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Decarbonizing the Industry Sector and its Effect on Electricity Transmission Grid Operation - Implications from a Model Based Analysis for Germany

21st September 2022

Agenda

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Research shows that green hydrogen production of electrolyzer capacity planned for Germany in 2030 imputes increased electricity demand

- Green Hydrogen electrolysis is considered a promising technology in providing low-carbon fuels and feedstock to decarbonize the industry sector
  - German Legislation plans to expand Electrolyzer Capacities up to **10 GW** until 2030
  - Production will need an additional electricity demand of approximately **28 TWh**
- Research shows, the additional load by electrolyzers pose a large impact on the transmission grid operation
- Recent studies focus on electrolyzer distribution near renewable power production sites
  - Recommendations towards either a near-supply or near-demand distribution is not possible
- **Evaluating the effects of a near-demand green hydrogen production on transmission grid operation seems necessary**

Agenda

Methodology: Use of a two-stage Market- and Gridmodelling

Market Results	Load Flow
Market Model *Optimization of Day-Ahead market clearing with zonal trading capacitites*	**Redispatch-Model** *Simulation of congestion management considering transmission grid restrictions*

Methodology: Use of a two-stage Market- and Gridmodelling

Market Results

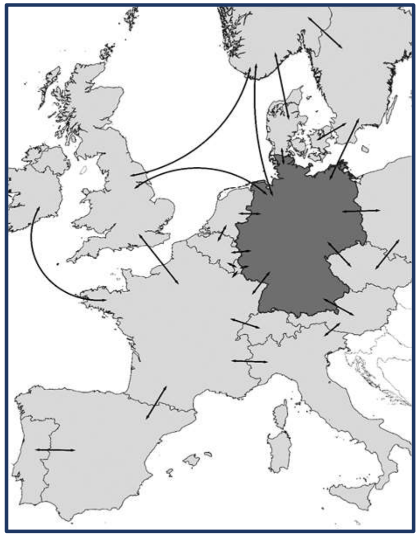
Load Flow

Market Model
Optimization of Day-Ahead market clearing with zonal trading capacitites

Redispatch-Model
Simulation of congestion management considering transmission grid restrictions

- *Generation Capacity*
- *RES time series*
- *Fuel prices*
- *CO_2 prices*
- *Variable costs*
- *Electricity Demand*
- *NTC-capacities*
- ***Electrolyzer Capacities***

Model Input



$$min \sum_{p,t} G(p,t) * cost(p)$$

$$s.t. \sum_{p} G(p,t) - \sum_{n} dem(n,t) = 0$$

$$pmax(p) * avail(p,t) \leq G(p,t)$$

Basic formulation of the optimization problem

- *Electicity Prices*
- ***Plant Dispatch***
- ***Electrolyzer Dispatch***
- *CO_2 – Emission*

Model Output

Methodology: Use of a two-stage Market- and Gridmodelling

Market Results

Load Flow

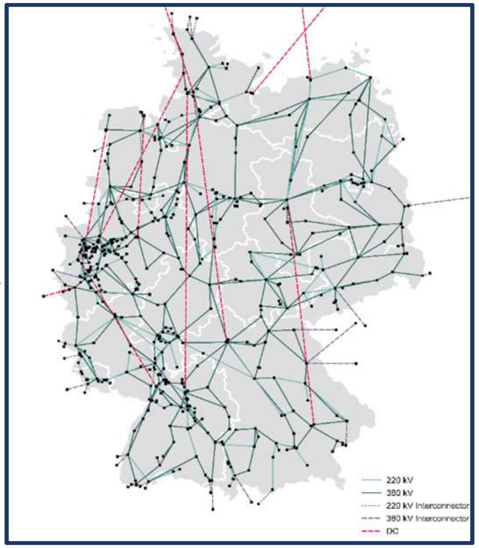
Market Model
Optimization of Day-Ahead market clearing with zonal trading capacitites

Redispatch-Model
Simulation of congestion management considering transmission grid restrictions

Fixed Dispatch

- *Grid Topology Graph*
- *Transmission Line Capacities*
- *Nodal Electricity Demand*
- *Electricity Demand*
- ***Electrolyzer Capacity Distribution***

Model Input



$$min \sum_{p,t} (RDup(p,t) - RDdown(p,t)) * cost(p)$$

$$s.t. \sum_{p,n} g\_da + RDup(p,t) - RDdown(p,t)) - dem(n,t) - NetI(n,t) = 0$$

$$g_{da(p,t)} + RDup(p,t) \leq pmax(p) * avail(p,t)$$

$$RDdown(p,t) \leq g\_da(p,t)$$

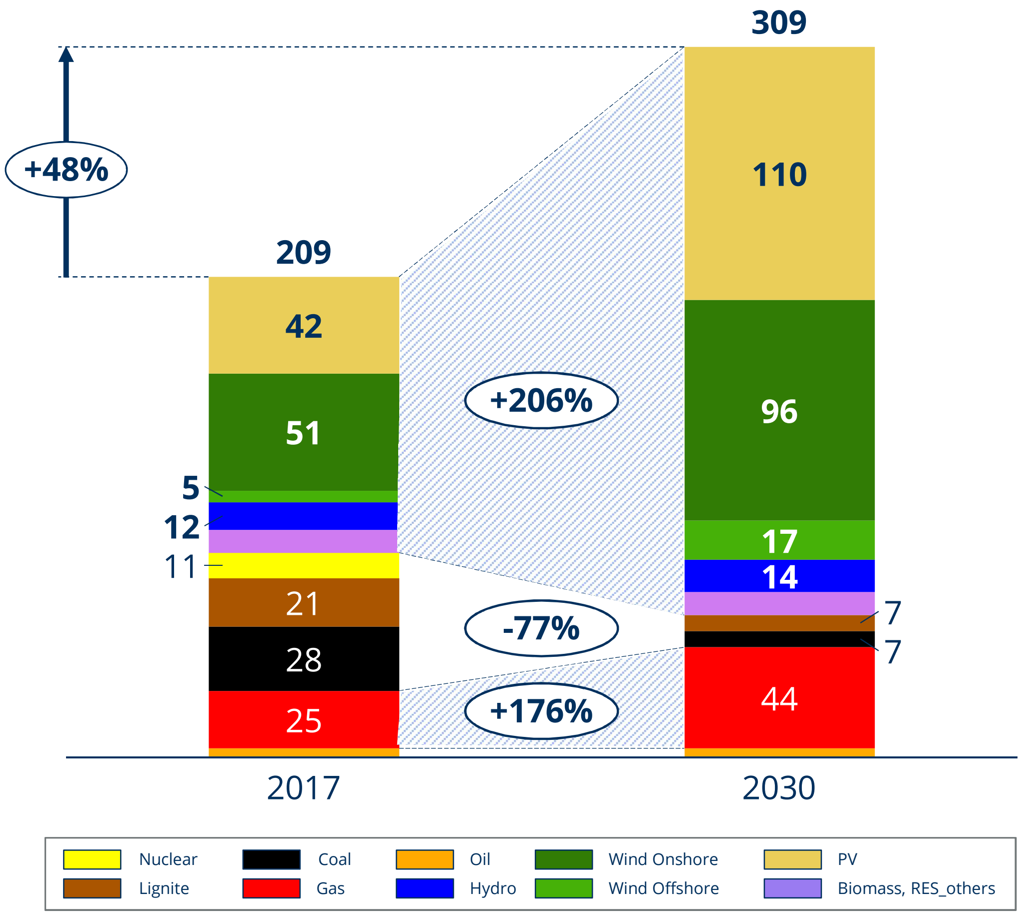
Basic formulation of the optimization problem

- *Lineflow*
- *Line Congestions*
- ***Redispatch (Plants & EL)***
- ***RES Curtailment***

Model Output

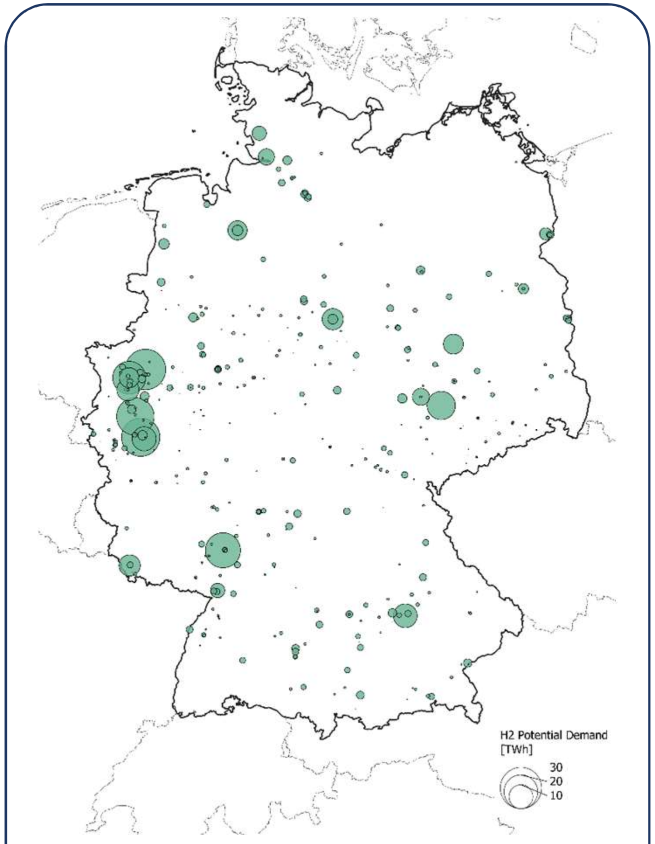
Agenda

Underlying input data towards the target year 2030 is based on TYNDP2020



- RES Capacities almost doubled
- No Nuclear power, highly reduced Lignite and coal capacities
- Additional gas-fired power plant capacities are spatially assigned to nodes where coal, lignite and nuclear power is phased out to compensate for the loss of flexible generation capacitites
- Fuel prices, CO_2 prices, NTC‘s and the generation capacities of other countries are taken from ENTSOE TYNDP 2020 scenario *„Distributed Energy“*
- Transmission Grid expansion is taken from NEP2030 and TYNDP2020

The scenario framework is based on specific hydrogen demand for industry processes



H_2 Potential Demand

- The order in which the industry sector is decarbonized affects the regional distribution electrolyzer capacities
- H_2 demand is taken from a study by Neuwirth et al. (2022)*

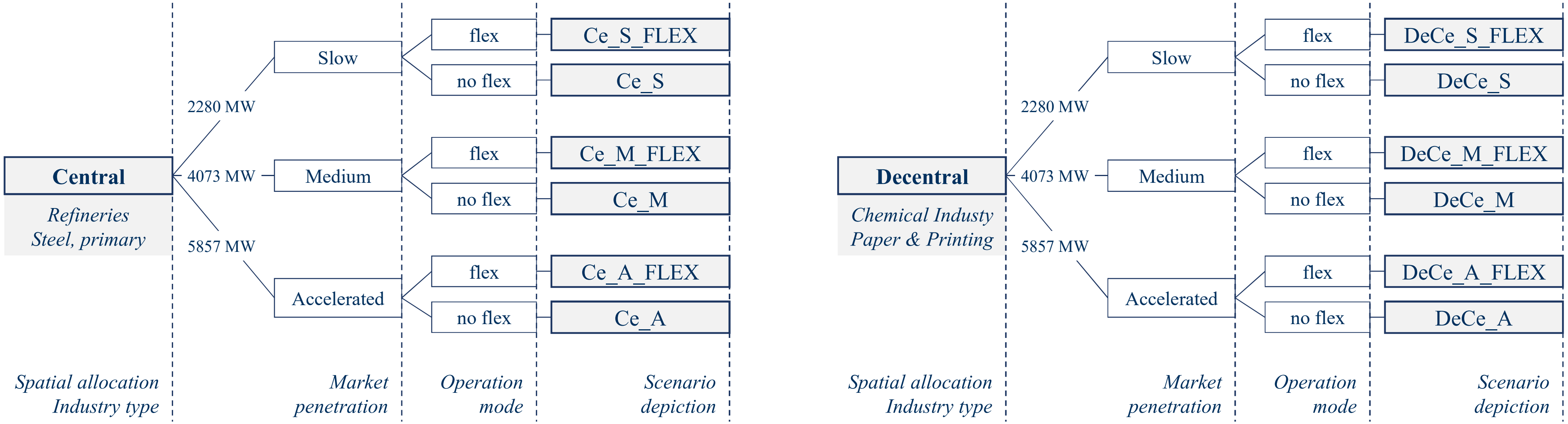
Industry Sector	Potential H_2 Demand [TWh]	No. of Sites	TRL**	Regional Distribution
Refineries	22.6	16	8-9	Central
Chemical Industry	161.0	30	8-9	Decentral
Paper and Printing	30.5	162	8-9	Decentral
Non-metallic Minerals	8.3	46	4-5	Decentral
Mineral Processing	30.7	84	4-5	Decentral
Metal Processing	18.0	30	4-5	Decentral
Non-ferrous metals	3.7	4	4-5	Central
Steel, primary	52.2	8	7-8	Central

* Neuwirth, M., Fleiter, T., Manz, P., Hofmann, R., 2022. The future potential hydrogen demand in energy-intensive industries - a sitespecific approach applied to germany. Energy Conversion and Management 252. doi:10.1016/j.enconman.2021.115052.

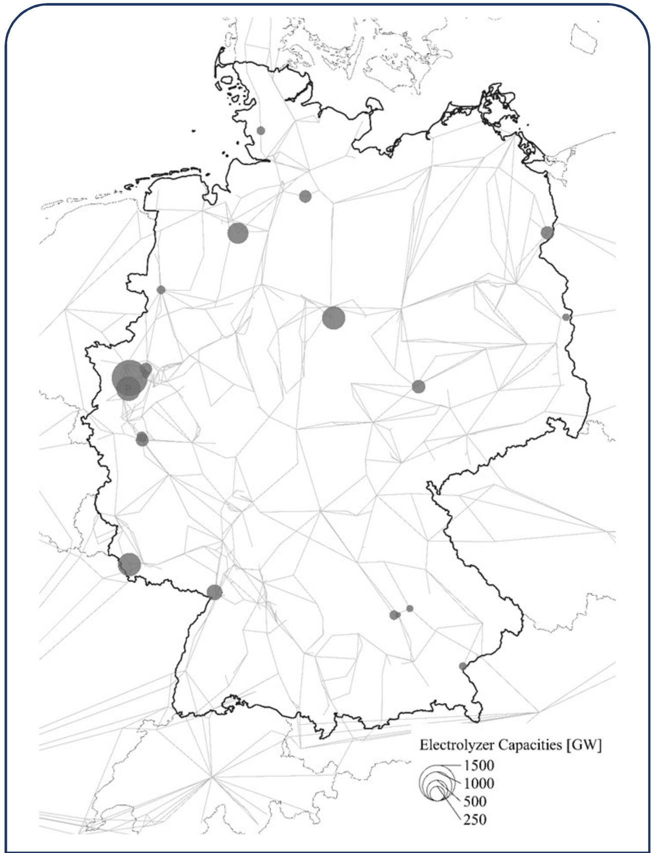
** Technology Readiness Level: Describes the technological maturity for short- and medium-term implementation of hydrogen

12 different scenario cases regarding spatial distribution of electrolyzer capacities and their operation mode are considered

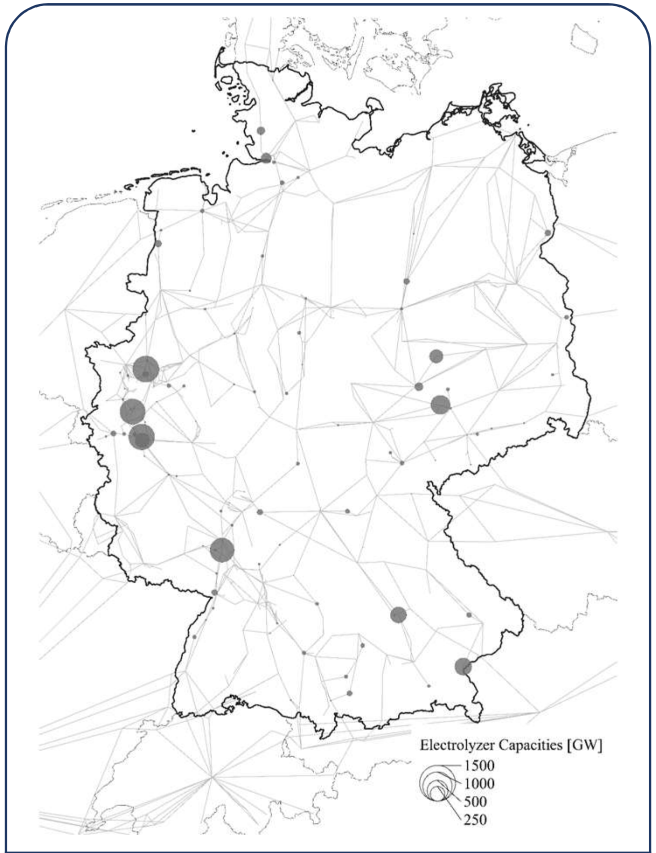
1. Considering only industries with high TRL (*Refineries*, *Chemical Industry*, *Paper & Printing* and *Primary Steel*)
2. Distinguish between a *centralized* and *decentralized* spatial allocation
3. Assuming a *slow*, *medium* and *accelerated* market penetration of electrolyzer capacities
4. Considering two different modes of electrolyzer operation



Spatial distribution of electrolyzer capacities forms additional input for the grid model



Distribution of EL capacities (***central***)



Distribution of EL capacities (***decentral***)

- Assignment of electrolyzer capacities to grid nodes is essential to determine effects on congestion management
- Centralized distribution (24 sites) concentrates electrolyzer capacities in Western and Northern Germany
- Decentralized distribution (192 sites) of electrolyzer capacities is more widespread with centres in West, East and South Germany
- Sensitivity of electrolyzer impact is reflected through different capacity volumes

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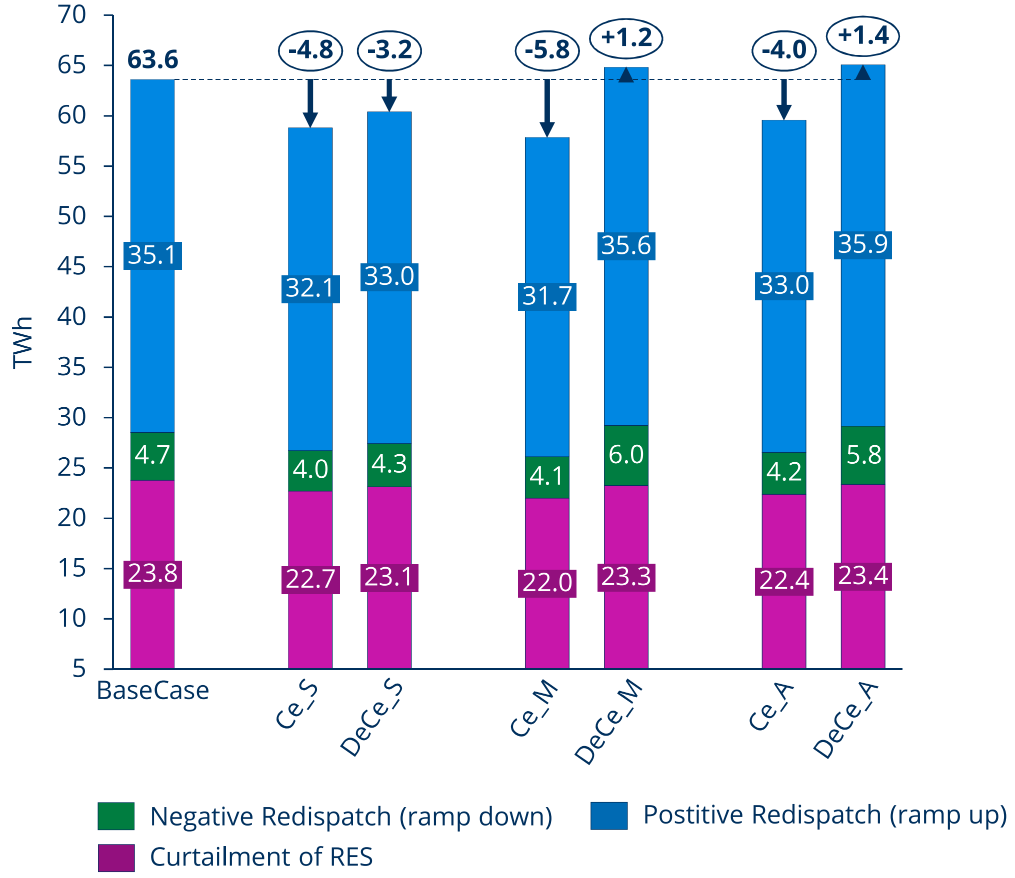
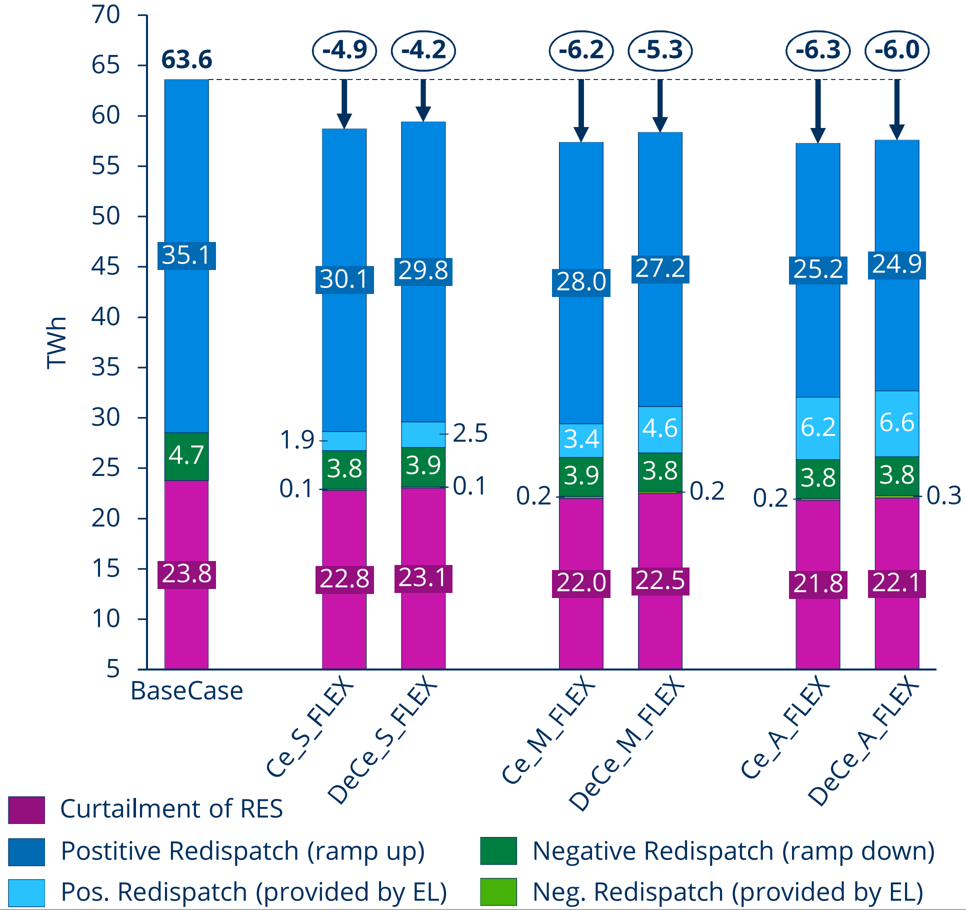
Aggregated Results (*no_flex*): Electrolyzer distribution in the central scenario causes no additional increase in congestion management volumes



- Varying effects of electrolyzer operation on the transmission grid can be observed in every scenario compared to a benchmark base case
- Congestion management volume increases in a decentral distribution (chemical industry, paper & printing) with increasing penetration levels
- Congestion management volumes stay below the base case volumes in the central scenarios (chemical industry, primary steel)
- Reduced curtailment volumes can be observed in every scenario

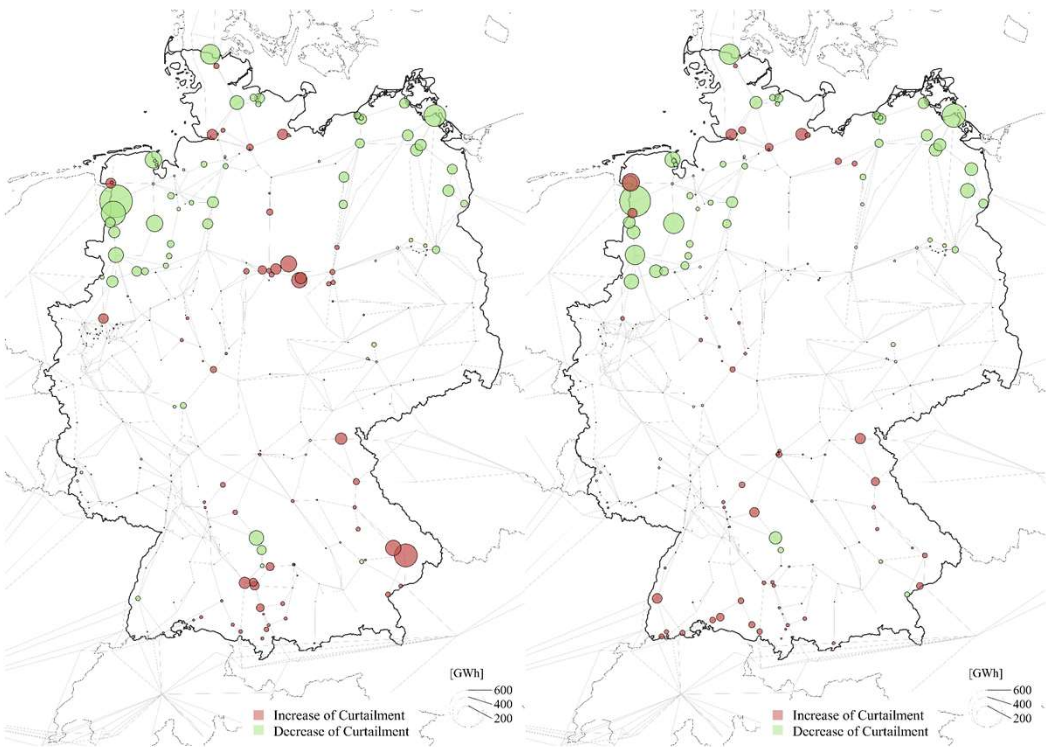
Aggregated Results (*flex*): Electrolyzer capacities contribute significantly to grid relief by providing a flexible load capacity



- Mitigation effects of electrolyzer operation on the transmission grid can be observed in every scenario compared to a benchmark base case
- Congestion management volume decreases in proportion to the market penetration of electrolyzer capacities
- Difference between the scenarios regarding their spatial distribution (central vs. decentral) varies only by small margin
- Electrolyzer redispatch increasingly replaces redispatch provided by conventional power stations
- Reduced curtailment volume observed in every scenario

Regional Results (*centralized*): Flexible operation of electrolyzers mitigate the increase in curtailment volumes

Increase/decrase of **Curtailment** in the **centralized** Scenarios

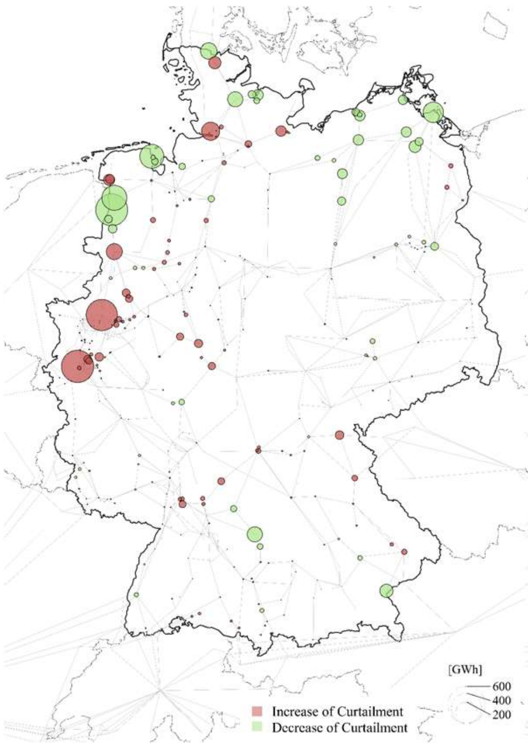


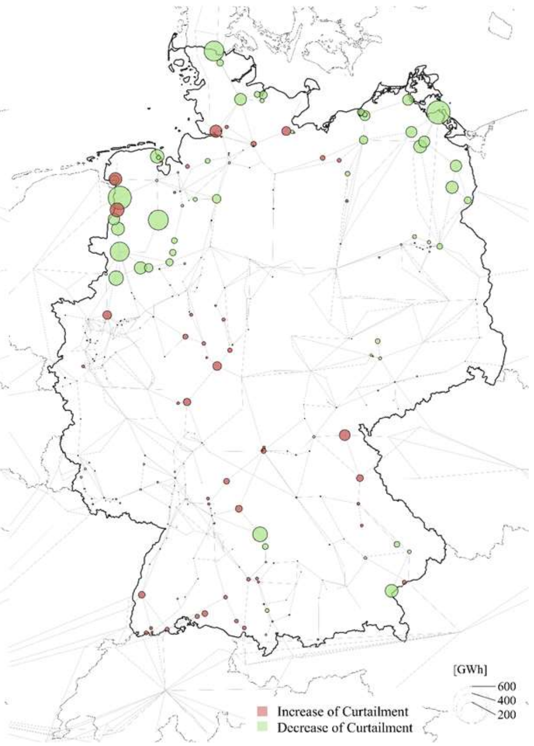
No flexibility of electrolyzers | With flexibility of electrolyzers

- Distribution of electrolyzer capacities coincides with regions of large curtailment
- Electrolyzer operation decreases curtailment volumes especially in North-West Germany considering both modes of operation
- Increase of curtailment in Central and South Germany in a scenario with no flexibility of electrolyzer
  - ➢ Additional load from electrolyzers exerts stress on transmission grid lines in certain regions
  - ➢ Effect can be counterbalanced if electrolyzers are dispatched for congestion management

Regional Results (*decentralized*): Electrolyzer distribution in the decentral scenario risks integration of RES feed-in along critical corridors

Increase/decrase of **Curtailment** in the **decentralized** Scenarios





No flexibility of electrolyzers | With flexibility of electrolyzers

- Distribution of electrolyzer share a great proximity with electricity load centres in West and South Germany
- Curtailment increase significantly at two nodes in West Germany
- Electrolyzer operation in the decentral scenario creates additional bottlenecks at the north-to-south corridor
  - Integrating large volumes of RES feed-in is compromised
- Bottlenecks can be avoided if a flexible operation is assumed

Conclusion: Near-site production of green hydrogen at locations with refineries and steel production should be prioritized

- Integrating increasing amounts of electrolyzer capacities poses **particular challenges** for transmission system operators
- Renewable energy integration can **benefit** from electrolyzer operation depending on the geographic distribution
  - ➢ Total congestion volumes can be reduced if electrolyzer capacities are installed at locations with **refineries** and **steel production facilities** regardless of the operation mode
  - ➢ Operation of electrolyzer capacities at **chemical industry** and **paper & printing** facilities additionally stresses transmission grid lines

Conclusion: Electrolyzer capacities have to be considered a flexibility option when designing future congestion management frameworks

- A **regulatory framework** how electrolyzers can be integrated into ancillary services is needed especially when industries are spatially decentralized
- Regulations must enable owners to participate in grid management
- **Incentives** for participation in congestion management have to be considered in future frameworks, involving some opportunity costs for electrolyzer owners
  - ➢ Future research should investigate potential design options for congestion management frameworks and incentive mechanisms for electrolyzer owners

A wide field of research opportunities opens regarding congestion management

- Conducted research at the chair of Energy Economics looking into to the effects of electrolyzer operation on transmission grid operation:

1. ***Decarbonizing the Industry Sector and its Effect on Electricity Transmission Grid Operation – Implications from a Model Based Analysis for Germany***
   - Working paper: https://www.econstor.eu/handle/10419/261839

2. ***Impact of hydrogen deployment scenarios on the economic efficiency of electricity transmission system operation: A model-based case study for the German market area***
   - Working paper: https://www.econstor.eu/handle/10419/262112

Thank you for your attention

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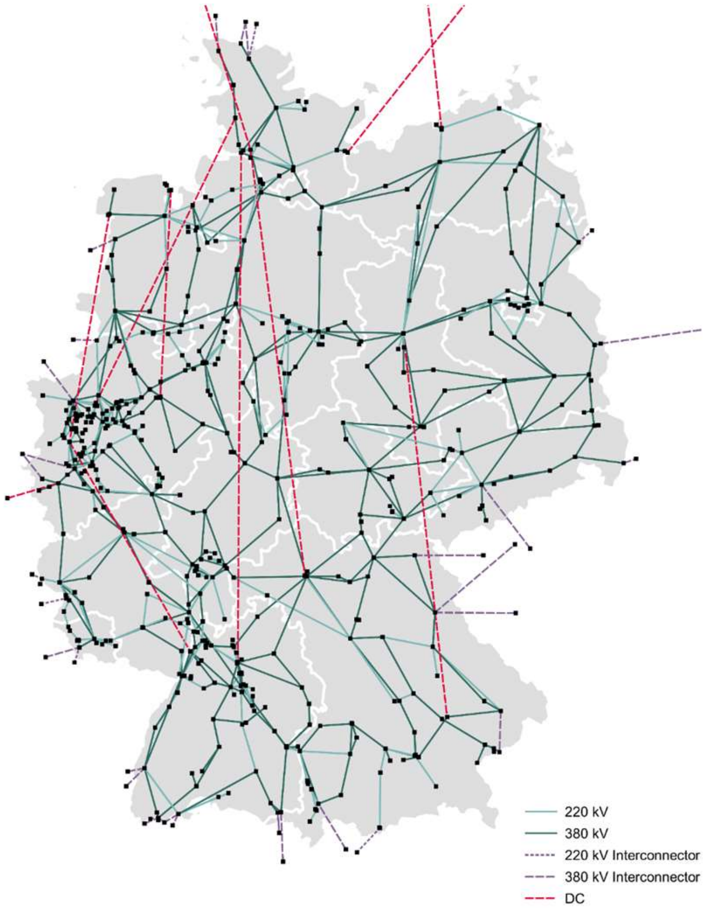
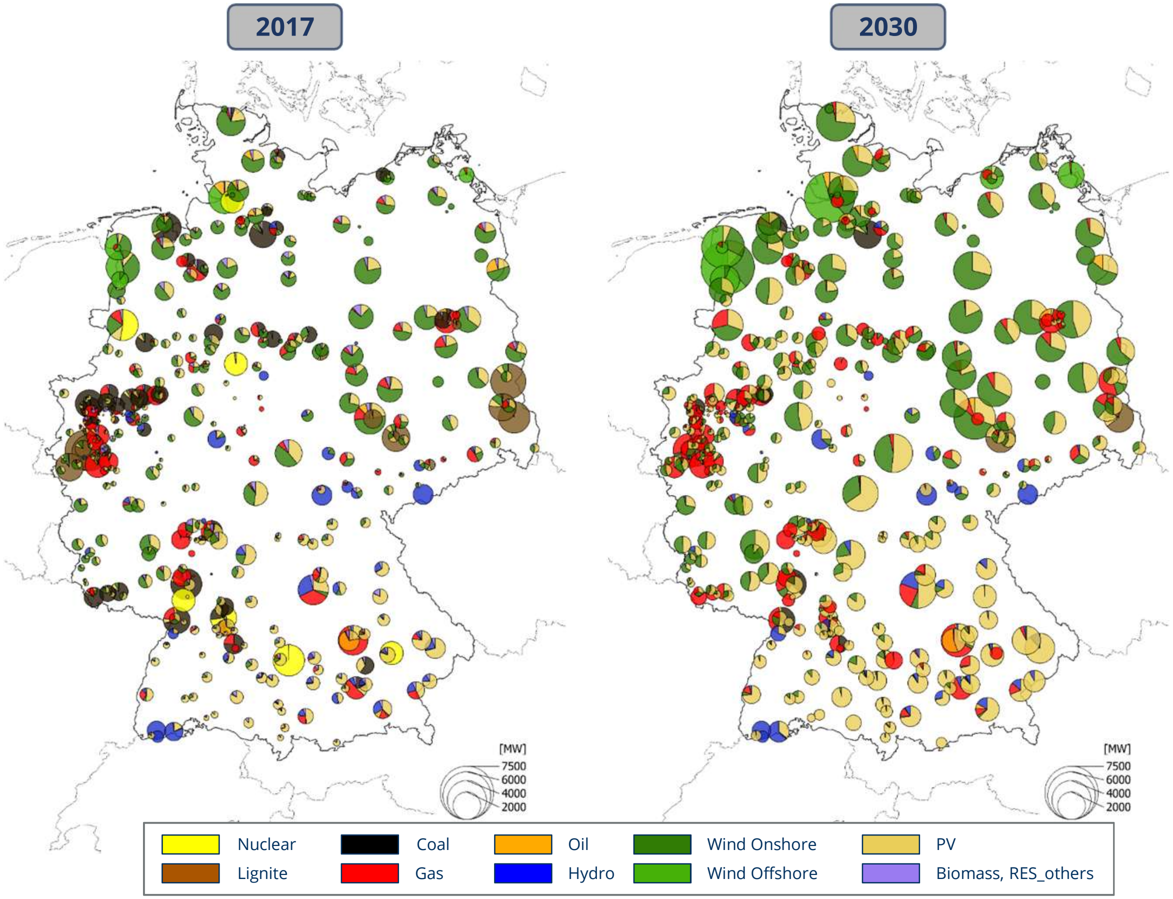
Back-up

ELMOD - a tool to look into the transmission grid optimization



- Model
  - A model to evaluate the volume of remedial actions (Redispatch and Curtailment) and Lineflows
  - Full year resolution, calculated with rolling planning (48h each horizon with an additional 24h overlap)
  - Implemented in GAMS as a linear program
  - Lineflow ist modelled with DC approximation to keep the problem linear
  - Minimization of system costs for remedial actions
- Grid
  - ELMOD includes the european transmission grid with voltage levels between 150kV and 750kV
  - For performance reasons, the grid of neighbour countries is simplified and modelled with aggregate nodes
  - Interconnectors and their capacities still remain

Adjusting the input data towards the target year 2030 is based on TYNDP2020 data



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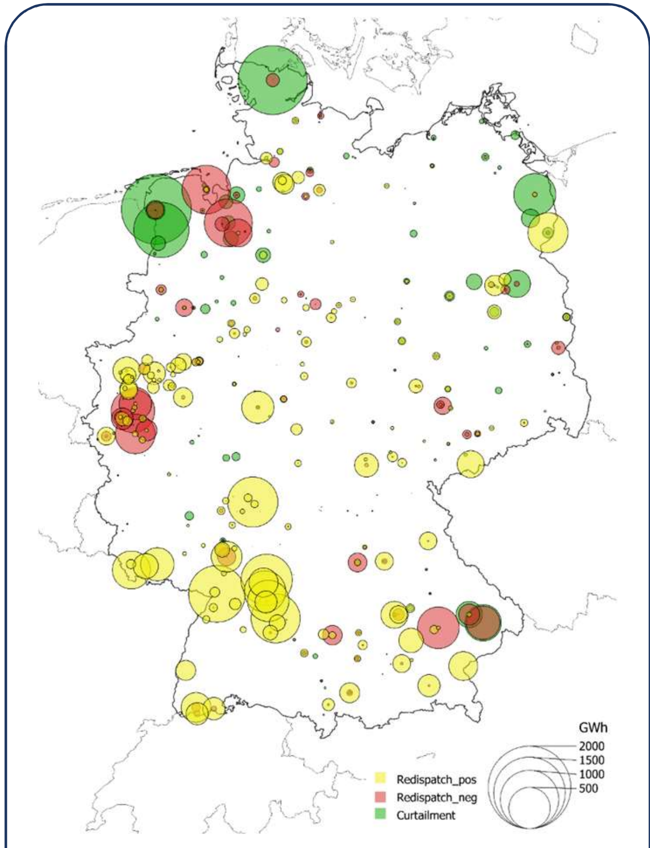
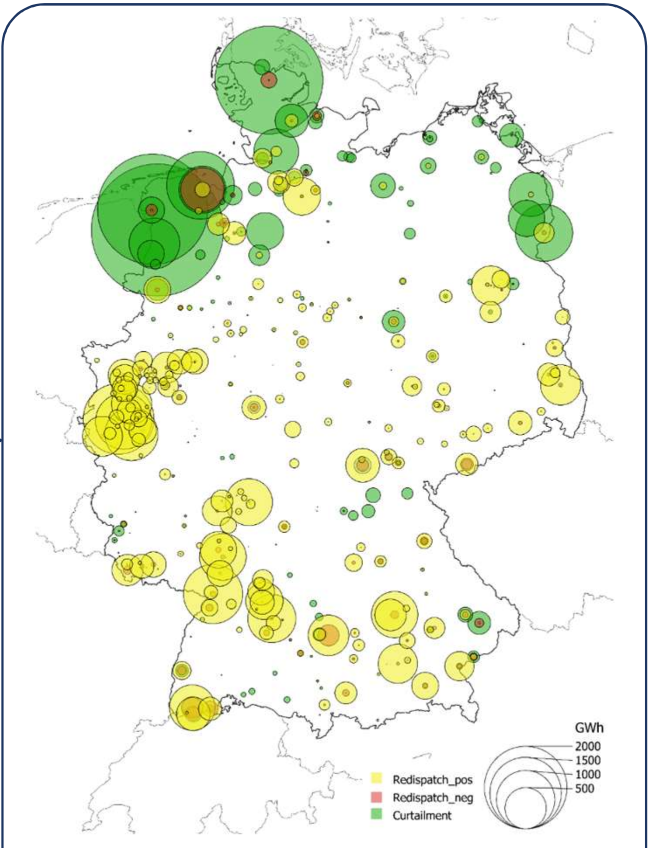
Reference Case (no electrolyzer yet) is showing high curtailment in the north and mainly positive redispatch in load centers for 2030 compared to 2017



Redispatch 2017

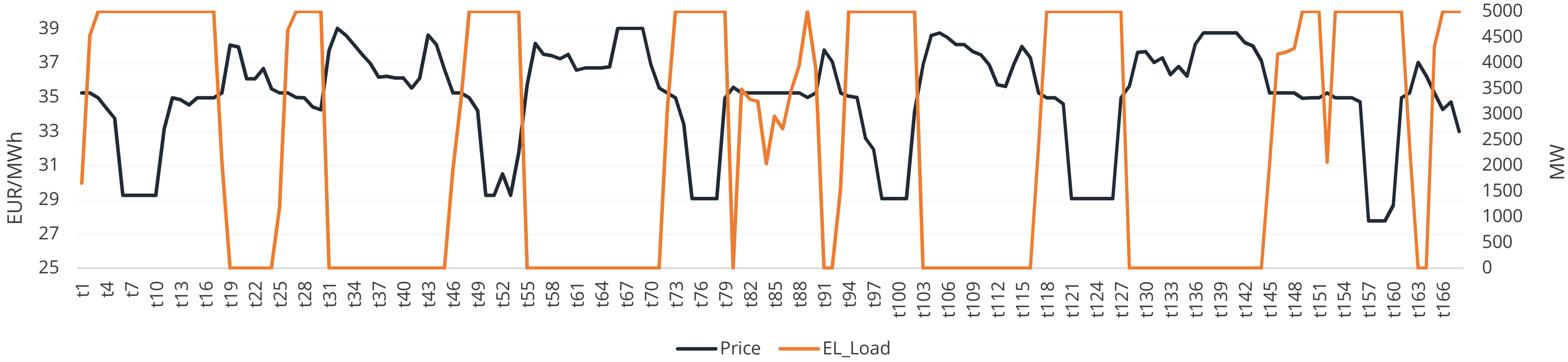


Redispatch Reference Case 2030

- High volumes of Curtailment at grid nodes with high renewable capacitites and comparable low demand
- Negative Redispatch significantly lower than in 2017
- High volumes of positive Redispatch due to insufficient transmission capacities

Market Optimization: Results from a ELTRAMOD run with electrolyzers (no explicit scenario)

- **exogenous**:
  - 5 GW of electrolyzer capacities
  - 28 TWh demand
- **endogenous**:
  - Dispatch of electrolyzers is market driven
  - Infinite hydrogen storage and transport capacitites are assumed (dezentral/zentral)



Methodology: Use of a 2-stage Market- and Gridmodelling

$$min \sum_{p,t} G(p,t) * cost(p)$$

$$s.t. \sum_{p} G(p,t) - \sum_{n} dem(n,t) = 0$$

$$pmax(p) * avail(p,t) \leq G(p,t)$$

g_da

$$min \sum_{p,t} (RDup(p,t) - RDdown(p,t)) * cost(p)$$

$$s.t. \sum_{p,n} g\_da + RDup(p,t) - RDdown(p,t)) - dem(n,t) - NetI(n,t) = 0$$

$$g_{da(p,t)} + RDup(p,t) \leq pmax(p) * avail(p,t)$$

$$RDdown(p,t) \leq g\_da(p,t)$$

Wholesale market clearing — **Grid-simulation (Redispatch)**

Note: All upper-case letters are endogenous variables, lower-case letters parametric model input