Modeling power-to-gas facilities in a multistage system of natural gas, electricity and emission trading markets

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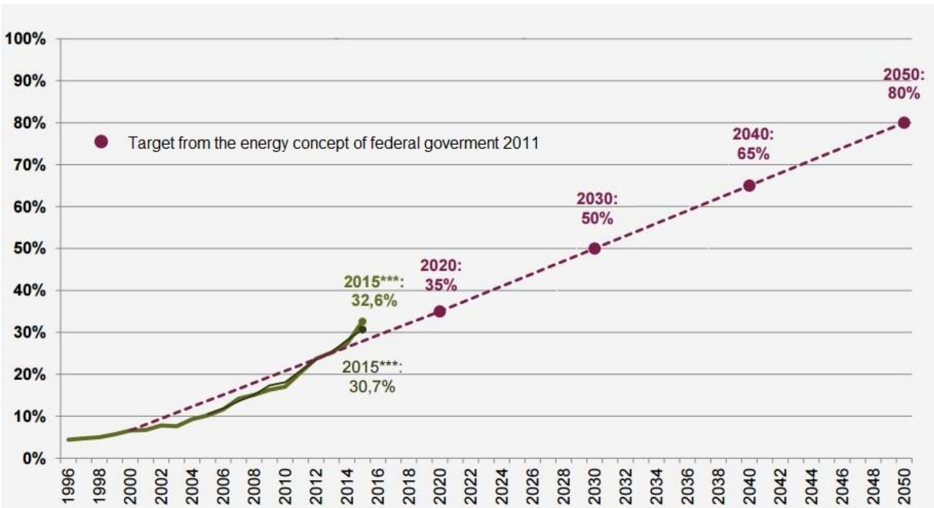
Agenda

Motivation

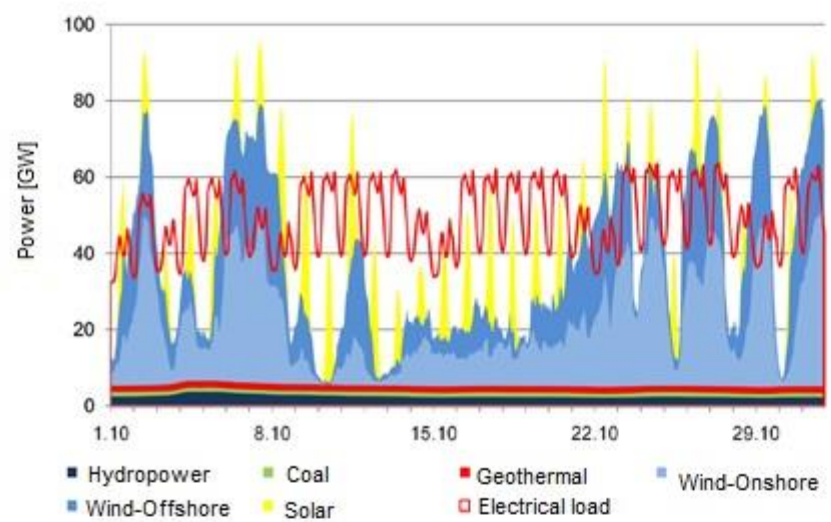
Introduction

- Energiewende: 80% of electricity generation from renewables by 2050



Source: BDEW Bundesverband der Energie- und Wasserwirtschaft e.V.

- Integration of renewables is challenging!



Exemplary load and feed in of renewables in october 2050
Source: Fraunhofer IWES

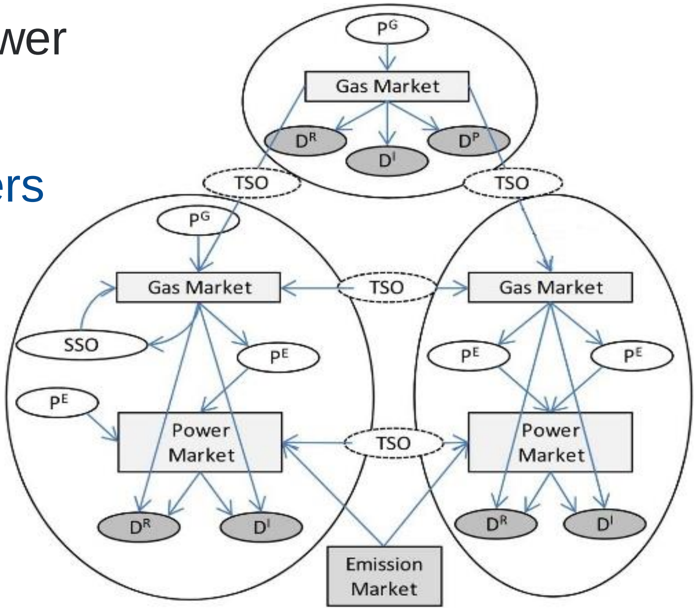
Research question

- Some general options to avoid curtailment of renewables:
  - grid expansions, demand-side managements, electricity storages, integration of energy sectors (sector coupling)
- Flexibility in power market is required in both:
  - Short term: battery storage, compressed air storage etc.
  - Long term: hydro reservoirs, Power-to-X (sector coupling)
- The aim of present study is to investigate:
  - the interactions of the electrical power and natural gas sectors in case of high share of renewables,
  - the influence of Power-to-Gas (PtG) technology on the aforementioned interaction
  - the possible contribution of PtG to the integration of renewables through increased coupling between energy sectors

CElGEM-Model

Model

- CElGEM-Model
  - Complementarity electricity & gas & emission market model
- A large-scale partial market equilibrium model based on the principles of Cournot-Nash equilibria
- Considers three sector of natural gas, power and emissions trading
- Analyzing the markets with and without market power
- Players of natural gas market at 3 levels
  - Upstream: producers and their associated traders
  - Midstream: TSOs and shippers (incl. pipelines and LNG terminals) as well as storage facilities
  - Downstream: gas hubs (final demand is aggregated to three sectors, one is the power sector)



CElGEM-Model

- Players of electricity market at 3 levels: producers, transmission system operators (TSOs) and consumers
- Electricity producers: renewable, conventional power plants & pump storages
- Producers are aggregated based on their technology class as well as their fuel type and technical properties
- production costs include a combination of fuel costs, CO_2 costs and start-up costs
- Players try to maximize their profits
  - However, perfect competition is considered in the electricity market.
  - In this case, market outcomes correspond to those obtained through minimization of the whole system costs

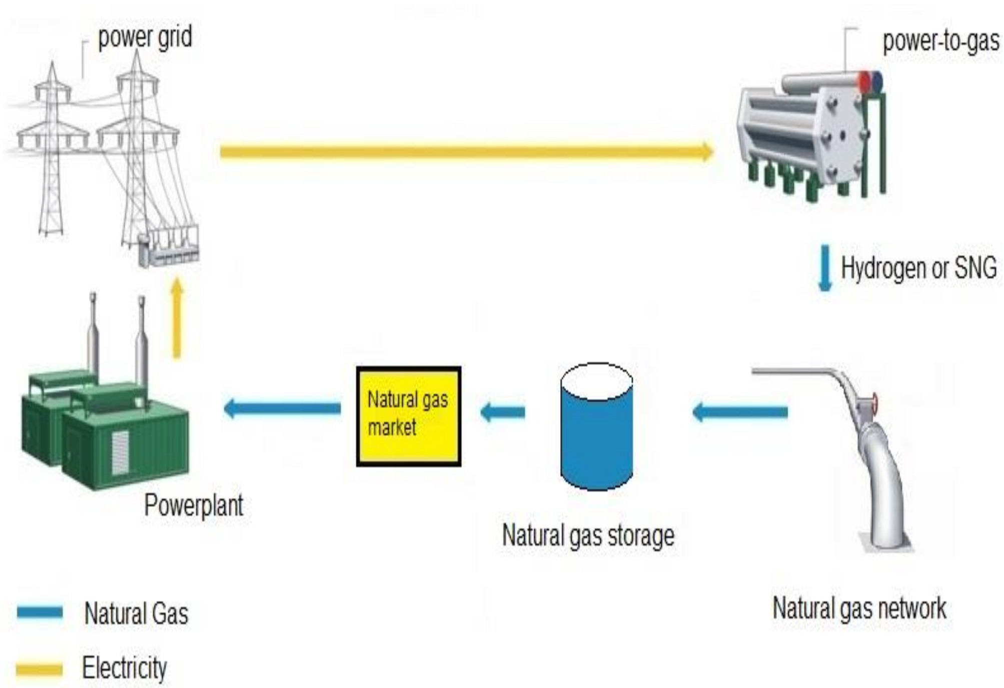
Power-to-Gas technology

Power-to-Gas

- PtG technology classified based on their output products:
  - hydrogen
  - synthesis gas (with methanation)

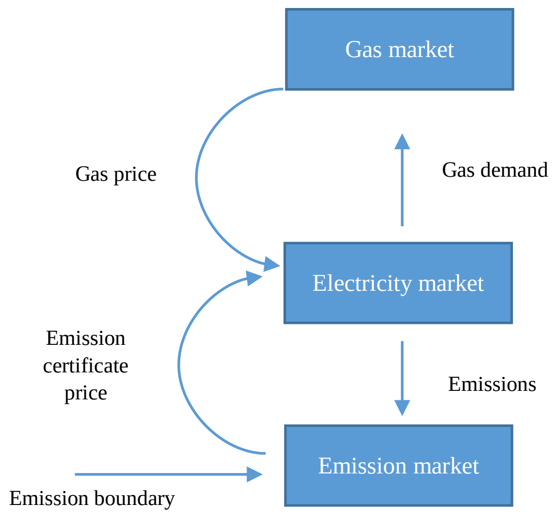
- Considered as ideal for capturing seasonal fluctuations of renewables given storage possibilities in the gas system

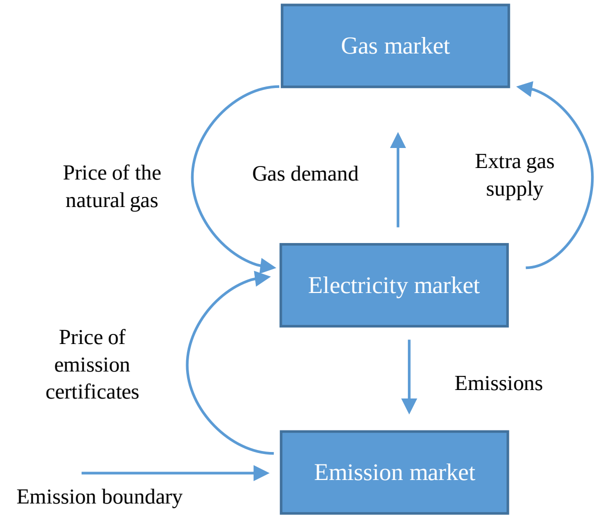
- Reinforces the integration of power and natural gas sectors



How PtG facilities change the model structure?

Power-to-Gas





Formal description of PtG operation

Maximization of operational profit

$$Max\left[\pi_{gas,t} \cdot P^{PtG}_{gas,t} - \pi_{Elec,t} \cdot P^{PtG}_{elec,t} - c^{PtG}_{ovar} \cdot P^{PtG}_{elec,t}\right]$$

s.t. $P^{PtG}_{elec,t} \leq K^{PtG}$

With Lagrangian multiplier λ^{PtG}_{t} for capacity constraint and efficiency $\eta^{PtG} = \frac{P^{PtG}_{gas,t}}{P^{PtG}_{elec,t}}$:

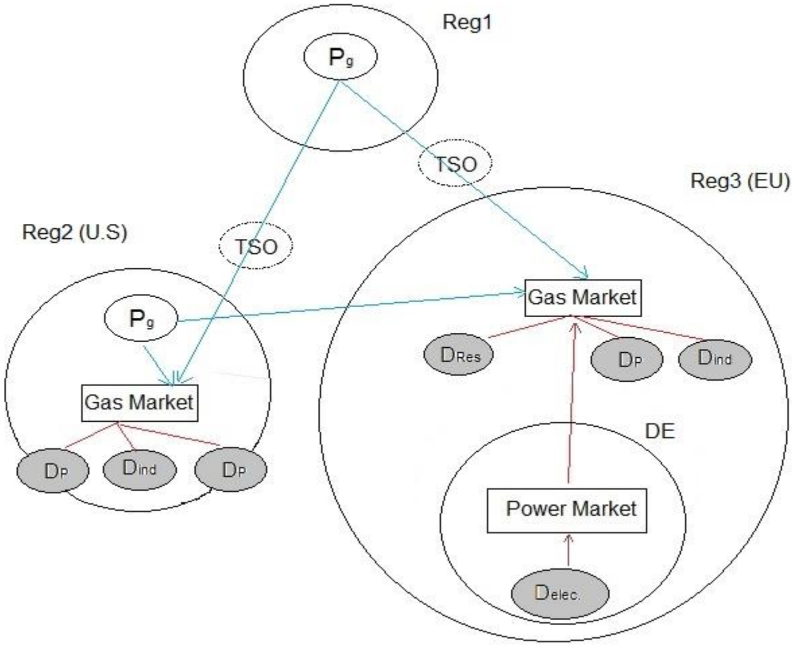
$$Max\left[\pi_{gas,t} \cdot \eta^{PtG} \cdot P^{PtG}_{elec,t} - \pi_{elec,t} \cdot P^{PtG}_{elec,t} - c^{PtG}_{ovar} \cdot P^{PtG}_{elec,t} - \lambda^{PtG}_{t} \cdot P^{PtG}_{elec,t}\right]$$

Resulting KKT condition:

$$c^{PtG}_{ovar} + \pi_{elec,t} + \lambda^{PtG}_{t} \geq \pi_{gas,t} \times \eta \quad \perp \quad P_{elec}$$

Key Elements Case Study – Gas market

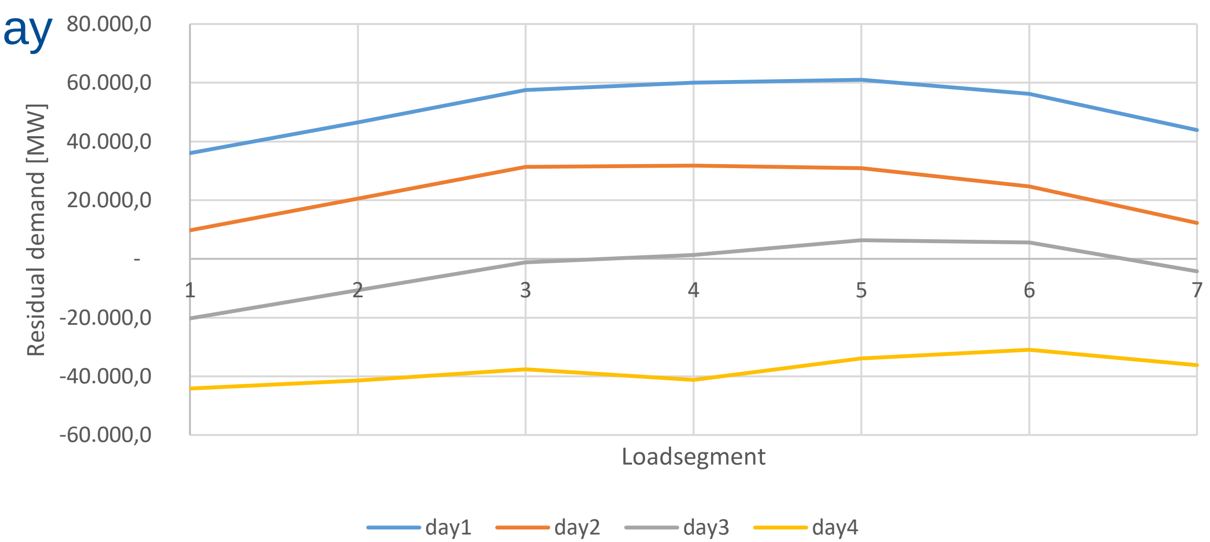
- Stylized model roughly calibrated to existing data
  - Data based on the reference year 2015
- Natural gas market:
  - 3 Regions
  - Reg1: only production (~ Russia etc.)
  - Reg2: production & consumption (~U.S.)
  - Reg3: only consumption (~ EU)
  - Demand at hubs is divided to 3 sectors: Power, Industry and Rest
  - 3 different seasons (winter, summer, transition)
  - 1 representative day per season



Key Elements Case Study – Power market

Application Case Study

- Detailed electricity market:
  - 1 Region (~Germany)
  - Renewable generation is scaled up to 85 % of Electricity demand
  - 3 seasons
  - 4 representative days for each season (constructed based on the residual load)
  - 7 load segments per day
- Exogenous Co2 Prices



Residual load in the winter season

Overview first preliminary results

Results

- Example of PtG operation
- Impact of PtG on electricity generation mix and renewable integration
- Impact of CO_2 price on electricity generation mix and PtG operation
- Impact of PtG on prices and system costs
- Impact of gas market structure on PtG operation

Operation of PtG - Example

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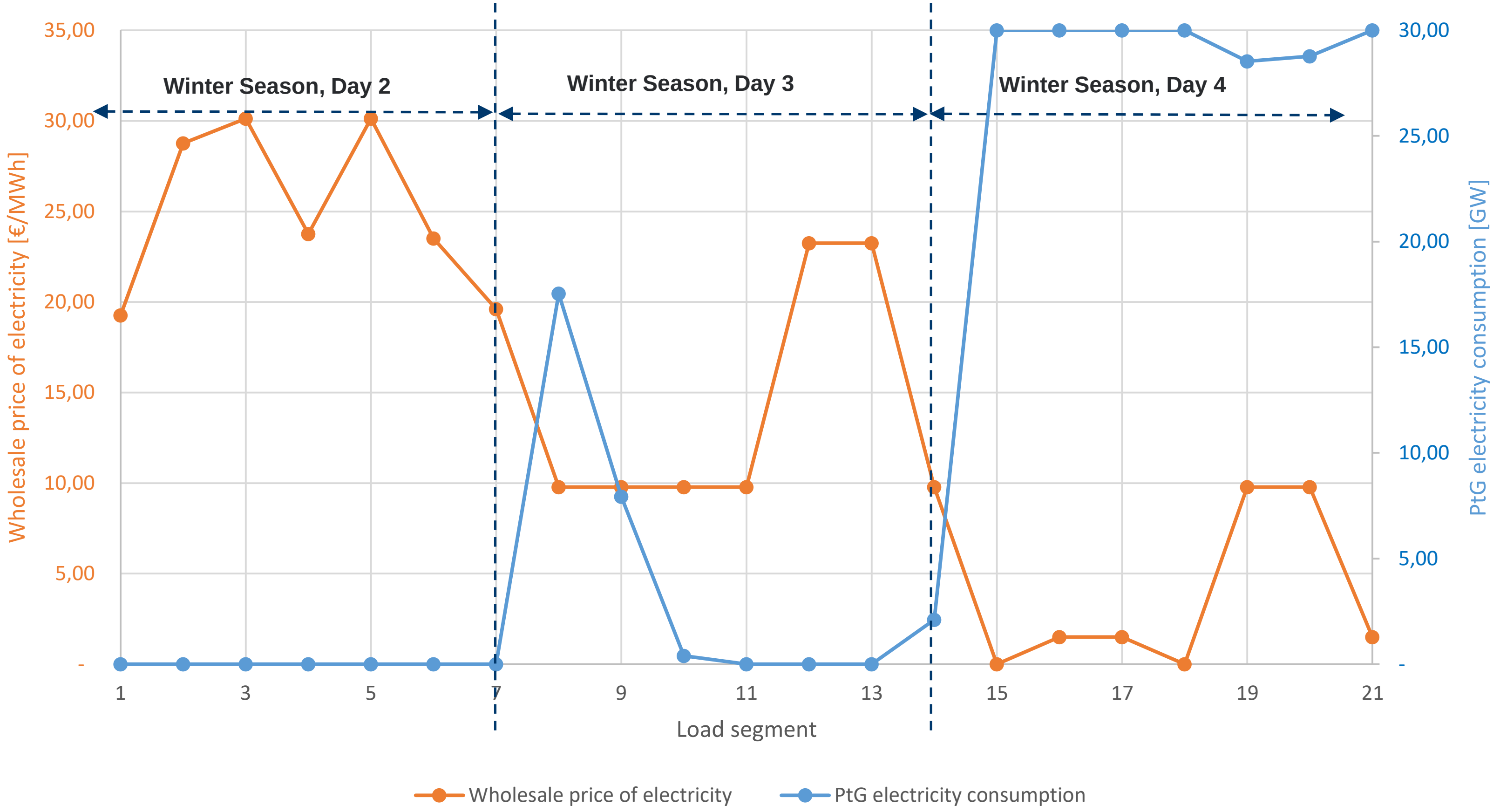
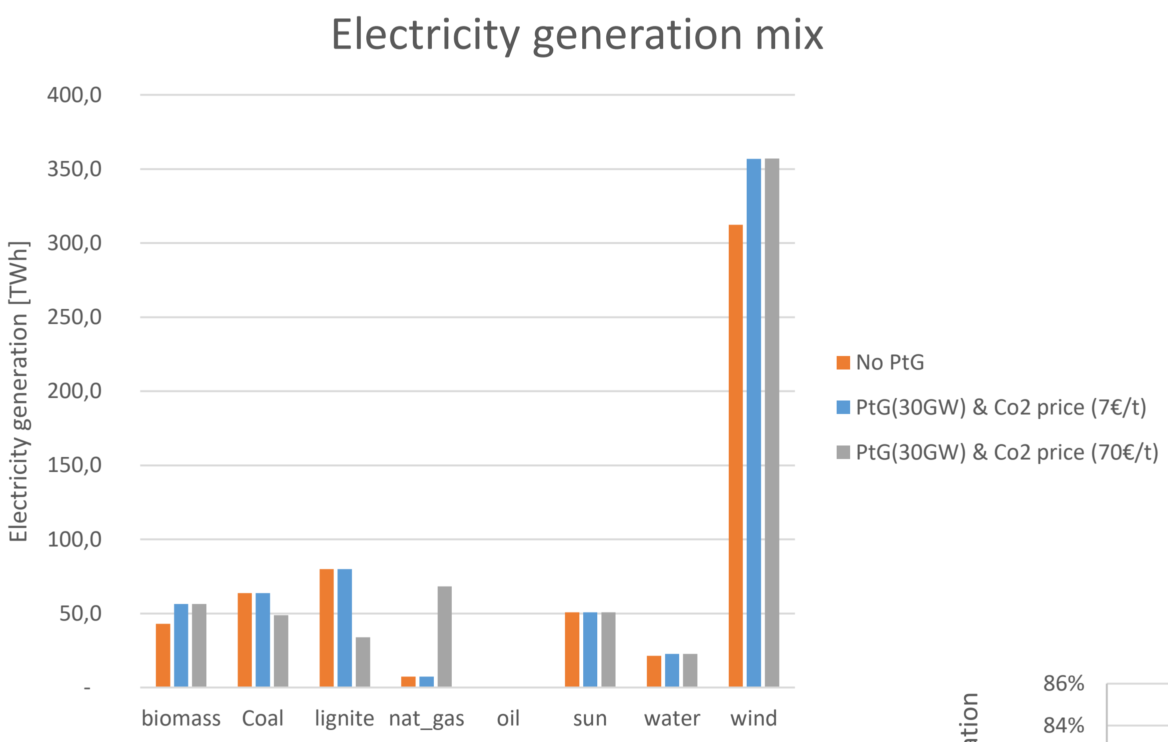
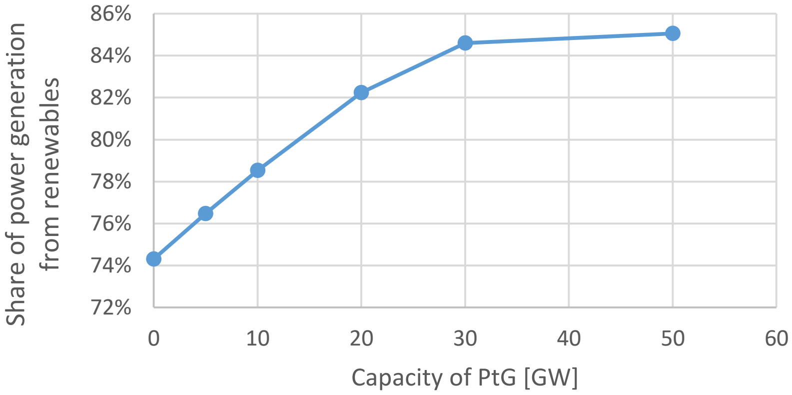
Results



Integration of renewables & electricity generation mix

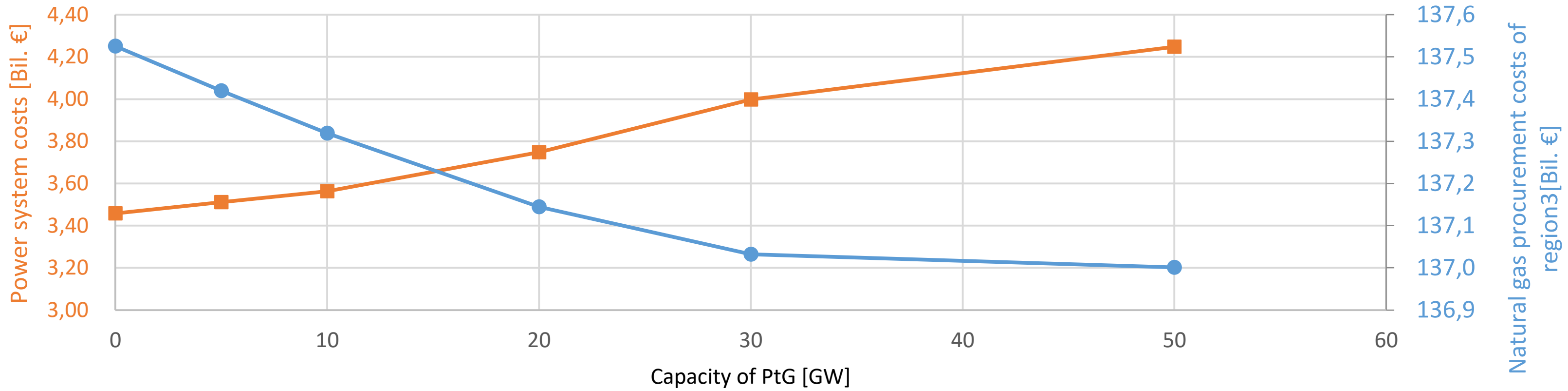
Results



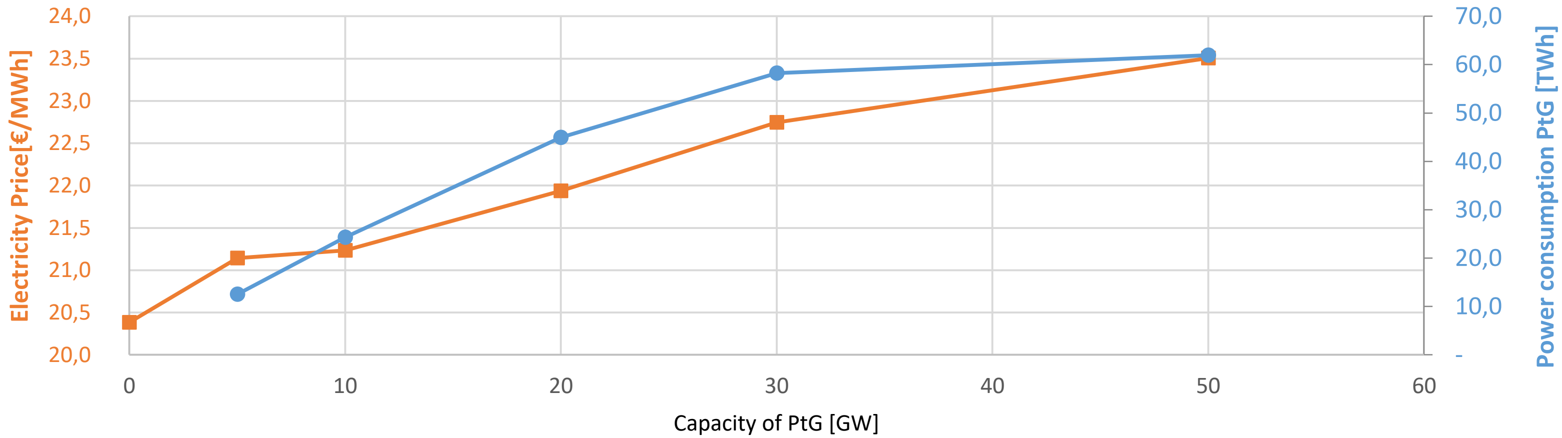


System costs & electricity prices

Results



CO_2 Price of 7 €/t



CO_2 Price of 7 €/t

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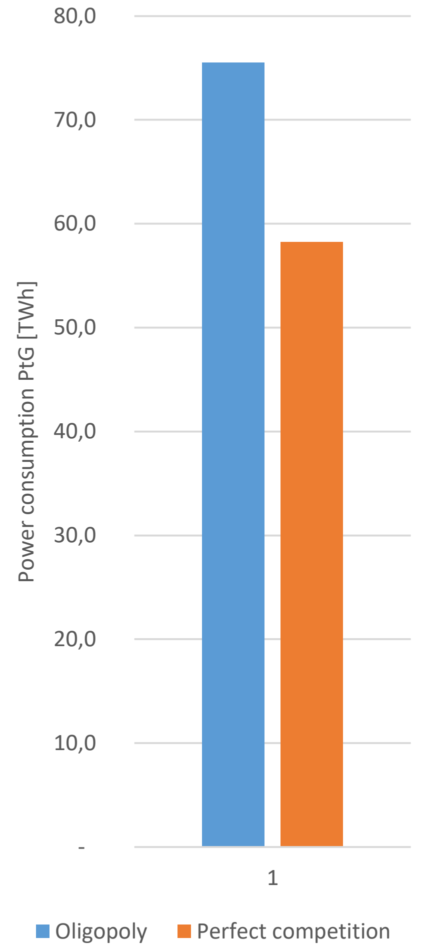
Oligopoly vs. Perfect Competition

Results

- In case of Oligopoly in the natural gas market, higher prices of the natural gas result in additional application of PtG.
- In this case, PtG is used until the wholesale price of electricity is less than the wholesale natural gas price plus PtG marginal costs
- PtG converts the electricity generated through lignite and coal units into the synthetic gas since it is economical for the PtG operators!
- With low CO_2 prices, the carbon externality is valued less than the limitation of market power by oligopolists!



Capacity of PtG 30 [GW] for both cases

Summary

- We use a multi-level market model to investigate the role of PtG in case of high shares of renewables
- PtG leads to bidirectional integration of power and natural gas sectors
- PtG runs based on price difference between the two sectors of electrical power and natural gas and is driven mostly by available excess electricity in the electricity grid
- PtG contributes to a reduction of the renewable curtailments
- It increases the power system costs and reduces the procurement cost of natural gas
- The electricity prices increase with the construction of PtG capacity until all the renewables can be integrated in the system and then it stays constant
- Higher CO_2 prices increase electricity generation through the natural gas units and therefore change the electricity generation mix as well as electricity prices, however do not affect the operation of PtG
- A high capacity of PtG in case of high natural gas prices can lead to externalities!
- The gas generated in PtG tends to be consumed in the same season (storage costs!)

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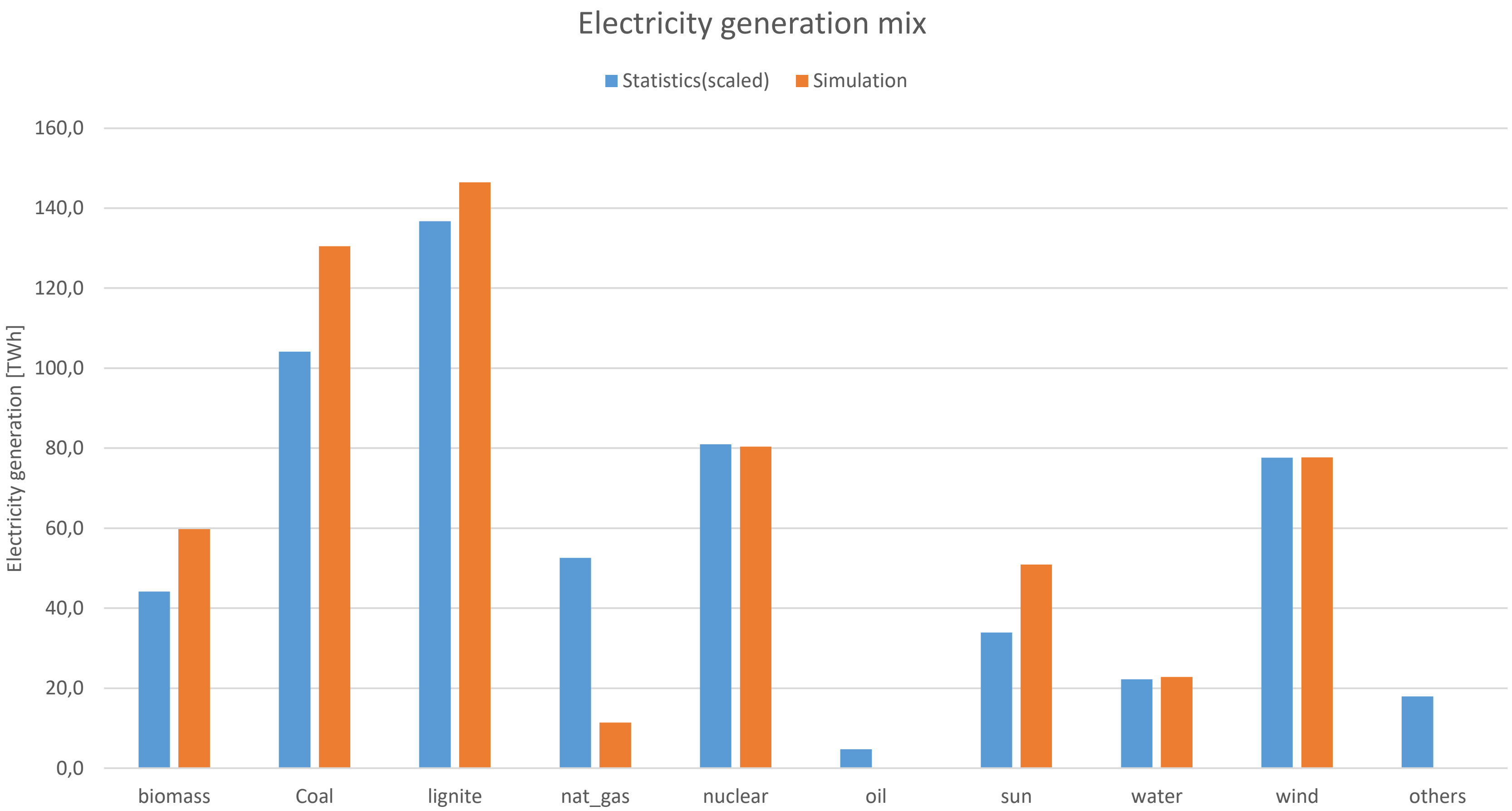
Thanks for your attention!

Back up slides

Electricity generation mix: Simulation vs. historical data



Electricity generation mix with high share of renewables

Results