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Accounting for seasonal storage dispatch in expansion planning of integrated power and gas systems via Benders Decomposition

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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

➢ For analysis of effects of hydrogen strategies integrated modelling approaches are required

Agenda

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 markets
  - Analysis of implications of different hydrogen strategies
  - Focus on the development of a mathematical model coupling approach

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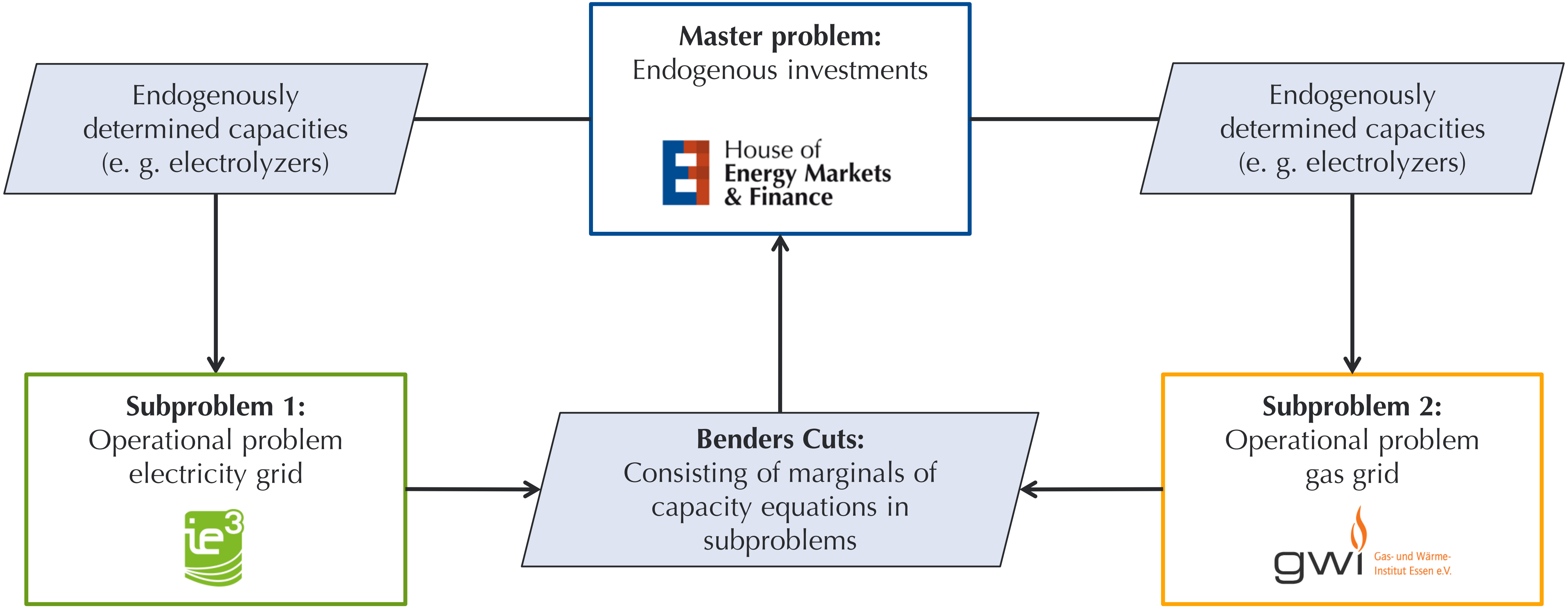
MOPPL: Benders Decomposition



Master problem:
Endogenous investments

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Endogenously
determined capacities
(e. g. electrolyzers)

Endogenously
determined capacities
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Subproblem 1:
Operational problem
electricity grid

Benders Cuts:
Consisting of marginals of
capacity equations in
subproblems

Subproblem 2:
Operational problem
gas grid

gwi Gas- und Wärme-
Institut Essen e.V.

MOPPL: Challenges

1. High level of detail in both subproblems
   - Nodal simulations with time-coupling contraints (e. g. storages)

- ➢ Reduction of computational burden necessary
  - Four typical weeks with hourly time steps will be simulated

2. High iteration count of Benders Decomposition expected
   - Esp. when endogenously optimizing expansion of several technologies

- ➢ Parallel computing of typical weeks in sub problems planned
  - Typical weeks must be independent of each other

Research Question:

How to combine Benders Decomposition with typical weeks and the modelling of seasonal storages?

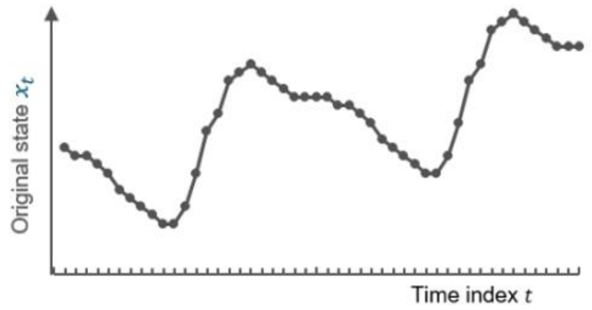
Modelling of typical weeks and seasonal storages

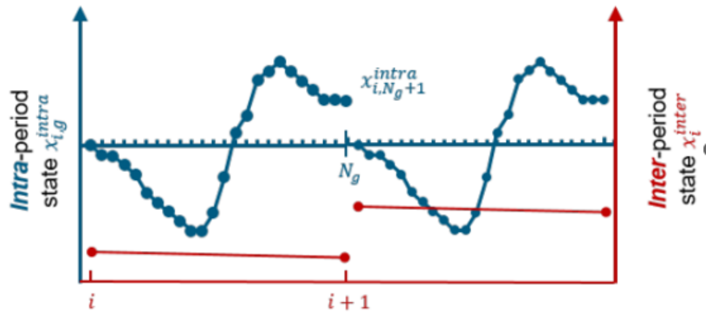
- Approach is based on the work of *Kotzur et al. (2018)* *

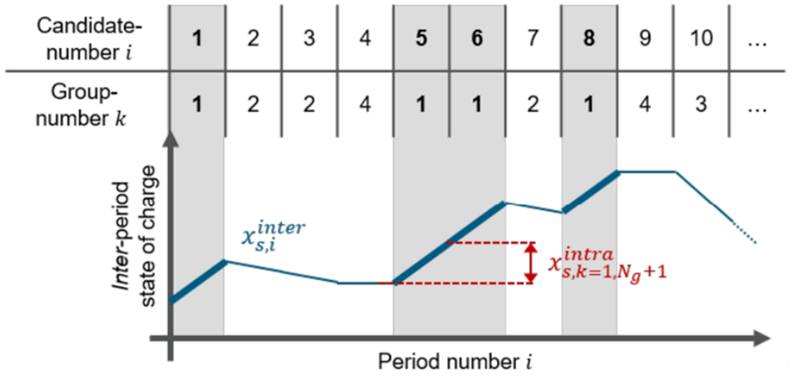
- Decomposition of filling levels into an intra-period filling level and an inter-period filling-level
  - Intra-period: hourly level within typical period
  - Inter-period: seasonal level of typical period
  - Next inter-period filling level determined by final intra-period filling level

➢ Yields consistent seasonal storage optimization based on typical weeks

➢ Application to Benders Decomposition
  - Inter-period optimization in master problem
  - Intra-period optimization in subproblem
  - → Transfer of storage bounds to the subproblem







Candidate-number i	**1**	2	3	4	**5**	**6**	7	**8**	9	10	…
Group-number k	**1**	2	2	4	**1**	**1**	2	**1**	4	3	…

* *Time series aggregation for energy system design: Modeling seasonal storage*
(Figures by Kotzur et al.)

Master and subproblem: objective functions

- **Stylized energy system model**
  - Master problem:
    Determination of capacity adjustment and seasonal storage bounds
  - Subproblem:
    Optimization of dispatch of generation and storage technologies

- **Objective function (overall problem)**

$$min!\ C^{total} = C^M + C^{op}$$

- **Master problem:**

$$C^M = \underbrace{\sum_{r,i} c_i^{inv} \cdot K_{r,i}}_{\text{Investment costs}} + \underline{\alpha}$$

Restricted by Benders Cuts

- **Subproblem:**

$$C^{op} = \underbrace{\sum_{tw,t,r,i} y_{tw,t,r,i} \cdot c_i^{var} \cdot freq_{tw}}_{\text{Generation costs}} + \underbrace{\sum_{tw,t,r} \omega_{tw,t,r} \cdot freq_{tw} \cdot 10^6}_{\text{Slack costs}} + \underbrace{\sum_{tw,t,r,iRes} a_{tw,t,r,iRes} \cdot freq_{tw} \cdot 50}_{\text{Curtailment costs}}$$

Sets:
tw – Typical weeks / w – Regular weeks
t – Time steps within a typical week (hourly)
r – Regions
i – Technologies
$iRes(i)$ – Subset for renewable technologies
$iStoH2(i)$ – Subset for seasonal H2 storage technologies
$iStoEl(i)$ – Subset for electricity sotrage technologies

Parameters:
c_i^{inv} / c_i^{var} – Investment and variable costs of technologies
$freq_{tw}$ – Count of typical week per year

Positive variables:
$K_{r,i}$ – Endogenously determined capacity adjustment
$y_{tw,t,r,i}$ – Electricity production of generation technologies

Master problem: seasonal storage equations (I)

- **Inter-period filling level (FL) (w/ circle condition):**

$$f^{inter}_{w+1,r,iStoH2} = f^{inter}_{w,r,iStoH2} + f^{intra,end}_{tw \in w\_tw(w,tw),r,iStoH2} \quad \forall\, w, r, iStoH2$$

  - Changes of inter-period FL driven by final intra-period FL

- **Max. intra-period filling level:**

$$f^{intra,end}_{tw,t,r,iStoH2} \leq f^{intra,max}_{tw,r,iStoH2} \quad \forall\, tw, t, r, iStoH2$$

  - Final intra-period FL limited by maximum intra-period FL

- **Min. intra-period filling level:**

$$f^{intra,end}_{tw,t,r,iStoH2} \geq f^{intra,min}_{tw,r,iStoH2} \quad \forall\, tw, t, r, iStoH2$$

  - Final intra-period FL limited by minimum intra-period FL

Free variables:

$f^{inter}_{w,r,iStoH2}$ – Inter-period filling level

$f^{intra,end}_{tw,r,iStoH2}$ – Final intra-period filling level

$f^{intra,max}_{tw,r,iStoH2}$ – Maximum intra-period filling level

$f^{intra,min}_{tw,r,iStoH2}$ – Minimum intra-period filling level

Master problem: seasonal storage equations (II)

Parameter:
ϵ – Energy-to-power ratio (storage volume factor)

- **Max. total filling level:**

$$f^{inter}_{w,r,iStoH2} + f^{intra,max}_{tw \in w\_tw(w,tw),r,iStoH2} \leq K_{r,iStoH2} \cdot \epsilon \quad \forall\, w, r, iStoH2$$

  - Combined FL limited by storage capacity and volume factor

- **Min. total filling level:**

$$f^{inter}_{w,r,iStoH2} + f^{intra,min}_{tw \in w\_tw(w,tw),r,iStoH2} \geq 0 \quad \forall\, w, r, iStoH2$$

  - Combined FL must be positive

- Plus auxiliary equations that prevent infeasible storage bounds in subproblem and accelerate convergence

Transferred to the subproblem:

- Max. intra-period filling level: $f^{intra,max}_{tw,r,iStoH2}$
- Min. intra-period filling level: $f^{intra,min}_{tw,r,iStoH2}$
- Final intra-period filling level: $f^{intra,end}_{tw,r,iStoH2}$

$\Big\}$ Parameters in the subproblem

Subproblem: main restrictions

- **Electricity demand:**

$$\underbrace{\sum_{i} y_{tw,t,r,i}}_{\text{Elec. generation}} + \underbrace{\sum_{iStoEl} y^{dis}_{tw,t,r,iStoEl} - \sum_{iStoEl} y^{cha}_{tw,t,r,iStoEl}}_{\text{Storage discharging and charging}} + \underbrace{\sum_{rr} (x^{exp,el}_{tw,t,rr,r} - x^{imp,el}_{tw,t,r,rr})}_{\text{Exports and imports}} + \underbrace{\omega_{tw,t,r}}_{\text{Slack}} = \underbrace{D_{tw,t,r}}_{\text{Demand}} \qquad \forall\, tw,t,r$$

- **Hydrogen demand:**

$$\underbrace{\sum_{iPtH2} y^{H2}_{tw,t,r,iPtH2} + \sum_{iConv} y^{cons,H2}_{tw,t,r,iPtH2}}_{\text{Electrolysis and consumption of H2 power plants}} + \underbrace{\sum_{iStoH2} y^{dis,H2}_{tw,t,r,iStoH2} - \sum_{iStoH2} y^{cha,H2}_{tw,t,r,iStoH2}}_{\text{Storage discharging and charging}} + \underbrace{\sum_{rr} (x^{exp,H2}_{tw,t,rr,r} - x^{imp,H2}_{tw,t,r,rr})}_{\text{Exports and imports}} + \underbrace{\omega^{H2}_{tw,t,r}}_{\text{Slack (3rd country imports)}} = \underbrace{D^{H2}_{tw,t,r}}_{\text{Demand}} \qquad \forall\, tw,t,r$$

- Further restrictions
  - Max. capacity and filling levels, renewable generation, max. transmission capacity, hydrogen production, …

Subproblem: seasonal storage equations

- **Max. charging & discharging:**

$$y^{cha,H2}_{tw,t,r,iStoH2} + y^{dis,H2}_{tw,t,r,iStoH2} \leq K_{r,iStoH2} \quad \forall\, tw,t,r,iStoH2 \quad | \quad \vartheta^{\max\_d-ch}_{tw,t,r,iStoH2}$$

- **Filling level restriction:**

$$f^{intra}_{tw,t,r,iStoH2} = f^{intra}_{tw,t-1,r,iStoH2} + y^{cha,H2}_{tw,t,r,iStoH2} \cdot \mu - y^{dis,H2}_{tw,t,r,iStoH2} \cdot \frac{1}{\mu} \quad \forall\, tw,t,r,iStoH2$$

- **Initial filling level:**

$$f^{intra}_{tw,t,r,iStoH2} - \left(y^{cha}_{tw,t,r,iStoH2} \cdot \mu - y^{dis}_{tw,t,r,iStoH2} \cdot \frac{1}{\mu} \right) = 0 \quad \forall\, tw,t_1,r,iStoH2$$

Storage bounds from master problem:

- Max. filling level: $f^{intra}_{tw,t,r,iStoH2} \leq f^{intra,max}_{tw,riStoH2} \quad \forall\, tw,t,r,iStoH2 \quad | \quad \vartheta^{\max\_vol}_{tw,t,r,iStoH2}$
- Min. filling level: $f^{intra}_{tw,t,r,iStoH2} \geq f^{intra,min}_{tw,r,iStoH2} \quad \forall\, tw,t,r,iStoH2 \quad | \quad \vartheta^{\min\_vol}_{tw,t,r,iStoH2}$
- Final filling level: $f^{intra}_{tw,t,r,iStoH2} = f^{intra,end}_{tw,r,iStoH2} \quad \forall\, tw,t_{168},r,iStoH2 \quad | \quad \vartheta^{end}_{tw,t_{168},r,iStoH2}$

Free variable:

$f^{intra}_{tw,t,r,iStoH2}$ – Intra-period filling level

Dual variables (marginals):

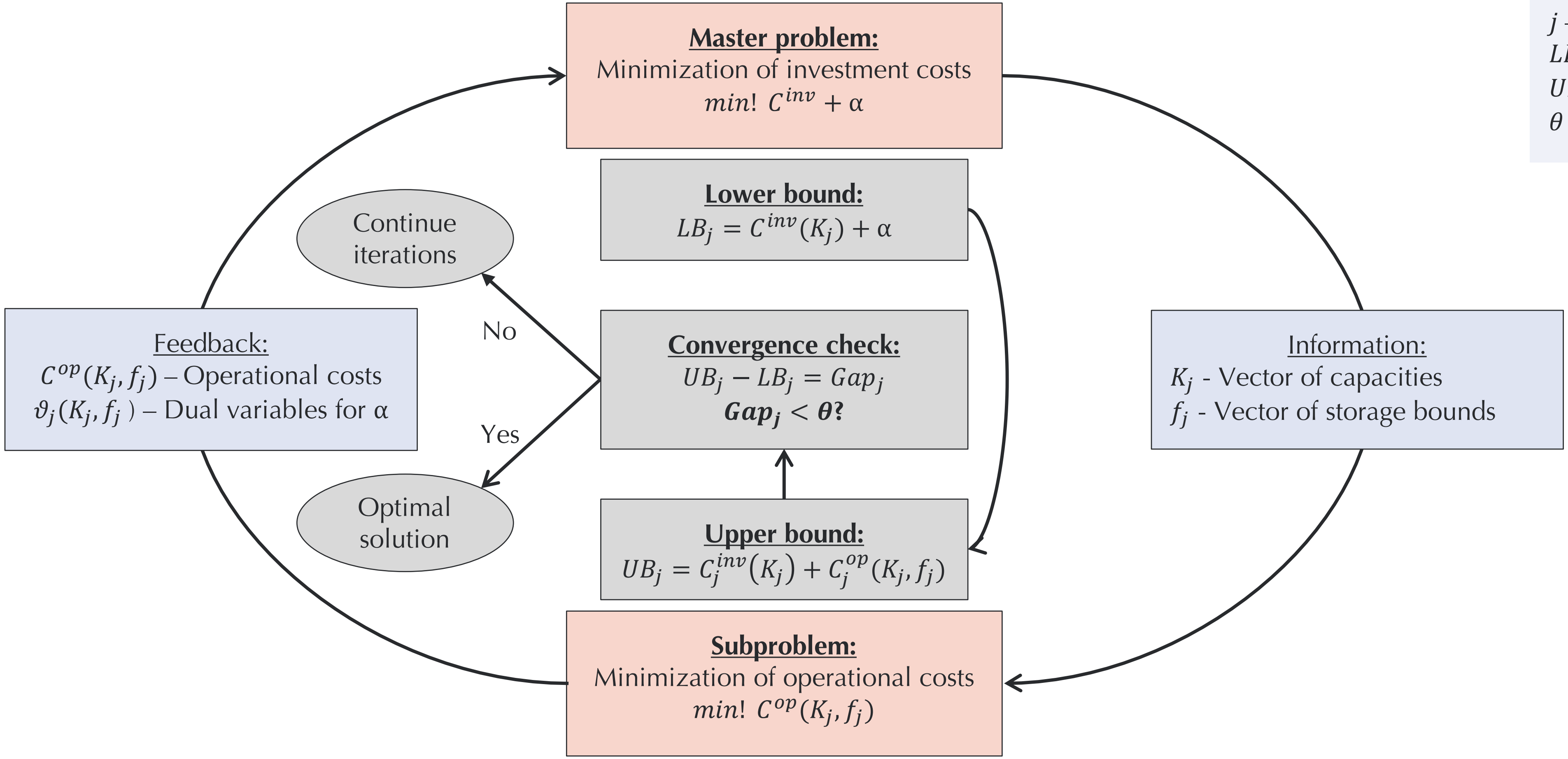
$\vartheta_{tw,t,r,iStoH2}$ – Variables of dual problem (marginals) for Benders Cut

Parameter:

μ – Charging and discharging efficiency
$f^{intra,max}_{tw,riStoH2}$ – Max. FL from master problem
$f^{intra,min}_{tw,r,iStoH2}$ – Min. FL from master problem
$f^{intra,end}_{tw,r,iStoH2}$ – Final FL from master problem

Summary

j – Iteration
LB_j – Lower bound
UB_j – Upper bound
θ – Threshold convergence



Master problem:
Minimization of investment costs
$min!\ C^{inv} + \alpha$

Information:
K_j - Vector of capacities
f_j - Vector of storage bounds

Subproblem:
Minimization of operational costs
$min!\ C^{op}(K_j, f_j)$

Feedback:
$C^{op}(K_j, f_j)$ – Operational costs
$\vartheta_j(K_j, f_j)$ – Dual variables for α

Lower bound:
$LB_j = C^{inv}(K_j) + \alpha$

Upper bound:
$UB_j = C_j^{inv}(K_j) + C_j^{op}(K_j, f_j)$

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

Master problem: Benders cuts

$$
\begin{aligned}
&\alpha \geq C^{op}_{j'} \\
&+ \sum_{tw,t,r,iConv} \vartheta^{\max\_cap}_{tw,t,r,iConv,j'} \cdot \left(K_{r,iConv,j} - K_{r,iConv,j'}\right) \\
&+ \ \ldots \\
&+ \sum_{tw,t,r,iStoH2} (\vartheta^{\max\_d-ch}_{tw,t,r,iStoH2,j'} \cdot \left(K_{r,iStoH2,j} - K_{r,iStoH2,j'}\right) \\
&+ \vartheta^{\max\_vol}_{tw,t,r,iStoH2,j'} \cdot \left(f^{intra,max}_{tw,r,iStoH2,j} - f^{intra,max}_{tw,r,iStoH2,j'}\right) \\
&+ \vartheta^{\min\_vol}_{tw,t,r,iStoH2,j'} \cdot \left(f^{intra,min}_{tw,r,iStoH2,j} - f^{intra,min}_{tw,r,iStoH2,j'}\right) \\
&+ \vartheta^{end}_{tw,t,r,iStoH2,j'} \cdot \left(f^{intra,end}_{tw,r,iStoH2,j} - f^{intra,end}_{tw,r,iStoH2,j'}\right)) \\
&\forall\, j'
\end{aligned}
$$

Operational costs of sub problem

Cutting plane of max. capacity restriction

Cutting planes of further capacity restrictions (RES, PtH2, …)

Cutting plane of charging and discharging restriction

Cutting plane of max. filling level restriction

Cutting plane of min. filling level restriction

Cutting plane of final filling level restriction

j – Current iteration
j' – Previous iterations

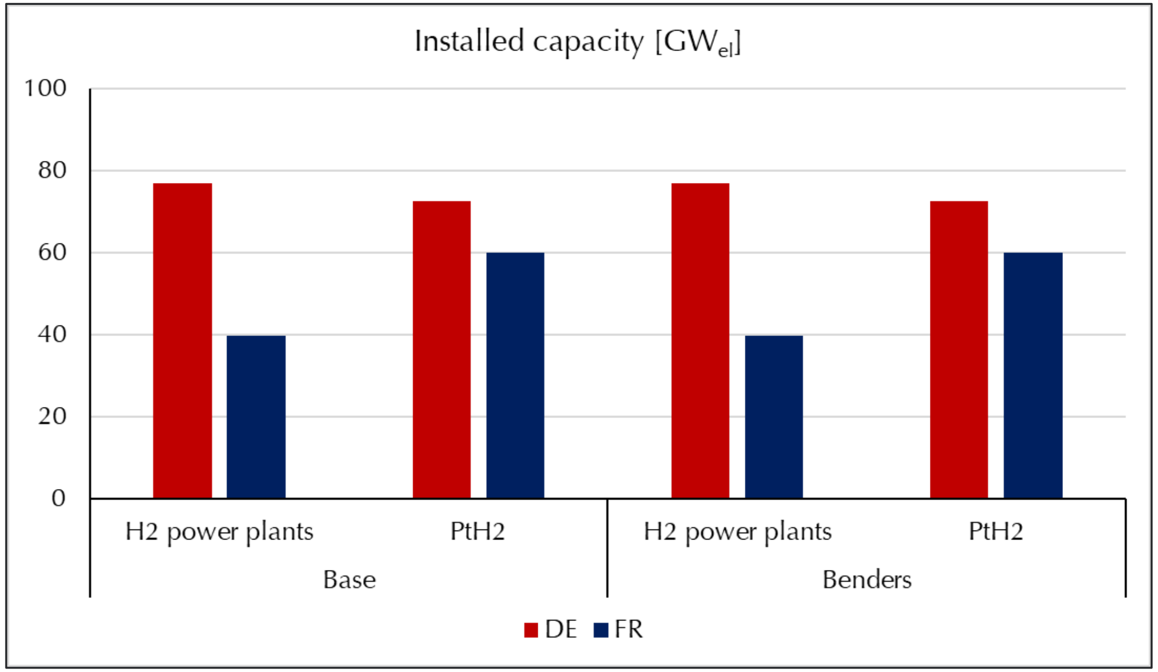
- α is added to the objective function in the master problem
- Marginals incentivize change of capacity expansion and storage bounds

Data and cases

- Setting
  - Two regions: DE and FR
  - Four typical weeks
    - tw_5, tw_22, tw_34 and tw_51
  - 168 time steps per week (hourly)
  - Simulation year 2045
- Cases
  - Base: Closed optimization
  - Benders: Decomposition with optimization of capacities and seasonal storage bounds in the master problem
- 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**)

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

Selected Results



Case	Annualized invest. costs [bn. €]	Operational costs [bn. €]
Base	24	115
Benders	24	115

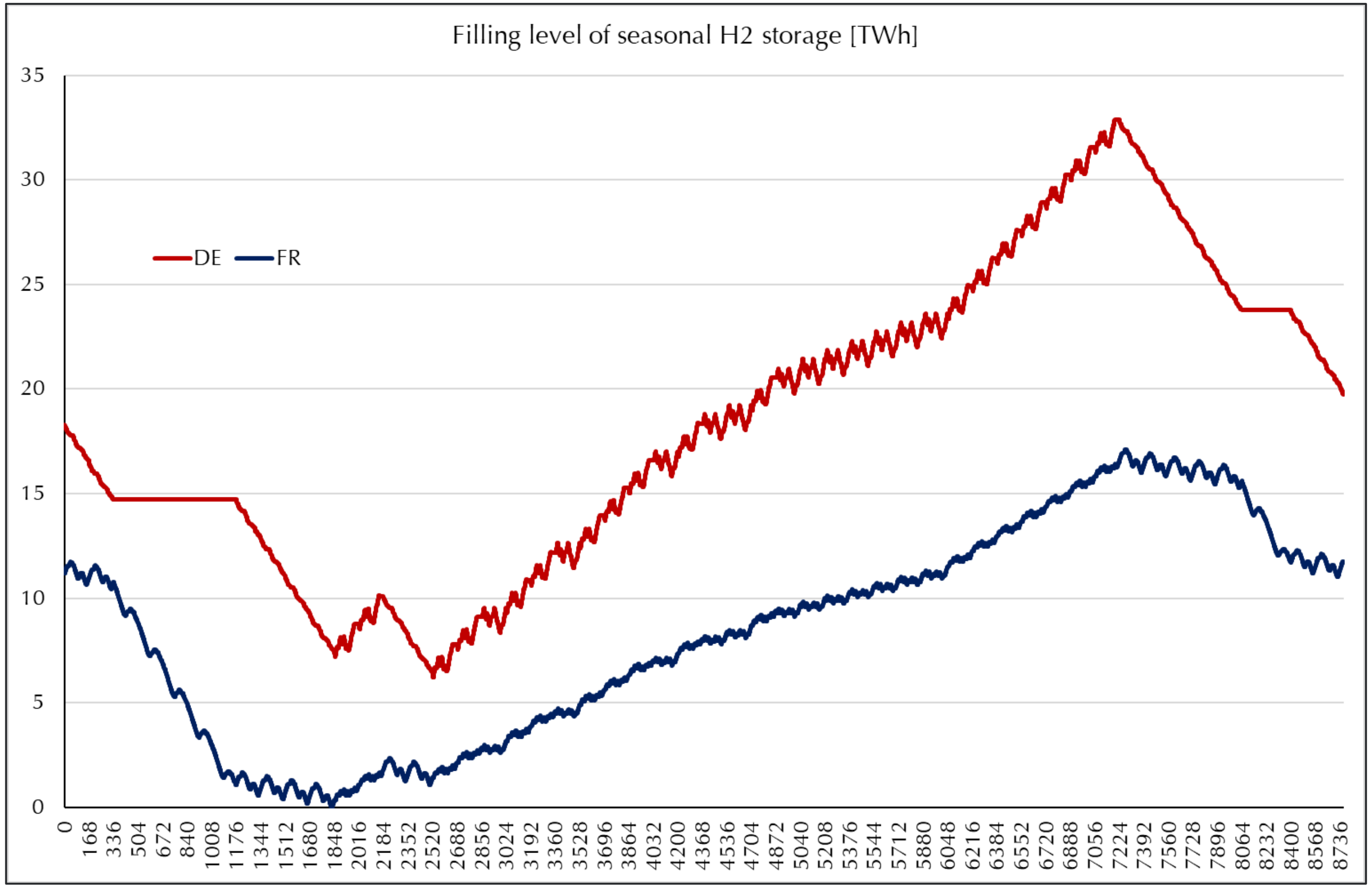
- ➢ Both cases result in nearly equal inv. and op. costs

Case	Runtime [MM:SS]	Iterations
Base	00:22	-
Benders	05:53	330

- ➢ Benders Decomposition case yields the same capacities as determined by the closed model
- ➢ Lower runtime in model without Benders Decomposition

Seasonal storage filling levels: DE and FR

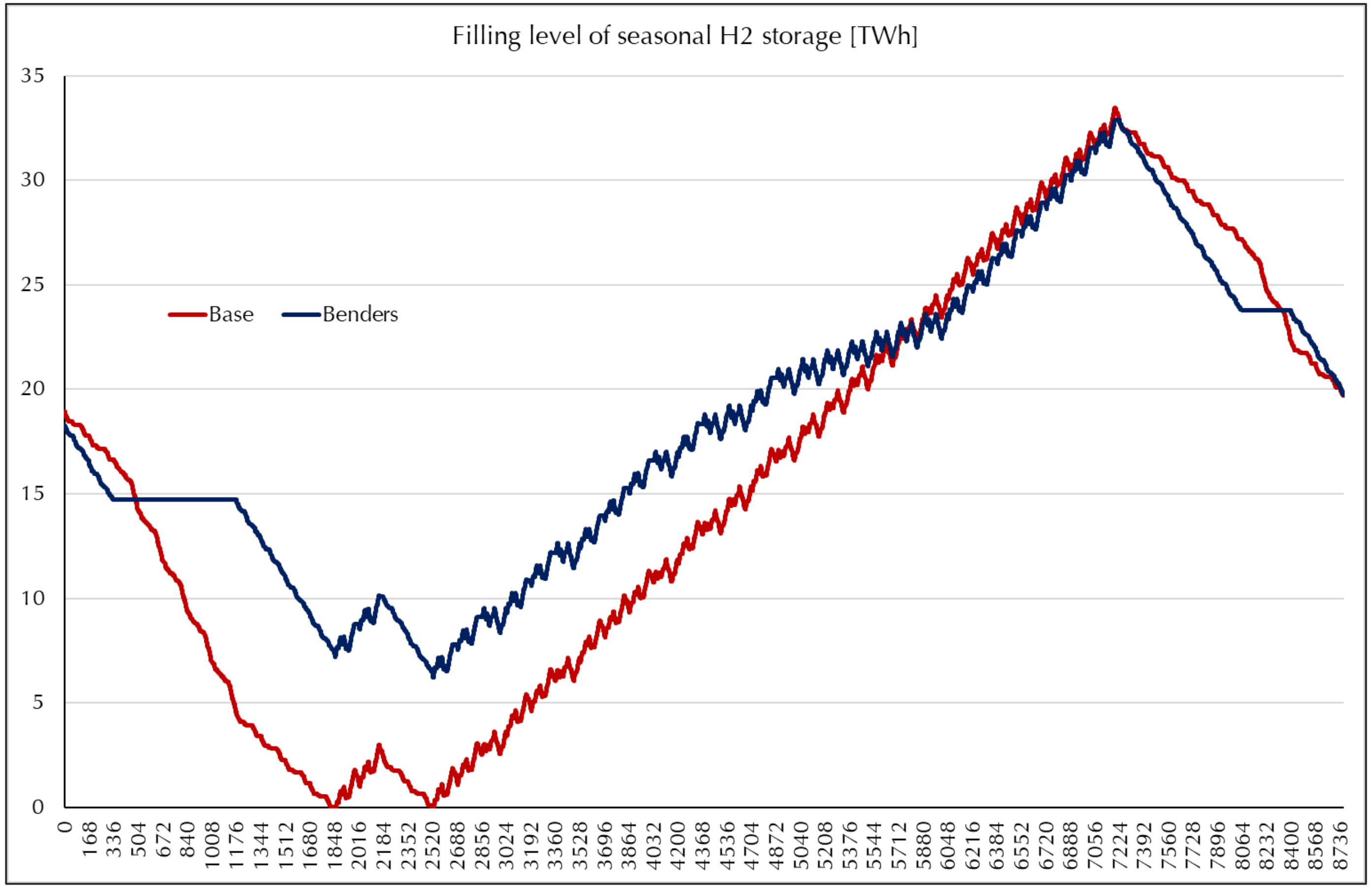
- Method yields consistent seasonal storage filling level
- Yearly reconstruction by adding
  - Intra-period filling level of typical weeks
  - Inter-period filling levels of all weeks
- Flat weeks caused by low intra-period storage level changes



Seasonal storage filling levels: Base vs. Bender (DE)

- Differences in course of storage filling level
  - No influence on system costs and endogenous capacities

➢ Different filling levels lead to an optimal solution


Filling level of seasonal H2 storage [TWh]

Conclusion and outlook

Main findings

- Method enables…
  - consistent storage optimization with Benders Decomposition and typical weeks
  - parallel computing of typical weeks in the subproblem
- Method beneficial…
  - when computational burden of integrated model is too high
  - for coupling of separate investment and dispatch models

Outlook

- Investigating techniques to accelarate convergence
- Application to more complex models
  - Higher spatial granularity
  - Separate subproblems for electricity and gas systems
- Coupling with detailed infrastructure models of project partners

Thank you for your attention

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