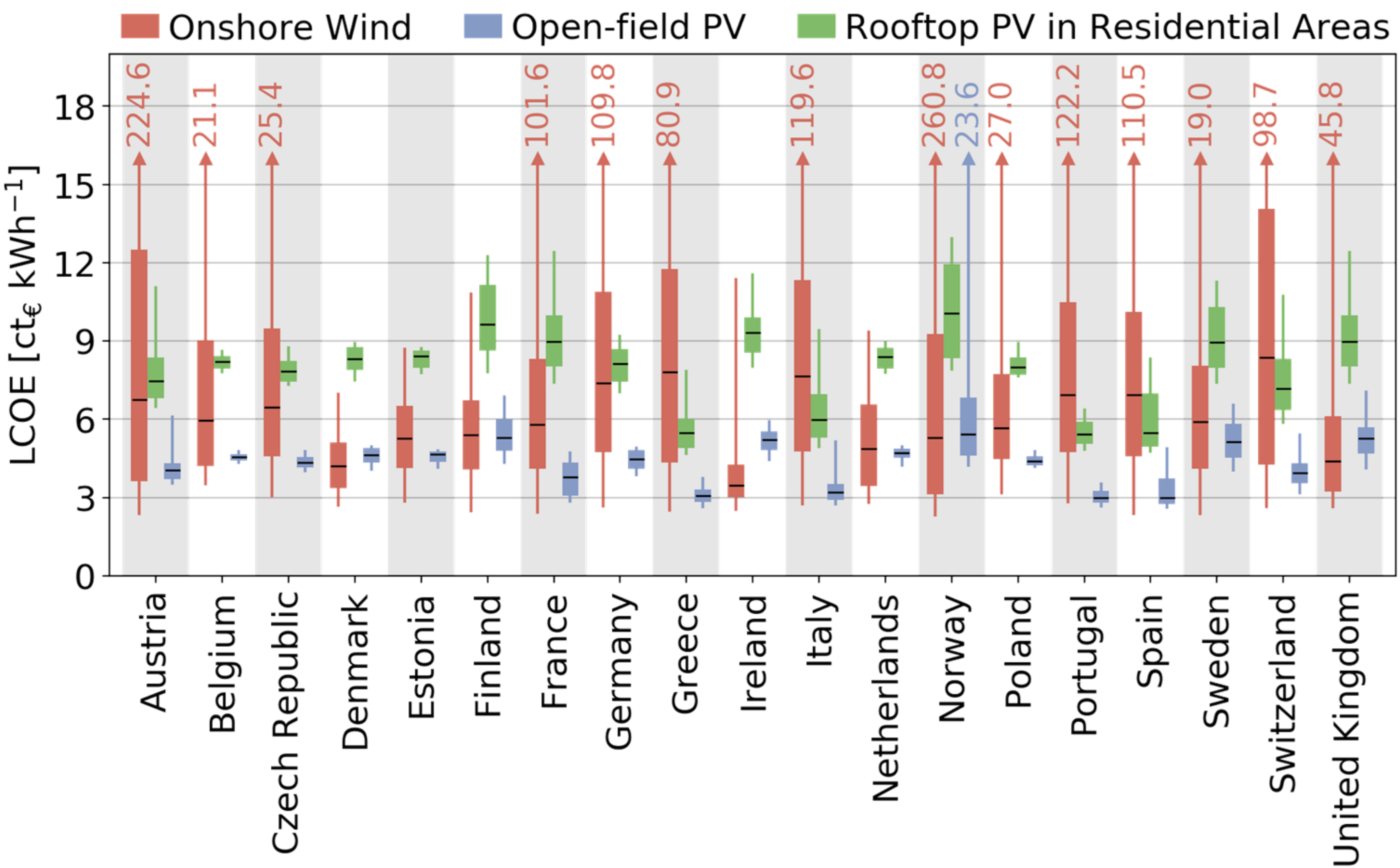
# The Future of European Onshore Wind Energy Potential

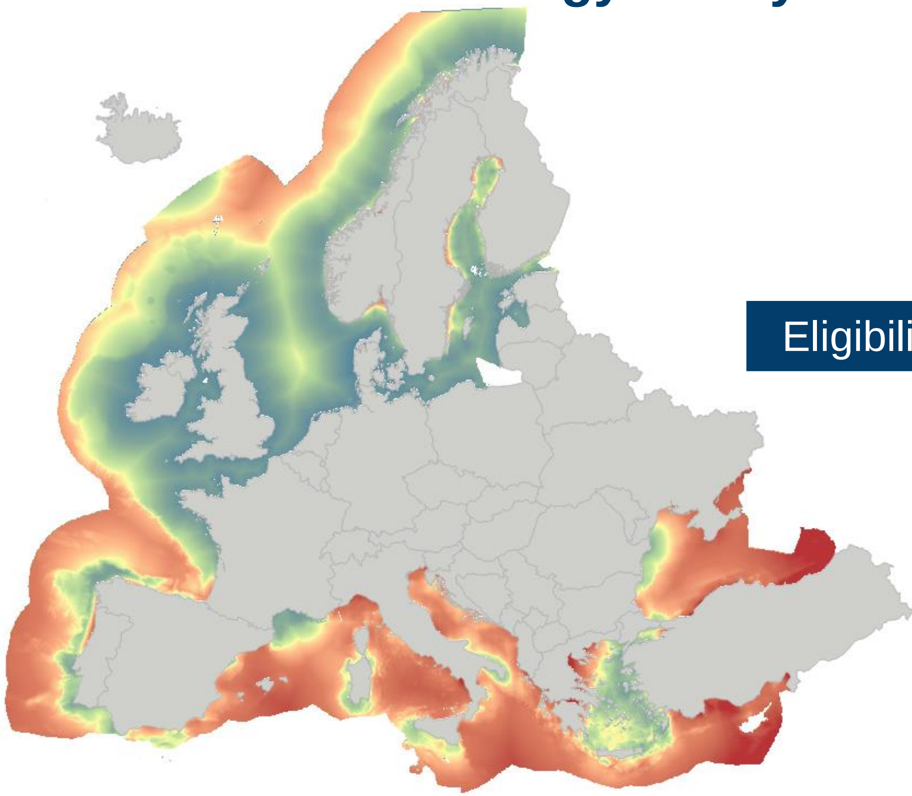


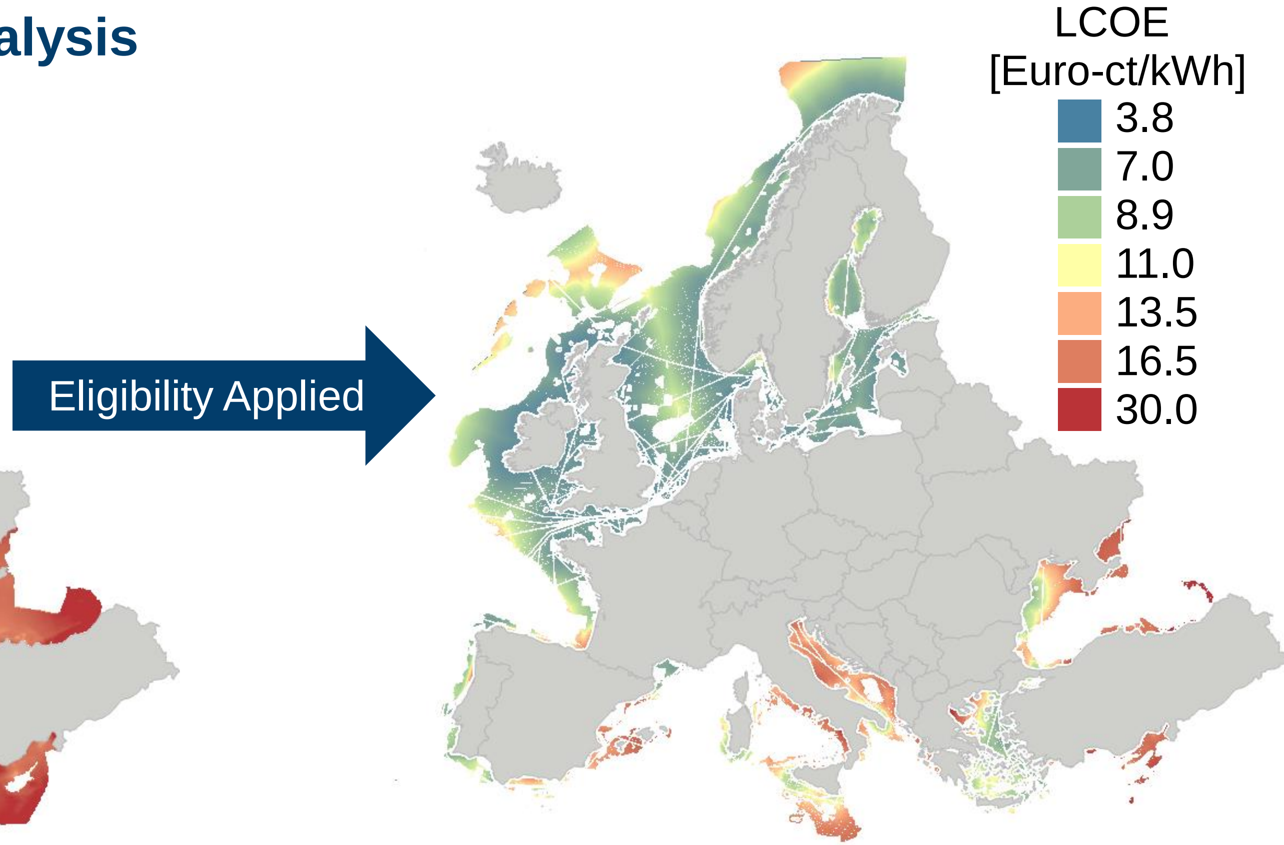

Ryberg et al. The Future of European Onshore Wind Energy Potential: Detailed Distribution and Simulation of Advanced Turbine Designs. https://www.preprints.org/manuscript/201812.0196/v1

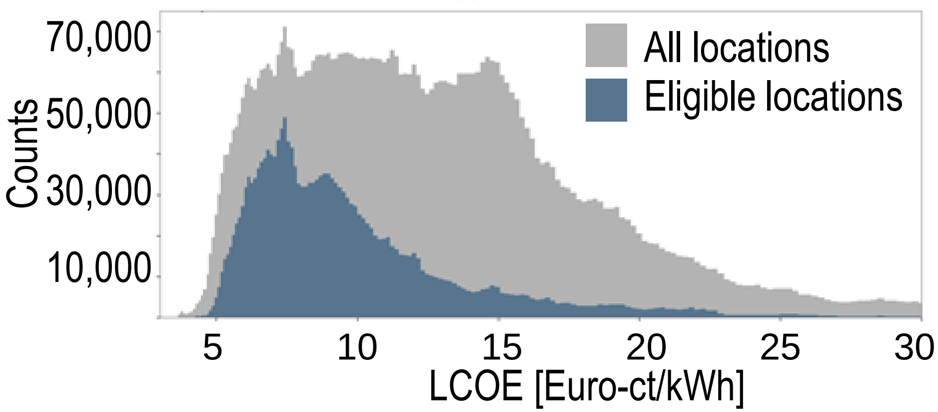
# The Future of RES LCOE in Europe



# Offshore Wind Energy: Analysis






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

LCOE: Levelized Cost of Electricity

Caglayan, D. et al. The Techno-Economic Potential of Offshore Wind Energy with Optimized Future Turbine Designs in Europe.

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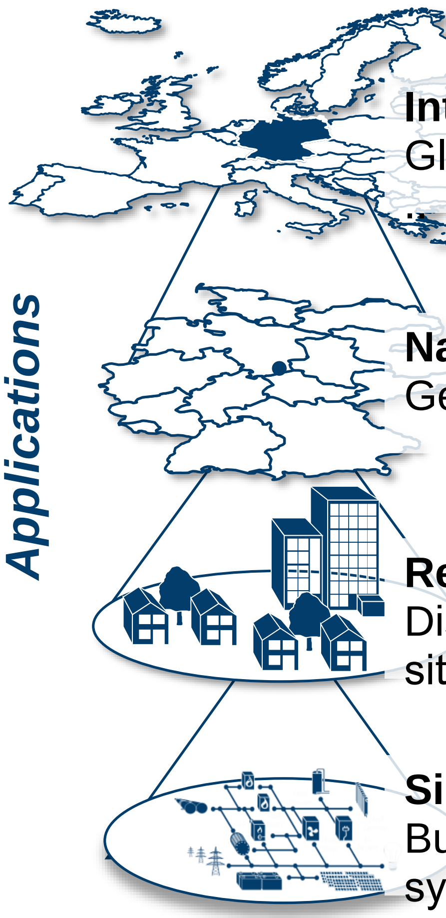
# FINE – A Framework for Integrated Energy System Assessment

## Applications



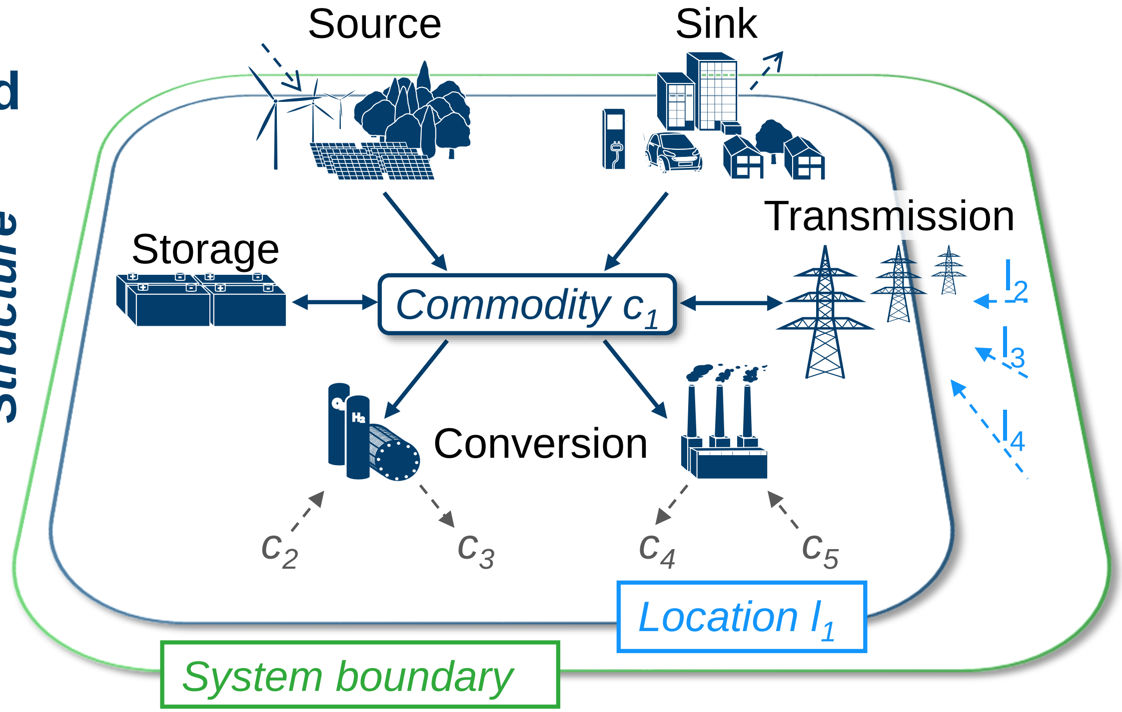
**International**
Global, European[1], …

**National**
Germany[2,3], …

**Regional**
District[4], industrial site, …

**Single-Node**
Building[5], island system, …

## Structure




## Collaboration

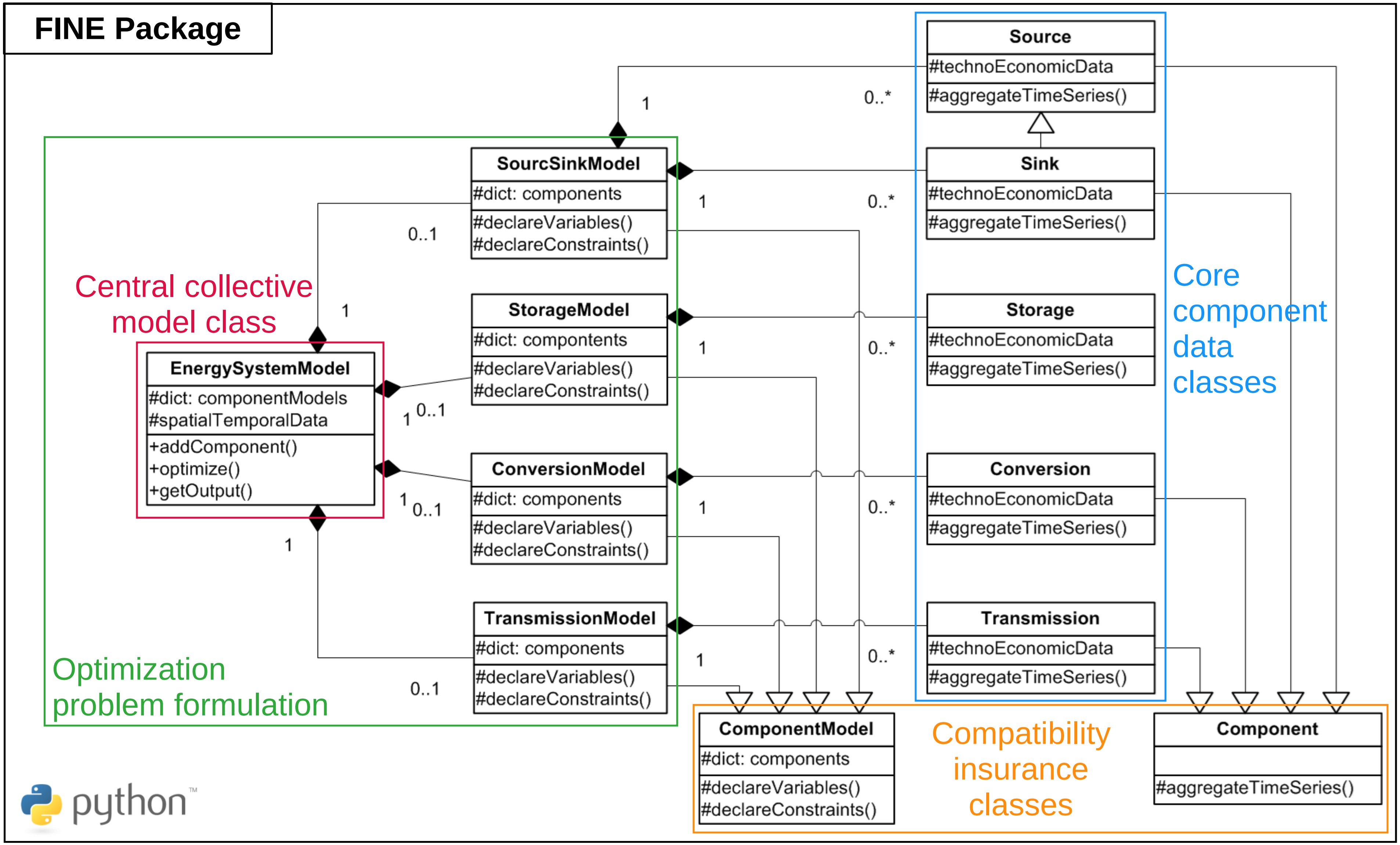
**Open-source** available via `pip install FINE`

or, with the option to include own contributions, at

https://github.com/FZJ-IEK3-VSA/FINE


**[1]** Caglayan, D.G. et al. *Impact of wind year selection on the design of green hydrogen supply pathways for transport needs.* (to be submitted) **[2]** Welder, L., et al., *Spatio-temporal optimization of a future energy system for power-to-hydrogen applications in Germany.* Energy, 2018. **[3]** Lopion, P. et al. *Cost Uncertainties in Energy System Optimisation Models: A Quadratic Programming Approach for Avoiding Penny Switching Effects* (submitted) **[4]** Kannengießer et al. *Optimal urban energy system design: Separating discrete and continuous decisions to reduce computational load* (to be submitted) **[5]** Kotzur, L., *Future Grid Load of the Residential Building Sector*, in *Faculty of Mechanical Engineering*. 2018, RWTH Aachen: Aachen.

# Object-oriented Code Implementation of the Generic Model Formulation



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METIS PLATFORM

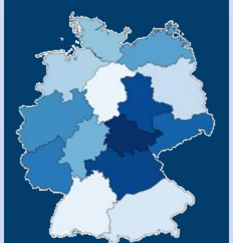
Input Data Aggregation

Complexity Management

Model Reduction

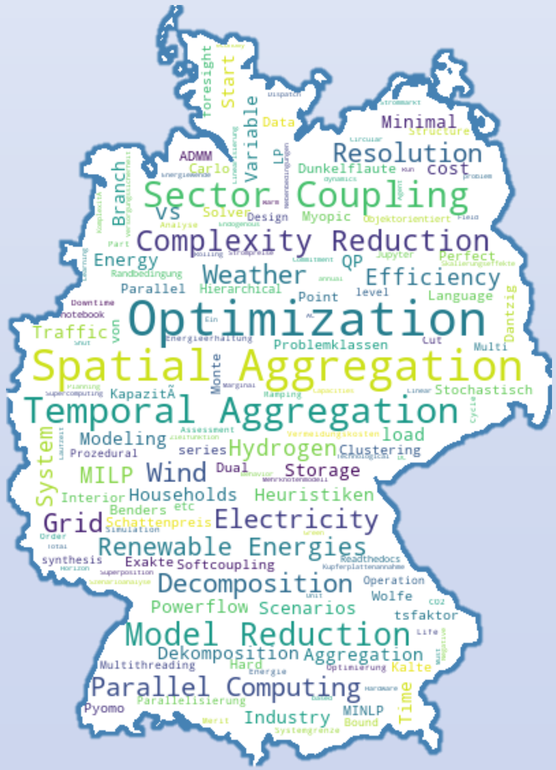
*Single-Node Model*

*Multiple-Node Model*



*Model Validation*

*HPC-Integration*




http://www.metis-platform.de

python™

open source initiative

github.com/FZJ-IEK3-VSA

GLAES FINE GEOKIT TSAM

*data complexity* *model complexity*

Methods and Models for Energy Transformation and Integration Systems

Bundesministerium für Wirtschaft und Energie

RWTH AACHEN UNIVERSITY

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

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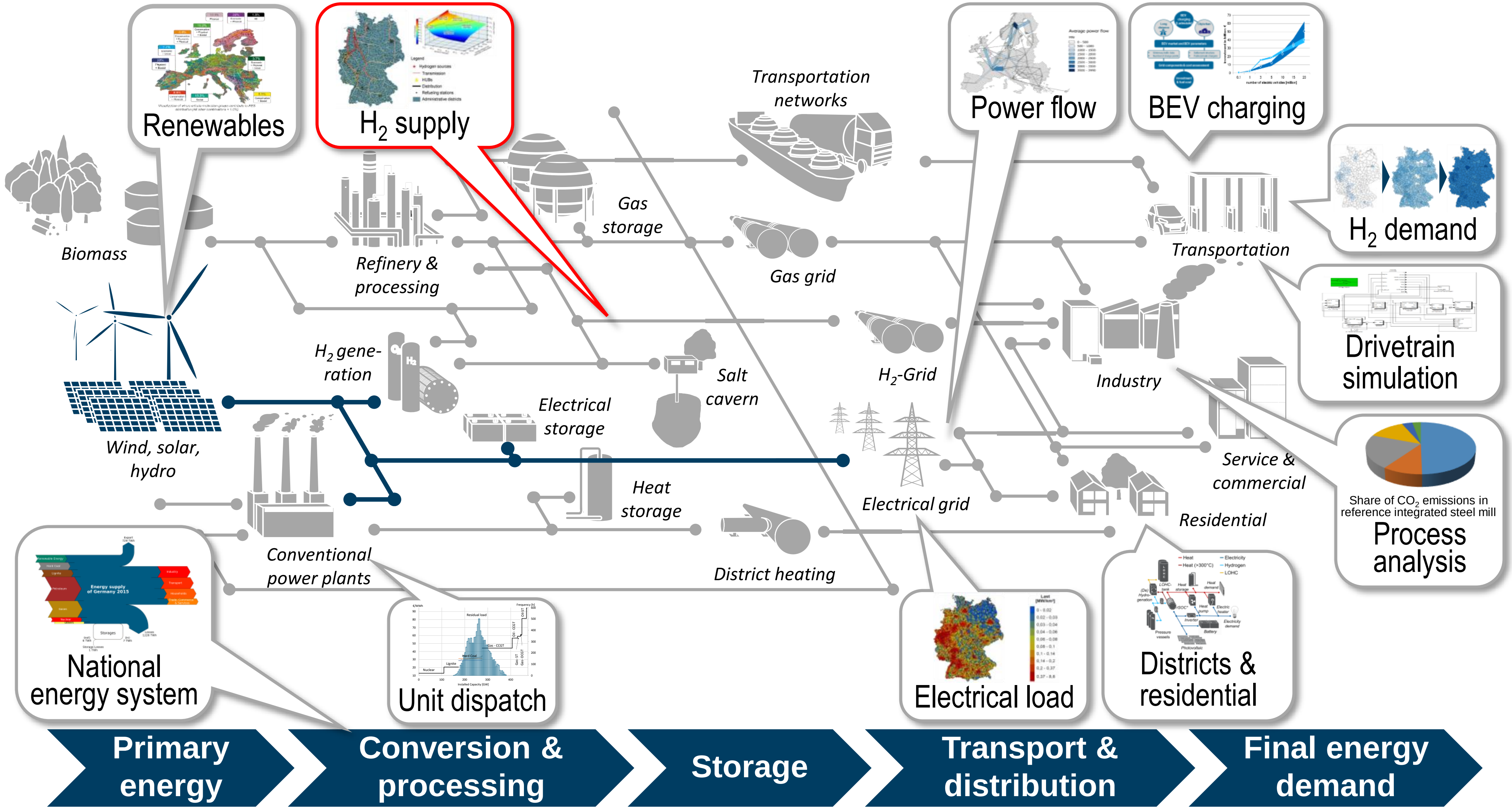
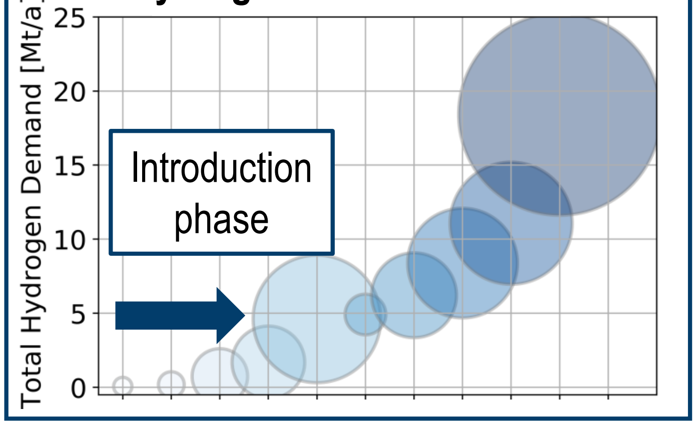
# Role in the Toolbox

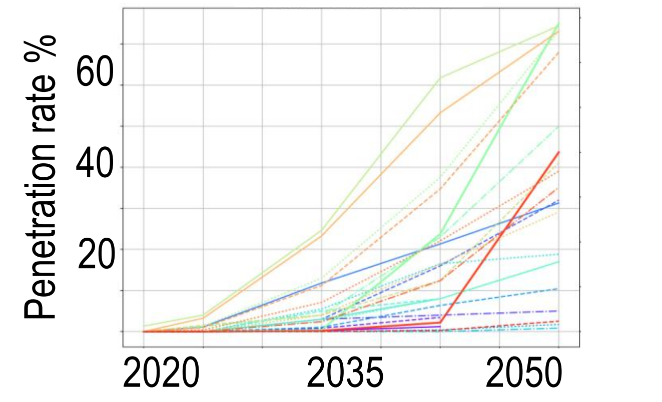


# Methodology

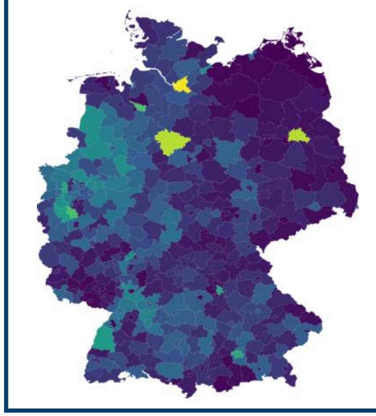
### Hydrogen Demand Potential



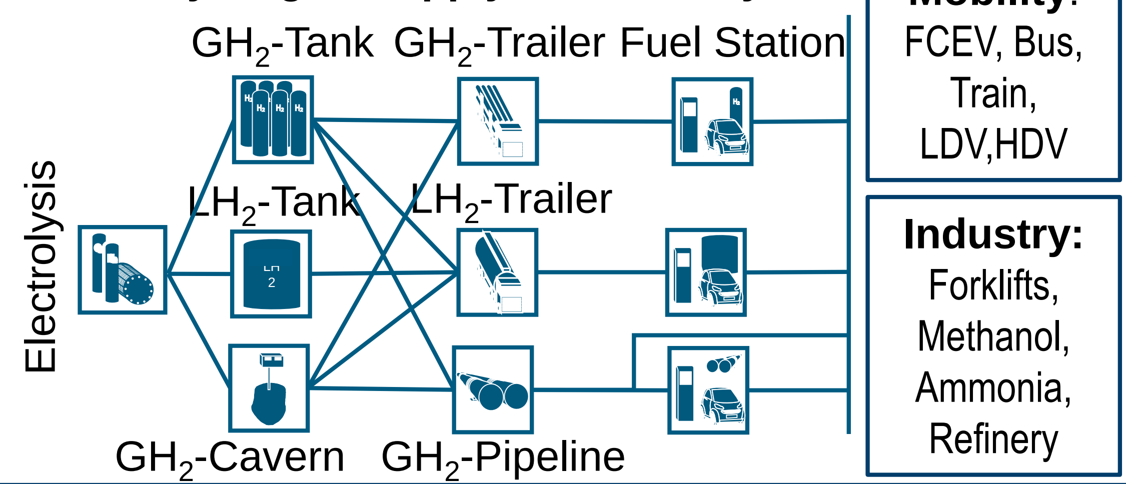

### Technology Diffusion Scenarios



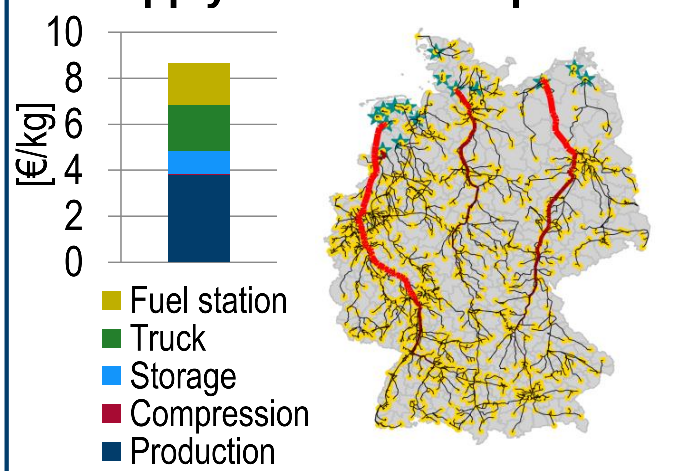

### Demand Localization



### Hydrogen Supply Chain Analysis




### Supply Chain Development

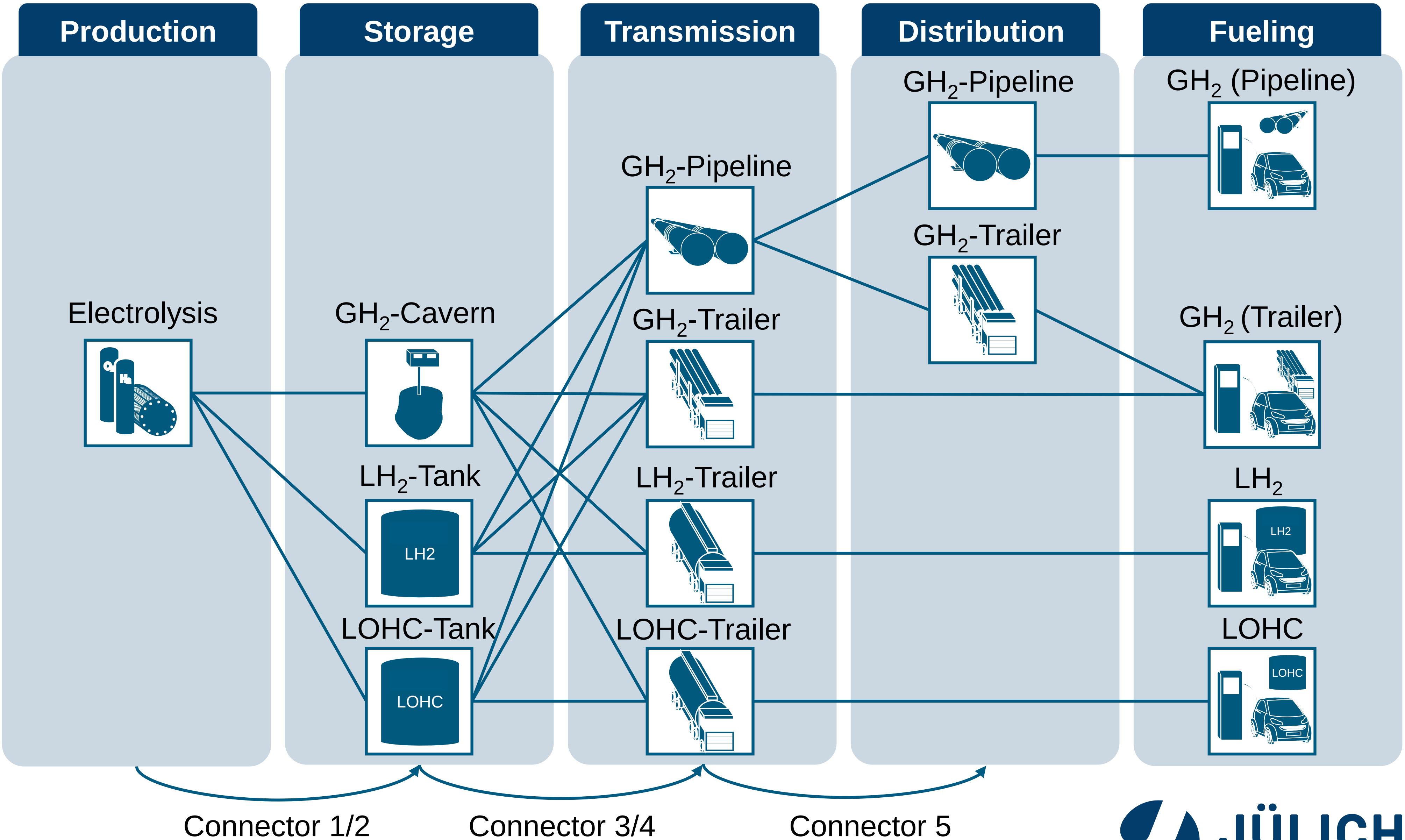



FCEV: Fuel cell electril vehicle, HDV: Heavy Duty Vehicle, LDV: Light Duty Vehicle,

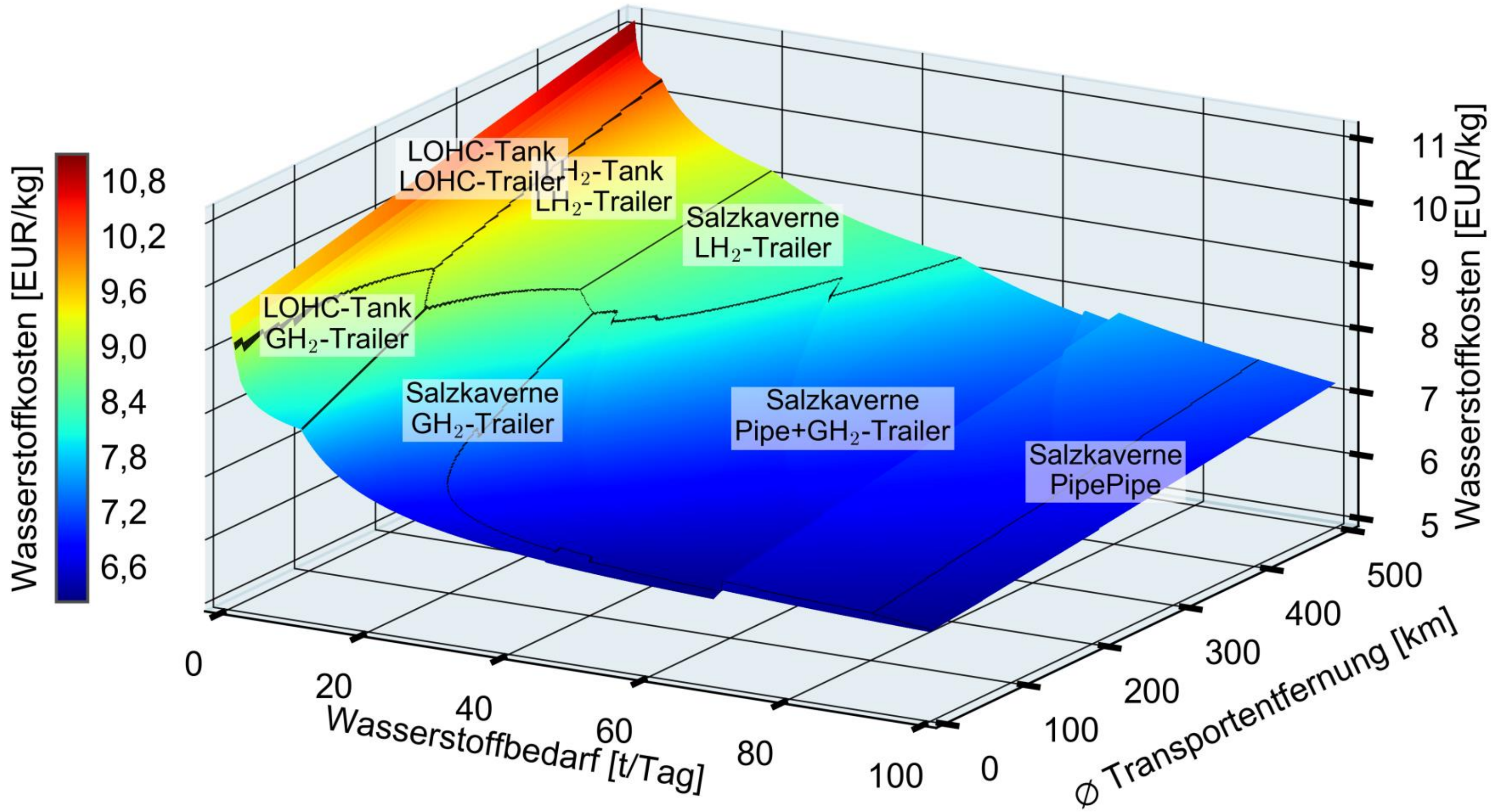
$GH_2$: Gasoues Hydrogen, $LH_2$: Liquid Hydrogen

Reuß, M., et al., *Seasonal storage and alternative carriers: A flexible hydrogen supply chain model.* Applied Energy, 2017.

# Hydrogen Supply Chain Model – Process Chain Analysis



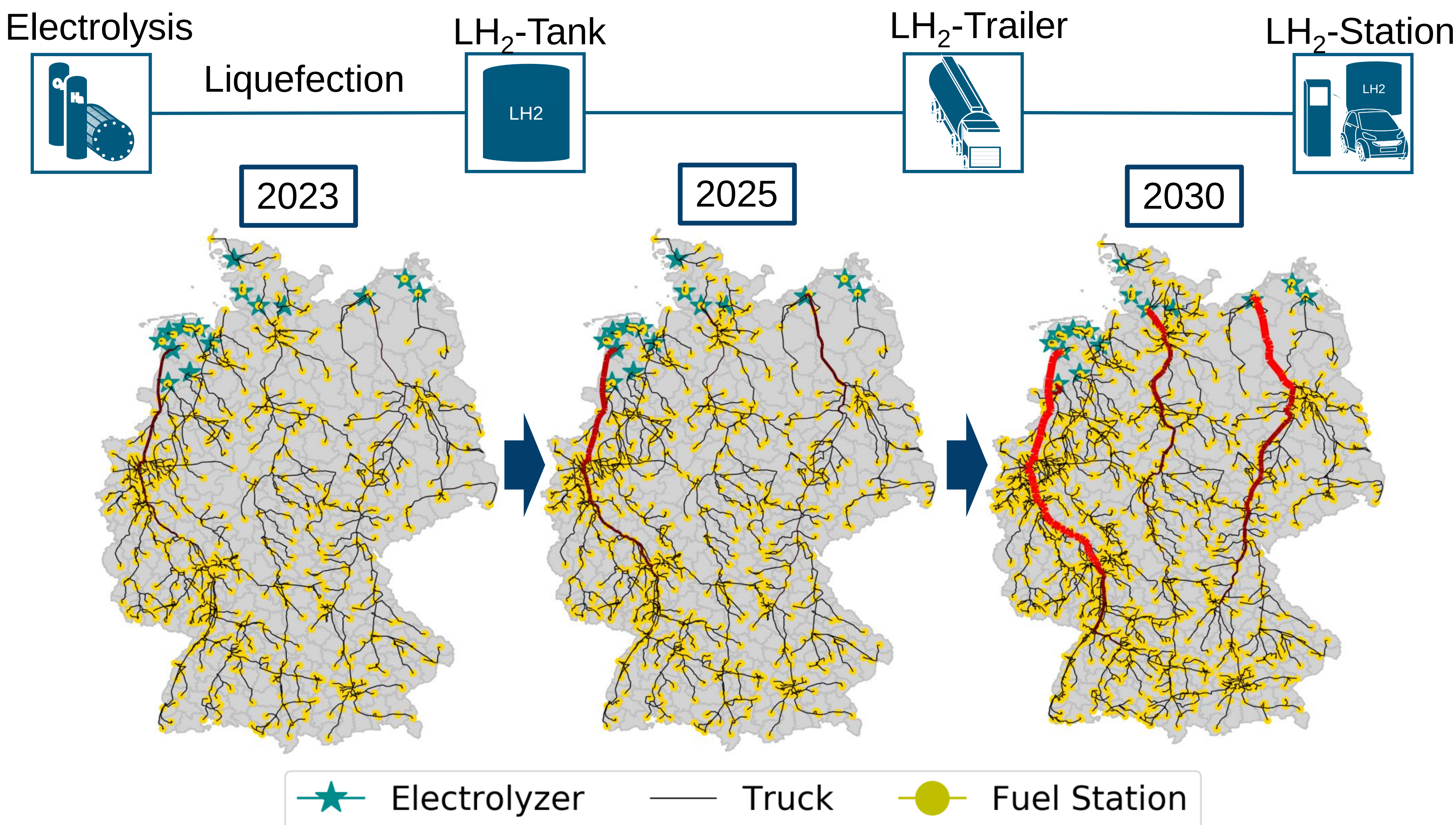
# Techno-economic Analysis of Supply Chains Alternatives




- LOHC pathways suitable for small hydrogen demand
- $LH_2$ applicable at medium demands and higher distances
- High demand lead to strong $GH_2$-focused pathways
- GH2-Trailer Transport over small distances and demand


Reuß, M., et al., Seasonal storage and alternative carriers: A flexible hydrogen supply chain model. Applied Energy, 2017. 200: p. 290-302.

# Methodology: Supply Chain Development: Example $LH_2$




Electrolysis locations after Robinius, M., et al., *Linking the Power and Transport Sectors-Part 2: Modelling a Sector Coupling Scenario for Germany.* Energies, 2017. **10**(7): p. 23.

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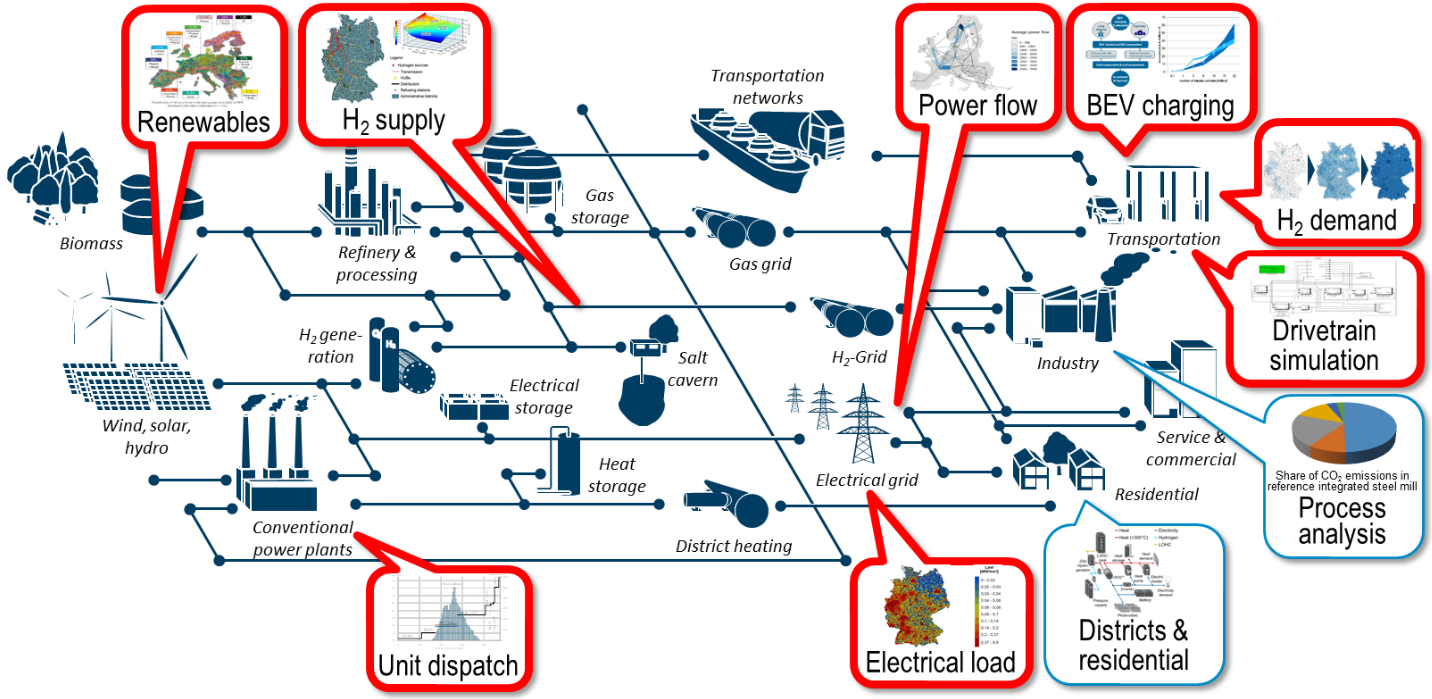
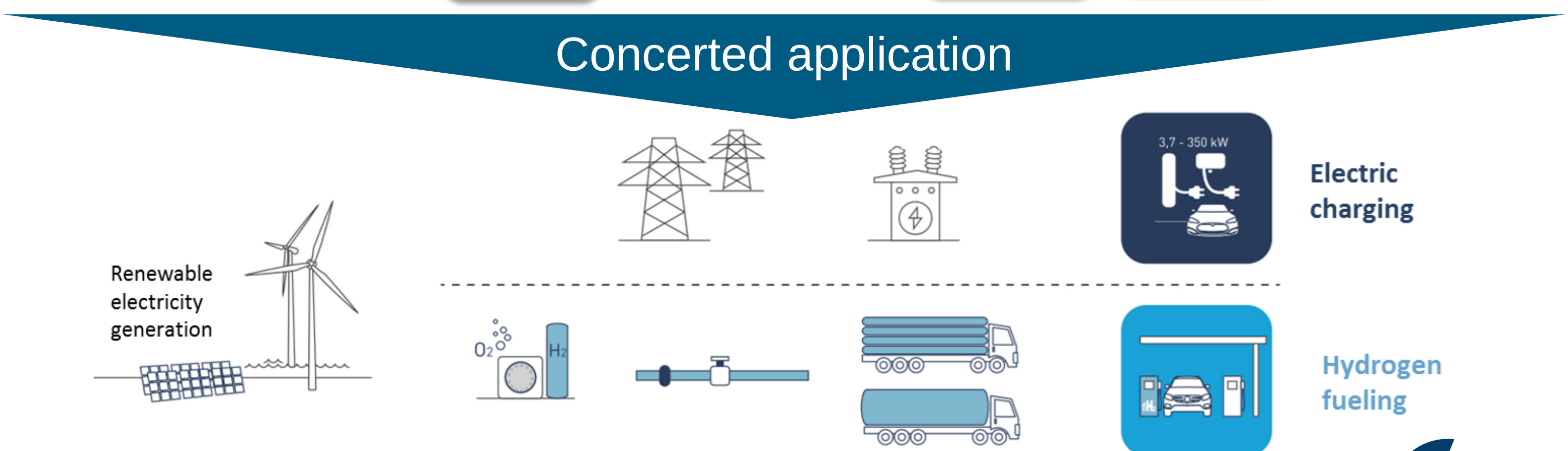
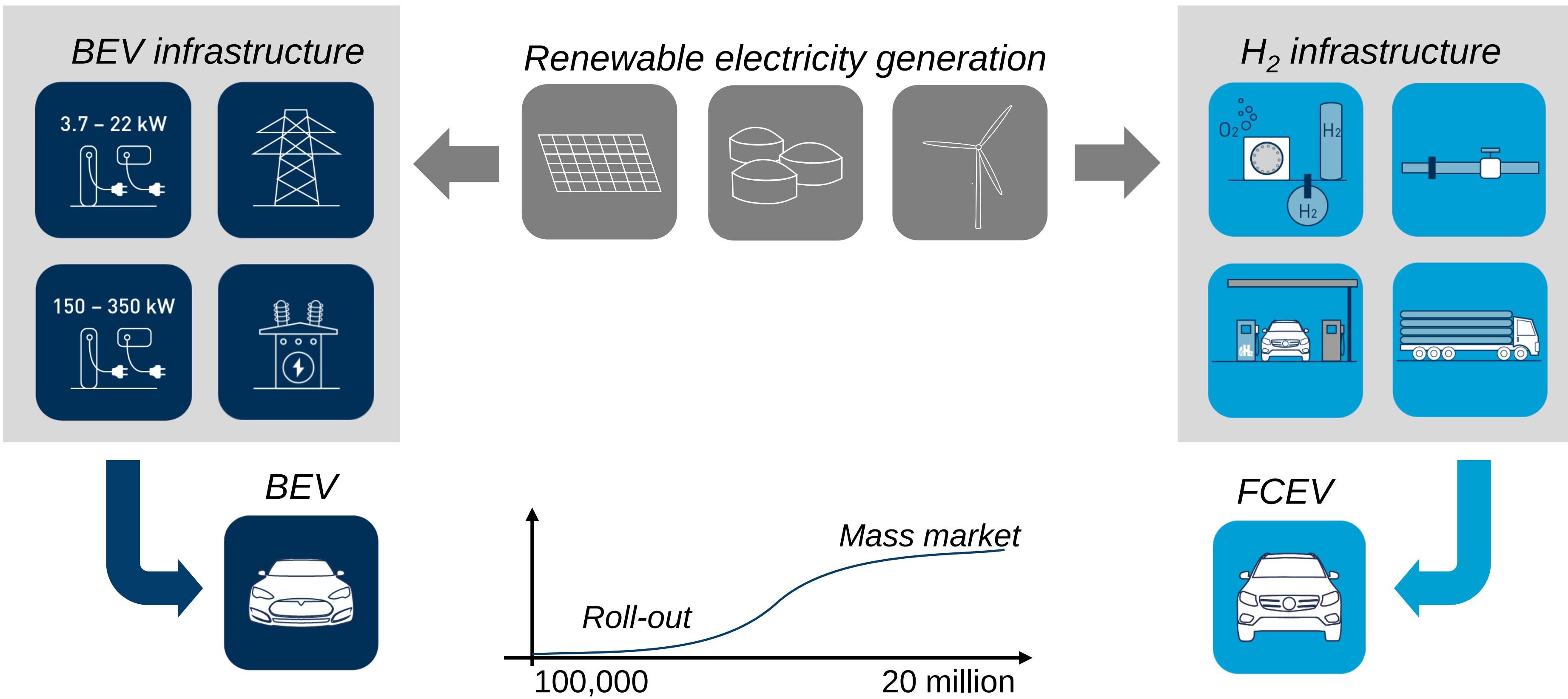
# Applied Model Portfolio



# Battery-Electric Vehicles (BEVs) & Fuel-Cell Electric Vehicles (FCEVs): Key Elements for Zero-Emission Transportation

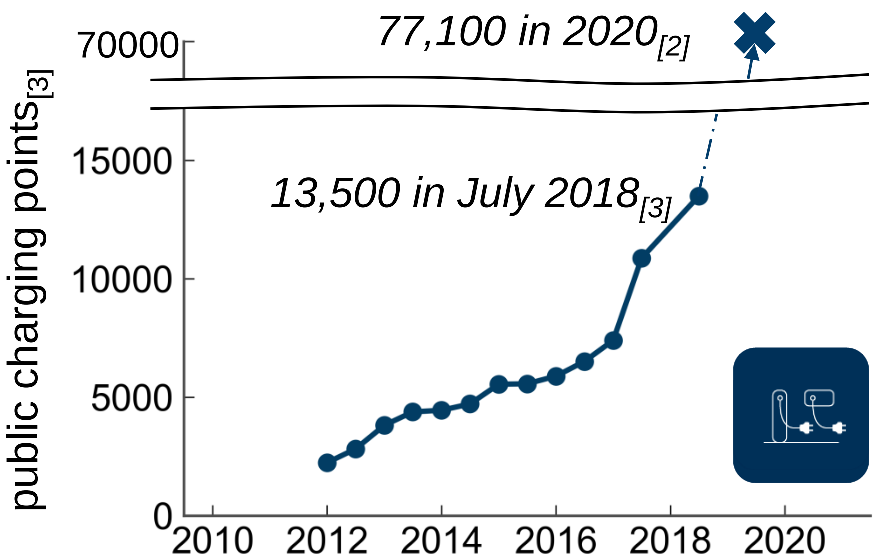



What are the **investments**, costs,
efficiencies and emissions of the required supply infrastructures?

# Status Quo of EVs and Infrastructures in Germany

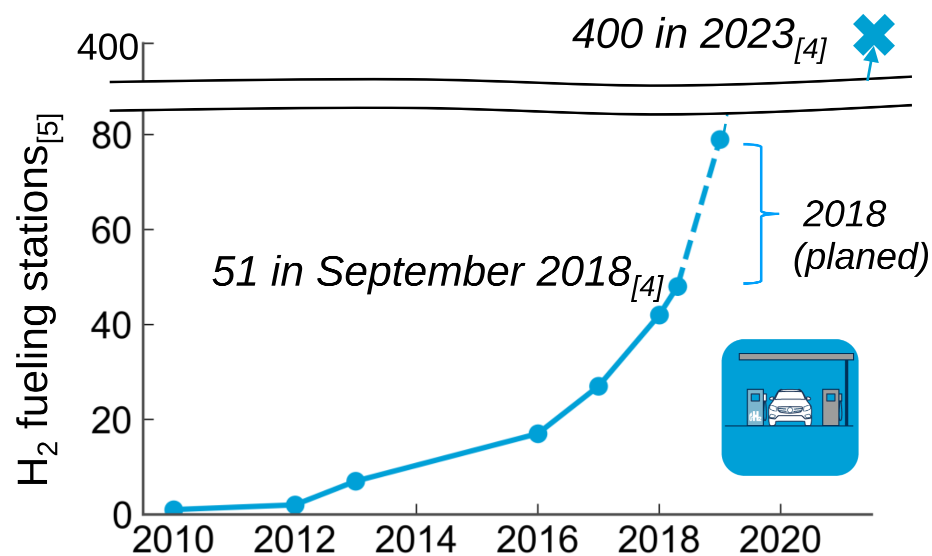
## Battery-electric vehicles (BEV)

44.419 Plug-in hybrids and 53.861 BEVs (1.1.2018)[1]




## Fuel cell-electric vehicles (FCEV)

325 passenger cars, 15 busses, 4 trucks, (1.1.2018)[1]




**Supply infrastructures ready for market and required technologies mature**

**[1]** KBA. *Bestand am 1. Januar 2018 nach Motorisierung*. 2018 (FCEV Auf Anfrage) **[2]** Nationale Plattform Elektromobilität: *Wegweiser Elektromobilität.* 2016. **[3]** BDEW, Erhebung Ladeinfrastruktur. 2017: Berlin. **[4]** H2 MOBILITY: *H2-Stations*. 2018 **[5]** HyARC, *International Hydrogen Fueling Stations*. 2018.

# 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**

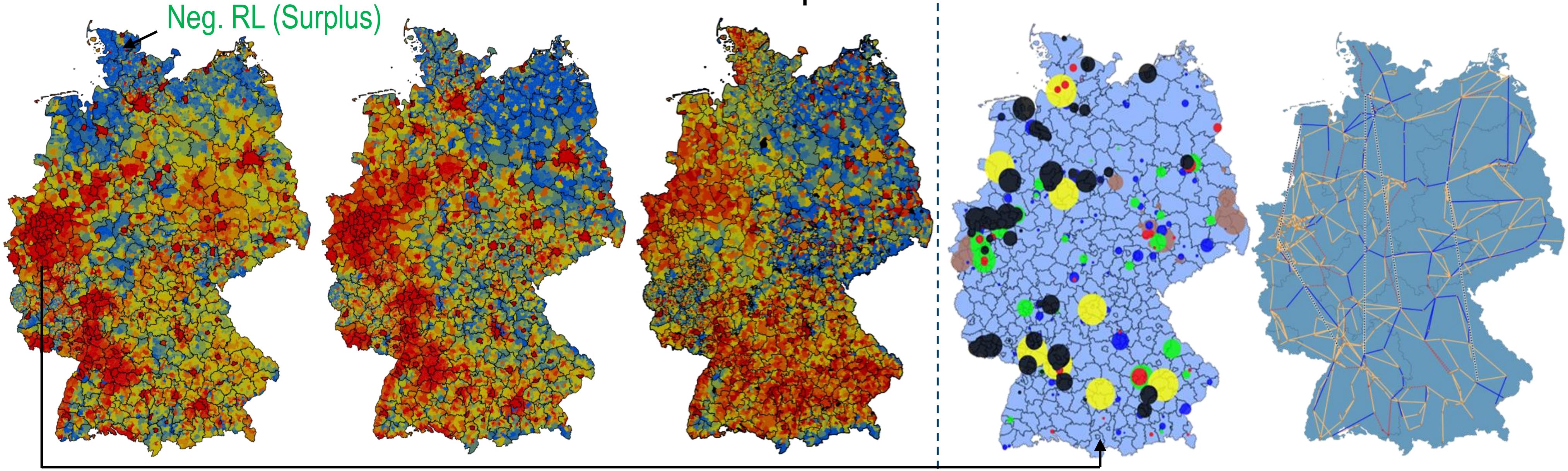
**Further assumptions:** grid electricity: **528 TWh**; imports: 28 TWh; exports: 45 TWh; pos. residual: natural gas

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

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

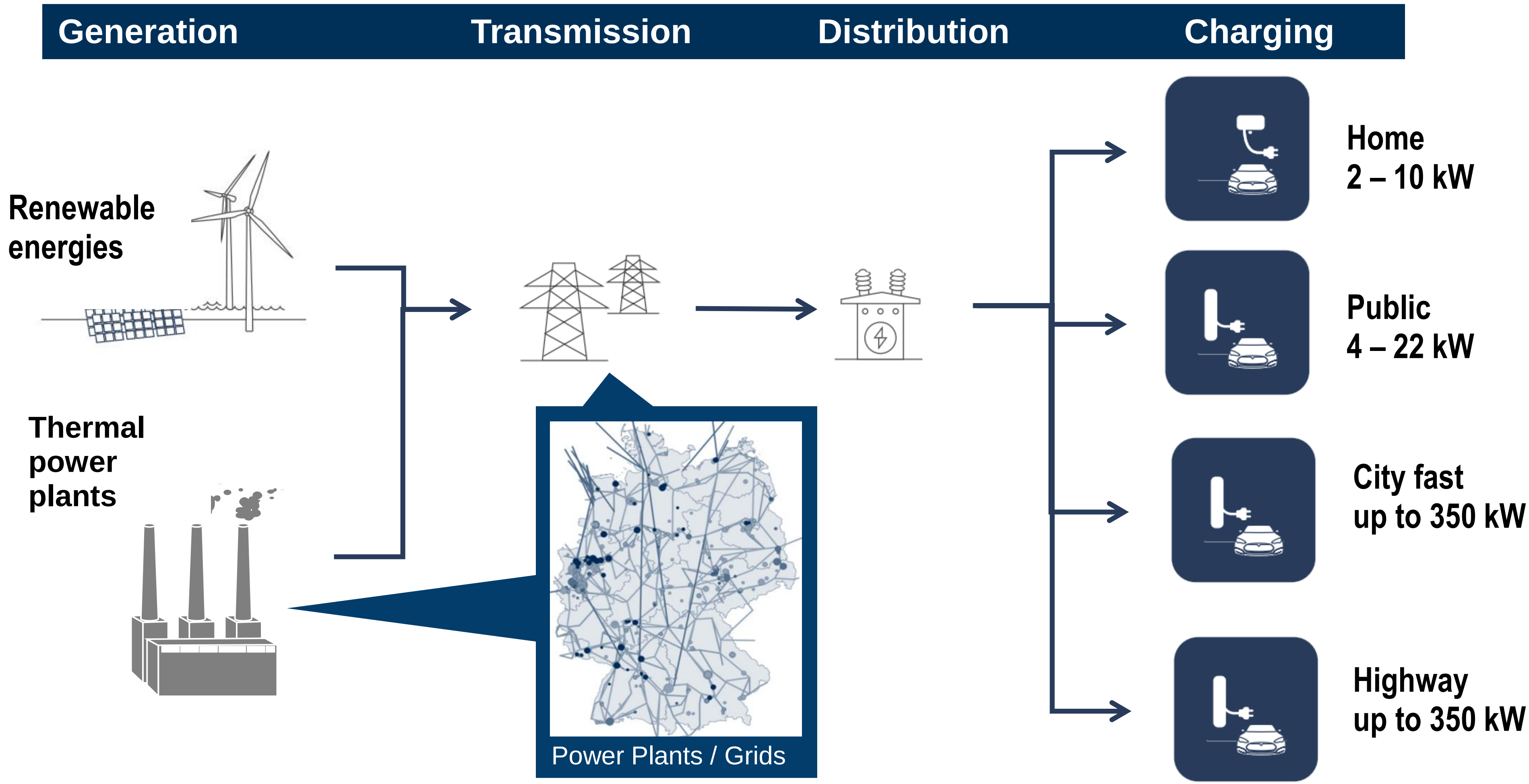
RES: Renewable Energy Sources

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




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

# Components of Charging Infrastructure




Requirement: Modeling with high spatial and temporal resolutions

# Europower[1,2]

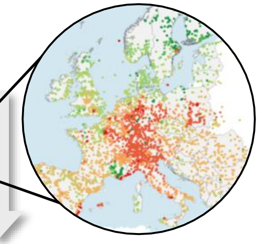
## *Methodology*

1. Schedule generation and storage operation

**Countries**
annual perfect foresight operation

**Full grid**
hourly optimal power flow

2. Clustering by nodal prices



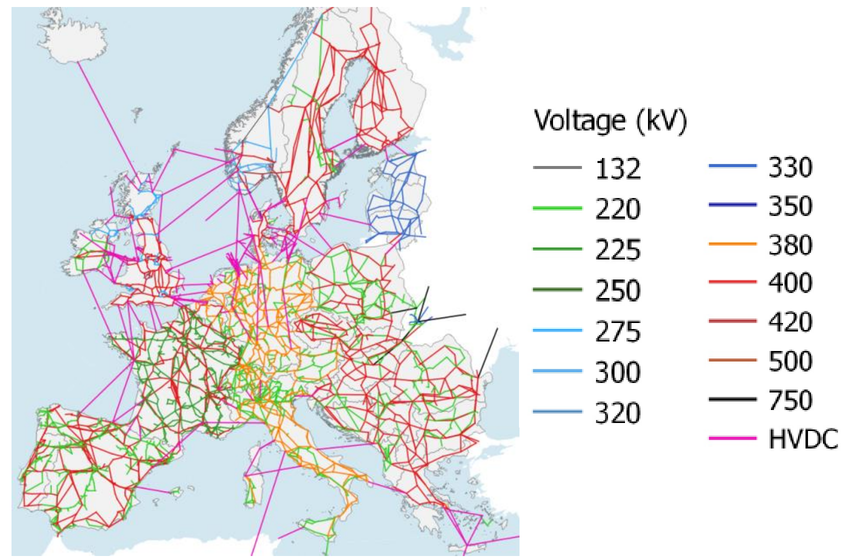
**Spatial clusters**
daily foresight with rolling horizon

3. Re-dispatch

- Verified for 2015
- Scenarios for 2030/2040/2050

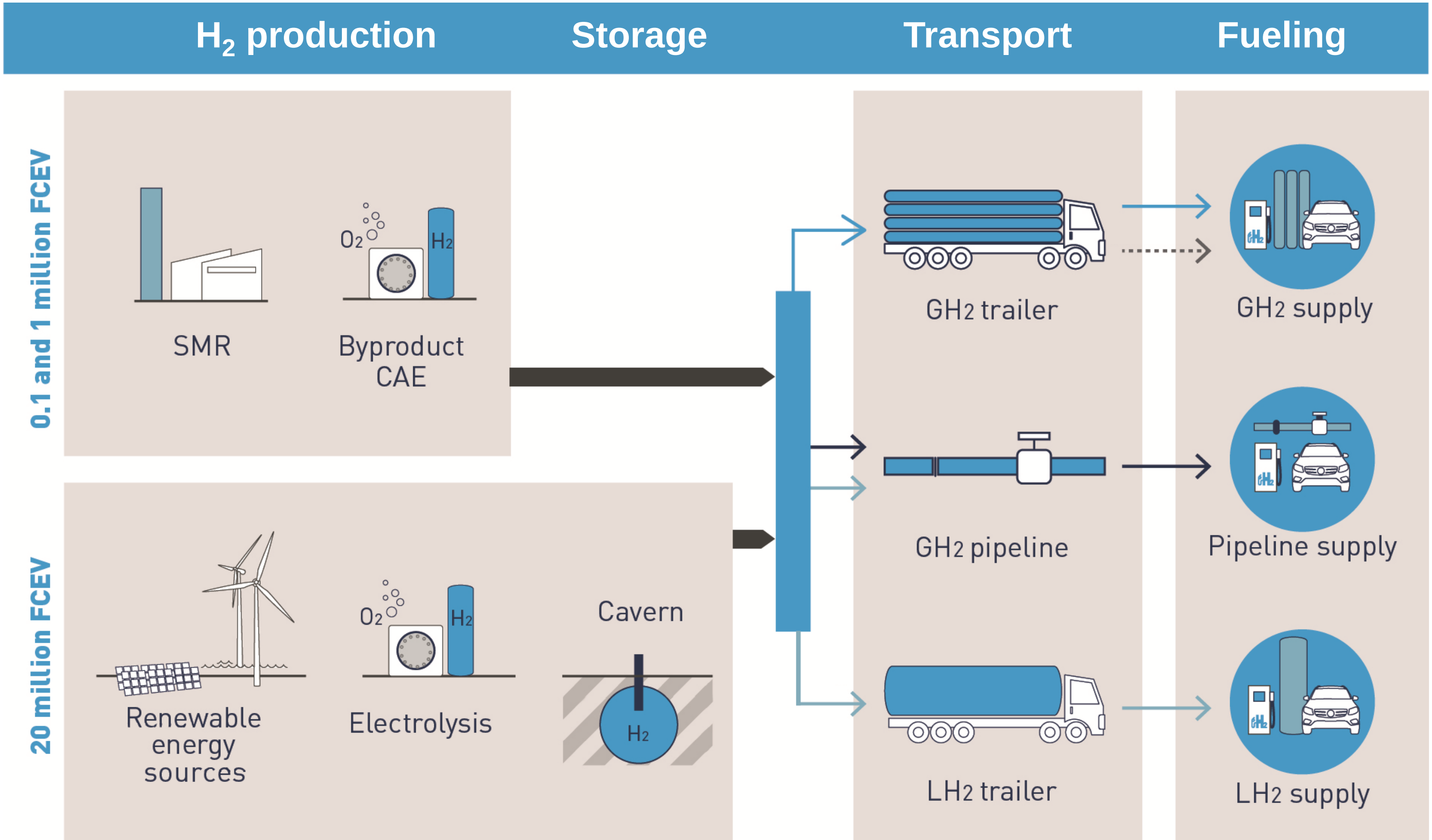
## *Features*

- **Transmission grid** based on the Ten Year Network Development Plant (TYNDP) 2016
  - 3790 nodes
  - 5113 lines, 274.380 km
- **Power plants** (excl. hydro/wind/solar) from open sources, including efficiency estimation
  - 1333 plants
  - 489 GW installed capacity
- **Hydro power plants** with weather-based inflow
- **Wind, PV and CSP** generation based on weather data in high spatial resolution
- **Flexible demand**




[1] K. Syranidis, J. Linssen, P. Markewitz, M. Robinius and D. Stolten, “Flexible demand for higher integration of renewables into the European power system”, 15th international conference on the European Energy Market (EEM) 2018. IEEE 2018
[2] K.Syranidis, M. Robinius and D. Stolten, “Control techniques and the modeling of electrical power flow across transmission networks”, Renewable and Sustainable Energy Reviews 2018

# Components of $H_2$ Infrastructure



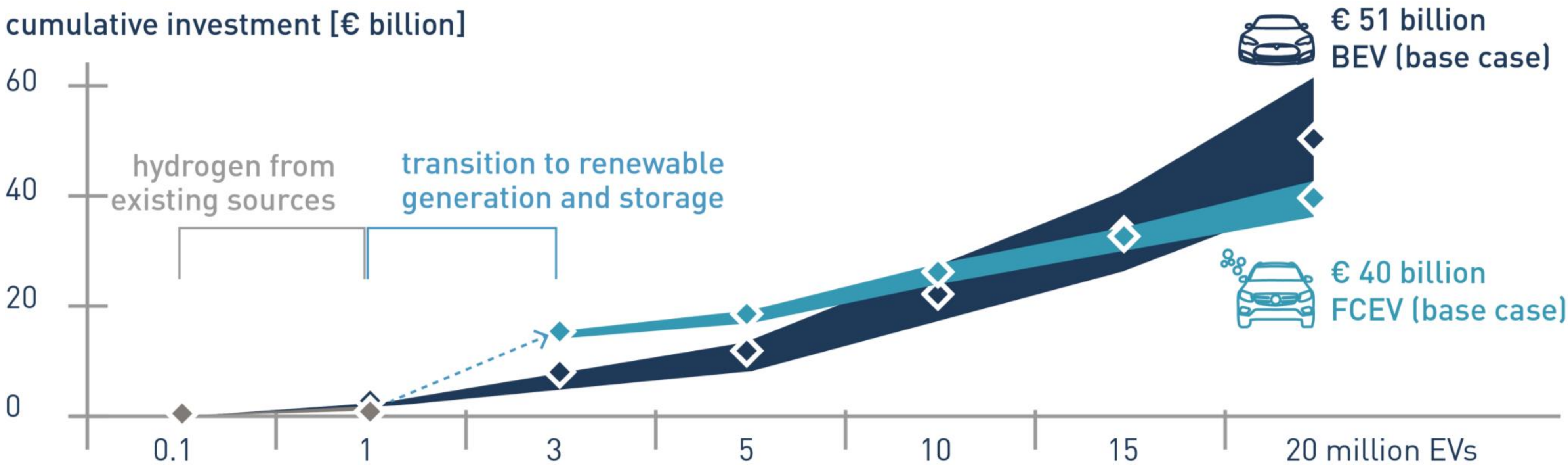

**Requirement: Modeling with high spatial and temporal resolutions**

# Selected Infrastructure Characteristics

| | 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 |
| | **Ramp up** | **Mass market** | | |
| 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 |

- ► $H_2$ infrastructure: Inherent seasonal storage for renewable electricity included
- ► Hydrogen transmission pipeline already beneficial at 3 million FCEV
- ► BEV benefit from existing infrastructure components in the ramp up

# Comparison of Investment for Infrastructure Installation



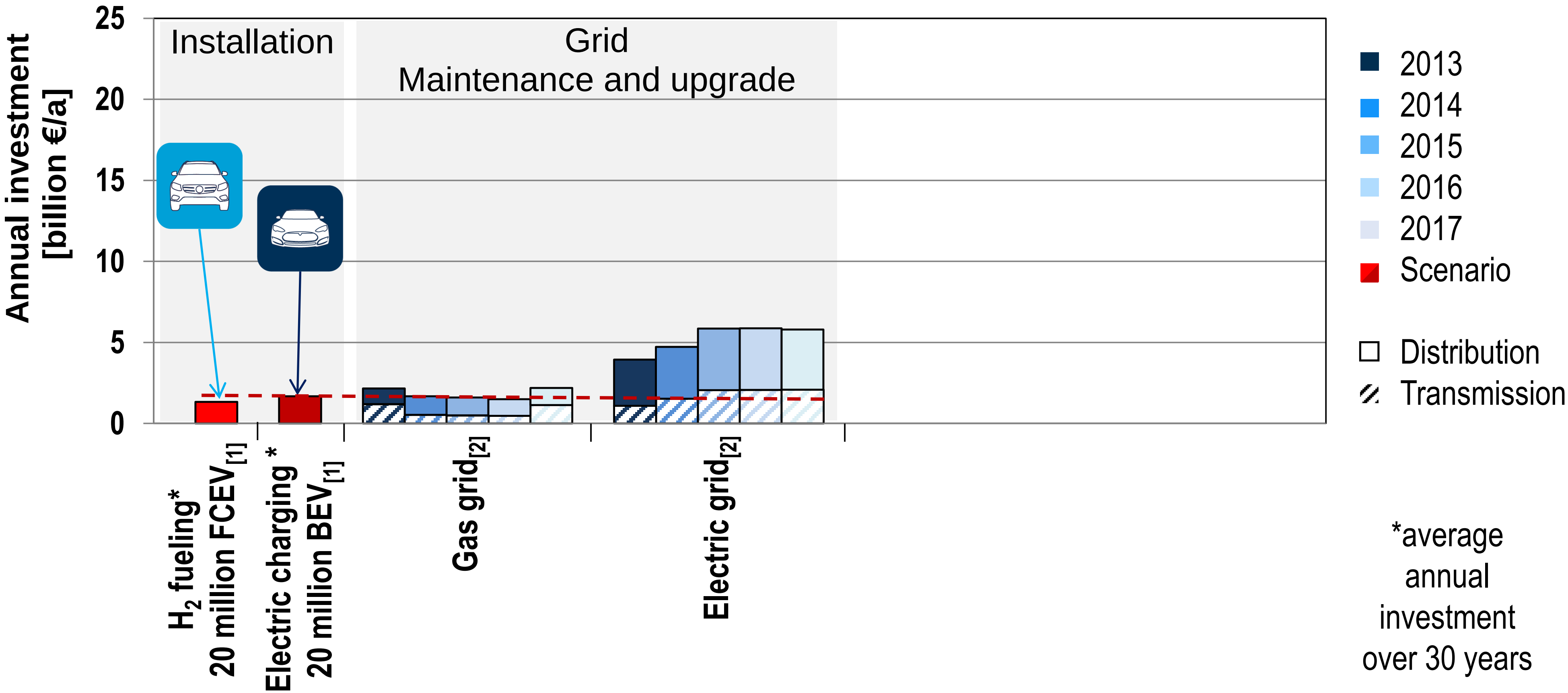

- ► Similar investment in phase of roll-out and mass market
- ► Future charging behavior unclear – high uncertainty for charging investment
- ► $H_2$ infrastructure with strong scaling effects

# Comparison of Annual Investment in Energy Supply Infrastructures


*average annual investment over 30 years


[1] Robinius, M. et al.: Comparative Analysis of Infrastructures: Hydrogen Fueling and Electric Charging of Vehicles. 2018 [2] BNetzA: Monitoringbericht 2017. [3] BDEW: Investitionen der deutschen Stromwirtschaft. 2018 [4] BMWi: Erneuerbare Energien in Zahlen. 2017

# Comparison of Annual Investment in Energy Supply Infrastructures

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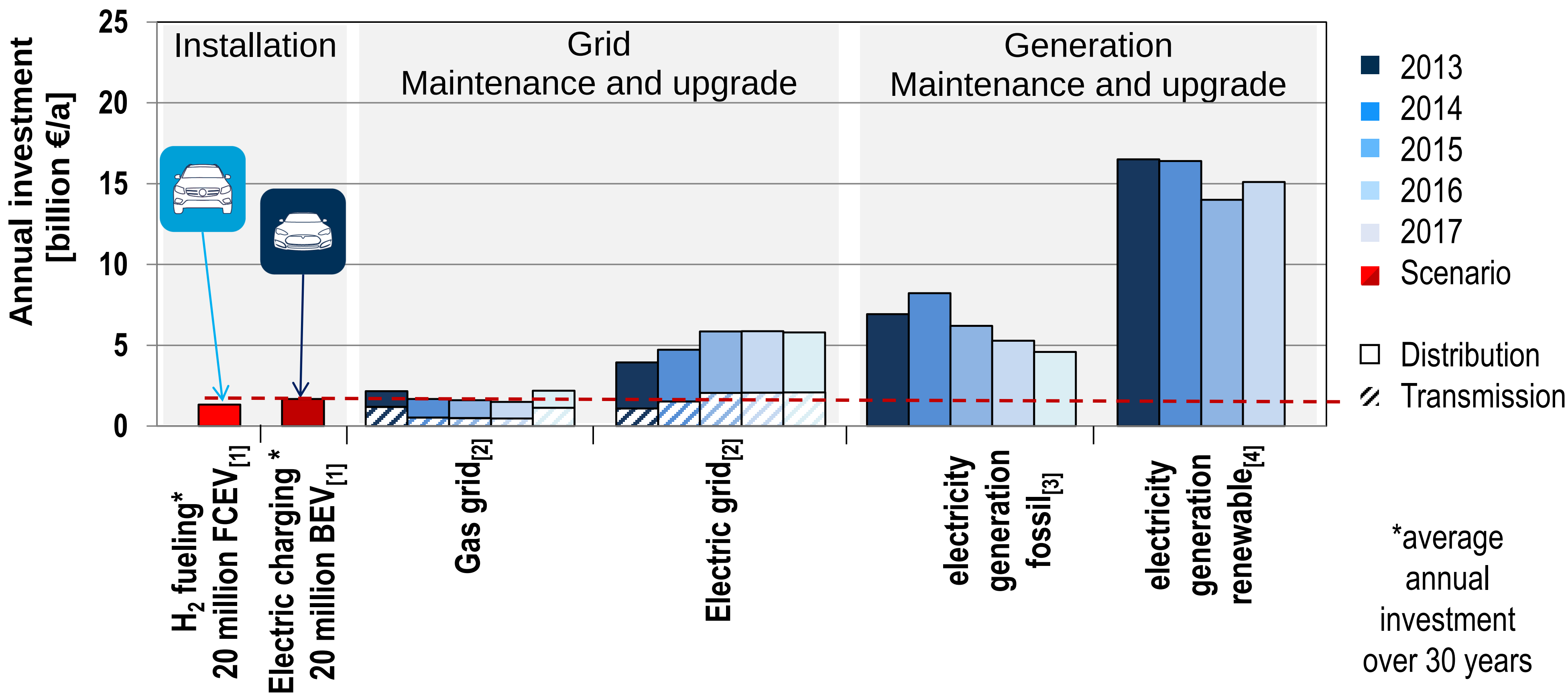
# Comparison of Annual Investment in Energy Supply Infrastructures

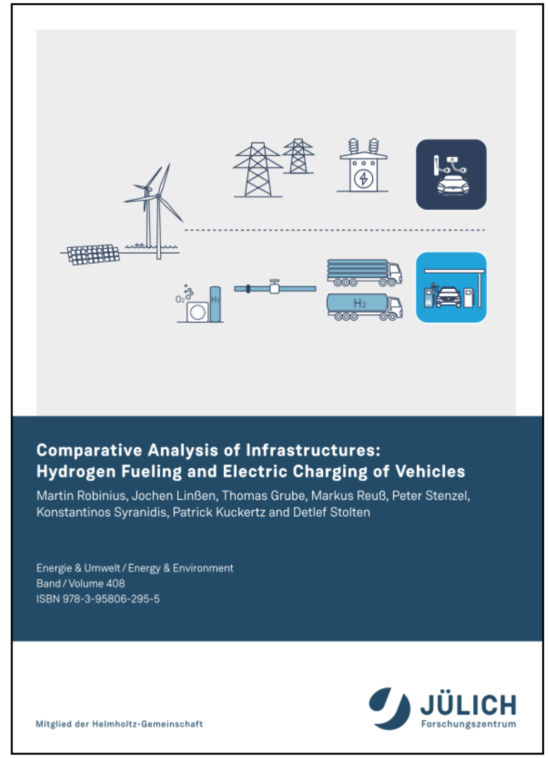



$H_2$ and charging infrastructure: Annual investment low in comparison to maintenance and upgrade investment of existing energy supply infrastructures

**[1]** Robinius, M. et al.: Comparative Analysis of Infrastructures: Hydrogen Fueling and Electric Charging of Vehicles. 2018 **[2]** BNetzA: Monitoringbericht 2017. **[3]** BDEW: Investitionen der deutschen Stromwirtschaft. 2018 **[4]** BMWi: Erneuerbare Energien in Zahlen. 2017

**Report available at:**

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


Comparative Analysis of Infrastructures:
Hydrogen Fueling and Electric Charging of Vehicles
Martin Robinius, Jochen Linßen, Thomas Grube, Markus Reuß, Peter Stenzel, Konstantinos Syranidis, Patrick Kuckertz and Detlef Stolten

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**Scientific team:**

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

# Battery and Fuel Cells

# Table of Contents

# Energy System Design - Methodology

## Input Generator Modules

Onshore simulation | Pipeline builder | Salt caverns
Offshore simulation | Hydrogen demand | Other technologies
PV simulation | Electricity demand | Input to NetCDF

netCDF (input)

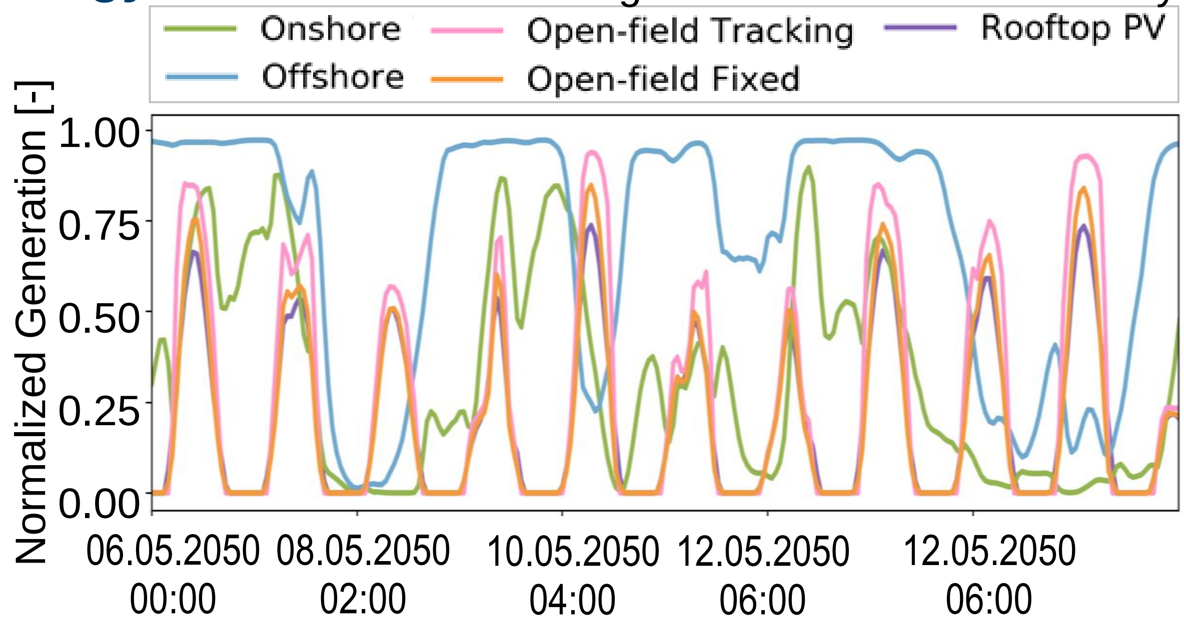
## Optimization Manager

Unpack input netCDF | Pass inputs to FINE

netCDF (input/output)

## Output Manager (Visualization)

Region: North-western Germany




***Variable Renewable Energy Simulations:***
RES
Geokit

***Output:*** Techno-economic parameters & time series (clustering is possible)

# Energy System Design - Methodology

## Input Generator Modules

| | | |
|---|---|---|
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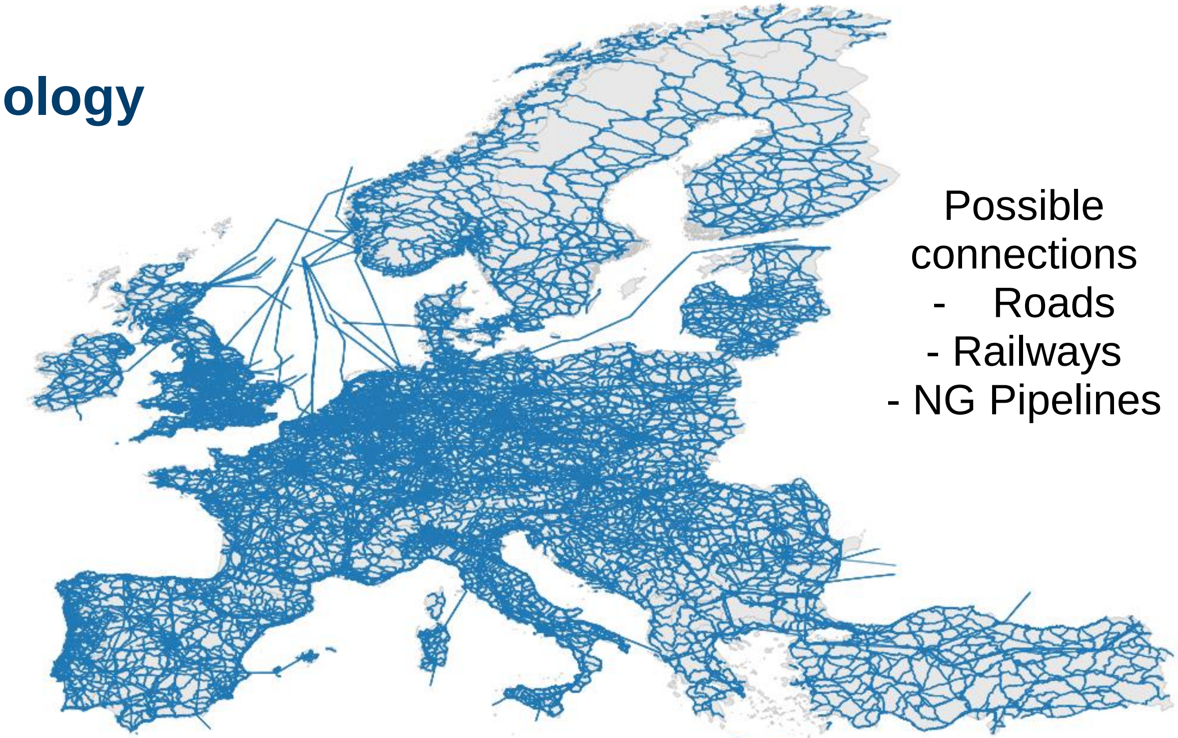
## Output Manager (Visualization)

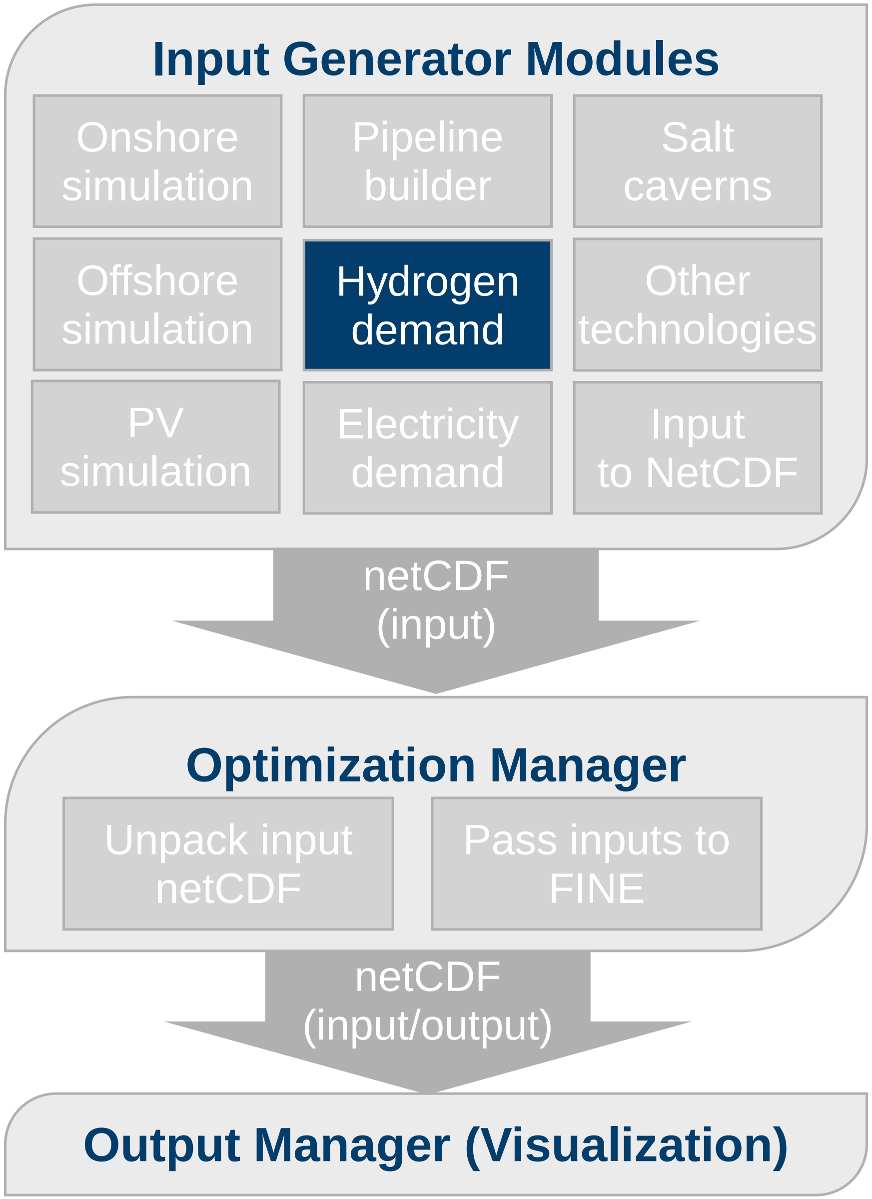


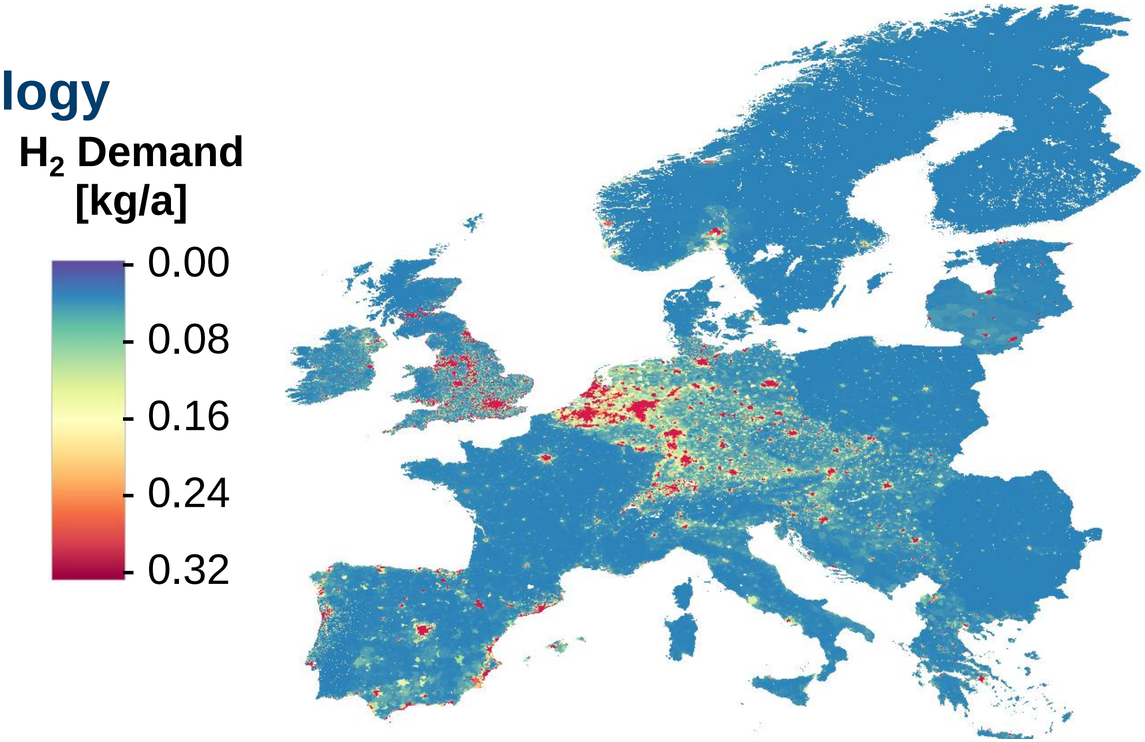
Possible connections
- Roads
- Railways
- NG Pipelines

***Pipeline Builder***

***Output:*** Shortest connection between regions & shape file

# Energy System Design - Methodology




***Hydrogen Demand for Passenger Cars:***

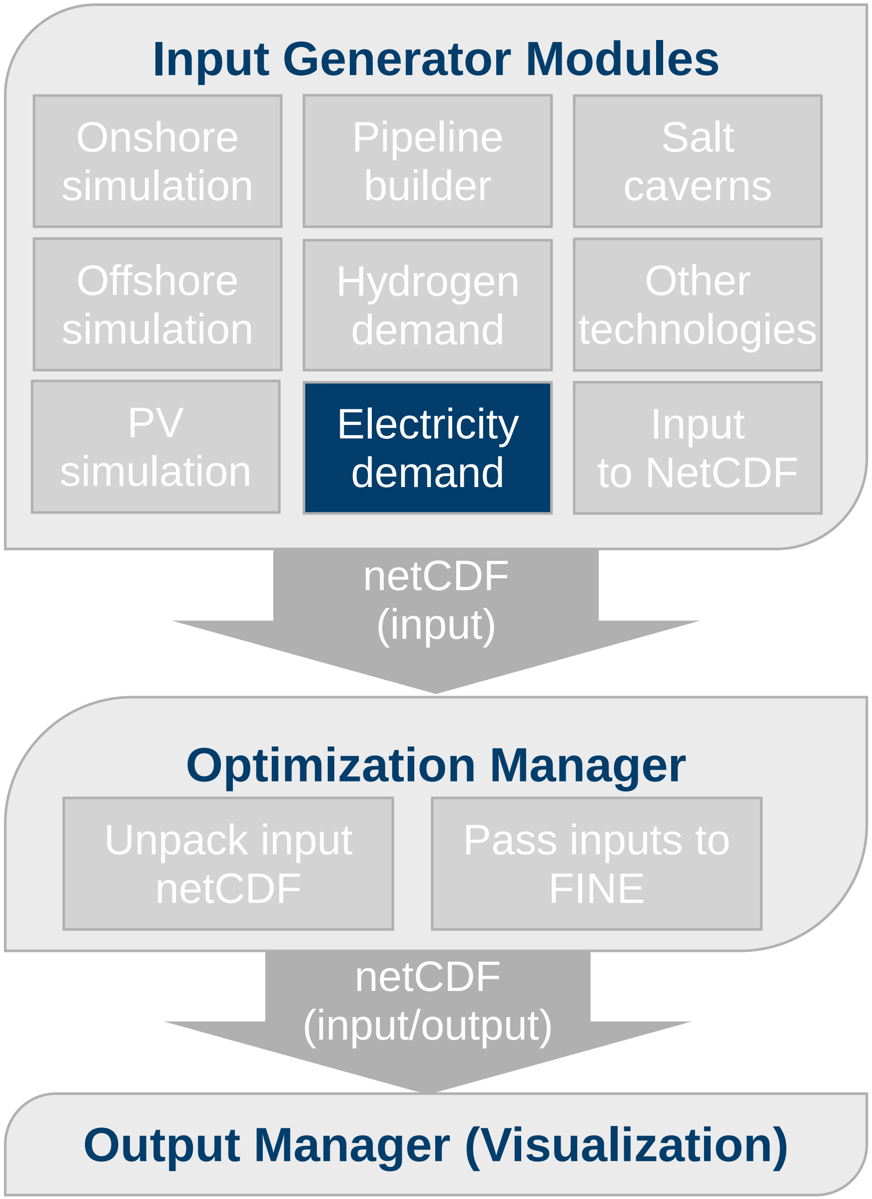
***Output:*** Demand time series & centroid

$$H_2Demand = CarNumber^{*} \times AnnualDrivingDistance^{*} \times FuelConsumption \times MarketPenetration$$

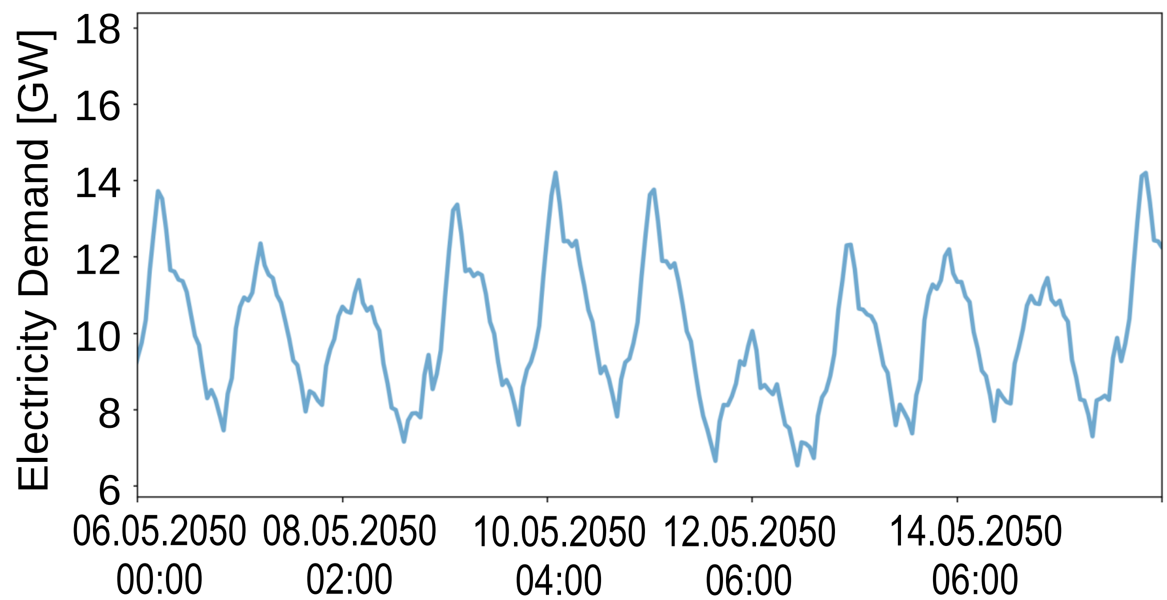
Method and fuel consumption data are obtained from Robinius et al. [1]
* Values are obtained from E-Highway "100% RES" Scenario [2]

[1] Robinius et al. (2017). *Energies*, vol. 10 (957). doi:10.3390/en10070957.
[2] Sanchis, "Europe's future secure and sustainable electricity infrastructure: e-Highway2050 project results," 2015.

# Energy System Design - Methodology




Region: Northwestern Germany




***Electricity Demand***

***Output:*** Hourly demand & population centroid [1]

$$ElectricityDemand = \frac{Pop_{region}}{Pop_{country}} \; x \; Demand_{country}$$

**Pop: Population**

Countrywise electricity demand and method are obtained from Syranidis[2]

[1] http://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/population-distribution-demography/clusters (2011) [2] Syranidis., "Investigation of Renewable Energy Sources Integration into the Future European Power System and the Impact of Demand Flexibility". RWTH Aachen (2019).

# Energy System Design - Methodology

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↓ netCDF (input/output)

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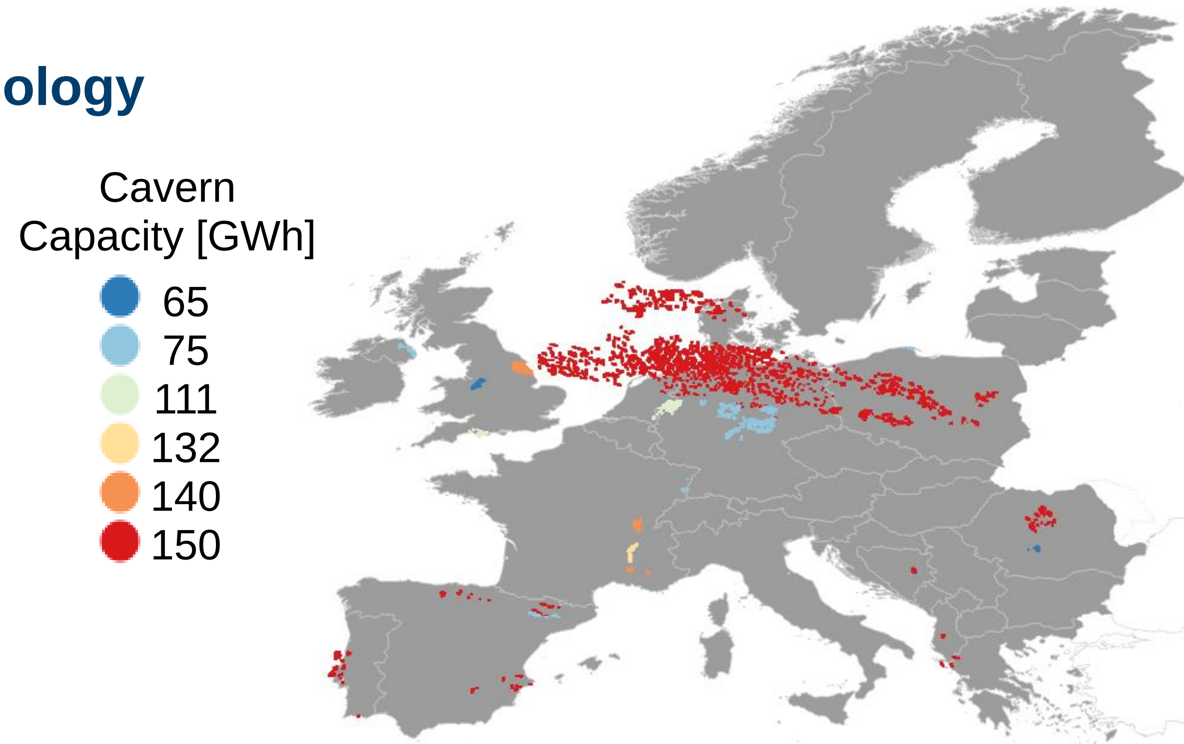
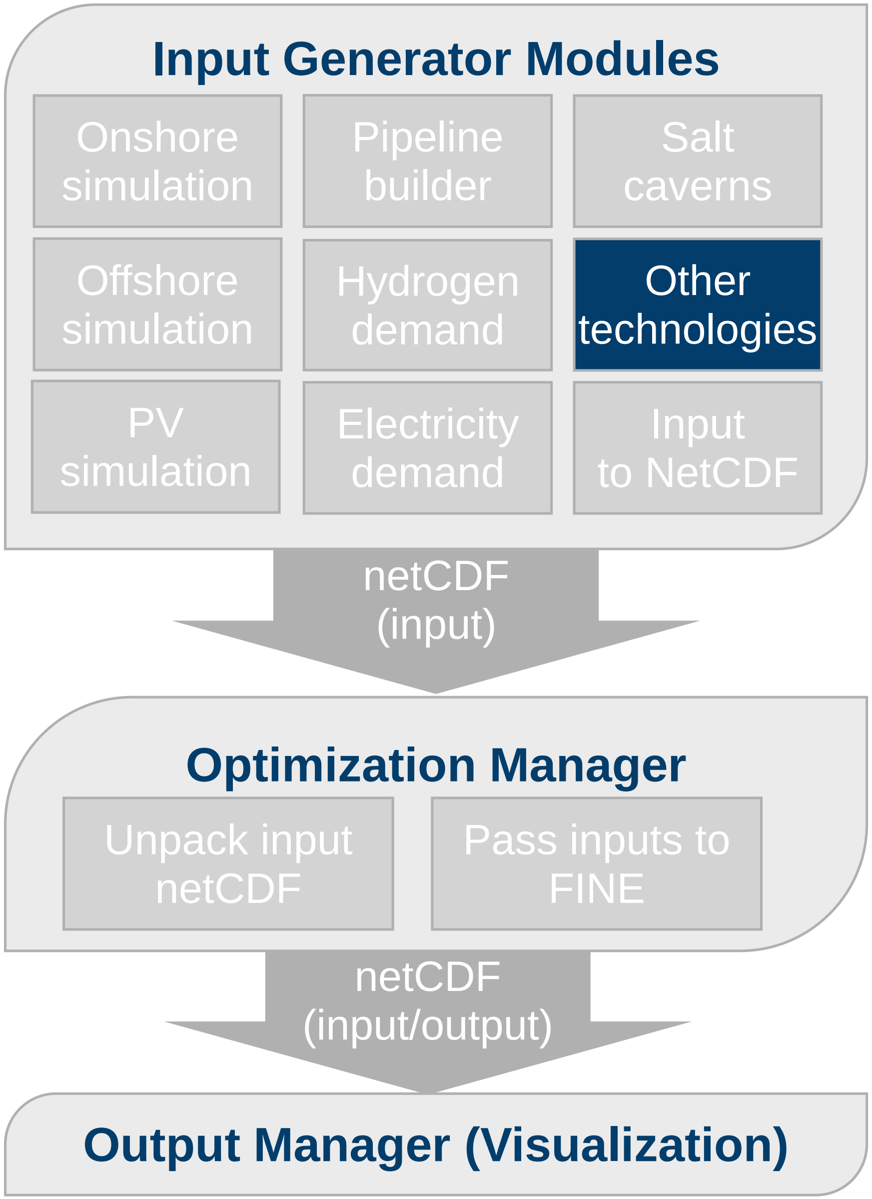



***Salt Cavern Potential***

***Output:*** Techno-economic potential of salt caverns

# Energy System Design - Methodology



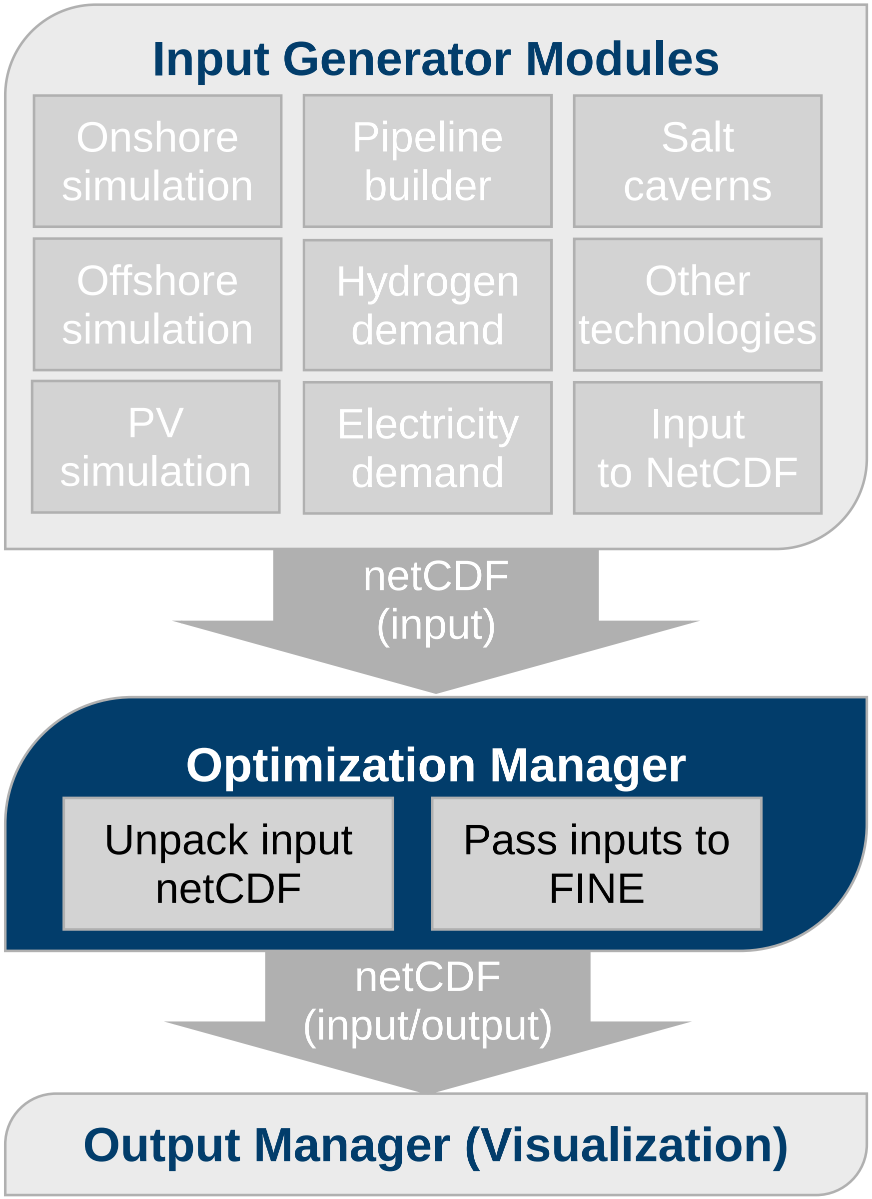

- Allows the model to be adapted for different applications
- Consideration of additional technologies
  - i.e. Fossil fuel

***Other Technologies***

***Output:*** Technology object

It enables the user to add any technology manually… (hard coded i.e. reading from an excel file)

# Energy System Design - Methodology




- ➢ Unpacks the input parameters from the netCDF file
- ➢ Pass each technology to FINE automatically
- ➢ Run the optimization
- ➢ Save the results of the optimization to the **netCDF** file with input parameters
  - ➢ Smaller file size
  - ➢ Easy for versioning (both input & output)

***Optimization Manager***
FINE

***Output:*** netCDF file with optimal system design

Connection between input generator and optimization manager is fully automated…



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# Energy System Design - Methodology

## Input Generator Modules

- Onshore simulation
- Pipeline builder
- Salt caverns
- Offshore simulation
- Hydrogen demand
- Other technologies
- PV simulation
- Electricity demand
- Input to NetCDF

netCDF (input)

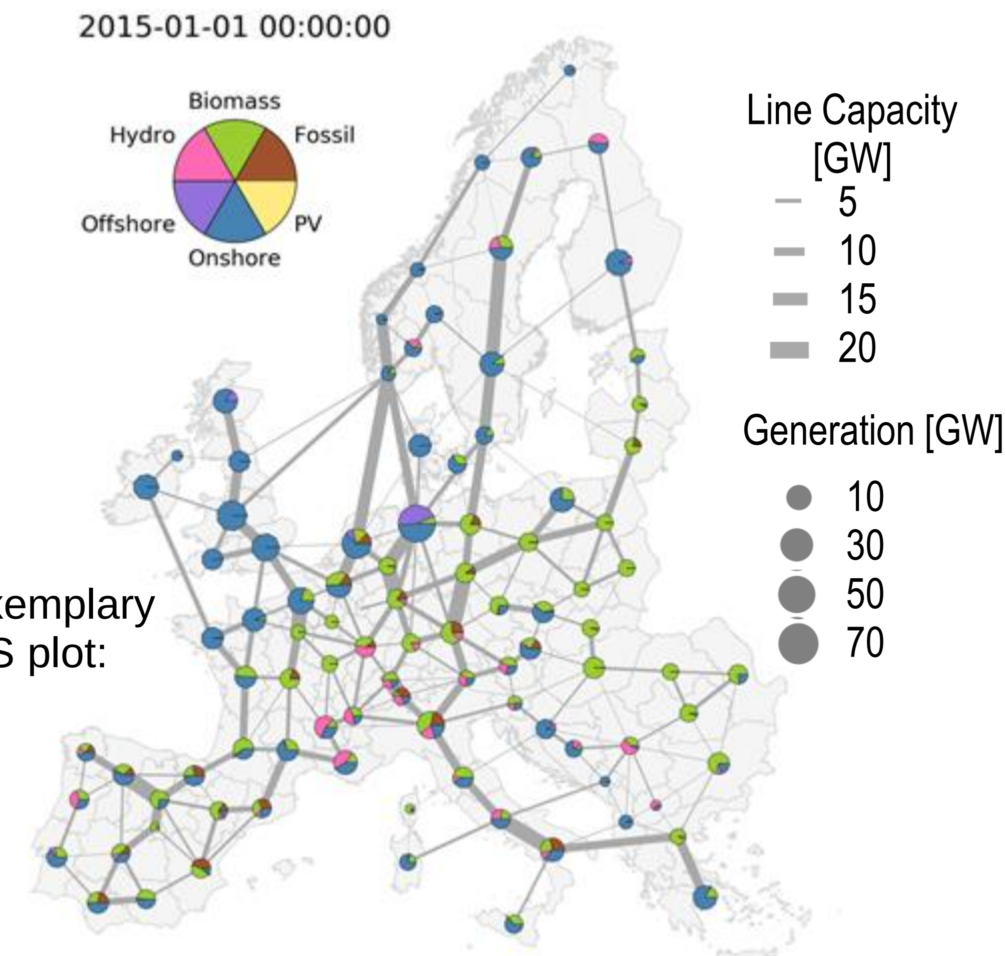
## Optimization Manager

- Unpack input netCDF
- Pass inputs to FINE

netCDF (input/output)

## Output Manager (Visualization)

An exemplary GIS plot:

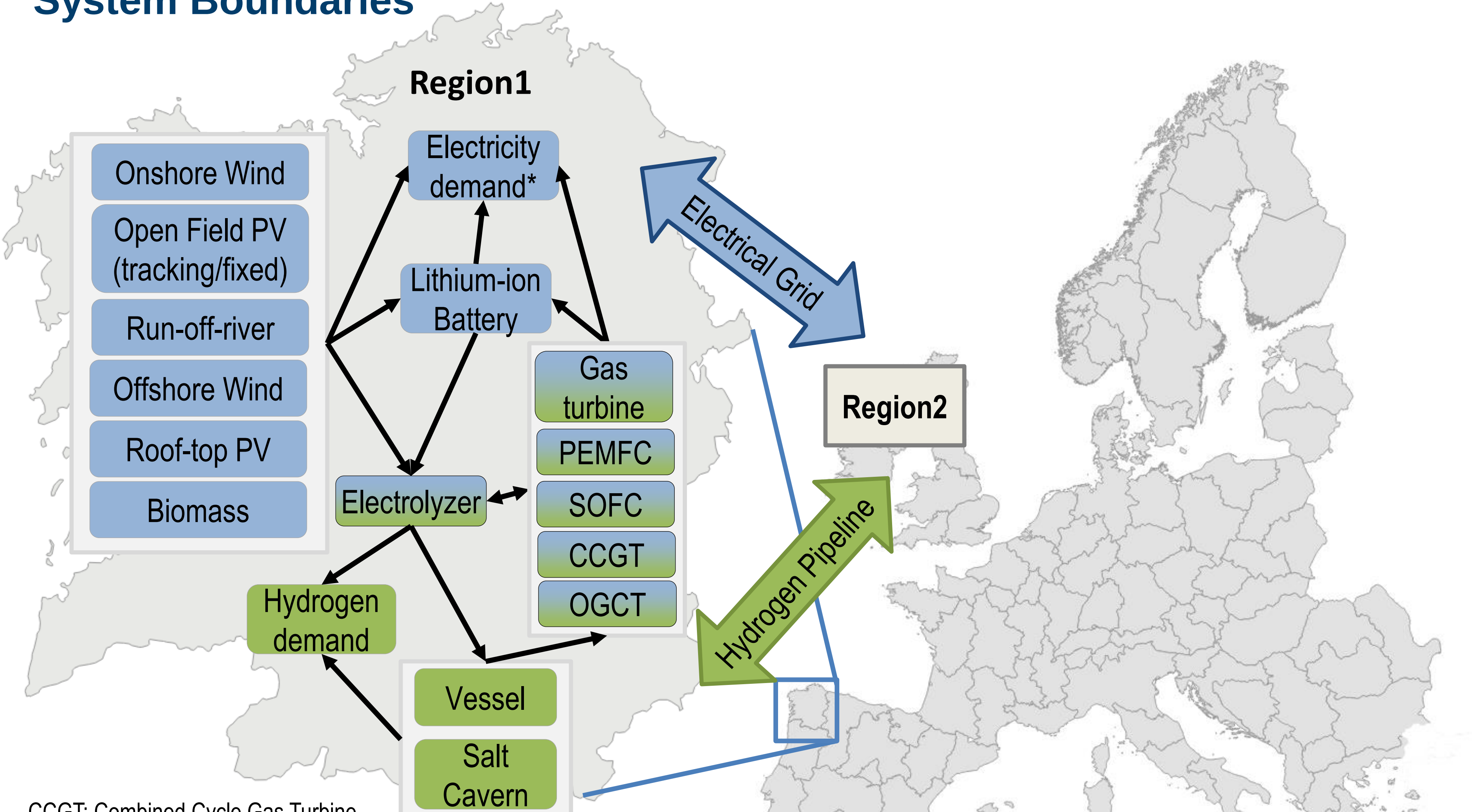



***Output Manager***

***Output:***
*Tables, figures of results of optimal system design*

# European Reference Scenario Definition & Results

# System Boundaries




CCGT: Combined Cycle Gas Turbine
OCGT: Open Cycle Gas Turbine
SOFC: Solix-Oxide Fuel Cell
PEMFC: PEM Fuel Cell
PV: Photovoltaics

*Electrified heat demand Is included

- Technology class
- Technology working with $H_2$
- Technology working with electricity
- Conversion ($H_2$ and electricity)

# Input Parameters – Techno-Economic Parameters

| | Investment [€/kW] | Fixed O&M | Variable O&M [€/MWh] | Lifetime [years] | Source |
|---|---|---|---|---|---|
| Onshore Wind | ~1100* | 2.0% Capex | 0 | 20 | [1] |
| Offshore Wind | ~2300* | 2.0% Capex | 0 | 25 | [1] |
| Open-field(FixedTilt) | 520 | 1.7% Capex | 0 | 25 | [1] |
| Open-field(Tracking) | 710 | 1.5% Capex | 0 | 25 | [1] |
| Rooftop PV | 880 | 2.0% Capex | 0 | 25 | [1] |
| Hydro(Run-of-river) | 5000 | 1.5% Capex | 5.0 | 60 | [1] |
| Biomass | 1700 | 91.3 | 11.3 | 30 | [2] |
| Lithium-ion battery | 151[€/kWh] | 0 | 151,000 | 22 | [3] |
| Vessel | 7.5 [€/kWh] | 2% Capex | 0 | 20 | [4] |
| Salt cavern | 0.363 [€/kWh] | 2% Capex | 0 | 30 | [4-5] |
| PEM Electrolyzer | 500 | 3% Capex | 0 | 10 | [5] |
| PEM Fuel Cell | 1126 | 0 | 9.15 | 10 | [5] |
| SOFC | 1830 | 2.44 €/kW | 0 | 10 | [5] |
| Gas Engine | 873 | 4.88 €/kW | 8.46 | 20 | [5] |
| OGCT | 615 | 6.19 €/kW | 9.13 | 25 | [5] |
| CCGT | 927 | 13.52 €/kW | 2.88 | 25 | [5] |
| Pipeline | 0.11702 | 5 €/m/a | 0 | 40 | [6] |

*** Turbine costs are for onshore and offshore baseline turbines, yet average cost of turbines changes in each region.**


[1]JRC (2014), “ETRI 2014 - Energy Technology Reference Indicator projections for 2010-2050,”.

[2] Schröder et al. (2013), “Current and Prospective Costs of Electricity Generation until 2050”.

[3] Elsner et al. (2015), “Energiespeicher Technologiesteckbrief zur Analyse „Flexibilitätskonzepte für die Stromversorgung 2050“.

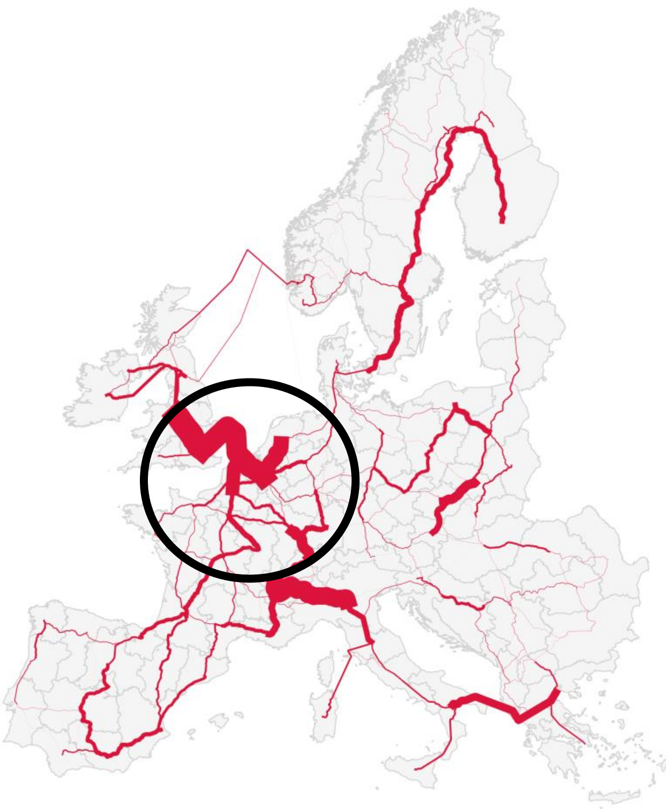
[4] Beccali et al. (2013) *Applied Energy*, vol. 102, pp. 534–544.

[5] Stolzenburg (2014), “Integration von Wind-Wasserstoff-Systemen in das Energiesystem,”.

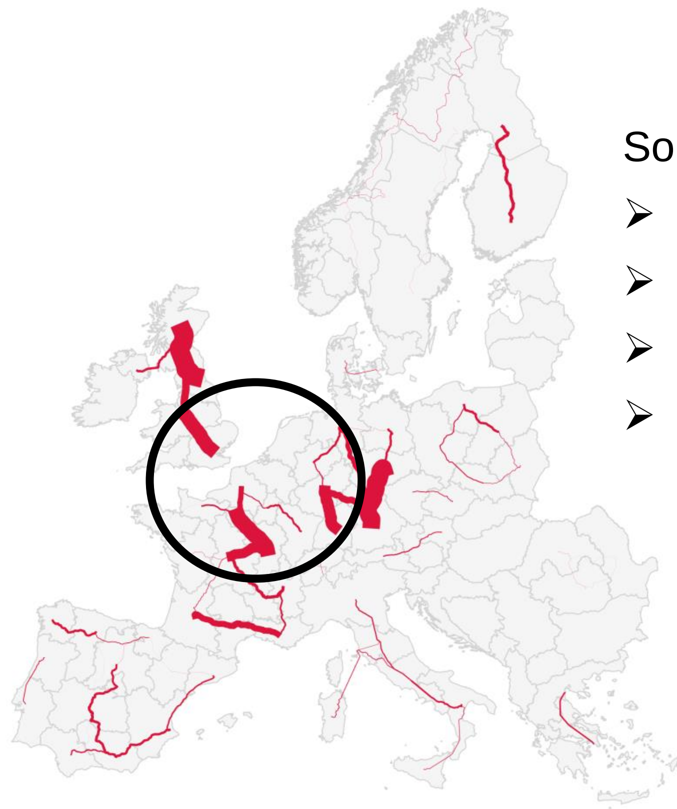
[6] Mischner (2011),"gas2energy.net : Systemplanung in der Gasversorgung ; gaswirtschaftliche Grundlagen," Edition gwf, Gas, Erdgas.

# European Scenario – Value of Pipeline Connections

Baseline (Fully Connected): All regions sharing a border can have pipeline connection
Disconnect Countries : Pipeline **cannot** be installed between two countries
Pipeline Disabled : Not allowing pipeline connections



Fully connected

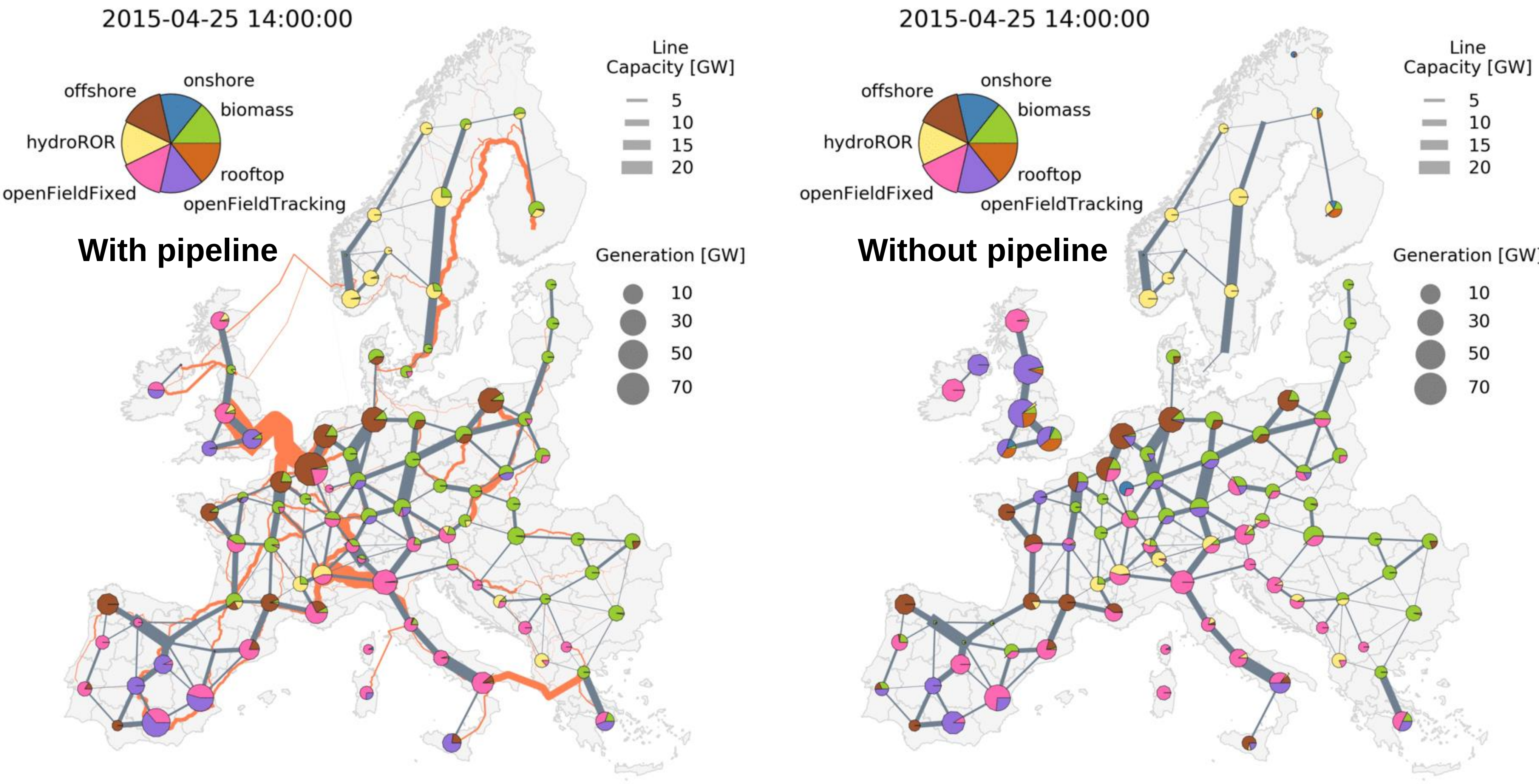


Disconnected countries

Some pipeline connections between:

- U.K and continental Europe
- France and Italy
- Greece and Italy
- All connections between Balkan countries…

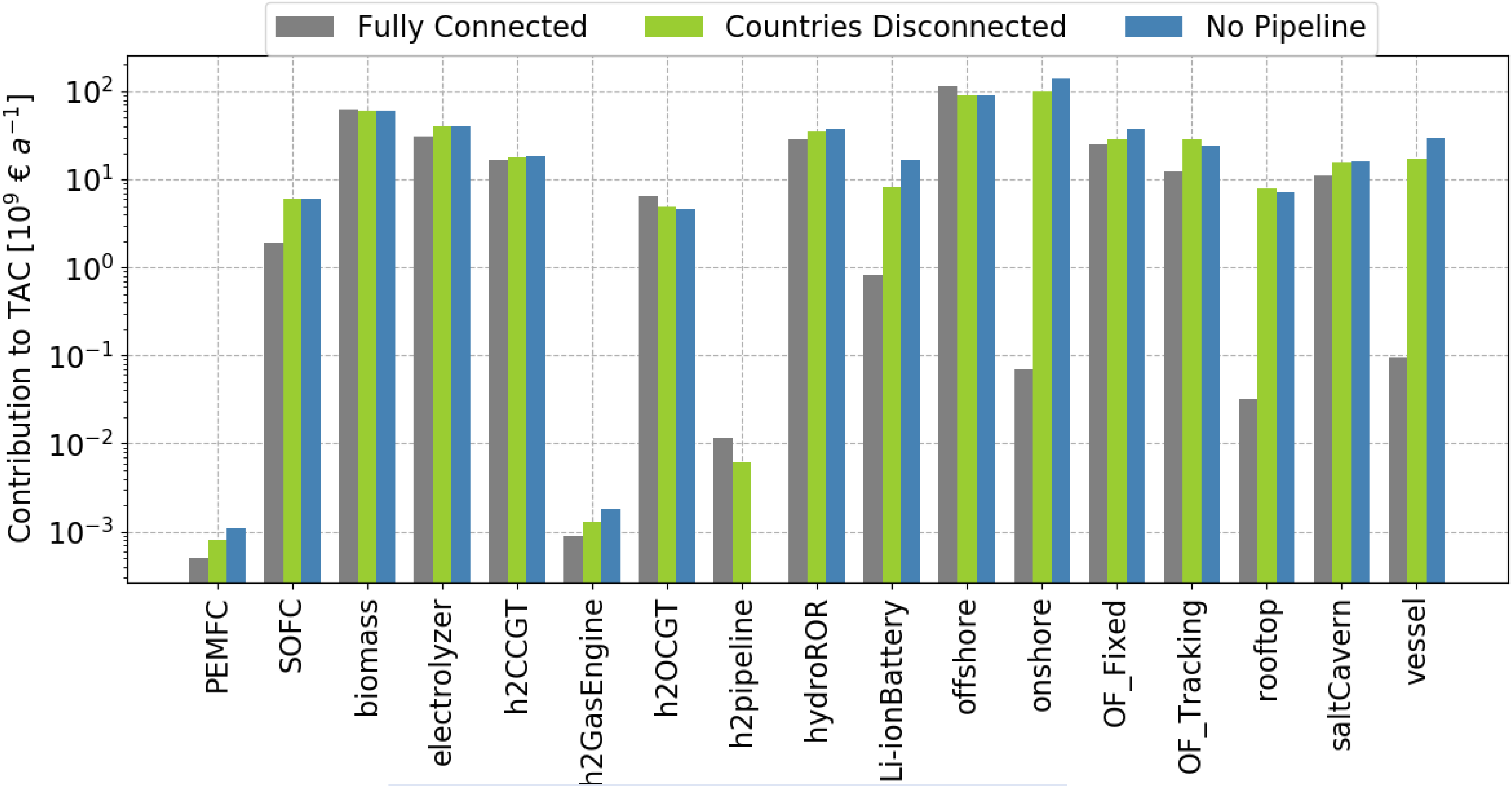
# European Scenario– Value of Pipeline Connections




**<u>Same</u>** input parameters and system configuration, **<u>only</u>** pipeline is disabled (30 typical days).

Pipeline
AC Cables } Line capacity applies for both of these technologies

# European Scenario– Value of Pipeline Connections



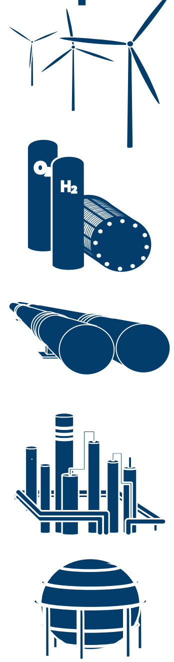

**Baseline (Fully Connected) : 311 Billion €/a**
**Disconnect Countries : 460 Billion €/a**
**Pipeline Disabled : 526 Billion €/a**

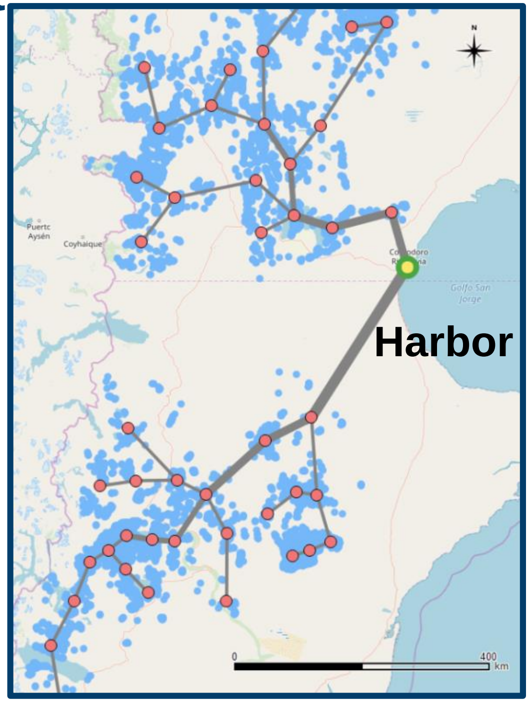
# Global Hydrogen Supply Pathways

# Worldwide Hydrogen Infrastructure – Methodology

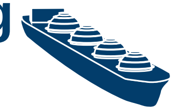
## 1 $H_2$ costs at port

- Wind & Solar energy
- Electrolysis
- Domestic pipeline
- Conversion ($LH_2$/LOHC)
- Buffer storage

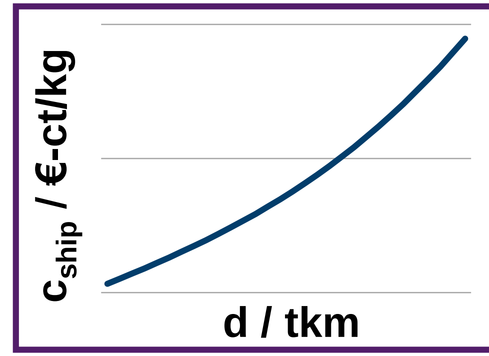





## 2 Shipping costs



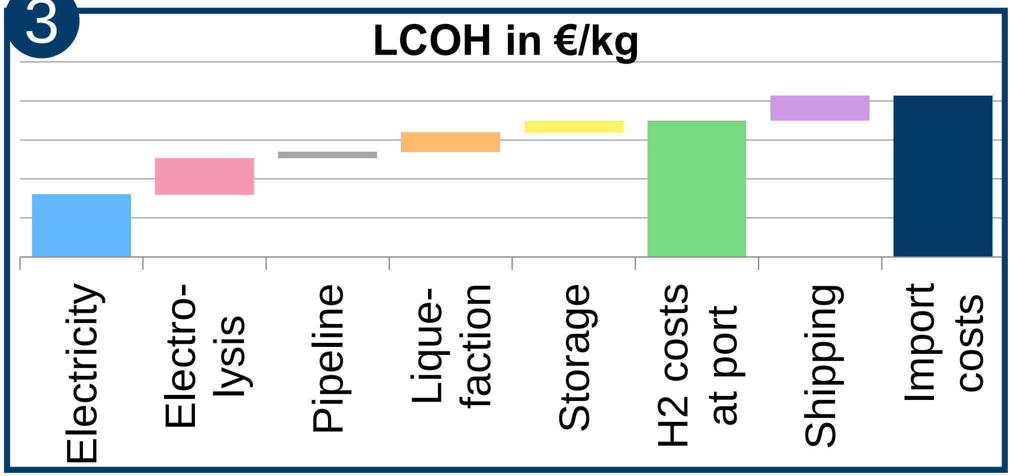
Depend on
- distance
- condition ($LH_2$, LOHC)
- propulsion mode ($H_2$, oil)




**For $LH_2$ carrier and $H_2$ propulsion:**

$c_{ship}(d) = 0.002\,d^3 + 0.01\,d^2 + 3.72\,d + 2.74$

## 3



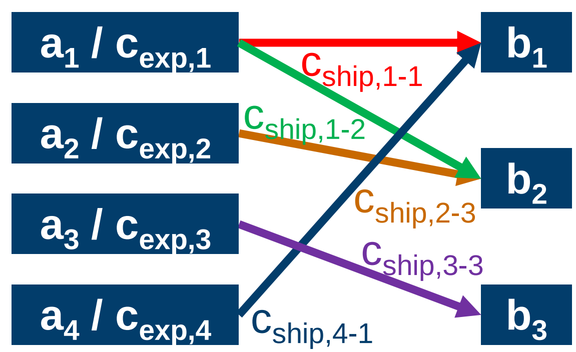

## 4 $H_2$ allocation → cover total demand

$x_{ij}$ : amount of hydrogen transported from $A_i$ to $B_j$

$c_{ij}$ : costs for $H_2$ unit from $A_i$ to $B_j$

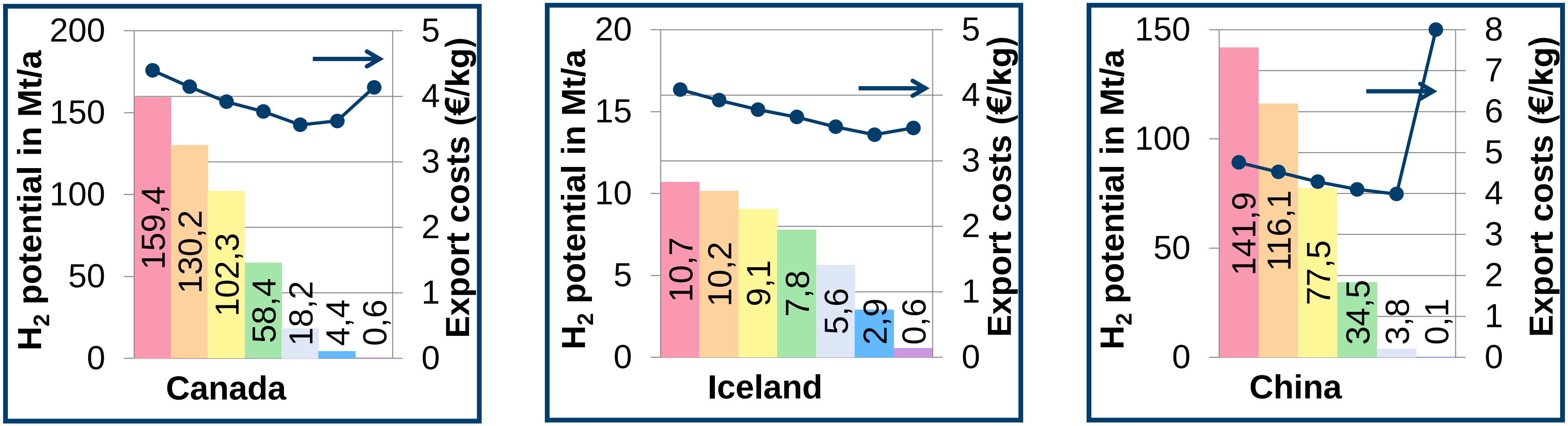
→ Minimize objective function z (global costs)

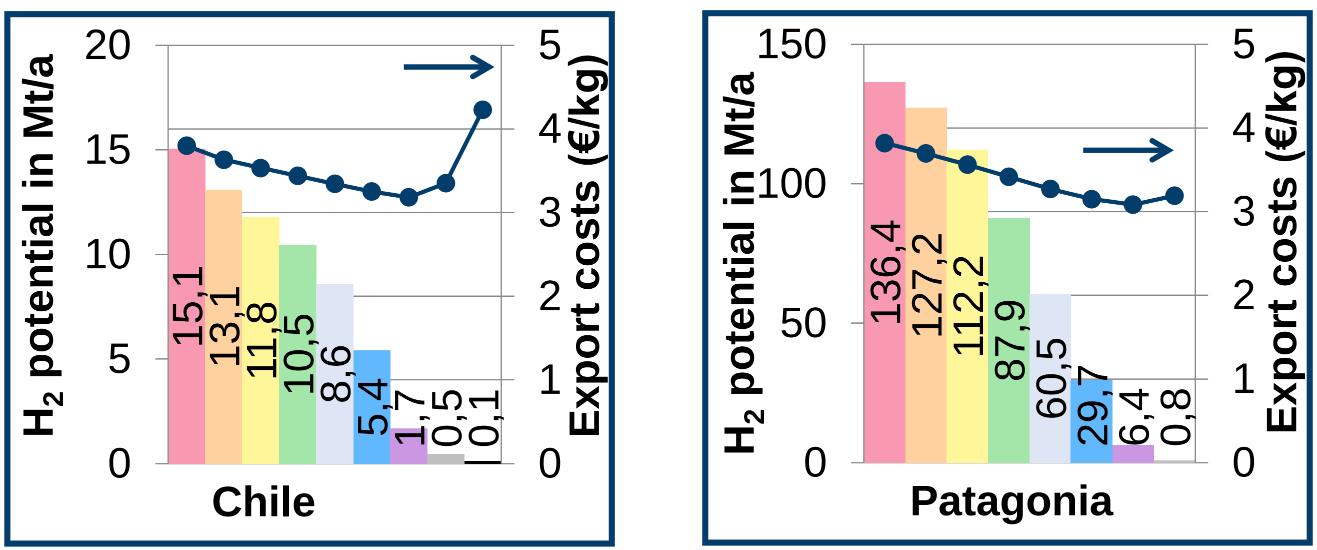
$$z = \sum_{i=1}^{m} \sum_{j=1}^{n} \left(c_{exp,i} + c_{trans,ij}\right) * x_{ij}$$

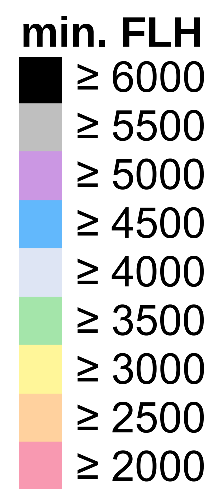



Constraints:
1. $\sum_{j=1}^{n} x_{ij} \leq a_i \;\; \forall i$
2. $\sum_{i=1}^{m} x_{ij} = b_j \; \forall j$
3. $x_{ij} \geq 0 \; \forall i \; \forall j$

# Worldwide $H_2$ Export Potential in Exemplary Strong Wind Countries (*)

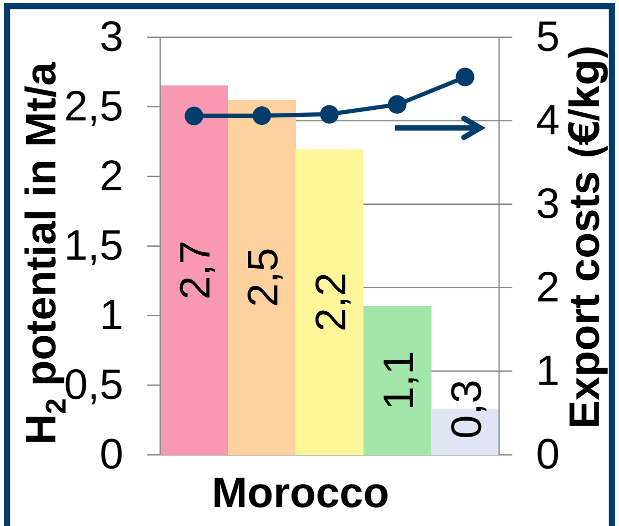


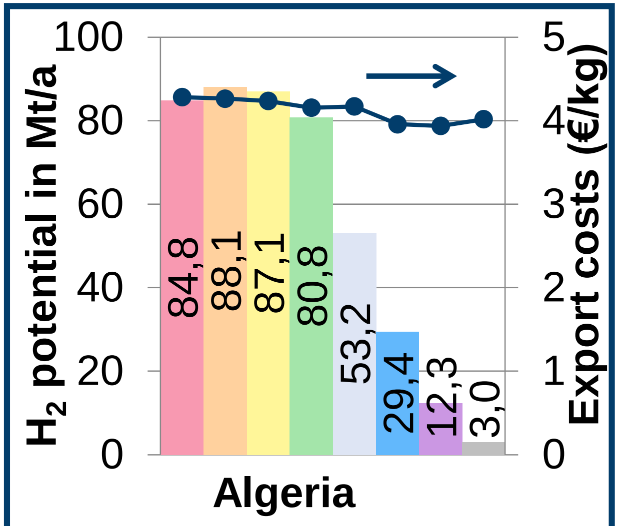



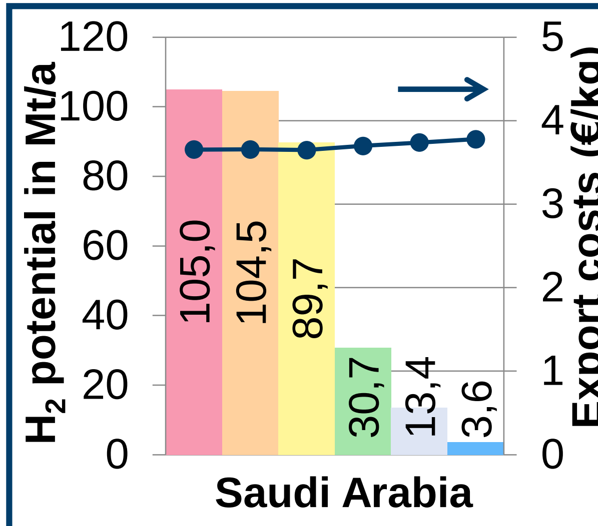



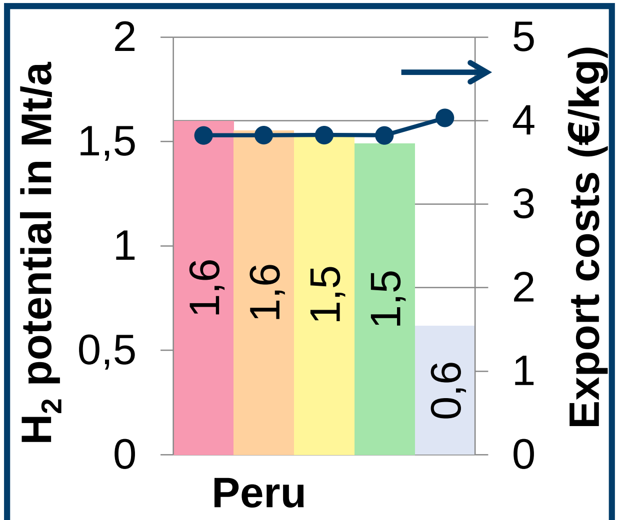

(*) Export costs excl. shipping costs

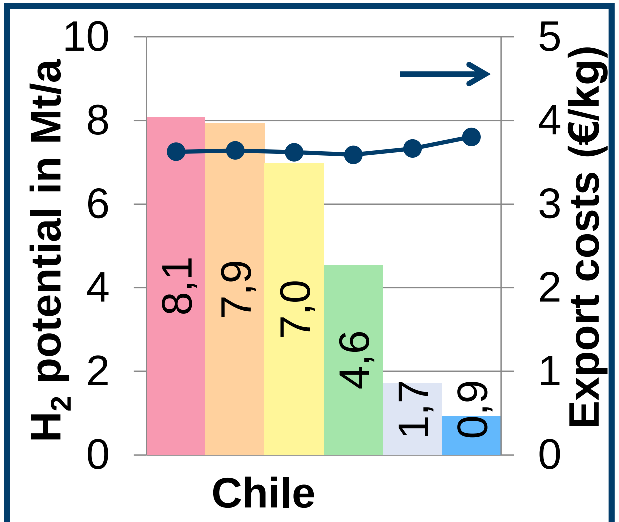
# Worldwide $H_2$ Export Potential in Exemplary High Insolation Countries (*)



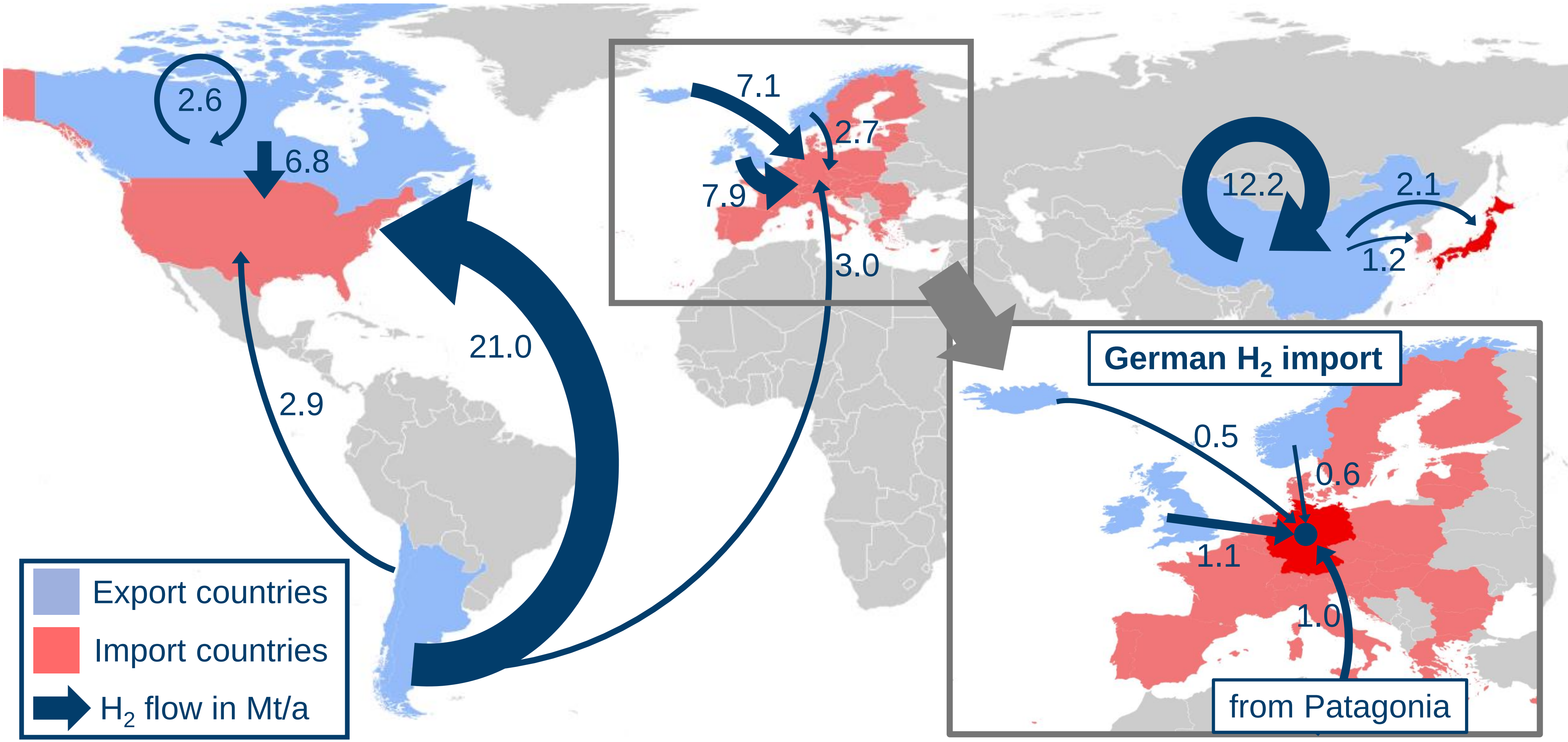

**Capacity expansion state**

- No. 8
- No. 7
- No. 6
- No. 5
- No. 4
- No. 3
- No. 2
- No. 1

Capacity expansion
=
Degree of potential utilization

(*) Export costs excl. shipping costs

# Worldwide $H_2$ Flow Allocation with Minimized Overall Costs (75% Scenario)




| | Germany | Japan | EU | USA | Canada | China | South Korea |
|---|---|---|---|---|---|---|---|
| **Demand in Mt/a (75% Scenario)** | 3.14 | 2.05 | 17.58 | 30.61 | 2.55 | 12.22 | 1.15 |
| **Import LCOH in €/kg (*)** | 4.66 | 4.81 | 4.67 | 4.34 | 4.66 | 4.71 | 4.77 |

(*) Import LCOH incl. shipping costs

# Thank you for your attention

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m.robinius@fz-juelich.de



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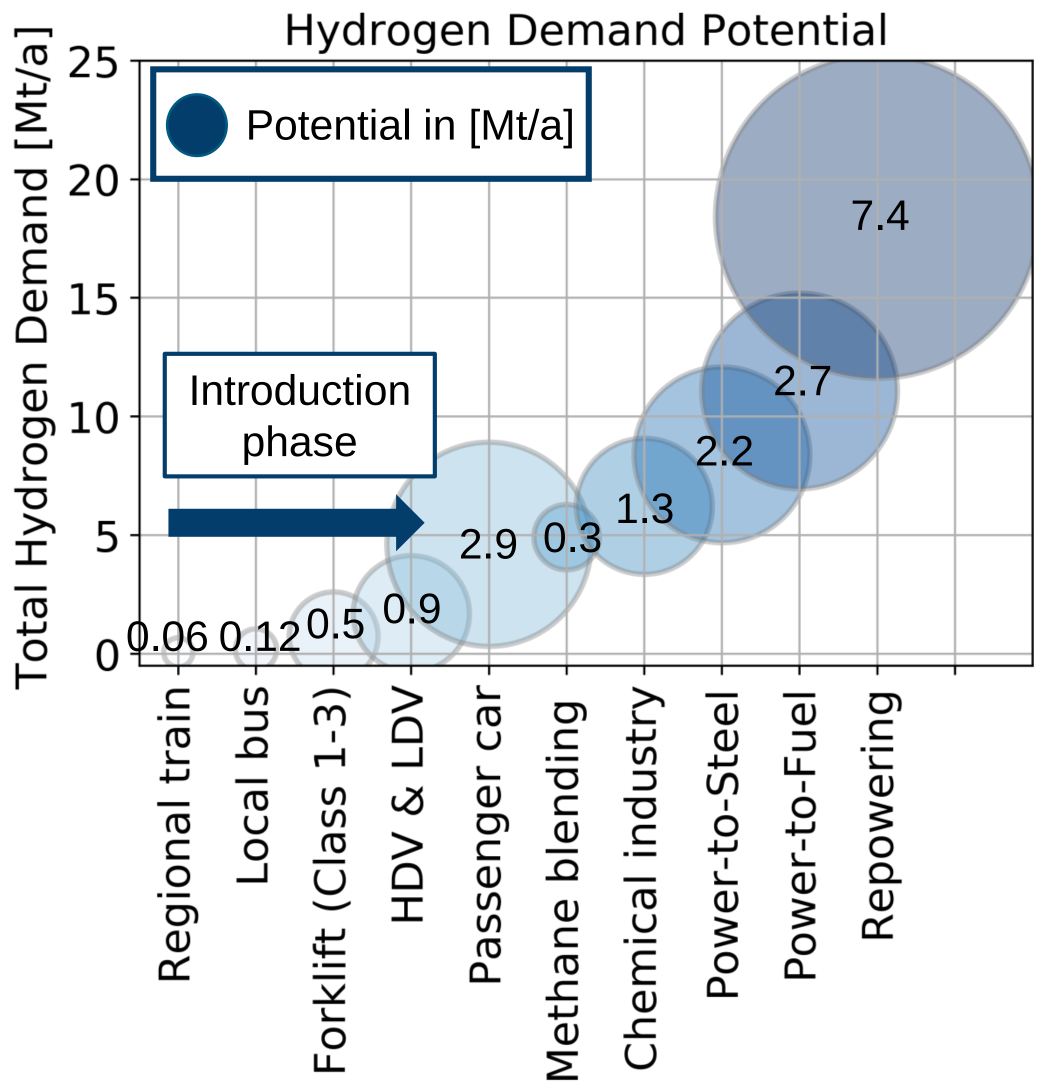
# Motivation

- **Hydrogen demand potential** assessment for various hydrogen applications in Germany
- Highest potential in the **introduction phase**:
  - Regional non-electrified **trains**
  - Local **busses**
  - **Forklifts** of the class 1 to 3
  - Heavy and light **duty vehicles**

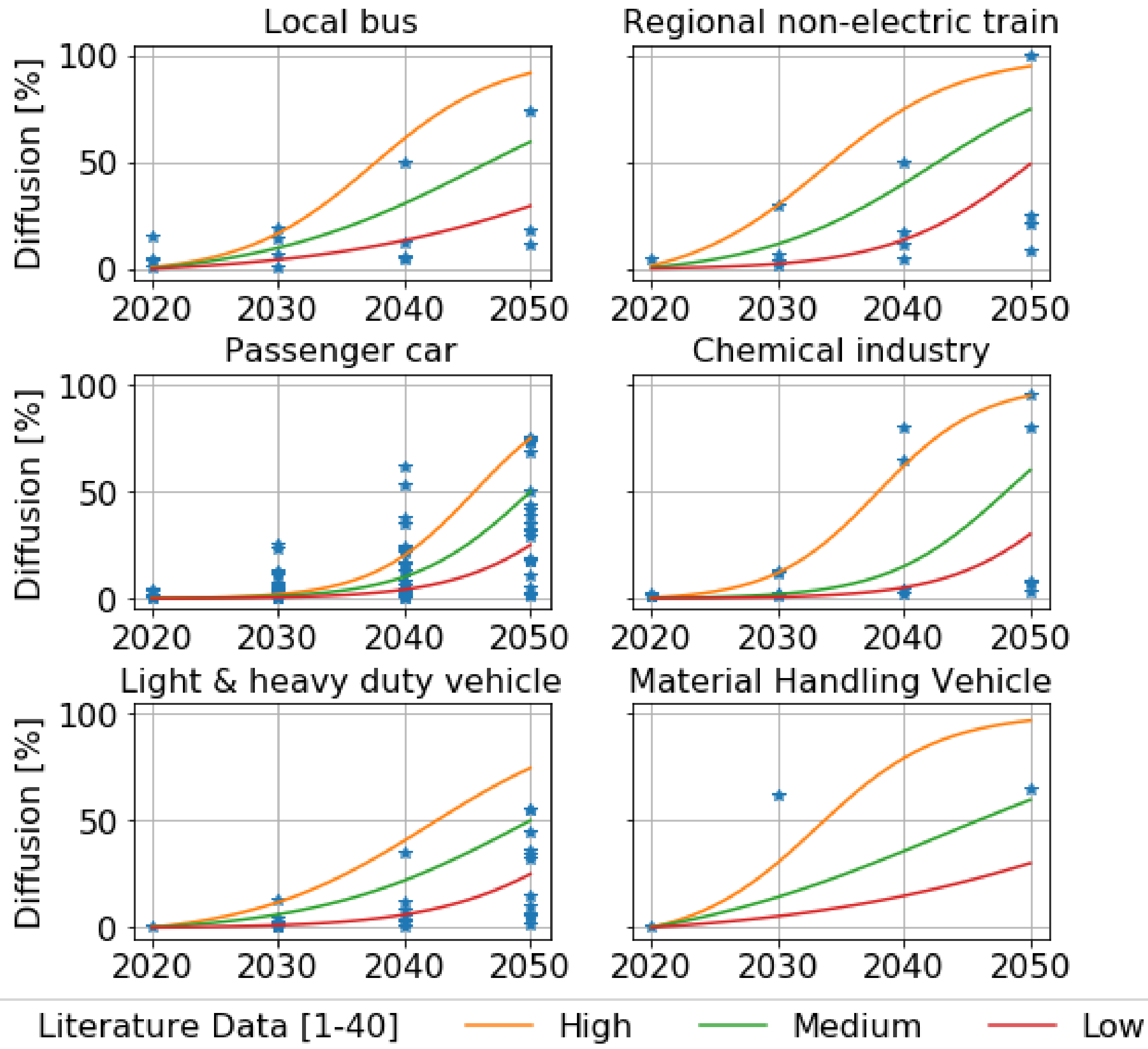
> ➢ **Vehicles with requirements for**:
> - high utilization
> - fast fueling
> - long range
> - high power capacity




Regional train: non-electrified lines only, HDV: Heavy Duty Vehicle, LDV: Light Duty Vehicle,
Chemical industry: Ammonia, Methanol, Petrochemical industry

# Market Penetration Scenarios

- **Scenario data** base for key technologies and application fields in the introductory phase
- Formulation of **exploratory** scenarios to analyse how hydrogen infrastructure cost might unfold
- Formulation of **high**, **medium** and **low diffusion scenarios** for each hydrogen application depending on level of:
  - political support
  - economic incentives
  - technological progress
  - technology acceptance
  - willingness to pay for emission free applications




Regional train: non-electrified lines only, HDV: Heavy Duty Vehicle, LDV: Light Duty Vehicle,
MHV: Material Handling Vehicle (Forklift Class 1-3), Chemical industry: Ammonia, Methanol, Petrochemical industry

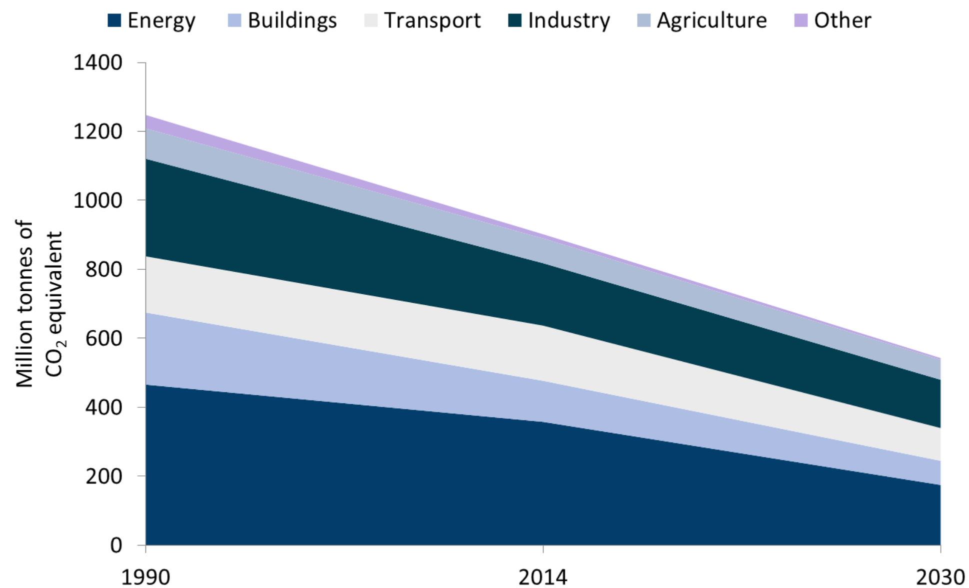
# Climate Action Plan Germany

## Climate Action Plan 2050 [1]:

| | 1990 MT$CO_2$ Eq. | 2014 MT$CO_2$ Eq. | 2014 vs. 1990 | Goals 2030 MT$CO_2$ Eq. | Goals 2030 vs. 1990 |
|---|---|---|---|---|---|
| Germany | 1248 | 902 | - 27.7% | 543- 562 | 55-56% |

## Goals for 2030 (reference 1990) :

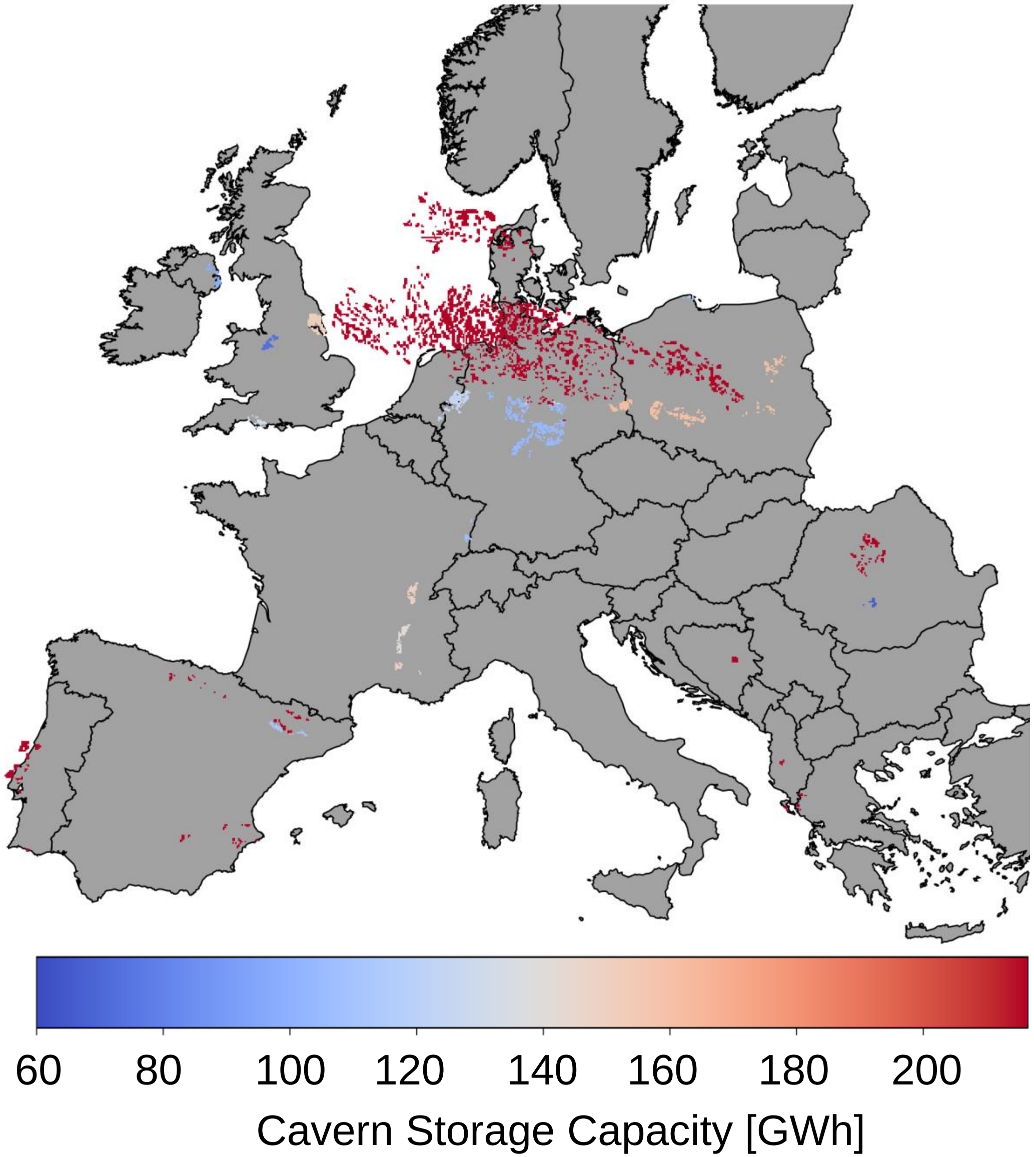
- **Energy**:
  GHG - 61-62% | 175-183 MT$CO_2$ Eq.
- **Transport:**
  GHG - 40-42% | 95-98 MT$CO_2$ Eq.
- **Industry:**
  GHG - 49-51% | 140-143 MT$CO_2$ Eq.
- **Buildings:**
  GHG - 66-67% | 70-72 MT$CO_2$ Eq.
- **Agriculture:**
  GHG - 31-34% | 58-61 MT$CO_2$ Eq.

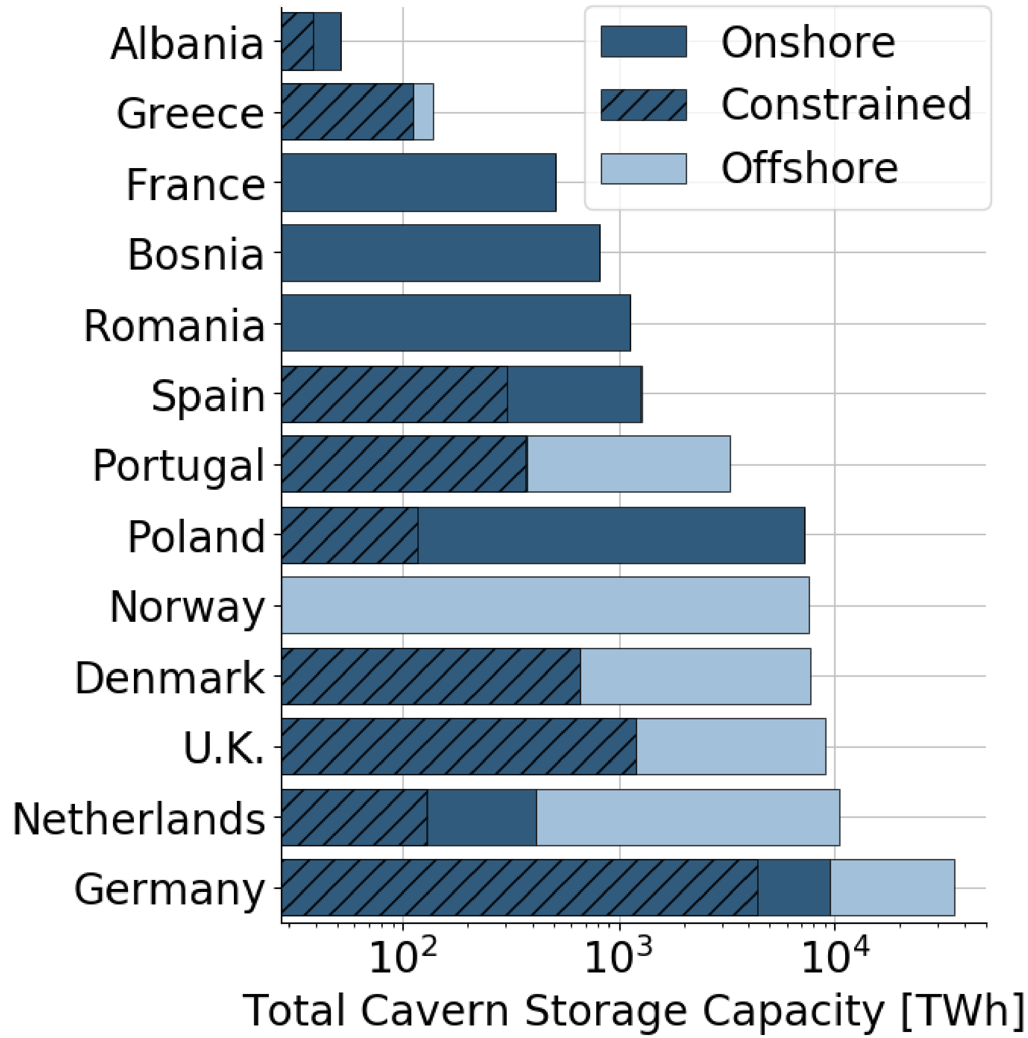



*Emissions from areas based on Climate Action Plan 2050 [1]*

[1] Climate Action Plan 2050; Federal Gouvernement

# Technical Potential of Salt Caverns




**Onshore: 23.2 PWh (7.3 PWh Constrained)**
**Offshore: 61.8 PWh**

**Paper will be submitted to Energy and Environmental Science**