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Influence of CO_2 taxation and hydrogen utilization on the cost-optimal development of the German power system by 2050

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Outline

1. Motivation for the study

2. Methodological overview

3. Model analyses
   a) CO_2 tax-instead-of-limit
   b) Hydrogen utilization scenarios for electricity supply

4. Conclusions

Outline

1. Motivation of the study

German energy system to become **carbon-neutral** by 2045 (German climate protection law 2021)

Decarbonization instruments include:

- carbon trading schemes **(volume-driven)** or
- direct CO_2 taxation **(price-driven)**

Utilization of H_2 in electricity sector offers options for tackling the intermittency of renewables

- **in-land generation** by surplus renewable production
- **import** from abroad

Goal of the study: an assessment of options via optimization of a simplified electricity system model of Germany with sensitivities on the *CO_2 price*, *electricity demand* and *import price of hydrogen*

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2. Methodological overview

Energy system modelling framework *urbs*

Energy system modelling

Representation of an energy system of a given scale/resolution as a mathematical optimization model

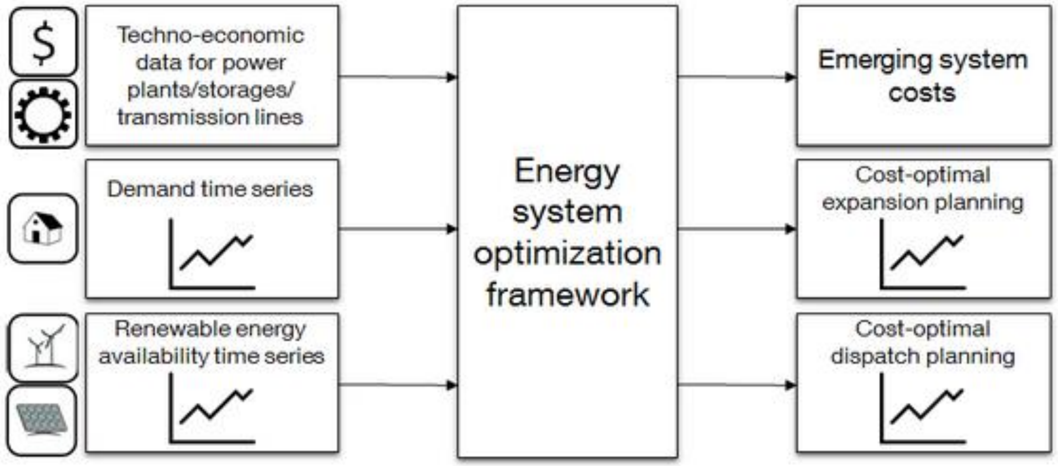
$$\min_{\boldsymbol{x}} f(\boldsymbol{x}) \quad \rightarrow \text{total system costs}$$

$$\left.\begin{aligned} \text{s.t. } \boldsymbol{g}(\boldsymbol{x}) &\leq \boldsymbol{0} \\ \boldsymbol{h}(\boldsymbol{x}) &= \boldsymbol{0} \end{aligned}\right\} \quad \rightarrow \text{system operation constraints}$$

$$\boldsymbol{x} \quad \rightarrow \text{system operation/investment decisions}$$

Determination of the cost-optimal evolution of the energy system s.t.:

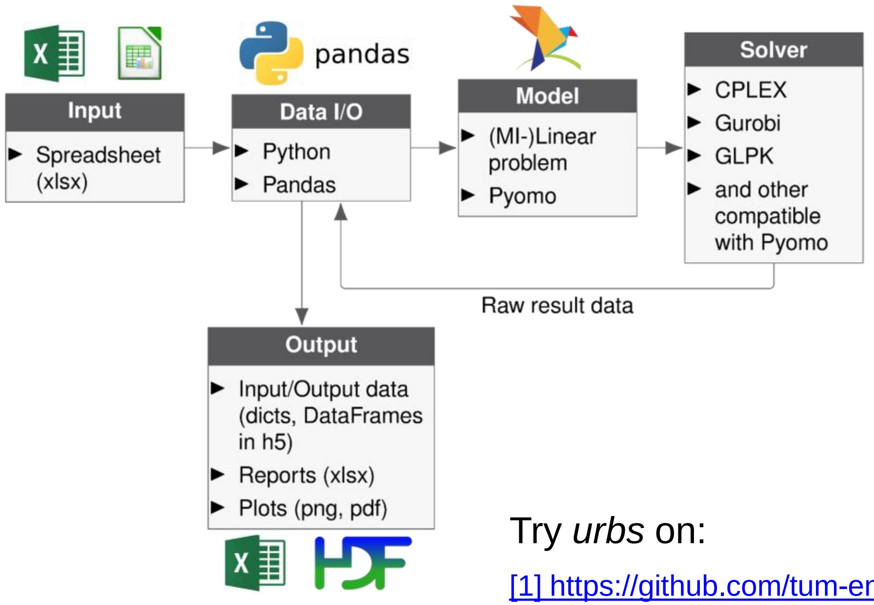
- sum of costs is minimized
- while ensuring that energy balances are met at all times



urbs framework

Open-source[1] energy system modelling framework developed by TUM ENS

Temporal scale: single-year or intertemporal (for expansion pathways)
Temporal resolution: variable (typically 1h)
Regional scale: user-defined model regions (countries, counties, cities…)



Try *urbs* on:

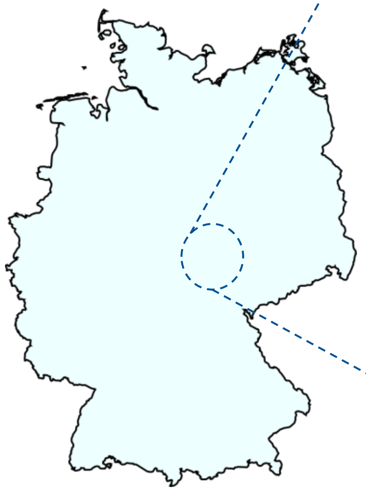
[1] https://github.com/tum-ens/urbs

2. Methodological overview

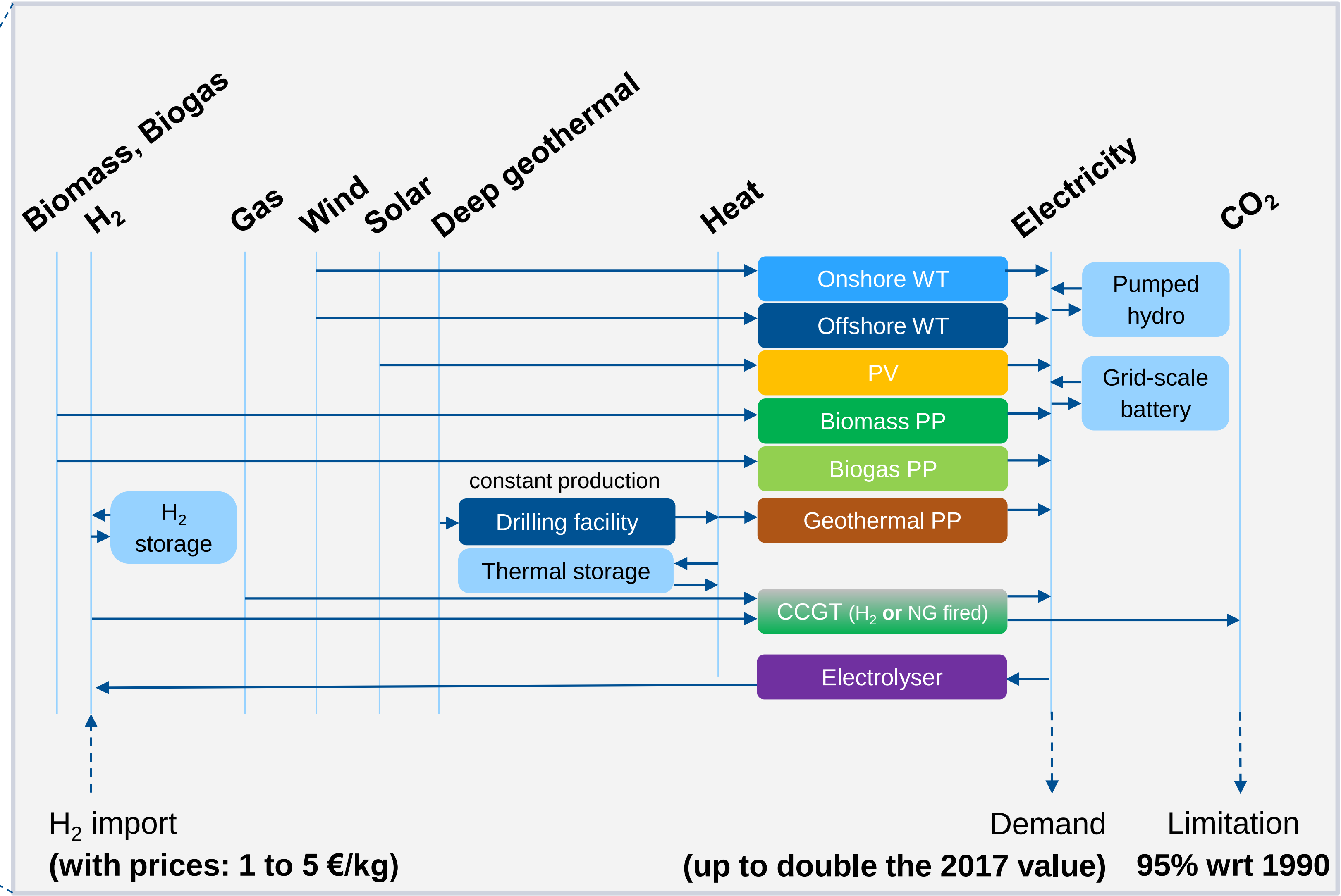
Model overview for the study

Model basics

- Single node (Germany + offshore),
- Single year (snapshot 2050), hourly resolution
- Coal and nuclear phase-out
- 95% emission reduction in electricity sector compared to 1990
- „Almost“ greenfield: PV/wind replaced, rest decommissioned



The reference energy system



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3. Model analyses

CO2 tax-instead-of-limit, approach

Goal

- Investigate the reaction of the cost-optimal electricity system to varying CO2 prices
- Quantify the tax „revenues“ which could in practice be excluded from the system costs (by distribution back to the society as dividends: example „*Energiegeld*“)

Scenario generation

1. Under a given electricity demand and H_2 import price. solve the system model with 95% CO_2 reduction constraint → Cost-optimal solution that satisfies the CO_2 goal

2. Read the dual variable associated with the total CO_2 limitation constraint → = the shadow price (or the **marginal abatement cost**) of CO_2

3. Solve the same system model, now without the CO_2 cosntraint but with 10% increments of the shadow price

3. Model analyses

CO_2 tax-instead-of-limit, results

Presented case: H_2 import price: 90€/MWh_{th} (~3€/kg), electricity demand: ~800 TWh
-> **marginal abatement cost: 211€/ton** (for reference: price corridor 55-65€/ton in 2026 in DE)

Emission pathway

(a) 70% emission reduction achieved without CO_2 pricing

Capacities

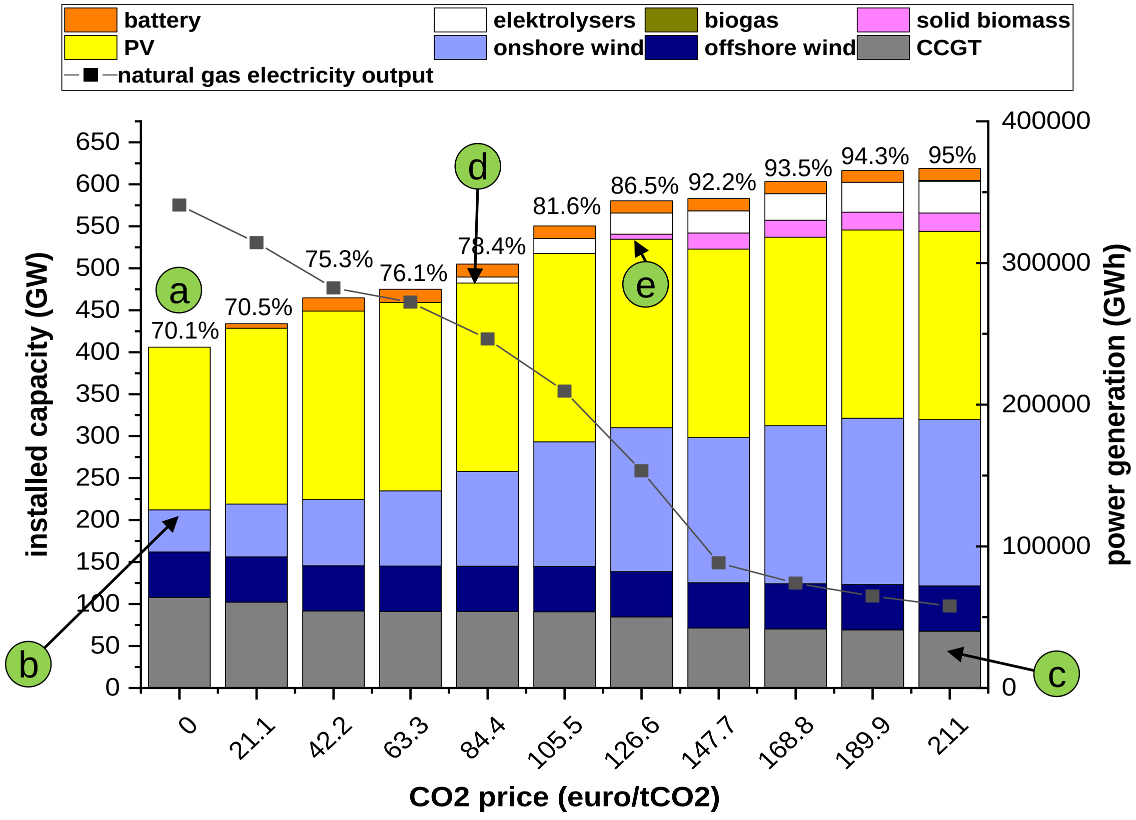
(b) PV and wind (onshore + offshore) among the cheapest options even at a zero price on CO_2

(c) Back-up capacity for dispatchable CCGT (min. 50 GW) always necessary

(d) Electrolyser build-up after CO_2 price of 84€/ton

(e) Biomass starts replacing gas at >126.6€/ton (break-even of marginal costs)

- Electricity production by deep geothermal not economical



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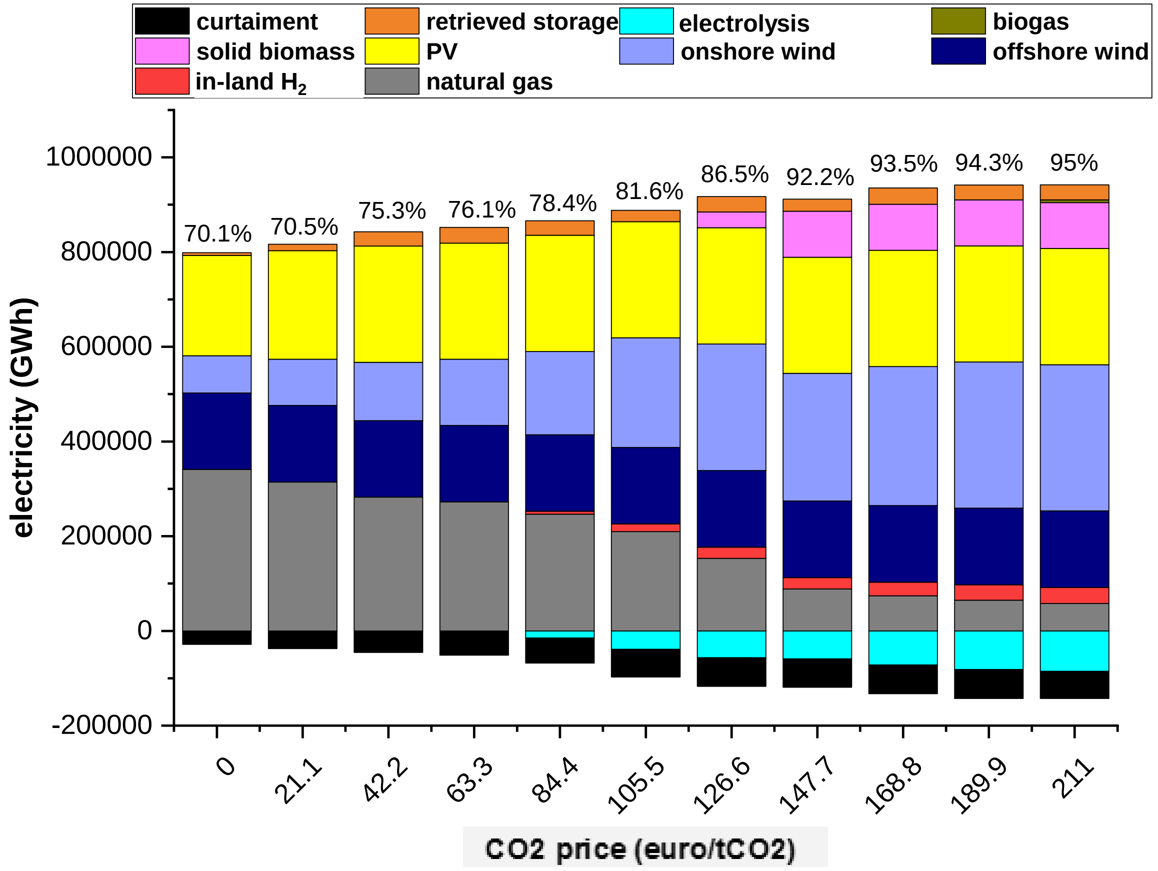
Electricity balance

- No hydrogen import for electricity supply



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CO_2 tax-instead-of-limit, results

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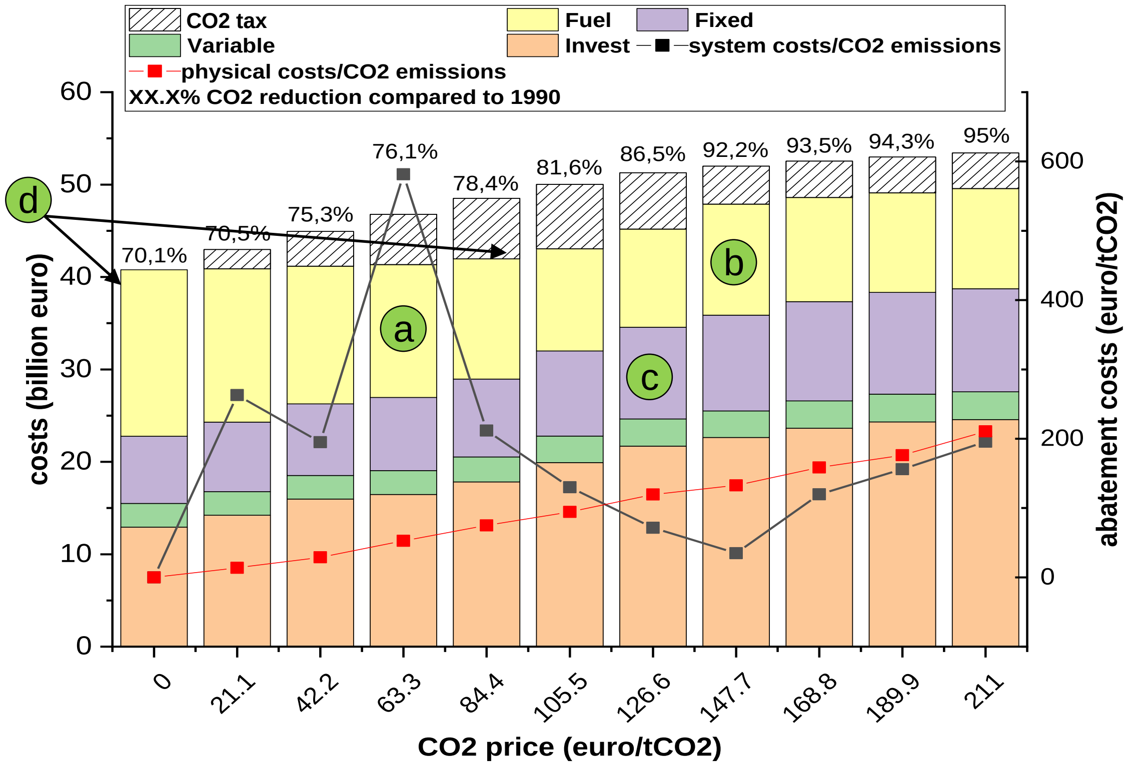
System costs

As the CO2 price increases:

- Fuel costs reduce (a) (reduced use of natural gas) and then slightly increase (b) (increased use of biomass)
- Then the fixed and investment costs increase (as the PV, wind, battery capacities increase) (c)
- <u>Very minimal increase</u> in the „physical" costs (total costs minus CO_2 tax payments) for CO_2 prices up to 84€/ton (d)
- Emission reduction from 70% to 95% is achieved with
  - +30% total costs,
  - of which +20% „physical" costs



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Hydrogen utilization scenarios for electricity supply

Research question

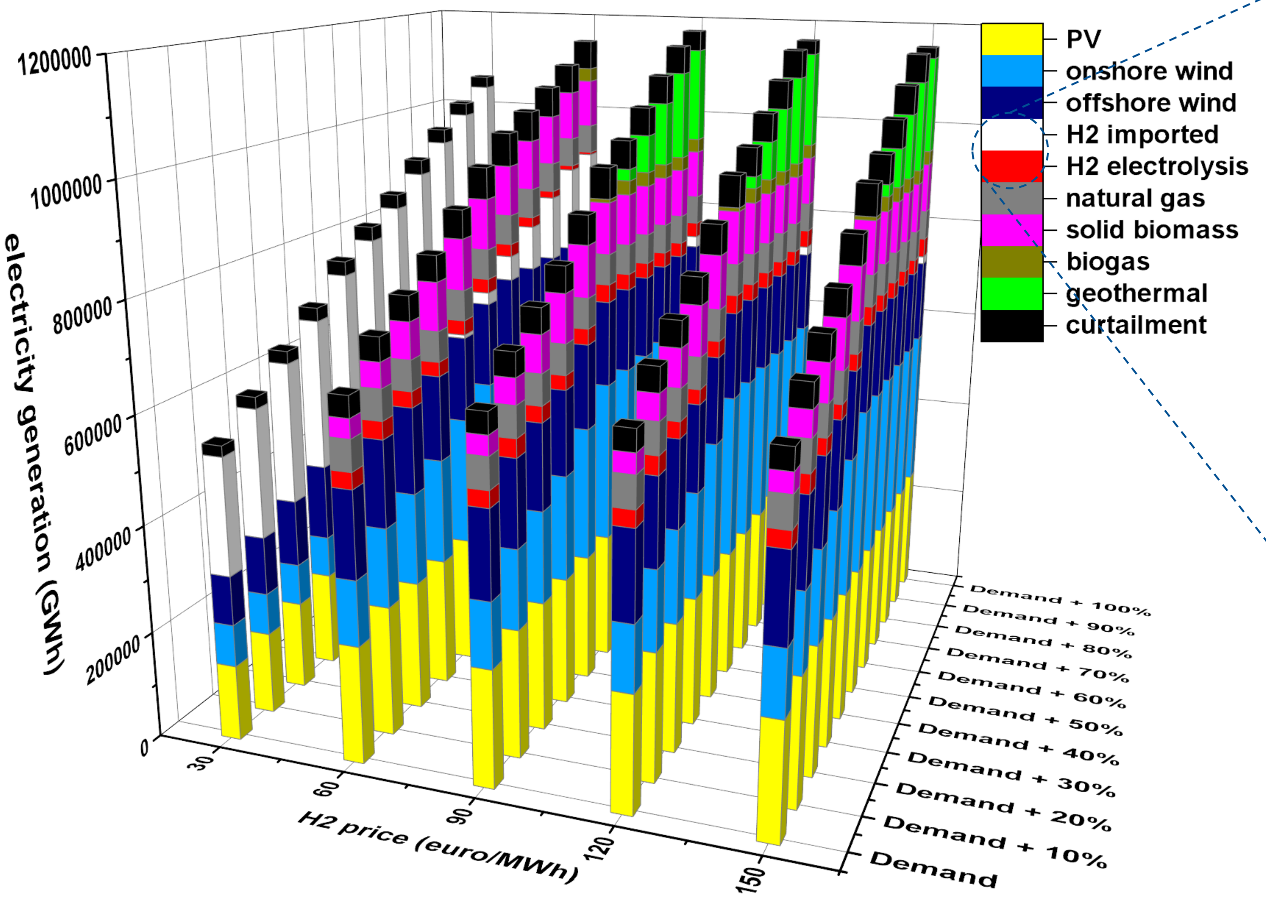
+ Where should the hydrogen be sourced for the utilization in the cost-optimal power system? (import or locally produced)

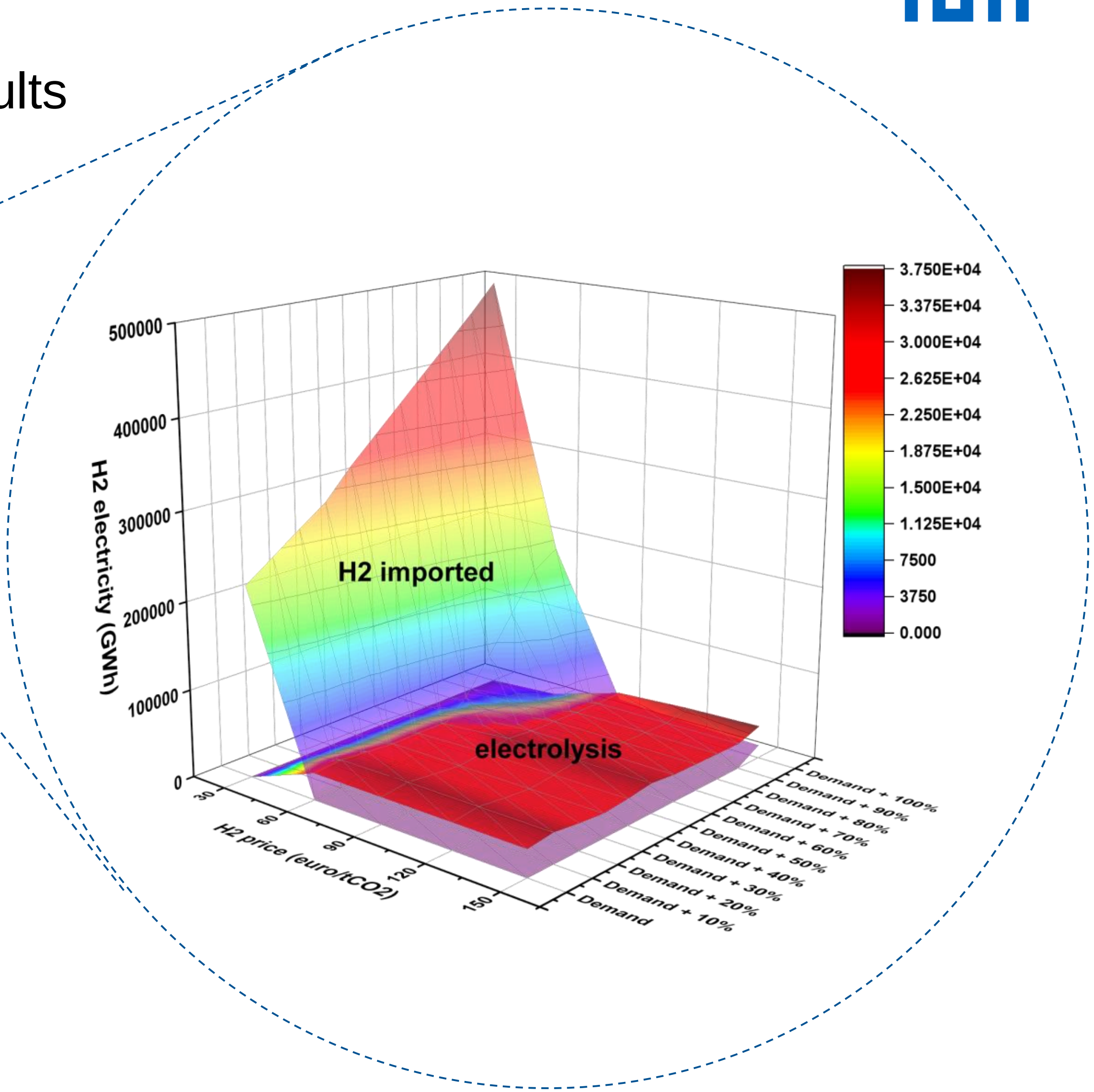
Method

+ Set CO_2 target to 95%,
+ Parameter sweep on
  + the **electricity demand** (100% to 200% of the annual demand in 2017), and
  + the **hydrogen import price** (30 to 150€/MWh, or 1 to 5€/kg)

3. Model analyses

Hydrogen utilization scenarios for electricity supply, results





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Summary

+ System costs to the society and consumer may be overestimated with carbon taxation
+ Feasibility of the imported and locally produced hydrogen observed to be an open topic (co-presence possible also at realistic ranges of demand and price assumptions)

Remarks

+ Simplified model (one-node, linear representations of technologies…), the actual numbers mentioned should always be taken with a grain of salt (as with any energy system model)
+ Sector coupling has been ignored; hydrogen has high potential in other sectors such as direct use in industry and long-range mobility