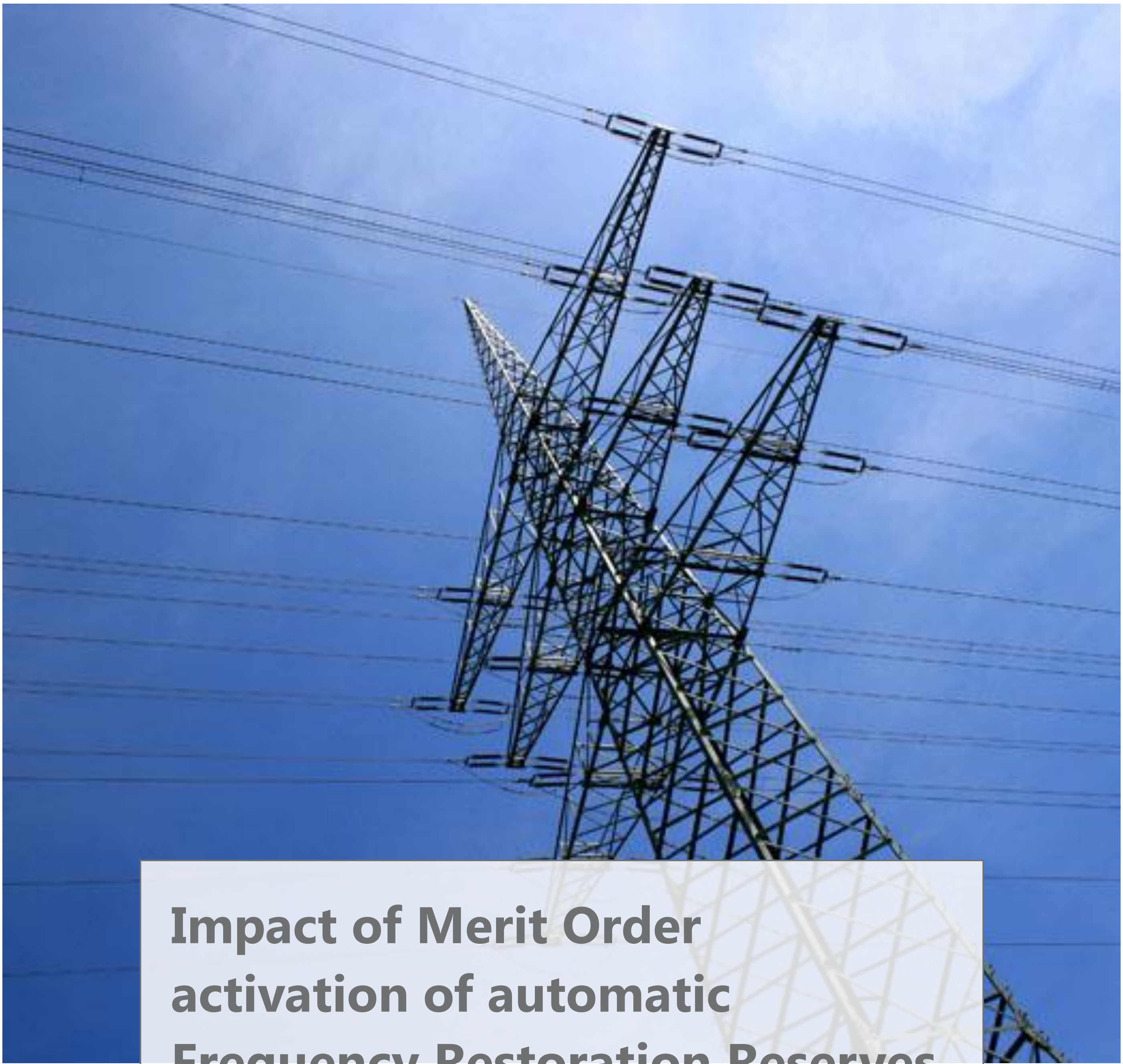

Impact of Merit Order activation of automatic Frequency Restoration Reserves and harmonised Full Activation Times

On behalf of ENTSO-E

29 February 2016

Version: 1.2 (final)

E-Bridge
competence in energy

IAEW
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IMPACT OF MERIT ORDER ACTIVATION OF AUTOMATIC FREQUENCY RESTORATION RESERVES AND HARMONISED FULL ACTIVATION TIMES

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Executive Summary

Introduction

The draft Network Code on Electricity Balancing (NC EB) foresees that no later than one year after entry into force of this Network Code, all transmission system operators (TSO) shall develop a proposal for a list of standard products for Balancing Capacity and for Balancing Energy for Frequency Restoration Reserves and Replacement Reserves.

As an input for their standard product development process, ENTSO-E asked E-Bridge Consulting and Institute of Power Systems and Power Economics (IAEW) of RWTH Aachen University to provide *technical* background information on requirements for automatic Frequency Restoration Reserves (aFRR) throughout Europe. Furthermore, ENTSO-E asked E-Bridge and IAEW to quantitatively study the technical impact of a change to a merit order activation scheme for aFRR and a harmonised aFRR response (aFRR Full Activation Time) for all LFC Blocks.

In this report, we present the results of our study. We note that the focus of this study is technical. A market study was not included in the scope and consequently, conclusive quantitative statements on commercial issues cannot be made. Where possible, we will qualitatively address market issues.

We are grateful for the support of all TSOs that supported our analysis with information, data and good discussion. We also thank stakeholders who provided us with useful comments and suggestions during the preparation of this study.

Use of aFRR in Europe

The objective of the frequency restoration process (FRP) is to restore frequency to the target frequency, in Europe usually 50.00Hz. For this, the FRP is using manual and automatic Frequency Restoration Reserves (FRR). Automatic FRR (aFRR) is automatically instructed by the central Load Frequency Controller (LF Controller) of the TSO and automatically activated at the aFRR provider. The LF Controller is working continuously, i.e. typically every 4 to 10s the TSO's LF Controller may provide new aFRR activation requests to aFRR providers. aFRR is provided by units that are 'spinning' and therefore aFRR providers can follow the TSO's request from their current setpoint within typically one minute.

Continental European (CE) and Nordic TSOs apply aFRR, however differently. On the continent, LFC Areas are defined and each of the areas has its own LF Controller. Some LFC Areas are aggregated in LFC Blocks in which the aFRR activation of several TSOs is coordinated. For other LFC Areas, the LFC Block consists of one LFC Area only. The objective of the LF Controllers is to restore the Frequency Restoration Control Error (FRCE), which is for LFC Blocks in CE the difference between measured total power value and scheduled control program for the power interchange of the LFC Block, taking into account the effect of the frequency bias for that control area. The objective of all continental European LF Controllers together is to restore and maintain the system frequency in the European synchronous system. In the Nordic synchronous area the four TSOs only apply one LF Controller for the entire synchronous area. The objective of this LF Controller is to restore the frequency to the target frequency.

Although the objectives and the high level set-up is very similar, there are major differences in the aFRR requirements and the use of aFRR by the TSOs throughout Europe. We also found large differences in applied LF Controllers and parameterisation of these controllers. Furthermore, some TSOs only exceptionally apply manual FRR and balance their system with close to 100% aFRR while other TSOs perform system balancing mainly manually and apply aFRR for less than 10%.

PRO-RATA VS MERIT ORDER

Most TSOs instruct aFRR providers in parallel and the requested aFRR is distributed pro-rata to the aFRR providers connected to the LF Controller (pro-rata activation). Five TSOs select the cheapest aFRR energy bids first based on a merit order (merit order activation). We have quantitatively analysed the impact on regulation quality of a transition from a pro-rata to a merit order activation of aFRR. For this, we applied a simple merit order activation scheme. In this scheme, aFRR bids are selected one-by-one up to the required aFRR. We did not make other changes to the existing LF Controllers, i.e. we did not tune the LF Controller to the new situation. We performed simulations for 18 LFC Blocks/Areas using high resolution (≤10s) FRCE data and aFRR activation data for the entire months of February and June 2015. We found that for TSOs that currently apply a pro-rata scheme, the standard deviation of five minutes FRCE values (a measure of regulation quality) will increase on average with 31% (typical range between 10 and 50%) when changing to this simple merit order activation while leaving the LF controller settings unchanged.

The main reason for the quality decline after a change to this merit order scheme is that fewer aFRR bids are selected and activated to deliver the requested aFRR volume whereas in a pro-rata activation always all bids are selected to deliver the same aFRR volume. Consequently, with a merit order activation scheme, the provider of a selected bid needs to activate more aFRR per selected bid which will take more time. The activation will therefore be slower than in the pro-rata scheme and may consequently reduce the FRCE quality. However – under the assumption of identical most expensive energy bids – in the merit order activation scheme average aFRR activation price may decrease since only the cheapest bids are activated[1]. As a second consequence, assuming an increase of aFRR energy prices in the merit order, the energy price of the marginally activated bid will increase in magnitude with the magnitude of the system imbalance. This is not the case with a pro-rata activation where the marginally activated bid is always the most expensive bid in the merit order.

For large aFRR activations caused by e.g. a power plant trip, the differences between pro-rata schemes and merit orders schemes are smaller. In this case both pro-rata schemes and merit orders schemes require a lot of aFRR activation at the same time and will effectively activate many bids simultaneously. Therefore, we expect a similar response if the LF Controllers are optimised with the same objective. Since our simulations did only take the existing LF Controller set-up and settings into account (also for the change to the simple merit order scheme), we see that for most TSOs the settling time increases but for some TSOs the settling time decreases. We note that the results are highly sensitive to the current LF controller set-ups and settings. These would need to be revised and optimised to the new situation in case of a transition to a merit order activation scheme.

The main reason that the pro-rata scheme perform technically better than the merit order scheme is that the simultaneous response of all aFRR providing units together is faster than the response of only a few bids at the same time. Consequently, an effective technical mitigation measure is to increase the speed of the aFRR providers' response, e.g. by reducing the aFRR Full Activation Time (FAT). The impact of this measure is described in the section below. Alternatively, a merit order scheme can be implemented that activates more bids in parallel if required for following the LF Controller's request for aFRR. This results in activation of more expensive bids, but never more than is really needed which leaves intact that the price of the marginally activated bid varies with the requested aFRR energy. Another possibility is implementing a feedback loop that allows the LF Controller to take into account not yet activated reserves.

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[1] For the avoidance of any doubt, the effect on aFRR activation cost could not be determined because it depends on several factors such as the price of activation and the activated volume (aFRR activation cost may increase or decrease).

In some LFC Blocks with existing merit order activation, aFRR response is in practice very fast. This is achieved by a fast reaction of the aFRR providers combined with a set-up of the LF Controller that allows fast activation of aFRR.

We conclude that pro-rata schemes have a better response than simple merit order activation schemes, especially for smaller imbalances. However, for smaller imbalances merit order activation schemes only select the cheapest bids where pro-rata schemes select all bids that are available to the TSO. For the same quality, merit order activation schemes require faster reserves (e.g. higher ramp rates or mitigation measures) or activation of more bids in parallel. Faster reserves may primarily have an impact on the aFRR capacity procurement costs. Activation of more bids in parallel increases the aFRR energy activation price. Under assumption of identical most expensive energy bids under both schemes[2] the aFRR energy activation price with an improved merit order activation scheme will however not be more than with a pro-rata activation scheme[1].

aFRR Full Activation Time

We compared the aFRR Full Activation Time (FAT), which is defined as the period between requesting an aFRR energy delivery by the LF Controller and the corresponding completion of the delivered aFRR energy. Throughout Europe, the FAT ranges from 2 to 15 minutes. Harmonising the FAT in Europe may have two effects. Firstly, it may affect the frequency quality since generally a smaller FAT results in better frequency quality. Secondly, the FAT may affect the volume of aFRR capacity that can fulfil these requirements, i.e. for a smaller FAT we expect smaller aFRR volumes than for a larger FAT. Both effects are discussed below.

We performed similar simulations as described above for 18 LFC Blocks/Areas for the entire months of February and June 2015 for a FAT of 2.5, 5, 7.5, 10 and 15 minutes, all with the simple merit order activation scheme. Again, we applied the standard deviation of 5 minutes FRCE as quality measure. We conclude that a FAT of 5 minutes results in FRCE quality that is on average 42% (typical range between 20% to 60%) better than for a FAT of 15 minutes. We note that for an LFC Block with an even smaller FAT than 5 minutes, also a FAT of 5 minutes already results in a big reduction (80%) in FRCE quality.

The other effect of reducing the FAT is that this may reduce the aFRR capacity that can fulfil these requirements and that can be offered by the aFRR providers to the TSO. As a proxy for this capacity, we have studied the theoretical aFRR capability of hydro and thermal power plant to provide aFRR for different FATs throughout Europe, irrespective from the activation scheme (pro-rata or merit order). We define theoretical aFRR capability of a unit as the maximum aFRR capacity that can be provided from operating point P_{min} for upward aFRR or P_{max} for downward aFRR. *We note that the theoretical aFRR capability will not be the aFRR capacity that will be offered to the TSO. However, it provides an indication of the impact of a change of the FAT on the available aFRR capacity.*

We conclude that for LFC Blocks with dominantly thermal generation units the theoretical aFRR capability for a FAT of 15 minutes is 30-40% larger than for a FAT of 5 minutes. For LFC Blocks with dominantly hydro generation this is less than 10%. Technically, we see potential for upward aFRR provided by demand and up- and downward aFRR provided by renewables. Furthermore, we consider storage and small generation plant – including engine motors – technically capable to provide aFRR. We note that demand, renewables, storage and flexible plant may participate at any FAT. Consequently, their theoretical aFRR capability may be hardly influenced by a change of FAT.

[2] This assumption is realistic as long as the aFRR energy product requirements under a pro-rata and merit order scheme remain the same, e.g. the FAT is unchanged.

CONTENTS

1. Introduction

1.1. Background to this study

The draft Network Code on Electricity Balancing (NC EB) foresees that no later than one year after entry into force of this Network Code, all transmission system operators shall develop a proposal for a list of Standard Products for Balancing Capacity and Standard Products for Balancing Energy for Frequency Restoration Reserves and Replacement Reserves. All TSOs shall jointly define principles for each of the algorithms applied for the imbalance netting process function, the capacity procurement optimisation function, the transfer of balancing capacity function and the activation optimisation function. For this study, only the capacity procurement optimisation function and the activation optimisation function for automatic Frequency Restoration Reserves (aFRR) products are in scope.

ENTSO-E concluded[3] that the current implementation of aFRR products is significantly different throughout Europe, both from a market and a technical perspective. Furthermore, TSOs in different countries apply different activation schemes for aFRR: most countries apply pro-rata activation, while a few countries apply a merit order activation, which is the preferred solution by the NC EB.

As an input for their standard product development process, ENTSO-E requires additional *technical* background information. Furthermore, ENTSO-E would like to quantitatively understand the impact of a change to a merit order activation scheme and a harmonised aFRR response (aFRR Full Activation Time).

ENTSO-E asked E-Bridge Consulting and Institute of Power Systems and Power Economics (IAEW) at RWTH Aachen University to undertake a study addressing these issues. In this report, we present the results.

We are grateful for the support of all TSOs that supported our analysis with information, data and good discussion. We also thank stakeholders who provided us with useful comments and suggestions during the preparation of this study.

1.2. Objective and Focus

The objective of this study is to provide ENTSO-E with the following technical background information[3]:

- *Overview of technical differences* in the implementation of aFRR products (activation requirements, volume, prequalification, settlement etc.) and aFRR activation schemes (pro-rata, merit order) throughout Europe;
- *Quantitative* analysis of the impact a *transition from a pro-rata to a merit order activation* for aFRR on *regulation quality*, both for:
    - the existing control systems and response requirements;
    - for different response requirements (aFRR Full Activation Times, FAT).
- *Quantitative* understanding of the impact of aFRR response requirements (FAT) on the *theoretical aFRR capability to provide aFRR bids* for each LFC Block.

[3] ‚Terms of Reference for a study assessing aFRR products' – v1 -, by ENTSO-E WGAS subgroup 5, 9 December 2014.

ENTSO-E further asked to provide an assessment of the impact of above-mentioned changes on the aFRR capacity and energy markets as wells as local access tariffs. Although we strongly believe that quantitative market models and simulations are required to be conclusive on these effects, where feasible we will *qualitatively discuss the effect of the changes on these markets and on the consequent aFRR capacity procurement costs and local access tariffs which are usually covered by the end customers.*

This study addresses selected topics related to aFRR. These were selected by ENTSO-E and have been summarised in Table 1.

Table 1: Focus of the study

Focus of this study	Consequence for this study, results and conclusions
Technical	• *Our quantitative results relate to technical parameters. Further quantitative market analysis is required to quantitatively conclude on impact on markets and cost.*
aFRR	• *Only if required, we will address other automatic reserves (FCR) or manual Frequency Restoration Reserves (mFRR).*
ENTSO-E control blocks that operate aFRR	• *We will study the Continental European and Nordic synchronous area*[4]*.*
aFRR activation schemes (merit order/pro-rata)	• *We focus on the pro-rata and merit order activation schemes. The set-up and settings of TSO's Load-Frequency Controller (LFC) are not changed or optimised to the merit order activation scheme or a different response (aFRR Full Activation Time).*
Existing imbalance, generation portfolio	• *Our overviews present the current situation. If known, we indicate planned changes;* • *For our studies we applied measured FRCE and aFRR data for February and June 2015;* • *Our theoretical aFRR capability calculations are based on the 2014 power generation fleet. For future developments we recommend scenario analysis which is outside the scope of our project.*
Reference is the current situation	• *We report the relative impact of a change compared to the current theoretical aFRR capability, quality etc.*
System Balancing	• *Congestions and other network issues that may require out-of-merit activation may complicate the activation of aFRR energy. These issues are not discussed and not considered in this report.*

1.3. This report

In chapter 2 of this report we provide an overview of technical characteristics of aFRR throughout Europe. Along with this, we will provide a technical description of aFRR and the different parts of the technical design of the Load-Frequency Controller (LF Controller). Chapter 3 discusses the quantitative impact of a change from the existing aFRR activation scheme to a simple merit order activation scheme on the technical regulation quality for each individual LFC Block. We will also discuss measures that can be implemented in the merit order activation scheme to achieve the same regulation quality as today. In chapter 4 we will add the analysis of different aFRR Full Activation Times (FATs) to the results in chapter 3. In addition, we provide an overview of the influence on changing the FAT on the technical aFRR capabilities.

[4] Technical aFRR capability is also determined for Great Britain, Northern Ireland and Ireland (see section 4.2.).

2. Overview of technical implementation of automatic Frequency Restoration Reserves throughout Europe

In this chapter, we provide an overview of the technical implementation of automatic Frequency Restoration Reserves (aFRR) throughout Europe. Along with this, we will provide a technical description of aFRR and the different parts of the technical design of the Load-Frequency Controller. This chapter is based on information that is available in the public domain and information provided by individual TSOs.

2.1. Automatic Frequency Restoration Reserves

For keeping the power system frequency within secure limits, TSOs shall maintain the balance between load and generation on a short term basis. For this, TSOs initially apply Frequency Containment Reserves (FCR). These reserves are activated fast (typically within 30s), stabilise the power system frequency and make sure that the frequency will not further deviate from 50Hz. Frequency Restoration Reserves (FRR) are intended to replace FCR and restore the frequency to the target frequency, in Europe usually 50.00Hz. Where applied, Replacement Reserves (RR) restore or support the required level of FRR to be prepared for additional system imbalances.

The Guideline on transmission system operation[5] (System Operation Guideline) defines FRR as the *'active power reserves activated to restore system frequency to the nominal frequency and in a synchronous area consisting of more than one LFC area power balance to the scheduled value.* The last part of this definitions currently only applies to the Continental European (CE) synchronous system. The System Operation Guideline further distinguishes two types of FRR: *automatic* FRR (aFRR) and *manual* FRR (mFRR). Both types of FRR are used for restoring the power balance to the scheduled value and consequently the system frequency to the nominal value. At the same time FRR replaces the activation of FCR and where applied, RR replaces activated FRR.

This report focuses on automatic Frequency Restoration Reserves (aFRR), defined by the System Operation Guideline as *'the FRR that can be activated by an automatic control device*'. This control device shall be an *'automatic control device designed to reduce the Frequency Restoration Control Error (FRCE) to zero*'. In this study, we apply the term 'Load-Frequency Controller' or LF Controller for this control device. In literature, also Automatic Generation Controller (AGC) and Frequency Restoration Controller is sometimes used.

The Load-Frequency Controller (LF Controller) is physically a process computer that is usually implemented in the TSOs' control centre systems (SCADA/EMS). The LF Controller processes FRCE measurements every 4-10s and provides - in the same time cycle – automated instructions to aFRR providers that are connected by data communication links.

In the next sections we will go into more detail on the LF Controller while describing the applications of aFRR in the different European countries.

[5] Article 3 (definitions) of the draft Guideline on transmission system operation, 27 November 2015.

2.2. European synchronous areas applying aFRR

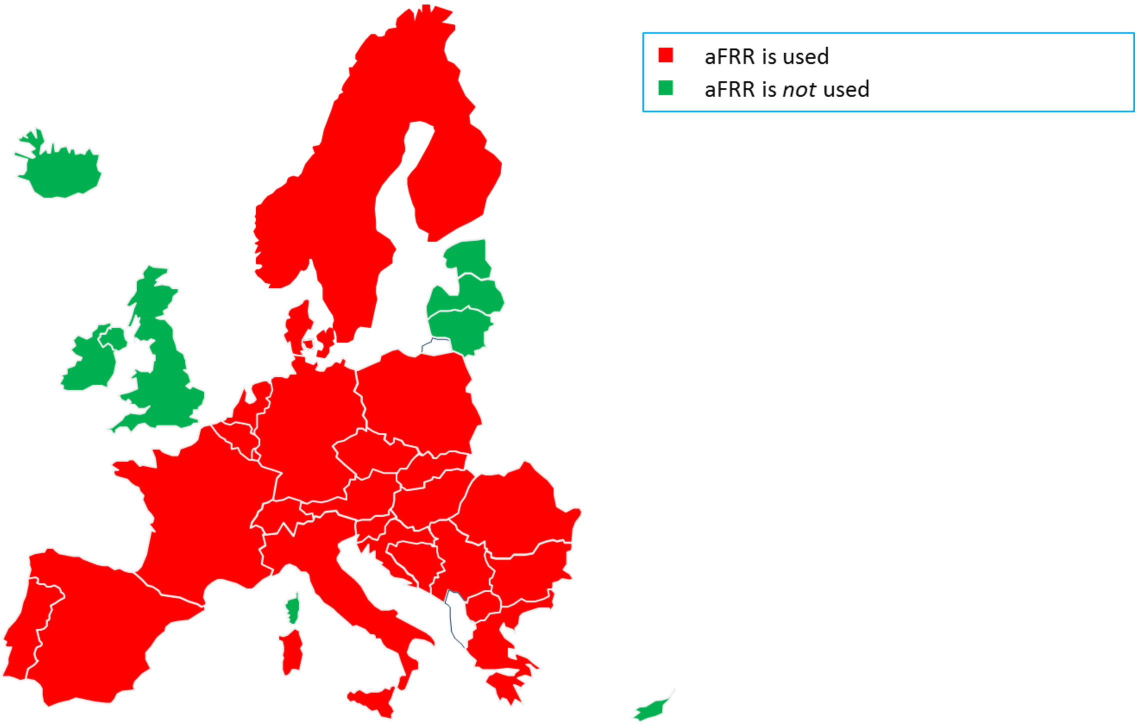

Figure 1: Overview of ENTSO-E members that apply automatic Frequency Restoration Reserves (aFRR)

Figure 1 shows the geographic area in which the TSOs operate an LF Controller. This area consists of two synchronous areas: the Continental European (CE) area and the Nordic area. Although both areas apply an LF Controller, Table 2 shows that many differences exist.

Table 2: Main differences between Continental European (CE) and Nordic synchronous areas

Continental European (CE) synchronous area	Nordic synchronous area
Many LFCs blocks/LFC Areas, often countries	Only one LFC Block comprising Denmark/East, Finland, Norway and Sweden
Each LFC Block/LFC Area has own LF Controller	One LF Controller for the entire synchronous area
FRCE is defined as the difference between the scheduled and measured exchange of the LFC Block/LFC Area, corrected for FCR activation in the area	FRCE is defined as the system frequency deviation in the Nordic system
LFC control mode is *'Tie-line Bias Control'*[6], i.e. each LFC Block controls its own Frequency Restoration Control Error (FRCE) and only indirectly the CE system frequency.	LFC control mode is *'Constant Frequency Control'*[7], i.e. Nordic LF Controller directly impacts Nordic system frequency.

[6] 'Tie-line Bias control' controls the FRCE that is defined by the frequency error (k.Δf) and the interchange error (scheduled minus measured flow).

[7] 'Constant frequency control' controls the FRCE that is defined by the frequency error (k.Δf), in which k is area frequency bias factor (MW/Hz) and Δf the difference between the target frequency and the actual frequency.

Continental European (CE) synchronous area	Nordic synchronous area
Quality targets for aFRR related to FRCE quality per LFC Block (based on tie-line exchange) and system frequency quality.	Quality target for aFRR related to frequency quality for the entire Nordic region only: FRCE and minutes outside 49.9Hz to 50.1Hz band.
aFRR is applied for all hours	In 2013-2015 aFRR was only applied in a selection of hours[8]

2.3. Share of aFRR energy in total activated FRR/RR balancing energy

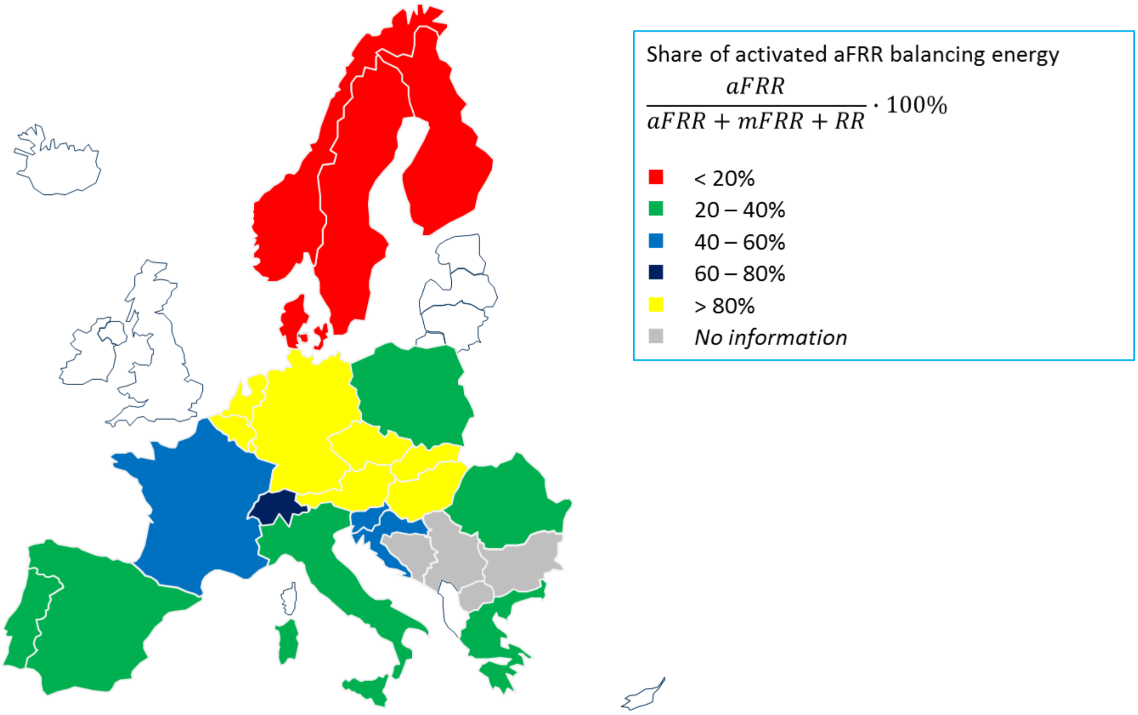

Figure 2: Share of aFRR energy in total activated FRR/RR balancing energy, based on figures for February and June 2015[9].

TSOs that apply aFRR, also apply manual FRR (mFRR) and sometimes Replacement Reserves (RR). Figure 2 shows that the shares of aFRR in the total balancing energy are very different throughout Europe.

[8] since 2015/week 52 no aFRR capacity is being contracted (refer to http://www.nordpoolspot.com/message-center-container/nordicbaltic/exchange-message-list/2015/q4/no.-482015---update-on-exchange-information-no.-362015-frr-a-contracting/)

[9] Based on data from the ENTSO-E Transparency platform and information provided directly by TSOs.

2.4. LFC system and required aFRR for activation

Figure 3 provides a generic overview of the automatic frequency restoration process, which consists of the TSO's LF Controller and the response of the aFRR Balance Service Providers (BSP). The input to the LF Controller is FRCE which is defined as the *power balance to the scheduled value* for the LFC Area/LFC Block and the *system frequency deviation* for the Nordic synchronous area.

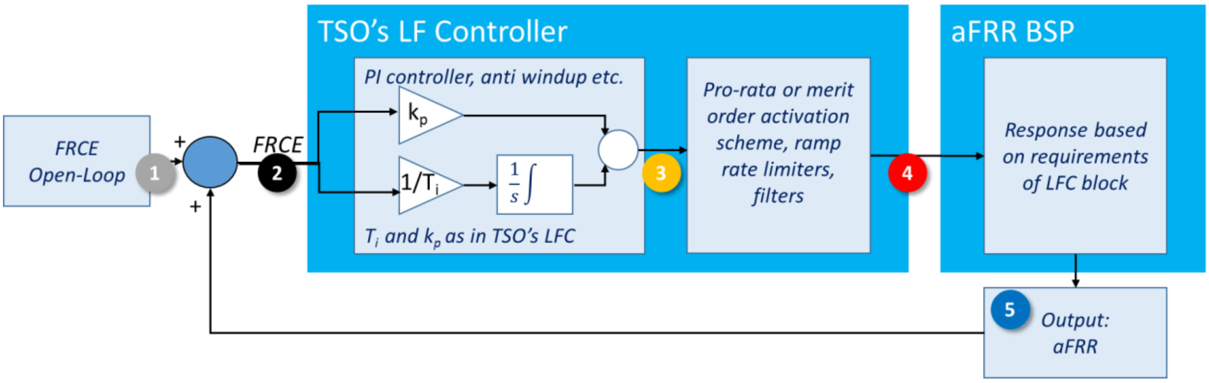

Figure 3: Generic overview of automatic frequency restoration process

Figure 4 shows an example of a 100MW generation trip at time t=0s, assuming no other imbalances in the system. The imbalance of 100MW created by this trip is indicated by line 1 (called FRCE Open Loop), the resulting FRCE by line 2[10]. At t = 0, the FRCE is equal to the imbalance and therefore the input to the TSO's LFC is -100MW. The PI controller will respond to this by a partly proportional response to the FRCE (10% in Figure 4) and by an increasing part that is caused by the integrator of the PI Controller[11]. Consequently, the output of the PI controller (see no. 3 in Figure 3 and Figure 4) needs to be distributed to the aFRR providers (see section 2.5), taking the maximum total ramp rate of the aFRR providing units into account. The signal is now sent to the aFRR providers (see no. 4), which is typically done every 4-10 seconds (see section 2.6). aFRR providers automatically receive and process these activation signals. They start ramping-up or down their aFRR providing units within (typically) 30-60s and with (at least) the required ramp rate (see section 2.7). This response (see no. 5) reduces the FRCE and consequently makes the input to the LF Controller smaller.

[10] Typical, the power system will respond by activating FCR which are outside of the scope and are excluded from the FRCE.

[11] We present a simplified model here and therefore do not include input filters, anti-windup, ramp-rate limiters, saturation etc. in this description. The models that we applied in chapter 3 and 4 include these components as applied by the TSOs.

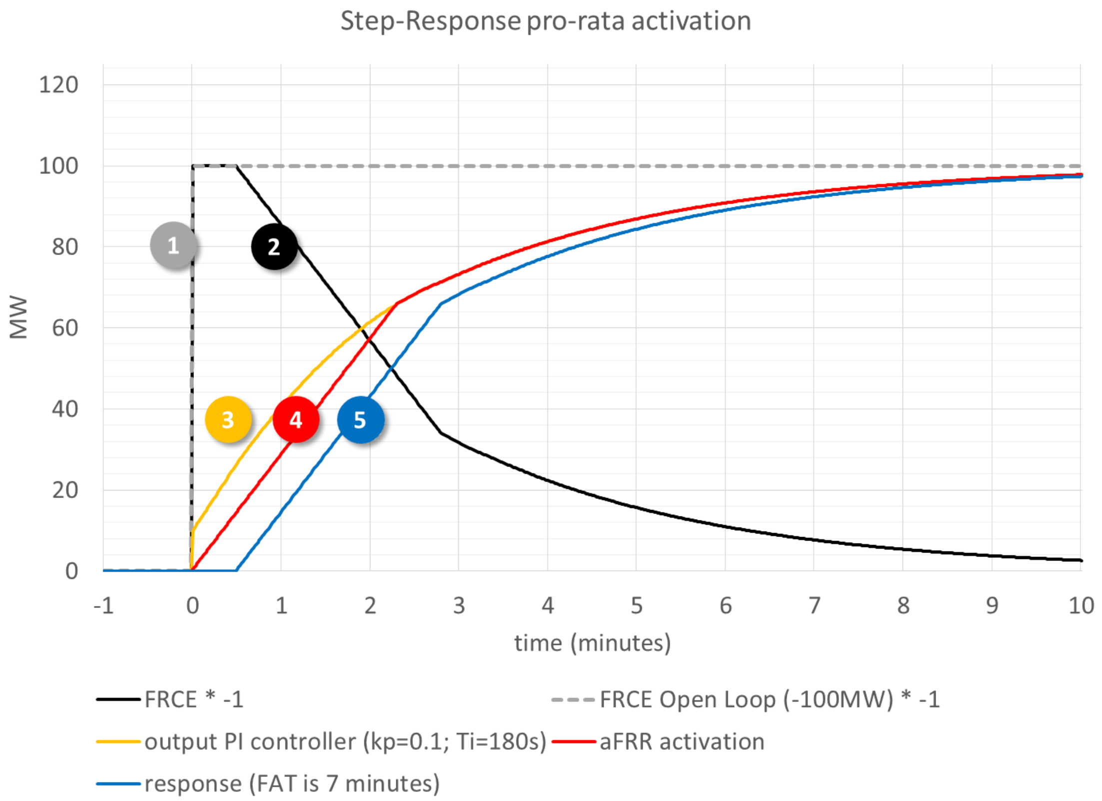

Figure 4: Typical response of generic automatic frequency restoration process to a 100MW generation trip[12]

2.5. Merit order and Pro-rata activation schemes

TSOs apply two types of activation schemes for distributing the output of the PI controller (no. 3 in Figure 3 and Figure 4) to their aFRR providers: pro-rata schemes and merit order schemes (see Figure 5). In a pro-rata scheme, all aFRR providing units are activated simultaneously which ensures that all available ramping speed is used. However, the activation does not take into account differences in energy price or energy cost. A merit-order activation scheme activates aFRR bids one-by-one in energy price order. Consequently, only the ramping speed of the activated bids is used (we refer to chapter 3 for further quantification and discussion of the technical differences).

Figure 5 shows the LFC Blocks in which pro-rata schemes are applied and the LFC Blocks in which merit order schemes are applied.

[12] In this example it is assumed that the total imbalance is covered by the available aFRR volume. It shall be noted that this is not required by the System Operation Guideline.

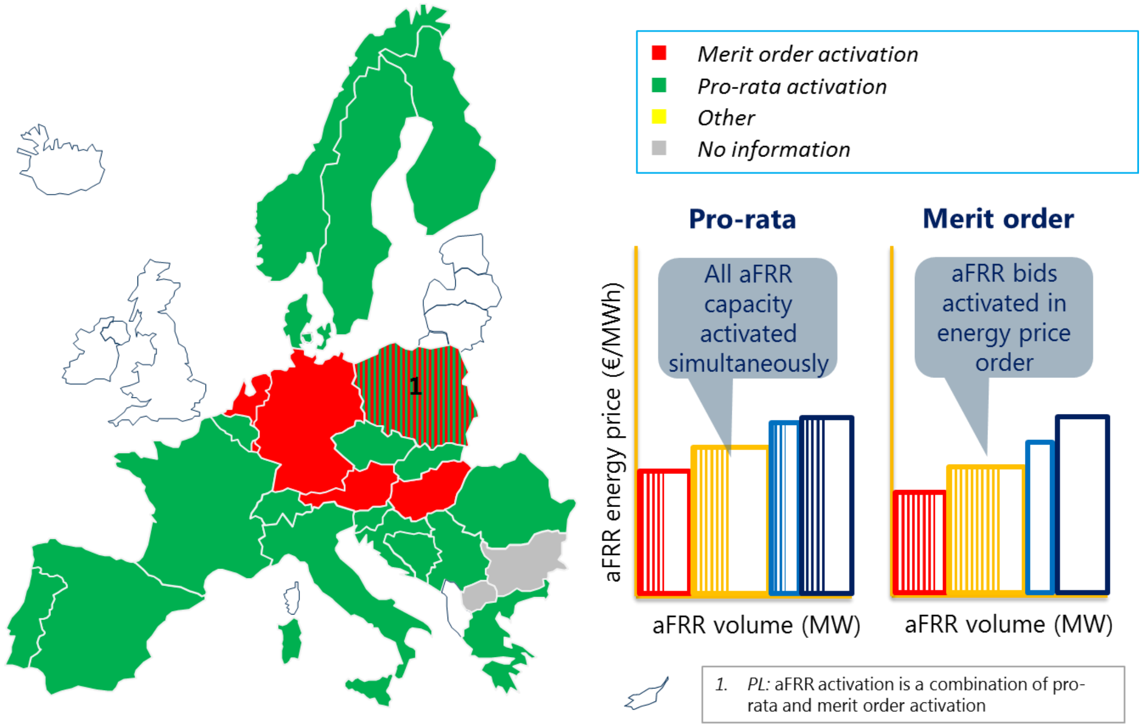

Figure 5: Overview of TSOs that apply a pro-rata activation scheme or a merit-order activation scheme.

2.6. Step-wise or continuous activation

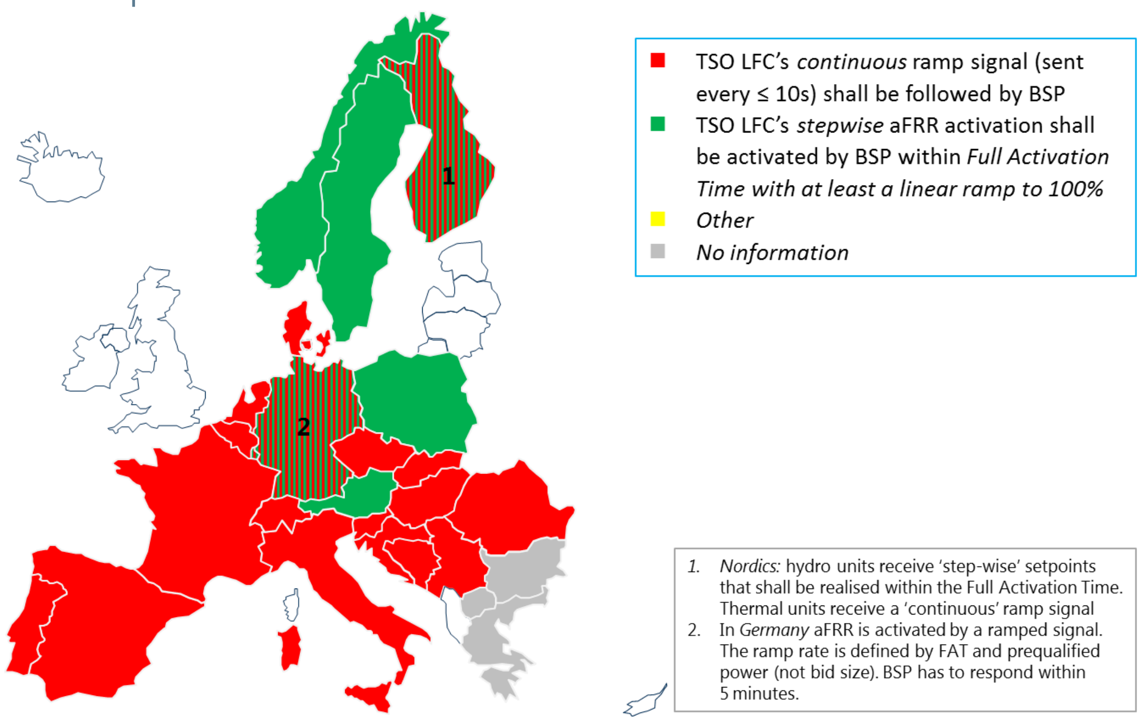

Figure 6: aFRR activation, continuous or stepwise

Figure 6 shows that two different methods are applied by European TSOs to activate aFRR. Most LFC Blocks apply 'continuous' activation, which is explained in Figure 7.a: The signal that the LF Controller sends to the TSO is updated every 4-10s with the new aFRR setpoint following the required ramp for the aFRR provider. The aFRR providers are required to follow this signal typically within 30-60s.

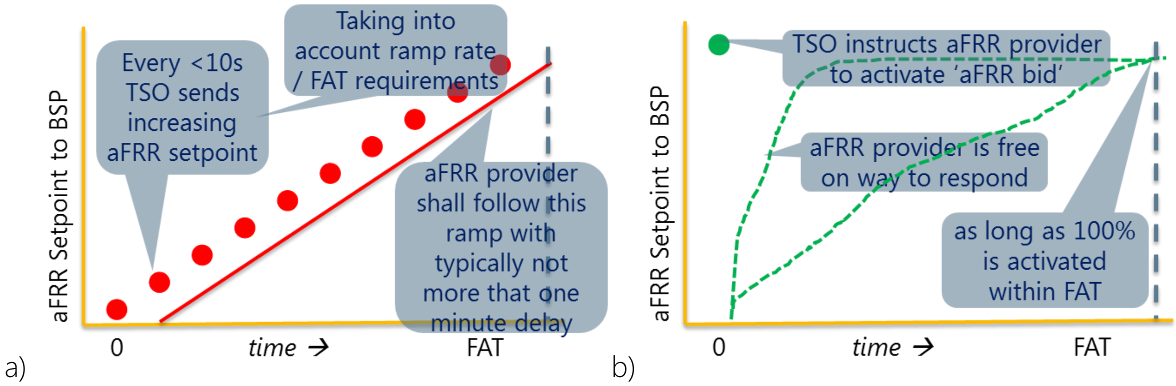

Figure 7: Explanation of a) continuous activation and b) stepwise activation.

Figure 7.b explains step-wise activation: The TSO activates an energy bid at once by a single setpoint change. The aFRR provider shall respond within the aFRR Full Activation Time, and at least with a linear ramp rate.

Continuous activation is typically used in LFC Blocks with pro-rata activation and step-wise activation in LFC Blocks with merit order activation (see section 2.5). However, there are two exceptions. In the Nordic LFC Block, a step-wise activation signal is applied for the aFRR provision with hydro units that provide the largest share of aFRR in the Nordics, while a minority of thermal providers receive 'step-wise' instructions[13]. In the Netherlands, the TSO provides continuous signals to the aFRR provider.

TSOs that apply continuous activation typically use the activation signal for settlement of aFRR energy where TSOs with stepwise activation typically apply a metered value for settlement. Figure 34 in appendix A provides an overview of the settlement methodologies.

2.7. Different aFRR response requirements / aFRR Full Activation Times

The aFRR providers shall be able to follow the ramp rate in LF Controller's activation signal. For this, minimum requirements are specified in most LFC Blocks. These minimum requirements are stipulated in different ways: Some TSOs require an aFRR Full Activation Time (FAT), defined as a time period between the instruction by the LF controller and the corresponding activation or deactivation of aFRR. Other TSOs define the maximum time to first response and a minimum ramp rate. In order to make them comparable, we converted the last set to a FAT as explained in Figure 8 ('time to first response' + 1/'minimum ramp rate').

[13] In the Nordic LFC Block hydro units are selected using a 'round robin' mechanism that selects the bids one-by-one. The aFRR bids are selected in a way that - aggregated over time – results in a distribution of the activated aFRR energy pro-rata to the capacity that is connected to the LFC.

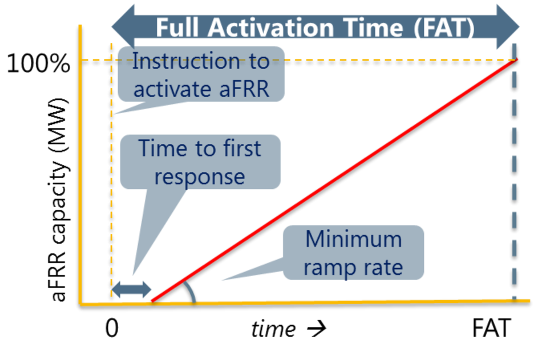

Figure 8: Conversion of time to first response and a minimum ramp rate to aFRR Full Activation Time

Figure 9 shows the different response requirements throughout Europe. It can be concluded that the range is large, from 2 minutes in the Nordic LFC Block, 2-3 minutes in Switzerland and 3 minutes in Italy to 15 minutes in many other blocks. In addition, we note that in Germany and Austria, the ramp rate requirements apply to the prequalified volume of the aFRR provider. Inevitably, with aFRR activation bids smaller than the prequalified volume this results in higher ramp rates and faster response.

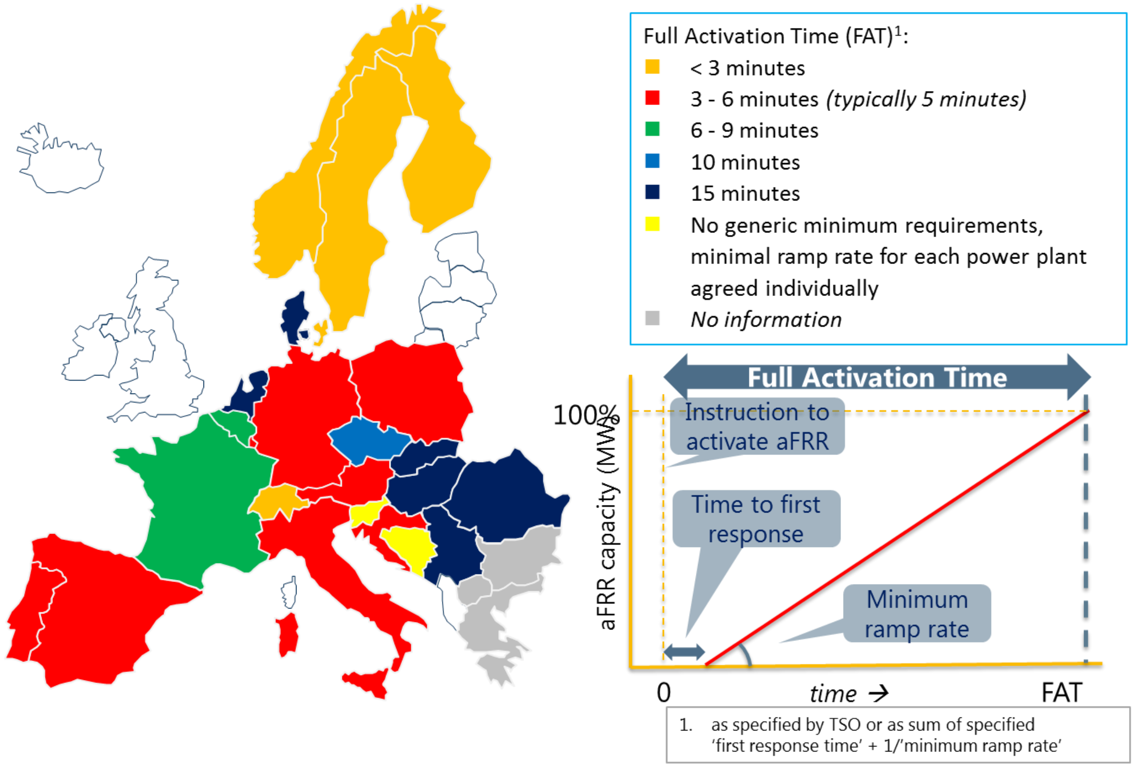

Figure 9: aFRR response requirements (for some countries the requirements are converted to aFRR Full Activation Times)

2.8. Other differences

Appendix A includes overviews of other differences between LFC Blocks and a comparison of aFRR, including an overview of the aFRR capacity, the contracted capacity as share of the peak consumption and the 'Operation Handbook Policy 1' dimensioning formula, the actual response of the aFRR providers, settlement of aFRR, prequalification tests, real time and ex-post compliance check.

3. Quantitative understanding of impact on regulation quality of a transition from a pro-rata to a merit order activation of aFRR

In this chapter 3, we present the results of our quantitative analysis on the impact of a transition from a pro-rata to a merit order activation on regulation quality (section 3.2). Before that, in section 3.1 we discuss the differences between both schemes qualitatively. Section 3.3 provides a description of mitigation measures that may reduce the impact of a change to merit-order activation.

3.1. Merit order scheme vs. a pro-rata activation scheme

There are many different implementations of aFRR merit order activation schemes. In its most simple form, the merit order activation scheme instructs bids up to the aFRR volume that is requested by the LF Controller's PI controller (see section 2.4). The instruction will be in price order of the aFRR energy bids. If the required aFRR volume increases, the scheme will activate the cheapest remaining bid. This bid will be activated and the new setpoint is reached after the Full Activation Time.

Figure 10 compares the merit order activation scheme with the pro-rata scheme. If the PI controller (see Figure 3) requests more aFRR (dashed black line in the right hand figure), the pro-rata scheme distributes this request over all aFRR providers that are connected to the LF Controller. Accordingly, all aFRR providing units ramp to the requested new set-points simultaneously (blue lines). Because the pro-rata scheme uses the combined ramp-rate of all the units (red line), the required response is often reached before the Full Activation Time. For merit order activation schemes, less bids are activated and it will take the aFRR Full Activation Time until the total response will be delivered[14].

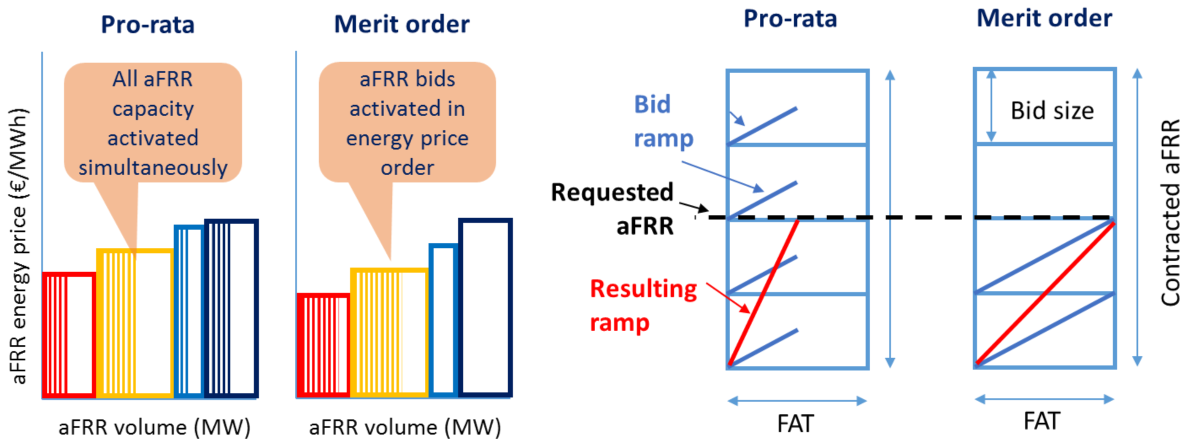

Figure 10: Comparison of Pro-rata and Merit order activation scheme

The advantages and disadvantages work out differently for aFRR activations that are small and aFRR activations that are large in comparison to the aFRR volume that is available to the LF Controller. For *small aFRR activations*, the pro-rata scheme makes sure that the aFRR is delivered very quickly. The disadvantage is that the average price paid for the aFRR energy is fixed as always all bids are activated. The advantage under merit order activation is that the average price paid for aFRR energy varies with the activated volume. Assuming that the most expensive bid for both activation schemes

[14] In order to speed-up the response, many TSOs with a merit order activation scheme took measures to mitigate the slower response. These measures are discussed in section 3.3.

is identical[15], this is always lower or equal to the average price paid for aFRR energy under a pro-rata scheme. This holds under both a "pay as bid" as well as a "pay as cleared" aFRR energy remuneration scheme[16]. The disadvantage under merit order activation is that it takes the full FAT to get the complete response.

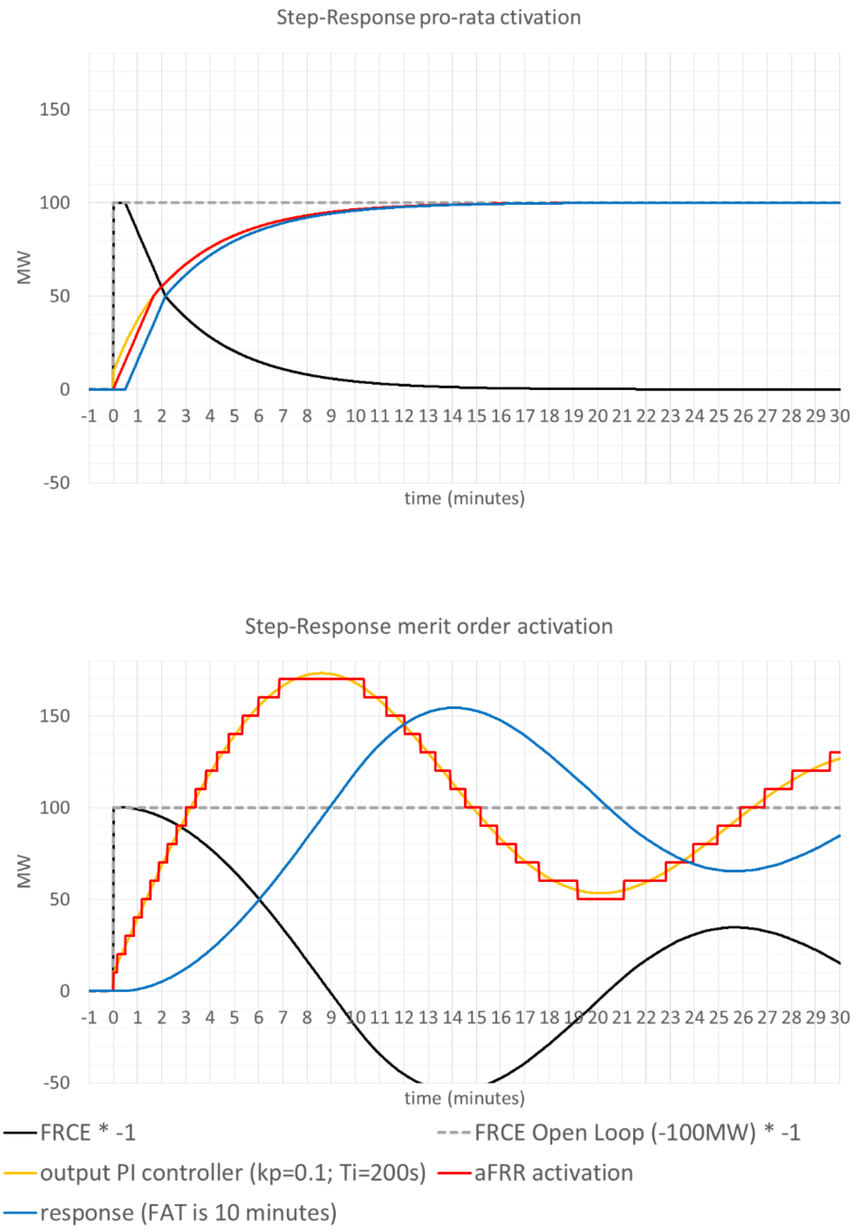

Figure 11: Small deviation (100MW step response) for pro-rata (upper figure) and merit-order (lower figure) activation scheme (300MW of aFRR connected to the LFC) **[12,]** [17].

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[15] This is a realistic assumption if the aFRR energy product requirements (like FAT) are identical under both activation schemes.

[16] Congestions and other network issues that may require out-of-merit activation may complicate this but are out of scope of this study.

[17] The choice of parameters is an example. It shall be noted that TSOs in Europe apply very different k_p and T_i values. The values applied reflect a rough average of these parameters.

Figure 11 provides an example for an LFC Block with 300MW aFRR connected to the LF Controller and a FAT of 10 minutes. At t=0, a step imbalance is introduced of -100MW and it is assumed that there are no other imbalances. In the first minute after the imbalance, the PI controller responds similar in both the pro-rata and merit order activation schemes, also the aFRR activation instructions to the aFRR providers are similar. However, in the pro-rata scheme, the instructions are to all aFRR providing units simultaneously, while for the merit order scheme the aFRR bids of 10MW are activated one-by-one. Since in the pro-rata scheme all connected units (300MW in this example) are used simultaneously, the response of this pro-rata scheme is faster. Consequently, the FRCE will reduce faster. Since this FRCE is the input of the LF Controller, the PI controller's integrator output will increase on a slower pace and reach the target value. Since the aFRR providers in the merit order activation scheme only complete their response after the FAT, the FRCE will only be reduced later and consequently, the LF Controller's integrator output will keep increasing, even above the value of the original imbalance. Figure 11 shows that this may result in an overshoot in aFRR activation[18]. Consequently, the FRCE will go fluctuate around zero before it will stabilise to zero eventually.

For *large aFRR activations*, i.e. activations close to the aFRR volume that is available to the LF Controller, both the pro-rata scheme and the merit order scheme will activate close to all available aFRR bids simultaneously. In that case, the response of a pro-rata and a merit order scheme is very similar: they both make use of the ramping speed of all available aFRR providing units and they both activate all of them, i.e. with both low and high energy cost/price. Therefore we would not expect very different response or costs for these activations.

[18] The overshoot could be prevented for by a longer integration time that better matches the response. However, this will again make the response slower.

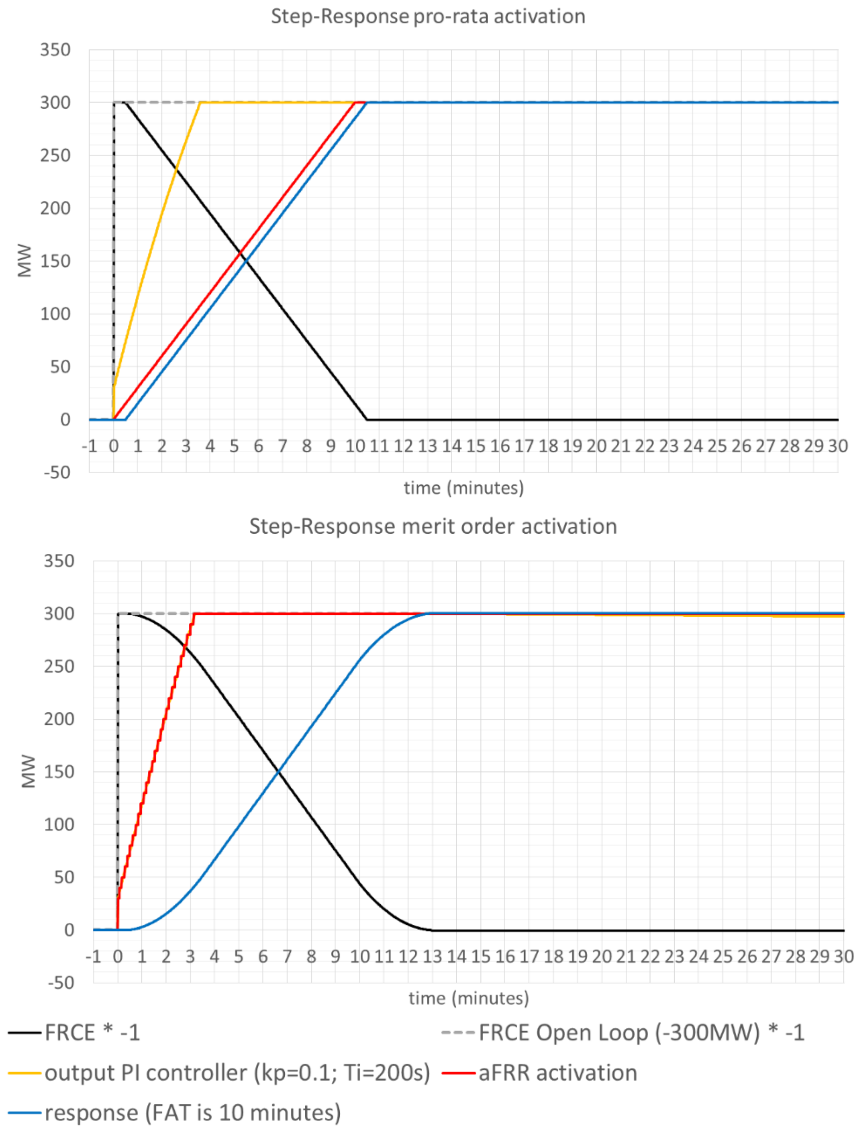


Figure 12: Large deviation (300MW step response) for pro-rata (upper figure) and merit-order (lower figure) activation scheme (300MW of aFRR connected to the LF Controller) [12, 17].

Figure 12 provides an example for an LFC Block with 300MW aFRR connected to the LF Controller and a generation trip of 300MW. The PI controller responds similar in both the pro-rata and merit order activation schemes. The instructions for the pro-rata case are 'delayed' though by a ramp-rate limit that takes into account the ramping speed of the connected bids. However, the delivery of aFRR is very similar in both cases again.

3.2. Quantification of regulation quality resulting from a pro-rata and merit order activation scheme

This section 3.2 quantifies the influence on regulation quality resulting from the differences between pro-rata and merit order activation schemes that are explained qualitatively in section 3.1. For this, we prepared simulation models based on information provided by the TSOs. We have simulated the LFC Blocks/Areas for both the current situation and FAT (base case) and with a hypothetical situation with a change to the simple merit order activation as described in section 3.1 (merit order) and the same FAT as today (in section 4.3 we present simulations with different FAT). In section 3.2.1 we provide the results of simulations with time series and in section 3.2.2 with large deviations. The results form a starting point for further discussions on required mitigation measures for merit order activation schemes in section 3.3.

3.2.1. Simulations for February and June 2015

Firstly, we performed simulations with time-series of FRCE, available aFRR capacity and aFRR activations for the entire months of February and June 2015[19]. For this, the TSOs made time series of FRCE and their aFRR activations on a 4-10s resolution available and also provided us with historical data for the available aFRR. We furthermore assumed a merit order with aFRR activation bids with a bid size of 10MW[20].

The simulations result in time series of FRCE and aFRR activations for both the existing situation and the situation with merit order activation. In order to compare the regulation quality of different schemes we calculated the *standard deviation of the FRCE time series, based on 5 minutes average values of FRCE*[21]. Figure 13 shows the results of the merit order activation scheme relative to the quality of the existing activation scheme (for the full results we refer to Appendix B): A change to the simple merit order activation scheme will increase the FRCE standard deviation on average with 31% (typical range between 10 and 50%, but with Switzerland as extreme).

Also for the LFC Blocks that currently apply a merit order activation scheme, the simulation results show that the FRCE standard deviation of the 'simple merit order' is larger than for their existing merit order scheme. This can be explained by the fact that these LFC Blocks' merit order activation schemes have different characteristics from the 'simple merit order' that has been used for this study. It shall be noted that these characteristics are not the same for the different LFC Blocks with merit order activation. Section 3.3.1 describes some of them.

[19] According to long term statistics frequency quality is typically different in summer and winter. Since aFRR was not used in the Nordic countries in week 1 and 2 and in week 27-31, together with ENTSO-E we selected February and June 2015 as study months.

[20] We performed sensitivity analysis with 5MW and 20MW bids and concluded that the influence was limited.

[21] We note that in article 20 of the Network Code on Load-Frequency Control and Reserves [NC LFC&R], a 15 minutes FRCE is defined for the regulation quality managed by both aFRR and mFRR. Since we only focus on aFRR and aFRR FAT is between 2 and 15 minutes, we compare 5 minutes averages.

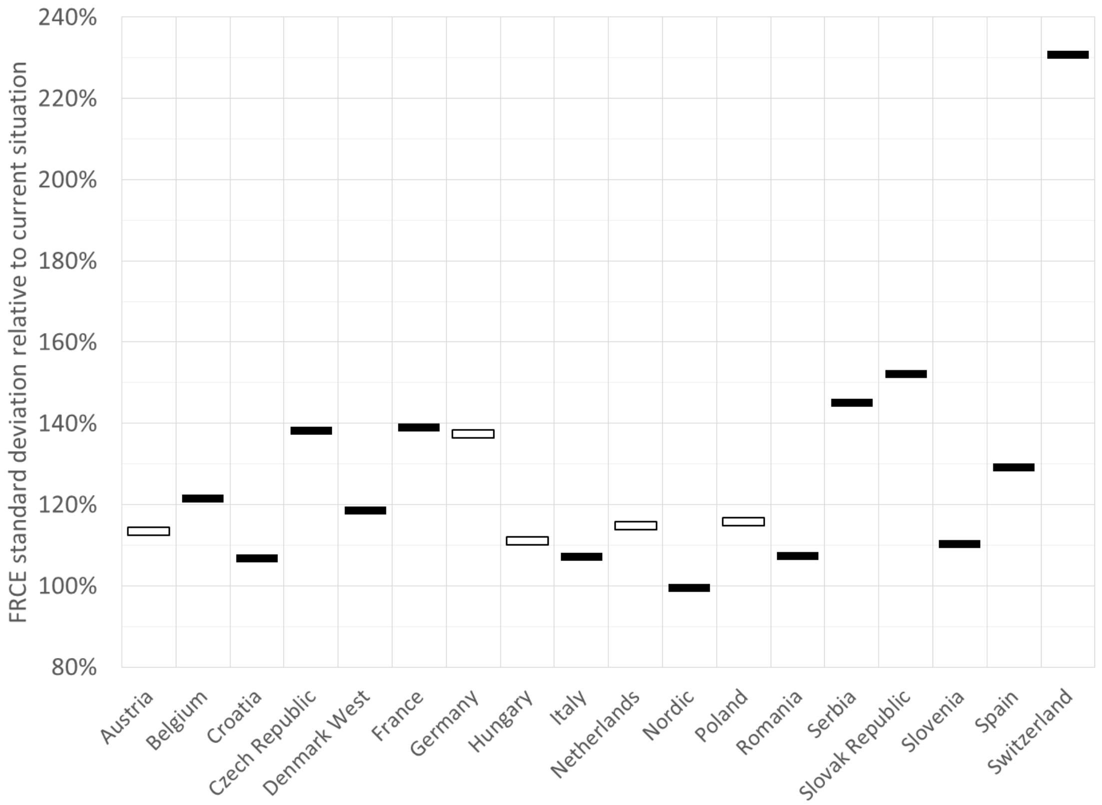


Figure 13: FRCE standard deviation for a simple merit order scheme, relative to the FRCE standard deviation for the existing situation (open boxes show LFC Blocks that currently apply other merit order activation schemes)[22]

3.2.2. Large deviations

In most LFC Blocks, the aFRR volume that is available to the LF Controller is a lot smaller than the largest generation trip in the LFC Block. Consequently, in these LFC Blocks the available aFRR can never return the FRCE to zero without additional mFRR activations. Since this study is focusing on aFRR, we simulated large deviations as a loss of generation with the size of the available aFRR volume[23]. The simulations have been performed for the current activation scheme and the simple merit order activation scheme. For the resulting FRCE, we calculated the settling time, which is defined in Textbox 1.

[22] Note that this overview only includes the LFC Blocks for which we had sufficient data available.

[23] Since for Germany the contracted aFRR volume is larger than the dimensioning incident, we simulated the large deviation with the dimensioning incident for Germany instead of the aFRR volume.

Textbox 1: Explanation of calculation of settling time

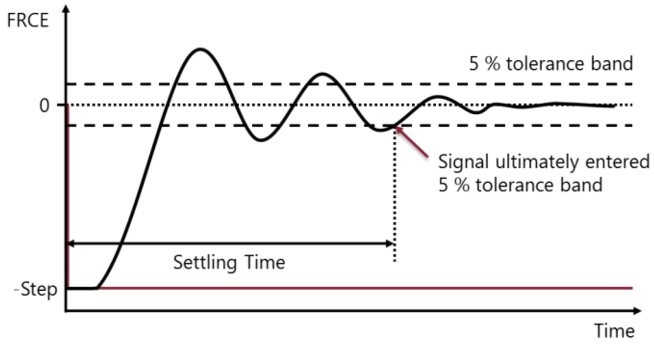


Figure 14: Calculation of settling time

Figure 14 illustrates the calculation of the settling time which is specified by the elapsed time from a step input to the LF controller until the FRCE has entered and remained within a 5% tolerance band around zero. The shorter the settling time is, the faster the aFRR response reaches the required output.

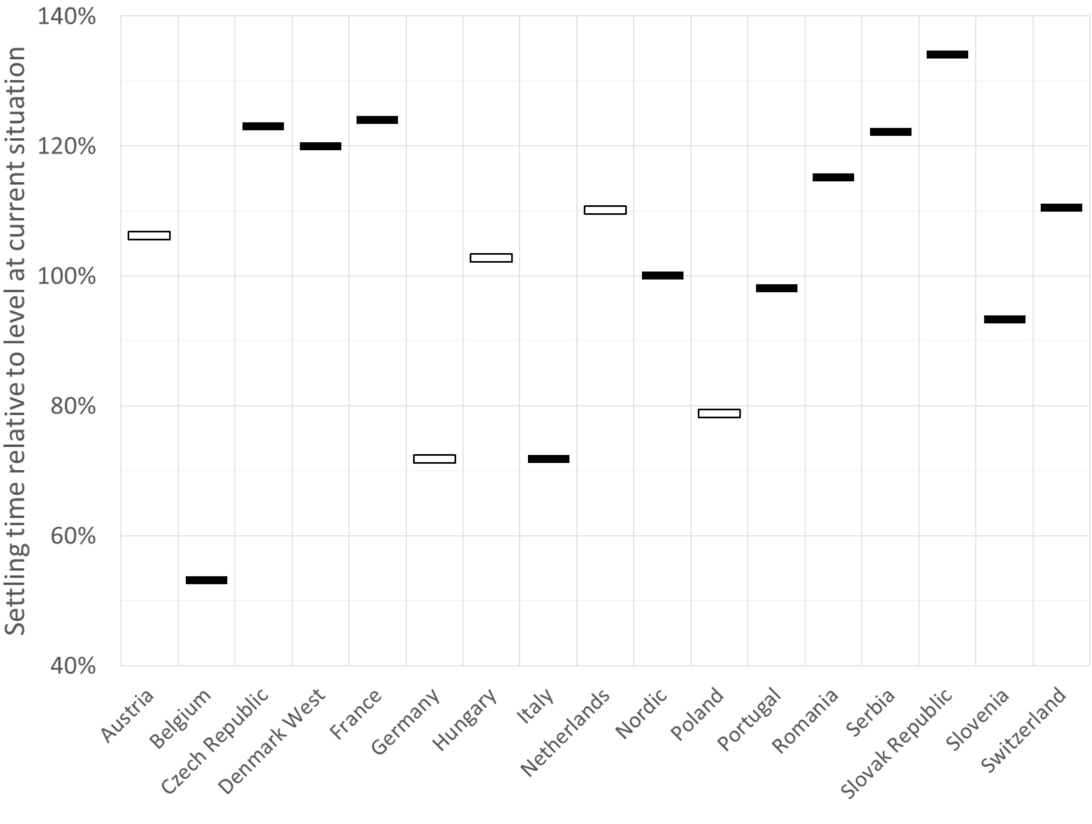


Figure 15: Settling time for large deviations for a simple merit order, relative to the settling time for the existing situation (open boxes show LFC Blocks that currently apply other merit order activation schemes)[24]

[24] Some countries are not included because – due to the LFC set-up – we are not able to calculate a settling time. Please refer to appendix B.

Figure 15 shows the settling time for the simple merit order activation scheme relative to the values for the existing scheme (for the full results we refer to appendix B). The graph shows that a change to the simple merit order activation scheme without changing anything else will change the settling time for most LFC Blocks with not more than 34%. For most TSOs the settling time increases but for some TSOs the settling time even decreases.

We note that the results are highly sensitive to the current LF controller set-ups and settings. These would need to be revised and optimised to the new situation in case of a transition to a merit order scheme, not only for large deviations but simultaneously also for the small changes.

3.3. Mitigation measures to improve FRCE quality of merit order activation schemes

In section 3.2 we show that for most LFC Blocks the FRCE standard deviation with a simple merit order scheme is larger than for the existing activation scheme. Even for the countries with a merit order activation scheme at the moment, the regulation quality with the existing scheme is significantly higher. Section 3.3.2 discusses possible mitigation measures that may improve the regulation quality of the merit order activation schemes. Before this, in section 3.3.1 we will first provide background to the merit order activation schemes in Austria, Germany, the Netherlands and Poland. Finally, in section 3.3.3 we address some measures that may improve the FRCE quality of merit order activation schemes but not necessarily on their own. They may need to be combined with other measures in order to improve FRCE quality under merit order activation to the desired level.

3.3.1. Existing merit order activation schemes

3.3.1.1. Austria and Germany

The merit order activation schemes in Austria and Germany apply stepwise activation (see section 2.6). aFRR providers have to be able to ramp-up the total pre-qualified aFRR volume in 5 minutes. Since the prequalified volume of a typical portfolio in Germany and Austria is many times higher than the bid size, the response to smaller activation signals can be a lot faster than with a constant ramp rate referring to FAT and bid size as in the simple merit order scheme. Another reason for a possible fast response is that the PI controllers in Austria and Germany are tuned for a merit order scheme and have a relatively high proportional part. Consequently they respond very quickly to changes.

3.3.1.2. Poland

In 2015 the Polish aFRR pro-rata activation mechanism was replaced with an advanced merit order, which comprises economic components. Originally, it was planned to implement simple merit order aFRR activation, but during model simulations PSE discovered two important disadvantages. Firstly, this scheme would result in decreasing of regulation quality and consequently a longer time to restore FRCE to zero. Secondly, there were technical (thermal) problems for the unit that was activated last to cover FRCE[25].

[25] PSE mentions that often up and down aFRR power activation (full bid – in principle ±5% power of unit) results in thermal problems (on boiler) and in consequence temporary deactivation and inaccessibility of aFRR. Note that in Poland only centrally dispatched units (thermal) participate in aFRR.

Changing the settings of the PI controller and optimising the aFRR activation mechanism did not bring the expected positive effect. However, negative consequences could be mitigated by an advanced merit order solution with simultaneous activation of all aFRR providing units, using the bid prices for determining the share per unit in the total activation[26]. According to PSE's experience, this solution ensures cost optimisation of aFRR utilisation and maintains regulation quality almost as good as provided by pro-rata mechanism.

In addition to this, the required FAT of 5 minutes is referring to the prequalified volume of a unit (typically +/-5% of P_{max}), which equals the bid size. Similar to what is described for Austria and Germany in section 3.3.1.1, the response to smaller activation signals can be a lot faster than with a constant ramp rate referring to FAT and bid size as in the simple merit order scheme.

3.3.1.3. Netherlands

The situation in the Netherlands is quite different from many other European countries since the input to the frequency restoration process (FRCE Open Loop) in the Netherlands is already close to zero for most time and the LF Controller does not require a lot of aFRR activations. The reason for this is that Balance Responsible Parties (BRPs) contribute actively to the system imbalance without instruction by the TSO. BRPs can do this because the Dutch TSO provides real-time information about the system balance and BRPs are incentivised to keep their energy balance and even reduce the system imbalance in real-time.

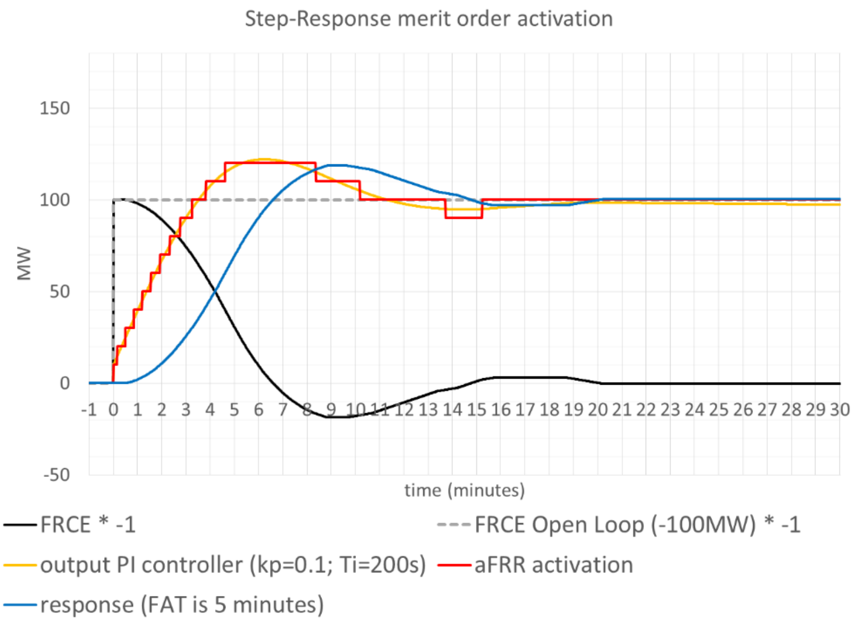
3.3.2. Mitigation measures

In this section we present some mitigation measures that could improve FRCE quality of merit order activation schemes. We note that the situation in the different LFC Blocks varies. Differences include volatility of the imbalance (mostly fluctuating around zero or in one direction for a longer time), PI controllers (largely proportional to only integral), anti-windup, zero crossing detection and FAT (response time). Consequently, the mitigation measures below will not have the same impact in all LFC Blocks. When implementing a merit order activation scheme TSOs may therefore require different (combinations of) mitigation measures while also optimising their own set-up and settings.

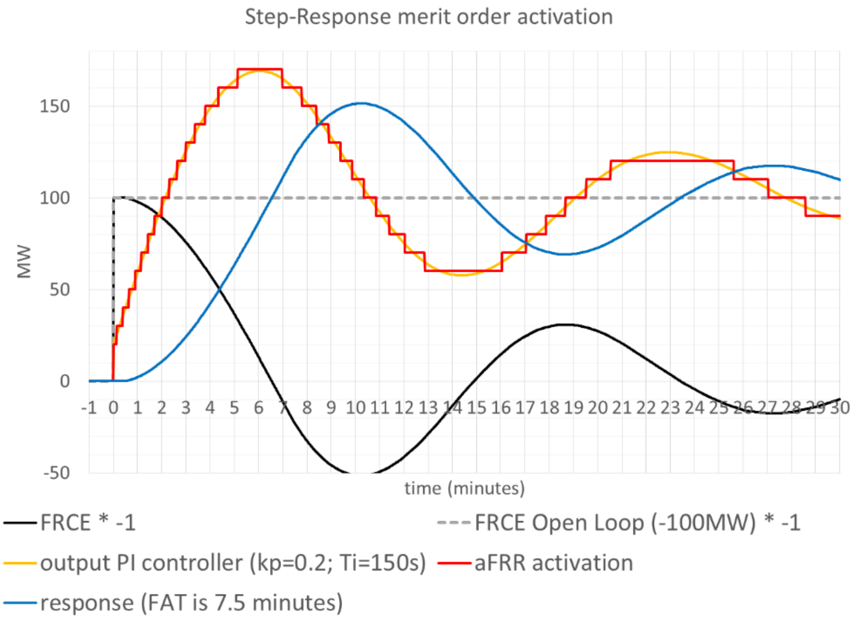
3.3.2.1. Mitigation measure 1: Applying smaller FAT

The most straight forward measure of improving the aFRR quality is to decrease the FAT. Figure 16 shows that the total response with a simple merit order activation with a smaller FAT is more similar to the pro-rata response with the original FAT than the merit order response with the original FAT (see Figure 11).

[26] Taking into consideration the price of the bids, the LF Controller - based on the quadratic goal minimisation function - distributes required aFRR power among providing regulation units.



a)



b)

Figure 16: Step response for 100MW step of merit-order activation scheme with a smaller FAT: FAT is reduced from 10 minutes to 5 minutes in figure a) and to 7.5 minutes in figure b) (to be compared with Figure 11) [12, 17].

This mitigation measure will technically work, but – as further discussed in section 4.2 – may have an impact on the aFRR market: a smaller FAT may reduce the aFRR offered and may increase the aFRR price.

We note that of the LFC Blocks that apply a merit order activation scheme, the Austrian, German and the Polish LFC Block have a very fast response, which is explained in sections 3.3.1.1 and 3.3.1.2. For the Nordic LFC Block, the existing 'pro-rata scheme with round robin' for hydro units[13] is technically not very different from a merit order scheme since also here the bids will be activated one-by-one. We note that the FAT for hydro units in the Nordics is only 2 minutes, i.e. the fastest response in our sample.

Conclusion is that technically a smaller FAT will likely be an effective mitigation measure. However, it may also exclude theoretical aFRR capability from slower (typically thermal) providers (see section 4.2).

3.3.2.2. Mitigation measure 2: Activating more bids in parallel

Another way to achieve a faster response is to activate all bids – and not more than that – that can deliver the required *change* from the previous PI controller output. E.g. if the PI controller output is 10MW higher than the previous PI controller output 5s ago, the selected bids shall be capable of ramping 10MW in 5s. By doing this, the PI output is exactly followed by the activation signals. However, compared to the simple merit order scheme, more bids will be activated which may result in a higher marginal aFRR energy price which then reflects the lowest possible marginal aFRR energy price for the same FRCE quality.

3.3.2.3. Mitigation measure 3: Feedback loop for preventing overshoot in response

The main reason for an overshoot in the response (see section 3.1, Figure 11) is that the integrator of the LF Controller's PI controller does not take into account what aFRR will be activated within the next minutes. Consequently, the LF Controller's PI controller keeps integrating and the activation scheme keeps activating more aFRR, resulting in more activations than the original deviation. This issue can be mitigated by 'informing' the LF Controller's PI controller about the expected response of aFRR that has been activated but not yet realised and therefore not yet reduced the FRCE. The measured FRCE will be reduced with this value. Figure 17 shows a possible scheme.

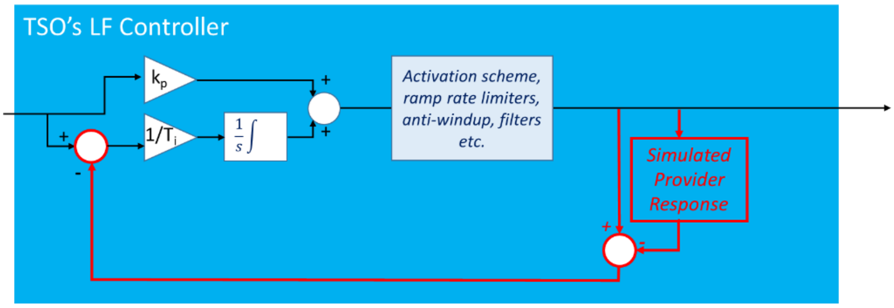


Figure 17: Simplified scheme that feeds back the expected response of aFRR providers

Figure 18 shows the resulting step-response. The overshoot disappeared which also means that not more bids are activated than required for mitigating the imbalance. We note that this methodology may make the controller 'slower' for smaller imbalances that would not have resulted in an overshoot. Advantages and disadvantages therefore have to be evaluated carefully.

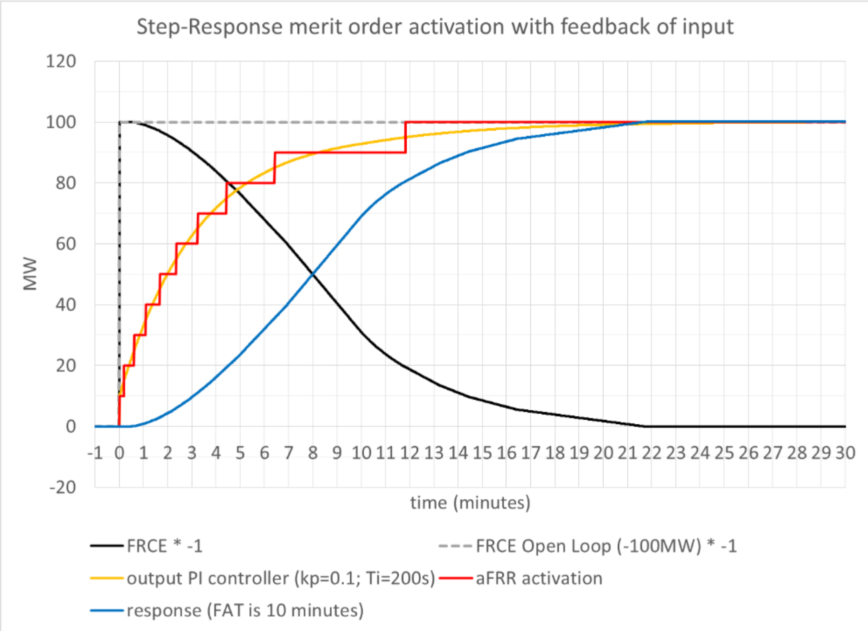


Figure 18: Step response for 100MW step of merit-order activation scheme with a feedback loop (to be compared with Figure 11) [12, 17].

3.3.3. Mitigation measures that need to be combined with other measures

In this section we present mitigation measures that may only work in combination with measures described in section 3.3.2. Again, the effectiveness of the measures very much depends on the situation in the individual LFC Blocks and needs to be evaluated carefully for individual situations.

3.3.3.1. Larger proportional response, shorter integration time

The PI controller in the LF Controllers can be tuned faster to enable fast response. This can be done by increasing the proportional part of the PI controller or by decreasing the integration time (see Figure 19). Increasing the proportional part results in a higher share of the deviation that will directly result in aFRR activations. A decreased integration time will result in a faster changing aFRR activation output of the LF Controller. Both tuning actions will result in the activation of more aFRR and consequently more bids. The downside of a faster LF Controller is that it will be more likely that the response overshoots, which will result in even more activations. Hence, this measure needs to be combined with a faster response (smaller FAT) which will only be feasible if sufficient aFRR can be provided at a smaller FAT. The Austrian and German LF Controller have a relatively large proportional response and short integration time. This results in good response because of the very fast response of the aFRR providers on the step-wise activation signals (see section 3.3.1.1). The LF Controller settings shall safeguard a stable operation of the automatic Frequency Restoration Process. Therefore this measure has to be evaluated very carefully.

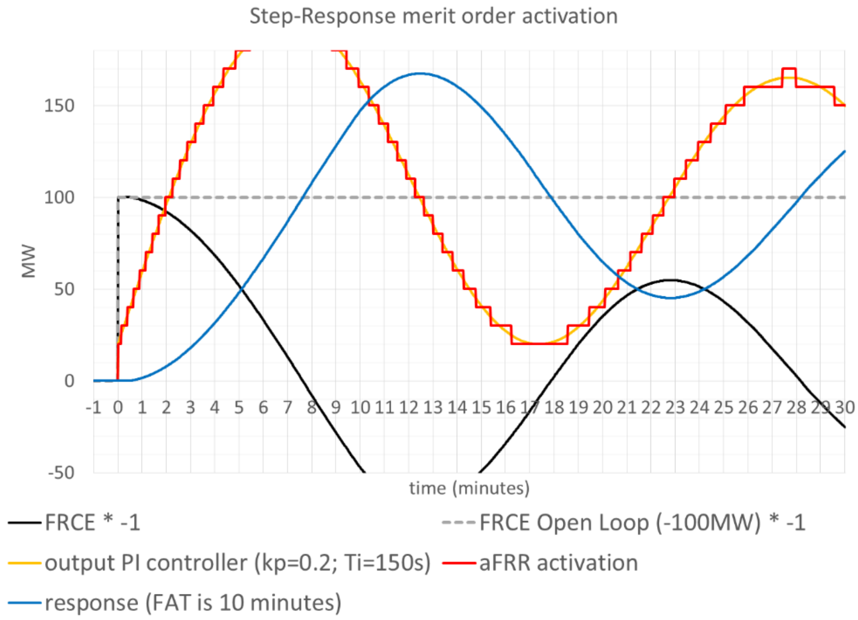


Figure 19: Step response for 100MW step of merit-order activation scheme with a smaller integration time T_i (to be compared with Figure 11) [12, 17]

3.3.3.2. More aFRR connected to the LF Controller

If more aFRR can be activated by the TSO's merit order activation scheme, this will *not* change the behaviour of the LF Controller and activation scheme up to the aFRR volume that is currently connected to the LF Controller. Hence, the bids will still be activated one-by-one and up to the amount that is calculated by the LF Controller's PI controller. Consequently, this mitigation measure will only improve frequency quality if the aFRR activation would otherwise be saturated. This mitigation measure therefore rather mitigates the issue of having too little aFRR capacity or too limited mFRR replacement of activated aFRR than the issues resulting from a change from pro-rata to merit order activation scheme.

3.4. Conclusion

Assuming a constant FAT, a change from a pro-rata scheme to a simple merit order scheme will result in a lower FRCE quality. Without any mitigation measures, the FRCE standard deviation of individual LFC blocks will increase with on average 31% (typical range between 10-50%). However, for one TSO we see an increase with 130%.

For large deviations (close to aFRR volume that is connected to the LF Controller), this picture is less clear. For most TSOs the settling time increases but for some TSOs the settling time even decreases. We note that these results are highly sensitive to the LF controller set-ups and settings. These would need to be revised and optimised to the new situation in case of a transition to a merit order scheme, not only for large deviations but simultaneously also for the small changes.

Some of the mitigation measures for improving the FRCE quality either require a smaller FAT and/or require activation of more bids in parallel. Both measures have influence on aFRR markets: smaller FAT will reduce the capacity eligible for providing aFRR and therefore may impact availability and price of aFRR capacity and energy negatively. Activating more bids in parallel may result in a higher average price paid for aFRR energy[27].

We conclude that with a given FAT and for identical merit orders, a pro-rata scheme will deliver a certain FRCE quality at an average aFRR energy price invariant to the magnitude of the system imbalance while a merit order scheme may be able of delivering a still sufficient FRCE quality at a lower average aFRR energy price variant to the magnitude of the system imbalance. This holds both for a 'pay as bid' remuneration scheme as well as for a 'pay as cleared' remuneration[28].

[27] Under assumption of equal most expensive bids in the merit order between pro-rata and merit order schemes, the average price paid for activated aFRR energy would under a merit order scheme always be lower or equal to the average price paid for aFRR energy under a pro-rata scheme.

[28] For the avoidance of any doubt, the effect on aFRR activation cost could not be determined because it depends on several factors such as the price of activation and the activated volume (i.e. aFRR activation cost may increase or decrease).

4. Effects of harmonising aFRR Full Activation Time

4.1. Introduction

Section 2.7 shows that aFRR Full Activation Times (FAT) in the European LFC Blocks range from 2 minutes to 15 minutes. This chapter 4 studies the impact of harmonising the FAT. In section 4.2 we discuss the impact of a changing FAT on the theoretical aFRR capability to provide aFRR capacity and energy as well as the effect on the aFRR energy and capacity markets. In section 4.3 we study the effect on the regulation quality.

4.2. Analysis of theoretical aFRR capability to provide aFRR bids and the effect on energy and capacity markets

4.2.1. Theoretical aFRR Capability of generation units per LFC Block as function of FAT

In this section we provide an analysis of the theoretical aFRR capability of generation units to provide aFRR bids for different FATs throughout Europe. We define theoretical aFRR capability of a generation unit as the *maximum* upward aFRR that can be provided at the minimum stable capacity P_{min} or downward aFRR at the rated capacity P_{max}. We aggregate the values on LFC Block level. Textbox 2 provides further details.

In section 4.2.3 and 4.2.4 we will also address the theoretical aFRR capability of demand and renewables. Section 4.2.5 and 4.2.6 address theoretical aFRR capability of storage and peak units.

We note that the theoretical aFRR capability will not be the aFRR capacity that will be offered to the TSO. However, it provides an indication of the aFRR capacity that can potentially be offered to the TSO. The theoretical aFRR capability is irrespective from the activation methodology (merit order or pro-rata).

Textbox 2: Theoretical aFRR capability

Definition of theoretical aFRR capability

Theoretical aFRR Capability of a generation unit is defined as the *maximum* upward aFRR that can be provided at the minimum stable capacity P_{min} or downward aFRR at the rated capacity P_{max}. The Theoretical aFRR Capability is a function of the aFRR Full Activation Time (FAT).

Theoretical aFRR Capability aggregated for LFC Blocks for 2014 situation

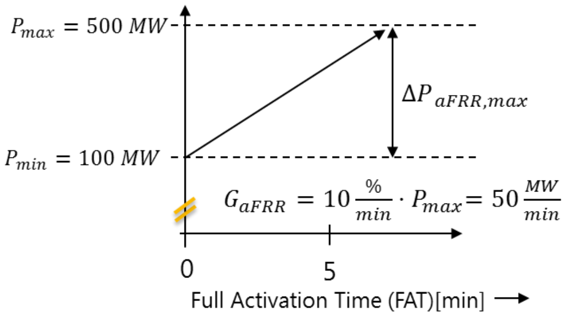
Our overviews provide the *theoretical aFRR capability for LFC Blocks for the power generation fleet in the year 2014*. In principle, we included all generation units that are able to provide aFRR. This includes units that are currently not connected to the LF Controller, but could *technically* be connected to the LF Controller in order to provide aFRR. I.e. we did not take into account the *economic* feasibility of connecting to the LF Controller. As exception to the rule, we excluded nuclear capacity that is subject to safety, environmental, nuclear authority or other non-technical regulation/legislation that likely prevents for (part of the) capacity of a nuclear unit to provide aFRR. As a result of these assumptions, we also included units that are currently expected to be decommissioned in the coming years.

We note that the resulting *theoretical aFRR capability* is not the same as the prequalified aFRR volume or the aFRR capacity that is or will be offered to the market, which may depend on the operation point of the unit (e.g. related to spot market results), requirements for Frequency

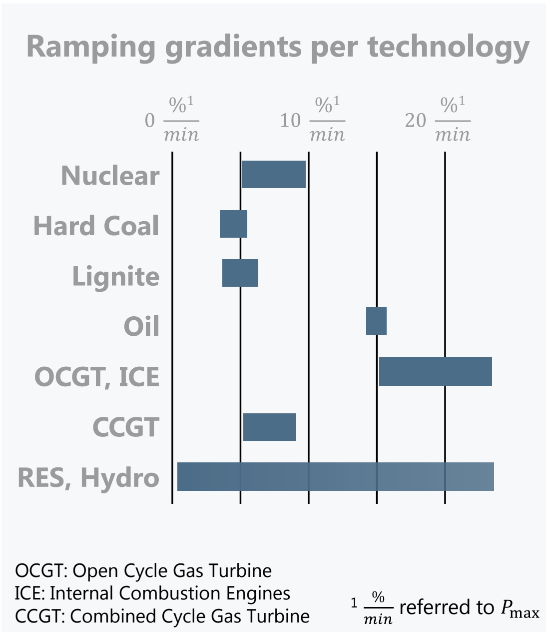
Containment Reserves (FCR), available connection to the LF Controller and economic feasibility to connect to the LF Controller etc. .

Calculation methodology Theoretical aFRR Capability per unit

The figure below explains how we calculated the *theoretical aFRR capability* for one unit. Starting from the situation that the power plant is running at its *minimum* stable capacity (P_{min}), we increase the output with the applicable ramp rate for *spinning* units (G_{aFRR}) until the ramp reaches the *rated capacity* (P_{max}) of the unit. The *theoretical aFRR capability* of this unit (as function of FAT) is defined as the difference ($\Delta P_{aFRR,max}$) between the ramped value and the minimum stable capacity P_{min}. E.g. for the example in the figure, 5 minutes after starting the ramp, the output increased with 250MW from 100MW to 350MW. Consequently, the *theoretical aFRR capability* of this unit is 250MW for a FAT of 5 minutes. After 8 minutes of ramping, the output will be equal to rated capacity P_{max}. Consequently, output will not increase anymore and the *theoretical aFRR capability* for FATs of 8 minutes and more will be equal to the difference between P_{max} and P_{min}.



FAT	Technical aFRR capability
5 min	250 MW
10 min	400 MW
15 min	400 MW



Per technology, we calculated the minimum stable capacity P_{min} based on rated capacity P_{max} and the typical characteristics of this technology for minimum stable operation. In addition we use the ramp rates for *the situation that the units are 'spinning', i.e. producing power*. We note that these ramp rates may be different from the ramp rates of starting units! We also note that due to specific technology and emission constraints, some units may not be able to meet the ramp rates presented in the diagram.

Input data for this calculation

We aggregated the *theoretical aFRR capability per generation class* for each LFC Block. For this, we applied a database with over 2,500 generation units in Europe consisting of power plant information based on ENTSO-E and national publications for the year 2014. We assumed a certain technical non-availability (revisions, power plant outages) based on historic statistical data dependent on generation class and country. Furthermore, we excluded nuclear, hard coal and lignite units with commissioning date (and without revision) before 1985.

Figure 20 provides an example for one LFC Block. This example shows the theoretical aFRR capability for the different generation technologies in this LFC Block. The horizontal axis shows the FAT and the vertical axis the accumulated theoretical aFRR capability of different classes of generation. The graph indicates the theoretical aFRR capability of each generation class as function of the FAT and the sum for the LFC bock.

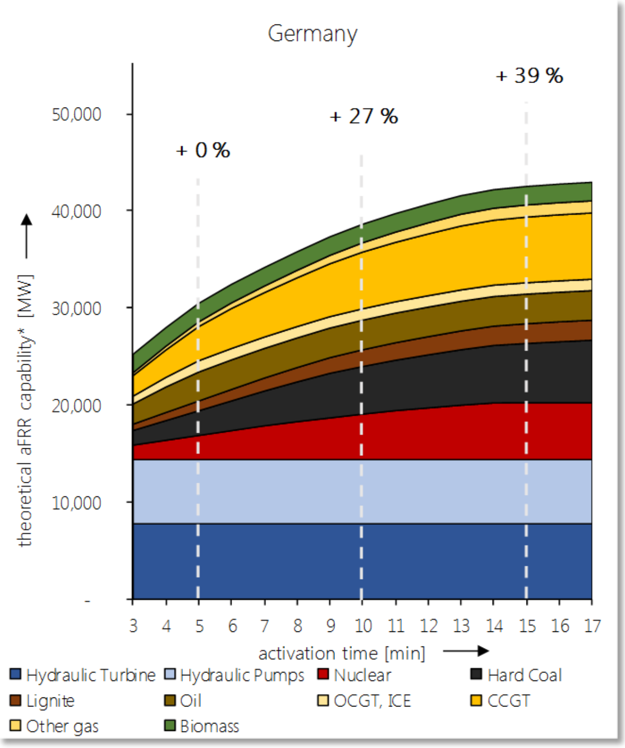


Figure 20: Example of a theoretical aFRR capability diagram for Germany (percentages are the change from current FAT) * Upward and downward, not symmetric

We performed this analysis for all Continental European and Nordic LFC Blocks that operate an LF Controller as well as for Great Britain, Ireland and Northern Ireland. For the detailed results we refer to appendix C.

Figure 21 provides the theoretical aFRR capability for all LFC Blocks relative to the theoretical aFRR capability for the existing FAT. Hence, it shows the relative changes to the existing theoretical aFRR capability if the FAT is changing. E.g. for Germany, the current FAT is 5 minutes. If the FAT will increase to 15 minutes, the theoretical aFRR capability of generation units will increase by 39%.

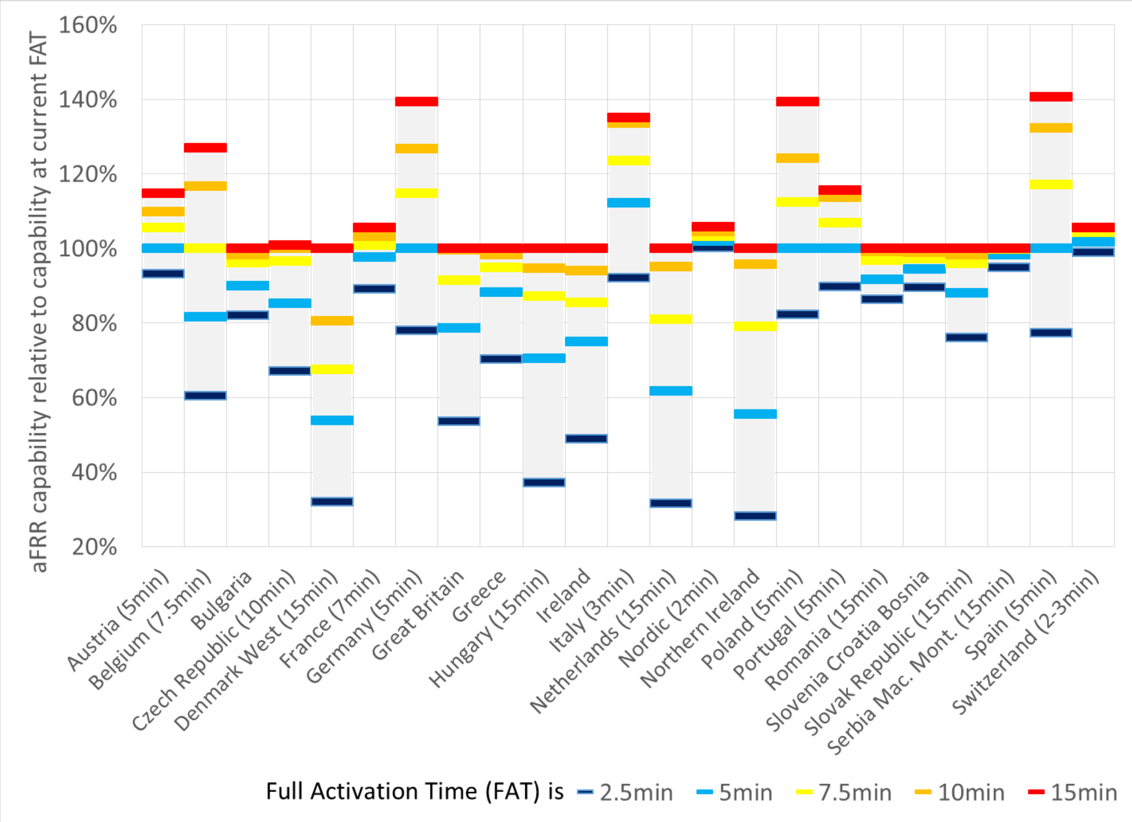


Figure 21: Overview of relative aFRR capabilities in European LFC Blocks (between brackets: the current FAT)

Figure 21 (and appendix C) show that the theoretical aFRR capability of a number of LFC Blocks (e.g. Nordics, Switzerland) are hardly affected by a change in FAT. These LFC Blocks are typically dominated by hydro units which are able to ramp-up or down very quickly. These units can already provide the whole available aFRR within a FAT of 2.5 minutes and no capability is added if the FAT will be longer. On the other hand, LFC Blocks with dominantly thermal units (e.g. Belgium, Netherlands, Poland), will have significantly more theoretical aFRR capability for a FAT of 15 minutes since it takes more than 2.5 minutes to ramp-up all thermal units.

4.2.2. Impact of changing FAT on liquidity in aFRR capacity markets and aFRR energy markets

Since theoretical aFRR capability is only the theoretical amount of aFRR that can be offered as aFRR capacity, the results in Figure 21 shall not be interpreted as the aFRR capacity that will be offered to the TSO as function of FAT. The reasons for this are that not all potential aFRR providers have a connection with the TSO's LF Controller or will invest in connecting their units to the TSO's LF Controller. Moreover, if the units are connected, the aFRR capacity offered to the TSO also depends on the generation unit's opportunity costs, i.e. what can the unit earn in e.g. the wholesale market. This is different for almost every hour since this depends on the wholesale market price and the prices of primary fuels such as coal and natural gas. Consequently, for a quantitative statement of the effect of the FAT on the markets, a detailed market analysis is required, which was not within the scope of this study. What we can say though, is that especially in the LFC Blocks *without* an abundance of hydro units aFRR volumes offered to the market will likely be lower and prices be higher for smaller FATs. For LFC Blocks with abundance of hydro units, additional aFRR capacity/energy from thermal units will only have an effect if it is offered cheaper than hydro units.

Dependent on time-of-the day or season, this can be the case. However – as said before – without a detailed quantitative market analysis it is impossible to make quantitative statements.

4.2.3. Potential theoretical aFRR capability from renewable units

Technically, wind and solar power plant are very well able to provide aFRR. It is possible to connect the control systems of wind and solar power plant to the TSO's LFC and the ramp rates are very fast and they should be able to provide all aFRR within less than 2.5 minutes.

Although field tests show that it is technically feasible to provide aFRR with wind and solar plant, in our survey we did not come across examples of LFC Blocks in which these plant are applied for providing aFRR capacity and/or energy at the moment.

The main issue with wind and solar plant is that they are dependent on the availability of sun or wind. Hence, if sun or wind are not available, it is not possible to increase or decrease the output of these plant. If sun and wind are available, provision of aFRR with wind and solar plant is automatically related to spilling of sun and wind. I.e. if sun or wind plant provides downward aFRR, it needs to reduce the output by spilling the available wind. For upward aFRR, the spilling needs to be done already before-hand in order to be able to ramp-up the unit by not spilling anymore. Consequently, we see more potential in providing downward aFRR energy and capacity than for upward aFRR energy capacity.

4.2.4. Potential theoretical aFRR capability from demand customers

From a technical perspective, a selection of demand customers shall be able to continuously ramp up and down and therefore provide aFRR within the specified FAT. These demand customers may range from large industries using e.g. electrolysis, heating or cooling in their production processes down to small demand customers with 'smart' demand appliances, e.g. for smart electrical vehicle charging, electrical heating or cooling. For both types of customers, a real time connection to the LF Controller (in many cases via an aggregator[29]) is required.

Furthermore, it is important to avoid that aFRR activation (e.g. reduced cooling load) results in compensation by the customer in the other direction immediately after the activation (e.g. increased cooling load). However, we believe that this can be taken into account (e.g. by aggregators using intraday markets) and therefore we see a large technical potential in future for aggregators of small demand units up to large industries.

In practice, we only found that electrical boilers (e.g. in Denmark) are at this moment sometimes applied for providing aFRR. A major issue of course is that there shall be 'rampable' load in order to provide aFRR, i.e. if there is no load or the load cannot be ramped, aFRR provision will not be possible. This issue may be addressed within a portfolio of an aFRR provider.

4.2.5. Potential theoretical aFRR capability from storage

Energy storage units such as batteries and flywheels should technically also be a feasible provider of aFRR, at least with respect to ramping possibilities and possibility to control. A technical limitation for storage devices though is that they are limited with respect to the amount of energy that they can store. Since – especially in a merit order activation scheme – the aFRR activation energy can be

[29] Aggregators shall work in a coordinated way respecting the TSO's (geographical) restrictions.

very unpredictable, the energy balance of the aFRR storage devices shall be controlled within the portfolio of the aFRR provider.

4.2.6. Small units, peak units

We found that within the aggregated portfolios of aFRR providers, part of the aFRR is sometimes provided by small thermal generation plant. Although there are many different small generation plant, some types of small plant – including gas engines – should be technically able to provide aFRR.

4.3. Effect of changing FAT on the regulation quality

In this section 4.3 we describe the effect of a changing FAT on the regulation quality. As reference scenario, we apply the simple merit order activation scheme as described in section 3.1 and applied in the simulations in section 3.2. For this scheme, we will perform simulations for the existing FAT of the LFC Block and FAT of 2.5, 5, 7.5, 10 and 15 minutes. We describe the effect for both time series of FRCE (section 4.3.1) and large deviations (section 4.3.2).

4.3.1. Simulations for February and June 2015

We performed simulations of different FATs with time-series of FRCE and aFRR activations for the entire months of February and June 2015[19].

Figure 22 shows the resulting standard deviation of the FRCE for different FATs in relation to the quality of the simple merit order scheme with the existing FAT (for the full results we refer to appendix B)[30]. Figure 22 shows that a FAT of 5 minutes results in FRCE quality that is for most TSOs between 20% to 60% better than for a FAT of 15 minutes (see explanation of FRCE standard deviation in section 3.2). We note that for Switzerland – with a current FAT of 3 minutes – also a FAT of 5 minutes already results in a big reduction in FRCE quality.

[30] In this report we do not compare the FRCE quality with the compliance targets. We note though that the compliance with the absolute targets may be an even more important reference than the current situation.

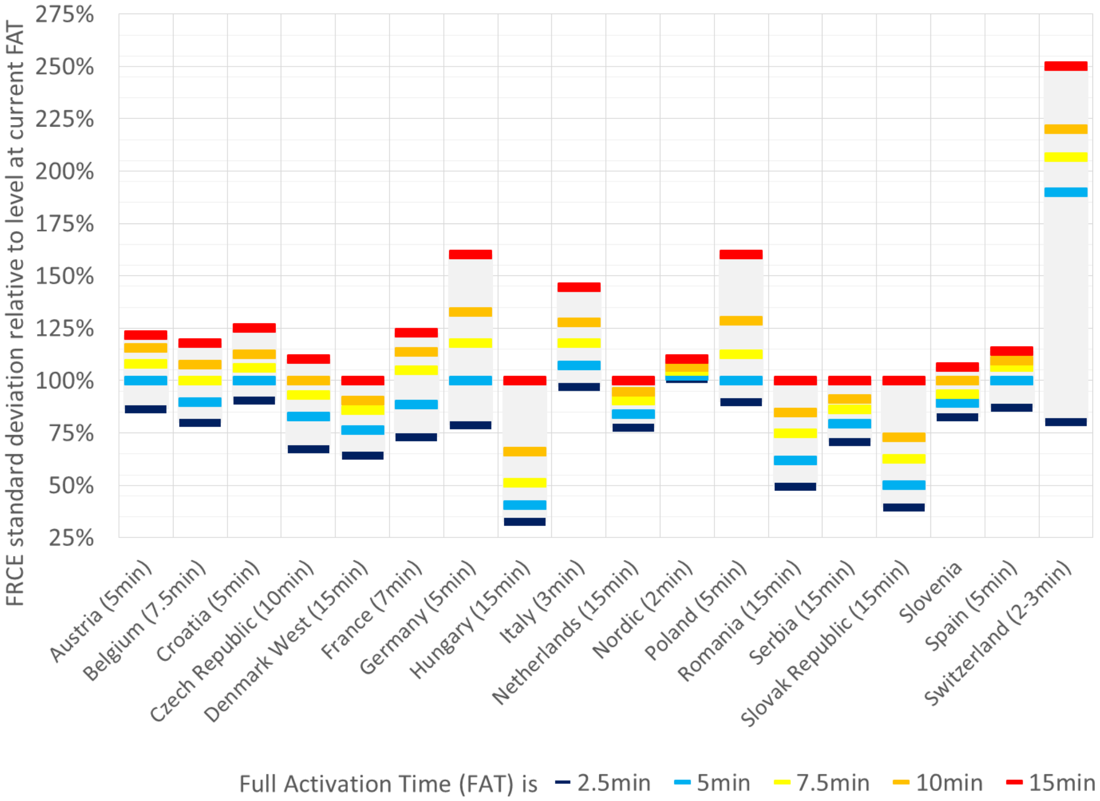


Figure 22: FRCE standard deviation for a change from the existing FAT to a FAT of 2.5, 5, 7.5, 10 and 15 minutes, relative to the situation with a simple merit order activation scheme and the existing FAT (between brackets FAT)[22]

4.3.2. Large deviations

For the reasons that have been explained in section 3.2.2, we simulated large deviations as a loss of generation with the size of the available aFRR volume[23]. Figure 23 shows the settling time (see Textbox 1 on page 17 for explanation) for FATs of 2.5, 5, 7.5, 10 and 15 minutes relative to the values for the existing FAT (for the full results we refer to appendix B).

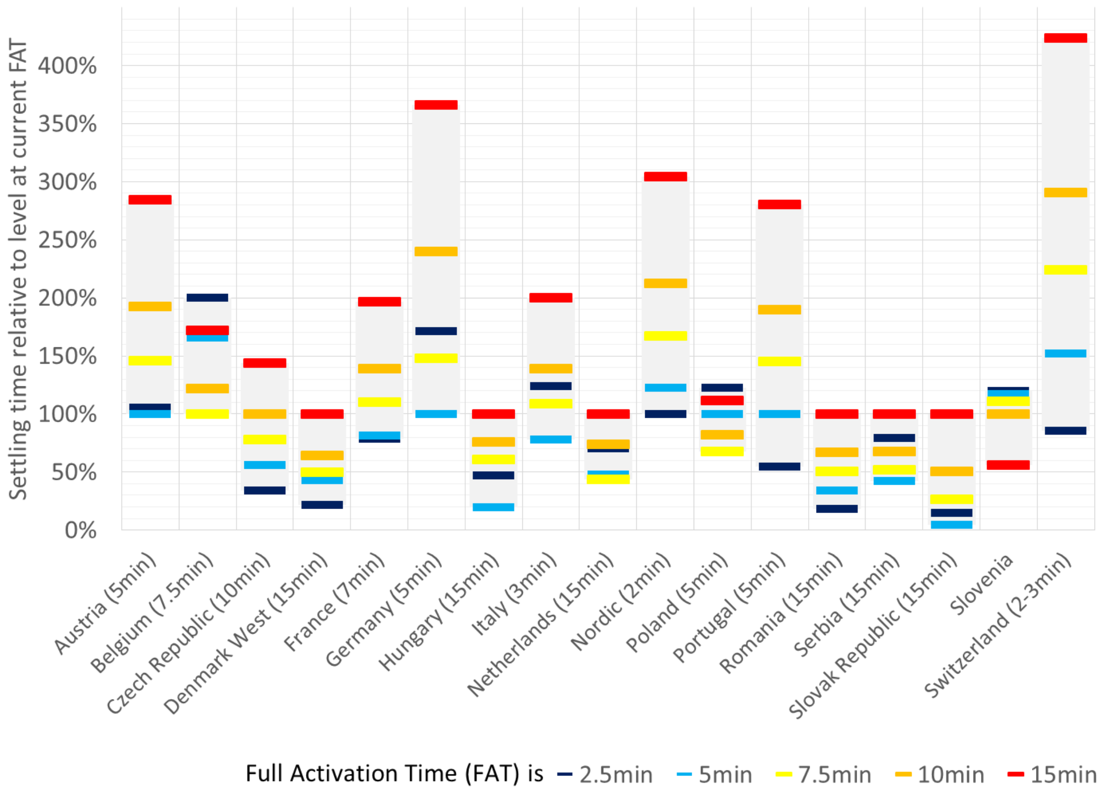


Figure 23: Settling time for a change from the existing FAT to a FAT of 2.5, 5, 7.5, 10 and 15 minutes, relative to the situation with a simple merit order activation scheme and the existing FAT (between brackets, the existing FAT) [22]

Since the simulations have been performed with the simple merit order activation scheme (see section 3.1) without any mitigation measures (see section 3.3), the observations and conclusions in the last paragraph of section 3.2.2 also apply to the results provided in Figure 23.

5. Conclusions

In chapter 2 we provided an overview of the technical implementation of automatic Frequency Restoration Reserves (aFRR) in Continental Europe and the Nordic countries. Although the objectives and the high level set-up is very similar, there are major differences in the aFRR requirements and the use of aFRR by the TSOs throughout Europe, we found:

- Large differences in shares of aFRR in the TSOs' total activations of frequency restoration reserves (aFRR and manual FRR) and Replacement Reserves (RR): this ranges from less than 10% to close to 100%;
- Different activation schemes: most LFC Blocks apply a pro-rata activation scheme, five LFC Blocks apply a merit order activation scheme;
- Large differences in applied Load-Frequency controllers (LF-Controller) and parameterisation of these controllers;
- Large differences in aFRR Full Activation Time, ranging from 2 to 15 minutes;
- In Continental European (CE), LFC Areas are defined and each of the areas has its own LF Controller. In the Nordic synchronous area the four TSOs only apply one LF Controller for the entire synchronous area;
- The objective of the LF Controllers in continental Europe is to restore the Frequency Restoration Control Error (FRCE), which is the difference between measured total power value and scheduled control program for the power interchange of the LFC Block, taking into account the effect of the frequency bias for that control area. The objective of all continental European LF Controllers together is to restore and maintain the system frequency in the European synchronous system. The objective of the Nordic LF Controller is to restore the frequency to the target frequency.

In chapter 3 we studied the change of the existing activation scheme (mostly pro-rata) to a *simple* merit order activation scheme. We found that for TSOs that currently apply a pro-rata scheme, the standard deviation of five minutes FRCE values (a measure of regulation quality) will increase on average with 31% (typical range between 10 and 50%), although for one TSO the increase was 130%. The main reason for the quality decline is that fewer aFRR providers are selected for activation. Consequently, each provider needs to activate more aFRR which will take more time. The activation will therefore be slower than in the pro-rata scheme and may consequently reduce the FRCE quality. However, for this situation and assuming bids are unchanged compared to a pro-rata scheme aFRR activation price may decrease since only the cheapest bids are activated. The effect on aFRR activation cost could not be determined because it depends on several factors, for example both on the price of activation and activated volume (i.e. aFRR activation cost may increase or decrease).

For large aFRR activations caused by e.g. a power plant trip, the differences between pro-rata schemes and pure merit orders schemes become less clear. For most TSOs the settling time increases but for some TSOs the settling time even decreases. We note that the results are highly sensitive to the LF controller set-ups and settings. These would need to be revised and optimised to the new situation in case of a transition to a merit order scheme.

The main reason that the pro-rata schemes perform technically better than merit order schemes is that the simultaneous response of all aFRR providing units together is faster than the response of only a few bids at the same time. Consequently, an effective technical mitigation measure is to increase the speed of the aFRR providers' response, e.g. by reducing the aFRR Full Activation Time (FAT). Alternatively, a merit order scheme can be implemented that activates more bids in parallel if required for following the LF Controller's request for aFRR. Another possibility is implementing a feedback loop that allows the LF Controller to take into account not yet activated reserves.

We conclude that pro-rata schemes have a better response than pure merit order activations, especially for smaller imbalances. However, for smaller imbalances, pure merit order activation schemes only select the cheapest bids where pro-rata schemes select all bids that are available to the TSO. For the same quality, merit order activation schemes require faster reserves (e.g. higher ramp rates or mitigation measures) or activation of more bids in parallel. Both may increase the aFRR activation price, but assuming the same quality, and for identical bids in the merit order for a pro-rata and merit order activation scheme, the average activation price will not go beyond that of a pro-rata activation. The effect on aFRR activation cost could not be determined because it depends on several factors, for example both on the price of activation and activated volume (i.e. aFRR activation cost may increase or decrease).

In chapter 4 we describe the effects of harmonising the aFRR Full Activation Time, assuming a change to merit order activation. We conclude that a FAT of 5 minutes results in FRCE quality that is on average 42% better (typical range between 20% to 60%) better than for a FAT of 15 minutes. We note that for an LFC Blocks with an even smaller FAT than 5 minutes, also a FAT of 5 minutes already results in a big reduction in FRCE quality.

The other effect of reducing the FAT is that this may reduce the aFRR capacity that can fulfil these requirements and that can be offered by the aFRR providers to the TSO. As a proxy for this capacity, we have studied the theoretical aFRR capability of hydro and thermal power plant to provide aFRR for different Full Activation Times throughout Europe. We conclude that for LFC Blocks with dominantly thermal generation units the theoretical aFRR capability for a FAT of 15 minutes is 30-40% larger than for a FAT of 5 minutes. For LFC Blocks with dominantly hydro generation is less than 10%.

Technically, we see potential for upward aFRR provided by demand and downward aFRR provided by renewables. Furthermore, we consider storage and small generation plant – including engine motors – technically capable to provide aFRR. We note that demand, renewables, storage and flexible plant may participate at any FAT. Consequently, their theoretical aFRR capability may be hardly influenced by a change of FAT. We note that demand, renewables, storage and flexible plant may participate at any FAT. Consequently, their theoretical aFRR capability may be hardly influenced by a change of FAT.

APPENDIX

A. Overview of technical characteristics of automatic Frequency Restoration Reserves in Europe

B. Simulation of FRCE quality for LFC Blocks

C. Simulation of FRCE quality for LFC Blocks

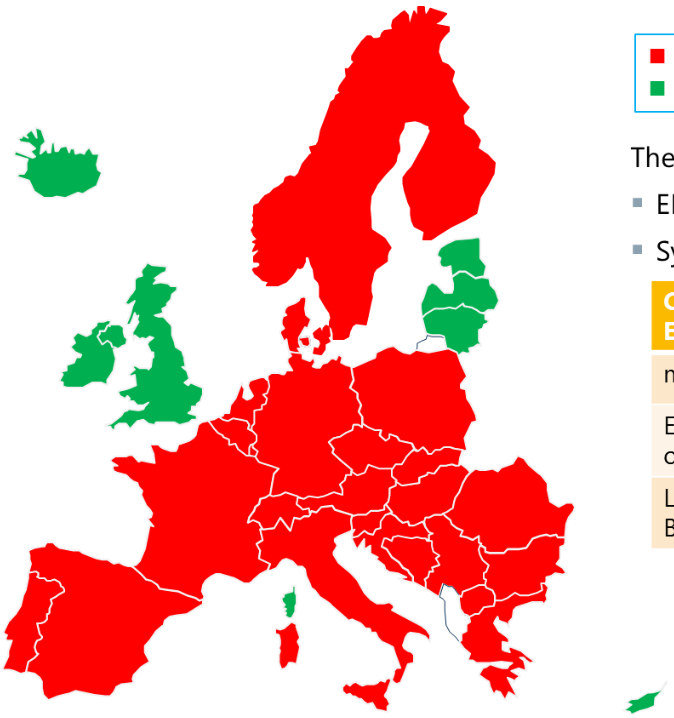
D. Glossary and Abbreviations

E. List of Figures

A. Overview of technical characteristics of automatic Frequency Restoration Reserves in Europe

This appendix includes an overview of the existing aFRR situation in the ENTSO-E countries. The information in this presentation is based on public documents and information directly received from TSOs by questionnaires and follow-up questions. The overviews include:

- ENTSO-E countries that apply aFRR
- Required aFRR volumes by LFC Block and synchronous area
- Share of aFRR balancing energy compared to TSO's total activated FRR/RR energy
- Minimum response requirement for Full Activation Time / Ramp Rate
- Flexibility of Full activation time / ramp rate
- Activation methodology:
- merit order or pro-rata
- Continuous or stepwise
- Settlement: activation signal or measurements
- Compliance check
- Real Time / Ex-Post
- Prequalification



- aFRR is used
- aFRR is *not* used

The focus of this overview is:

- ENTSO-E members
- Synchronous areas that apply aFRR

Continental Europe (CE)	Nordic
many LFC blocks	one LFC block
Each LFC block has one or more LFCs	only one LFC for entire area
LFC on 'Tie-line Bias control'	LFC on 'frequency control'

Figure 24: Use of aFRR throughout Europe

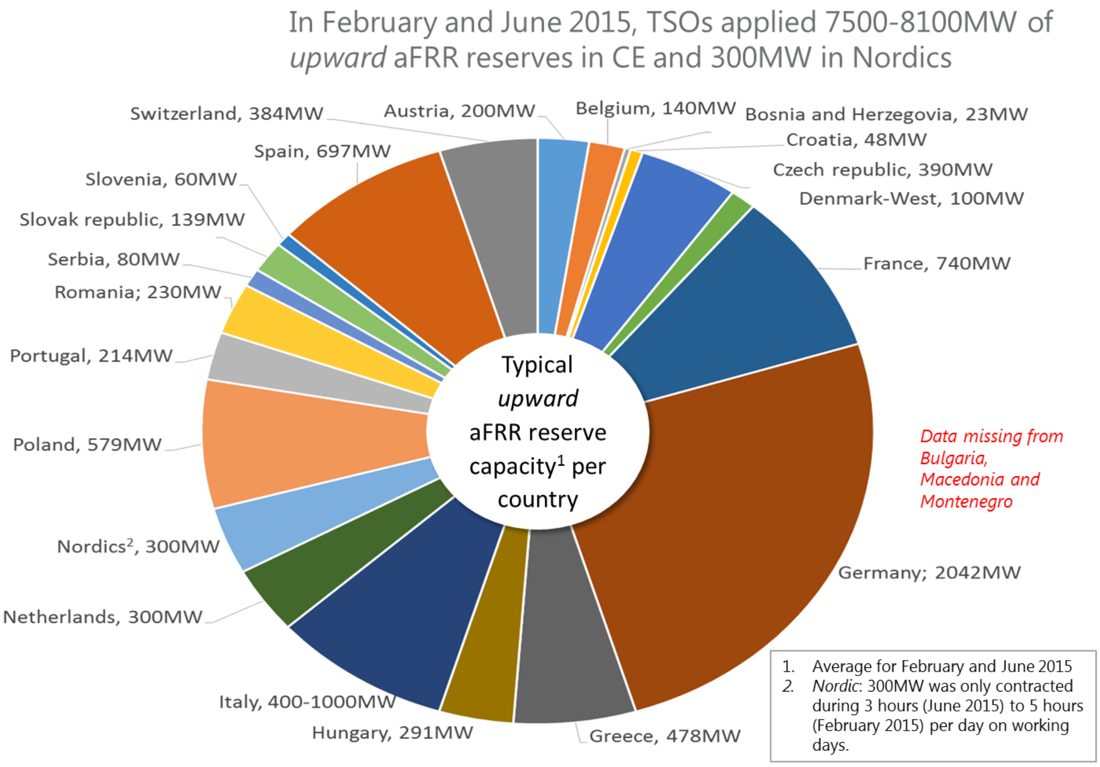


Figure 25: aFRR *Upward* reserve capacity throughout Europe in February and June 2015

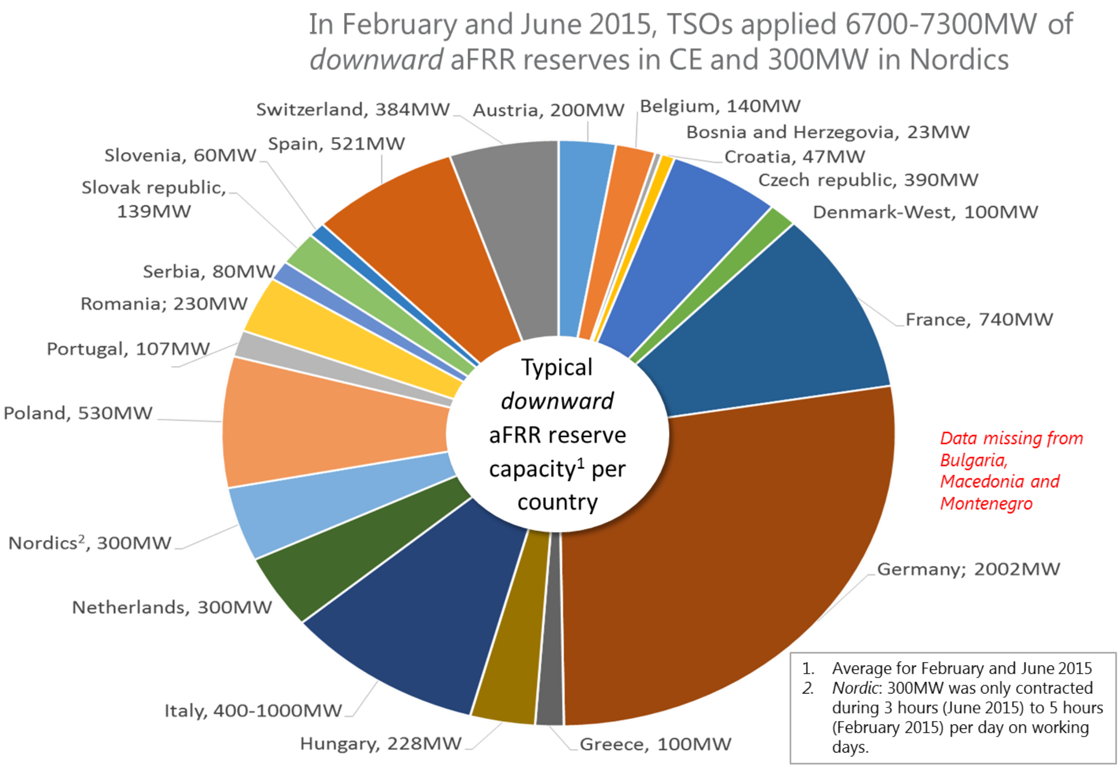


Figure 26: aFRR *Downward* reserve capacity throughout Europe in February and June 2015

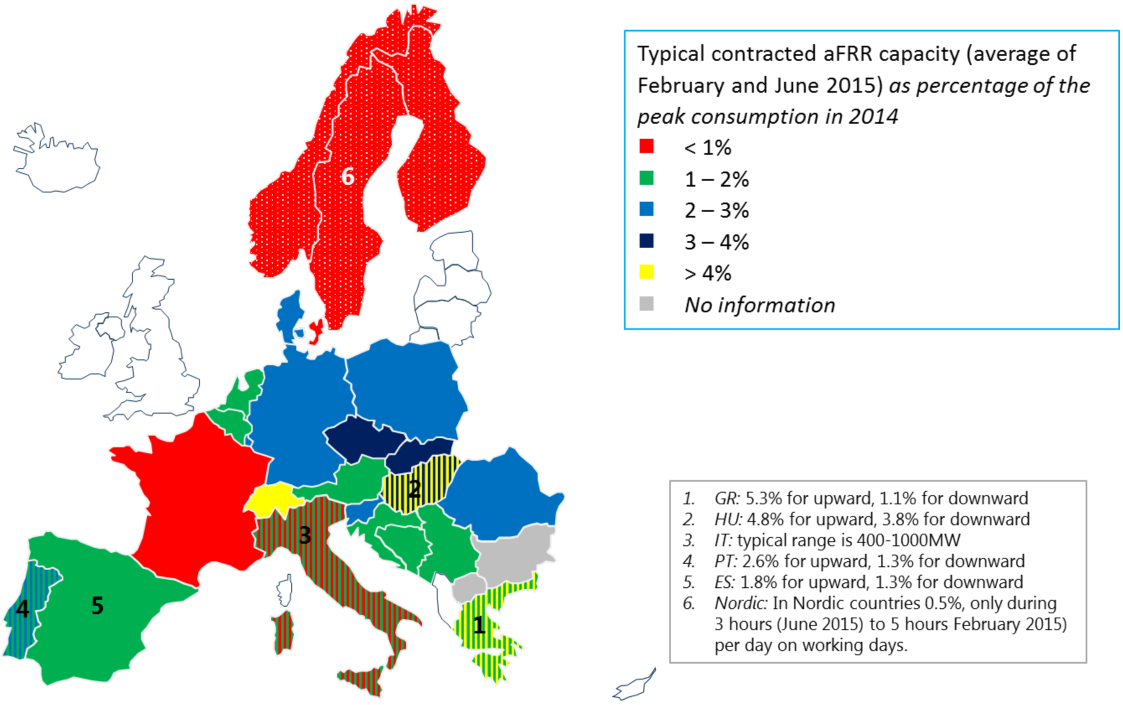


Figure 27: Typical contracted aFRR capacity (average of February and June 2015) as percentage of the peak consumption in 2014.

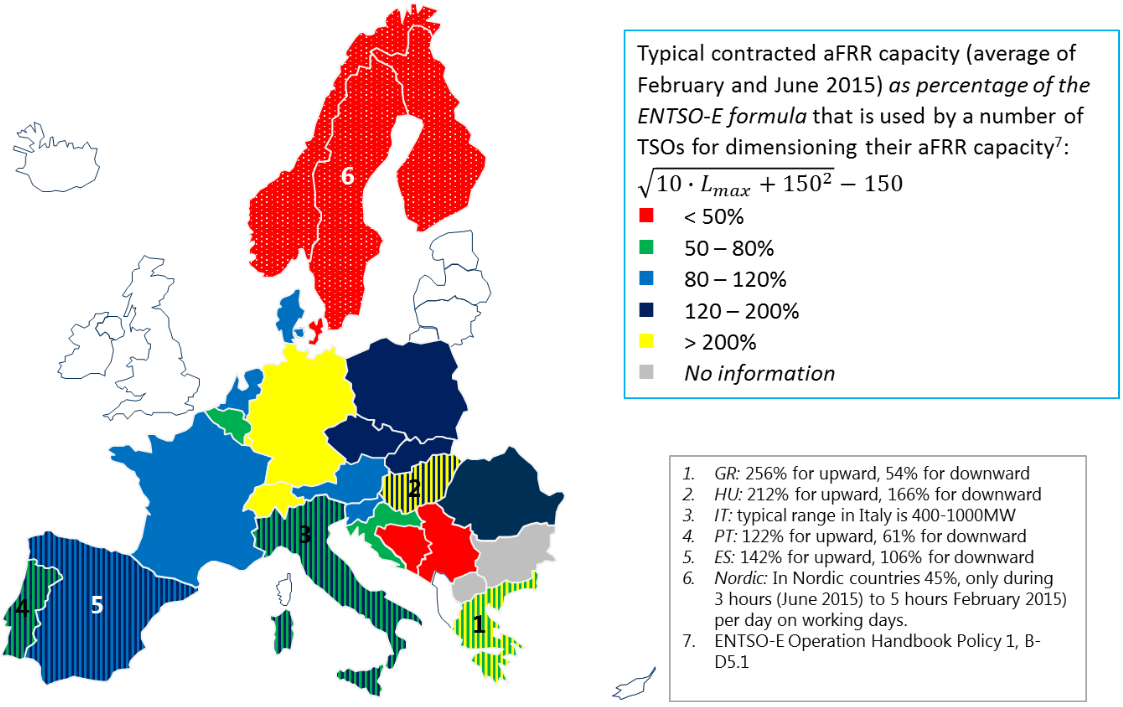


Figure 28: Typical contracted aFRR capacity (average of February and June 2015) *as percentage of the ENTSO-E policy 1 formula* that is used by a number of TSOs for dimensioning their aFRR capacity: $\sqrt{\mathbf{10 \cdot L_{max} + 150^2}} - \mathbf{150}$ *(source: ENTSO-E Operation Handbook Policy 1, B-D5.1)*

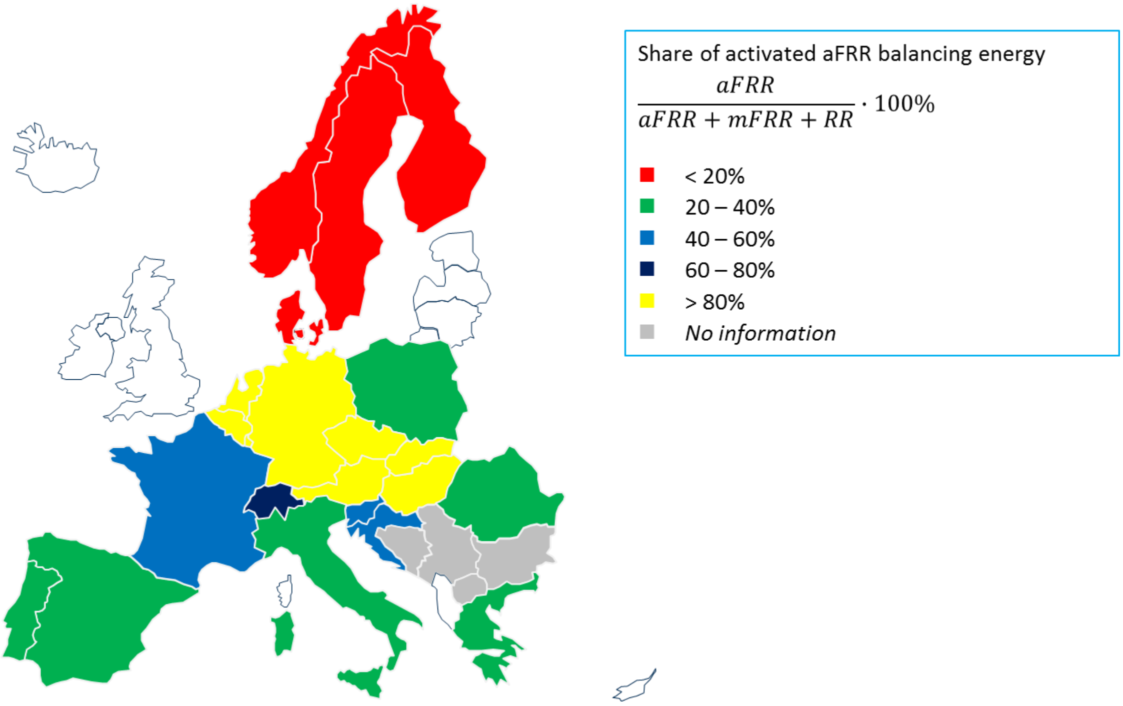


Figure 29: Share of aFRR in total balancing energy, based on figures for February and June 2015

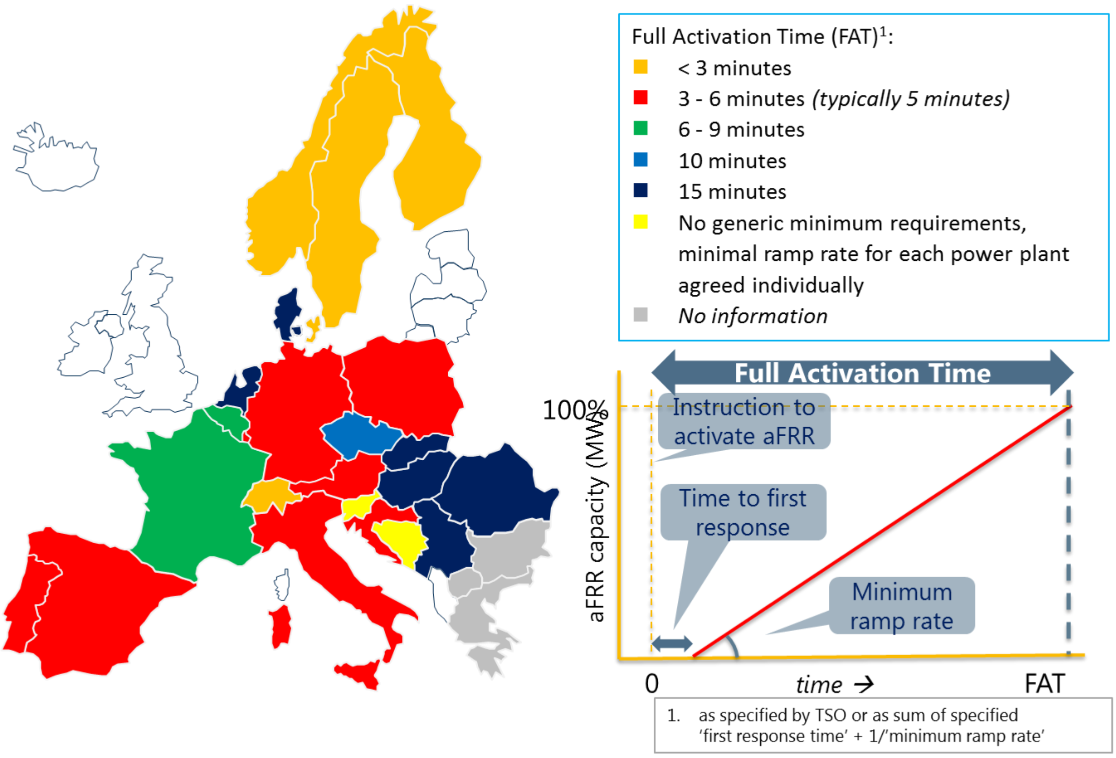


Figure 30: aFRR response requirements (for some countries the requirements are converted to aFRR Full Activation Times)

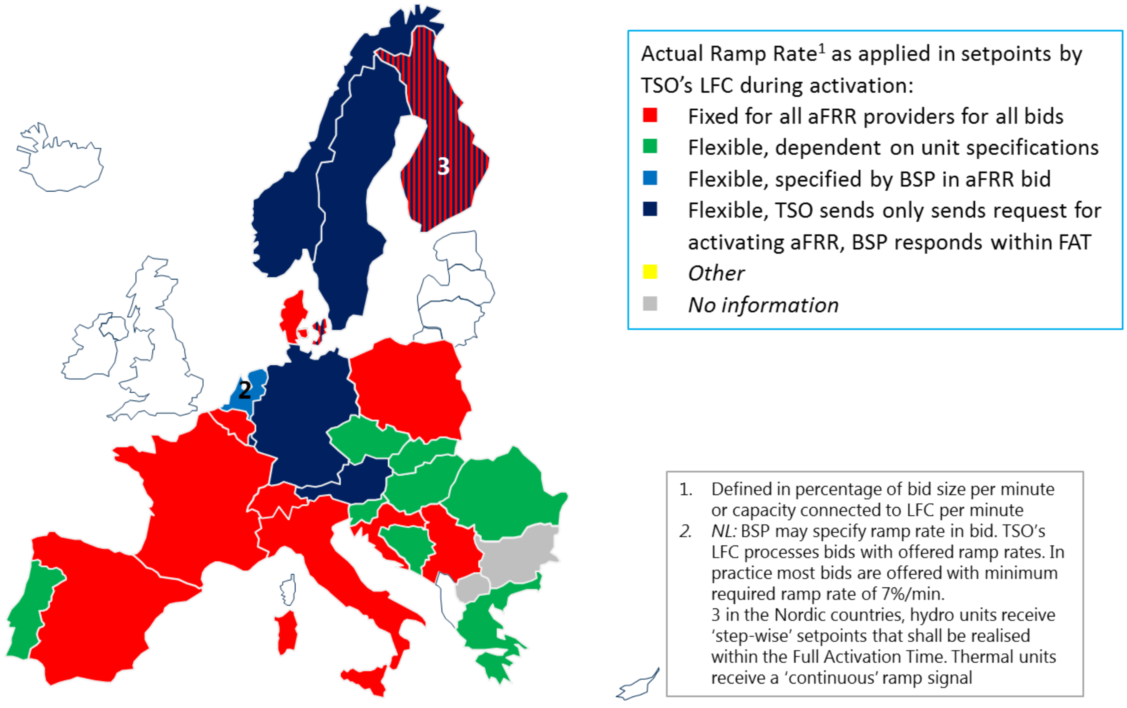


Figure 31: aFRR actual response of aFRR providers

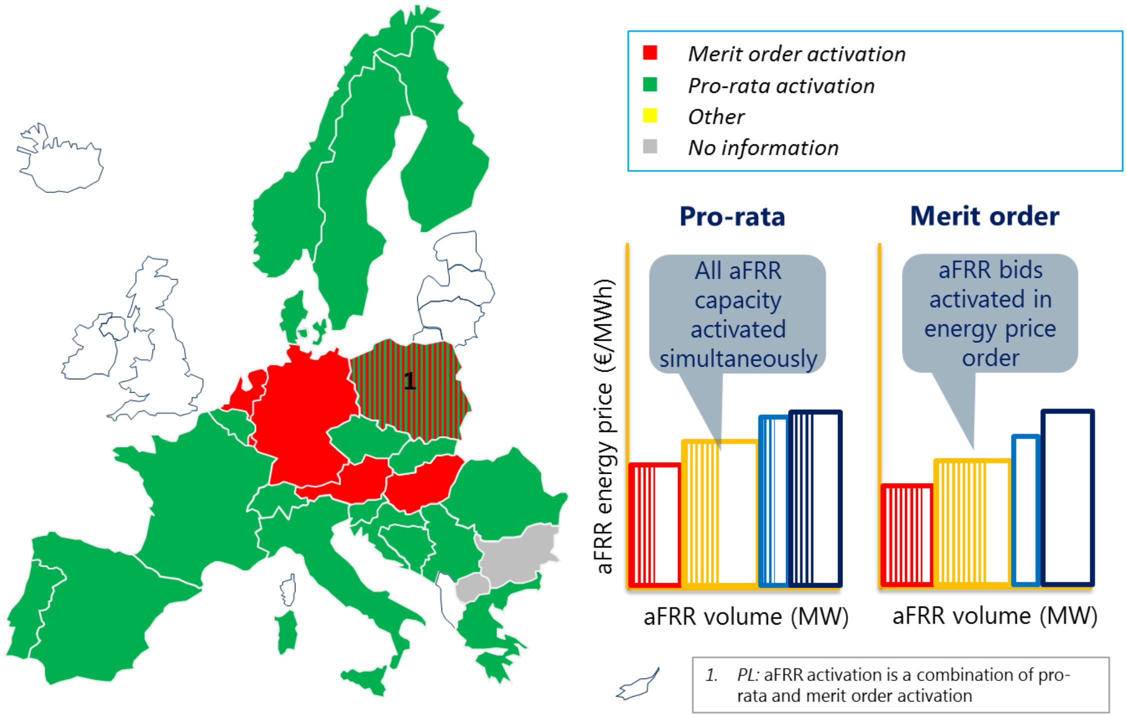


Figure 32: TSOs that apply a pro-rata activation scheme or a merit-order activation scheme

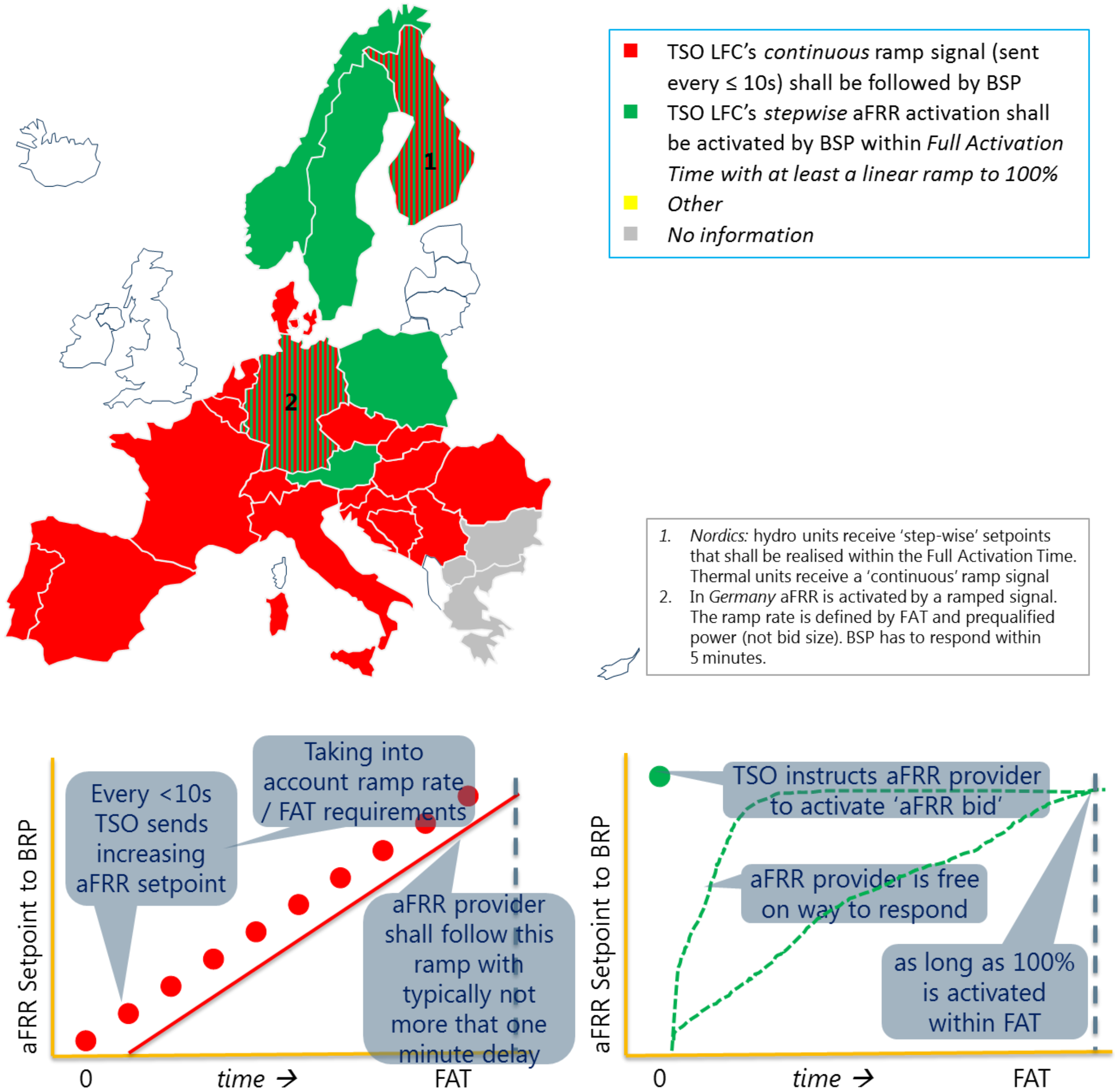


Figure 33: aFRR activation, continuous or stepwise

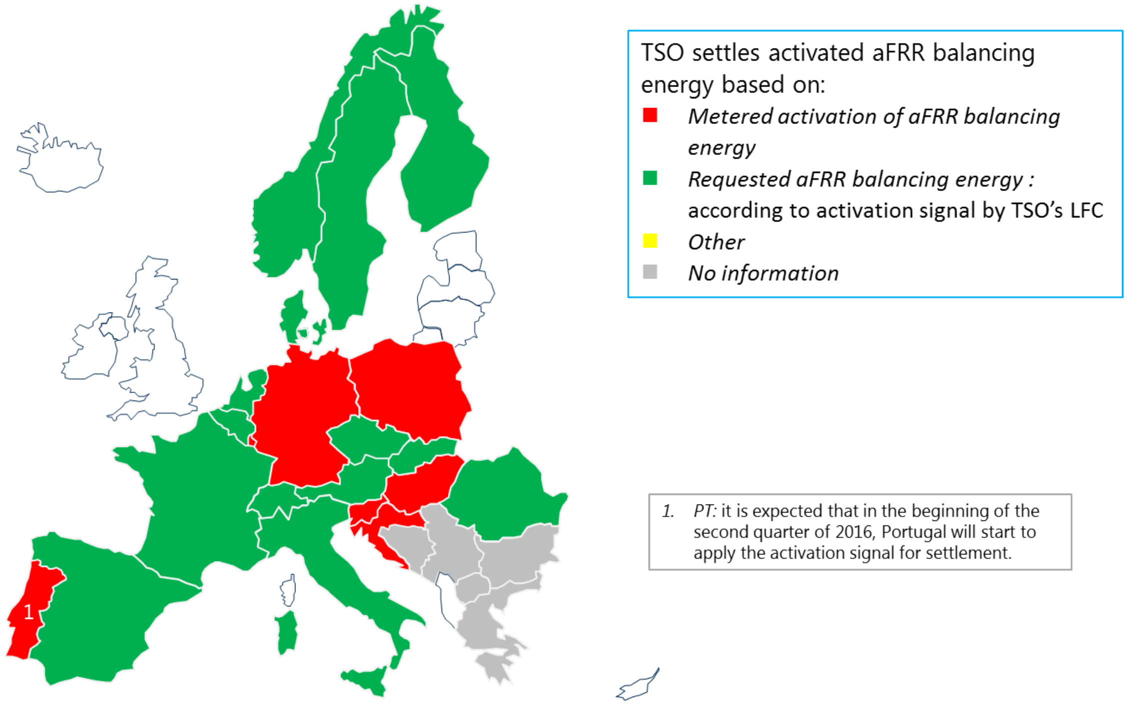


Figure 34: Settlement of aFRR balancing energy

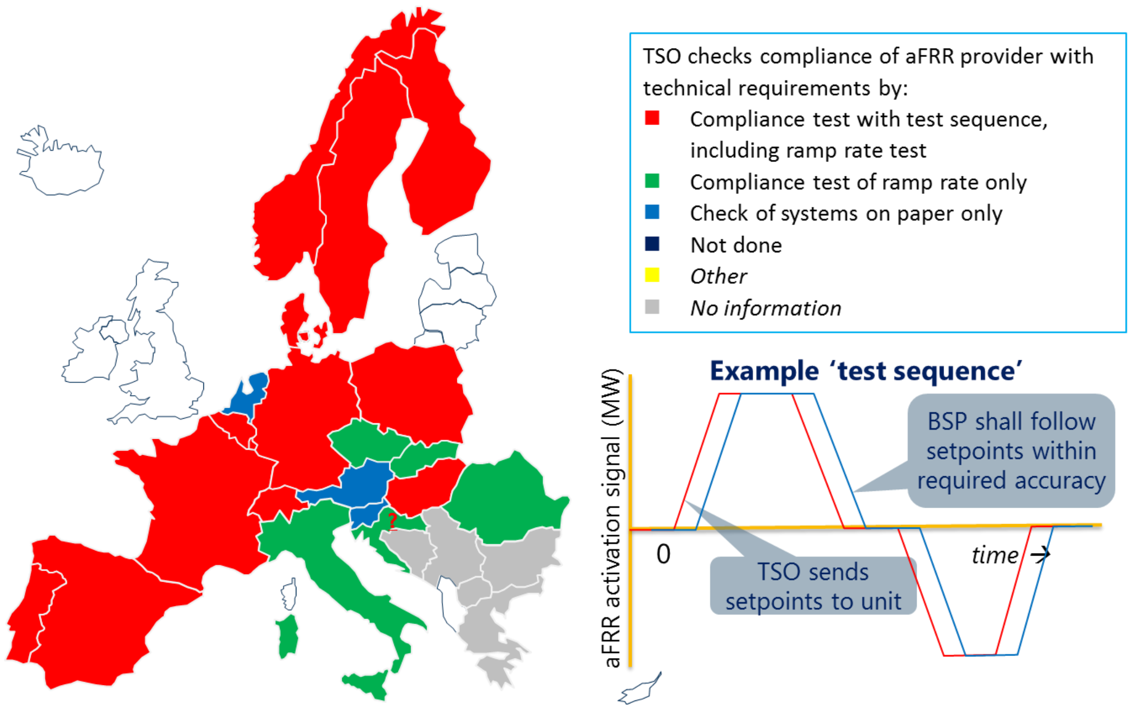


Figure 35: Compliance check: Prequalification tests

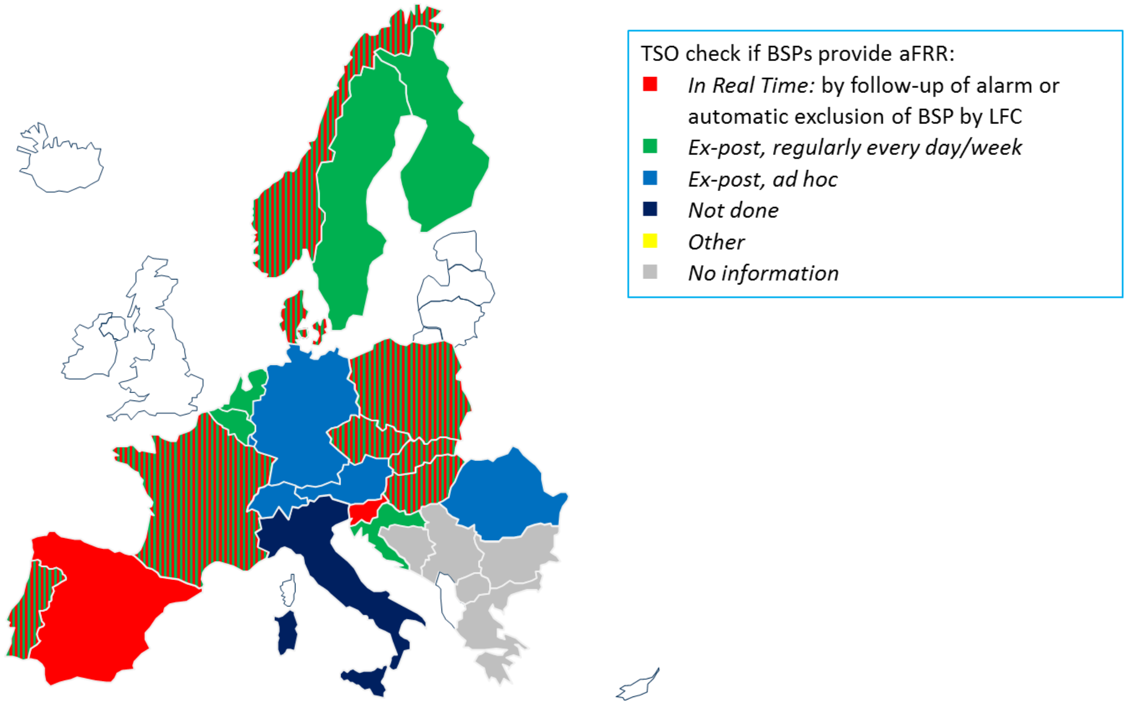


Figure 36: Compliance check: Real Time / Ex-Post

B. Simulation of FRCE quality for LFC Blocks

Description of methodology

One of the objectives of the study is to get a quantitative understanding of the impact of a transition from a pro-rata to a merit order activation for aFRR on regulation quality for each LFC Block, both for:

- the existing control systems and response requirements;
- different response requirements (aFRR Full Activation Times, FAT).

Therefore, this appendix gives a general overview of the simulation models, used data and the made assumptions. In the end, the simulation results for the historic data (February and June 2015) as well as the step responses of each controller are given.

Simulation Models

As the main objective of this study is to understand the effect of aFRR activation schemes and Full Activation Times on *mainly the FRCE*, for the simulation models a constant frequency of 50.00 Hz is assumed, thereby neglecting the influences of FCR on the frequency response. This allows to fully focus on the influence of the effect of aFRR activation schemes and Full Activation Times on mainly the FRCE and to transparently compare the FRCE regulation quality between different activation schemes.

The general concept of the simulation model per LFC Block is shown in Figure 37 and described in this paragraph. The input of the model is an FRCE open-loop signal. This signal is sent to the model which is handling the aFRR activation. The resulting aFRR response signal is added to the initial FRCE open-loop signal. The resulting signal of this summation is the FRCE which will be used for the calculation of the standard deviation for different activation schemes and response requirements. For this model two different input signals are simulated:

- Historic Time Series: With the historically measured FRCE and activated aFRR time series data provided by the TSOs, we have calculated the difference between the FRCE and activated aFRR time series to get the FRCE open-loop time series. For this adjusted signal it is now possible to apply a different activation scheme or a different Full Activation Time.
- Step: The model will be supplied with a constant step.

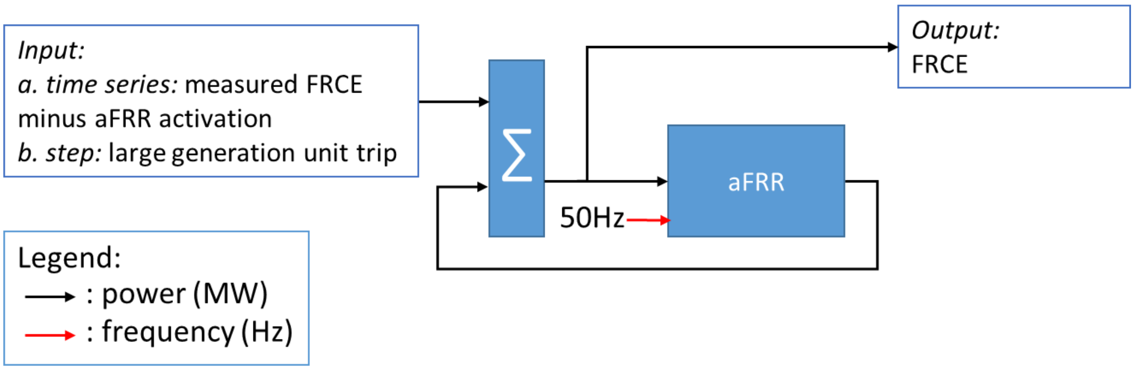


Figure 37: High level Matlab/Simulink model of the individual LFC Blocks in the CE system

The applied aFRR model is shown in Figure 38 in more detail. For the Continental European LFC Blocks the input of the aFRR model is the FRCE signal of the LFC Block. This signal is send to a controller which is usually consisting of a proportional part with a small gain K_p and an integral part with a time constant T_i. The integral part is mainly responsible for leading back the FRCE to zero. Following the PI controller's output, the activation scheme is simulated. For the simulations we applied separately the existing activation schemes (pro-rata or merit order) and the harmonised strict merit order scheme. Based on the applied activation scheme, the signal may get limited by different ramp rate limitations. For pro-rata the ramp rate will be limited to the available aFRR capacity and the requirements of the LFC Block, namely the Full Activation Time. For the merit order scheme the ramp rate is limited by the activated bids and the ramp rate requirements for each bid. The block representing the aFRR response mainly applies time delays and special additional limitations to the output signal. The overall output of the aFRR model is the actually activated aFRR power.

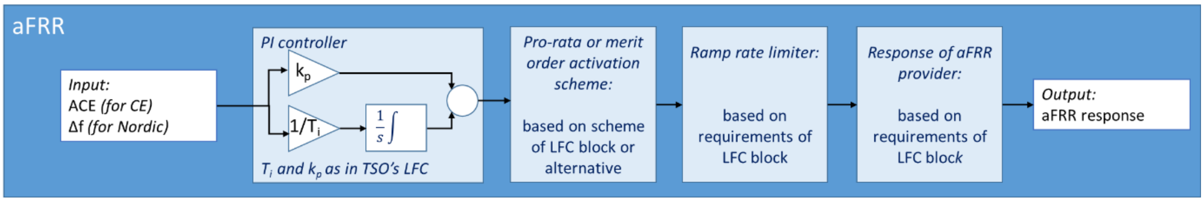


Figure 38: Simplified version of Matlab/Simulink aFRR model

We got individual feedback for each LFC Block concerning the structure, the parameters and settings of the LF Controller.

Furthermore, some LFC Blocks have special controllers, filters and controller features like Anti-Windup and Zero-Crossing-Detection. These details of the LF Controller model have been analysed and implemented individually for each LFC Block to get a realistic aFRR response and a good match to the historic values.

Manually activated controller settings or only manually changeable options are not considered in this study and have not been applied during the simulations.

Simple Merit Order Scheme

To assess the impact of an activation scheme change from pro-rata to merit order and in order to get comparable results the simulations are performed for a simple merit order scheme. This simple activation scheme instructs bids up to the aFRR volume that is requested by the LF Controller's PI controller. The instruction will be in price order of the aFRR energy bids. All bid sizes are standardised and identical. The activation of partial bids is allowed. The ramp rate of one bid is only determined by the bid size and the FAT. As shown in Figure 39, the resulting ramp rate is dependent upon the number of activated bids which is determined by the requested power in total and the bid size of one bid. A parallel activation of more bids than needed to reach a higher ramp rate has not been used in the simulations.

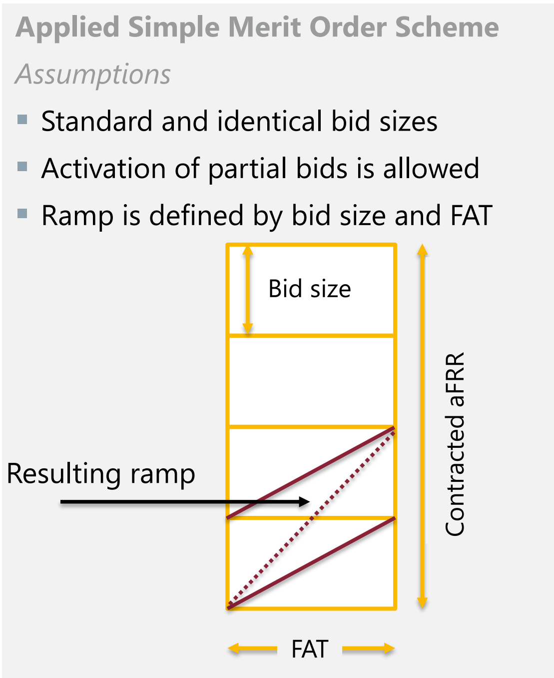


Figure 39: Simple Merit Order Scheme

Data

The data basis we operated on are the measured historically FRCE and actually activated aFRR time series for each LFC Block separately. Furthermore, we got data concerning the available aFRR capacity as time series or constant value depending on the LFC Block.

The resolution of the FRCE and aFRR time series provided by the TSOs varies between 1 s and 10 s. The resolution of the available aFRR capacity does not always have the same resolution as the FRCE and aFRR time series. In this case a constant value for the available aFRR capacity between the time steps is assumed.

Simulations

The simulations we performed is a time series simulation given the historically provided time series and a step response analysis:

- Historic FRCE and aFRR time series
- Step Response Small: 30% of the averaged available aFRR capacity
- Step Response Large: Minimum of available aFRR capacity and largest generation unit trip

The historic measured FRCE and aFRR time series have also been used for testing our simulation models.

Time Series Simulation Result

In Figure 40 an exemplary result table for the time series simulation is shown. The first line is representing the FRCE standard deviation for the historic FRCE time series that was provided by the TSO. The line below is representing the simulation results for the currently used activation scheme and the currently used Full Activation Time. The standard deviation of the FRCE is used as quality indication to determine the impact of a change from the existing scheme to merit order using different FATs and bid sizes. The standard deviation is given with different averages of time intervals of 1, 5, 10 and 15 min (X min in). In this context "as simulated" means the FRCE standard deviation without any averaging in the same time resolution as the ACE / aFRR time series provided by the TSO. The totally activated aFRR energy has also been calculated.

Time Series			FRCE standard deviation (MW)		aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	X min	upwards	downwards
Historic FRCE						
Existing (?)	?	?				
Merit Order	2.5	5				
Merit Order	5	5				
Merit Order	7.5	5				
Merit Order	10	5				
Merit Order	15	5				
Merit Order	2.5	10				
Merit Order	5	10				
Merit Order	7.5	10				
Merit Order	10	10				
Merit Order	15	10				
Merit Order	2.5	20				
Merit Order	5	20				
Merit Order	7.5	20				
Merit Order	10	20				
Merit Order	15	20				

Figure 40: Example result table for time series simulation

Step Response

Furthermore the step responses for each controller are simulated. Figure 41 provides an example result for one LFC block.

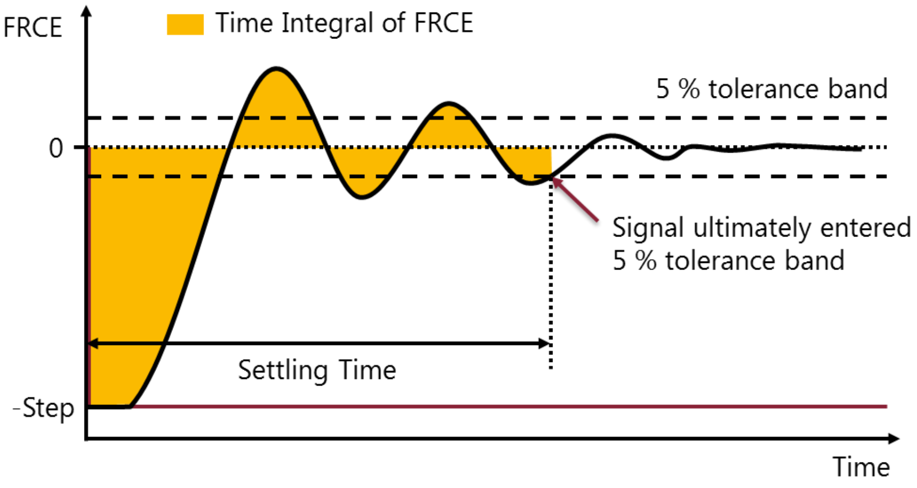


Figure 41: Evaluation Criteria for Step Response

The evaluated criteria for the step response are as follows:

- The Settling Time is specified by the elapsed time from the application of an ideal step input to the LFC controller until the FRCE has entered and remained within a 5% tolerance band around zero. A graphical visualisation of the criteria can be seen in Figure 41. The shorter the Settling Time is, the faster the aFRR response reaches the needed output.
- The second criterion for the step response is the time integral of FRCE. This value is the area between the absolute value of FRCE and zero until the FRCE has ultimately entered the tolerance band. In the figure above this area is marked yellow. The unit of this criterion is energy and may be interpreted as the energy needed from the system to get the FRCE within the tolerance band. Although the Settling Time may be short, the energy deviation can be high because of a severe overshoot.

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards
Historic FRCE			55	48	42	36	33		
Existing (MO)	5	100*	57	51	45	38	34	29,833	- 43,631
Merit Order	2.5	5	57	51	44	37	33	31,866	- 45,870
Merit Order	5	5	64	59	52	42	35	33,614	- 47,428
Merit Order	7.5	5	68	63	56	47	38	34,159	- 48,207
Merit Order	10	5	71	66	59	51	43	34,200	- 48,392
Merit Order	15	5	74	69	63	56	49	33,663	- 47,672
Merit Order	2.5	10	56	50	44	36	33	31,478	- 45,488
Merit Order	5	10	64	59	51	41	35	33,293	- 47,104
Merit Order	7.5	10	68	63	55	47	38	33,905	- 47,924
Merit Order	10	10	71	66	59	51	42	34,013	- 48,199
Merit Order	15	10	74	69	62	56	49	33,573	- 47,570
Merit Order	2.5	20	55	49	43	36	33	30,809	- 44,824
Merit Order	5	20	63	58	50	41	35	32,657	- 46,454
Merit Order	7.5	20	67	62	55	46	38	33,357	- 47,302
Merit Order	10	20	70	65	58	50	42	33,564	- 47,714
Merit Order	15	20	73	69	62	56	48	33,311	- 47,295

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (MO)	5	100*	414	2038	290	8746
Merit Order	2.5	5	354	2039	316	6409
Merit Order	5	5	512	3040	314	9817
Merit Order	7.5	5	762	4435	460	14041
Merit Order	10	5	918	5617	606	18284
Merit Order	15	5	1434	8348	898	26796
Merit Order	2.5	10	372	2039	324	6408
Merit Order	5	10	480	2905	308	9630
Merit Order	7.5	10	742	4291	450	13749
Merit Order	10	10	900	5464	592	17879
Merit Order	15	10	1260	7896	876	26172
Merit Order	2.5	20	402	2039	334	6410
Merit Order	5	20	404	2644	306	9526
Merit Order	7.5	20	704	4020	448	13653
Merit Order	10	20	868	5179	590	17786
Merit Order	15	20	1040	7328	874	26073

Figure 42: Simulation results for the Austrian LFC Block (*Assumption: prequalified volume per BSP)

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards
Historic FRCE			87	82	69	59	54		
Existing (pro rata)	7.5		83	77	65	57	53	52,123	- 38,089
Merit Order	2.5	5	81	75	63	56	51	54,239	- 40,011
Merit Order	5	5	89	84	72	63	57	55,560	- 41,654
Merit Order	7.5	5	97	92	80	70	64	55,659	- 42,395
Merit Order	10	5	101	97	86	76	69	54,828	- 42,051
Merit Order	15	5	108	104	93	84	78	52,204	- 39,968
Merit Order	2.5	10	80	75	63	55	51	53,998	- 39,757
Merit Order	5	10	89	84	71	62	56	55,185	- 41,261
Merit Order	7.5	10	96	91	79	70	63	55,364	- 42,069
Merit Order	10	10	101	97	85	76	69	54,592	- 41,808
Merit Order	15	10	108	103	93	84	77	52,095	- 39,918
Merit Order	2.5	20	80	74	62	55	50	53,643	- 39,383
Merit Order	5	20	87	82	70	61	55	54,537	- 40,589
Merit Order	7.5	20	95	90	78	68	62	54,861	- 41,505
Merit Order	10	20	100	95	84	74	67	54,267	- 41,496
Merit Order	15	20	107	102	92	83	76	52,041	- 39,970

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (pro rata)	7.5		1030	3568	940	11917
Merit Order	2.5	5	1000	3570	990	11898
Merit Order	5	5	850	3569	810	11902
Merit Order	7.5	5	490	3792	510	13043
Merit Order	10	5	1060	4975	620	15669
Merit Order	15	5	1640	7300	880	21264
Merit Order	2.5	10	1010	3571	1000	11911
Merit Order	5	10	890	3570	830	11903
Merit Order	7.5	10	470	3611	500	12861
Merit Order	10	10	900	4593	610	15400
Merit Order	15	10	1580	6980	860	20823
Merit Order	2.5	20	1010	3568	1000	11900
Merit Order	5	20	940	3569	860	11914
Merit Order	7.5	20	670	3569	490	12538
Merit Order	10	20	520	3979	590	14957
Merit Order	15	20	1430	6286	820	19968

Figure 43: Simulation results for the Belgian LFC Block

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards
Historic FRCE									
Existing (pro rata)	3*								
Merit Order	2.5	5							
Merit Order	5	5							
Merit Order	7.5	5		CANNOT BE SIMULATED					
Merit Order	10	5		aFRR only available in 15-min steps.					
Merit Order	15	5							
Merit Order	2.5	10							
Merit Order	5	10							
Merit Order	7.5	10							
Merit Order	10	10							
Merit Order	15	10							
Merit Order	2.5	20							
Merit Order	5	20							
Merit Order	7.5	20							
Merit Order	10	20							
Merit Order	15	20							

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (pro rata)	3		205	110	180	1647
Merit Order	3	10	200	110	175	1635
Merit Order	2.5	5	200	130	150	1411
Merit Order	5	5	420	239	285	2573
Merit Order	7.5	5	625	363	425	3741
Merit Order	10	5	1230	598	560	4903
Merit Order	15	5	2485	1247	835	7233
Merit Order	2.5	10	205	110	150	1406
Merit Order	5	10	245	137	285	2567
Merit Order	7.5	10	470	242	425	3735
Merit Order	10	10	705	375	560	4897
Merit Order	15	10	1395	701	835	7227
Merit Order	2.5	20	205	110	145	1387
Merit Order	5	20	205	110	285	2555
Merit Order	7.5	20	180	110	420	3717
Merit Order	10	20	245	137	560	4885
Merit Order	15	20	470	242	835	7215

Figure 44: Simulation results for the LFC Block of Bosnia and Herzegovina (*calculated based on fixed ramp rate of 5-10 MW/min)

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards
Historic FRCE			32	31	29	28	27		
Existing (pro rata)	5		33	32	30	29	28	22,778	- 16,206
Merit Order	2.5	5	33	32	29	28	27	23,629	- 17,022
Merit Order	5	5	35	34	32	30	29	23,951	- 17,274
Merit Order	7.5	5	38	37	34	33	31	23,881	- 17,191
Merit Order	10	5	40	39	37	35	34	23,622	- 16,888
Merit Order	15	5	43	42	40	38	37	22,972	- 16,140
Merit Order	2.5	10	32	31	29	28	27	23,452	- 16,859
Merit Order	5	10	35	34	32	30	28	23,791	- 17,145
Merit Order	7.5	10	37	36	34	32	31	23,785	- 17,119
Merit Order	10	10	39	38	36	35	33	23,564	- 16,866
Merit Order	15	10	42	42	40	38	37	22,985	- 16,190
Merit Order	2.5	20	32	31	29	27	26	23,216	- 16,646
Merit Order	5	20	34	33	31	29	28	23,569	- 16,949
Merit Order	7.5	20	36	35	33	31	30	23,633	- 17,004
Merit Order	10	20	38	37	35	33	32	23,502	- 16,867
Merit Order	15	20	41	41	39	37	36	22,995	- 16,327

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (pro rata)	5					
Merit Order	2.5	5				
Merit Order	5	5	PI Controller designed in a		PI Controller designed in a	
Merit Order	7.5	5	way that FRCE does not		way that FRCE does not	
Merit Order	10	5	reach zero		reach zero	
Merit Order	15	5				
Merit Order	2.5	10				
Merit Order	5	10				
Merit Order	7.5	10				
Merit Order	10	10				
Merit Order	15	10				
Merit Order	2.5	20				
Merit Order	5	20				
Merit Order	7.5	20				
Merit Order	10	20				
Merit Order	15	20				

Figure 45: Simulation results for the Croatian LFC Block

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)		aFRR capacity (MW)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards	upwards	downwards
Historic FRCE			52	49	40	31	22				
Existing (pro rata)	10		54	51	42	34	26	33,667	- 40,511	387	387
Merit Order	2.5	5	52	49	39	28	21	34,582	- 41,904		
Merit Order	5	5	61	58	49	39	29	35,282	- 43,239		
Merit Order	7.5	5	66	63	55	47	37	35,252	- 43,184		
Merit Order	10	5	69	67	59	52	42	35,044	- 42,908		
Merit Order	15	5	74	72	64	58	50	34,212	- 42,125		
Merit Order	2.5	10	52	49	39	28	20	34,401	- 41,739		
Merit Order	5	10	60	58	48	39	29	35,036	- 43,046		
Merit Order	7.5	10	66	63	54	47	36	35,026	- 42,987		
Merit Order	10	10	69	67	58	52	42	34,844	- 42,724		
Merit Order	15	10	74	72	64	58	50	34,017	- 41,977		
Merit Order	2.5	20	51	48	38	27	20	34,273	- 41,519		
Merit Order	5	20	60	57	48	38	28	34,724	- 42,721		
Merit Order	7.5	20	65	62	54	46	35	34,696	- 42,713		
Merit Order	10	20	69	66	58	51	41	34,526	- 42,386		
Merit Order	15	20	73	71	63	58	49	33,713	- 41,674		

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (pro rata)	10		430	4747	520	35328
Merit Order	2.5	5	220	4879	220	19248
Merit Order	5	5	310	6805	360	28562
Merit Order	7.5	5	380	8301	500	37823
Merit Order	10	5	440	9524	640	47086
Merit Order	15	5	540	11644	920	65623
Merit Order	2.5	10	220	4811	220	19106
Merit Order	5	10	310	6731	360	28444
Merit Order	7.5	10	380	8225	500	37731
Merit Order	10	10	440	9456	640	47007
Merit Order	15	10	540	11550	920	65582
Merit Order	2.5	20	220	4661	220	18941
Merit Order	5	20	300	6530	350	28006
Merit Order	7.5	20	370	8027	490	37114
Merit Order	10	20	430	9253	630	46218
Merit Order	15	20	530	11341	900	64362

Figure 46: Simulation results for Czech LFC Block

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)		aFRR capacity (MW)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards	upwards	downwards
Historic FRCE			287	276	254	233	221				
Existing (pro rata)	100/15*		289	277	252	228	212	262,178	- 263,442	738	738
Merit Order	100/15*	10	386	377	350	315	288	272,661	- 278,137		
Merit Order	2.5	5	296	284	256	227	209	269,179	- 269,607		
Merit Order	5	5	349	339	311	278	248	273,620	- 277,358		
Merit Order	7.5	5	402	394	368	332	310	271,035	- 277,233		
Merit Order	10	5	431	423	398	364	347	263,508	- 271,135		
Merit Order	15	5	460	453	430	401	381	249,154	- 259,504		
Merit Order	2.5	10	295	284	255	227	209	268,951	- 269,357		
Merit Order	5	10	348	338	310	277	247	273,416	- 277,116		
Merit Order	7.5	10	401	393	367	331	309	270,964	- 277,132		
Merit Order	10	10	430	423	398	363	346	263,474	- 271,065		
Merit Order	15	10	460	453	430	400	381	249,219	- 259,529		
Merit Order	2.5	20	294	282	254	226	209	268,509	- 268,880		
Merit Order	5	20	346	336	308	275	245	272,997	- 276,634		
Merit Order	7.5	20	400	391	365	330	307	270,837	- 276,944		
Merit Order	10	20	429	422	396	362	345	263,426	- 271,002		
Merit Order	15	20	459	452	429	399	380	249,299	- 259,663		

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (pro rata)	100/15*		565	11795	395	89461
Merit Order	100/15*	10	920	22614	490	128705
Merit Order	2.5	5	400	11799	380	79605
Merit Order	5	5	740	18231	400	108326
Merit Order	7.5	5	1000	25005	540	139399
Merit Order	10	5	1180	30626	680	170311
Merit Order	15	5	1870	44690	965	232145
Merit Order	2.5	10	415	11790	385	79652
Merit Order	5	10	725	17938	400	108133
Merit Order	7.5	10	990	24702	540	139102
Merit Order	10	10	1170	30331	680	169948
Merit Order	15	10	1825	44045	965	231595
Merit Order	2.5	20	440	11789	390	79627
Merit Order	5	20	700	17368	400	107804
Merit Order	7.5	20	975	24148	535	138446
Merit Order	10	20	1160	29814	675	169103
Merit Order	15	20	1735	42687	960	230394

Figure 47: Simulation results for the French LFC Block (*calculated based on given ramp rate of 15%/min of available capacity)

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards
Historic FRCE			152	136	100	76	64		
Existing (MO)	5	500*	169	151	115	81	61	259,664	- 125,120
Merit Order	2.5	5	177	161	124	87	64	265,184	- 130,640
Merit Order	5	5	208	195	159	115	82	270,601	- 136,057
Merit Order	7.5	5	232	220	187	145	107	275,743	- 141,199
Merit Order	10	5	252	242	210	173	134	280,973	- 146,429
Merit Order	15	5	289	281	254	222	186	293,740	- 159,191
Merit Order	2.5	10	176	160	124	86	64	264,950	- 130,406
Merit Order	5	10	207	194	158	114	81	270,331	- 135,787
Merit Order	7.5	10	231	220	186	145	106	275,438	- 140,895
Merit Order	10	10	251	241	210	172	133	280,665	- 146,121
Merit Order	15	10	288	280	253	221	185	293,333	- 158,785
Merit Order	2.5	20	175	159	122	86	63	264,492	- 129,948
Merit Order	5	20	206	193	157	113	80	269,793	- 135,249
Merit Order	7.5	20	230	218	185	143	105	274,843	- 140,299
Merit Order	10	20	250	240	208	171	132	280,067	- 145,522
Merit Order	15	20	287	278	251	219	184	292,524	- 157,975

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (MO)	5	500*	712	34745	624	80391
Merit Order	2.5	5	768	34766	768	80369
Merit Order	5	5	448	34713	448	80316
Merit Order	7.5	5	664	45311	668	105008
Merit Order	10	5	1072	61057	1076	141555
Merit Order	15	5	1496	87831	1640	220082
Merit Order	2.5	10	768	34760	768	80362
Merit Order	5	10	448	34649	448	80264
Merit Order	7.5	10	644	45011	664	104780
Merit Order	10	10	1068	60819	1076	141328
Merit Order	15	10	1496	87621	1640	219649
Merit Order	2.5	20	768	34748	768	80347
Merit Order	5	20	484	34843	448	80143
Merit Order	7.5	20	628	44649	648	104184
Merit Order	10	20	1064	60500	1072	140847
Merit Order	15	20	1488	87140	1632	218605

Figure 48: Simulation results for the German LFC Block (*Assumption: prequalified volume per BSP)

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards
Historic FRCE			95	91	82	71	62		
Existing (MO)	15	200*	95	91	81	71	62	41,490	- 40,528
Merit Order	2.5	5	87	83	72	61	52	46,528	- 45,990
Merit Order	5	5	93	89	79	67	58	47,629	- 46,715
Merit Order	7.5	5	98	94	84	73	64	48,419	- 47,329
Merit Order	10	5	101	97	88	78	69	48,950	- 47,720
Merit Order	15	5	106	102	94	84	75	49,202	- 47,826
Merit Order	2.5	10	87	82	72	60	51	45,574	- 45,052
Merit Order	5	10	93	88	78	67	58	46,326	- 45,612
Merit Order	7.5	10	97	93	84	73	64	46,949	- 46,213
Merit Order	10	10	101	97	88	77	68	47,477	- 46,579
Merit Order	15	10	105	102	93	83	74	48,082	- 46,834
Merit Order	2.5	20	86	81	71	60	51	44,749	- 44,170
Merit Order	5	20	92	87	77	66	57	44,955	- 44,381
Merit Order	7.5	20	97	92	83	72	63	45,144	- 44,548
Merit Order	10	20	100	96	87	76	67	45,548	- 45,031
Merit Order	15	20	105	101	92	82	73	46,133	- 45,298

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (MO)	15	200*	1000	10068	1376	97908
Merit Order	2.5	5	992	10072	1068	58833
Merit Order	5	5	544	10367	704	58834
Merit Order	7.5	5	924	12692	668	69411
Merit Order	10	5	952	14167	1144	85830
Merit Order	15	5	1008	16765	1524	112772
Merit Order	2.5	10	1012	10067	1068	58812
Merit Order	5	10	544	10097	724	58833
Merit Order	7.5	10	880	12323	664	69064
Merit Order	10	10	936	13879	1124	85069
Merit Order	15	10	1012	16505	1516	112154
Merit Order	2.5	20	1040	10071	1076	58834
Merit Order	5	20	748	10069	760	58822
Merit Order	7.5	20	896	11917	660	68503
Merit Order	10	20	880	13280	1108	84227
Merit Order	15	20	992	15973	1512	111508

Figure 49: Simulation results for the Dutch LFC Block

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards
Historic FRCE			88	83	71	61	53		
Existing (mix)	5		91	87	76	66	58	94,983	- 130,810
Merit Order	2.5	5	95	91	79	68	60	95,889	- 131,714
Merit Order	5	5	104	100	88	76	67	98,123	- 133,939
Merit Order	7.5	5	115	111	100	88	78	101,247	- 137,123
Merit Order	10	5	127	124	114	102	91	104,998	- 140,965
Merit Order	15	5	154	151	143	132	121	112,940	- 148,742
Merit Order	2.5	10	95	90	79	68	60	95,731	- 131,555
Merit Order	5	10	103	99	88	76	66	97,848	- 133,663
Merit Order	7.5	10	114	110	99	87	77	100,852	- 136,726
Merit Order	10	10	126	123	113	101	90	104,540	- 140,506
Merit Order	15	10	153	150	141	130	119	112,458	- 148,276
Merit Order	2.5	20	94	90	78	67	59	95,491	- 131,316
Merit Order	5	20	102	98	86	75	65	97,343	- 133,159
Merit Order	7.5	20	112	108	97	85	75	100,121	- 135,987
Merit Order	10	20	124	121	110	98	88	103,656	- 139,621
Merit Order	15	20	151	148	139	128	117	111,474	- 147,327

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (mix)	5		1167	17630	1188	58080
Merit Order	2.5	5	1128	17630	1145	58078
Merit Order	5	5	927	17631	928	58075
Merit Order	7.5	5	631	19415	636	64171
Merit Order	10	5	1371	25579	771	75735
Merit Order	15	5	1943	35863	1050	98944
Merit Order	2.5	10	1133	17630	1147	58081
Merit Order	5	10	952	17630	937	58076
Merit Order	7.5	10	625	19159	635	63924
Merit Order	10	10	1336	25062	769	75481
Merit Order	15	10	1922	35353	1048	98676
Merit Order	2.5	20	1142	17631	1150	58079
Merit Order	5	20	994	17631	953	58076
Merit Order	7.5	20	613	18649	631	63392
Merit Order	10	20	1271	24079	765	74954
Merit Order	15	20	1878	34316	1045	98178

Figure 50: Simulation results for the Polish LFC Block

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards
Historic FRCE			45	42	38	34	31		
Existing (pro rata)	15*		49	45	40	36	33	37,323	- 30,562
Merit Order	2.5	5	50	47	41	36	33	38,334	- 31,547
Merit Order	5	5	55	52	46	40	36	38,272	- 31,815
Merit Order	7.5	5	59	56	50	44	40	37,530	- 31,437
Merit Order	10	5	62	59	54	48	43	36,632	- 30,814
Merit Order	15	5	66	63	58	53	48	34,926	- 29,190
Merit Order	2.5	10	50	47	41	36	33	38,169	- 31,382
Merit Order	5	10	55	52	46	40	36	38,117	- 31,653
Merit Order	7.5	10	59	56	50	44	39	37,399	- 31,313
Merit Order	10	10	61	59	53	47	43	36,520	- 30,730
Merit Order	15	10	66	63	58	53	48	34,847	- 29,164
Merit Order	2.5	20	49	46	41	36	33	37,905	- 31,117
Merit Order	5	20	54	51	45	39	36	37,825	- 31,351
Merit Order	7.5	20	58	55	49	43	39	37,157	- 31,081
Merit Order	10	20	61	58	53	47	42	36,295	- 30,549
Merit Order	15	20	65	63	58	52	48	34,672	- 29,100

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (pro rata)	15*		756	1289	722	4123
Merit Order	2.5	5	706	1289	692	4123
Merit Order	5	5	436	1289	324	4142
Merit Order	7.5	5	614	1676	462	5742
Merit Order	10	5	992	2285	602	7382
Merit Order	15	5	1398	3354	886	10687
Merit Order	2.5	10	718	1288	700	4125
Merit Order	5	10	564	1289	376	4123
Merit Order	7.5	10	500	1558	458	5666
Merit Order	10	10	876	2061	598	7305
Merit Order	15	10	1310	3106	882	10616
Merit Order	2.5	20	724	1288	710	4124
Merit Order	5	20	626	1288	468	4124
Merit Order	7.5	20	358	1288	450	5512
Merit Order	10	20	624	1680	592	7169
Merit Order	15	20	1246	2830	876	10477

Figure 51: Simulation results for the Serbian LFC Block (*Simulated with a fixed ramp rate of 25 MW/min according to questionnaire.)

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards
Historic FRCE			26	24	19	15	11		
Existing (pro rata)	9*		31	28	23	20	15	15,002	- 22,848
Merit Order	2.5	5	28	25	19	14	10	15,441	- 23,234
Merit Order	5	5	33	30	25	19	13	17,007	- 24,802
Merit Order	7.5	5	37	35	31	26	19	18,641	- 26,487
Merit Order	10	5	41	39	35	31	26	20,068	- 27,945
Merit Order	15	5	54	53	50	47	43	24,326	- 32,228
Merit Order	2.5	10	27	24	19	13	10	15,213	- 23,013
Merit Order	5	10	32	30	24	19	13	16,620	- 24,407
Merit Order	7.5	10	37	35	30	25	18	18,196	- 26,028
Merit Order	10	10	40	39	35	31	25	19,630	- 27,490
Merit Order	15	10	53	51	48	45	42	23,706	- 31,596
Merit Order	2.5	20	27	24	18	13	10	14,930	- 22,740
Merit Order	5	20	31	29	23	18	12	16,015	- 23,801
Merit Order	7.5	20	35	33	29	24	17	17,410	- 25,225
Merit Order	10	20	39	38	33	29	24	18,809	- 26,652
Merit Order	15	20	51	49	46	43	39	22,588	- 30,463

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (pro rata)	9*		3016	5560	2520	19437
Merit Order	2.5	5	2980	5493	1000	9193
Merit Order	5	5	2436	4516	300	8146
Merit Order	7.5	5	704	2909	1780	15649
Merit Order	10	5	3116	6593	3412	24154
Merit Order	15	5	3708	8895	6684	41212
Merit Order	2.5	10	2984	5503	1000	9191
Merit Order	5	10	2636	4878	300	8092
Merit Order	7.5	10	400	2639	1756	15517
Merit Order	10	10	2944	6082	3380	23988
Merit Order	15	10	3644	8613	6656	41060
Merit Order	2.5	20	3020	5566	1004	9199
Merit Order	5	20	2792	5156	296	7965
Merit Order	7.5	20	768	2694	1704	15234
Merit Order	10	20	2064	4378	3336	23747
Merit Order	15	20	3568	8124	6608	40806

Figure 52: Simulation results for Slovakian LFC Block (*adjusted to match with the historic time series)

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards
Historic FRCE			39	29	16	10	7		
Existing (pro rata)	3		40	26	13	9	6	42,238	- 29,361
Merit Order	3	10	52	44	30	13	8	49,410	- 36,548
Merit Order	2.5	5	49	40	25	11	8	48,074	- 35,201
Merit Order	5	5	77	72	58	30	11	59,638	- 46,870
Merit Order	7.5	5	79	74	63	41	20	60,881	- 48,551
Merit Order	10	5	80	75	66	51	29	61,187	- 49,258
Merit Order	15	5	87	82	75	65	47	60,647	- 50,877
Merit Order	2.5	10	48	39	24	11	7	47,350	- 34,476
Merit Order	5	10	76	71	57	29	11	59,099	- 46,336
Merit Order	7.5	10	78	73	62	40	19	60,335	- 47,955
Merit Order	10	10	80	75	66	50	29	60,862	- 48,885
Merit Order	15	10	86	82	75	65	46	60,514	- 50,717
Merit Order	2.5	20	47	38	22	10	7	46,112	- 33,235
Merit Order	5	20	73	67	54	27	10	57,444	- 44,692
Merit Order	7.5	20	76	71	60	38	18	58,970	- 46,566
Merit Order	10	20	79	74	64	49	27	60,042	- 48,021
Merit Order	15	20	86	81	74	64	45	60,253	- 50,389

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (pro rata)	3		200	2448	190	13097
Merit Order	3	10	380	5193	210	15600
Merit Order	2.5	5	340	4603	180	13882
Merit Order	5	5	600	8036	320	22456
Merit Order	7.5	5	1720	18741	470	31060
Merit Order	10	5	2240	27556	610	39562
Merit Order	15	5	4250	47104	890	56580
Merit Order	2.5	10	330	4519	180	13848
Merit Order	5	10	550	7708	320	22408
Merit Order	7.5	10	1710	18251	470	31022
Merit Order	10	10	2130	25752	610	39536
Merit Order	15	10	4210	47089	890	56554
Merit Order	2.5	20	320	4322	180	13715
Merit Order	5	20	520	7449	320	22078
Merit Order	7.5	20	1720	16043	460	30427
Merit Order	10	20	1950	24729	600	38763
Merit Order	15	20	4040	43844	870	55353

Figure 53: Simulation results of the Swiss LFC Block

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards
Historic FRCE			49	48	45	42	41		
Existing (pro rata)	?*		45	43	39	35	32	11,778	- 9,894
Merit Order	2.5	5	45	43	39	35	32	12,041	- 10,146
Merit Order	5	5	48	46	41	37	34	12,215	- 10,327
Merit Order	7.5	5	50	48	44	39	36	12,222	- 10,381
Merit Order	10	5	52	50	46	42	38	12,092	- 10,307
Merit Order	15	5	55	53	49	45	41	11,638	- 9,999
Merit Order	2.5	10	45	42	38	34	32	11,967	- 10,073
Merit Order	5	10	47	45	41	36	33	12,115	- 10,223
Merit Order	7.5	10	50	48	43	39	35	12,132	- 10,284
Merit Order	10	10	52	50	46	41	38	12,031	- 10,234
Merit Order	15	10	54	53	49	44	41	11,607	- 9,950
Merit Order	2.5	20	44	42	38	34	32	11,879	- 9,988
Merit Order	5	20	46	44	40	35	33	11,978	- 10,081
Merit Order	7.5	20	48	46	42	38	34	11,977	- 10,115
Merit Order	10	20	51	49	44	40	36	11,894	- 10,077
Merit Order	15	20	54	52	48	43	40	11,534	- 9,834

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (pro rata)	?*		2200	3325	2162	9511
Merit Order	2.5	5	2190	3327	2170	9511
Merit Order	5	5	2122	3296	2110	9515
Merit Order	7.5	5	2016	3262	1984	9511
Merit Order	10	5	1778	3161	1748	9514
Merit Order	15	5	988	3256	1042	10358
Merit Order	2.5	10	2190	3328	2174	9509
Merit Order	5	10	2142	3322	2124	9514
Merit Order	7.5	10	2078	3292	2018	9512
Merit Order	10	10	1950	3227	1816	9514
Merit Order	15	10	1316	3160	1022	10061
Merit Order	2.5	20	2200	3325	2180	9508
Merit Order	5	20	2190	3325	2152	9514
Merit Order	7.5	20	2150	3292	2066	9511
Merit Order	10	20	2066	3227	1948	9515
Merit Order	15	20	1752	3160	1008	9472

Figure 54: Simulation results for Slovenian LFC Block (*Simulation used ramp rate of 8 MW/min according to questionnaire)

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards
Historic FRCE			37	34	30	27	23		
Existing (MO)	15	50	45	43	39	33	20	39,804	- 49,617
Merit Order	2.5	5	32	29	24	20	16	35,866	- 45,839
Merit Order	5	5	38	35	30	24	17	38,315	- 48,241
Merit Order	7.5	5	45	43	38	32	21	40,973	- 51,001
Merit Order	10	5	56	54	50	46	36	44,357	- 54,292
Merit Order	15	5	79	78	75	72	65	51,122	- 60,998
Merit Order	2.5	10	32	29	24	20	16	35,626	- 45,635
Merit Order	5	10	37	34	30	23	16	37,938	- 47,845
Merit Order	7.5	10	44	42	38	31	21	40,525	- 50,544
Merit Order	10	10	55	53	49	45	35	43,844	- 53,761
Merit Order	15	10	78	77	74	70	64	50,616	- 60,445
Merit Order	2.5	20	32	28	24	20	16	35,270	- 45,347
Merit Order	5	20	36	33	29	22	16	37,321	- 47,172
Merit Order	7.5	20	43	41	36	30	19	39,655	- 49,623
Merit Order	10	20	53	51	47	43	32	42,841	- 52,738
Merit Order	15	20	76	75	72	68	61	49,719	- 59,541

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (MO)	15	50	2160	10547	1410	62273
Merit Order	2.5	5	2300	10619	890	30945
Merit Order	5	5	310	4434	370	34038
Merit Order	7.5	5	2070	9959	1160	51188
Merit Order	10	5	2800	15281	1440	64665
Merit Order	15	5	3190	19564	1890	90214
Merit Order	2.5	10	2320	10702	890	30887
Merit Order	5	10	540	4678	370	33917
Merit Order	7.5	10	1970	9459	1150	50920
Merit Order	10	10	2770	15004	1440	64461
Merit Order	15	10	3170	19337	1890	90004
Merit Order	2.5	20	2350	10897	890	30794
Merit Order	5	20	1090	5571	370	33689
Merit Order	7.5	20	1710	8203	1140	50425
Merit Order	10	20	2700	14303	1430	63826
Merit Order	15	20	3130	18866	1870	89017

Figure 55: Simulation results for the Hungarian LFC Block

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards
Historic FRCE			59	57	49	42	37		
Existing (pro rata)	6.5*		69	66	55	47	42	78,283	- 84,195
Merit Order	2.5	5	54	48	39	34	32	81,450	- 87,699
Merit Order	5	5	64	60	49	41	37	79,671	- 85,626
Merit Order	7.5	5	73	70	59	50	45	78,159	- 84,141
Merit Order	10	5	80	77	67	58	52	76,894	- 83,067
Merit Order	15	5	91	89	79	71	65	74,707	- 81,275
Merit Order	2.5	10	54	48	39	34	32	81,441	- 87,686
Merit Order	5	10	64	60	49	41	37	79,660	- 85,614
Merit Order	7.5	10	73	70	59	50	45	78,153	- 84,133
Merit Order	10	10	80	77	67	58	52	76,891	- 83,060
Merit Order	15	10	91	89	79	71	65	74,701	- 81,269
Merit Order	2.5	20	54	48	38	34	32	81,523	- 87,776
Merit Order	5	20	63	60	48	41	37	79,780	- 85,764
Merit Order	7.5	20	72	69	58	49	44	78,294	- 84,278
Merit Order	10	20	79	76	66	57	51	77,064	- 83,191
Merit Order	15	20	90	88	78	70	64	74,938	- 81,471

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (pro rata)	6.5*		NaN	NaN	382	14471
Merit Order	2.5	5	NaN	NaN	156	6219
Merit Order	5	5	NaN	NaN	298	11412
Merit Order	7.5	5	NaN	NaN	440	16605
Merit Order	10	5	NaN	NaN	582	21799
Merit Order	15	5	7196	8826	868	32193
Merit Order	2.5	10	NaN	NaN	156	6219
Merit Order	5	10	NaN	NaN	298	11412
Merit Order	7.5	10	NaN	NaN	440	16605
Merit Order	10	10	NaN	NaN	582	21799
Merit Order	15	10	7196	8831	868	32193
Merit Order	2.5	20	NaN	NaN	150	6015
Merit Order	5	20	NaN	NaN	286	11006
Merit Order	7.5	20	NaN	NaN	424	16006
Merit Order	10	20	NaN	NaN	560	20997
Merit Order	15	20	7188	8865	834	30988

Figure 56: Simulation results for the Romanian LFC Block (*calculated based on provided ramp rates in practice)

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards
Historic FRCE			30	30	28	25	23		
Existing (pro rata)	5		33	33	27	24	22	24,385	- 36,044
Merit Order	2.5	5	34	34	27	23	21	26,104	- 37,663
Merit Order	5	5	39	39	33	26	23	26,839	- 38,369
Merit Order	7.5	5	41	41	36	30	25	26,179	- 37,607
Merit Order	10	5	43	43	39	33	28	25,391	- 36,747
Merit Order	15	5	46	46	42	38	32	24,038	- 35,518
Merit Order	2.5	10	34	34	27	23	21	25,850	- 37,405
Merit Order	5	10	38	38	32	26	23	26,653	- 38,196
Merit Order	7.5	10	41	41	36	30	25	26,105	- 37,529
Merit Order	10	10	43	43	38	33	28	25,346	- 36,709
Merit Order	15	10	46	46	42	37	32	23,998	- 35,458
Merit Order	2.5	20	33	33	27	23	21	25,377	- 36,929
Merit Order	5	20	37	37	32	26	23	26,267	- 37,824
Merit Order	7.5	20	41	41	36	29	25	25,898	- 37,308
Merit Order	10	20	42	42	38	33	27	25,224	- 36,561
Merit Order	15	20	45	45	42	37	32	23,903	- 35,331

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (Pro Rata)	5		120	875	300	4500
Merit Order	2.5	5	180	1017	240	3833
Merit Order	5	5	480	1905	360	5583
Merit Order	7.5	5	1380	4798	420	7444
Merit Order	10	5	1920	5861	540	9417
Merit Order	15	5	2340	6926	840	13639
Merit Order	2.5	10	360	1472	180	3600
Merit Order	5	10	660	2086	360	5500
Merit Order	7.5	10	1380	4114	420	7378
Merit Order	10	10	1980	6023	540	9350
Merit Order	15	10	2220	6578	840	13567
Merit Order	2.5	20	420	1300	180	3467
Merit Order	5	20	540	1876	360	5333
Merit Order	7.5	20	780	2441	480	7378
Merit Order	10	20	1500	4720	540	9217
Merit Order	15	20	2820	7696	840	13422

Figure 57: Simulation results for the western Danish LFC Block

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards
Historic FRCE			238	232	218	201	190		
Existing (pro rata)	200/60		244	238	224	207	196	136,470	- 207,111
Existing (MO)	200/60	10	262	257	240	217	205	141,050	- 211,226
Merit Order	2.5	5	255	250	233	212	200	140,112	- 210,537
Merit Order	5	5	280	275	258	232	217	141,895	- 211,669
Merit Order	7.5	5	305	300	284	256	240	139,549	- 208,653
Merit Order	10	5	328	323	308	281	263	135,076	- 203,428
Merit Order	15	5	366	362	348	323	304	124,376	- 190,203
Merit Order	2.5	10	255	249	233	212	200	139,926	- 210,365
Merit Order	5	10	279	274	257	231	217	141,722	- 211,513
Merit Order	7.5	10	305	300	283	256	240	139,433	- 208,546
Merit Order	10	10	327	323	307	280	262	135,015	- 203,367
Merit Order	15	10	366	361	347	322	303	124,334	- 190,191
Merit Order	2.5	20	254	248	232	212	200	139,604	- 210,069
Merit Order	5	20	278	273	256	230	216	141,527	- 211,356
Merit Order	7.5	20	303	298	281	254	238	139,514	- 208,679
Merit Order	10	20	325	321	305	278	260	135,326	- 203,769
Merit Order	15	20	363	359	345	320	301	124,910	- 190,975

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (pro rata)	200/60		650	7247	640	24101
Existing (MO)	200/60	10	500	7244	460	24109
Merit Order	2.5	5	580	7234	570	24129
Merit Order	5	5	450	8464	360	28324
Merit Order	7.5	5	910	12548	500	37555
Merit Order	10	5	1140	16073	640	46787
Merit Order	15	5	1420	21798	920	65394
Merit Order	2.5	10	590	7241	570	24108
Merit Order	5	10	390	8217	360	28208
Merit Order	7.5	10	890	12300	500	37494
Merit Order	10	10	1120	15753	640	46660
Merit Order	15	10	1420	21576	920	65315
Merit Order	2.5	20	600	7237	580	24144
Merit Order	5	20	330	7918	350	27854
Merit Order	7.5	20	870	11895	490	37012
Merit Order	10	20	1100	15274	620	45780
Merit Order	15	20	1410	21120	900	63975

Figure 58: Simulation results for the Italian LFC Block

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards
Historic FRCE									
Existing (pro rata)	5								
Merit Order	2.5	5							
Merit Order	5	5							
Merit Order	7.5	5		CANNOT BE SIMULATED					
Merit Order	10	5		Data for activated aFRR as time series not available.					
Merit Order	15	5							
Merit Order	2.5	10							
Merit Order	5	10							
Merit Order	7.5	10							
Merit Order	10	10							
Merit Order	15	10							
Merit Order	2.5	20							
Merit Order	5	20							
Merit Order	7.5	20							
Merit Order	10	20							
Merit Order	15	20							

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (pro rata)	5		394	2355	313	10618
Merit Order	2.5	5	340	2447	172	6243
Merit Order	5	5	1079	7719	313	10647
Merit Order	7.5	5	2348	14507	455	15054
Merit Order	10	5	3426	21778	596	19458
Merit Order	15	5	6781	43202	879	28269
Merit Order	2.5	10	326	2381	168	6145
Merit Order	5	10	1060	7403	307	10454
Merit Order	7.5	10	2450	13801	445	14758
Merit Order	10	10	3118	20693	583	19063
Merit Order	15	10	6596	41212	860	27675
Merit Order	2.5	20	235	2170	168	6131
Merit Order	5	20	1018	6808	306	10436
Merit Order	7.5	20	1707	11462	445	14743
Merit Order	10	20	2809	18514	583	19048
Merit Order	15	20	5882	36117	860	27660

Figure 59: Simulation results for the Portuguese LFC Block

Time Series			FRCE standard deviation (MW)					aFRR energy (MWh)	
Act. Scheme	FAT (min)	Bid Size (MW)	as simulated	1 min	5 min	10 min	15 min	upwards	downwards
Historic FRCE			107	97	65	52	44		
Existing (pro rata)	5		120	109	72	57	48	27,965	- 30,810
Merit Order	2.5	5	134	124	82	59	48	30,160	- 32,942
Merit Order	5	5	141	132	93	65	51	30,500	- 33,300
Merit Order	7.5	5	145	136	99	72	57	28,770	- 31,572
Merit Order	10	5	147	138	103	77	61	26,806	- 29,602
Merit Order	15	5	149	140	106	83	67	23,642	- 26,449
Merit Order	2.5	10	133	123	81	59	48	29,756	- 32,538
Merit Order	5	10	141	132	93	65	51	30,239	- 33,040
Merit Order	7.5	10	145	136	99	72	57	28,615	- 31,415
Merit Order	10	10	147	138	102	77	61	26,714	- 29,508
Merit Order	15	10	148	140	106	83	67	23,582	- 26,388
Merit Order	2.5	20	133	122	80	58	48	29,074	- 31,859
Merit Order	5	20	140	131	92	64	51	29,739	- 32,540
Merit Order	7.5	20	144	135	98	71	56	28,316	- 31,115
Merit Order	10	20	146	138	102	76	60	26,514	- 29,306
Merit Order	15	20	148	140	106	83	67	23,480	- 26,281

Step Response			30% contr. aFRR cap.		Large Step	
Act. Scheme	FAT (min)	Bid Size (MW)	Settling Time (sec)	FRCE Energy Error (kWh)	Settling Time (sec)	FRCE Energy Error (kWh)
Existing (pro rata)	5					
Merit Order	2.5	5				
Merit Order	5	5				
Merit Order	7.5	5				
Merit Order	10	5				
Merit Order	15	5				
Merit Order	2.5	10				
Merit Order	5	10				
Merit Order	7.5	10				
Merit Order	10	10				
Merit Order	15	10				
Merit Order	2.5	20				
Merit Order	5	20				
Merit Order	7.5	20				
Merit Order	10	20				
Merit Order	15	20				

Due to the specificities of Spanish AGC no reliable simulation results were obtained

Figure 60: Simulation results for the Spain LFC Block

FAT	Bid Size	standard deviation frequency	difference with existing frequency	minutes outside 49.9-50.1Hz	difference with existing minutes
no LFC	N/A	0.056Hz	54.4%	648	380.0%
historic	5MW	0.033Hz	-7.5%	135	0.0%
90s	5MW	0.036Hz	0.0%	135	0.0%
90s	10MW	0.036Hz	-0.6%	131	-3.0%
150s	10MW	0.036Hz	-0.1%	134	-0.7%
300s	10MW	0.037Hz	1.8%	139	3.0%
450s	10MW	0.037Hz	3.8%	145	7.4%
600s	10MW	0.038Hz	5.8%	158	17.0%
900s	10MW	0.040Hz	9.7%	181	34.1%

FAT	Bid Size	settling time 300MW step
90s	5MW	510s
90s	10MW	510s
150s	10MW	470s
300s	10MW	650s
450s	10MW	870s
600s	10MW	1040s
900s	10MW	1490s

Figure 61: Simulation results for the Nordic LFC Block (standard deviation is based on 5 minutes average frequency values)

C. aFRR Capability for LFC Blocks

Description of methodology

One of the objectives of the study is to get a quantitative understanding of the impact of aFRR response requirements (FAT) on the theoretical aFRR capability of each LFC Block. To assess this theoretical technical potential of the installed capacities of each LFC Block, the total maximum generation capacity per LFC Block which is able to provide aFRR is calculated.

Therefore, this appendix gives an overview of the used data basis, the applied methodology and the made assumptions as well as the conclusion which can be drawn. In the end, the results for each LFC Block are given.

Database

The analysis is based on the European electricity system in 2014. As data basis for the installed capacities, the generation unit database of IAEW was used. The installed capacities per country are according to the ENTSO-E factsheet 2014. In addition, the database contains further technical parameters per unit:

- Minimum stable capacity and rated capacity
- Power-dependent efficiencies
- Technical non-availably (revisions, power plant outages)
    - Thermal power plants in Germany: Based on VGB-statistics[31]
    - Other: Published availabilities on different platform's (e.g. EEX, Elia, etc.)[32]
- Reserve ramp rates

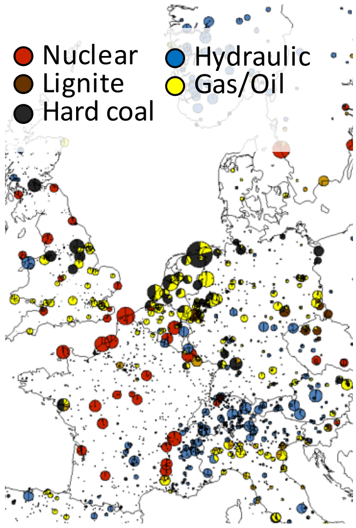


Figure 62: generation database (IAEW)

This data is used to determine the theoretical maximum theoretical aFRR capability per LFC Block for all units in operation in 2014.The theoretical aFRR capability of Nuclear Power Plants (NPP) is included as far as this capability is not subject to safety, environmental, nuclear authority or other non-technical regulation/legislation that likely prevents for NPP to provide aFRR even if:

- NPP is currently not equipped with control systems or other systems that prevent for providing aFRR, but can be equipped with the missing systems;
- NPP units need to go through the TSO's prequalification process for providing aFRR or more aFRR than prequalified today;
- Market considerations make it unlikely that NPP will provide aFRR in the country.

[31] The power plant information system KISSY of VGB contains availability data and performance indicators from international power plant providers of a total capacity (gross) of approx. 270 GW. Evaluated period from 2002 to 2011.
[32] Public data on power plant availability according to EU regulation no. 1227/2011 for different time periods between 2005 and 2014.

Parameters and Methodology

The resulting theoretical aFRR capability does not necessarily match prequalified volume and is dependent on the operation point of the unit. This means explicitly:

Result is maximum theoretical aFRR capability of a unit to provide upward aFRR at operating point $\boldsymbol{P_{min}}$ or downward aFRR at operating point $\boldsymbol{P_{max}}$[33].

The quantitative analysis does not take into account existing FCR requirements. Hence no simultaneous delivery of FCR on the units is assumed. Moreover, the power plants have to be in operation and spinning, this means the maximum theoretical aFRR capability $\Delta P_{aFRR,max}$ is determined through $P_{max} - P_{min}$. Aside from this, the capability is further reduced by a technical availability rate based on historic statistical data dependent on generation class and country. To insure a certain ability for load-following operation, no units with commissioning date (and without revision) before 1985 are taken into account.[34] The theoretical aFRR capability then, is a function of FAT which increases according to ramp rate which refers to P_{max}. For better understanding, an example calculation is given in the following. Besides that, the installed capacities of renewable energy sources is given, as their technical capability is dependent on the availability of wind or solar energy.

Real/Actual
aFRR capacity ≠ **Technical/Theoretical**
aFRR capability

Could be understand as:

- Prequalified aFRR volume
- aFRR capacity that is or will be offered to the market

Is meant as total maximum capability per unit, i.e.:

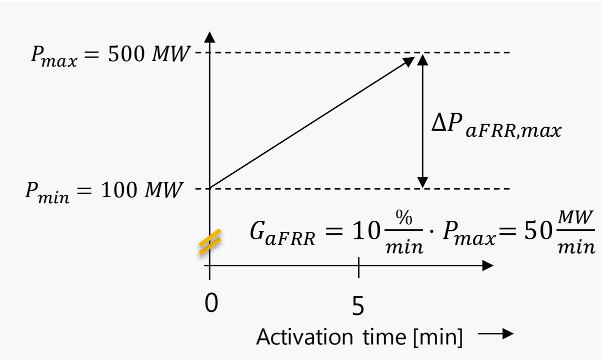
- Not necessarily economical
- Not necessarily equipped with a LF controller yet
- No consideration of FCR
- Optimal operation point of each unit for providing aFRR

→ Relative change of aFRR capability (depending on FAT) as an indicator for change of liquidity

[33] This means a non-symmetric capability.
[34] Not applied for Hydro, Biomass and oil-/natural gas-fired gas turbines due to flexibility.

Example Calculation

An exemplary power plant with a $P_{max} = 500\ MW$, $P_{min} = 100\ MW$ and a ramp rate of $10\frac{\%}{min}$ which is operated on either the rated capacity P_{max} or the minimum stable capacity P_{min}.



FAT	aFRR capability
5 min	250 MW
10 min	400 MW
15 min	400 MW

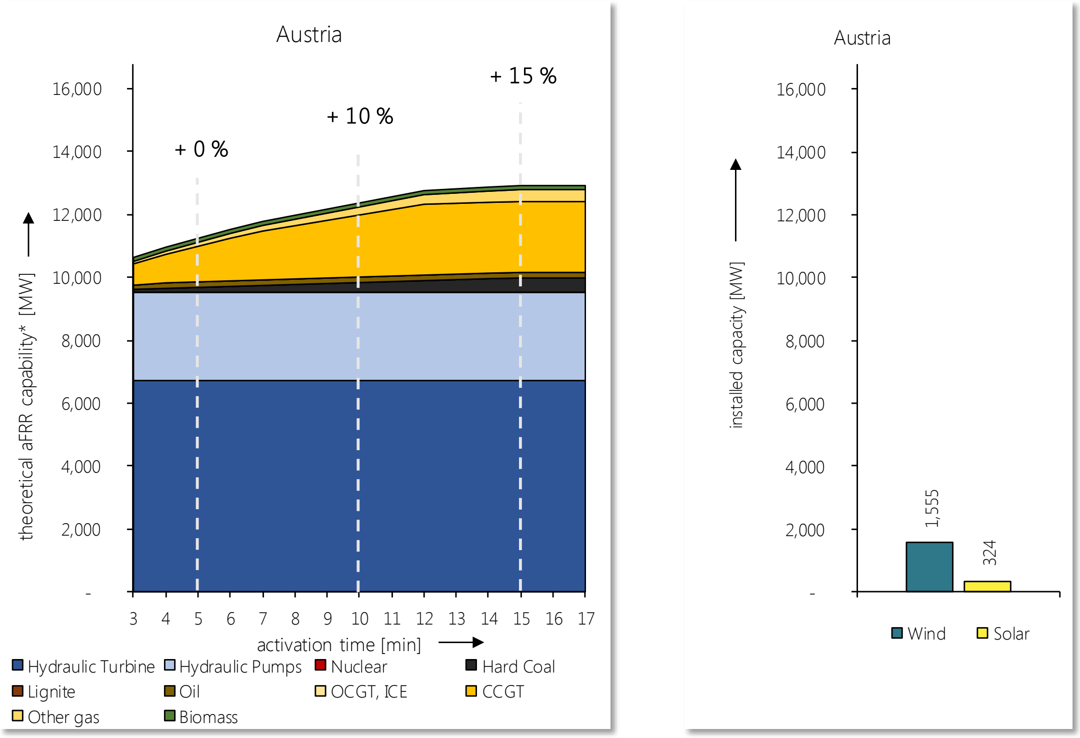
$\Delta P_{aFRR,max}$ is reached 10 minutes after receiving the LFC signal.

The ramp rate of $10\frac{\%}{min}$ leads to possible change in power output of $50\frac{MW}{min}$. This means that FAT of 3 minutes would lead to a theoretical aFRR capability of 150 MW, or with a FAT of 15 minutes to a capability of 400 MW.

Conclusions

The calculated figures with the methodology above lead to high potential of theoretical aFRR capability per LFC Block which cannot be directly transferred into prequalified volumes. The results rather lead to an indication whether a change of the FAT would have a considerable impact on the available aFRR capacity. The vertical dashed lines at the FAT of 5, 10 and 15 minutes indicates the change of capability referring to the current FAT in the respected LFC Block. In case of no aFRR activation scheme, no percentage is given.

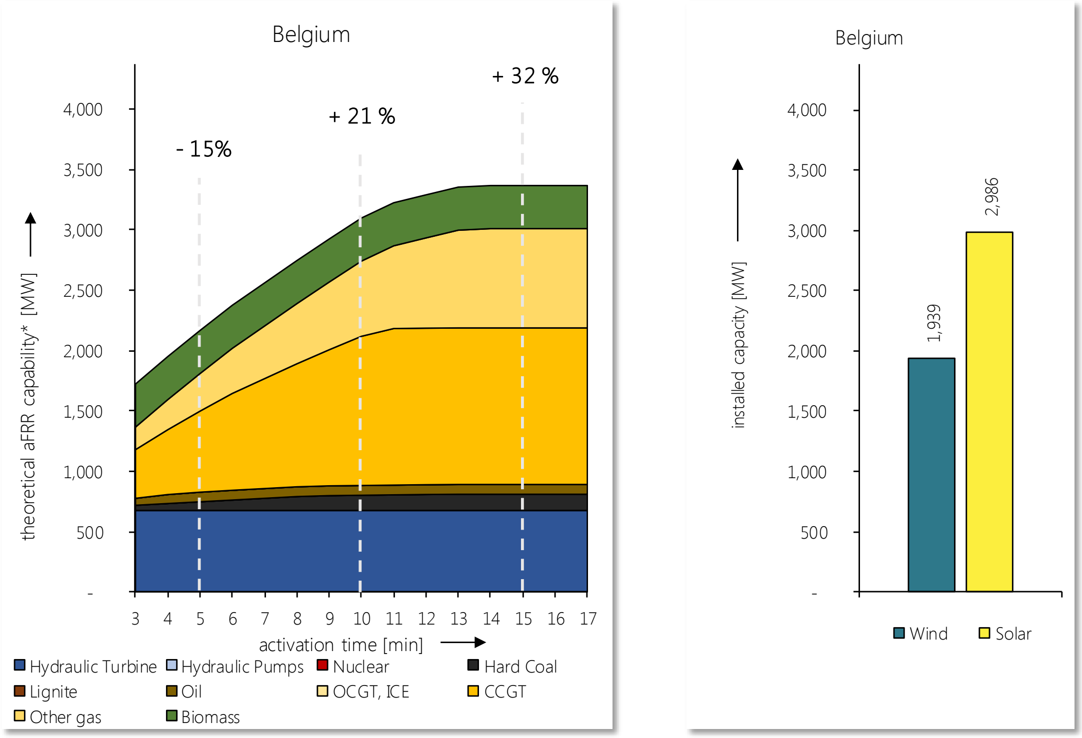
theoretical aFRR capability - Austria



*upward or/and downward, not symmetric

Figure 63: theoretical aFRR capability in Austria

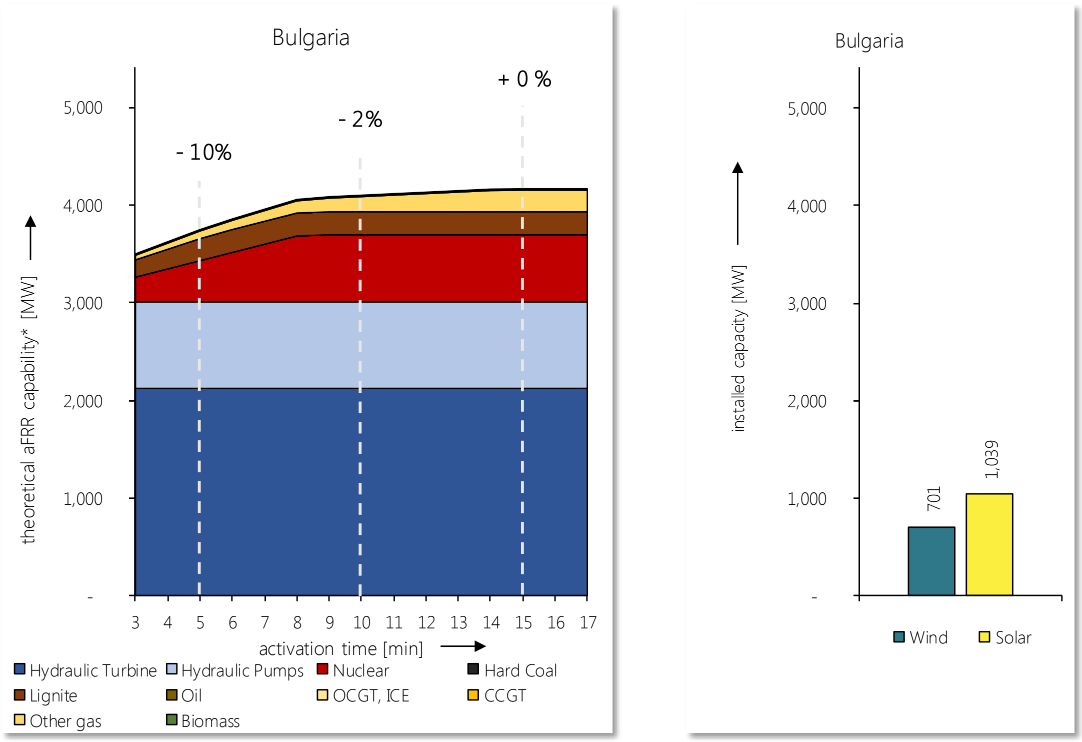
theoretical aFRR capability - Belgium



*upward or/and downward, not symmetric

Figure 64: theoretical aFRR capability in Belgium

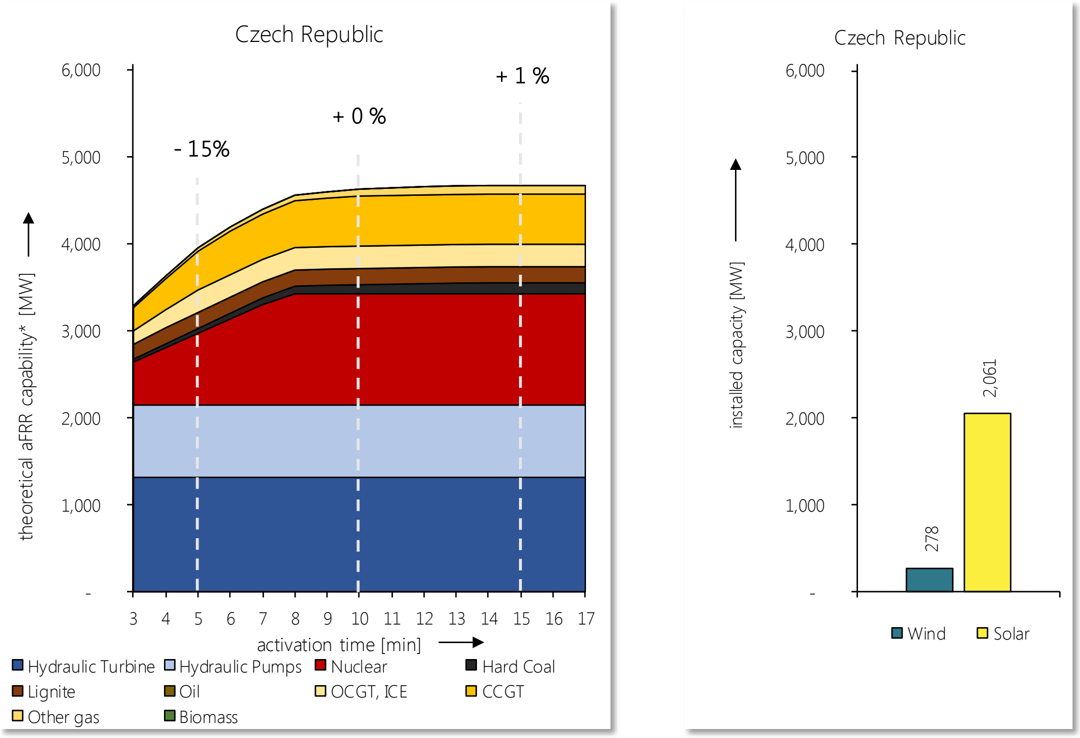
theoretical aFRR capability - Bulgaria



*upward or/and downward, not symmetric

Figure 65: theoretical aFRR capability in Bulgaria

theoretical aFRR capability - Czech Republic



*upward or/and downward, not symmetric

Figure 66: theoretical aFRR capability in Czech Republic

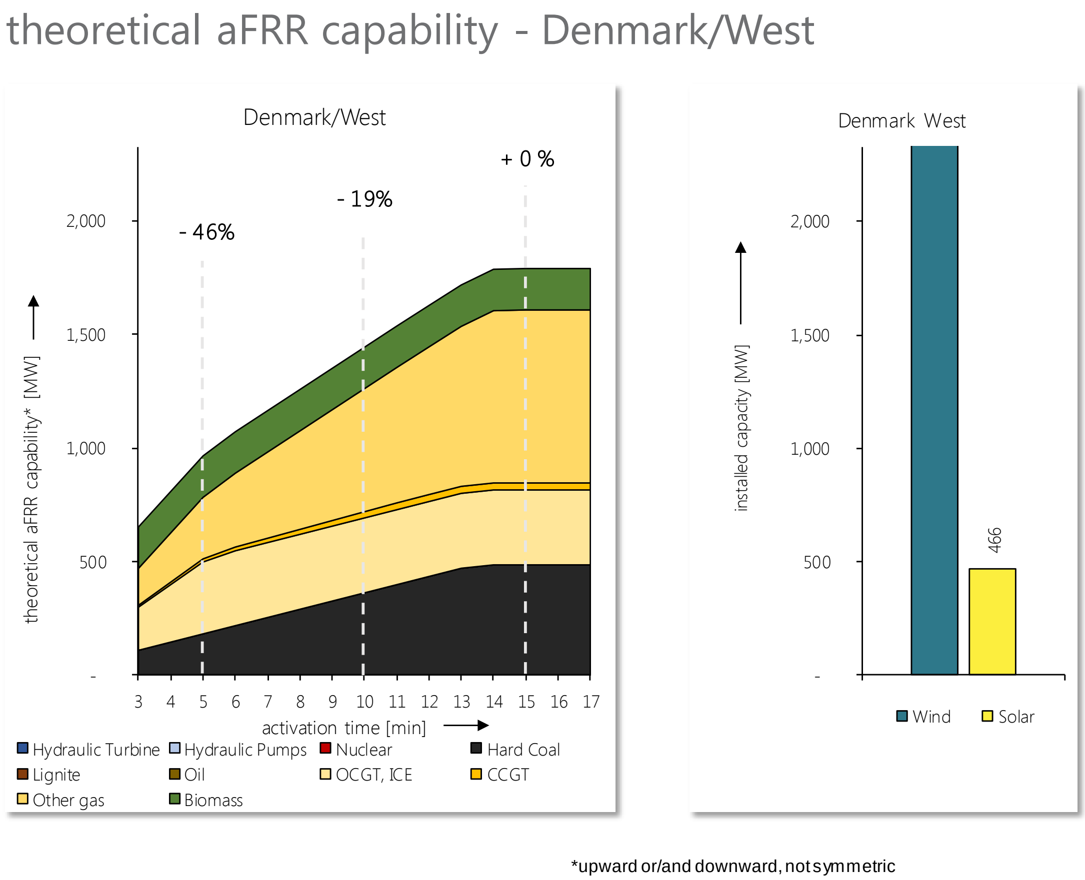
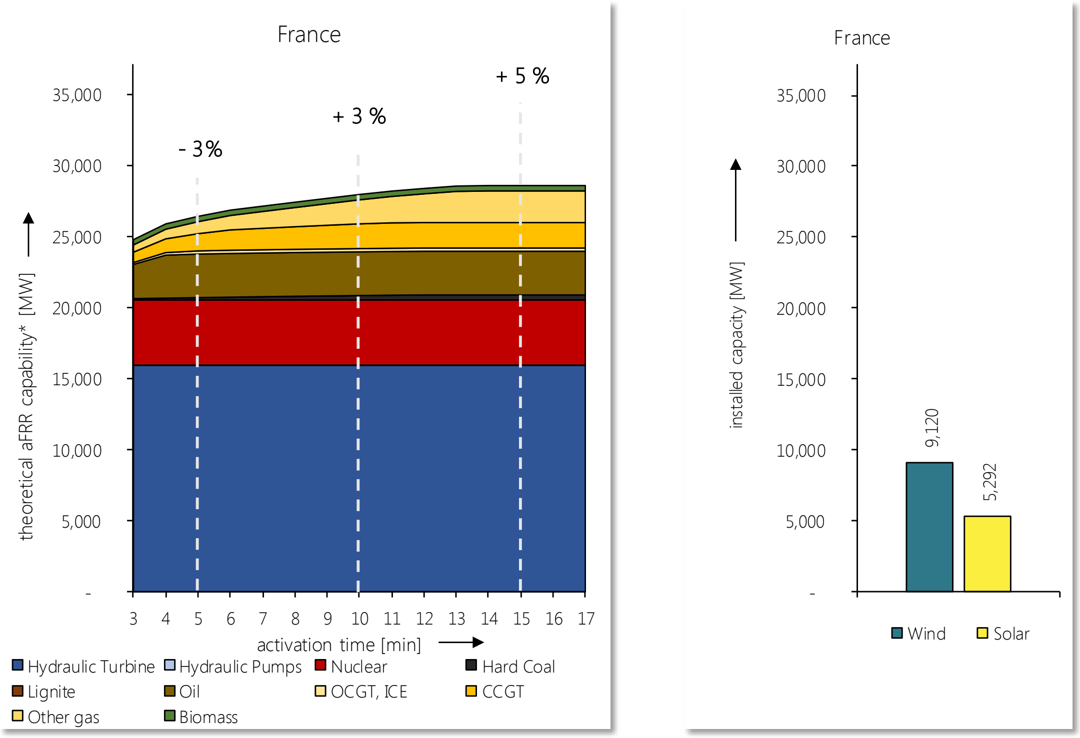


Figure 67: theoretical aFRR capability in Denmark/West

theoretical aFRR capability - France



*upward or/and downward, not symmetric

Figure 68: theoretical aFRR capability in France

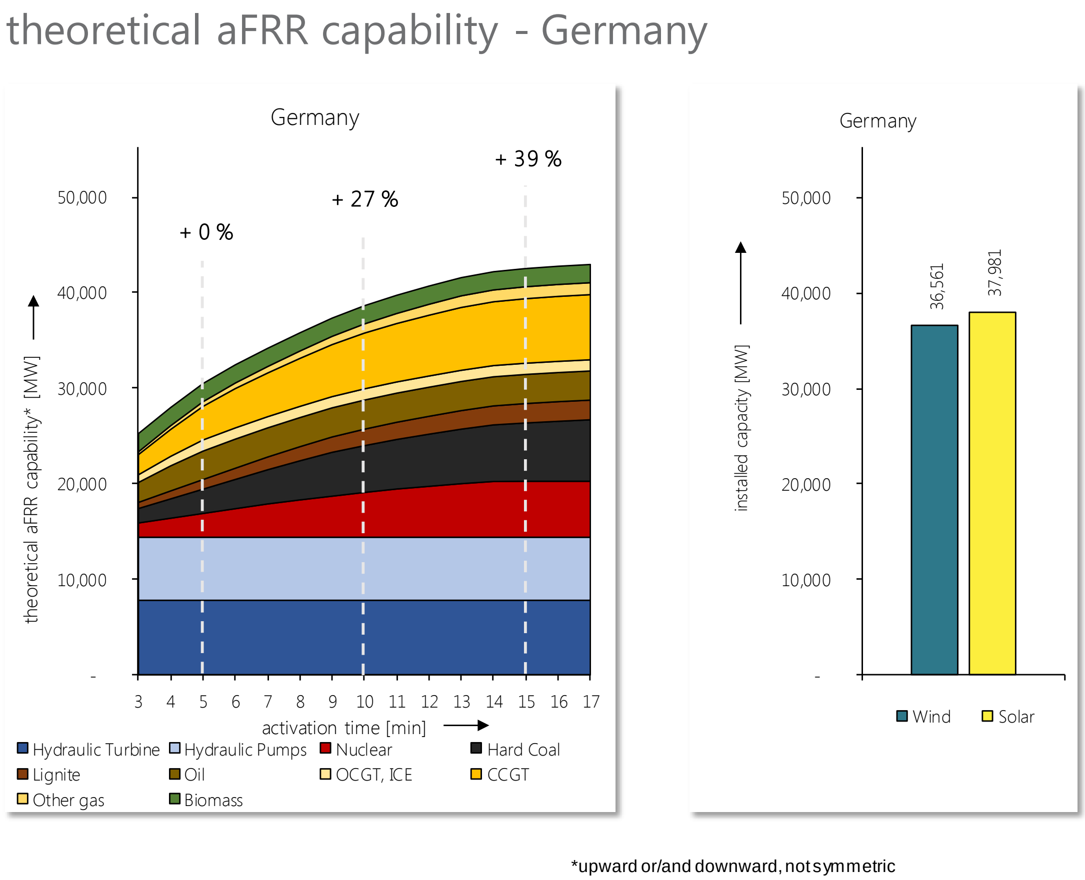
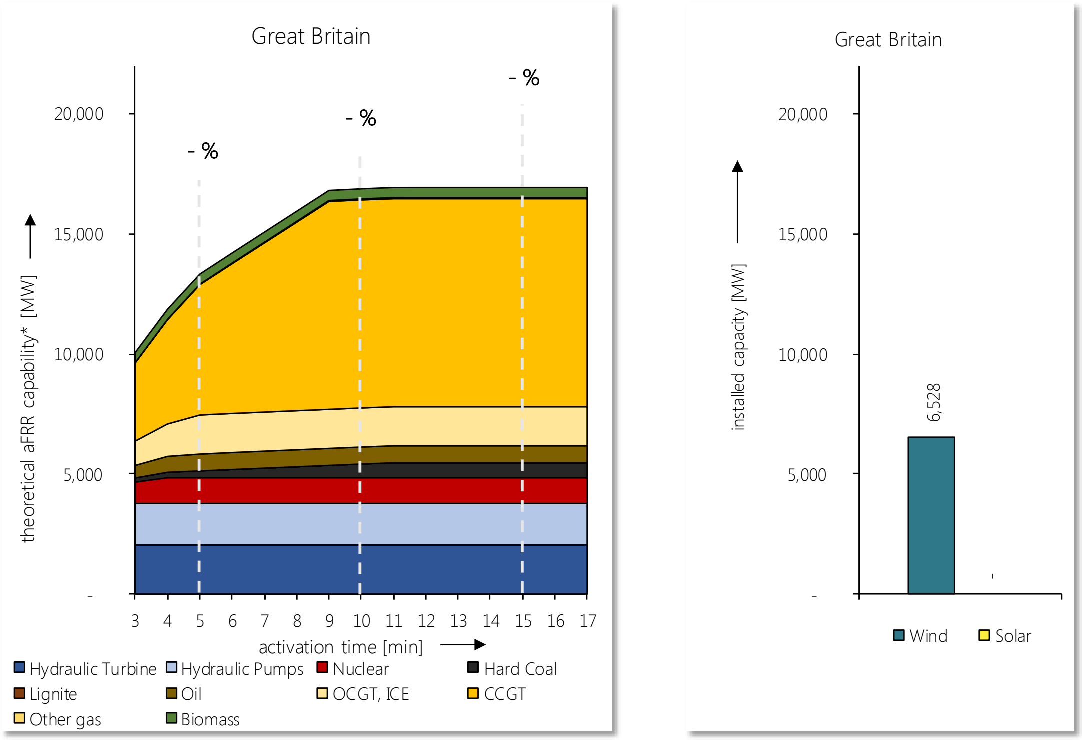


Figure 69: theoretical aFRR capability in Germany

theoretical aFRR capability - Great Britain



*upward or/and downward, not symmetric

Figure 70: theoretical aFRR capability in Great Britain

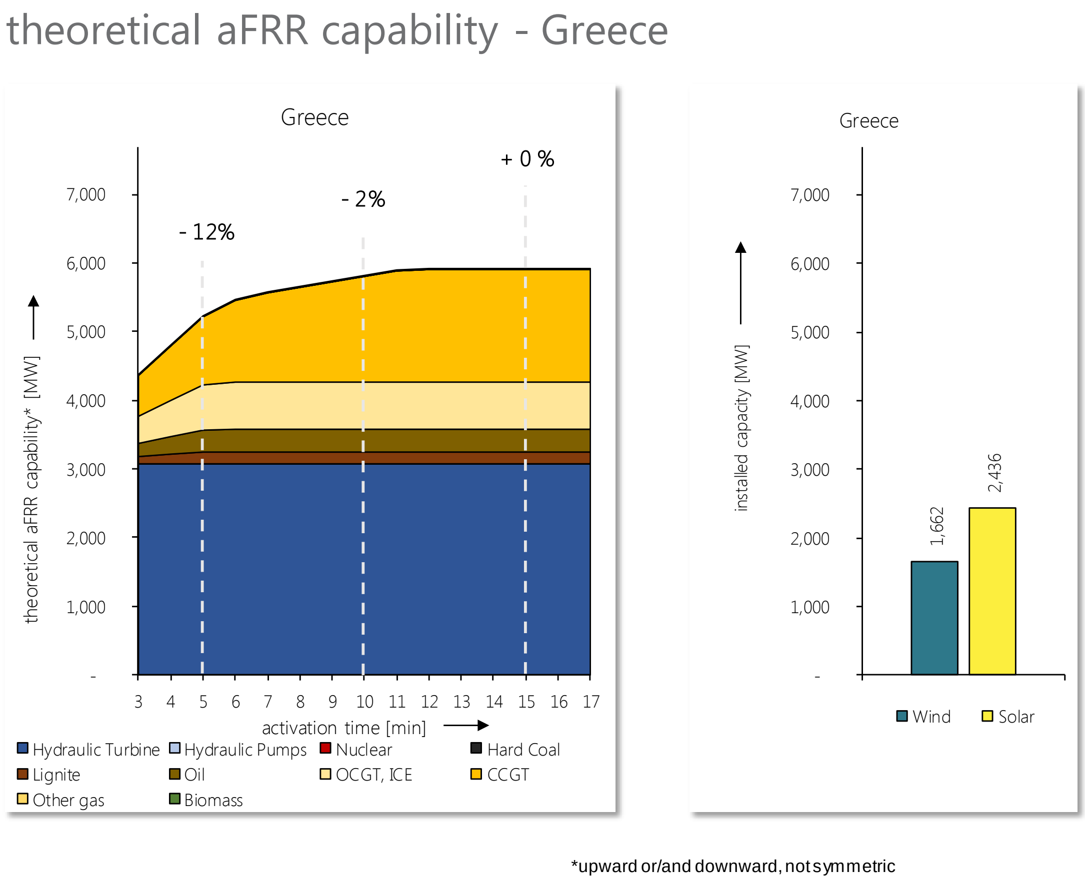
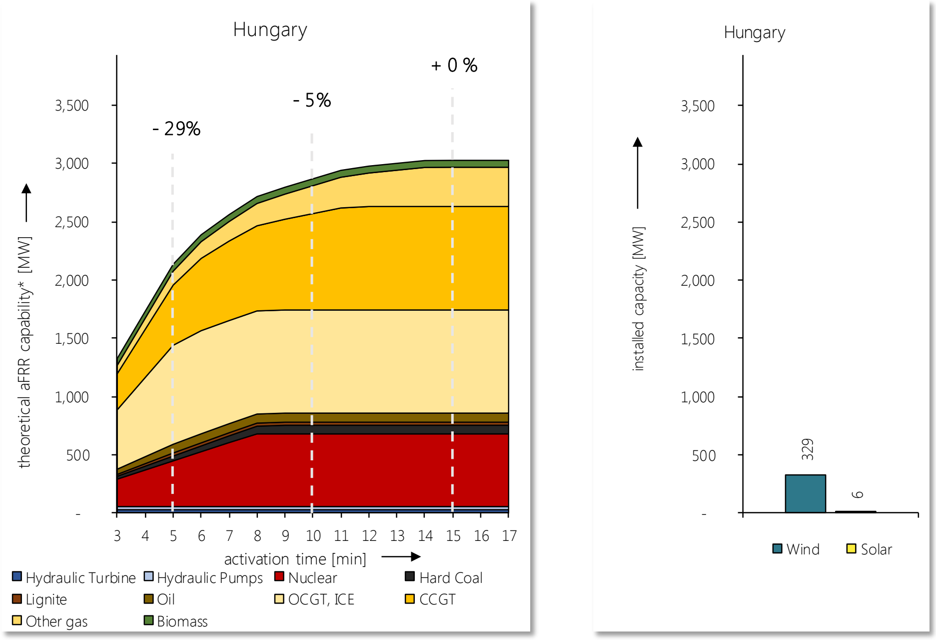


Figure 71: theoretical aFRR capability in Greece

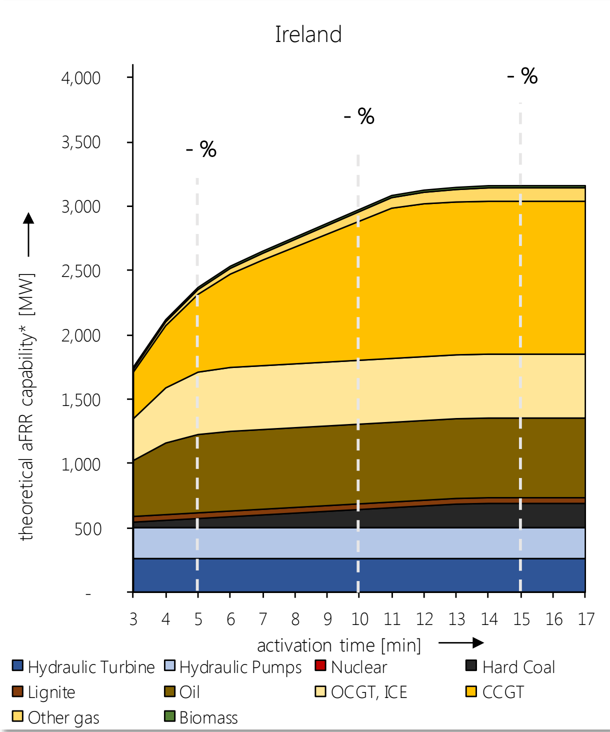
theoretical aFRR capability - Hungary

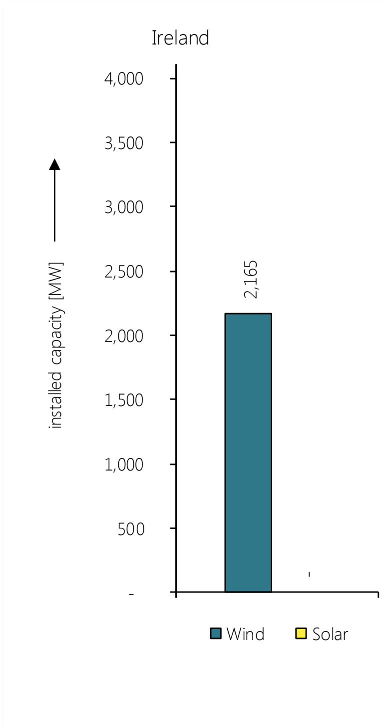


*upward or/and downward, not symmetric

Figure 72: theoretical aFRR capability in Hungary

theoretical aFRR capability - Ireland

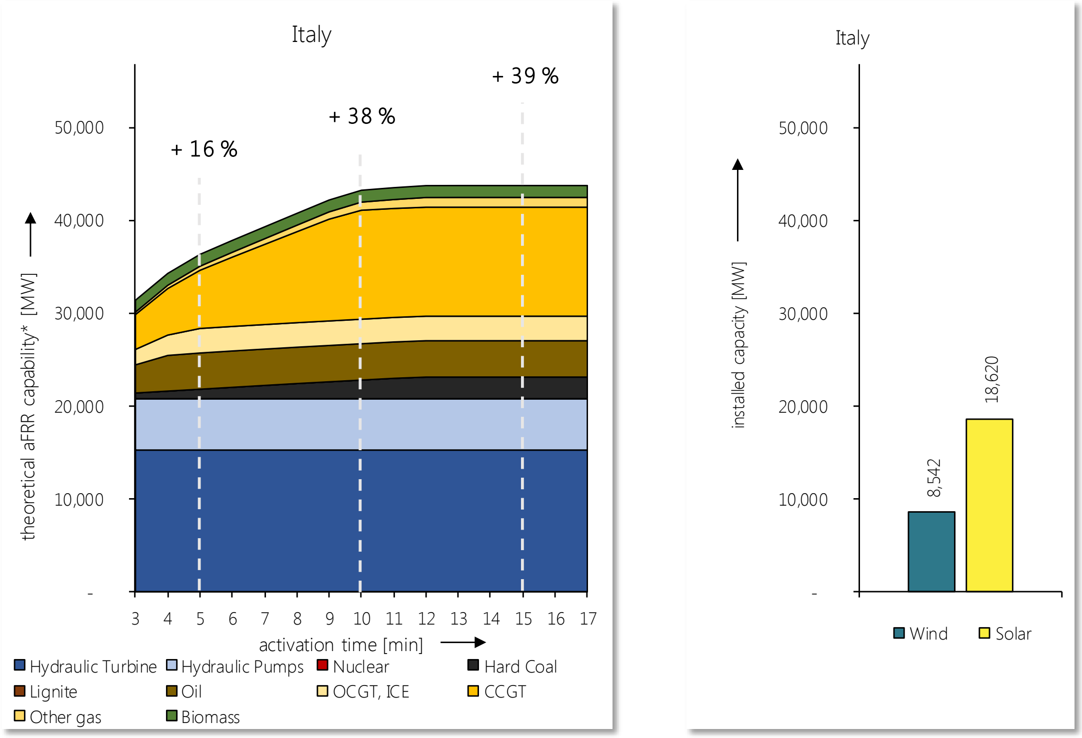




*upward or/and downward, not symmetric

Figure 73: theoretical aFRR capability in Ireland

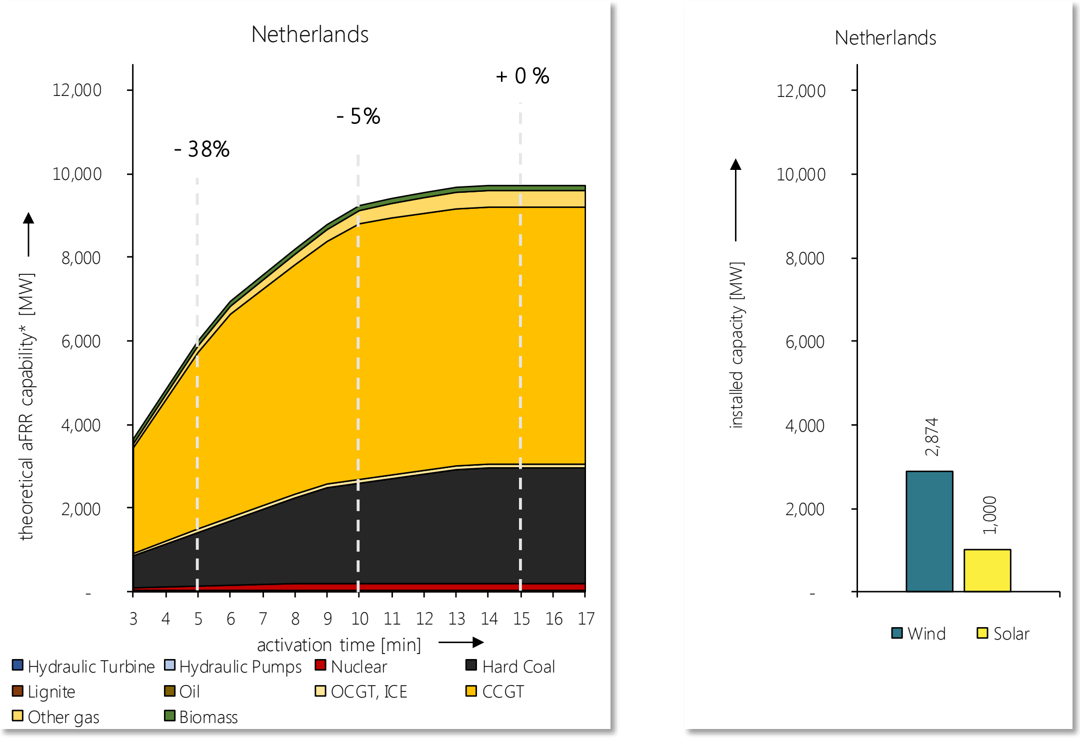
theoretical aFRR capability - Italy



*upward or/and downward, not symmetric

Figure 74: theoretical aFRR capability in Italy

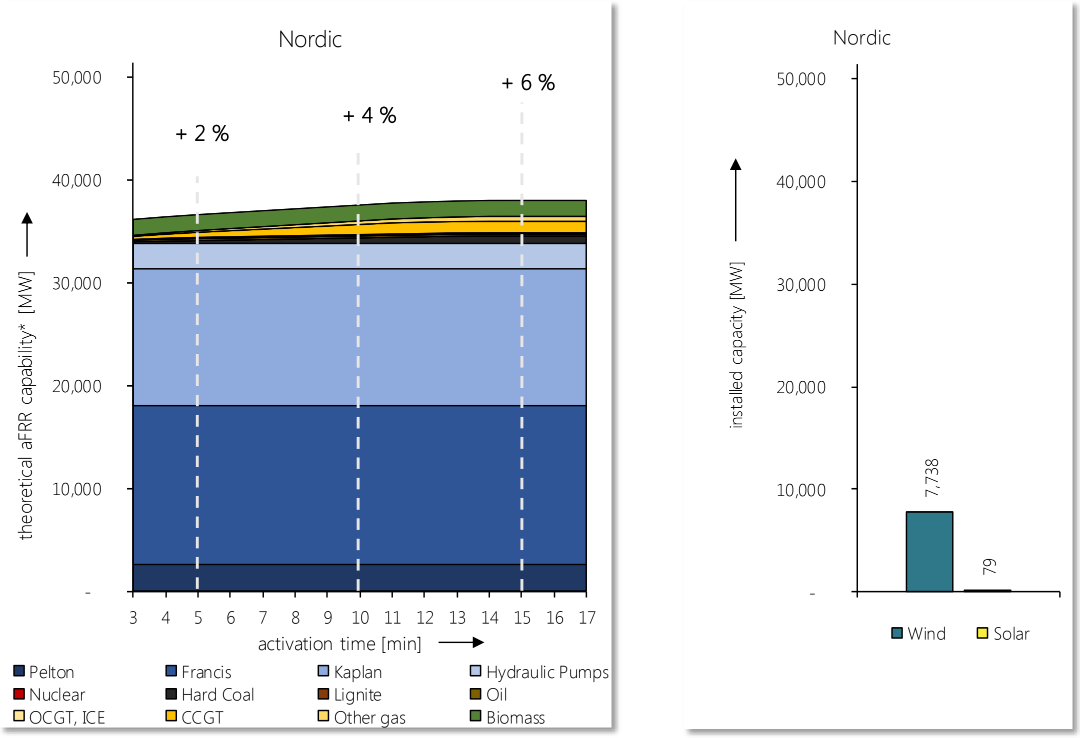
theoretical aFRR capability - Netherlands



*upward or/and downward, not symmetric

Figure 75: theoretical aFRR capability in the Netherlands

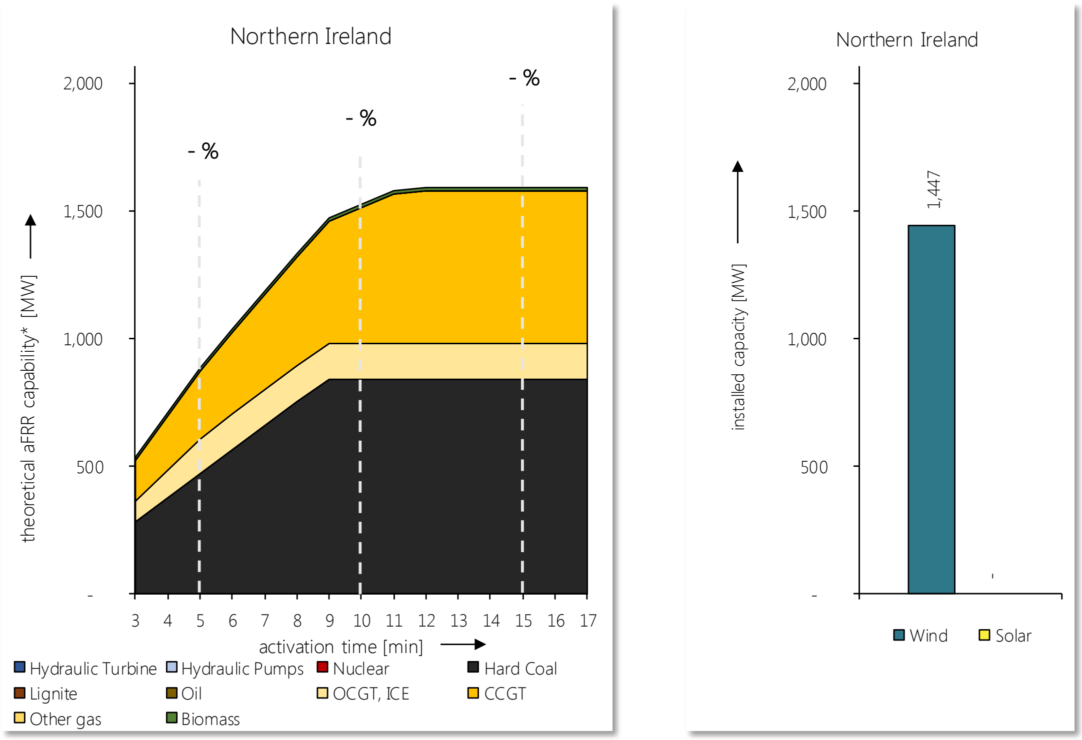
theoretical aFRR capability - Nordic



*upward or/and downward, not symmetric

Figure 76: theoretical aFRR capability in Nordic

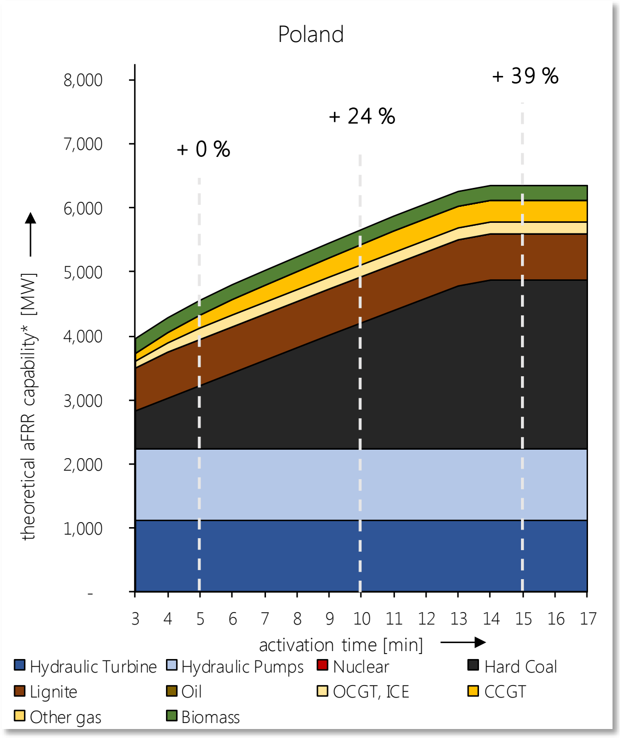
theoretical aFRR capability - Northern Ireland

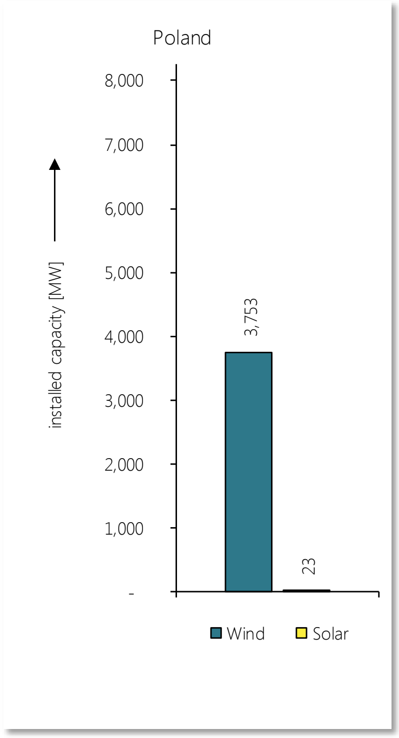


*upward or/and downward, not symmetric

Figure 77: theoretical aFRR capability in Northern Ireland

theoretical aFRR capability - Poland

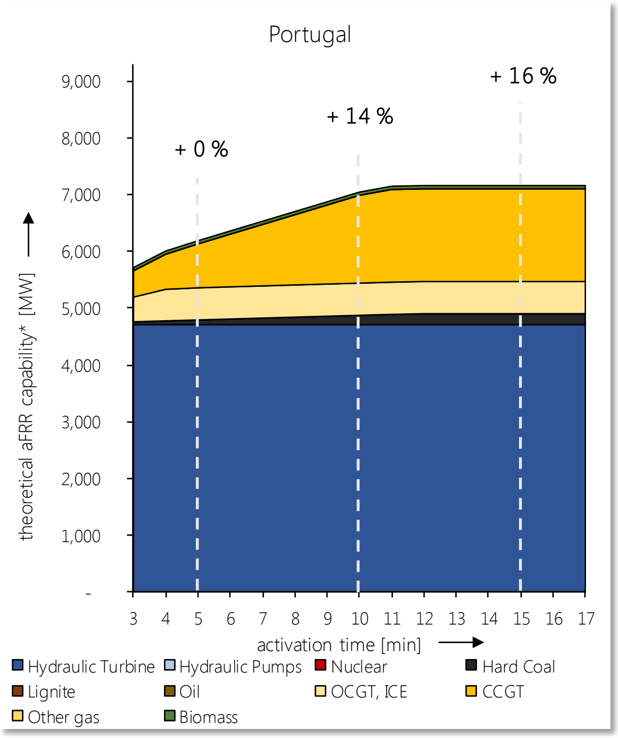


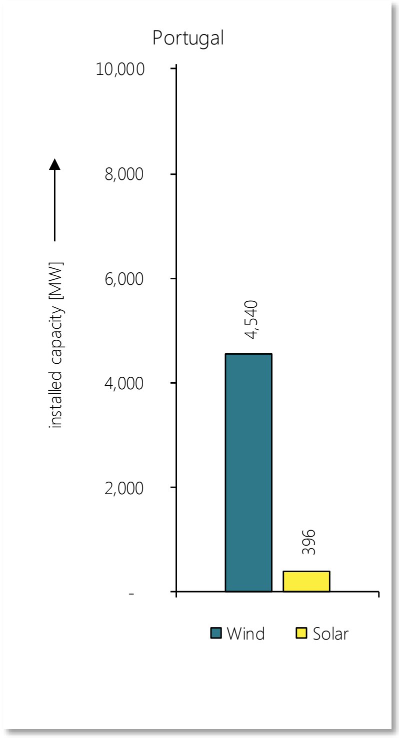


*upward or/and downward, not symmetric

Figure 78: theoretical aFRR capability in Poland

theoretical aFRR capability - Portugal

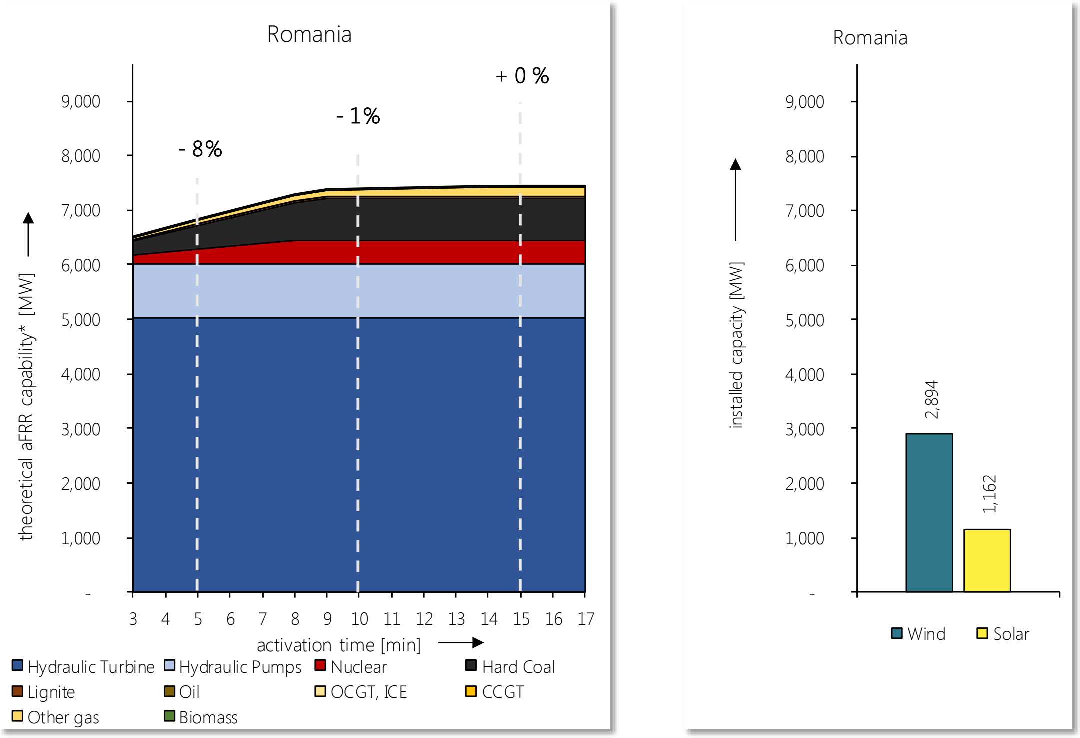




*upward or/and downward, not symmetric

Figure 79: theoretical aFRR capability in Portugal. At the moment there are no OCGT units in Portugal that provide aFRR by this technology.

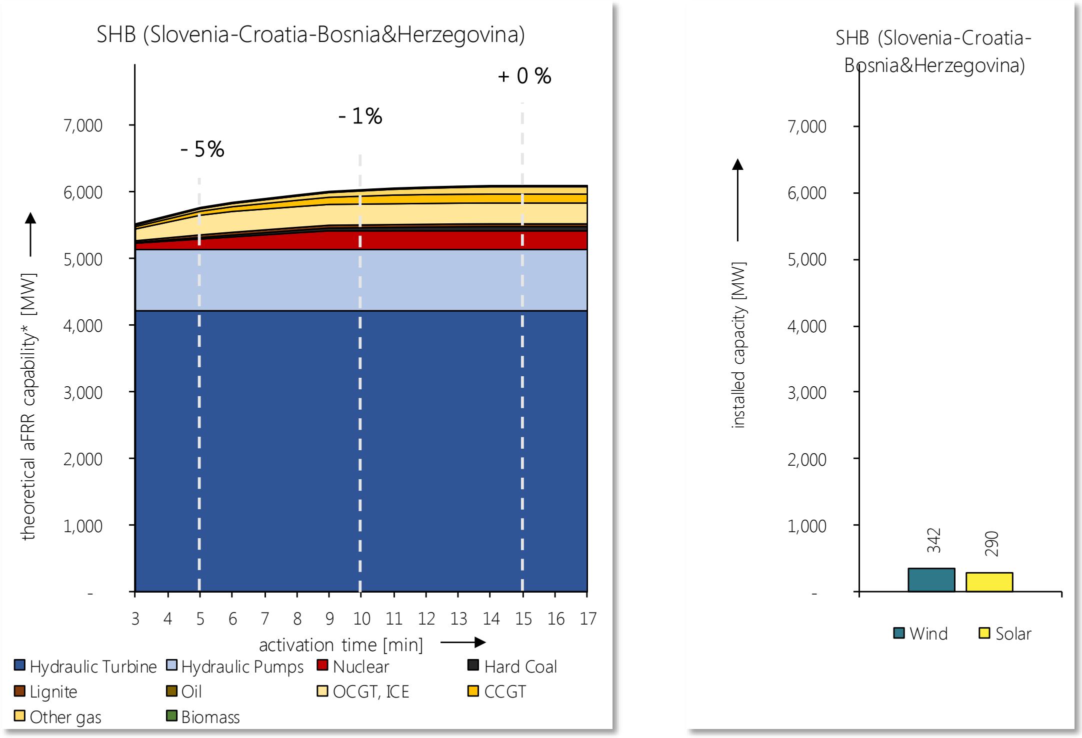
theoretical aFRR capability - Romania



*upward or/and downward, not symmetric

Figure 80: theoretical aFRR capability in Romania

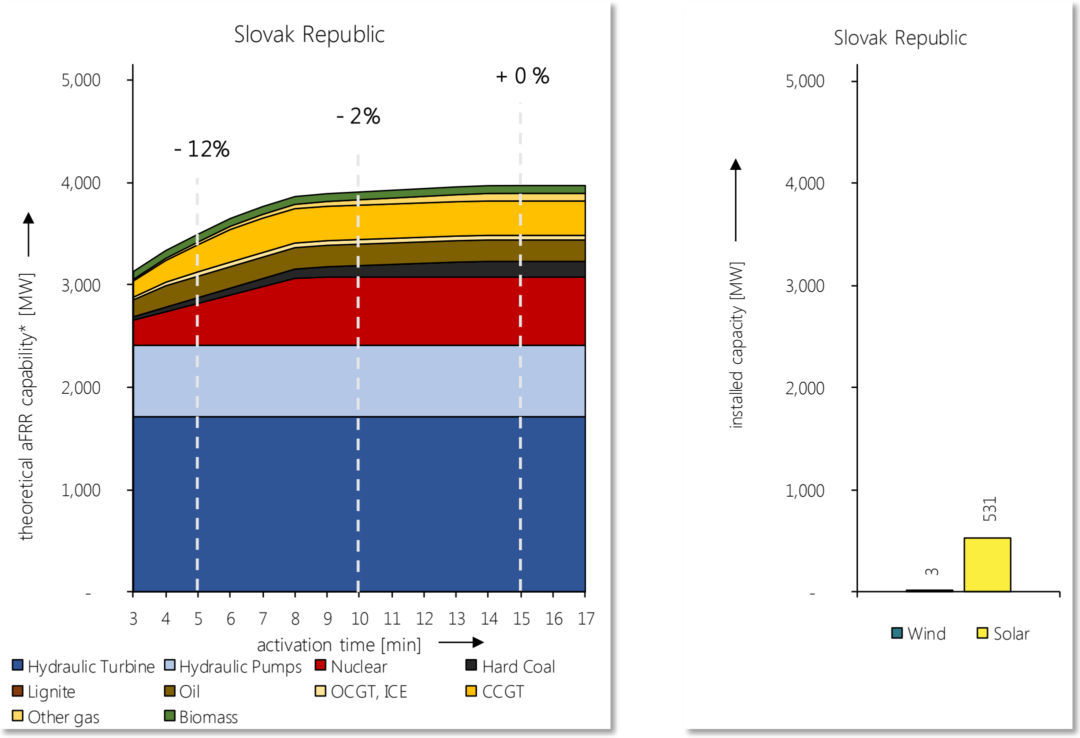
theoretical aFRR capability – SHB (Slovenia-Croatia-Bosnia&Herzegovina)



*upward or/and downward, not symmetric

Figure 81: theoretical aFRR capability in SHB

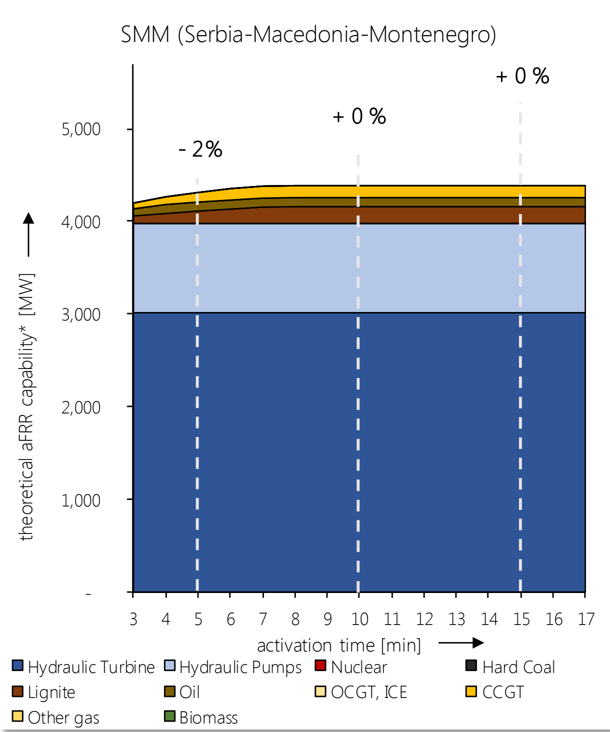
theoretical aFRR capability - Slovak Republic

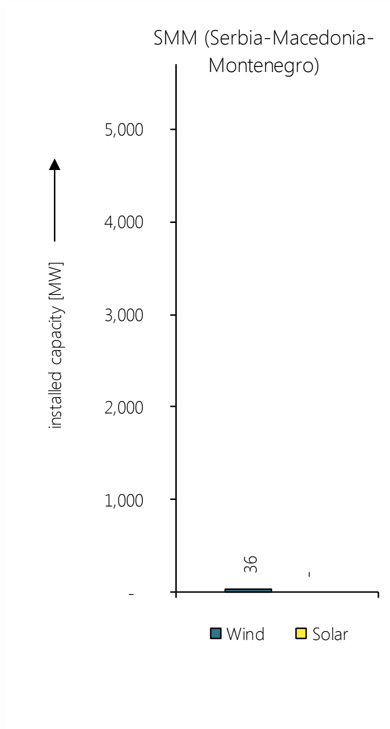


*upward or/and downward, not symmetric

Figure 82: theoretical aFRR capability in Slovak Republic

theoretical aFRR capability – SMM (Serbia-Macedonia-Montenegro)

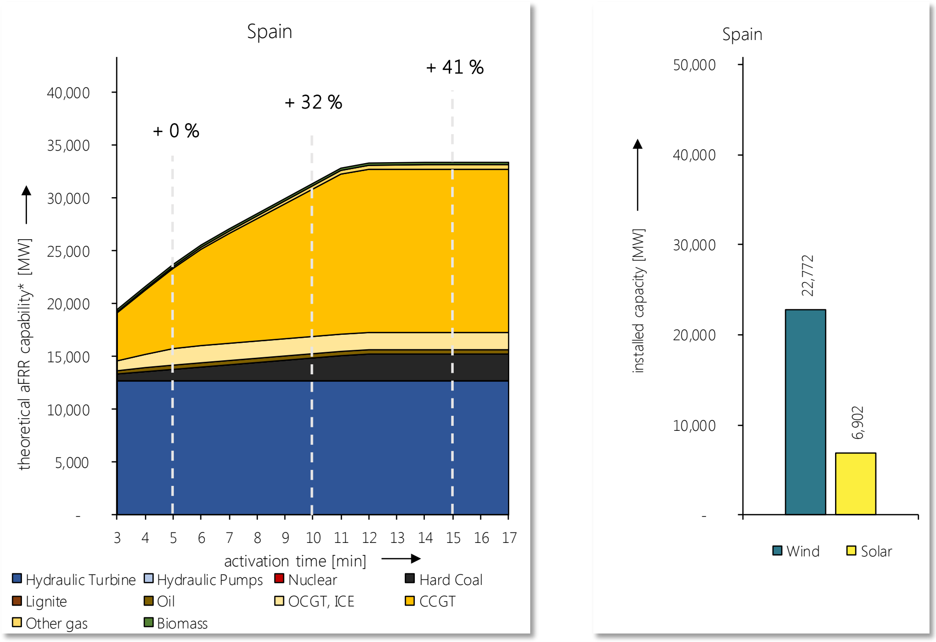




*upward or/and downward, not symmetric

Figure 83: theoretical aFRR capability in SMM

theoretical aFRR capability - Spain



*upward or/and downward, not symmetric

Figure 84: theoretical aFRR capability in Spain

theoretical aFRR capability - Switzerland

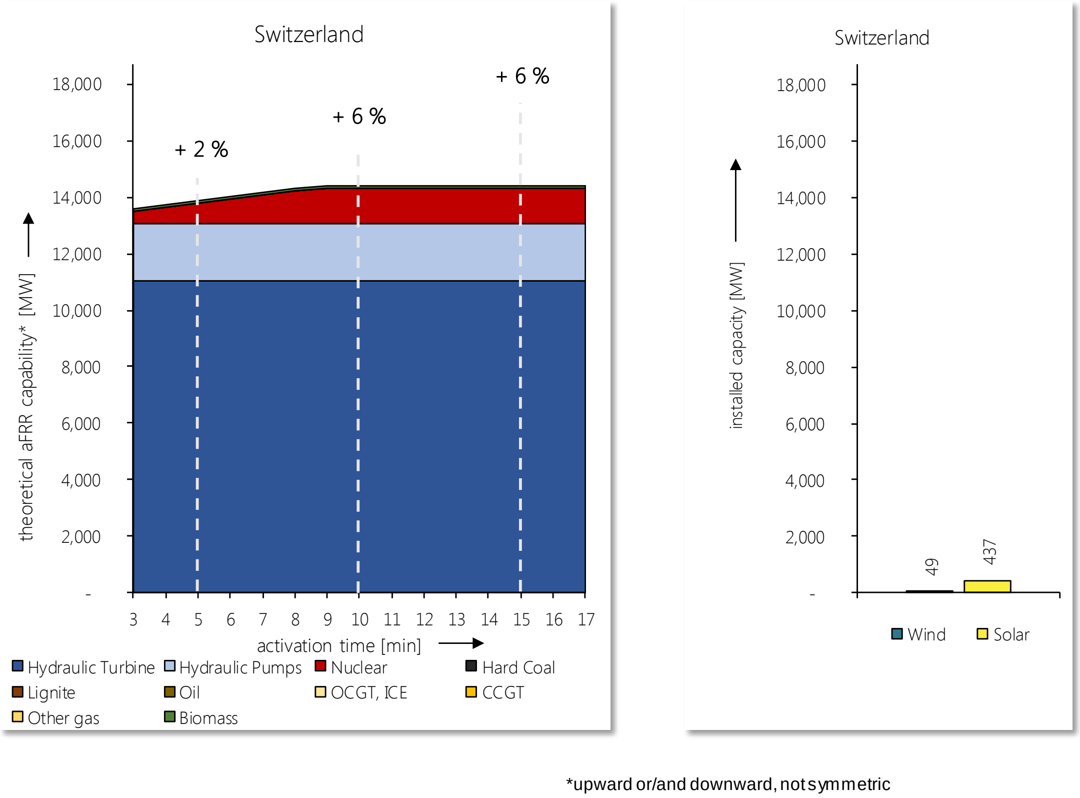


Figure 85: theoretical aFRR capability in Switzerland

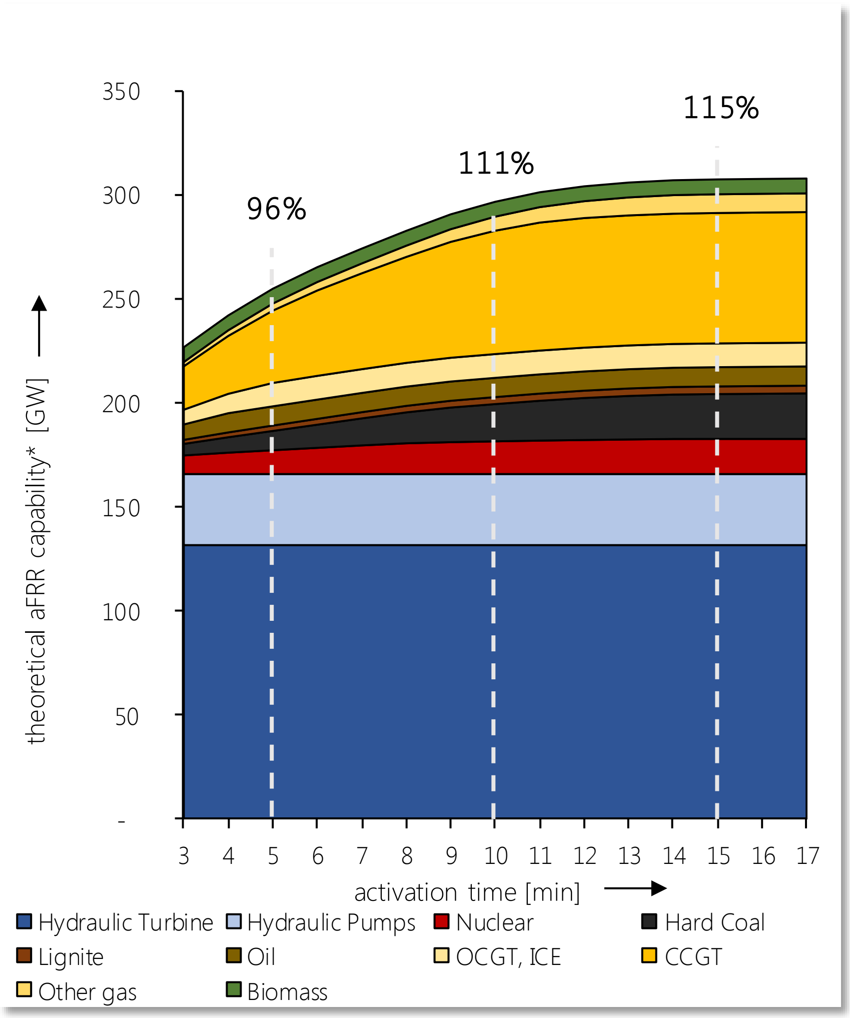


Figure 86: European aFRR capability - percentage referring to sum of all capabilities at existing FATs

D. Glossary and Abbreviations

Term	Abbreviation	Definition
Area Control Error	ACE	The Area Control Error is the instantaneous difference between the actual and the reference value for the power interchange of a control area, taking into account the effect of the frequency bias for that control area according to the network power frequency characteristic of that control area, and of the overall frequency deviation.
Automatic FRR	aFRR	Automatic FRR means FRR that can be activated by an automatic control device.
Automatic FRR Activation Delay		The period of time between the setting of a new setpoint value by the frequency restoration controller and the start of physical Automatic FRR delivery.
Automatic FRR Full Activation Time	FAT	Time period between the setting of a new setpoint value by the frequency restoration controller and the corresponding activation or deactivation of Automatic FRR.
Balance Responsible Party		Market-related entity or its chosen representative responsible for its Imbalances.
Balance Service Provider	BSP	Market Participant providing Balancing Services to its Connecting TSO, or in case of the TSO-BSP model, to its Contracting TSO.
Balancing Service Provider	BSP	A Market Participant providing Balancing Services to its Connecting TSO, or in case of the TSO-BSP Model, to its Contracting TSO.
Combined Cycle Gas Turbines	CCGT	
Continental Europe	CE	
Dimensioning Incident		The highest expected instantaneously occurring Active Power Imbalance within a LFC Block in both positive and negative direction.
European Network of Transmission System Operators for Electricity	ENTSO-E	
Frequency Containment Reserves	FCR	
Frequency Restoration Control Error	FRCE	The instantaneous difference between the actual and the reference value for the power interchange of a control area, taking into account the effect of the frequency bias for that control area according to the network power frequency characteristic of that control area, and of the overall frequency deviation.
Frequency Restoration Reserves	FRR	The Active Power Reserves activated to restore System Frequency to the Nominal Frequency and for Synchronous Area consisting of more than one LFC Area power balance to the scheduled value.

Term	Abbreviation	Definition
FRR Delay Time		The period of time between the set point change from TSO and the commencement of FRR delivery.
Generating Unit		A generating unit is an indivisible set of installations which can generate electrical energy. The generating unit may for example be a thermal power unit, a single shaft combined-cycle plant, a single machine of a hydro-electric power plant, a wind turbine, a fuel cell stack, or a solar module. If there are more than one generating unit within a power generating facility that cannot be operated independently from each other than each of the combinations of these units shall be considered as one generating unit.
Imbalance		Energy volume calculated for a Balance Responsible Party and representing the difference between the Allocated Volume attributed to that Balance Responsible Party, and the final Position of that Balance Responsible Party and any Imbalance Adjustment applied to that Balance Responsible Party, within a given Imbalance Settlement Period.
Instantaneous FRCE Data		A set of data of the FRCE for a LFC Block with a measurement period equal to or shorter than 10 seconds used for System Frequency quality evaluation purposes.
LFC Area		
LFC Block		
Load frequency control	LFC	Control scheme created to maintain balance between generation and demand, to restore the frequency to its set point value in the synchronous area and, depending on the control structure in the synchronous area, to maintain the exchange power to its reference value.
Load-Frequency Controller	LF Controller	Automatic control device designed to reduce the Frequency Restoration Control Error (FRCE) to zero. Physically this is a process computer that is usually implemented in the TSOs control centre systems (SCADA/EMS). The LF Controller processes FRCE measurements every 4-10s and provides - in the same time cycle – automated instructions to aFRR providers that are connected by telecommunication connections.
Manual Frequency Restoration Reserves	mFRR	Manual FRR Full Activation Time means the time period between the set point change and the corresponding activation or deactivation of manual FRR.
Merit Order	MO	
Net imbalance		The resulting imbalance that remains after netting of all BRP imbalances, i.e. the absolute sum of all imbalances.
Network Code Load Frequency Control and Reserves	NC LFC&R	

Term	Abbreviation	Definition
Network Code on Electricity Balancing	NC EB	
Nuclear Power Plant	NPP	
Open Cycle Gas Turbines	OCGT	
Open Loop Area Control Error	ACE OL	The open loop ACE for a control area is an indicator of the total imbalance, and is the sum of the ACE for that control area and the activated reserves.
Open Loop Frequency Restoration Control Error	FRCE OL	The open loop FRCE for a control area is an indicator of the total imbalance, and is the sum of the FRCE for that control area and the activated reserves.
Prequalification		The process to verify the compliance of a Reserve Providing Unit or a Reserve Providing Group of kind FCR, FRR or RR with the requirements set by the TSO according to principles stipulated in this code.
Replacement Reserves	RR	The reserves used to restore/support the required level of FRR to be prepared for additional system imbalances. This category includes operating reserves with activation time from Time to Restore Frequency up to hours.
Set point		A target value for any parameter typically used in control schemes.
Synchronous area	SA	A set of synchronously interconnected elements that have no synchronous interconnections with other areas. Within a synchronous area the system frequency is common on a steady state.
System frequency		The system frequency is the frequency in a synchronous area.
Time to restore frequency		The maximum expected time after the occurrence of an imbalance smaller than or equal to the Reference Incident in which the System Frequency returns to the Frequency Restoration Range for Synchronous Areas with only one LFC Area; for Synchronous Areas with more than one LFC Area the Time to Restore Frequency is the maximum expected time after the occurrence of an imbalance of an LFC Area within which the imbalance is compensated.
Transmission System Operator	TSO	

E. List of Figures

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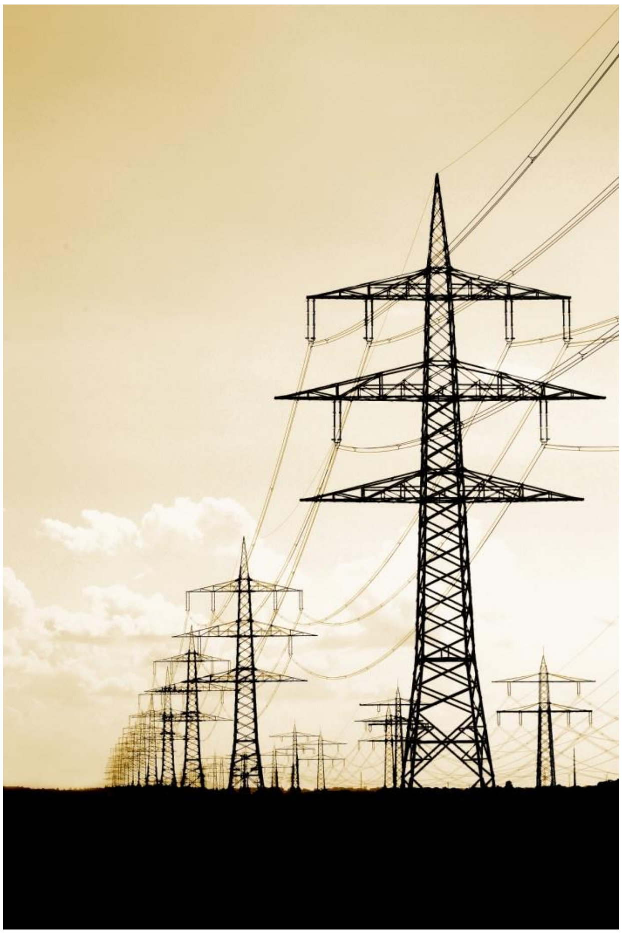

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