House of Energy Markets & Finance

# Coupling an investment model with two sequential infrastructure models using Benders decomposition

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UNIVERSITÄT DUISBURG ESSEN

*Open-Minded*

# Agenda

SDEWES Rome 2024

# The role of hydrogen for the energy transition

- Energy transition to reach climate neutrality major target of European energy policies

- Hydrogen is seen as an important building block to reach these goals
  - Adressed for example in *REPower EU*

- European countries have developed hydrogen roadmaps with ambitious goals
  - E. g. Germany: National Hydrogen Strategy

➢ Analyzing effects of hydrogen strategies requires integrated modelling approaches

# Context: Ongoing research project MOPPL

- „Model coupling (German: **Mo**dellko**ppl**ung) for the integrated optimization of long term transformation paths – coevolution, coordination and robustness under consideration of different system levels“
- Timeline
  - August 2022 – July 2025
- Project Partners
  - ie3 (Technical University of Dortmund)
  - GWI Essen e.V. (Gas and heating institute Essen)
- Tasks
  - Integrated modelling of electricity, gas and hydrogen systems
  - Analysis of implications of different hydrogen strategies
  - ➢ **Focus on the development of a mathematical approach to couple independent infrastructure models**

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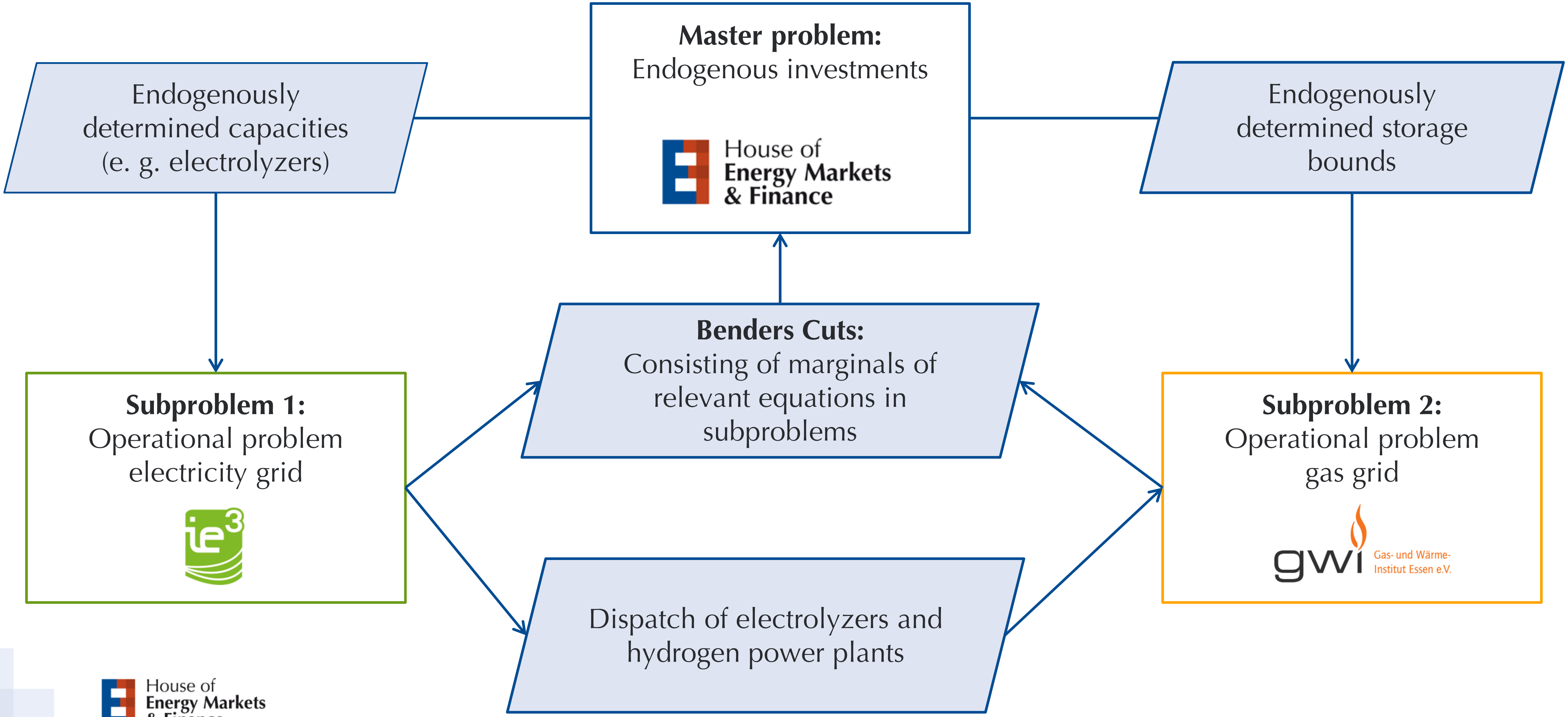
# MOPPL: Benders Decomposition



**Master problem:**
Endogenous investments

Endogenously determined capacities (e. g. electrolyzers)

Endogenously determined storage bounds

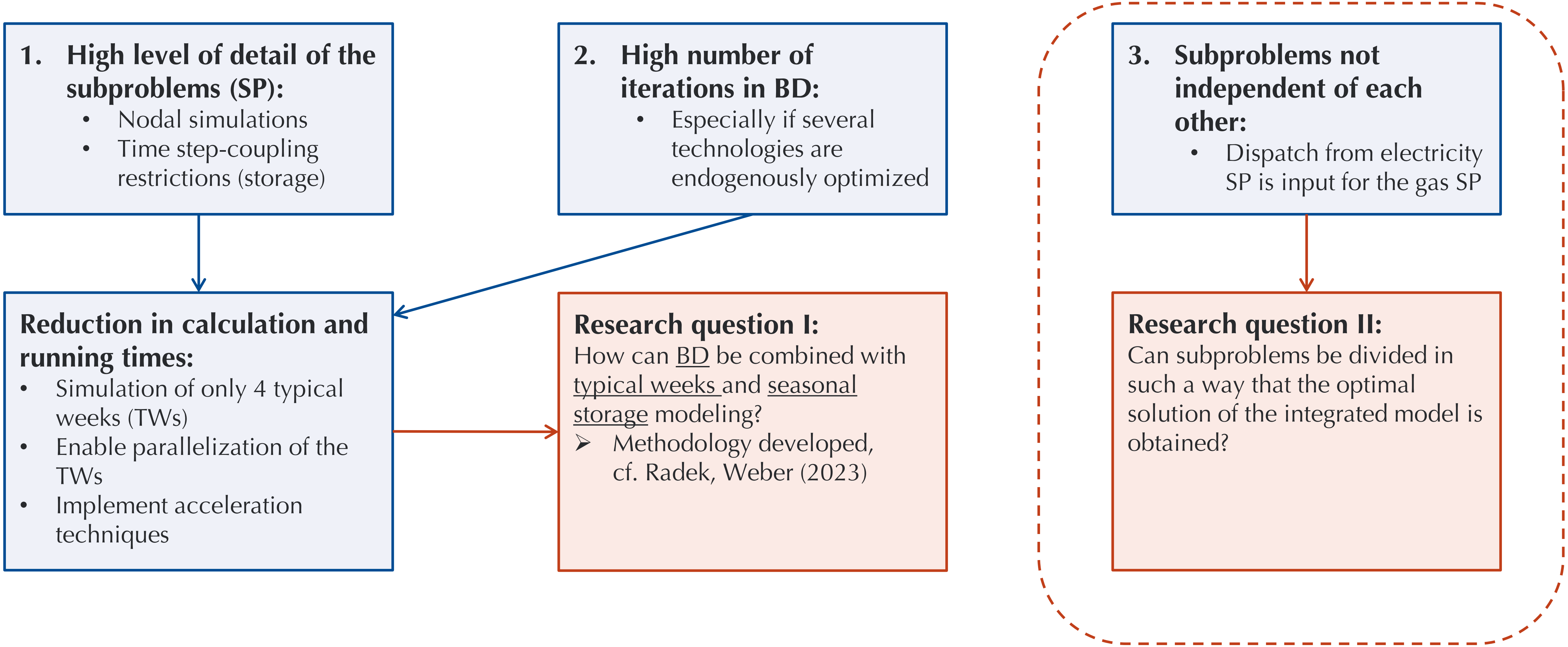
**Benders Cuts:**
Consisting of marginals of relevant equations in subproblems

**Subproblem 1:**
Operational problem electricity grid

**Subproblem 2:**
Operational problem gas grid

Dispatch of electrolyzers and hydrogen power plants

# Challenges



1. **High level of detail of the subproblems (SP):**
   - Nodal simulations
   - Time step-coupling restrictions (storage)

2. **High number of iterations in BD:**
   - Especially if several technologies are endogenously optimized

3. **Subproblems not independent of each other:**
   - Dispatch from electricity SP is input for the gas SP

**Reduction in calculation and running times:**

- Simulation of only 4 typical weeks (TWs)
- Enable parallelization of the TWs
- Implement acceleration techniques

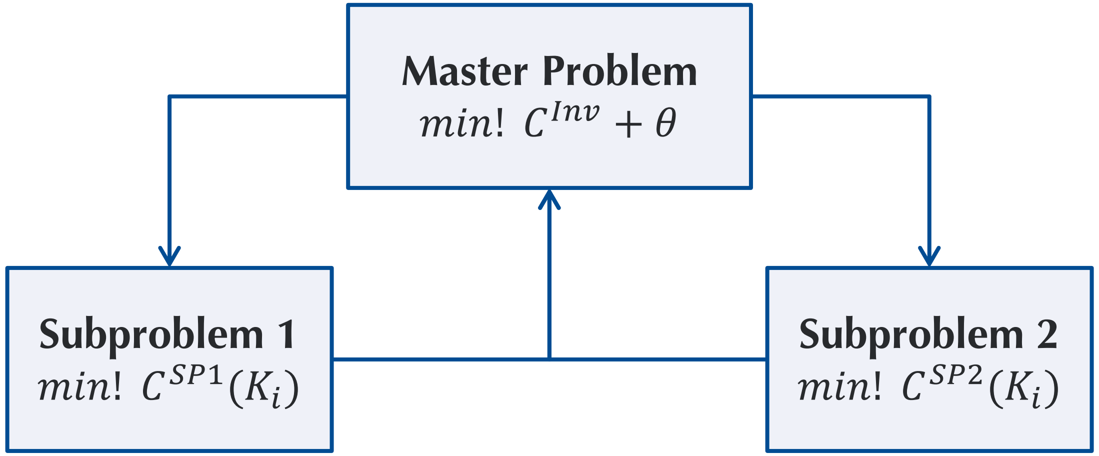
**Research question I:**
How can BD be combined with typical weeks and seasonal storage modeling?

➢ Methodology developed, cf. Radek, Weber (2023)

**Research question II:**
Can subproblems be divided in such a way that the optimal solution of the integrated model is obtained?

# Multiple subproblems – Overview

- Benders decomposition with multiple independent subproblems



**Master Problem**
$min!\ C^{Inv} + \theta$

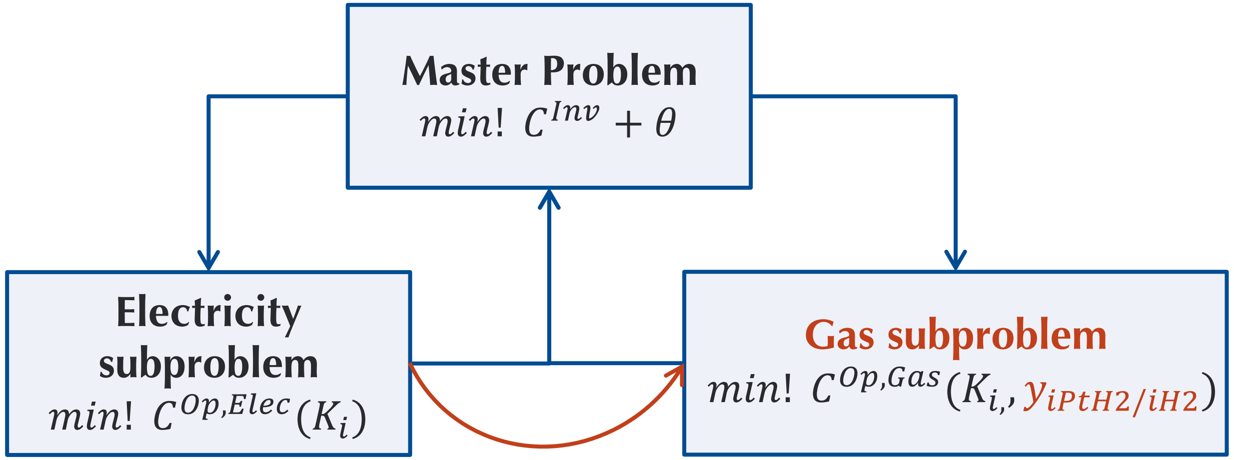
**Subproblem 1**
$min!\ C^{SP1}(K_i)$

**Subproblem 2**
$min!\ C^{SP2}(K_i)$

- e. g. different weather years for the same operational subproblem

➢ parallelization possible

- Benders decomposition with sequential subproblems



**Master Problem**
$min!\ C^{Inv} + \theta$

**Electricity subproblem**
$min!\ C^{Op,Elec}(K_i)$

**Gas subproblem**
$min!\ C^{Op,Gas}(K_{i,}, y_{iPtH2/iH2})$

- Gas subproblem depends on elec. subproblem

➢ no parallelization possible

# One integrated vs. two sequential subproblems

## One integrated subproblem

- Electricity and H2 demand are served within one optimization

➢ Direct incentive for dispatch of electrolyzers through h2 demand constraint
  - ➢ Comparison between production costs and third-country import price

➢ Direct incentive for dispatch of H2 power plants
  - – No fuel costs necessary in input data
  - ➢ Consumption is part of H2 demand constraint

## Two sequential subproblems

- Electricity system is optimized prior to H2 system

➢ Incentivization by fixed H2 price (electricity subproblem)
  - – Incentive for electrolyzer dispatch through revenue generation
  - – Incentive for H2 power plant dispatch by fuel costs

➢ Gas subproblem
  - – Seasonal H2 storages minimize third-country imports

# Objective functions

- **Master Problem:**

$$min!\ C^{M} = \sum_{r,i} c_i^{inv} \cdot K_{r,i} + \theta$$

- **Electricity subproblem:**

$$min!\ C^{Op,Elec} = \sum_{tw,t,r,i} y_{tw,t,r,i} \cdot c_i^{var} \cdot freq_{tw} \underbrace{- \sum_{tw,t,r,iPtH2} y^{H2}_{tw,t,r,iPtH2} \cdot c^{H2} \cdot freq_{tw}}_{\text{Revenue through H2 production}}$$

- **Gas subproblem:**

$$min!\ C^{Op,Gas} = \underbrace{\sum_{tw,t,r} \omega^{H2}_{tw,t,r} \cdot c^{H2} \cdot freq_{tw}}_{\text{Third country import costs}}$$

**Sets:**
$tw$ – Typical weeks
$t$ – Timesteps within a typical week
$r$ – Regions
$i$ – Technologies

**Parameters:**
$c_i^{inv}$ / $c_i^{var}$ – Investment and variable costs
$freq_{tw}$ – Frequency of typical week

**Positive Variables:**
$K_{r,i}$ – Endogenously optimized capacities
$y_{tw,t,r,i}$ / $y^{H2}_{tw,t,r,iPtH2}$ – Electricity / H2 production

**Parameters:**
$c^{H2}$ – H2 import costs

**Positive Variables:**
$\omega^{H2}_{tw,t,r}$ – Third country imports

# Integrated subproblem – Demand constraints

- **Electricity demand:**

$$\underbrace{\sum_{i} y_{tw,t,r,i}}_{\text{Elec. production}} + \underbrace{\sum_{iStoEl} y^{dis}_{tw,t,r,iStoEl} - \sum_{iStoEl} y^{cha}_{tw,t,r,iStoEl}}_{\text{Charging and discharging of elec storages}} - \underbrace{\sum_{iPtH2} y^{cha}_{tw,t,r,iPtH2}}_{\text{Charging of electrolyzers}} + \underbrace{\sum_{rr} (x^{exp,el}_{tw,t,rr,r} - x^{imp,el}_{tw,t,r,rr})}_{\text{Exports and imports}} + \underbrace{\omega_{tw,t,r}}_{\text{Slack}} = \underbrace{D_{tw,t,r}}_{\text{Exogenous demand}} \quad \forall\, tw,t,r$$

- **H2 demand:**

$$\underbrace{\sum_{iPtH2} y^{H2}_{tw,t,r,iPtH2} + \sum_{iH2} y^{cons,H2}_{tw,t,r,iH2}}_{\text{H2 production and consumption}} + \underbrace{\sum_{iStoH2} y^{dis,H2}_{tw,t,r,iStoH2} - \sum_{iStoH2} y^{cha,H2}_{tw,t,r,iStoH2}}_{\text{Charging and discharging of seasonal H2 storage}} + \underbrace{\sum_{rr} (x^{exp,H2}_{tw,t,rr,r} - x^{imp,H2}_{tw,t,r,rr})}_{\text{Exports and imports}} + \underbrace{\omega^{H2}_{tw,t,r}}_{\text{Third country imports}} = \underbrace{D^{H2}_{tw,t,r}}_{\text{Exogenous demand}} \quad \forall\, tw,t,r$$

- Further constraints
  - Max. capacity, RES production, max. transmission capacities, H2 production, storage filling levels, …

# Sequential subproblems – Demand constraints

- **Electricity demand:**

$$\underbrace{\sum_{i} y_{tw,t,r,i}}_{\text{Elec. production}} + \underbrace{\sum_{iStoEl} y^{dis}_{tw,t,r,iStoEl} - \sum_{iStoEl} y^{cha}_{tw,t,r,iStoEl}}_{\text{Charging and discharging of elec storages}} - \underbrace{\sum_{iPtH2} y^{cha}_{tw,t,r,iPtH2}}_{\text{Charging of electrolyzers}} + \underbrace{\sum_{rr} \left(x^{exp,el}_{tw,t,rr,r} - x^{imp,el}_{tw,t,r,rr}\right)}_{\text{Exports and imports}} + \underbrace{\omega_{tw,t,r}}_{\text{Slack}} = \underbrace{D_{tw,t,r}}_{\text{Exogenous demand}} \quad \forall\, tw, t, r$$

- **H2 demand:**

$$\underbrace{\sum_{iPtH2} y^{H2}_{tw,t,r,iPtH2} + \sum_{iH2} y^{cons,H2}_{tw,t,r,iH2}}_{\text{H2 production and consumption}} + \underbrace{\sum_{iStoH2} y^{dis,H2}_{tw,t,r,iStoH2} - \sum_{iStoH2} y^{cha,H2}_{tw,t,r,iStoH2}}_{\text{Charging and discharging of seasonal H2 storage}} + \underbrace{\sum_{rr} \left(x^{exp,H2}_{tw,t,rr,r} - x^{imp,H2}_{tw,t,r,rr}\right)}_{\text{Exports and imports}} + \underbrace{\omega^{H2}_{tw,t,r}}_{\text{Third country imports}} = \underbrace{D^{H2}_{tw,t,r}}_{\text{Exogenous demand}} \quad \forall\, tw, t, r$$

Variables → Parameters

- Further constraints
  - Max. capacity, RES production, max. transmission capacities, H2 production, storage filling levels, …

# Master Problem: Benders Cuts

$$
\begin{aligned}
\theta \geq\ & C_{j'}^{Op,Elec} + C_{j'}^{Op,Gas} \\
& + \sum\nolimits_{tw,t,r,iConv} \vartheta_{tw,t,r,iH2,j'}^{\max\_cap} \cdot \left(K_{r,iH2,j} - K_{r,iH2,j'}\right) \\
& + \sum\nolimits_{tw,t,r,iPtH2} \vartheta_{tw,t,r,iPtH2,j'}^{\max\_ptg} \cdot \left(K_{r,iPtH2,j} - K_{r,iPtH2,j'}\right) \\
& + \ldots \\
& \forall\, j'
\end{aligned}
$$

Obj. fct. values of subproblems

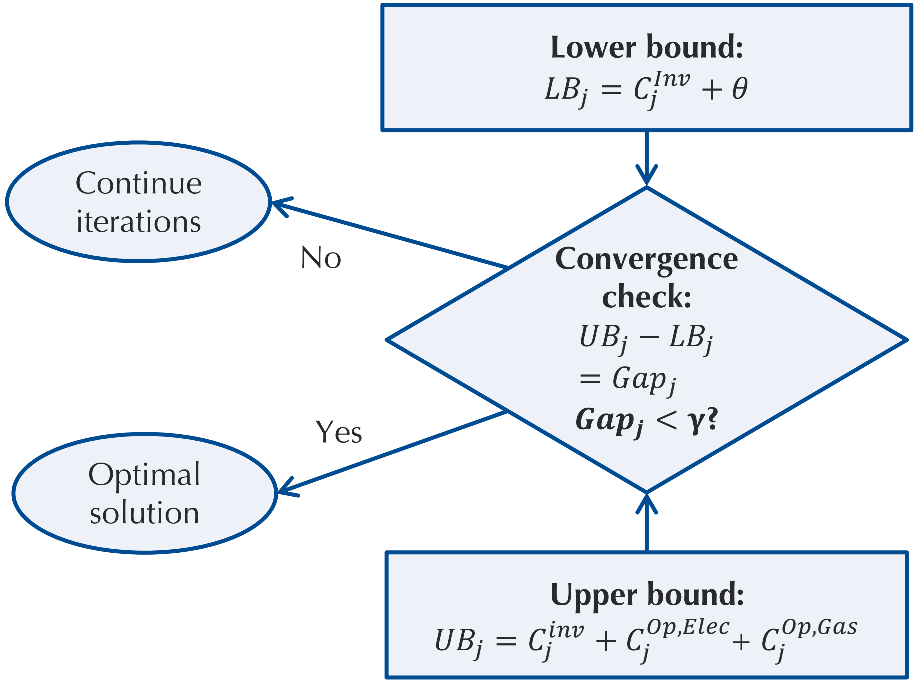
Cutting plane of H2 power plants

Cutting plane of electrolyzers (PtH2)

Potential further terms if capacities of more technologies are modelled endogenously

$j$ – Current iteration
$j'$ – Previous iterations
$\gamma$ – Optimality threshold

- $\theta$ is added to obj. fct. of master problem
- Dual values $\vartheta$ of capacity restrictions incentivize capacity adjustment in following iterations
- Added cuts reduce the solution space



**Lower bound:**
$LB_j = C_j^{Inv} + \theta$

**Convergence check:**
$UB_j - LB_j = Gap_j$
$\boldsymbol{Gap_j < \gamma}$**?**

**Upper bound:**
$UB_j = C_j^{inv} + C_j^{Op,Elec} + C_j^{Op,Gas}$

# Integrated vs. sequential subproblems – solutions

**Main challenge:**
How to properly handle excess production of hydrogen in the elec. SP?

**Naive approach:**
Implementation of slack variable in H2 demand constraint of the gas SP
- Opposite of import variable
- Surplus is sold and revenues are subtracted in obj. function
- ➢ Influences obj. function value
- ➢ No direct influence on Benders cuts

**Redispatch approach:**
Implementation of electrolyzer redispatch in the gas SP
- Negative redispatch in surplus hours
- Elec. price from elec. SP as compensation
- Dual of redispatch capacity constraint added to Benders cut
- ➢ Influences obj. function value
- ➢ Direct influence on Benders cuts

Note:
We exclude *nested Benders* with inner iteration loop between subproblems because it would take to much time due to the expected amount of iterations.

# Redispatch approach

- Adaption of objective function

$$min!\ C^{Op,Gas} = \sum_{tw,t,r} w^{H2}_{tw,t,r} \cdot c^{H2} \cdot freq_{tw} + \sum_{tw,t,r,iPtH2} \left(y^{RD+}_{tw,t,r,iPtH2} - y^{RD-}_{tw,t,r,iPtH2}\right) \cdot p^{el}_{tw,t,r} \cdot freq_{tw}$$

Elec. price from elec. SP

- New capacity constraint

$$y^{cha,fix}_{tw,t,r,iPtH2} + y^{RD+}_{tw,t,r,iPtH2} \leq K^{0}_{r,iPtH2} + K_{r,iPtH2} \quad \forall\, tw,t,r,iPtH2 \quad | \quad \vartheta^{max\_pth2\_rd}_{tw,t,r,iPtH2}$$

Elec. consumption of electrolyzer from elec. SP

Dual variable that is added to the Benders cut instead of the dual from the elec. SP

$$y^{cha,fix}_{tw,t,r,iPtH2} - y^{RD-}_{tw,t,r,iPtH2} \geq 0 \quad \forall\, tw,t,r,iPtH2$$

- Adaption of H2 demand contraint

$$\sum_{iPtH2}\left(y^{H2}_{tw,t,r,iPtH2} + \left(y^{RD+}_{tw,t,r,iPtH2} - y^{RD-}_{tw,t,r,iPtH2}\right) \cdot eff_{iPtH2}\right) + \sum_{iH2} y^{cons,H2}_{tw,t,r,iH2} + \sum_{iStoH2} y^{dis,H2}_{tw,t,r,iStoH2} - \sum_{iStoH2} y^{cha,H2}_{tw,t,r,iStoH2}$$

$$+ \sum_{rr}\left(x^{exp,H2}_{tw,t,rr,r} - x^{imp,H2}_{tw,t,r,rr}\right) + \omega^{H2}_{tw,t,r} = D^{H2}_{tw,t,r} \quad \forall\, tw,t,r$$

# Data and cases

- Settings
  - Two regions (DE & FR)
  - Four typical weeks
    - tw_5, tw_22, tw_34 and tw_51
  - 168 time steps per week (hourly)
  - Simulation year 2045
- Cases
  - Base: Integrated optimization
  - Sequential subproblem
    - SeqSP_Naive: Seq. SP with naive correction
    - SeqSP_RD: Seq. SP with redispatch
- Scenario data
  - DE: Grid Expansion Plan (B 2045) *
  - FR: TYNDP 2022 – Distributed Energy **
- Technologies
  - Endogenous capacity adjustment
    - **Electrolyzers (PtH2)**
    - **H2 power plants**
  - Exogenous capacities
    - Renewables (Wind onshore, W. offshore, PV, RoR)
    - Nuclear (only in FR)
    - Storage technologies (Batteries, Pump storage, Seasonal H2 storage)

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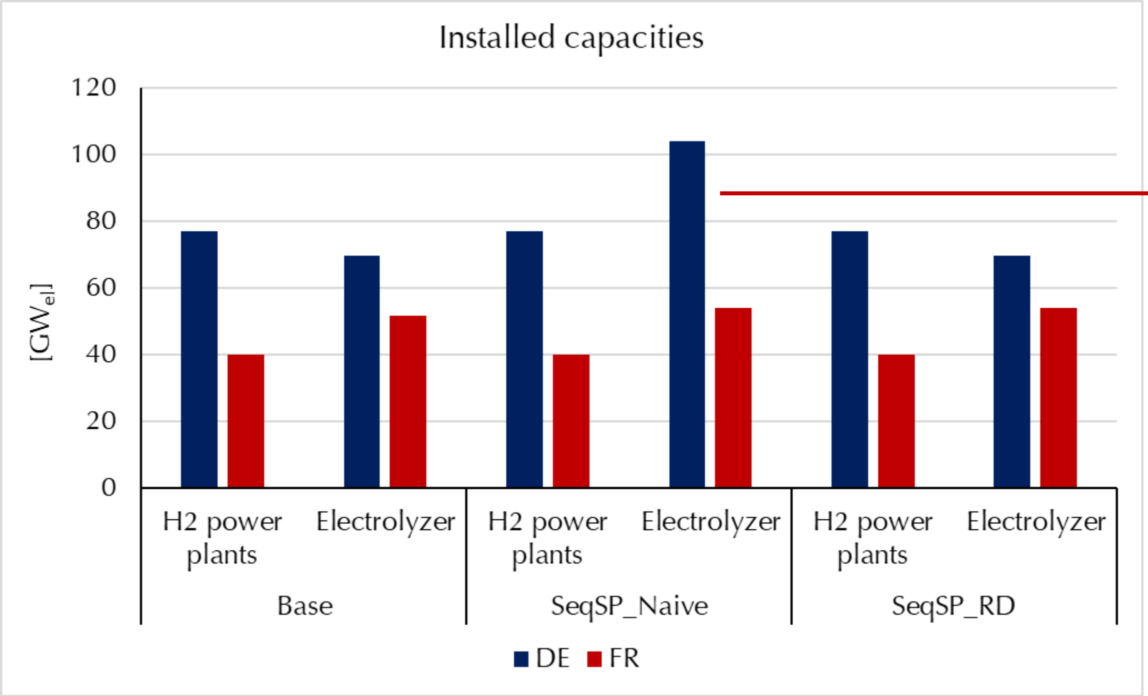
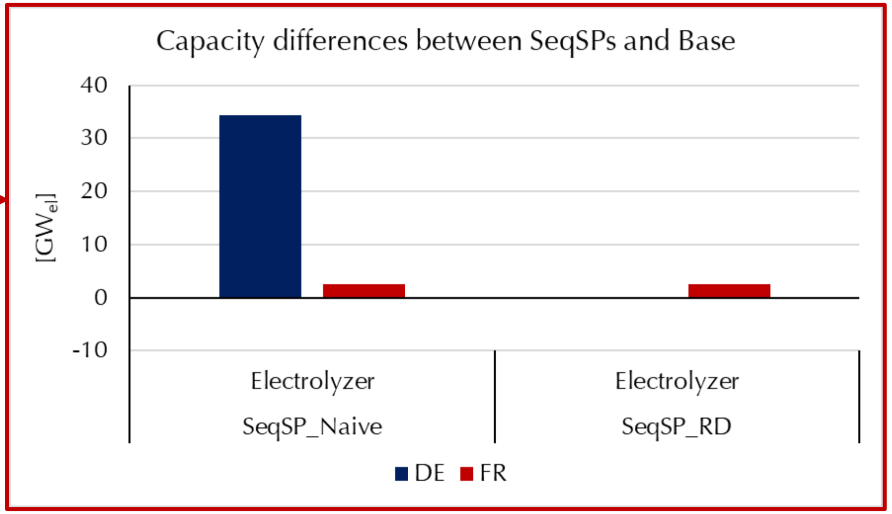
* *https://www.netzentwicklungsplan.de/sites/default/files/2023-01/Szenariorahmen_2037_Genehmigung.pdf*
** *https://2022.entsos-tyndp-scenarios.eu/download/*

# Results – Installed capacities



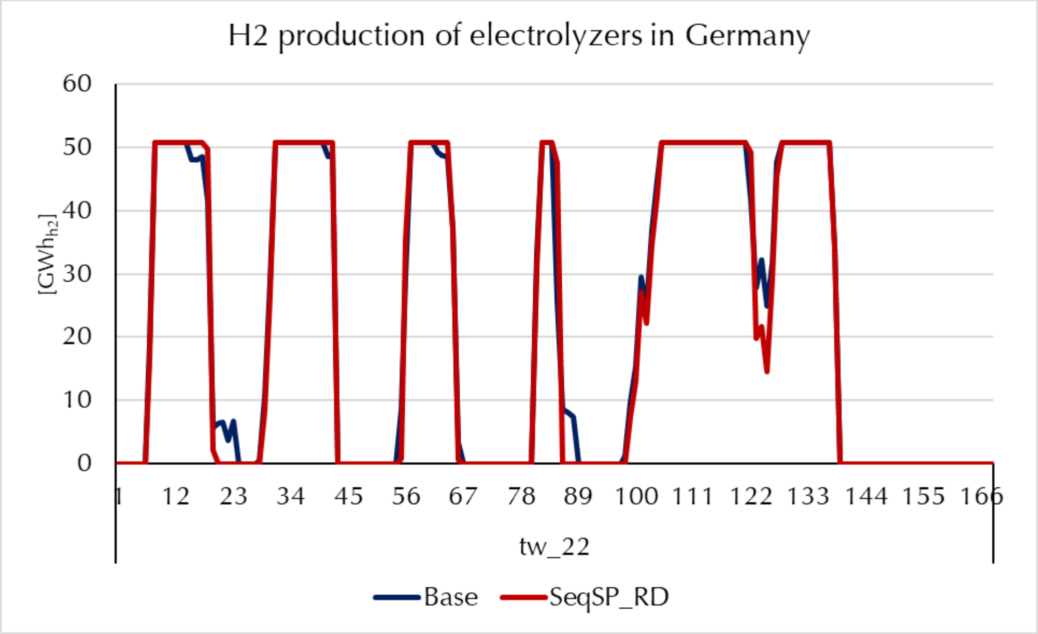


- In *SeqSP_RD*, capacity difference decreases from > 30 GW to 2.4 GW

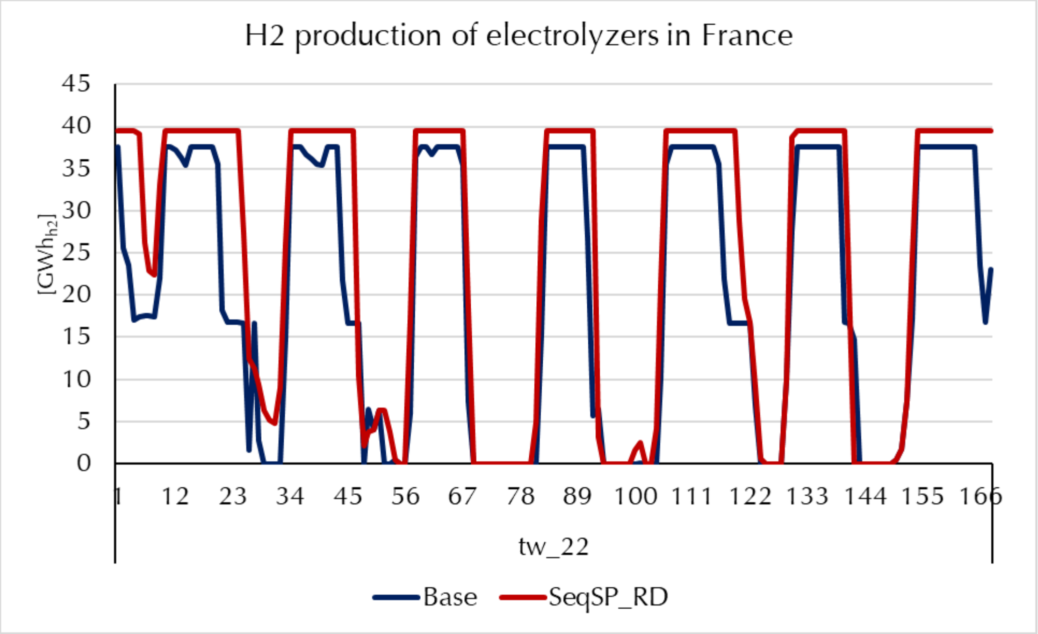
- Both *SeqSP* variants yield optimal H2 power plant capacities
- Subtantial difference of > 30 GW in electrolyzer capacity for *SeqSP_Naive*

| Case | Iterations |
|---|---|
| Base | 64 |
| SeqSP_Naive | 58 |
| SeqSP_RD | 72 |

# Results – Electrolyzer dispatch



- Larger differences in France due to larger difference in installed capacity



- Electrolyzer dispatch in Germany is approximated quite well

# Summary

- Sequential subproblems in expansion planning with Benders Decomposition pose challenges
    - No integrated optimization of hydrogen production, consumption and storage
    - Obstacle of missing integration needs to be overcome by adaptions

- Naive approach converges, but results differ subtantially from integrated results
    - excessive incentivization of electrolyzer capacity expansion due to overestimated revenues in gas SP

- Redispatch approach promising, yet results still differ in a two-region case
    - Iterative adaption of Benders cut with dual from gas SP leads to reasonable results
    - No (strong) excessive incentivization due to handling of surplus hours

# Conclusion and outlook

## Main findings

- Approach enables…
  - coupling of existing infrastructure models with an investment model in a sequential setting
  - integrated expansion planning of sector-coupled systems
- Approach beneficial…
  - when code owners cannot disclose proprietary information (e. g. full model code)
  - when integrated modeling of expansion planning in large system models computational too difficult

## Outlook

- Further develop method to reduce remaining gap in a multi region / node case
- Application to more complex models
  - currently ongoing work in the project → 39 regions case (NUTS2)

## Remaining questions

- Can the remaining gap (in the multi-region case) be reduced or is it an error that has to be accepted?

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# Thank you for your attention

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