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Programme

	June 6	June 7		June 8		June 9	June 10
	Tuesday	Wednesday		Thursday		Friday	Saturday
9:00 – 10:30	Registration	Sessions		Sessions		Sessions	
10:30 – 11:00		Coffee break		Coffee break		Coffee break	
11:00 -12:30	Opening** and Podium Session	Sessions		Sessions		Sessions	EEM 2017
12:30 – 14:00	Lunch	Lunch		Lunch		Lunch	to go on excursion jointly with
14:00 – 15:30	Podium Session	Sessions	Technical Tour 1 Lippendorf	Sessions	Technical Tour 2 Reick	Sessions	Enerconnect*
15:30 – 16:00	Coffee break	Coffee break		Coffee break		Coffee break	
16:00 – 17:30	Sessions	Sessions		Sessions		Closing Session**	
17:30 – 18:00							
18:00 – 20:00	Welcome Reception			Reception & Exhibition E-Mobility			
20:00 – 21:00	Poster Session Dülfersaal (TUD)			Gala Dinner with Awards Ceremony VW Manufactory			
21:00 – 23:00							

Interdependencies of harmonised procurement of manually and automatically activated FRR in selected Central European Balancing Markets

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***Abstract*—High shares of renewable electricity generation requires robust balancing measures and procedures in the electricity system. There are several electricity balancing pilot projects having already been started or will start in the near future.**

The work presented in this paper focuses on projects with the geographic scope of Central Europe. This includes the common activation of automatic Frequency Restoration Reserve (aFRR) in Austria and Germany as well as the common procurement of aFRR in the above-mentioned area, which is planned to start mid-2017. The start for common procurement and activation of manually activated Frequency Restoration Reserve (mFRR) has not yet been published, but will also be analysed within this work. In addition, the impact of a further extension of the common balancing area to Belgium and The Netherlands is analysed.

The focus of the study is on how common procurement of aFRR and mFRR influences wholesale electricity market clearings and how it interferes each other. The quantitative results confirm that common procurement of balancing capacity (aFRR and mFRR) in the simulated region has significant advantages in terms of cost reduction, CO_2 emissions and increased flexibility in the electricity system. Furthermore, the common procurement of mFRR interferes the procurement costs of aFRR in a positive way, meaning that further reductions can be achieved.

NOMENCLATURE

The sets with corresponding indices, the parameters and the decision variables which are used in the paper are listed below.

Sets and indices

H (index h)	set of time steps (hours)
I_{ca} (index i)	set of balancing groups in control area ca
CA (index ca)	set of control areas
L (index l)	set of transmission power lines
TH_i (index th)	set of thermal units in balancing group i
PS_i (index p)	set of pumped hydro storage units in balancing group i
$j = \{a, m\}$	automatically and manually activated FRR

Parameters

$CapL_l^{A\to B(B\to A)}$	capacity limit of transmission power line l from A to B (B to A)	MW
z_l	capacity share of line l for balancing purposes	$[0, 1]$
$A_{l,i}$	incidence matrix	$\{-1, 0, 1\}$
$\overline{FRR}^j_{ca}, \underline{FRR}^j_{ca}$	necessary up-/downward FRR of control area ca	MW/h

Decision variables

$\overline{\mathrm{thFRR}}^j_{h,th}, \underline{\mathrm{thFRR}}^j_{h,th}$	reserved capacity for up-/downward FRR of thermal unit th	MW/h
$\overline{\mathrm{psFRR}}^j_{h,p}, \underline{\mathrm{psFRR}}^j_{h,p}$	reserved capacity for up-/downward FRR of pumped hydro storage unit p	MW/h
$\overline{\mathrm{Exch}}^j_{h,i}, \underline{\mathrm{Exch}}^j_{h,i}$	exchanged reserve capacity for up-/downward j FRR	MW/h
$\overline{\mathrm{RCap}}^j_{l,h}, \underline{\mathrm{RCap}}^j_{l,h}$	reserved transmission capacity for j FRR on line l	MW/h
$\mathrm{Flow}_{l,h}$	power flow on transmission line l	MWh/h

I. INTRODUCTION

To achieve the so-called "European Internal Energy Market", the Agency for the Cooperation of Energy Regulators (ACER) and the European Network of Transmission System Operators for Electricity (ENTSO-E) play a key role. Among others, the task of ACER is to propose framework guidelines, providing the basis for the so-called Network Codes - developed by ENTSO-E - for a European cross-border electricity market and the corresponding integration of large-scale renewable electricity generation (RES-E). High shares of RES-E generation require also robust balancing measures and procedures in the electricity system. In this context, the "Framework Guidelines on Electricity Balancing" build the basis for the "Network Code on Electricity Balancing" (NC EB), [1], [2]. The main purpose of the NC EB is to achieve a well-functioning, integrated balancing electricity market in Europe. The main cornerstones of future cross-border balancing market design are well defined in the NC EB. However, there are still many open questions in terms of fine-tuning of balancing market design options in its practical implementation.

There are several electricity balancing pilot projects having already been started or will start in the near future. The work presented in this paper focuses on projects with the geographic scope of Central Europe. This includes the common activation of automatic Frequency Restoration Reserve (aFRR) in Austria and Germany (started in July 2016) as well as the common procurement of aFRR in the above-mentioned area, which is

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planned to start mid-2017. The start for common procurement and activation of mFRR has not yet been published, but will also be analysed within this work. In addition, the impact of a further extension of the common balancing area to Belgium and The Netherlands is analysed.

In a first step the analysis considers the currently existing installed electricity generation capacities in the respective countries to evaluate the influences of different balancing market designs on the current electricity markets. The "ENTSO-E Vision 3" scenario (see [3]) will be used to evaluate the challenges of future electricity systems with high shares of RES-E.

The used model is called EDisOn (Electricity Dispatch Optimization) and it is a fundamental market model, which has been developed in MATLAB (see [4]). The model computes the optimal (cost minimal) dispatch of thermal power plants in the electricity system and considers also RES-E generation of wind, solar, run-of-river and pumped hydro storages (PHS). Other storages like batteries can also be respected. It is designed as a linear programming problem (binary on-/off-conditions of thermal power plants are linearized) and is deterministic in nature, assumes a perfect competitive market with perfect foresight, and uses an hourly resolution of a full year. Furthermore, a detailed transmission grid via direct current (DC) load flow approach can be enabled. Shortly, the application of heat has been added in the EDisOn model, the nodal heat demand can be fulfilled either by thermal combined heat and power (CHP) units or by power to heat units.

In order to enable the consideration of balancing energy markets, a model extension recently has been developed [5]. In two additional steps the balancing energy market mechanisms are considered in the model EDisOn+Balancing. Firstly, the procurement of the balancing capacity, which is also based on an hourly resolution, is simulated and, subsequently, the activation of balancing energy for balancing the control areas imbalances on a quarter hourly resolution.

The geographical scope of the study comprises Central Europe, meaning that the control areas of Austria, Germany, Belgium and the Netherlands are considered in detail. For these countries different designs of balancing markets are analysed. The remaining neighbouring countries like Poland, Czech Republic, Hungary, Slovakia (currently no direct interconnection to Austria), Slovenia, Italy, Switzerland and France are considered for wholesale electricity market clearings only.

The focus of the study is on how common procurement of aFRR and mFRR influences wholesale electricity market clearings and how it interferes each other. Therefore, additional functionalities in the EDisOn+Balancing model have been needed, to implement the possibility of common procurement of mFRR for all respected transmission system operators (TSOs).

The quantitative results confirm that common procurement of balancing capacity (aFRR and mFRR) in the simulated region has significant advantages in terms of cost reduction, CO_2 emissions and increased flexibility in the electricity system. Furthermore, the common procurement of mFRR interferes the procurement costs of aFRR in a positive way, meaning that further reductions can be achieved.

In the next section, the main methodology of the model EDisOn+Balancing is explained and the currently added constraints for respecting common procurement for mFRR are shown. Section III shows the results for the year 2015 and the impacts on the current electricity system. Finally, the last section provides conclusions based on the quantitative assessment and an outlook on future work.

II. Method and mathematical formulation

EDisOn (**E**lectricity **Dis**patch **O**ptimizatio**n**) is a fundamental market model and has been developed in MATLAB. A detailed description of the EDisOn model can be found in [6]. The model computes the optimal (cost minimal) dispatch of thermal power plants in the electricity system and considers also RES-E generation of wind, PV and hydro. Concerning hydro three different types are considered, pumped hydro storage, hydro storage and run-of-river power plants. It is designed as a linear programming problem (binary on-/off-conditions are linearised, [7]) and is deterministic in nature, assumes a perfect competitive market with perfect foresight, and uses an hourly resolution of a full year. The transmission system can be respected in two ways either by applying Net Transfer Capacity (NTC) or DC load flow approach. Two new applications have also been added lately. Firstly, cogeneration of thermal power plants can be activated for fulfilling a certain heat demand. Secondly, different kind of storages, like batteries are implemented.

In order to enable the consideration of the balancing energy market, a model extension has been necessary. Therefore, in two additional simulation steps several balancing energy market mechanisms are considered in the model EDisOn+Balancing. Firstly, the procurement of balancing capacity based on an hourly resolution is simulated and, subsequently, the activation of balancing energy for balancing the control areas imbalances on a quarter hourly resolution. Figure 1 provides an overview of the different simulation steps and the corresponding inputs and outputs.

To answer the research question concerning interdependencies of harmonised procurement of mFRR and aFRR the focus is on the first step (the procurement of balancing capacity) of the balancing application. The objective of the first step is the minimization of wholesale electricity market costs on the one hand and the minimization of procurement costs of aFRR and mFRR on the other hand. For minimising balancing procurement costs, estimations on opportunity costs per balancing provider are necessary, these costs are calculated based on the outcomes of the EDisOn model, which is solved before. Therefore, the opportunity costs are one of the main drivers which determine whether a power plant provides balancing capacity or sell their energy on the wholesale electricity market. For further details see [5].

For analysing the implications of common procurement of mFRR, additional restrictions have been necessary in the tool.

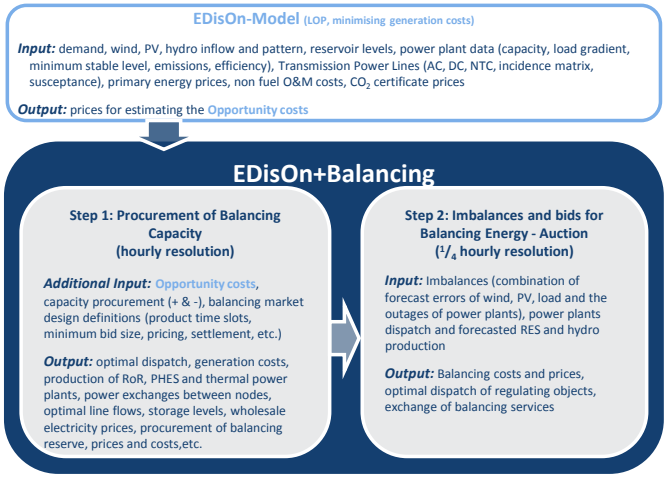

Fig. 1. Overview of the different simulation steps and the corresponding inputs and outputs.

Implicit allocation of transmission capacity for balancing: Originally, the common procuring of aFRR by several TSOs has been possible in the model only. The extension of implicit allocation for upward mFRR is shown in the following equations (see [8]). The variable $\overline{\mathrm{Exch}}^{j}_{i,h}$ for $j = \{a, m\}$ describes the net amount of exchanged balancing capacity for upward aFRR and mFRR. It is defined by the sum over all transmission power lines, where a certain amount, described with $\overline{\mathrm{RCap}}^{j}_{l,h}$, is reserved for upward balancing between TSOs. The matrix $A_{l,i}$ describes which nodes are connected with each other. Inequality (2) and (4) set the minimum required balancing capacity $\overline{FRR}^{j}_{ca}$ of type aFRR and mFRR for each control area ca. These required balancing capacities can be either provided by thermal power plants $\overline{\mathrm{thFRR}}^{j}_{h,th}$ and by pumped hydro storages $\overline{\mathrm{psFRR}}^{j}_{h,p}$ within the same control area, or by units of another control area if it is enabled $\overline{\mathrm{Exch}}^{j}_{h,i}$.

$$\overline{\mathrm{Exch}}^{a}_{i,h} = \sum_{l} A_{l,i} \cdot \overline{\mathrm{RCap}}^{a}_{l,h} = \begin{cases} + & \text{export upward aFRR} \\ - & \text{import upward aFRR} \end{cases} \quad (1)$$

$$\sum_{th,p,i} \overline{\mathrm{thFRR}}^{a}_{h,th} + \overline{\mathrm{psFRR}}^{a}_{h,p} - \overline{\mathrm{Exch}}^{a}_{h,i} \geq \overline{FRR}^{a}_{ca} \quad \forall ca \in CA \quad (2)$$

$$\overline{\mathrm{Exch}}^{m}_{i,h} = \sum_{l} A_{l,i} \cdot \overline{\mathrm{RCap}}^{m}_{l,h} = \begin{cases} + & \text{export upward mFRR} \\ - & \text{import upward mFRR} \end{cases} \quad (3)$$

$$\sum_{th,i} \overline{\mathrm{thFRR}}^{m}_{h,th} - \overline{\mathrm{Exch}}^{m}_{h,i} \geq \overline{FRR}^{m}_{ca} \quad \forall ca \in CA \quad (4)$$

Inequalities (5) and (6) describe the limitations on the transmission lines. The transmission capacity can be either used for wholesale electricity market clearings or either be reserved for balancing purposes, the variable $\overline{\mathrm{RCap}}^{a}_{l,h}$ is the reserved transmission capacity for upward aFRR and variable $\overline{\mathrm{RCap}}^{m}_{l,h}$ for mFRR. In addition, $z_l \in [0, 1]$ indicates on which line transmission capacity can be reserved or how much of total transmission capacity can be used for balancing purposes.

$$-(\overline{\mathrm{RCap}}^{a}_{l,h} + \overline{\mathrm{RCap}}^{m}_{l,h}) \leq CapL_l^{B\to A} + \mathrm{Flow}_{l,h} \quad (5)$$

$$-CapL_l^{B\to A} \cdot z_l \leq \overline{\mathrm{RCap}}^{a}_{l,h} + \overline{\mathrm{RCap}}^{m}_{l,h} \leq CapL_l^{A\to B} \cdot z_l \quad (6)$$

In the following equations the same is applied for downward aFRR and mFRR. One important distinction compared to upward is, that the meaning of the algebraic signs switch due to the need of reserving transmission capacity in a reversed manner. For downward, positive values of variable $\underline{\mathrm{Exch}}^{j}_{i,h}$ mean downward capacity is imported and negative means export. Thus the algebraic sign changes in inequality (8) and (10) as well.

$$\underline{\mathrm{Exch}}^{a}_{i,h} = \sum_{l} A_{l,i} \cdot \underline{\mathrm{RCap}}^{a}_{l,h} = \begin{cases} + & \text{import downward aFRR} \\ - & \text{export downward aFRR} \end{cases} \quad (7)$$

$$\sum_{th,p,i} \underline{\mathrm{thFRR}}^{a}_{h,th} + \underline{\mathrm{psFRR}}^{a}_{h,p} + \underline{\mathrm{Exch}}^{a}_{h,i} \geq \underline{FRR}^{a}_{ca} \quad \forall ca \in CA \quad (8)$$

$$\underline{\mathrm{Exch}}^{m}_{i,h} = \sum_{l} A_{l,i} \cdot \underline{\mathrm{RCap}}^{m}_{l,h} = \begin{cases} + & \text{import downward mFRR} \\ - & \text{export downward mFRR} \end{cases} \quad (9)$$

$$\sum_{th,i} \underline{\mathrm{thFRR}}^{m}_{h,th} + \underline{\mathrm{Exch}}^{m}_{h,i} \geq \underline{FRR}^{m}_{ca} \quad \forall ca \in CA \quad (10)$$

$$\underline{\mathrm{RCap}}^{a}_{l,h} + \underline{\mathrm{RCap}}^{m}_{l,h} \leq CapL_l^{A\to B} - \mathrm{Flow}_{l,h} \quad (11)$$

$$-CapL_l^{B\to A} \cdot z_l \leq \underline{\mathrm{RCap}}^{a}_{l,h} + \underline{\mathrm{RCap}}^{m}_{l,h} \leq CapL_l^{A\to B} \cdot z_l \quad (12)$$

III. Results

For modelling the current electricity system and balancing market design, different data sources have been used, but the input is mostly based on data of the 'Statistical Factsheet 2015' published by ENTSO-E, [9]. The geographical scope comprises central Europe, meaning that the control zones of Austria (APG), Germany (TenneT, TransnetBW, Amprion and 50hertz), Belgium and the Netherlands are considered in detail. For these countries the balancing market mechanisms are analysed in addition to the wholesale electricity market clearing. The remaining neighbouring countries like Poland, Czech Republic, Slovakia (currently no direct interconnection to Austria), Hungary, Slovenia, Italy, Switzerland and France are considered for wholesale electricity market clearings only. The simulated areas are shown in Figure 2.

To figure out which impacts different changes in the product design of aFRR and mFRR have, four scenarios have been defined:

Ref Current Design: Peak, Off-Peak and Weekend weekly products for aFRR in the control area APG, Peak and Off-Peak weekly products for aFRR in the remaining. Four hour daily products for mFRR in all control areas.

A Sensitivity 1: four-hour daily products for aFRR and mFRR in all control areas.

B Sensitivity 2: based on sensitivity 1 aFRR can be exchanged between all TSOs.

C Sensitivity 3: based on sensitivity 2 mFRR can be exchanged between all TSOs.

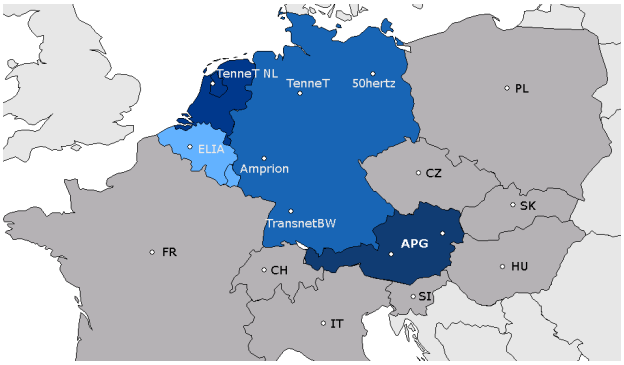

Fig. 2. Geographical scope of the simulations; blue: balancing and wholesale electricity market, darkgrey area: wholesale electricity market consideration only.

In the next sections the outcomes of above-mentioned scenarios are analysed in detail, starting with the impacts on the cost structure, divided into impacts on wholesale electricity generation costs and procurement costs for both balancing products aFRR and mFRR. Afterwards, the changes in terms of procured capacity and the corresponding reserved transmission capacities for providing balancing products are analysed. In the last subsection the environmental impacts are summarized.

A. Impacts on the cost structure

The wholesale generation costs are mostly influenced by balancing market design changes in the countries/control areas where the balancing market mechanisms are applied and analysed (TSOs balancing), like in Germany, Austria, Belgium and The Netherlands. In other simulated countries (TSOs wholesale), there can be observed that the costs are reduced as well, but not in the extent as for the others. In case C the generation costs can be reduced by 0.34% in total, see Figure 3, which are around 90 M Euro.

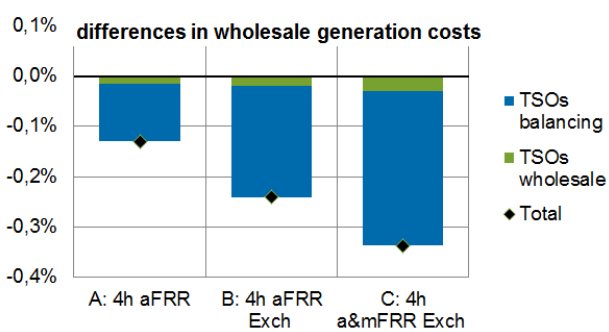

Fig. 3. Differences in total wholesale generation costs compared to the reference case separately for the wholesale electricity market only TSOs and balancing TSOs.

In Figure 4 the observed differences in terms of wholesale generation costs and procurement costs for FRR compared to the reference case for control areas, where balancing is respected, are shown. In all cases the costs can be reduced. The highest avoided costs are examined in case C, where the procurement costs for aFRR and mFRR are reduced by 31% and 27% (73 and 60 M EUR). Comparing the avoided costs of case A with B, it can be concluded, that introducing common procurement of aFRR by several TSOs has got higher impacts on costs, than changing the product design only. In addition, common procurement of mFRR (case C) reduces not only the costs for mFRR, but also for aFRR. Thus, positive effects can be observed by further harmonizing the procurement of FRR.

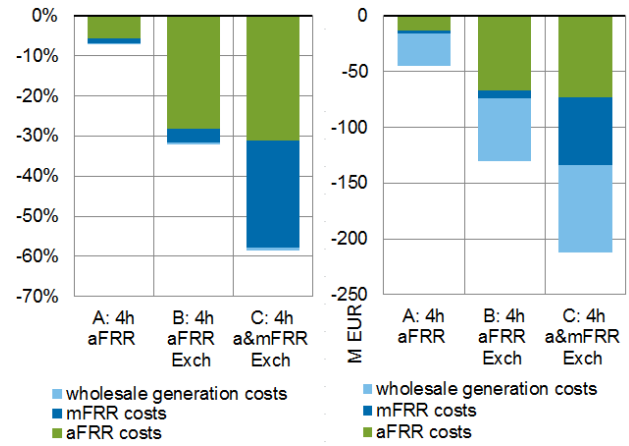

Fig. 4. Differences in wholesale generation costs and balancing procurement costs compared to the reference case for control areas, where balancing market is respected (AT, DE, BE, NL).

B. Interdependencies on procured capacities and exchanges

The average flows of wholesale electricity market clearing and the reserved capacity for upward capacity of FRR for case C are shown in Figure 5. Regarding transmission capacity, it is mostly used for wholesale electricity market flows, except on the interconnection APG to TenneT the available capacity is more often reserved for upward capacity of aFRR on average. This result can also be seen in Figure 6a in case C, where APG provides a lot of excess capacity for upward aFRR to the other control areas.

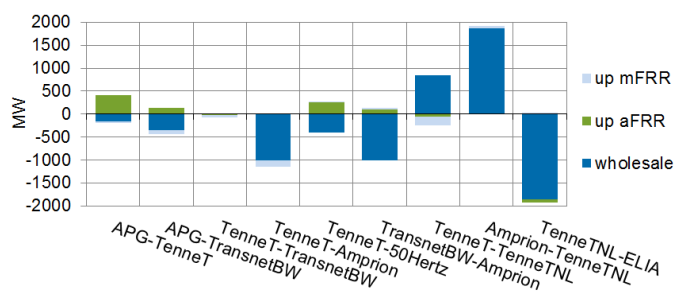

Fig. 5. Average flows of wholesale electricity market clearing and reserved capacity for upward capacity of FRR for case C. For the transmission line APG-TenneT positive values mean, that APG provides upward FRR or exports energy to TenneT, negative vice versa.

Figure 6 and 7 show how the required capacities of automatically and manually activated balancing capacity are procured on average. It is assumed, that thermal power plants can procure both aFRR and mFRR (U/D: therm a/mFRR), pumped

hydro storage (U/D: PHS a/mFRR) is allowed to provide aFRR only (will be further extended until the conference). In addition, the exchanged procurement of FRR (U/D: Exch a/mFRR) and the required capacity per product and control area (U/D: required a/mFRR) are shown in the figures.

Exchanging mFRR between TSOs is only allowed in case C. In this case the control areas of TransnetBW, Amprion and TenneT NL can procure more than they require on average for upward mFRR, as the diamonds in the figures indicate the required balancing capacity per control area. Therefore, they can procure the excess capacity for APG and TenneT. Concerning downward mFRR, TenneT and Amprion provide the TSOs 50Hertz, APG and TransnetBW with excess capacity.

C. Environmental Impacts

In Table I the reductions in terms of CO_2 emissions are summarized for all scenarios. In addition, the absolute value for the reference case is shown.

TABLE I
DIFFERENCES IN CO_2 EMISSIONS COMPARED TO THE REFERENCE CASE FOR CONTROL AREAS WHERE BALANCING MARKET IS RESPECTED.

	APG	Total
Ref:	4.2 Mt CO_2	231 Mt CO_2
A: 4h aFRR	-0.5%	-0.26%
B: 4h aFRR Exch	-0.8%	-1.43%
C: 4h a&mFRR Exch	-1.7%	-1.36%

Due to the shortening of aFRR product length and allowing common procurement of aFRR and mFRR (case C), flexibility is gained and, therefore, spillages of renewable electricity generation can be bisected. As a result the renewable share of electricity generation is increased from 28.5 % to 29.1% in the simulated area.

IV. CONCLUSIONS AND OUTLOOK

From the above-mentioned analysis several conclusions can be defined:

- The implementation of shorter balancing products and allowing common procurement of aFRR and mFRR by all TSOs reduces costs for procurement significantly.
- CO_2 emissions can be reduced by around 1.7% in Austria and by 1.4% for the respected area in total.
- The spillage of renewable generation can be bisected in Austria and the whole region.
- The renewable share of electricity generation is increased to 29.1% in the respected area.

Until the conference, additional topics will be conducted:

- analysing the impacts of considering wind farms as balancing capacity provider (especially for mFRR),
- pumped hydro storages shall also provide mFRR,
- other storages (like batteries) shall also procure balancing capacity (aFRR and mFRR),
- and additional simulation runs for the time horizon 2030 to analyse what challenges occur in a future electricity system with high penetration of RES-E.

ACKNOWLEDGMENT

I would like to thank my colleagues Daniel Schwabeneder and Georg Lettner for valuable input on modelling issues and result discussions.

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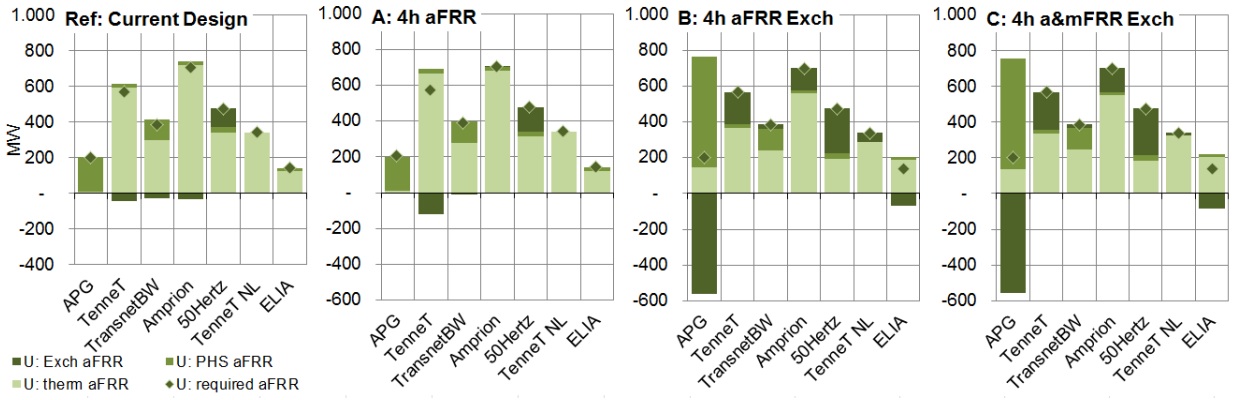
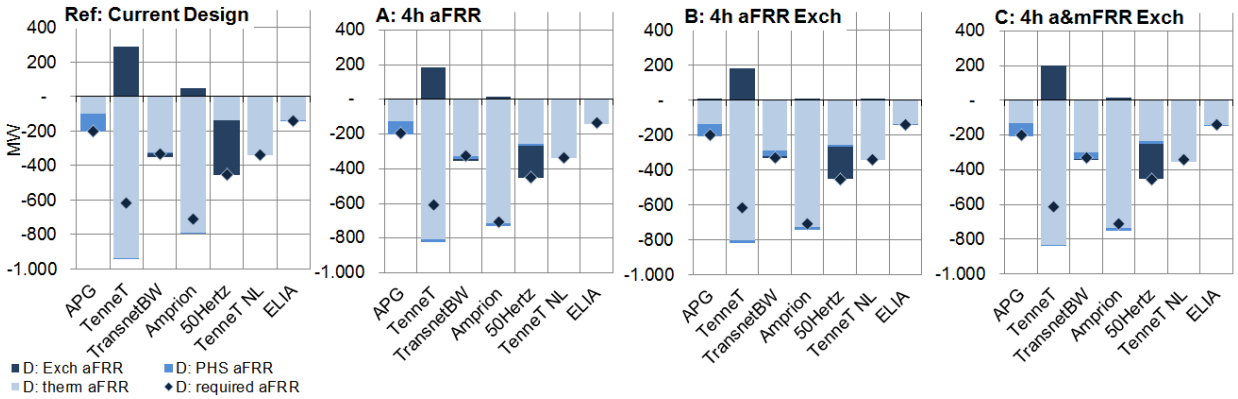
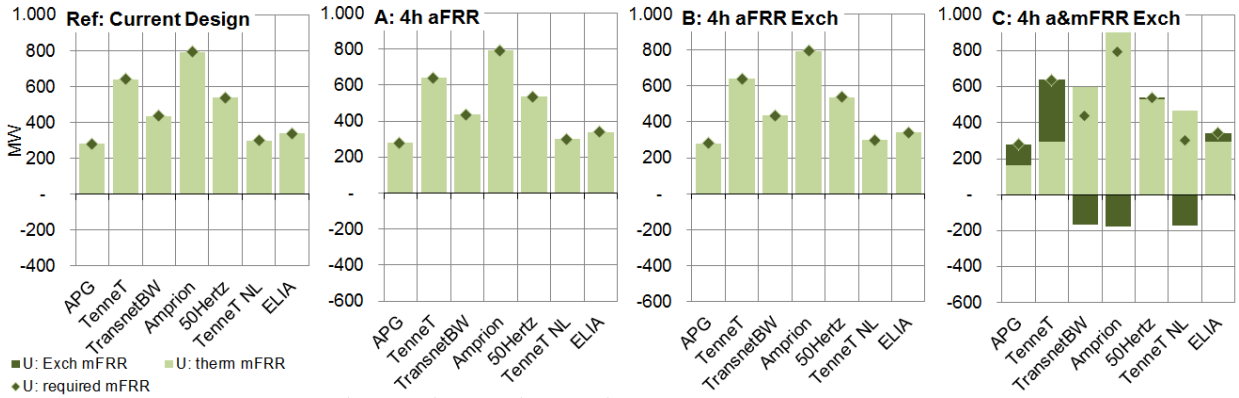


(a) Upward aFRR

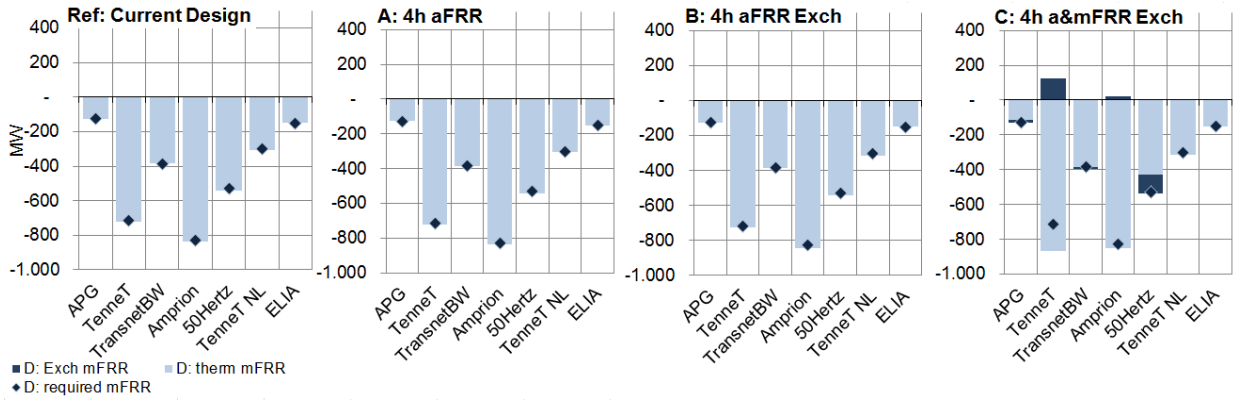


(b) Downward aFRR

Fig. 6. Average procured capacity for up- and downward aFRR for all four scenarios.



(a) Upward mFRR



(b) Downward mFRR

Fig. 7. Average procured capacity for up- and downward mFRR for all four scenarios.