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Assessment of future balancing market mechanisms

Post 2020 evolution of the Target Model: Quantitative assessments

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Overview

- Motivation

- Model – Methodology
    - Initial Model: EDisOn
    - Add on: EDisOn+Balancing

- Analyses – Market Designs
    - Results of the 2030 scenarios

- Preliminary conclusions and further developments

Motivation

- achievement and implementation of the Internal Energy Market - IEM
- Agency for the Cooperation of Energy Regulators
  → Framework Guidelines on Electricity Balancing (**FG EB**)
- European Network of Transmission System Operators for Electricity
  → Network Code on Electricity Balancing (**NC EB**)

  provides general guidelines, while it leaves many questions unanswered, e.g.

  - joint or separated organized procurement of positive and negative balancing capacity and balancing energy products,
  - different minimum bid sizes (from 1 MW to 5 MW),
  - the product pricing (pay-as-bid vs. marginal),
  - the pricing system (dual, single, combined),
  - and the settlement period (15 minutes to an hour).

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Initial Model: EDisOn

= Electricity Dispatch Optimization: Linear Programming (LP) developed in MATLAB® (yalmip) and solved by Gurobi-Solver! (based on (Burger et al., 2007), (Shahidehpour et al., 2002))

- deterministic and assumes a perfectly competitive market with perfect foresight
- Hourly resolution of a whole year at country level for Central Europe
- Energy-only market model

Objective function: minimising the total generation costs

$$TotalCosts = \min \sum_{\substack{h \in H, \\ ca \in CA, i \in I_{ca}}} \sum_{th \in TH_i} \mathrm{thP}_{h,th} \cdot SRMC_{h,th} + \mathrm{Str}_{h,th} \cdot C^{Start}_{h,th} + \mathrm{hyP}_{h,i} \cdot C^{Hydro} + (PV_{h,i} - \mathrm{Spill}^{\mathrm{PV}}{}_{h,i}) \cdot C^{PV} + (Wind_{h,i} - \mathrm{Spill}^{\mathrm{Wind}}{}_{h,i}) \cdot C^{Wind} + \mathrm{NSE}_{h,i} \cdot VoLL$$

$$SRMC_{h,i,th_i} = C^{O\&M} + C^{fuel}_{th_i} / \eta^{Th}_{i,th_i} + C^{CO_2} \cdot ThEm_{i,th_i} / \eta^{Th}_{i,th_i}$$

Constraints:

- demand=supply
- capacity
- ramping limits
- storage level equations
- curtailment of renewable energy sources
- net transfer capacity (NTC) or DC load flow (PTDF matrix) approach

(Van den Bergh et al., 2014)

Electricity market model + Balancing

EDisOn+Balancing

Add-on of the electricity market model.

In **Step 1** the procurement of balancing capacity is simulated (hourly resolution) and subsequently in **Step 2** the call of balancing energy (1/4 hourly).

EDisOn-Model (LOP, minimising generation costs)

Input: demand, wind, PV, hydro inflow and pattern, reservoir levels, power plant data (capacity, load gradient, minimum stable level, emissions, efficiency), Transmission Power Lines (AC, DC, NTC, incidence matrix, susceptance), primary energy prices, non fuel O&M costs, CO_2 certificate prices

Output: prices for estimating the Opportunity costs

EDisOn+Balancing

Step 1: Procurement of Balancing Capacity (hourly resolution)

Additional Input: Opportunity costs, capacity procurement (+ & -), balancing market design definitions (product time slots, minimum bid size, pricing, settlement, etc.)

Output: optimal production dispatch, production costs, production of RoR, PHES and thermal power plants, power exchanges between nodes, optimal line flows, storage levels, wholesale electricity prices, procurement of control reserve, prices and costs,etc.

Step 2: Imbalances and bids for Balancing Energy - Auction ($^1/_4$ hourly resolution)

Input: Imbalances (combination of forecast errors of wind, PV, load and the outages of power plants), power plants dispatch and forecasted RES and hydro production

Output: Balancing costs and prices, optimal dispatch of regulating objects, exchange of balancing services

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Functionalities

- Balancing areas can be split into balancing groups
- positive & negative automatic activated Frequency Restoration Reserve (aFRR) is procured in Peak, Off-Peak and Weekend products in the balancing area APG
- Haupttarif (Mo-Fr 8:00-20:00) and Nebentarif for the German TSOs
- 4-hour products for positive & negative manually activated Frequency Restoration Reserve (mFRR)
- Thermal units and Pumped hydro storages can provide balancing energy (incl. ramping)
- Rolling horizon optimization (daily or weekly)
- Implicit allocation of transmission capacity for balancing

Step 1: Procurement of balancing capacity

Objective function and important constraints

$$\min \boxed{\sum_{\substack{h\in H,\\ ca\in CA, i\in I_{ca}}} \sum_{th\in TH_i} \mathrm{thP}_{h,th} \cdot SRMC_{h,th} + \mathrm{Str}_{h,th} \cdot C^{Start}_{h,th} + \mathrm{hyP}_{h,i} \cdot C^{Hydro} + (PV_{h,i} - \mathrm{Spill}^{\mathrm{PV}}{}_{h,i}) \cdot C^{PV} + (Wind_{h,i} - \mathrm{Spill}^{\mathrm{Wind}}{}_{h,i}) \cdot C^{Wind} + \mathrm{NSE}_{h,i} \cdot VoLL}$$

← dispatch costs

$$\boxed{+ \sum_{j\in a,m} \overline{\mathrm{thFRR}}^j_{h,th} \cdot \overline{TC}^j_{h,th} + \underline{\mathrm{thFRR}}^j_{h,th} \cdot \underline{TC}^j_{h,th}}$$

← procurement costs

$$s.t. \quad \sum_{th\in TH_i \wedge i\in I_{ca}} \overline{\mathrm{thFRR}}^j_{h,th} + \overline{\mathrm{tuFRR}}^j_{h,i} \geq \overline{FRR}^j_{ca} \quad \forall ca \in CA \quad : \lambda^{\overline{FRR}^j}_{ca}$$

← procurement of positive FRR

$$\sum_{th\in TH_i \wedge i\in I_{ca}} \underline{\mathrm{thFRR}}^j_{h,th} + \underline{\mathrm{puFRR}}^j_{h,i} \geq \underline{FRR}^j_{ca} \quad \forall ca \in CA \quad : \lambda^{\underline{FRR}^j}_{ca}$$

← procurement of negative FRR

$$\overline{\mathrm{thFRR}}^j_{h,th}, \underline{\mathrm{thFRR}}^j_{h,th} \geq 0, \overline{\mathrm{tuFRR}}^j_{h,i} \geq 0, \underline{\mathrm{puFRR}}^j_{h,i} \geq 0$$

For $j = \{\mathrm{a}, \mathrm{m}\}$ automatic und manually activated FRR, $h \in H = \{1, \dots, 8760\}$ hours, $th \in TH_i = \{gas, coal, lignite, \dots\}$ thermal units, $i \in I_{ca} = \{BG_1, \dots BG_n\}$ balancing group of control area $ca \in CA = \{APG, TenneT, TransnetBW, \dots\}$.

$\overline{\mathrm{tuFRR}}^j_{h,i}$, $\underline{\mathrm{puFRR}}^j_{h,i}$ … procurement of positive/negative balancing capacity of pumped hydro storages

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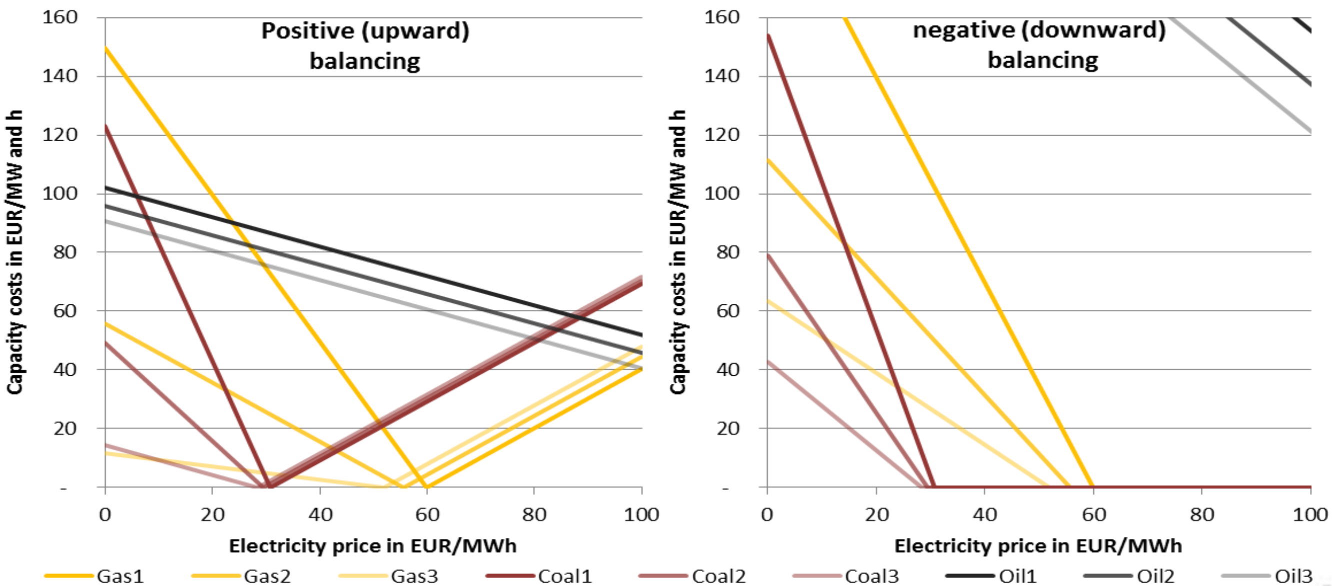
Pricing of procurement

Costs of positive balancing capacity (opportunity costs + expected costs of delivery):
(Müsgens, Ockenfels und Peek, 2014)

Opportunity costs of negative balancing capacity:
(Hirth und Ziegenhagen, 2015)

$$\overline{TC}^j = \begin{cases} (SRMC - p^{DA}) \cdot \frac{CAP^{Min}}{CAP^{Reserve}} + h \cdot SRMC & \text{, if } SRMC > p^{DA} \\ p^{DA} - SRMC + h \cdot SRMC & \text{, if } SRMC \leq p^{DA} \end{cases}$$

$$\underline{TC}^j = \begin{cases} SRMC - p^{DA} \cdot \frac{CAP^{Min} - CAPReserve}{CAP^{Reserve}} & \text{, if } SRMC > p^{DA} \\ 0 & \text{, if } SRMC \leq p^{DA} \end{cases}$$



$CAP^{Reserve} = \min\{\Delta CAP \cdot t^*; CAP^{Max} - CAP^{Min}\}$, and $h \in [0,1]$ ex-ante probability, that accepted capacity is called.

SRMC… short-run marginal costs, p^{DA} … expected day-ahead price

Capacity procurement of thermal units

Consideration of up- and down-ramping limits thermal units:

$$\overline{\text{thFRR}}^{a}_{h,th} \leq \text{X}^{Z}_{h,th} \cdot \min\left\{ThCap^{max}_{th}, \frac{rampLimit_{th}}{60} \boxed{\cdot 5}\right\}$$

$$\underline{\text{thFRR}}^{a}_{h,th} \leq \text{X}^{Y}_{h,th} \cdot \min\left\{ThCap^{max}_{th} - ThCap^{min}_{th}, \frac{rampLimit_{th}}{60} \boxed{\cdot 5}\right\}$$

→ 15 minutes for mFRR!!

- Linearization of On/Off-condition for thermal units $\text{X}^{Y} + \text{X}^{Z} \leq \min\{\text{X}^{X}, 1\},\ \ \text{X}^{X} \in [0,1]$
- Generation of thermal units: $\text{thP} = \text{X}^{X} \cdot ThCap^{min} + \text{X}^{Y} \cdot (ThCap^{max} - ThCap^{min})$
- $ThCap^{min}$ … minimum stable level

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Capacity procurement of pumped hydro storages

Consideration of pumped hydro storages:

$$storLv_{h,i} = storLv_{h-1,i} - \mathrm{tuP}_{h,i}/\eta^{tu} + \mathrm{puP}_{h,i} \cdot \eta^{pu} + Inflow_{h,i}$$

storage level equation

$$\left.\begin{aligned} storLv^{RV+}_{h,i} &= storLv^{RV+}_{h-1,i} - \overline{\mathrm{tuFRR}}^{a}_{h,i}/\eta^{tu} \\ storLv^{RV-}_{h,i} &= storLv^{RV-}_{h-1,i} + \underline{\mathrm{puFRR}}^{a}_{h,i} \cdot \eta^{pu} \\ EnMin_i &\leq storLv_{h,i} + storLv^{RV+}_{h,i} \\ storLv_{h,i} + storLv^{RV-}_{h,i} &\leq EnMax_i \end{aligned}\right\}$$

consideration of changes in storage levels, if procured capacity is called

$$\left.\begin{aligned} \mathrm{tuP}_{h,i} + \overline{\mathrm{tuFRR}}^{a}_{h,i} &\leq InstCap_i \\ \mathrm{puP}_{h,i} + \underline{\mathrm{puFRR}}^{a}_{h,i} &\leq PuCap_i \end{aligned}\right\}$$

installed capacity limitation

$$0 \leq \mathrm{tuP}_{h,i}, \quad 0 \leq \mathrm{puP}_{h,i}, \quad 0 \leq \overline{\mathrm{tuFRR}}^{a}_{h,i}, \quad 0 \leq \underline{\mathrm{puFRR}}^{a}_{h,i}$$

Step 2: Imbalances and bids for Balancing Energy

Objective function: minimising the total costs of balancing
(Morales, 2014)

$$\min \left\{ \sum_{\substack{h\in H,\\ ca\in CA, i\in I_{ca}}} \sum_{th\in TH_i} \sum_j \mathrm{thFRR}^{j+}_{h,th} \cdot \overline{TC}^{j}_{h,th} + \mathrm{thFRR}^{j-}_{h,th} \cdot \underline{TC}^{j}_{h,th} \right\}$$

$$s.t. \qquad Imb^{j}_{h,ca} = \sum_{th\in TH_i \wedge i\in I_{ca}} \mathrm{thFRR}^{j+}_{h,th} - \mathrm{thFRR}^{j-}_{h,th} \qquad \forall ca \qquad : \lambda^{Imb}$$

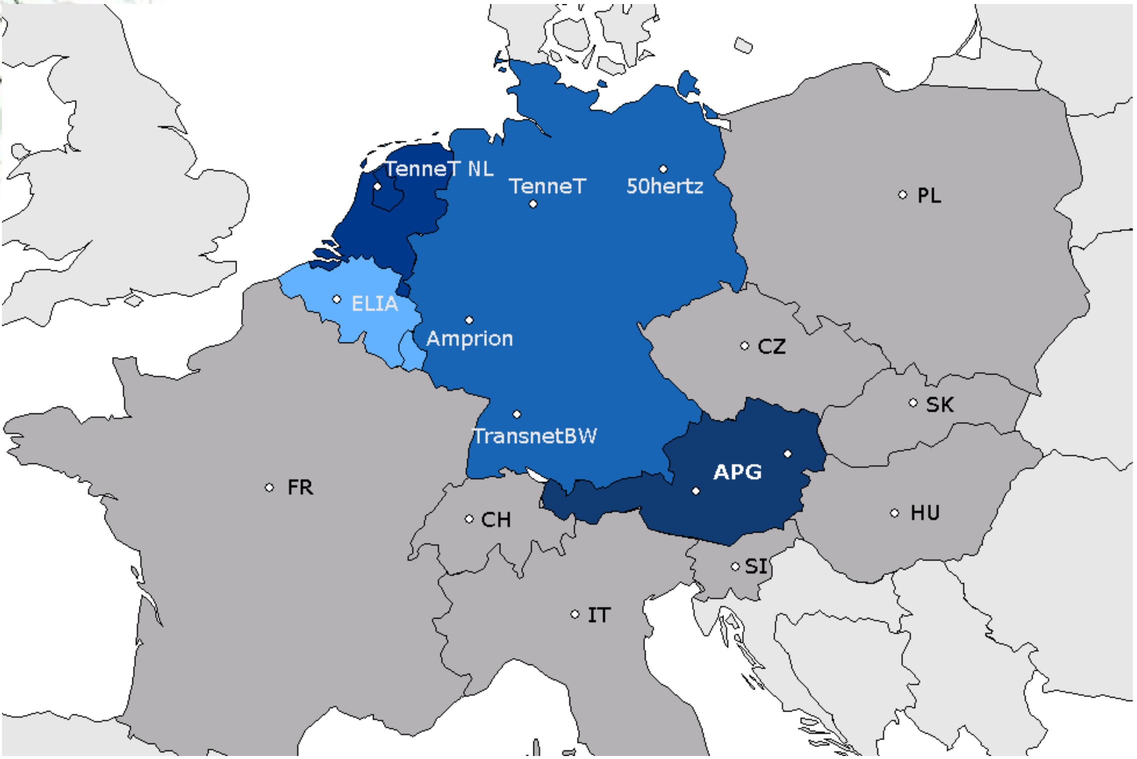
$$0 \leq \mathrm{thFRR}^{a+}_{h,th} \leq ThCap^{max}_{th} - \mathrm{thP}_{h,th} \qquad \forall h, th$$

$$0 \leq \mathrm{thFRR}^{a-}_{h,th} \leq \mathrm{thP}_{h,th} \qquad \forall h, th$$

Imbalances:

- **Now:** historic imbalances as time series per control area
- **Future:** composition of several stochastic processes consisting of the schedule deviations and forecast errors
  of PV, wind and load.

Geographical scope



- Balancing:
  APG, TransnetBW, Amprion, TenneT, 50Hertz, TenneT NL und ELIA.
- Day-ahead:
  FR, CH, IT, SI, HU, SK, CZ und PL.

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Qualitative assessment of balancing arrangements

Regelenergie Markt Design Analysen			
Procurement of balancing capacity and balancing energy products	Joint		Separated
	Poor		Good
Procurement of upward and down-ward balancing capacity products	Joint		Separated
	Poor		Good
Minimum bid size	Large (> 5MW)	Medium (1-5MW)	Small (≤1MW)
	Poor	Poor to fair	Good
Pricing of balancing products	Pay-as-bid		Marginal
	Poor to fair		Good
Imbalance pricing system	Dual	Single	Combined
	Poor to fair	Fair to good	Good
Settlement period	Long (1h)	Average (30min)	Short (15min)
	Poor	Fair	Good

Step 2: energy <= procurement

$$\mathrm{thFRR}^{j+}_{h,th} \leq \overline{\mathrm{thFRR}}^{j}_{h,th}, \mathrm{thFRR}^{j-}_{h,th} \leq \underline{\mathrm{thFRR}}^{j}_{h,th}$$

Step 1: positive = negative

$$\overline{\mathrm{thFRR}}^{j}_{h,th} = \underline{\mathrm{thFRR}}^{j}_{h,th}$$

Step 1: lower limit for bids

→ Caution: binary variables!!!

Step 1: pricing with opportunity costs or dual variables

After Step 2: calculation of revenues and expenditures per balance responsible party

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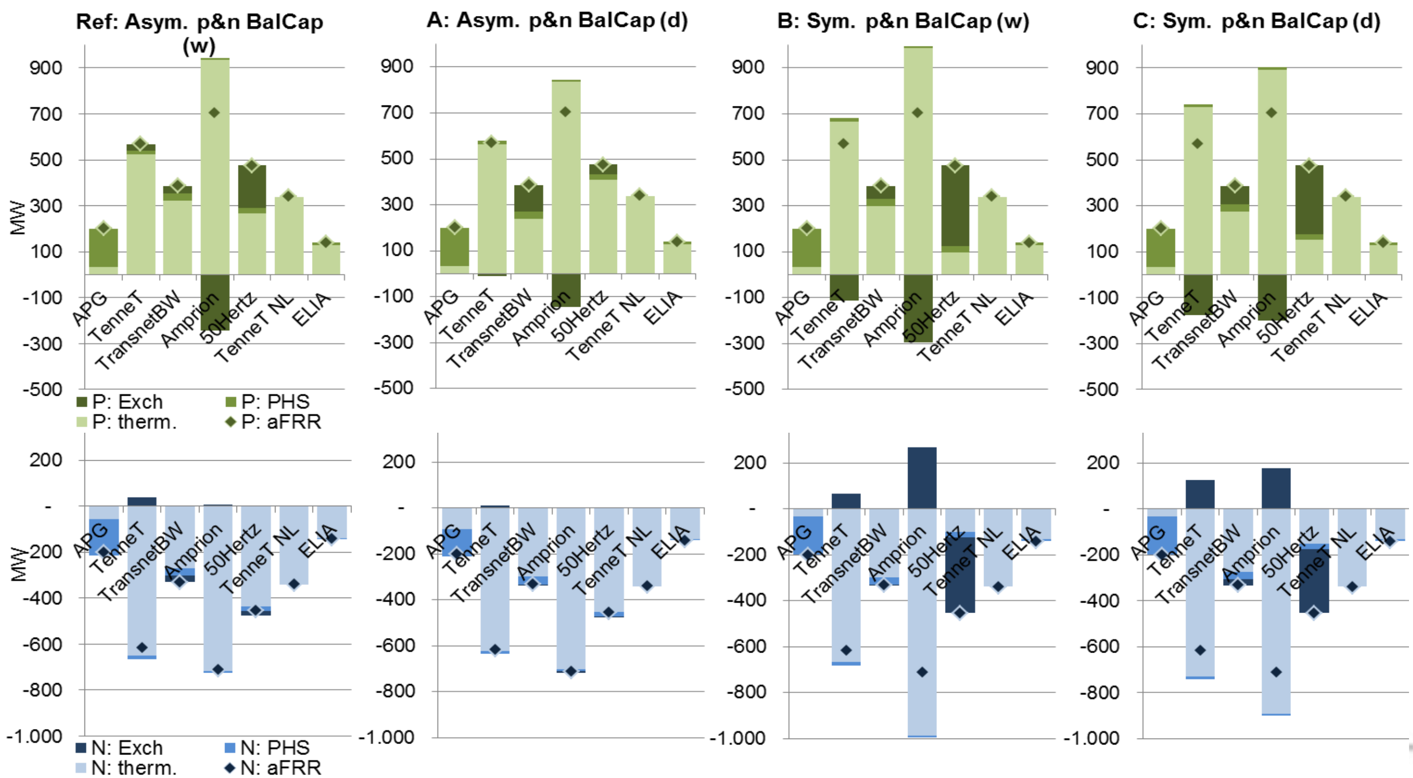
Defined Scenarios for 2030

Defined scenarios	
Reference Case	• **asymmetric/separated** procurement of positive and negative balancing capacity • **week-ahead** procurement of Peak, Off-Peak and Weekend aFRR products in AT, HT and NT aFRR products in DE, BE & NL • Daily procurement of 4-hour products for mFRR • **cooperation** between German TSOs/control areas only
Case A	• **day-ahead** procurement of aFRR products
Case B	• **symmetric/joint** procurement of positive and negative balancing capacity
Case C	• **symmetric/joint** procurement of positive and negative balancing capacity • **day-ahead** procurement of aFRR products
Case D	• **day-ahead** procurement of aFRR products • **cooperation** between all TSOs/control areas
Case E	• **12 hours-ahead** procurement of aFRR products • **cooperation** between all TSOs/control areas
Case F	• **hourly** procurement of hourly aFRR products • **cooperation** between all TSOs/control areas

Results: average procured capacity per TSO (I)

- Comparing (weekly) with (daily) → cooperation between German TSOs ↘
- Comparing Asym with Sym → cooperation between German TSOs ↗



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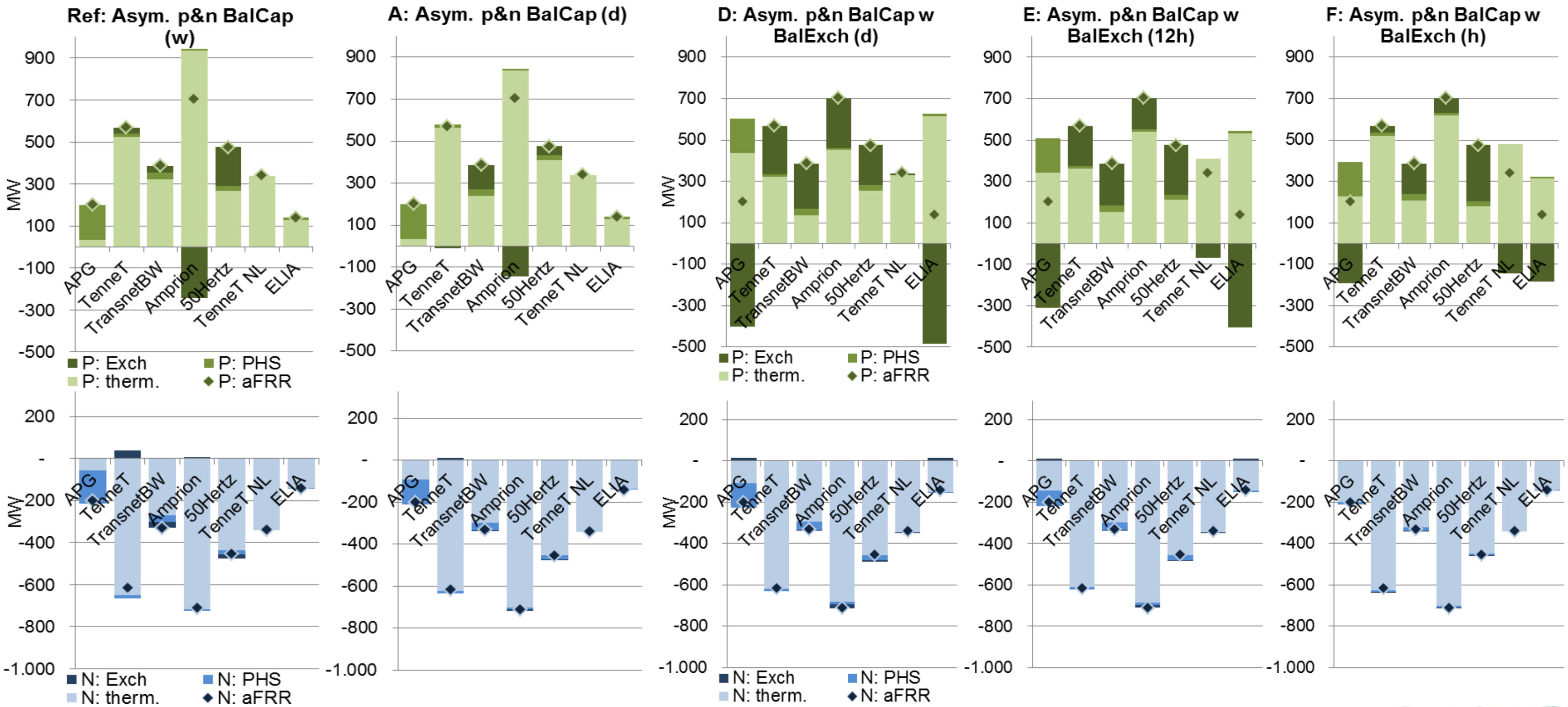
Results: average procured capacity per TSO (II)

- Comparing Asym (w), (d), (12h) & (h) → cooperation ↘
- Comparing Asym without/with cooperation → cooperation ↗



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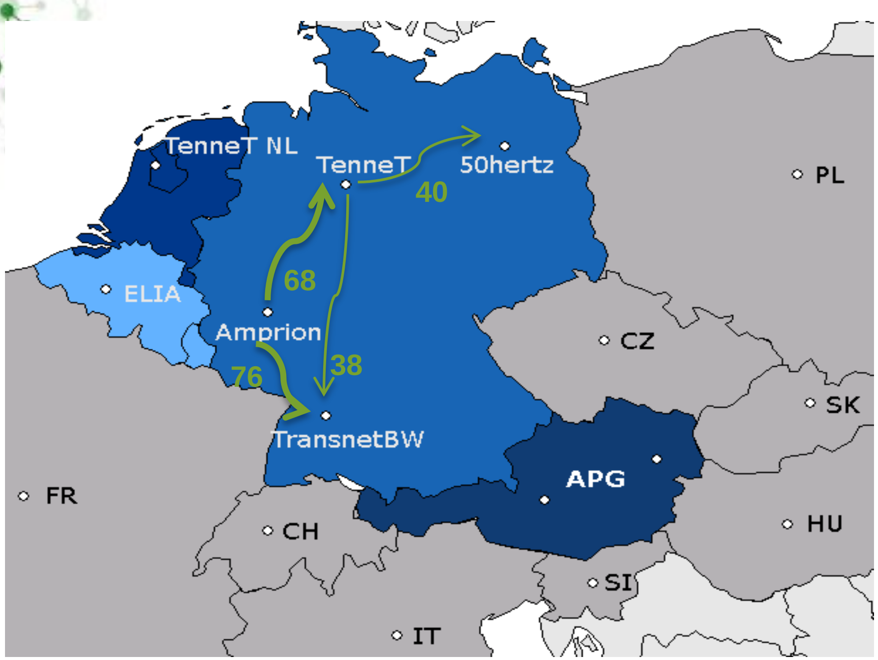
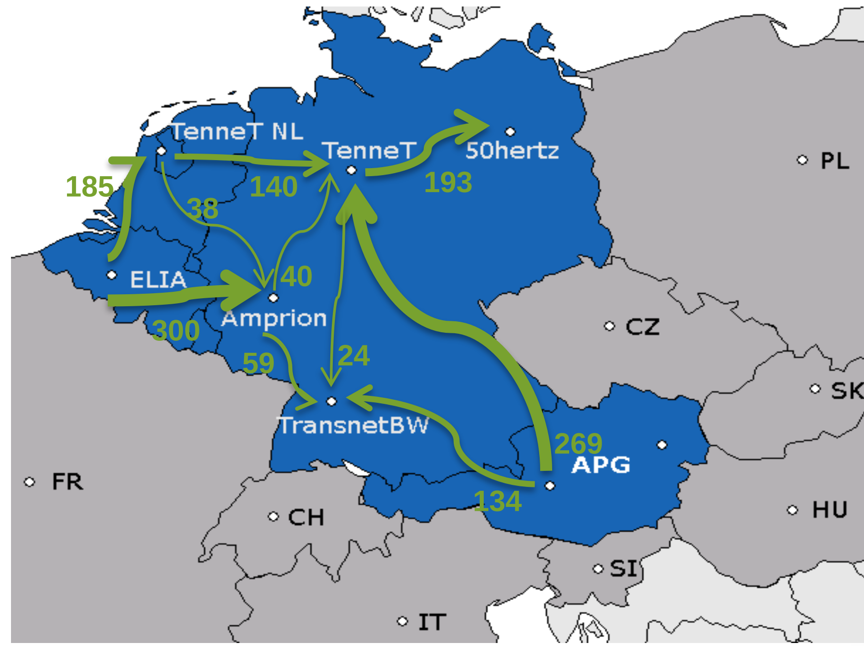
Results: average common procurement of positive balancing capacity (in MW)

Case A: Asymmetric pos&neg Balancing Capacity (daily)



Case D: Asymmetric pos&neg Balancing Capacity and Balancing Exchanges (daily)



→ procurement of positive balancing capacity within Germany remains nearly the same
→ increased procurement from Belgium and Austria to Germany

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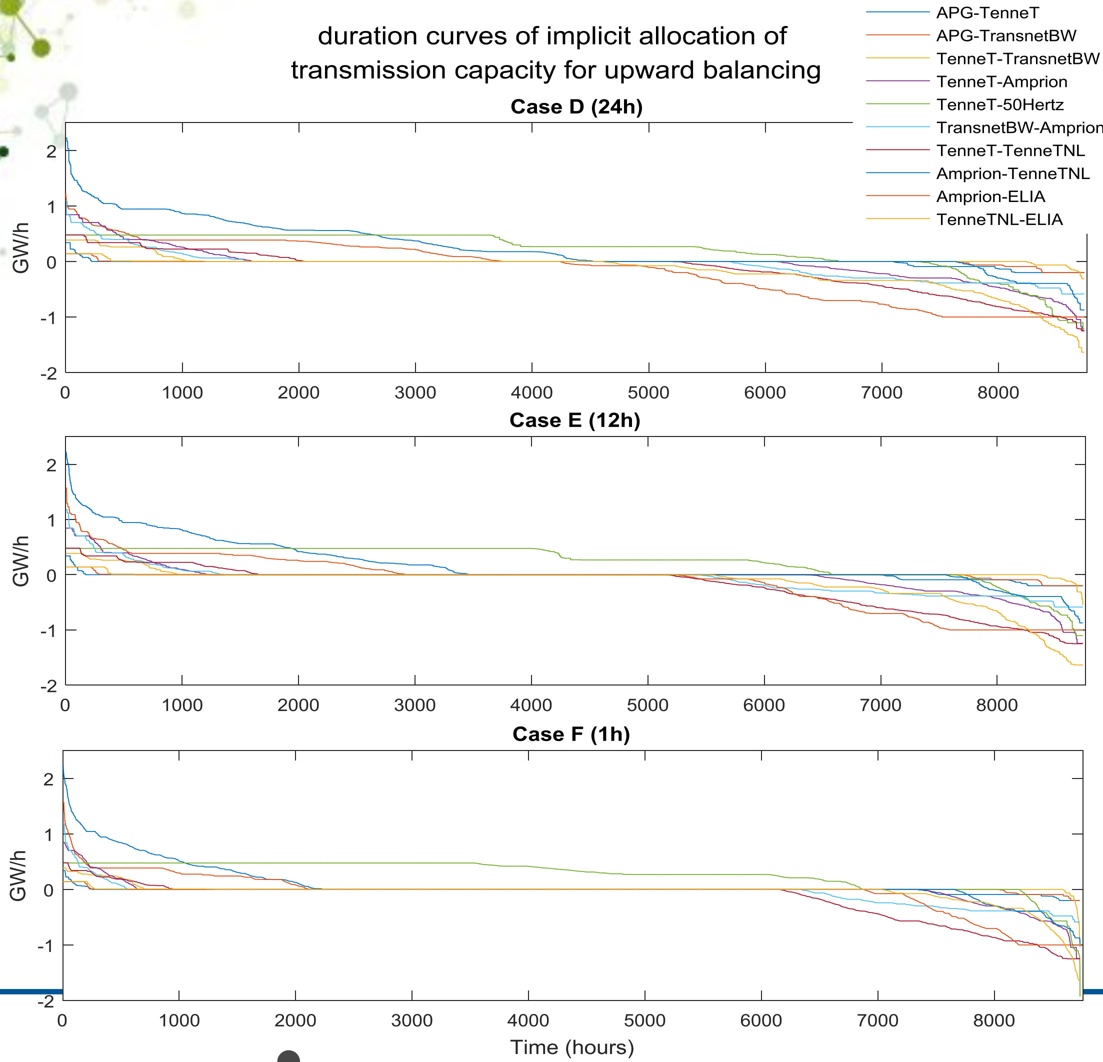
Results: duration curves for implicit allocation of transmission capacity for positive balancing



- Implicates: shortening the product length and procurement time → cooperation becomes less.

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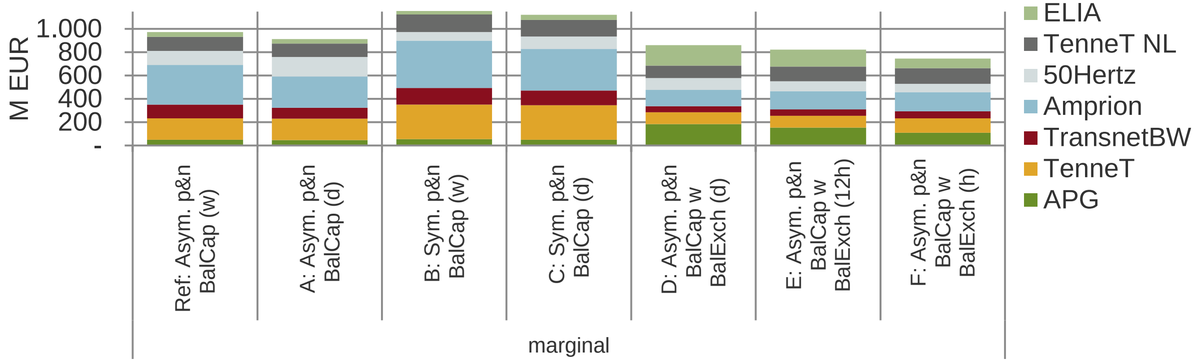
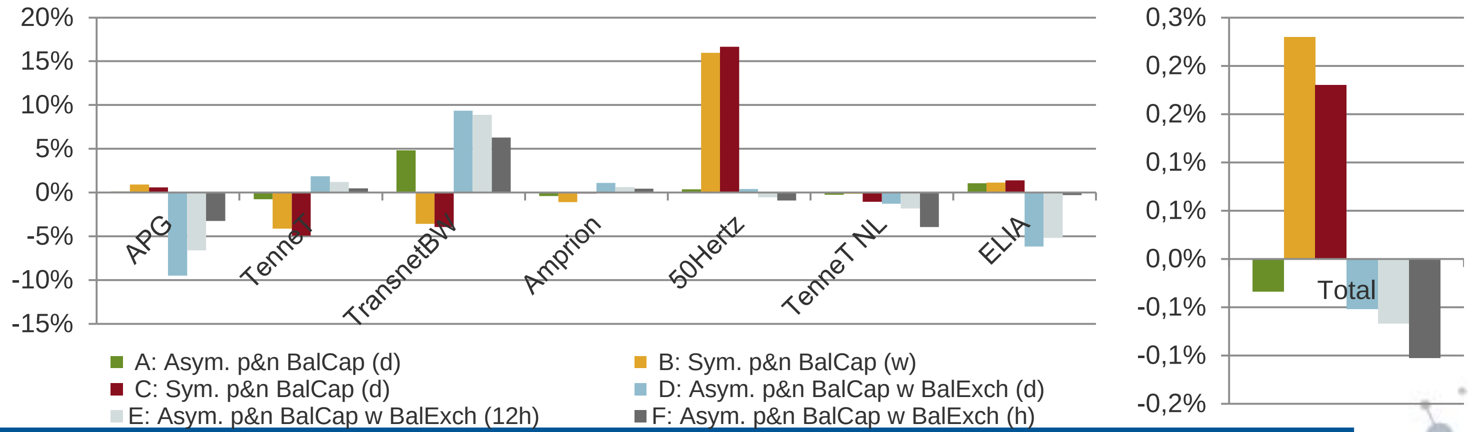
Results: procurement and generation costs

Procurement costs for positive and negative balancing capacity:



Differences in generation costs per control area and total:



Preliminary conclusions

- Symmetric/Joint procurement of positive and negative balancing capacity
  - increases total generation costs and balancing costs
  - increases cooperation between all TSOs
  - poor design for RES integration

- Allowing cooperation between all TSOs for common procurement
  - reduces total generation costs and balancing costs

- Shorter time frame for block products
  - reduces the need for international cooperation, total generation costs and balancing costs
  - good design for RES integration

Further developments

- allow Wind farms to provide balancing products (especially mFRR),
- more detailed integration of hydropower plants,
- integration of Demand Side Management (DSM),
- analyse additional scenarios of future market designs,
- further development of Step 2:
    - implementation of composite stochastic processes
    - implementation of Imbalance Netting
- and consideration of balancing markets in other EU countries.

Coordinated by SINTEF

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Results and news: www.market4RES.eu

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Thank you very much
for your attention

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