Impact of merit order activation of automatic Frequency Restoration Reserves and harmonised Full Activation times

On behalf of ENTSO-E

23 December 2015

Version: 0.1 (draft for review by ENTSO-E)

THIS DOCUMENT INCLUDES PARTS OF **Version: 0.1** (draft for review by ENTSO-E) ***THAT HAVE BEEN RELEASED BY ENTSO-E FOR THE BSG MEETING ON 15 JANUARY 2016***

E-Bridge
competence in energy

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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 WG AS SG5 (hereafter: 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 automatic Frequency Restoration Reserves (aFRR). 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. 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 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 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 16 LFC Blocks/Areas using high resolution (≤10s) FRCE data and aFRR activation data for the entire months of February and June 2015.

[for the BSG meeting on 15 January 2016, simulation results and discussion have been deleted from version 0.1]

aFRR Full Activation Time

We compared the aFRR Full Activation Time (FAT), which is defined as the period between setting of a new setpoint value by the LF Controller and the corresponding activation or deactivation of aFRR. Throughout Europe, the FAT ranges from 2 to 15 minutes. Harmonising the FAT in Europe may have two effects. Firstly, it may effect 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 larger aFRR volumes than for a larger FAT. Both effects are discussed below.

We performed similar simulations as described above for 16 LFC Blocks/Areas for the entire months of February and June 2015 for a FAT of 5, 7.5, 10 and 15 minutes.

[for the BSG meeting on 15 January 2016, simulation results and discussion have been deleted from version 0.1]

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 technical aFRR capability of hydro and thermal power plant to provide aFRR for different FATs throughout Europe. We define technical aFRR capability of a unit as the maximum aFRR capacity that can be provided from the most optimal setpoints for aFRR: upward aFRR at operating point P_{min} or downward aFRR at operating point P_{max}. *We note that the technical 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 technical 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.

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 following functions:

a) Imbalance Netting Process Function;
b) Capacity Procurement Optimisation Function;
c) Transfer of Balancing Capacity Function; and
d) Activation Optimisation Function.

For this study, only (b) and (d) are in scope. ENTSO-E WG AS SG5 (hereafter: ENTSO-E) concluded[1] that the current implementation of automatic Frequency Restoration Reserves (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[1]:

- *Overview of technical differences* in the implementation of aFRR products and aFRR activation schemes throughout Europe;
- *Quantitative* understanding 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).

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

- *Quantitative* understanding of the impact of aFRR response requirements (FAT) on the *technical aFRR capability to provide aFRR bids* for each LFC Block.

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.*

This study addresses selected topics related to aFRR. These were selected by ENTSO-E and are listed 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*[2].
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 technical 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 technical aFRR capability, quality etc.*

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.

[2] 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. We start in section 2.1 with a description of aFRR.

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 back to the target frequency, in Europe usually 50.00Hz.

The Network Code on Load-Frequency Control and Reserves[3] (NC LFC&R) defines FRR as 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'*. The NC LFC&R further distinguishes two types of FRR: *automatic* FRR (aFRR) and *manual* FRR (mFRR). Both types of FRR are used for restoring the power balance and consequently the system frequency. At the same time FRR replaces the activation of FCR.

This report focuses on automatic Frequency Restoration Reserves (aFRR), defined by the LFC&R 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 telecommunication connections.

There are four main areas in the Frequency Restoration processes that contribute to the FRCE quality. These are:

1) the aFRR Full Activation Time (FAT);
2) the LF Controller set-up and settings;
3) the selection of the participating aFRR energy bids and the distribution of the total required aFRR energy over the selected bids (aFRR activation scheme); and
4) the feedback of an *expected* aFRR activation into the LF controller.

Where 1) FAT and 3) activation schemes form the focus of this study, their impact on the regulation quality may highly depend on 2) LF controller settings and 4) feedback. In order to keep these effects

[3] Glossary and article 34 of Network Code on Load-Frequency Control and Reserves (NC LFC&R), 28 June 2013.

out, we have kept 2) and 4) in all quantitative analyses as they are in the existing Frequency Restoration Processes.

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.

2.2. European synchronous areas applying aFRR

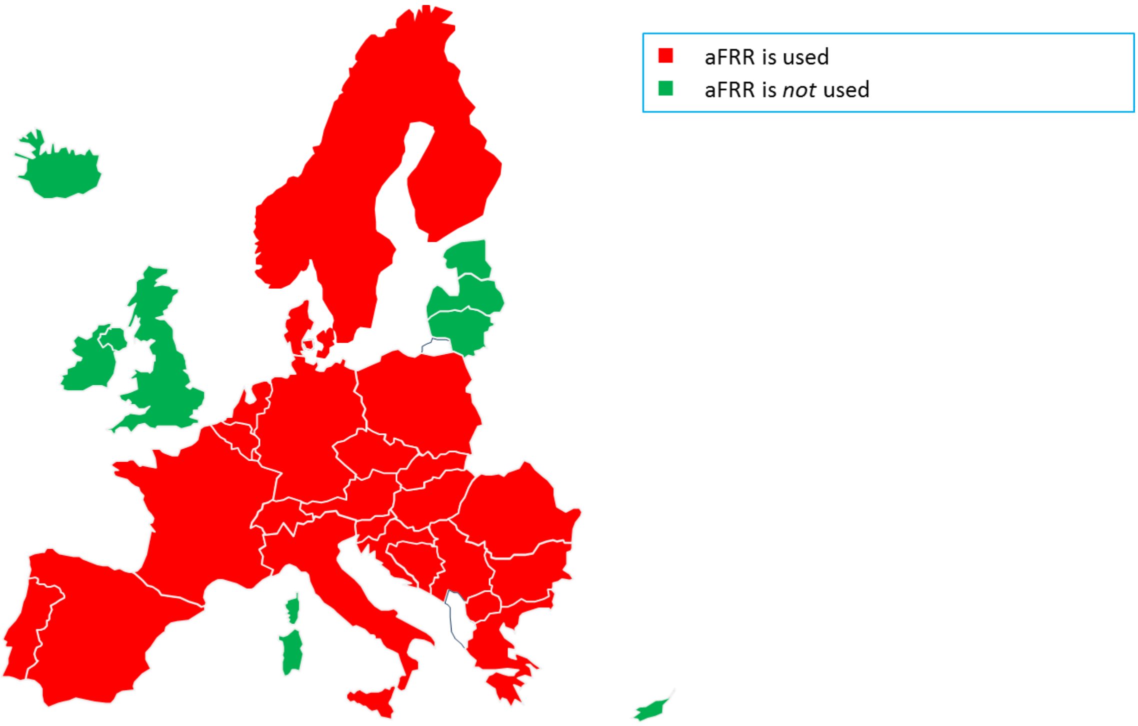


Figure 1: Overview of ENTSO-E members that apply automatic Frequency Restoration Reserves (aFRR)

Figure 1 shows the geographic area in which the TSOs operate an LF Controller. This area consists of two synchronous areas: the Continental European 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 in the Nordic system
LFC control mode is *'Tie-line Bias Control'*[4], 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'*[5], i.e. Nordic LF Controller directly impacts Nordic system frequency.
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.

2.3. Share of aFRR energy in total balancing

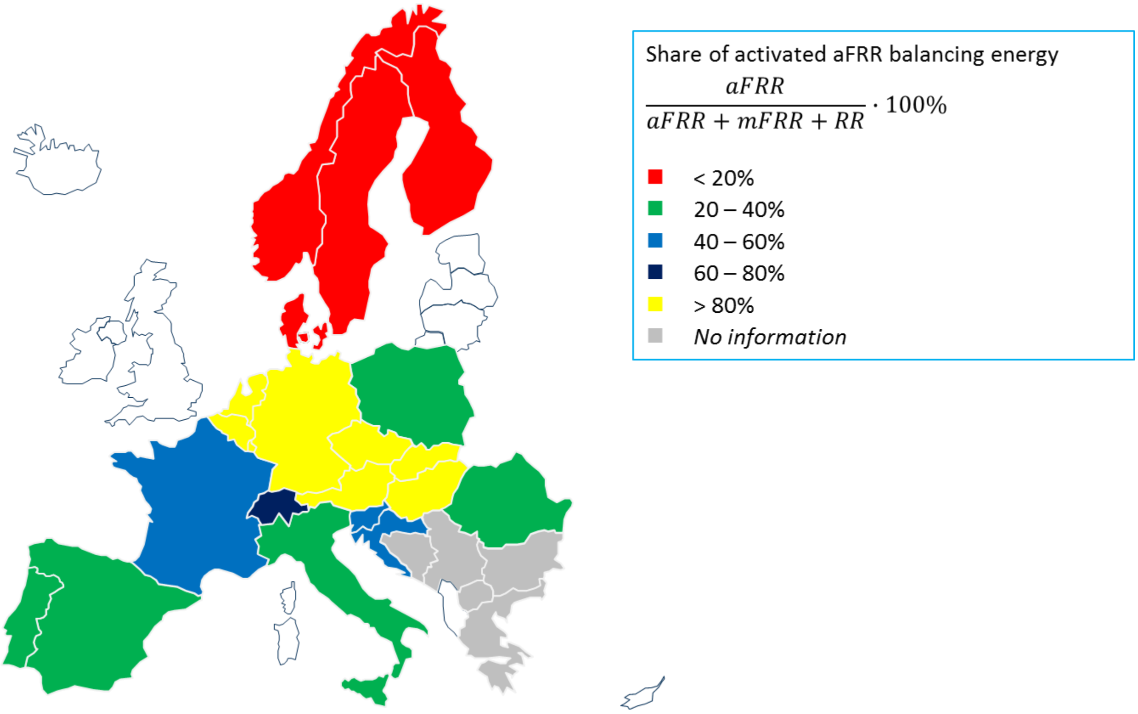


Figure 2: Share of aFRR in total balancing energy, based on figures for February and June 2015[6].

[4] 'Tie-line Bias control' controls the FRCE that is defined by the frequency error (k.Δf) and the interchange error (scheduled minus measured flow)).
[5] '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.
[6] Based on data from the ENTSO-E Transparency platform and information provided directly by TSOs.

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.

2.4. LFC system and required aFRR for activation

Figure 3 provides a generic overview of the automatic frequency restoration process. The input to the process is FRCE which is defined as the *power balance to the scheduled value* for the LFC Area/LFC Block and the *system frequency* for the Nordic synchronous area.

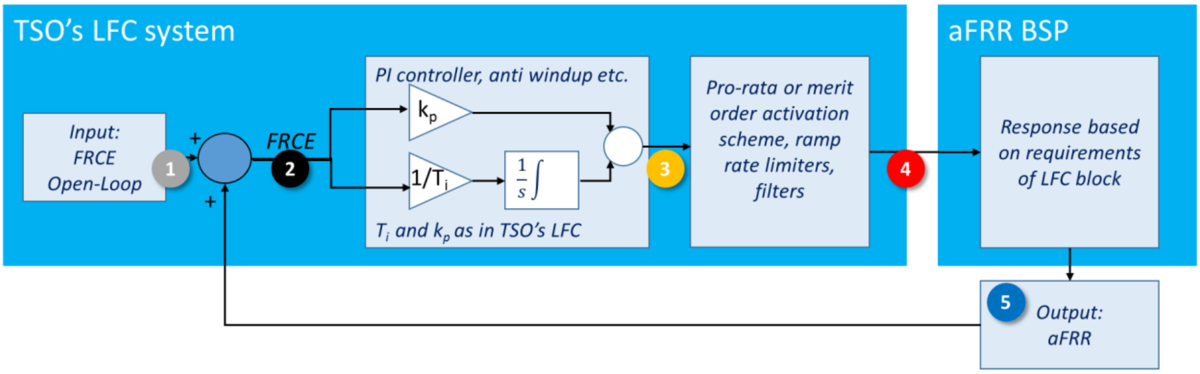


Figure 3: Generic overview of automatic frequency restoration process

Figure 4 shows an example of a 100MW generation trip at time t=0, 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[7]. At t = 0, the FRCE is equal to the imbalance and therefore the input to the TSO's LFC is -100MW. The LF Controller's 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 LF Controller[8]. Now 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.

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

[8] 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.

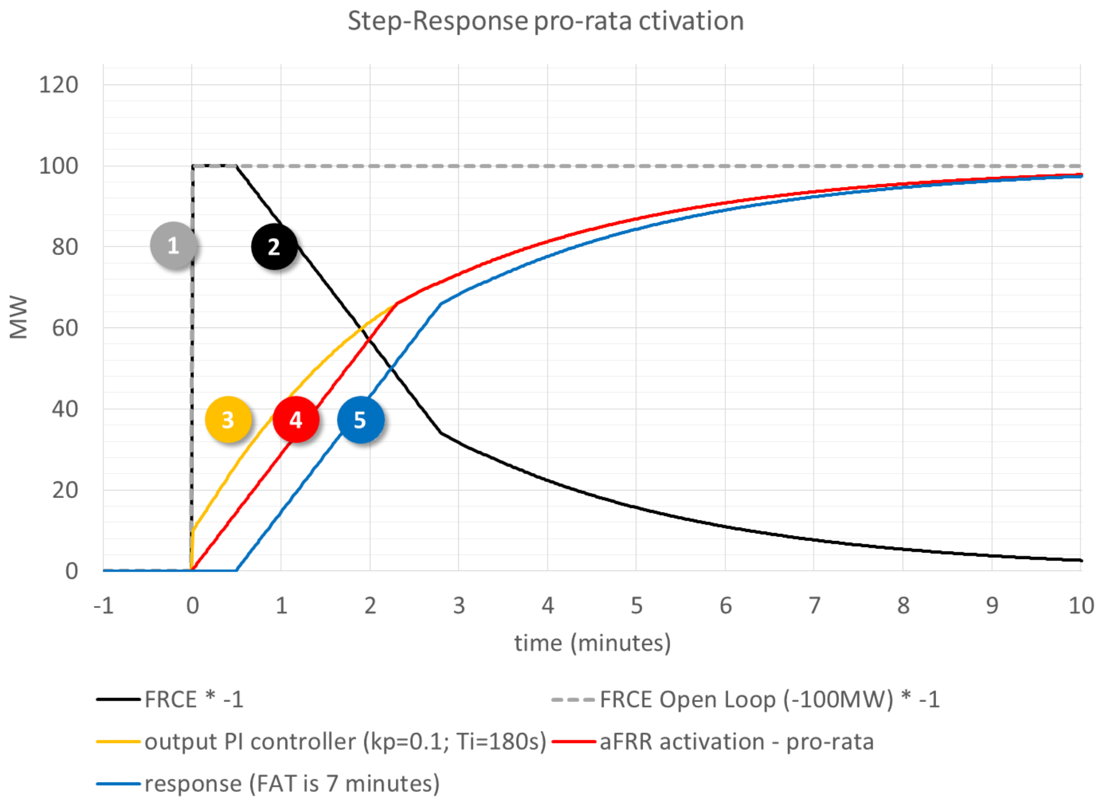


Figure 4: Typical response of generic automatic frequency restoration process to a 100MW generation trip

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.

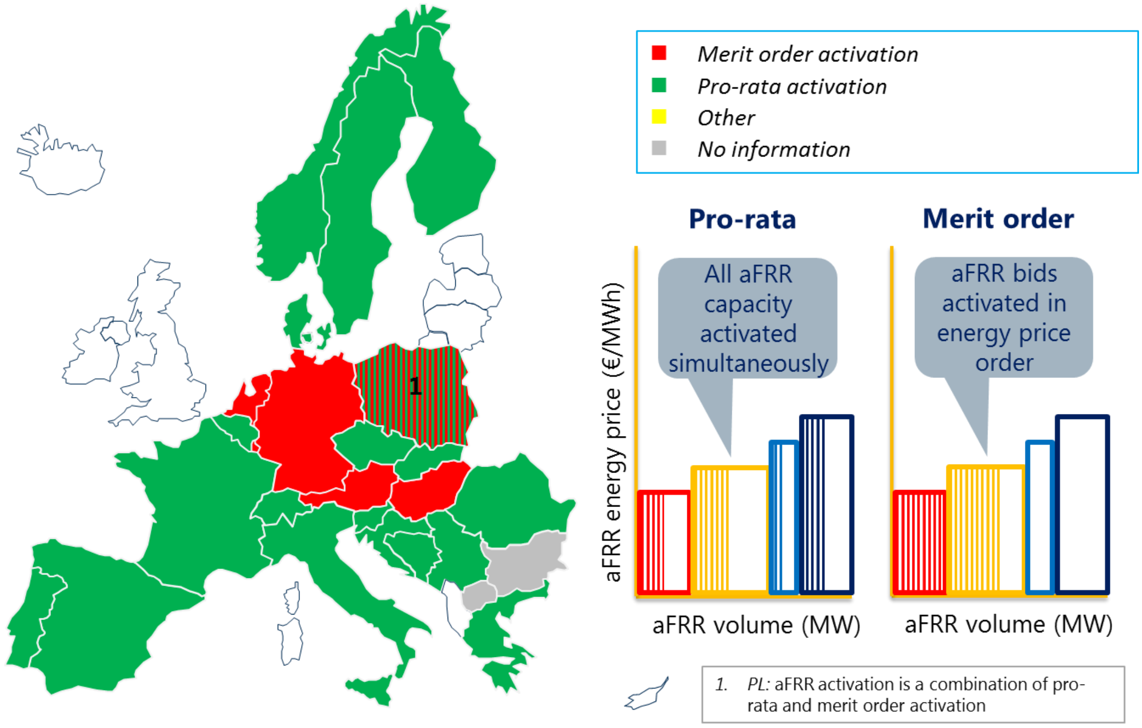


Figure 5: Overview of TSOs that apply a pro-rata activation scheme or a merit-order activation scheme.

2.6. Step-wise or continuous activation

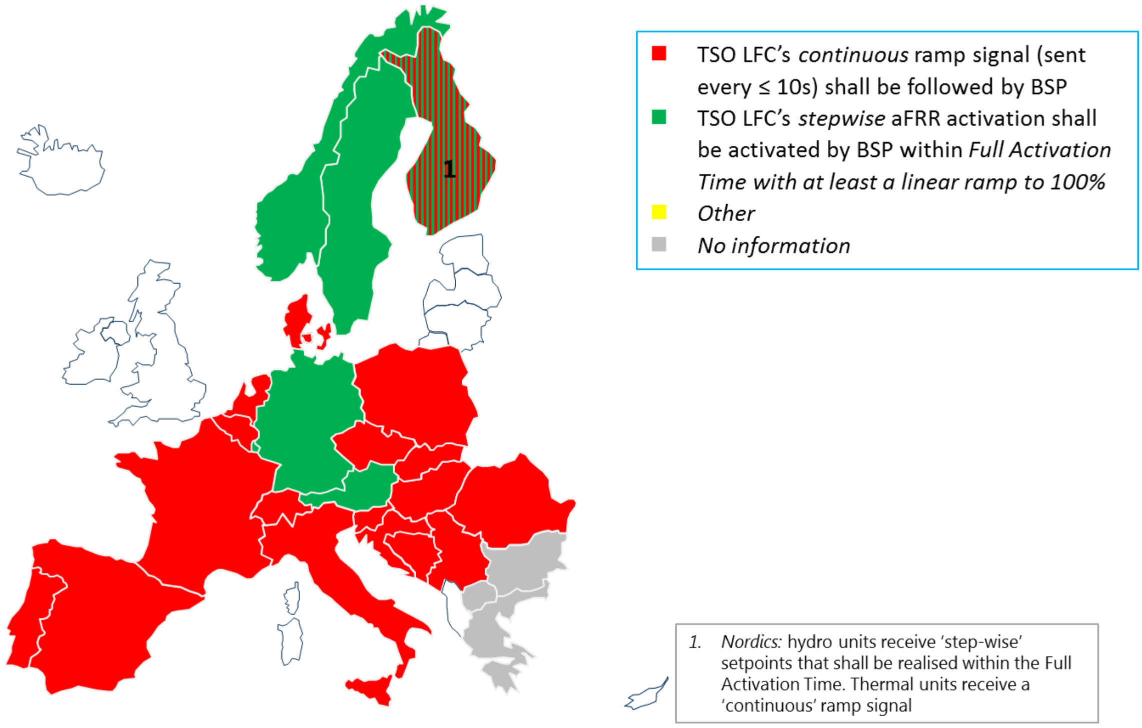


Figure 6: aFRR activation, continuous or stepwise

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.

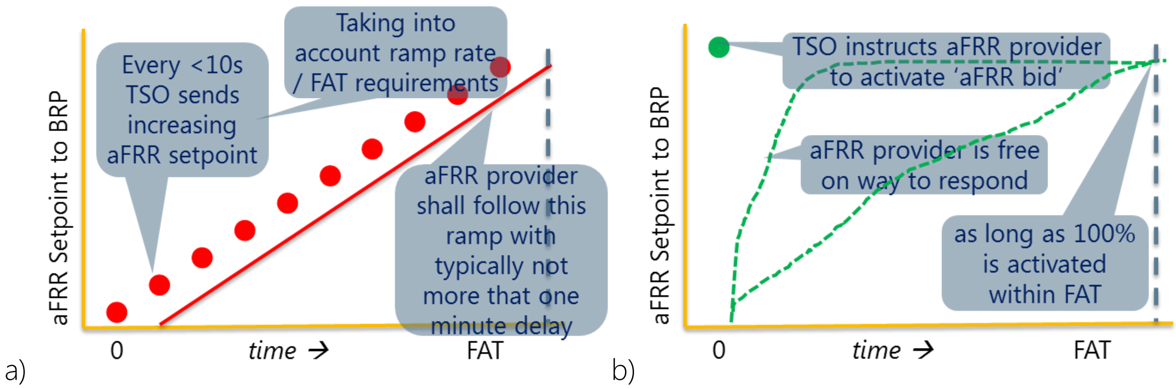


Figure 7: Explanation of a) continuous activation and b) stepwise activation.

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[9]. In the Netherlands, the TSO provides continuous signals to the aFRR provider.

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).

[9] 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.

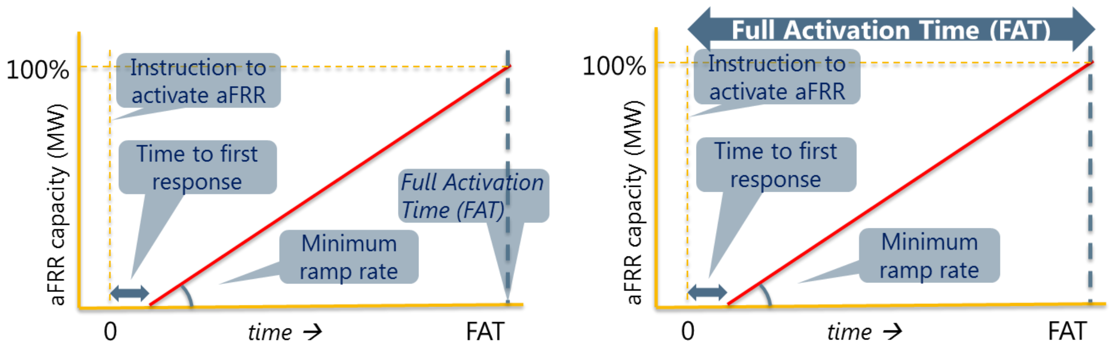


Figure 8: Conversion of time to first response and a minimum ramp rate to aFRR Full Activation Time

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 and 3 minutes in Switzerland and 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.

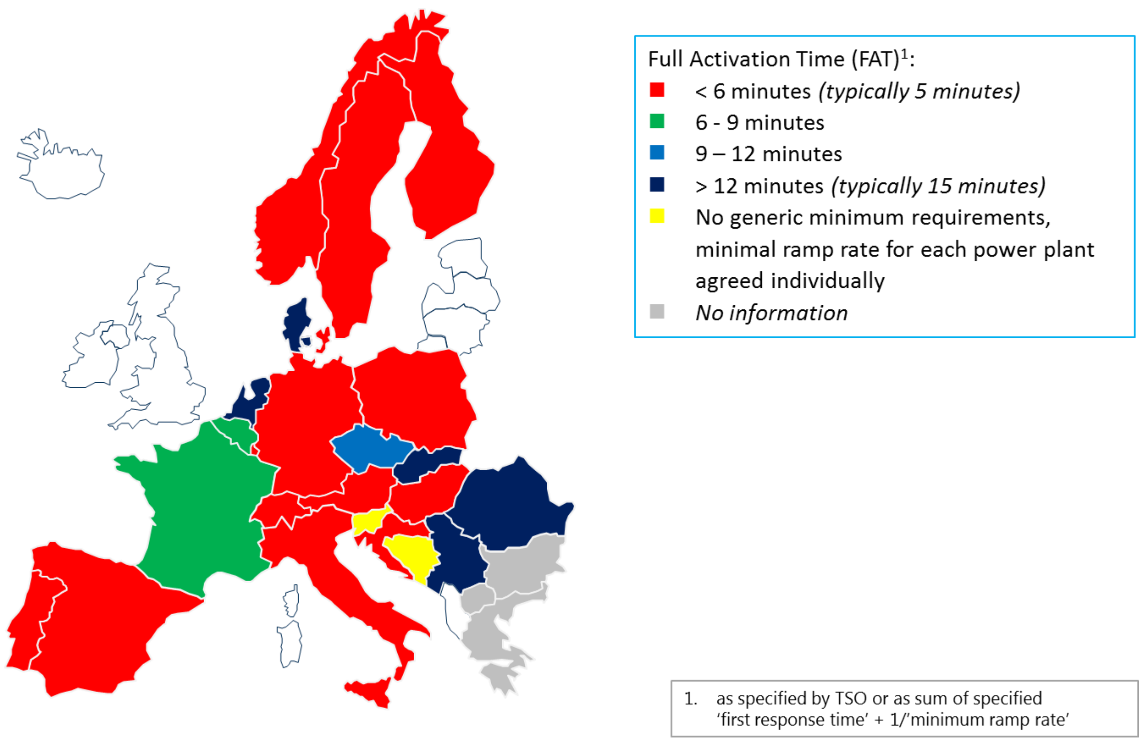


Figure 9: aFRR response requirements (for some countries the requirements are converted to aFRR Full Activation Times)

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 'Operations 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.

[for the BSG meeting on 15 January 2016, this chapter has been deleted from version 0.1]

3.1. Merit order scheme vs. a Pro-Rata activation scheme

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

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

3.4. Conclusion

4. Effects of harmonising aFRR Full Activation Time

4.1. Introduction

Section 2.7 shows that the difference between aFRR Full Activation Times (FAT) in the European LFC Blocks ranges 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 technical aFRR capability to provide aFRR capacity and energy as well as consequently on the aFRR energy and capacity markets. In section 4.3 we study the effect on the regulation quality.

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

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

In this section we provide an analysis of the technical aFRR capability of generation units to provide aFRR bids for different FATs throughout Europe. We define technical aFRR capability of a generation unit as the maximum aFRR capacity that can be provided from the most optimal setpoints for aFRR: upward aFRR at minimum stable capacity point P_{min} or downward aFRR at rated capacity P_{max}. We aggregate the values on LFC Block level. Textbox 1 provides further details.

In section 4.2.3 and 4.2.4 we will also address the potential technical aFRR capability of demand and renewables. Section 4.2.5 and 4.2.6 address potential technical aFRR capability of storage and peak units. *We note that the technical 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.*

Textbox 1: Technical aFRR capability

Definition of technical aFRR capability

Technical 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 Technical aFRR Capability is a function of the aFRR Full Activation Time (FAT).

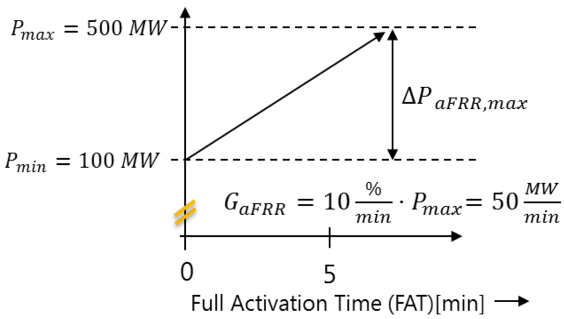
Technical aFRR Capability aggregated for LFC Blocks for 2014 situation

Our overviews provide the *technical 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 *technical 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. .

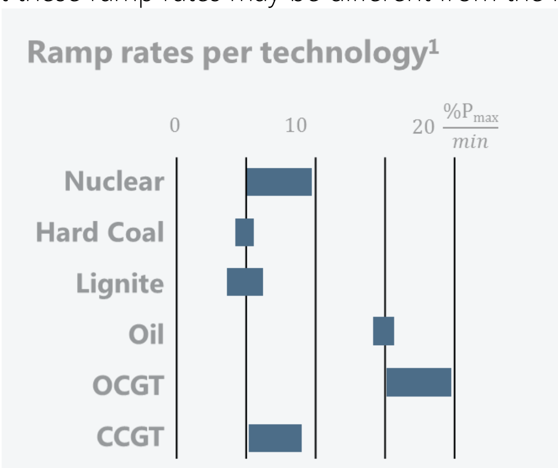
Calculation methodology Technical aFRR Capability per unit

The figure below explains how we calculated the maximum *technical 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 maximum *technical 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 *technical 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 *technical 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!



OCGT: Open Cycle Gas Turbine and gas engines
CCGT: Combined Cycle Gas Turbine
[1] dependent on commissioning year

Input data for this calculation

We aggregated the *technical 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.

Figure 10 provides an example for one LFC Block. This example shows the technical aFRR capability for the different generation technologies in this LFC Block. The horizontal axis shows the FAT and the vertical axis the accumulated technical aFRR capability of different classes of generation. The graph indicates the technical aFRR capability of each generation class as function of the FAT and the sum for the LFC bock.

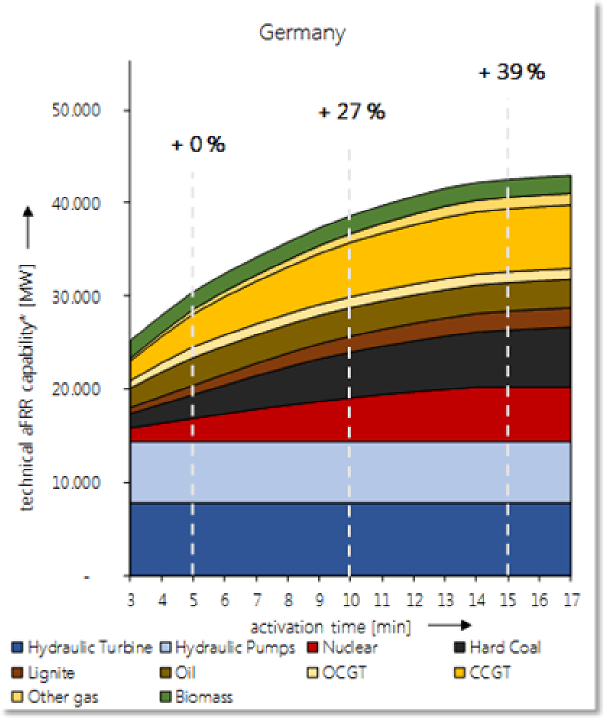


Figure 10: Example of a technical aFRR capability diagram for Germany (percentages are the change from current FAT) * Upward and downward, not symetric

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 11 provides the technical aFRR capability for all LFC Blocks relative to the technical aFRR capability for the existing FAT. Hence, it shows the relative changes to the existing technical 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 technical aFRR capability of generation units will increase by 39%.

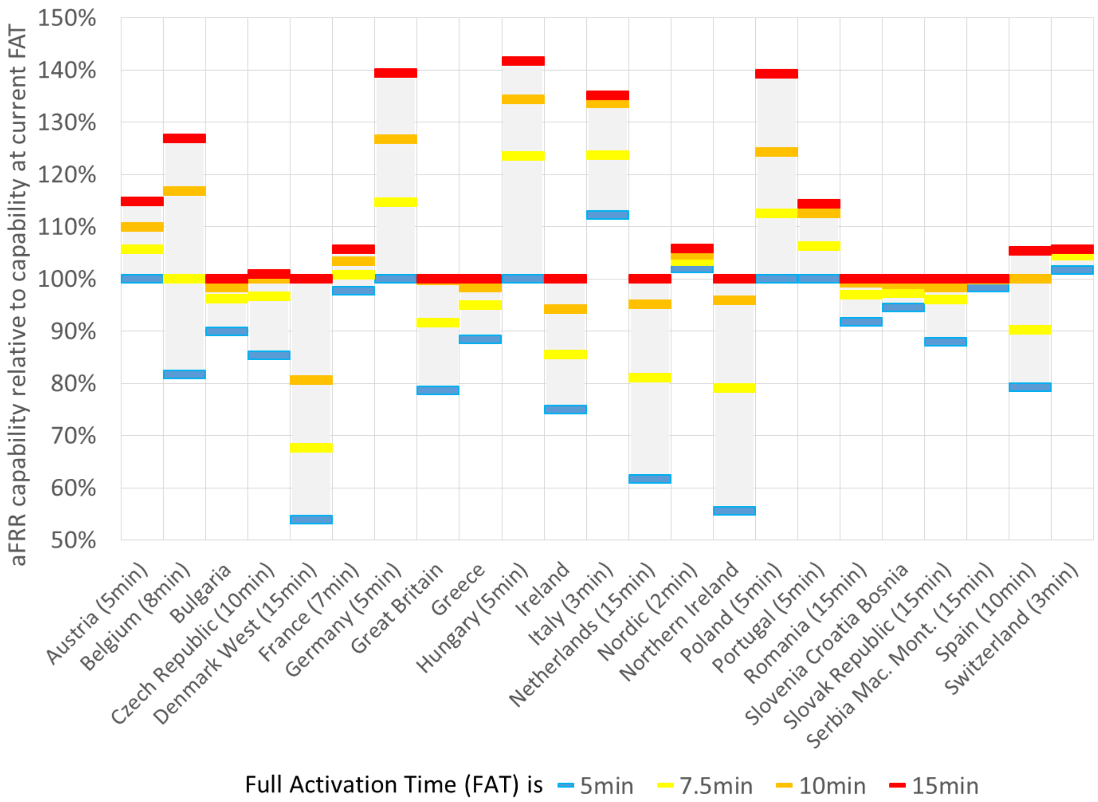


Figure 11: Overview of relative aFRR capabilities in European LFC Blocks (between brackets: the current FAT)

Figure 11 (and appendix C) show that the technical 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 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), will have significantly more technical aFRR capability for a FAT of 15 minutes since it takes more than 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 technical aFRR capability is only the theoretical amount of aFRR that can be offered as aFRR capacity, the results in Figure 11 shall not be interpreted in 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 technical 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 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 technical 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) 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.

4.2.5. Potential technical 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 – aFRR bids can be activated for a long time, 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 (merit order) 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 5, 7.5, 10 and 15 minutes. We describe the effect for both time series of FRCE (section Error! Reference source not found.) and large deviations (section Error! Reference source not found.).

[for the BSG meeting on 15 January 2016, this section has been deleted from version 0.1]

5. Conclusions

[for the BSG meeting on 15 January 2016, this chapter has been deleted from version 0.1]

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

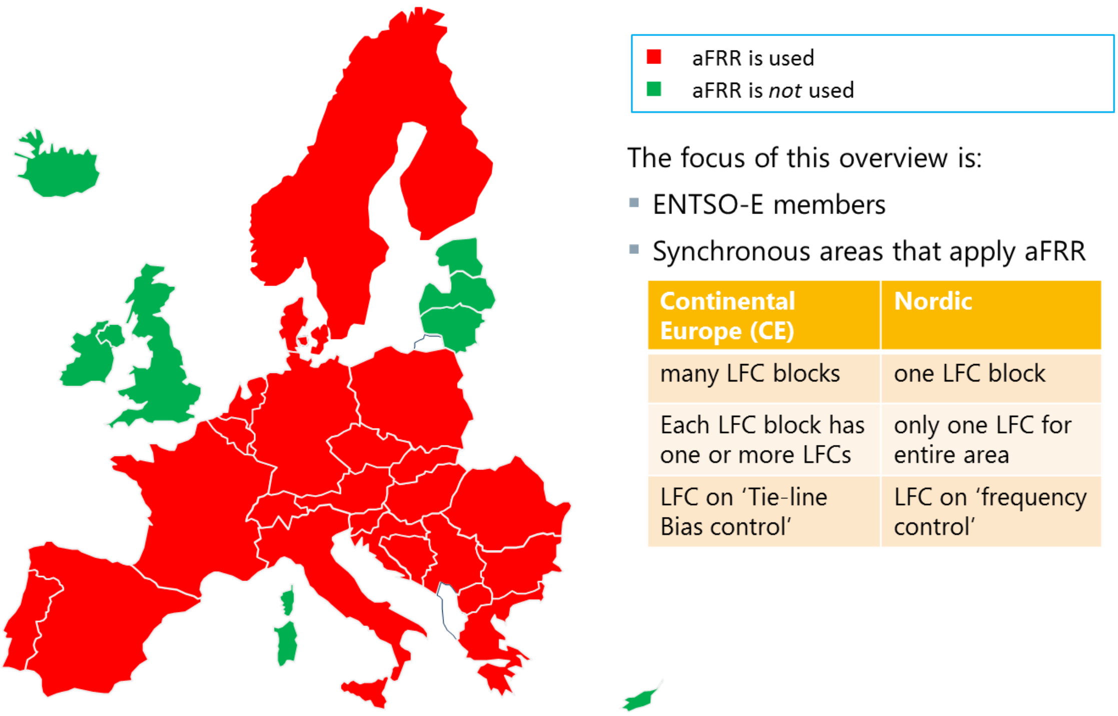
E. List of Figures

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

Continental European and Nordic countries use automatic Frequency Restoration Reserves (aFRR)



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 12: Use of aFRR throughout Europe

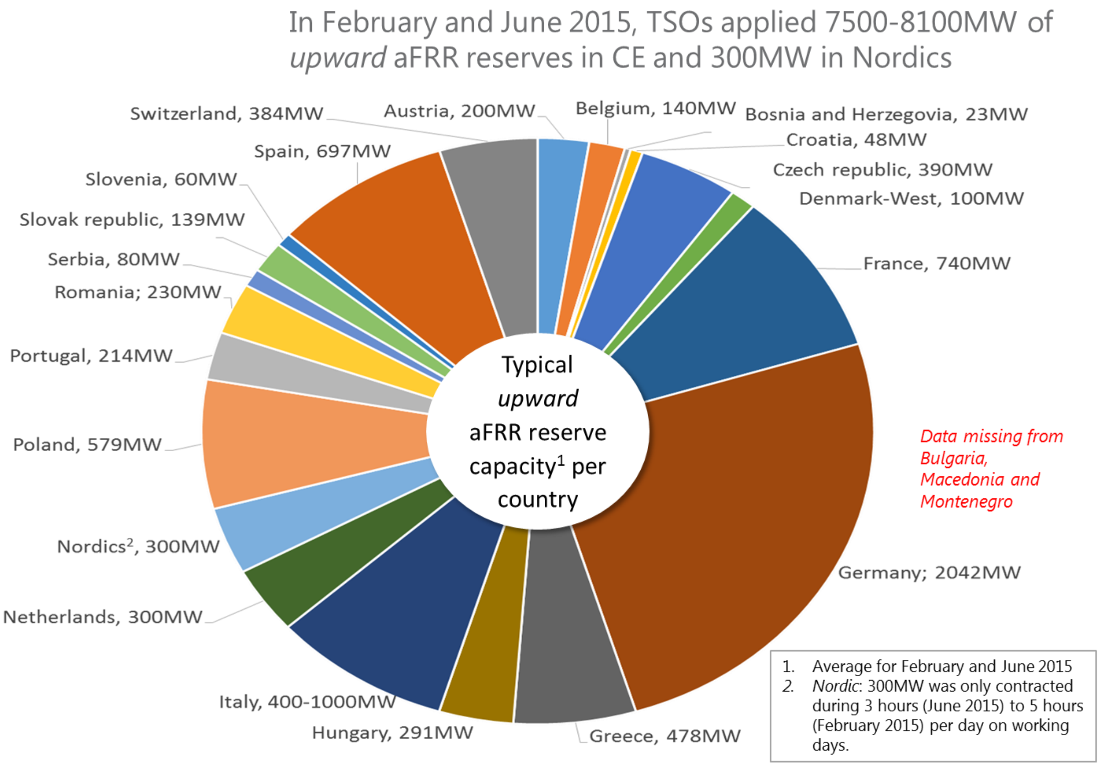


Figure 13: aFRR *Upward* reserve capacity throughout Europe in February and June 2015

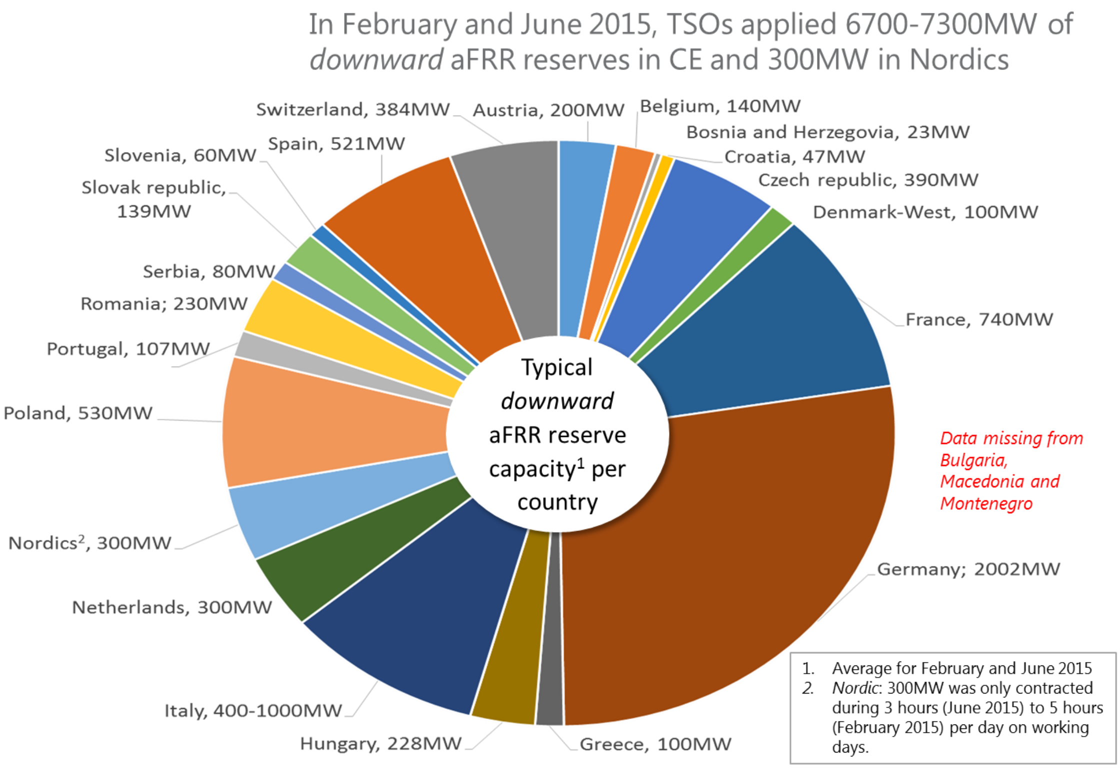


Figure 14: aFRR *Downward* reserve capacity throughout Europe in February and June 2015

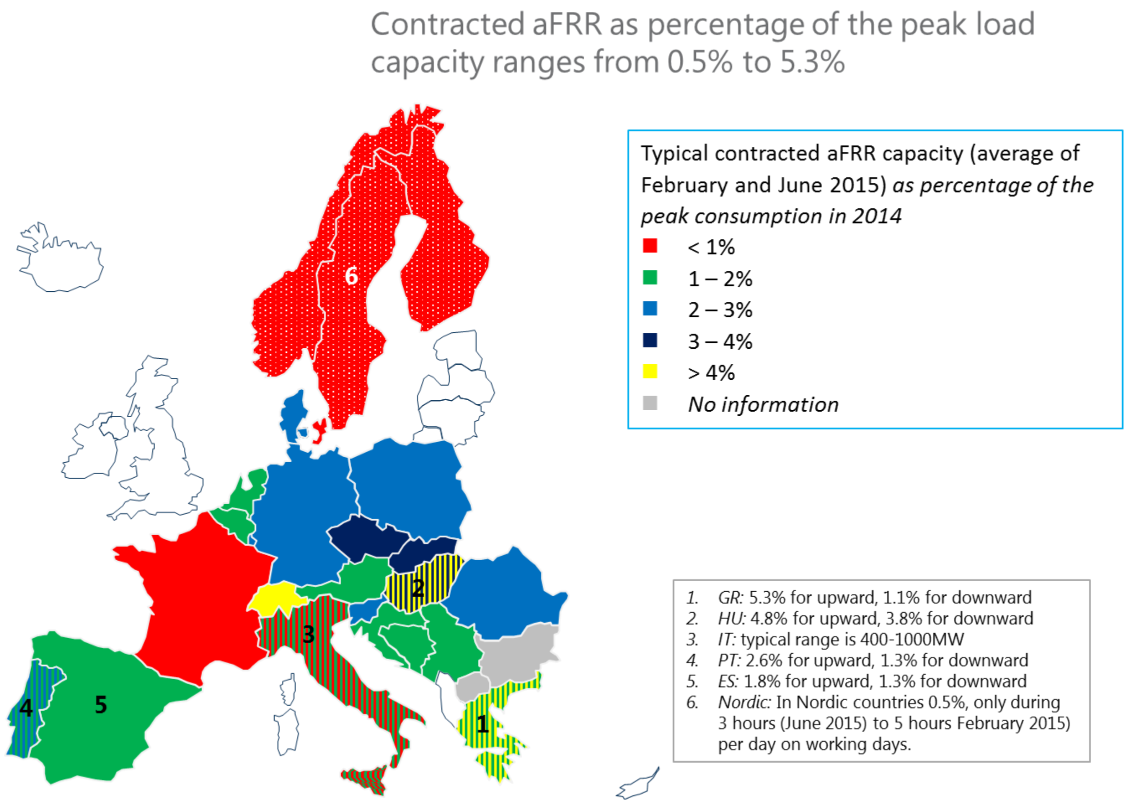


Figure 15: Typical contracted aFRR capacity (average of February and June 2015) as percentage of the peak consumption in 2014.

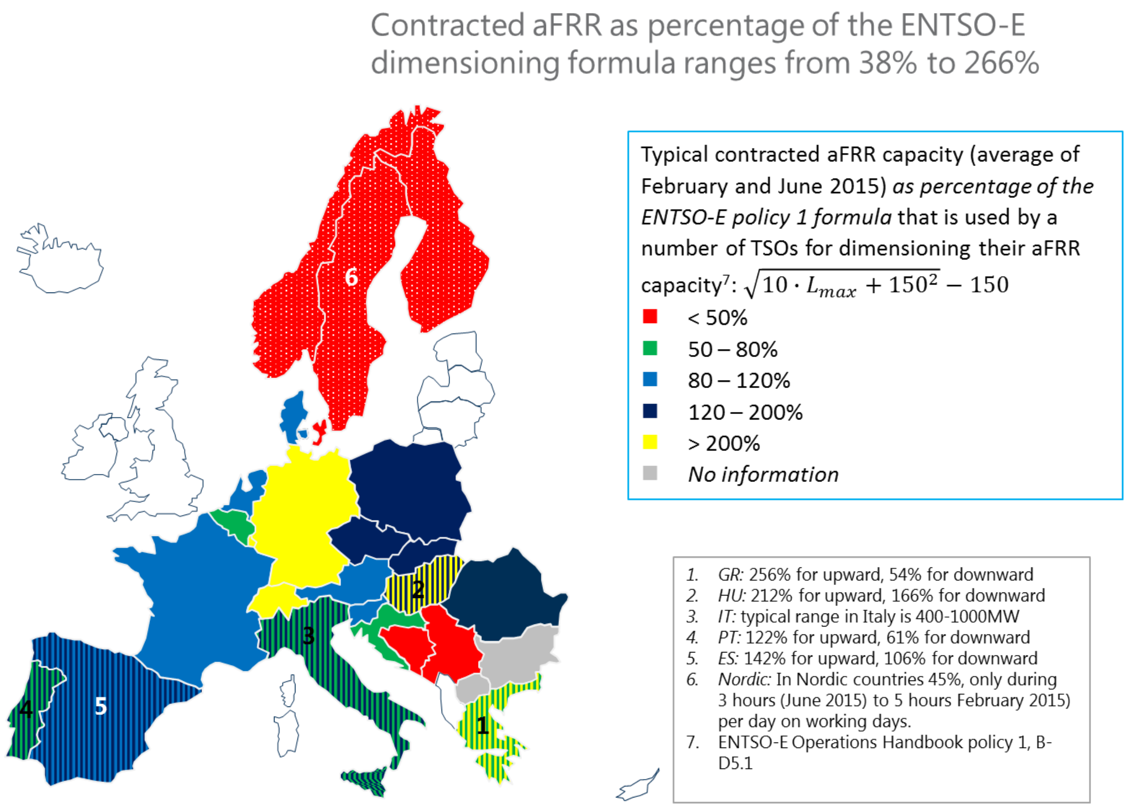


Figure 16: Typical contracted aFRR capacity (average of February and June 2015) *as percentage of the ENTSO-E policy 1 formula* that is used by a number of TSOs for dimensioning their aFRR capacity: $\sqrt{\mathbf{10 \cdot L_{max} + 150^2}} - \mathbf{150}$ *(source: ENTSO-E Operations Handbook policy 1, B-D5.1)*

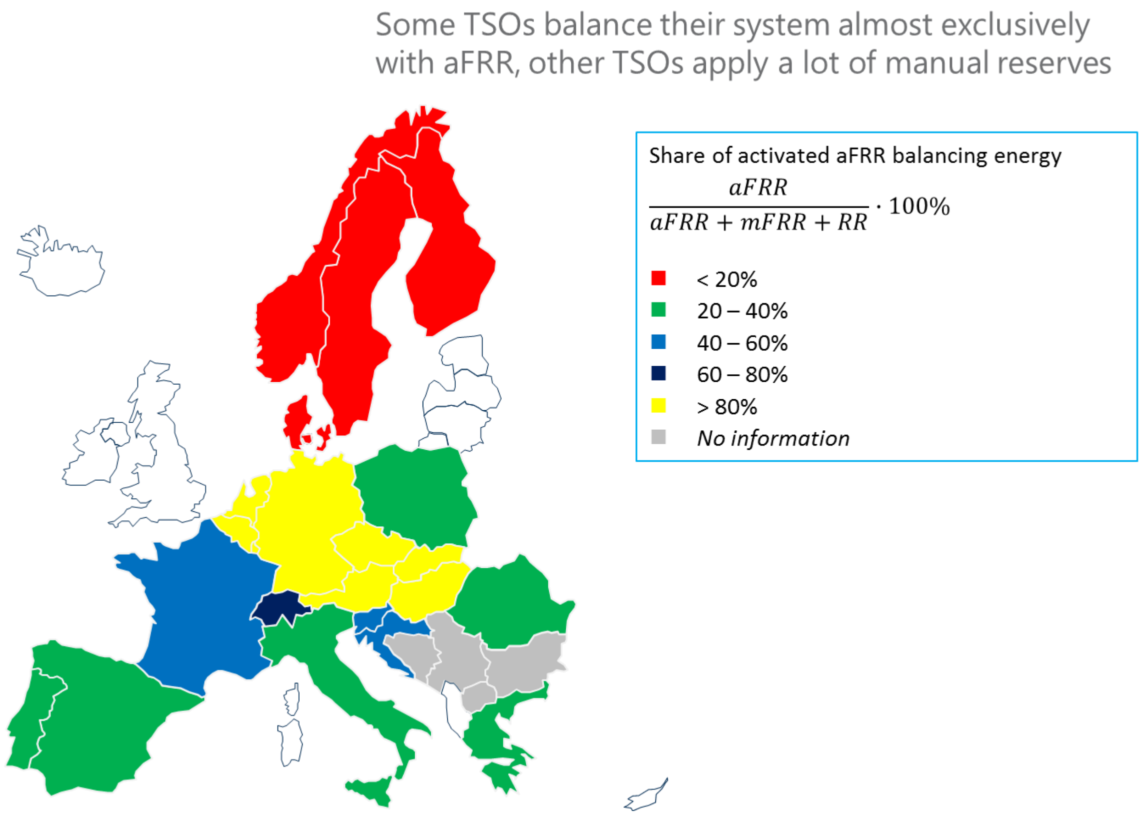


Figure 17: Share of aFRR in total balancing energy, based on figures for February and June 2015

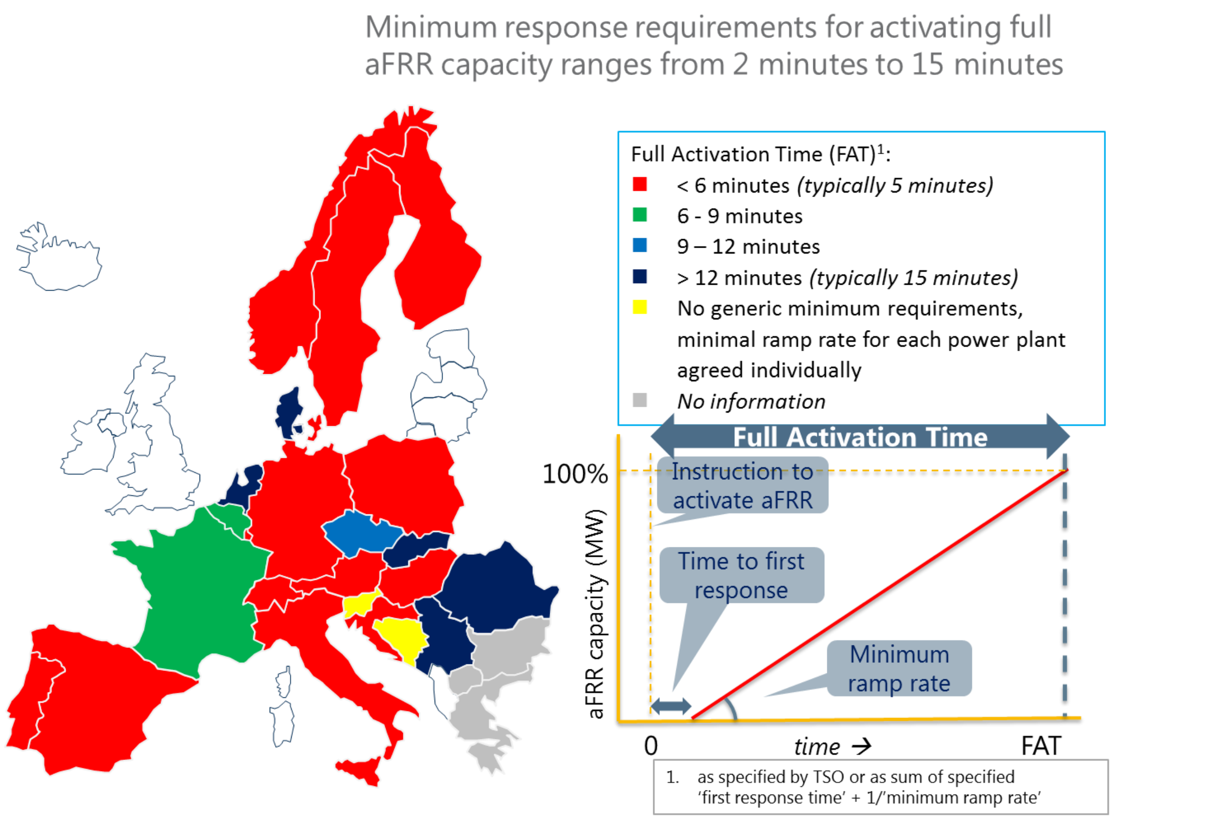


Figure 18: aFRR response requirements (for some countries the requirements are converted to aFRR Full Activation Times)

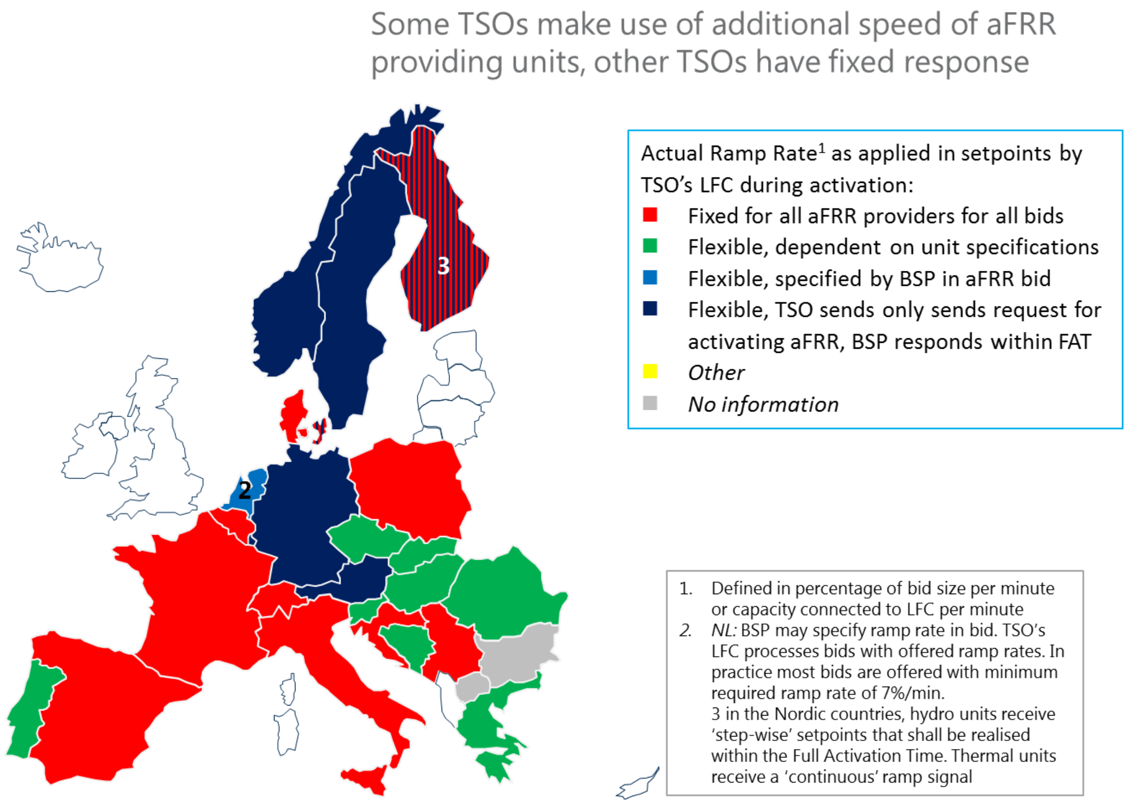


Figure 19: aFRR actual response of aFRR providers

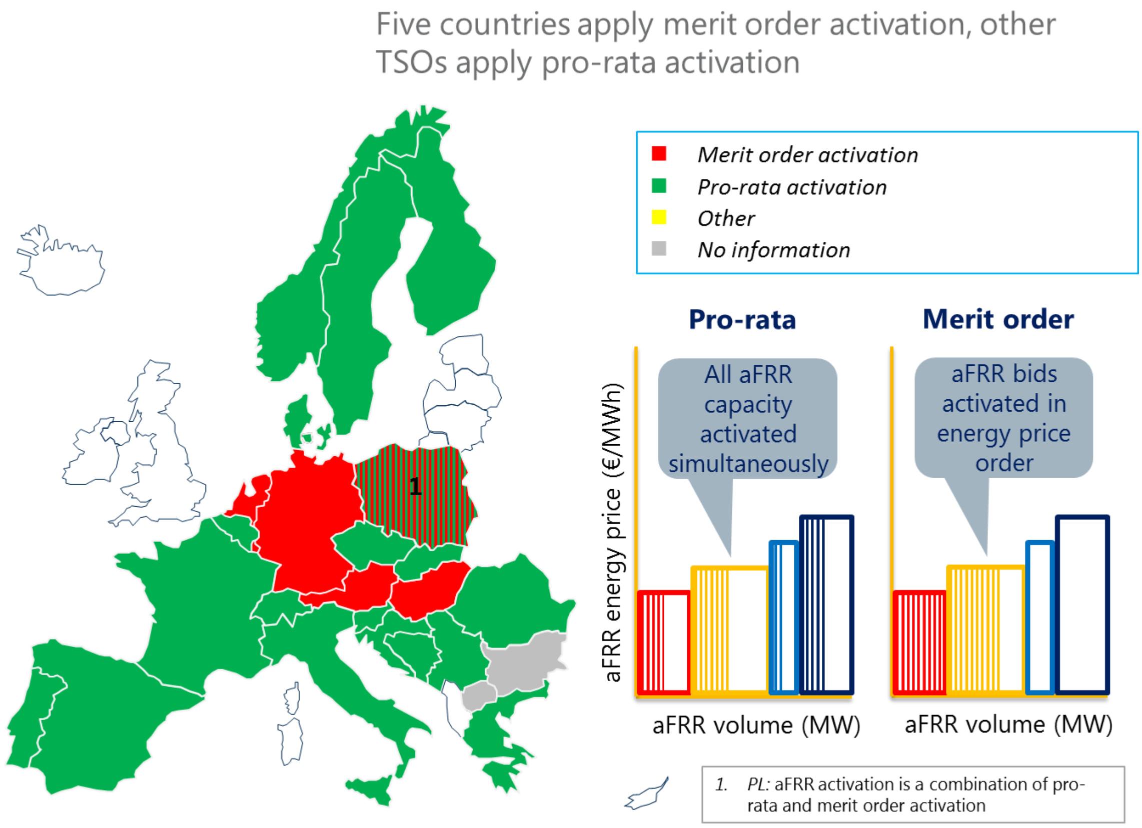


Figure 20: TSOs that apply a pro-rata activation scheme or a merit-order activation scheme

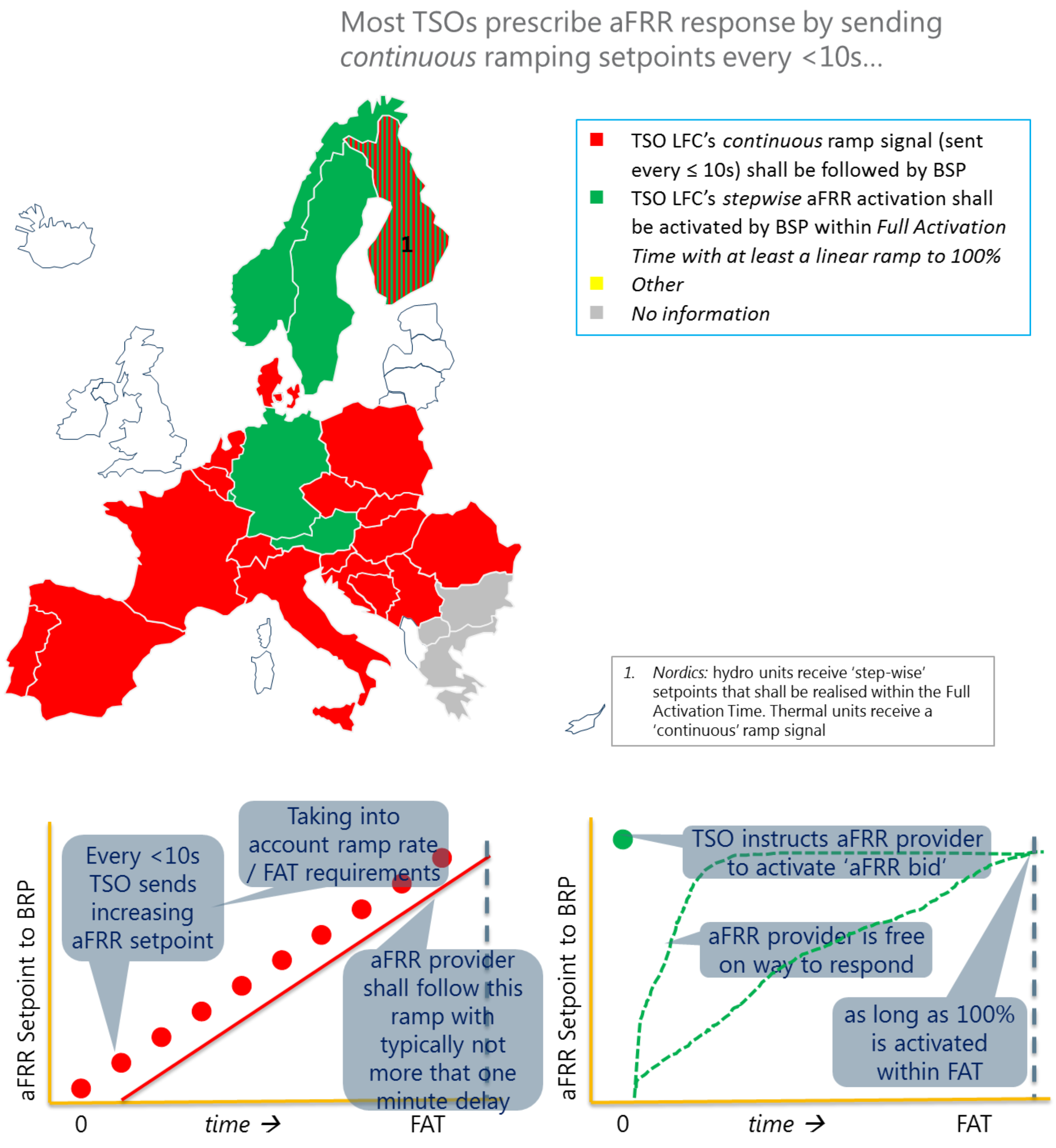


Figure 21: aFRR activation, continuous or stepwise

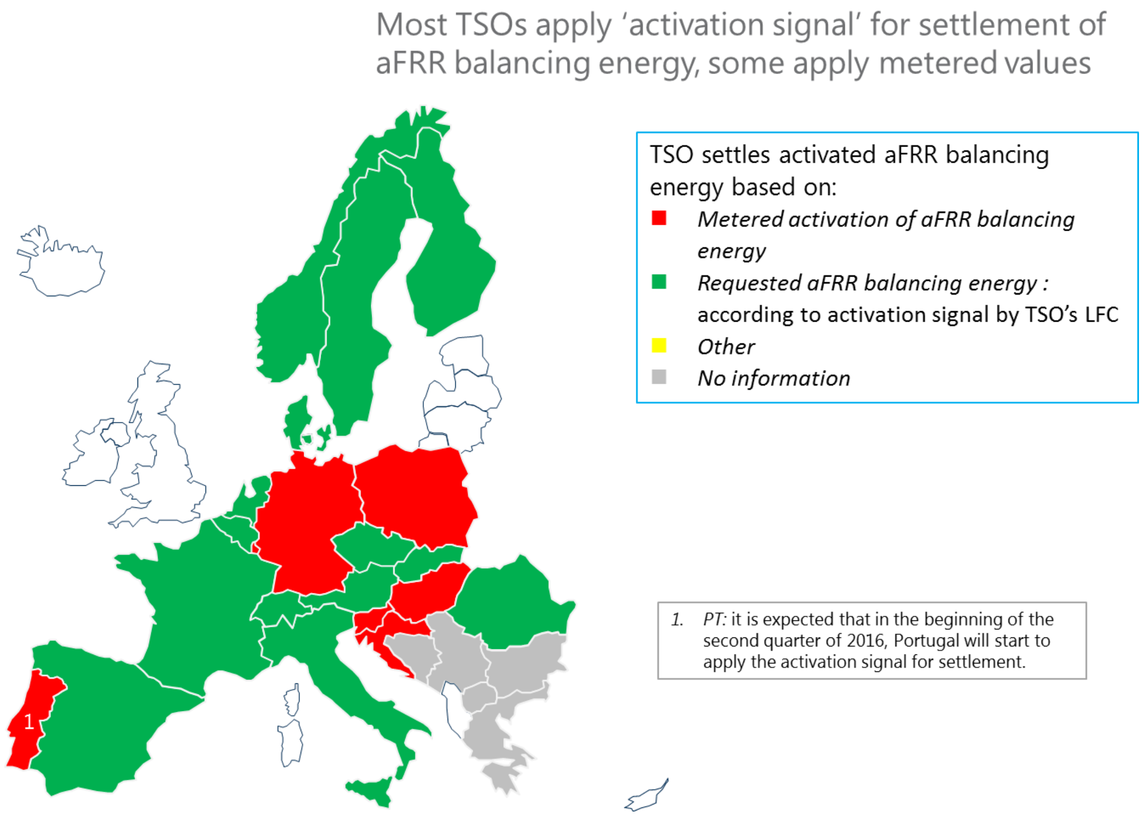


Figure 22: Settlement of aFRR balancing energy

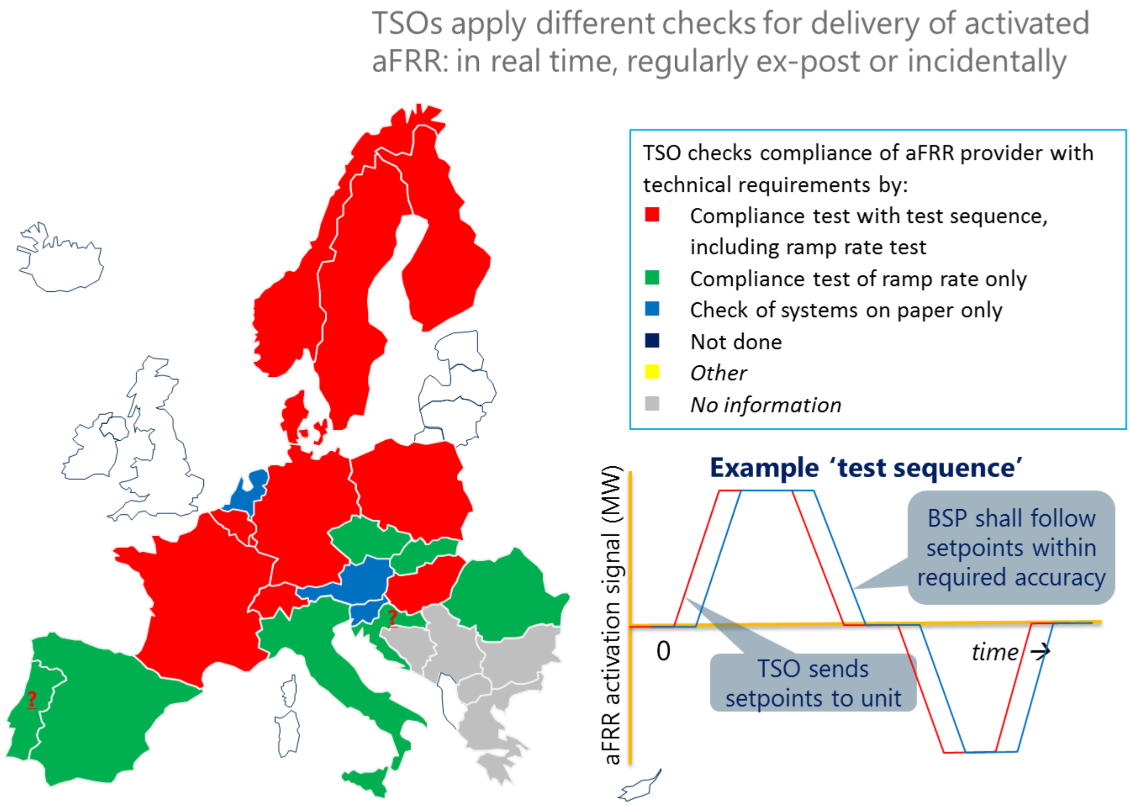


Figure 23: Compliance check: Prequalification tests

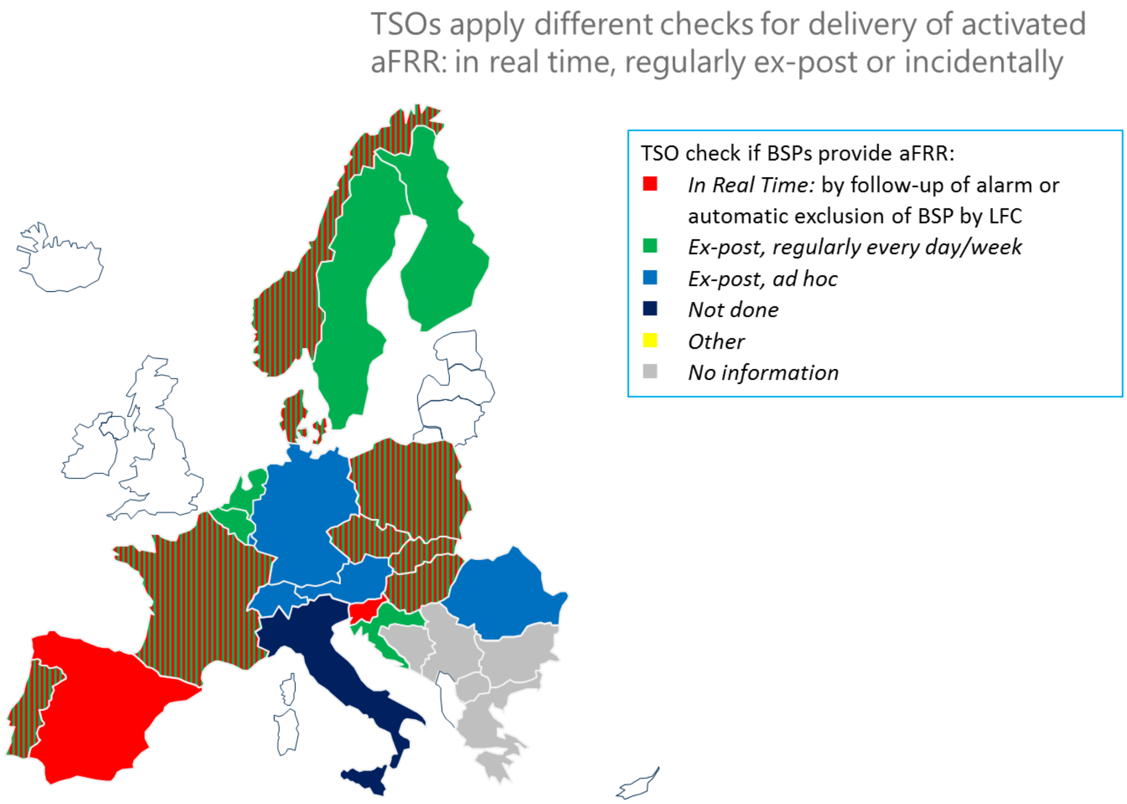


Figure 24: Compliance check: Real Time / Ex-Post

B. Simulation of FRCE quality for LFC Blocks

[for the BSG meeting on 15 January 2016, this appendix has been deleted from version 0.1]

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 technical 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[10]
  - Other: Published availabilities on different platform's (e.g. EEX, Elia, etc.)[11]
- Reserve ramp rates

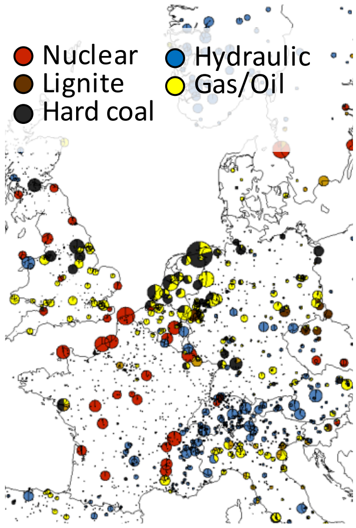


Figure 25: generation database (IAEW)

This data is used to determine the theoretical maximum technical aFRR capability per LFC Block for all units in operation in 2014.The technical 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.

[10] 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.
[11] Public data on power plant availability according to EU regulation no. 1227/2011 for different time periods between 2005 and 2014.

Parameters and Methodology

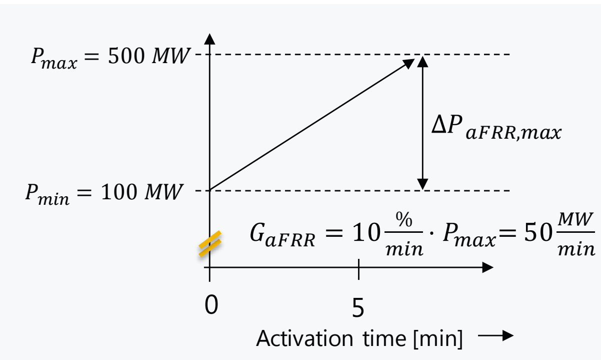
The resulting technical aFRR capability does not necessarily match prequalified volume and is dependent on the operation point of the unit. This means explicitly:

Result is <u>maximum</u> technical aFRR capability of a unit to provide upward aFRR at <u>operating point</u> $\boldsymbol{P_{min}}$ or downward aFRR at <u>operating point</u> $\boldsymbol{P_{max}}$[12].

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.[13] The technical 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.

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 technical 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 technical 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

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

change of capability referring to the current FAT in the respected LFC Block. In case of no aFRR activation scheme, no percentage is given.

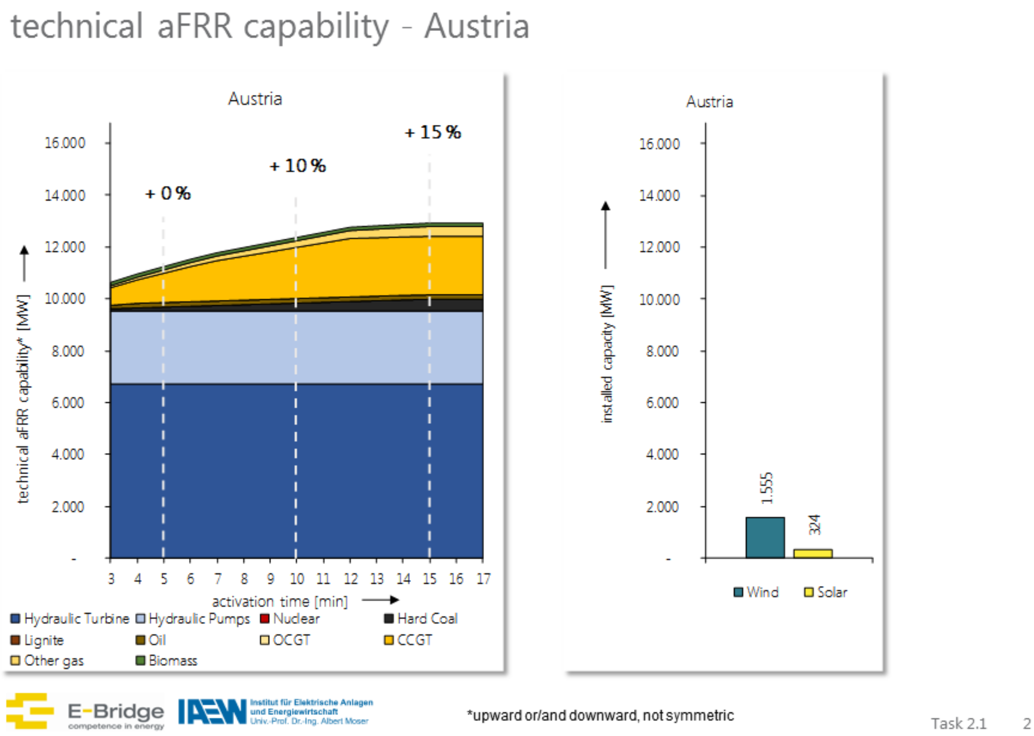


Figure 26: technical aFRR capability in Austria

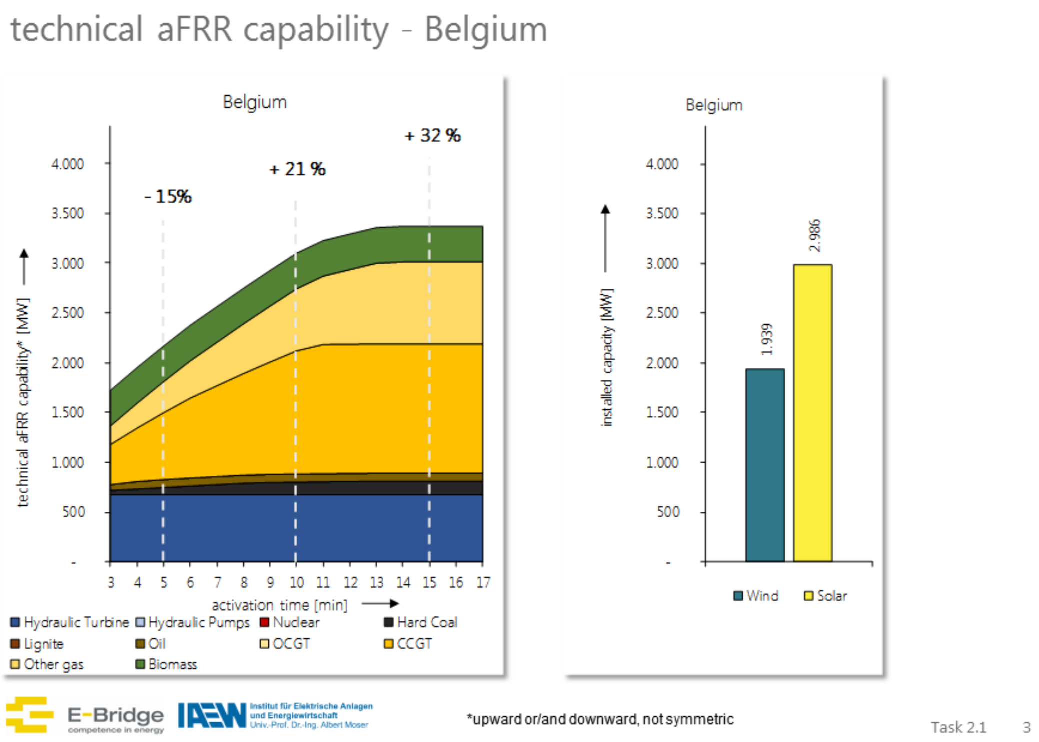


Figure 27: technical aFRR capability in Belgium

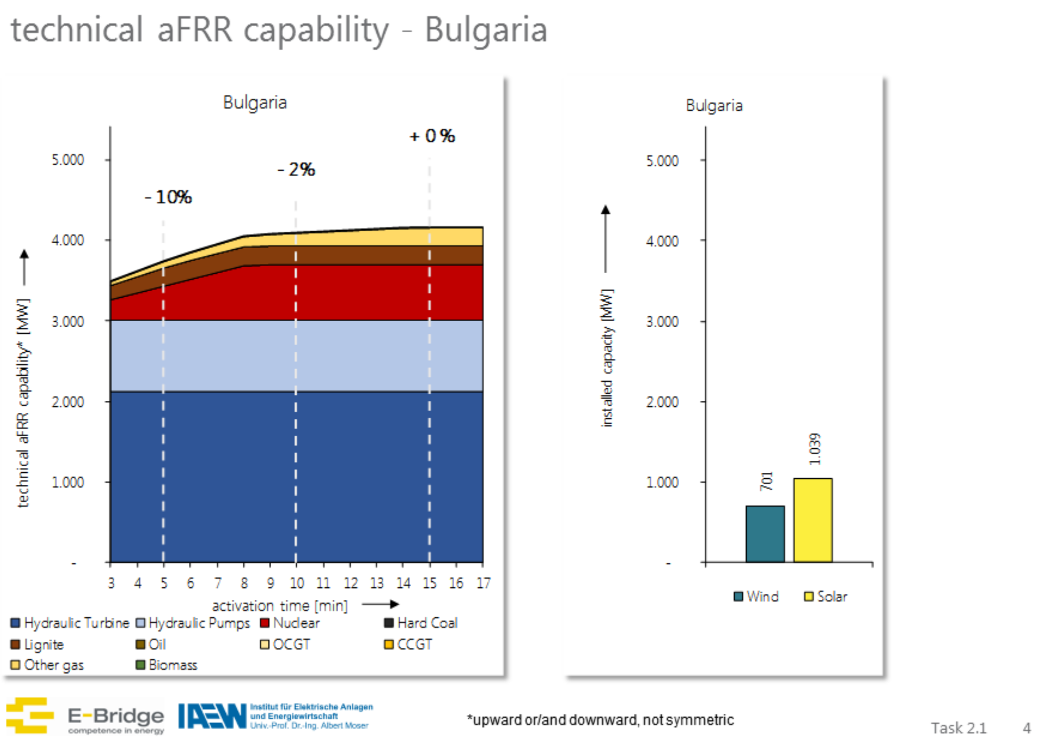


Figure 28: technical aFRR capability in Bulgaria

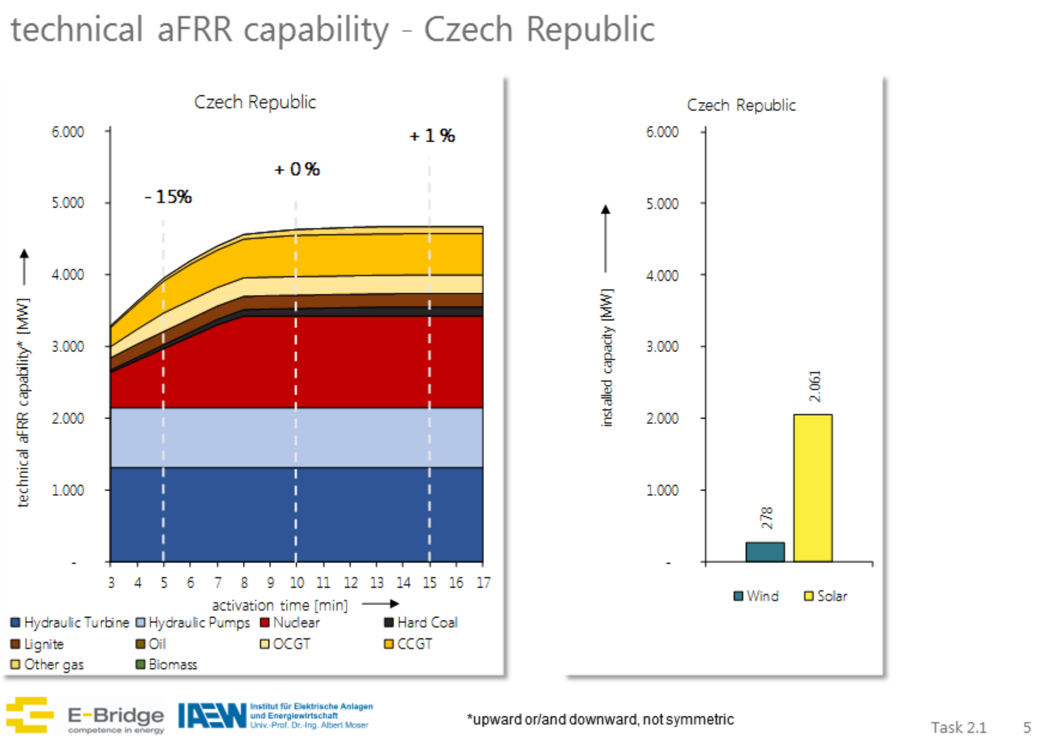


Figure 29: technical aFRR capability in Czech Republic

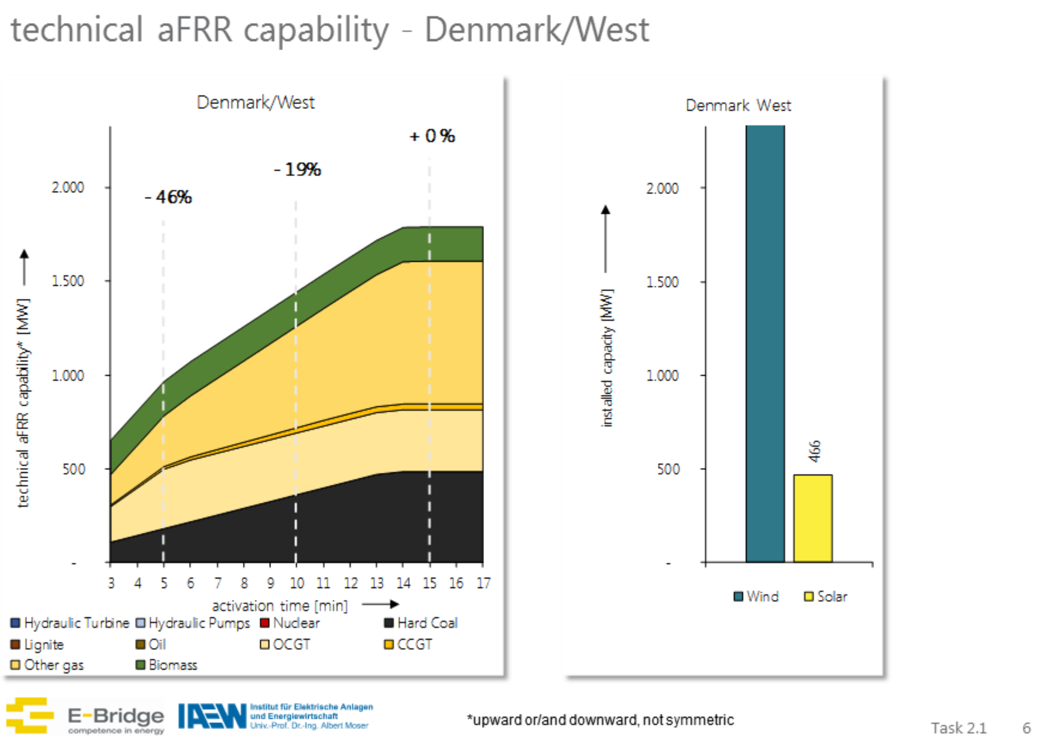


Figure 30: technical aFRR capability in Denmark/West

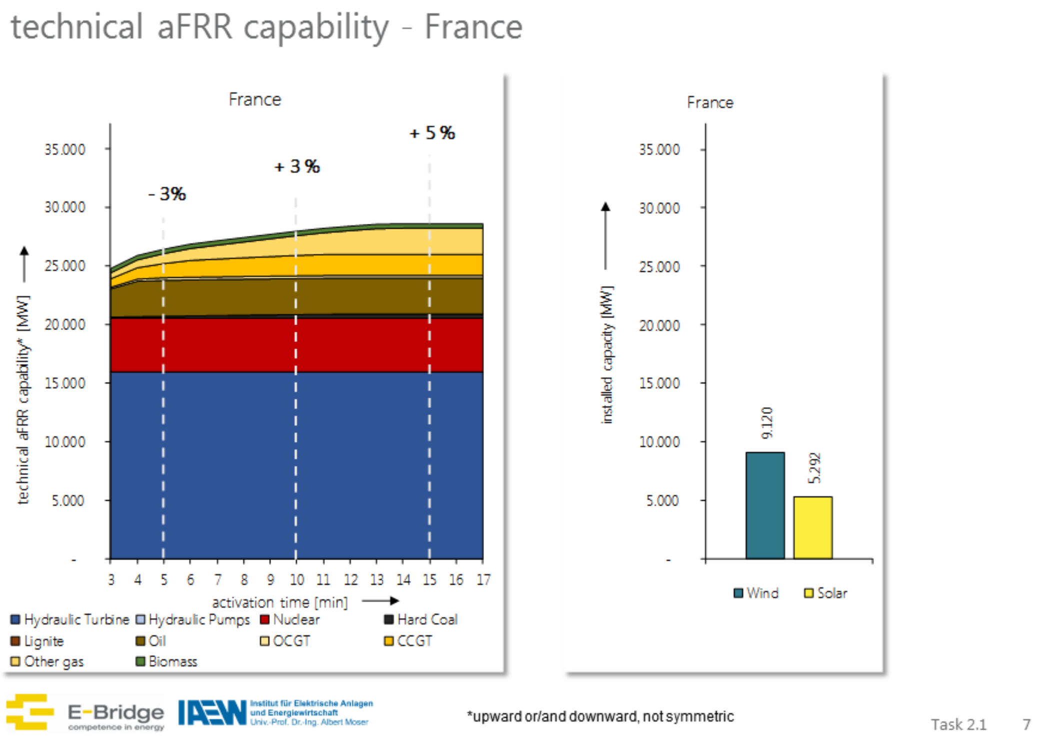


Figure 31: technical aFRR capability in France

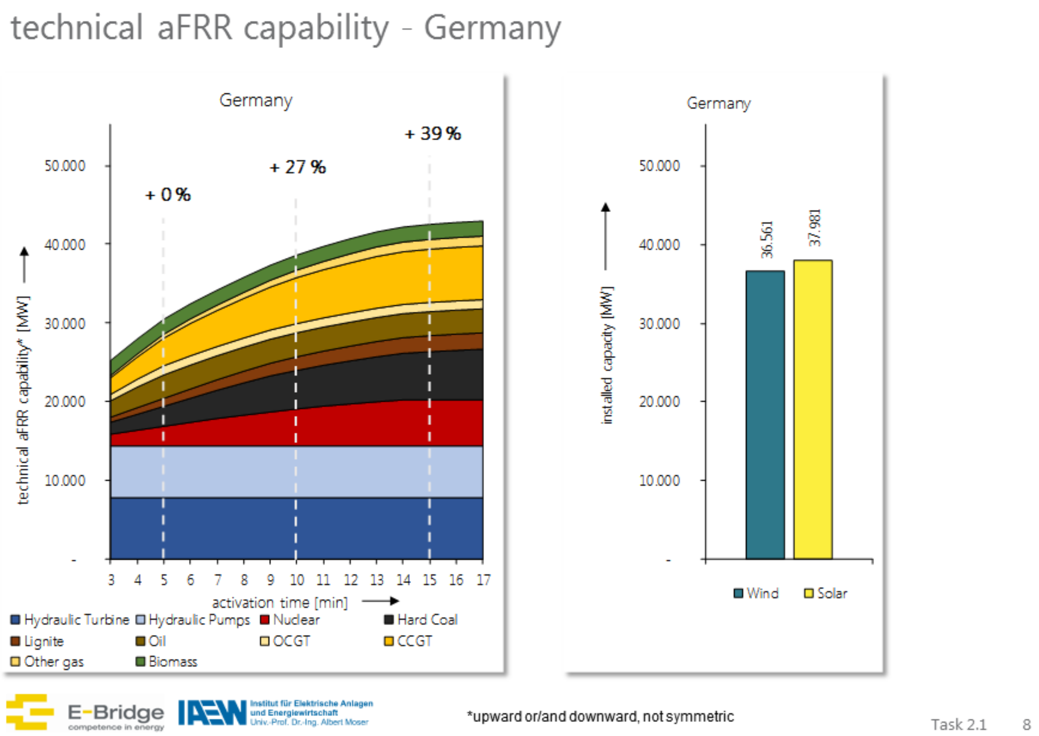


Figure 32: technical aFRR capability in Germany

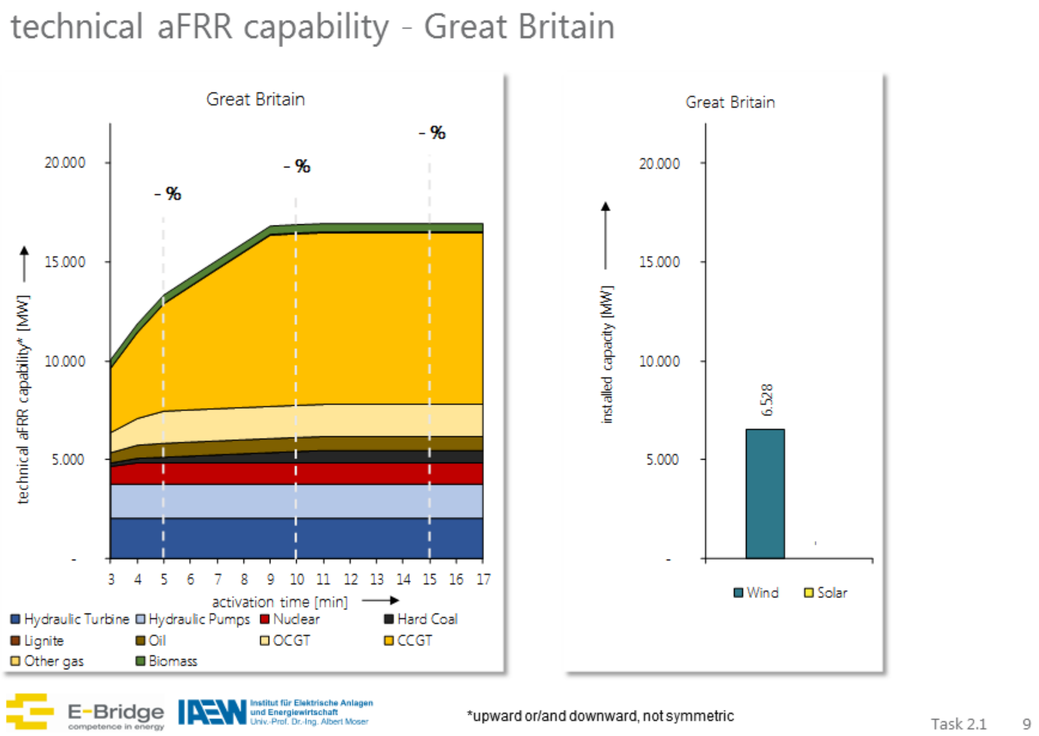


Figure 33: technical aFRR capability in Great Britain

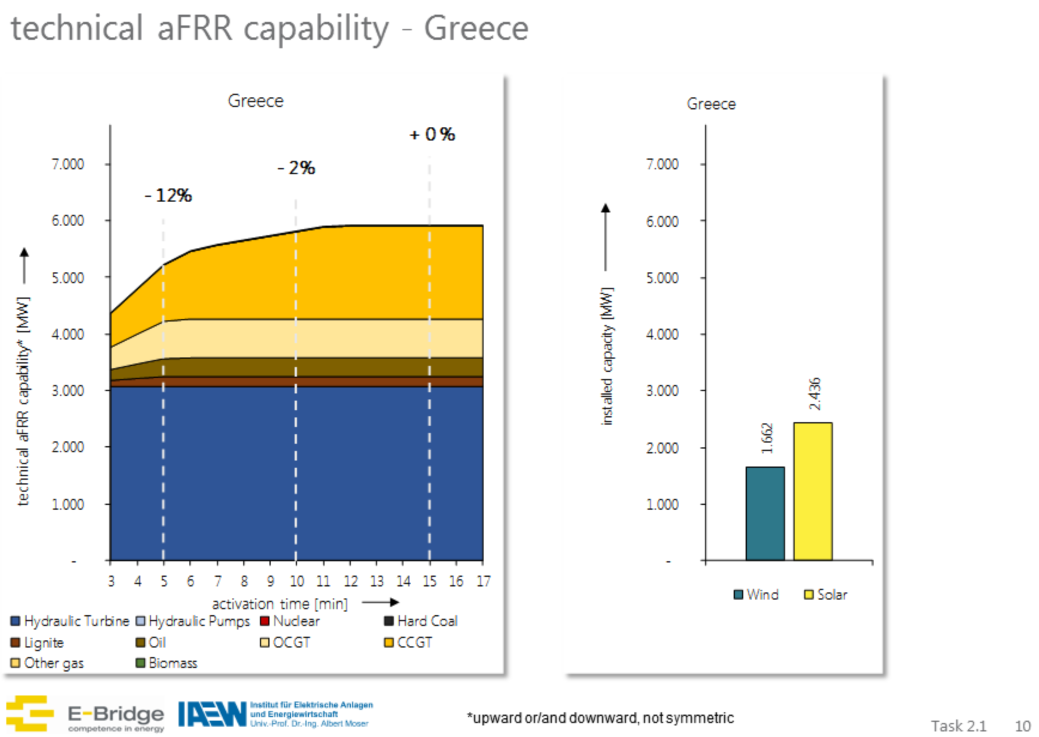


Figure 34: technical aFRR capability in Greece

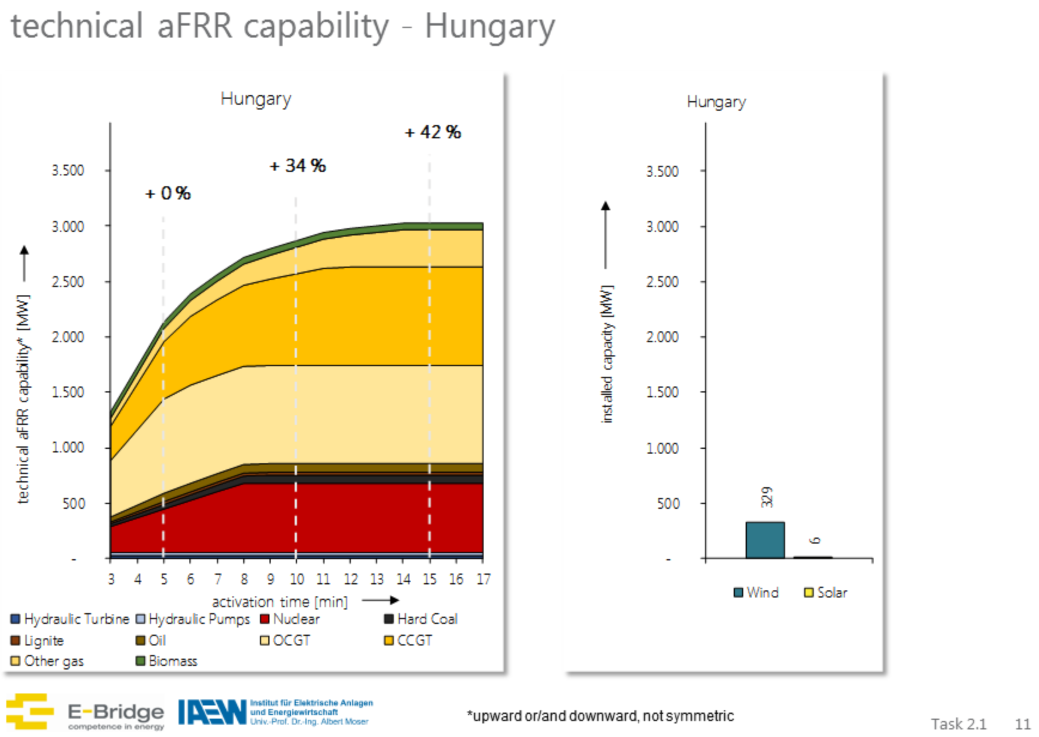


Figure 35: technical aFRR capability in Hungary

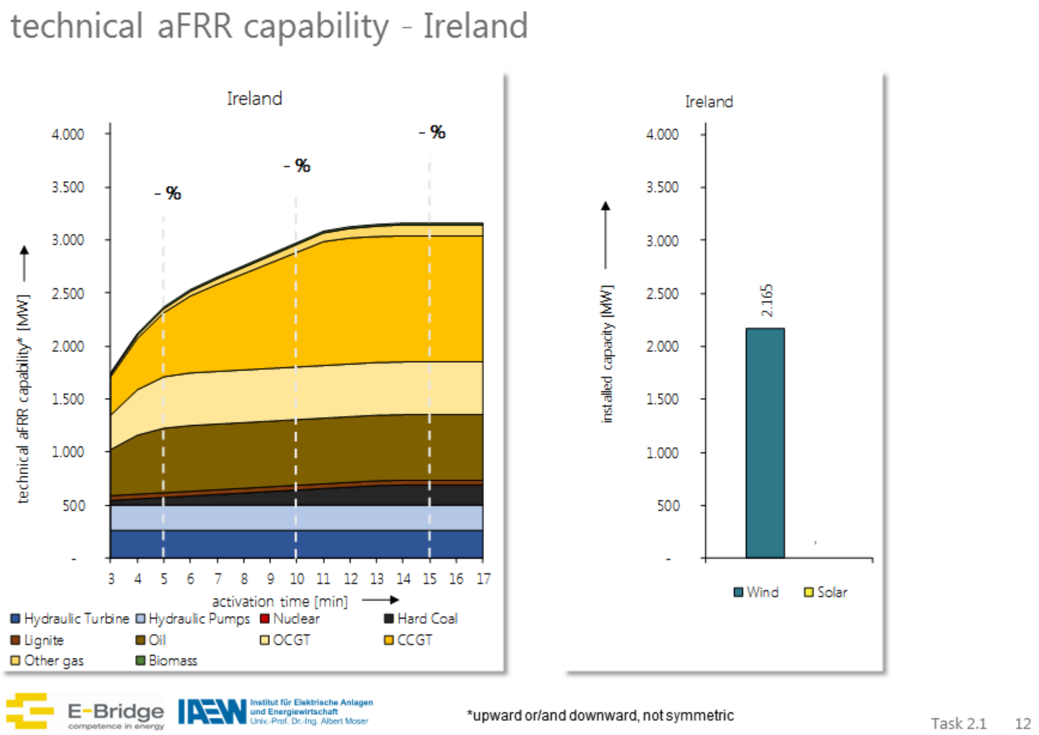


Figure 36: technical aFRR capability in Ireland

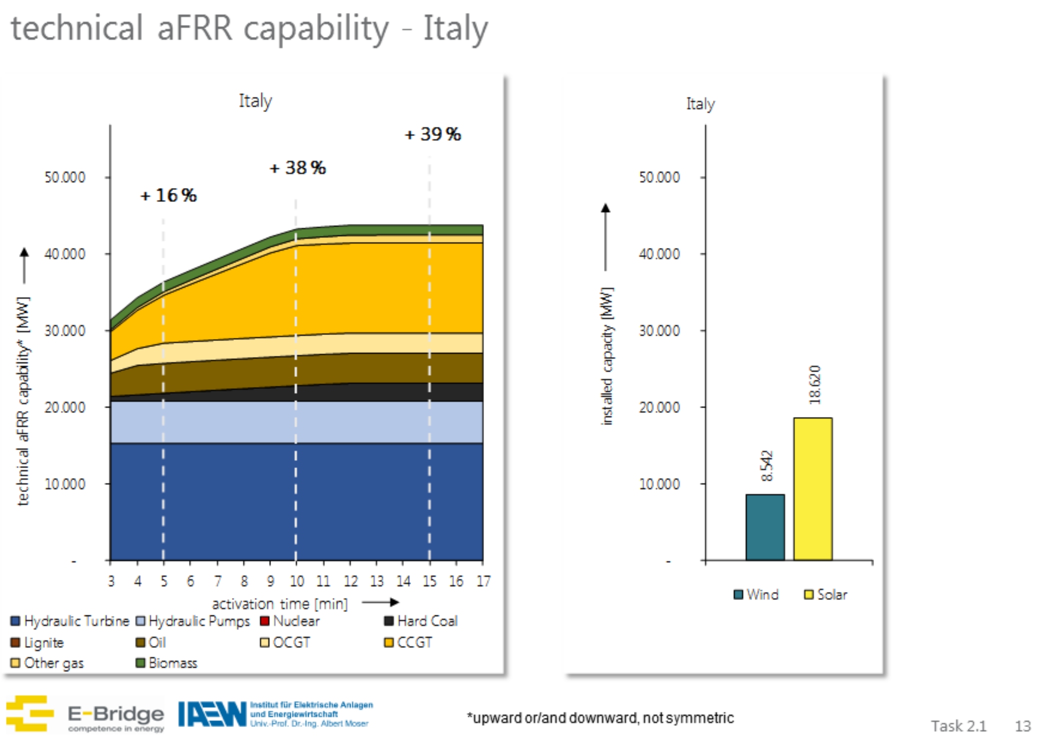


Figure 37: technical aFRR capability in Italy

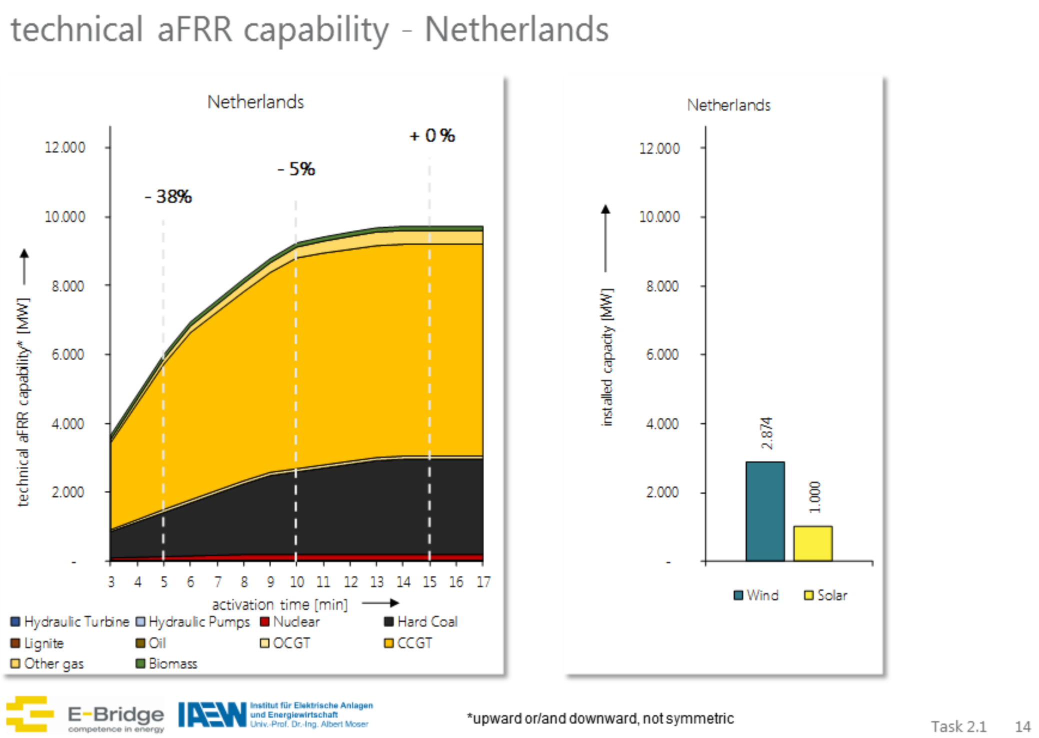


Figure 38: technical aFRR capability in the Netherlands

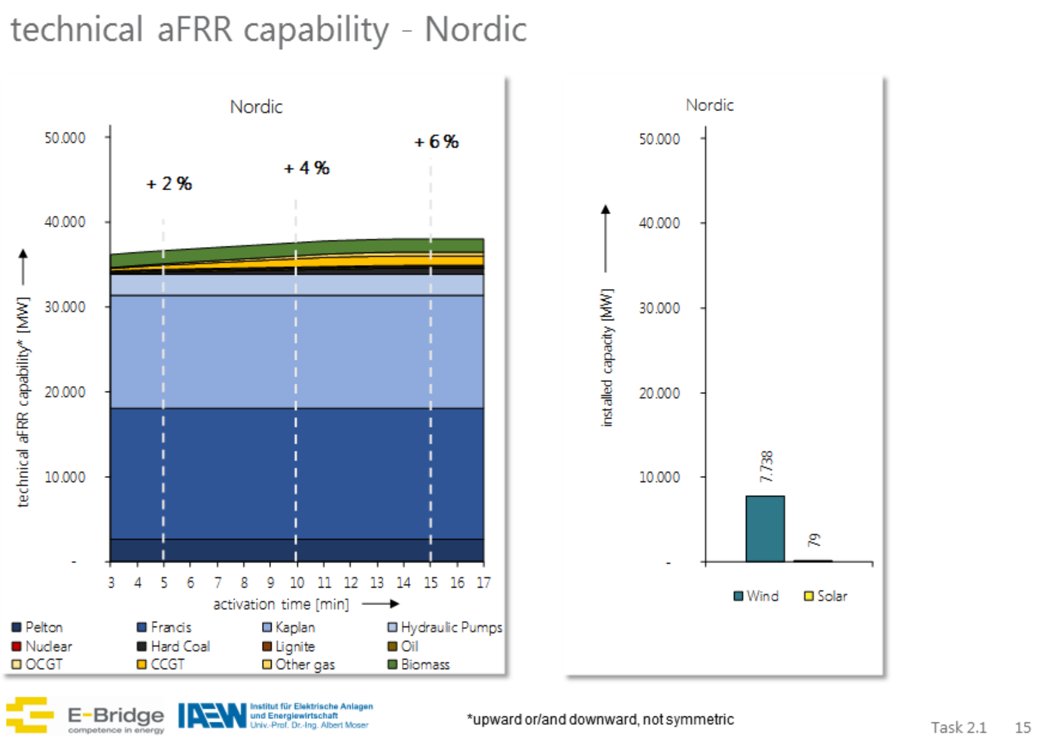


Figure 39: technical aFRR capability in Nordic

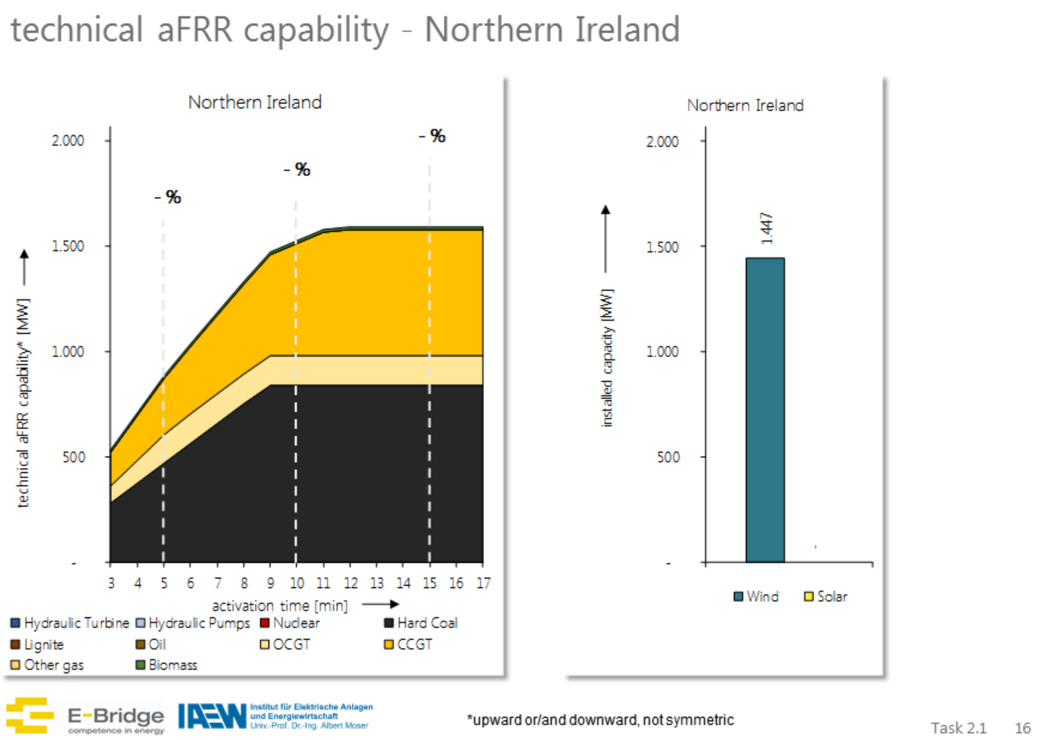


Figure 40: technical aFRR capability in Northern Ireland

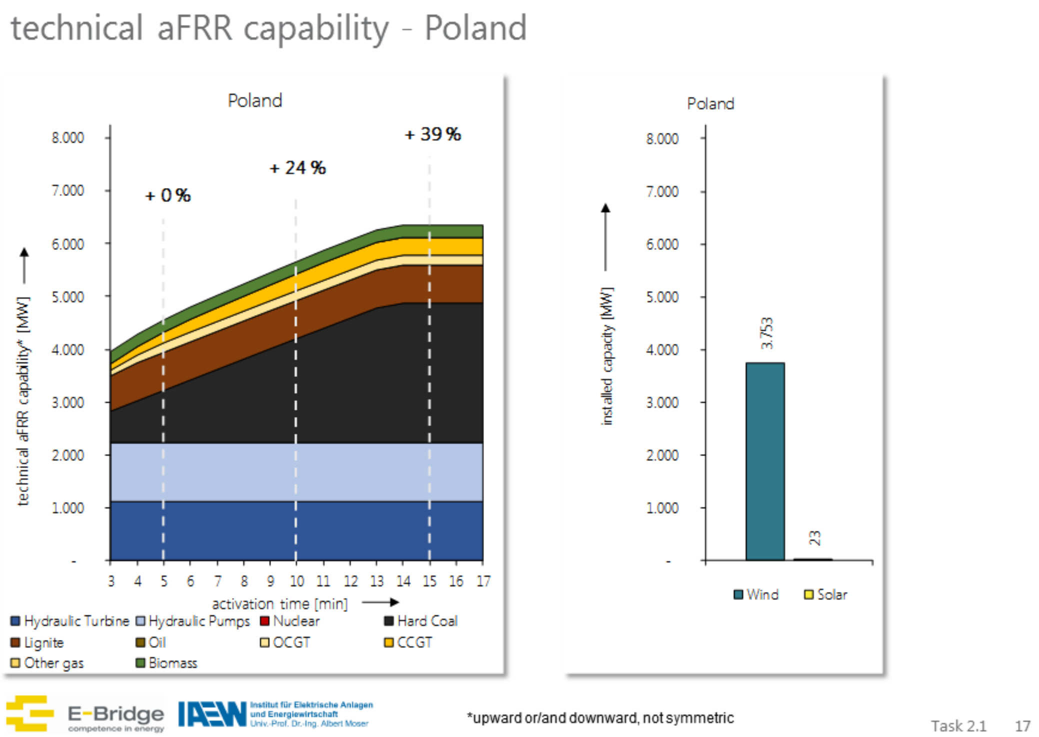


Figure 41: technical aFRR capability in Poland

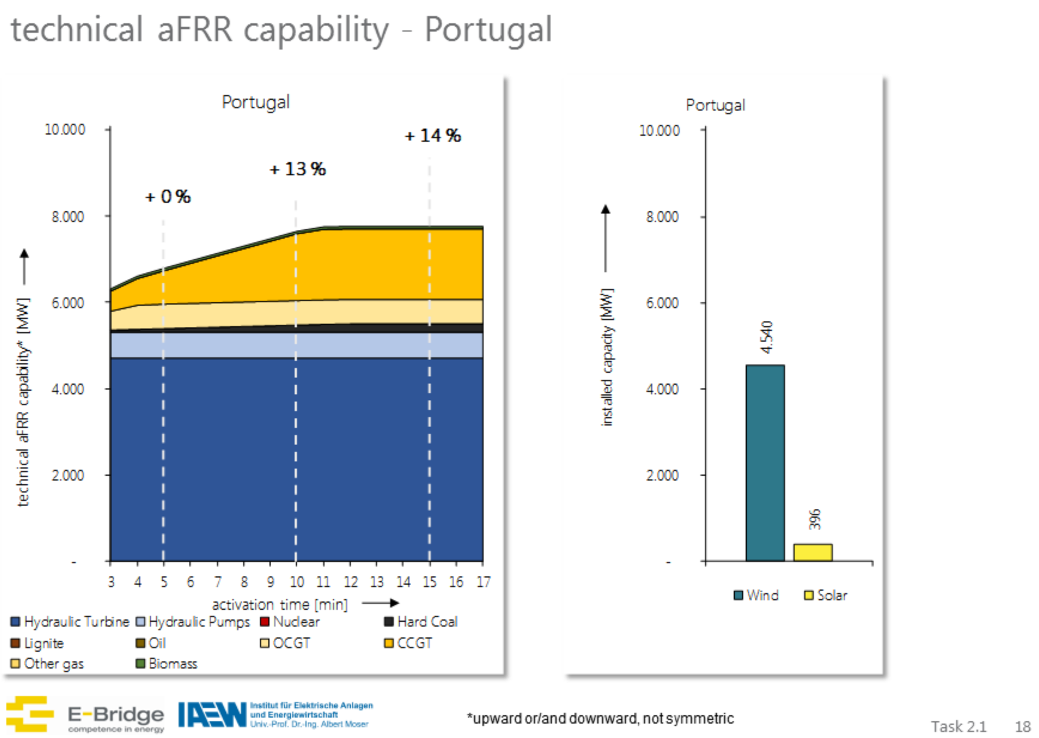


Figure 42: technical aFRR capability in Portugal

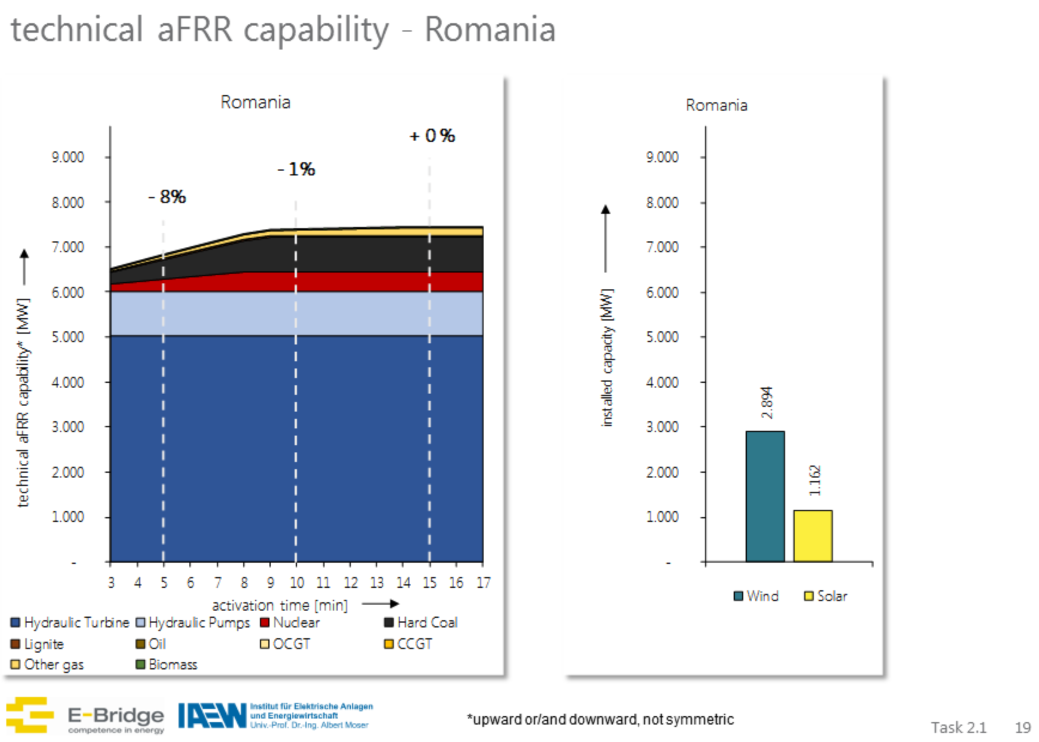


Figure 43: technical aFRR capability in Romania

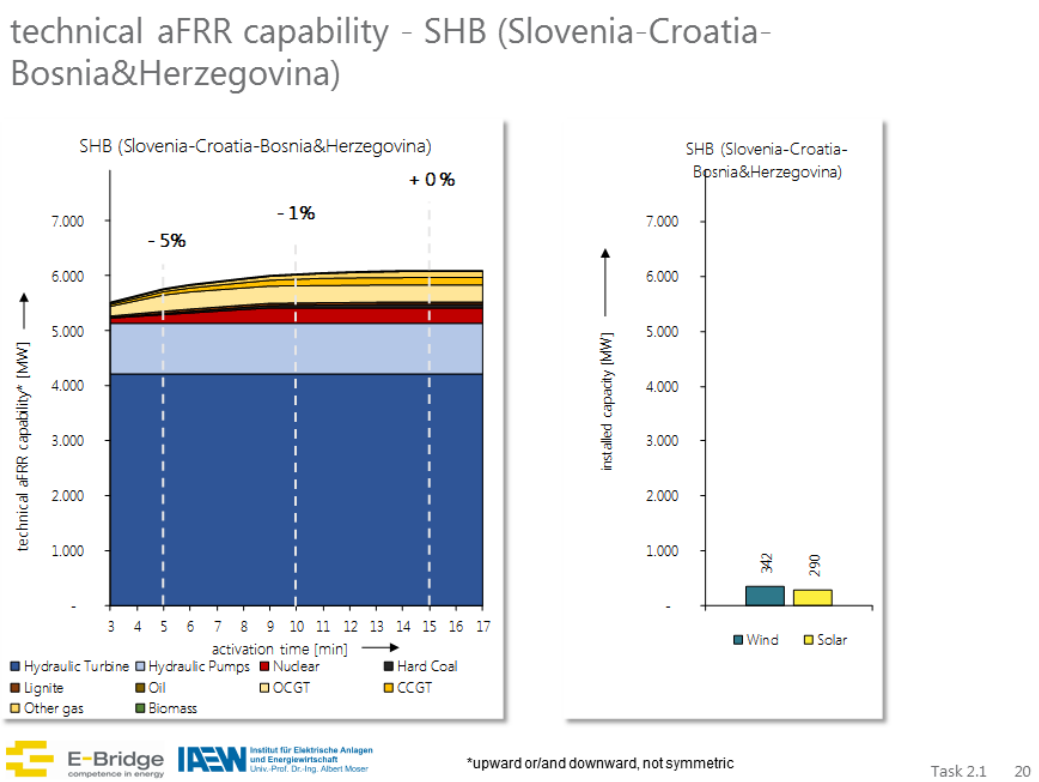


Figure 44: technical aFRR capability in SHB

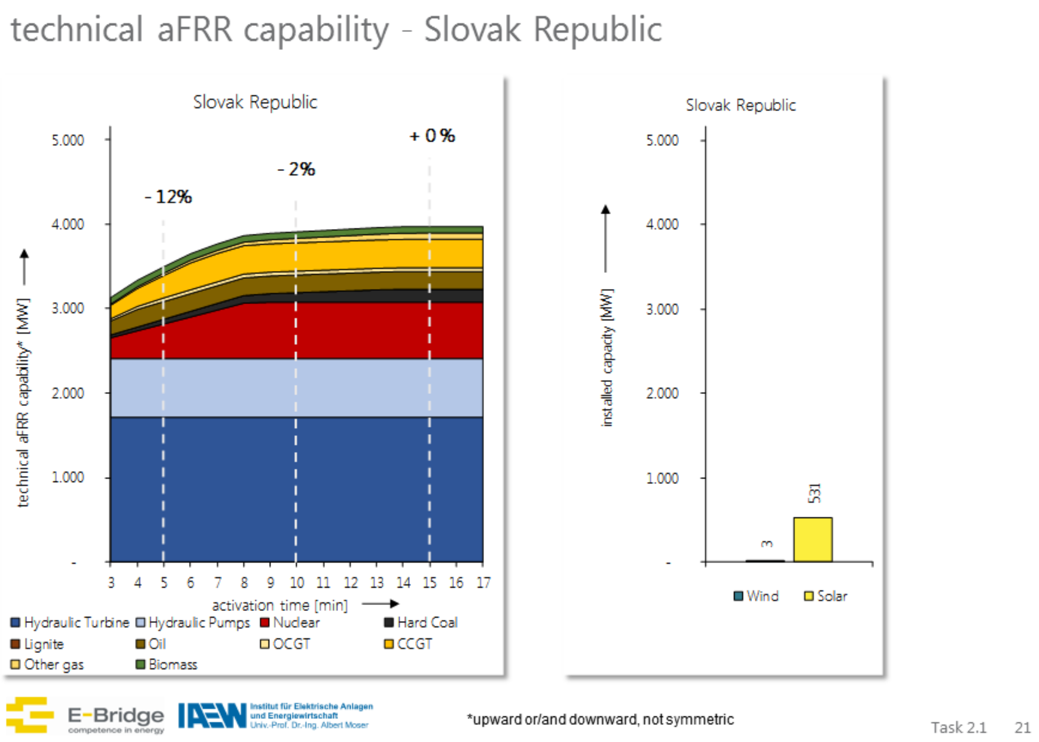


Figure 45: technical aFRR capability in Slovak Republic

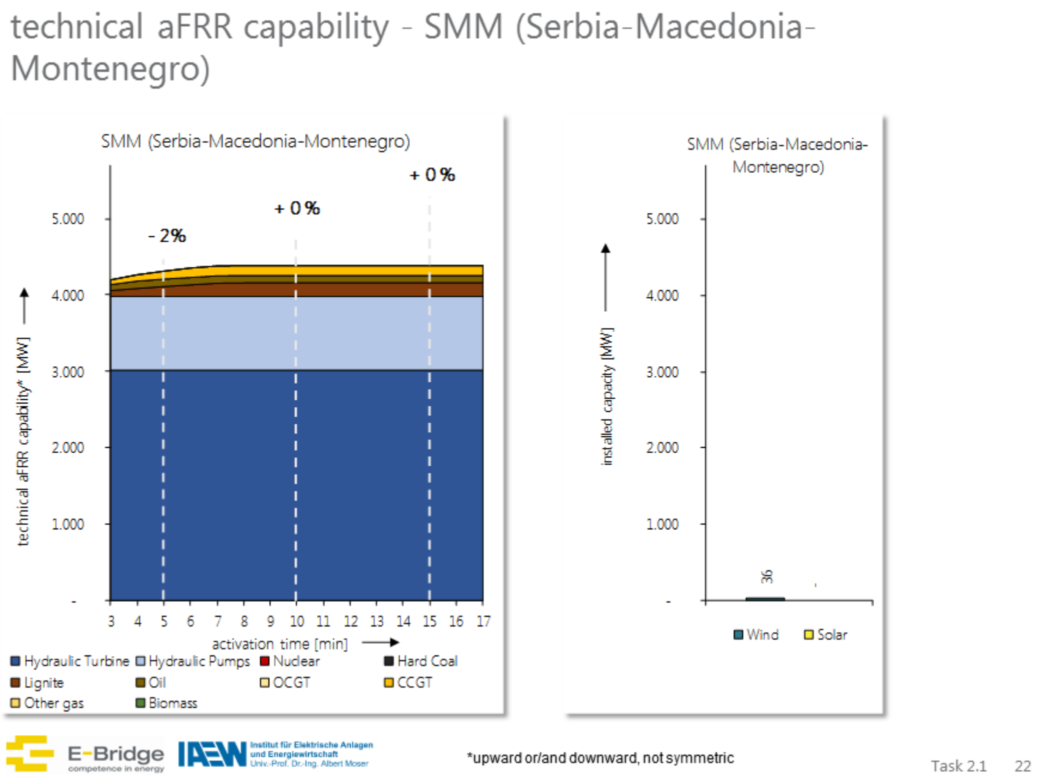


Figure 46: technical aFRR capability in SMM

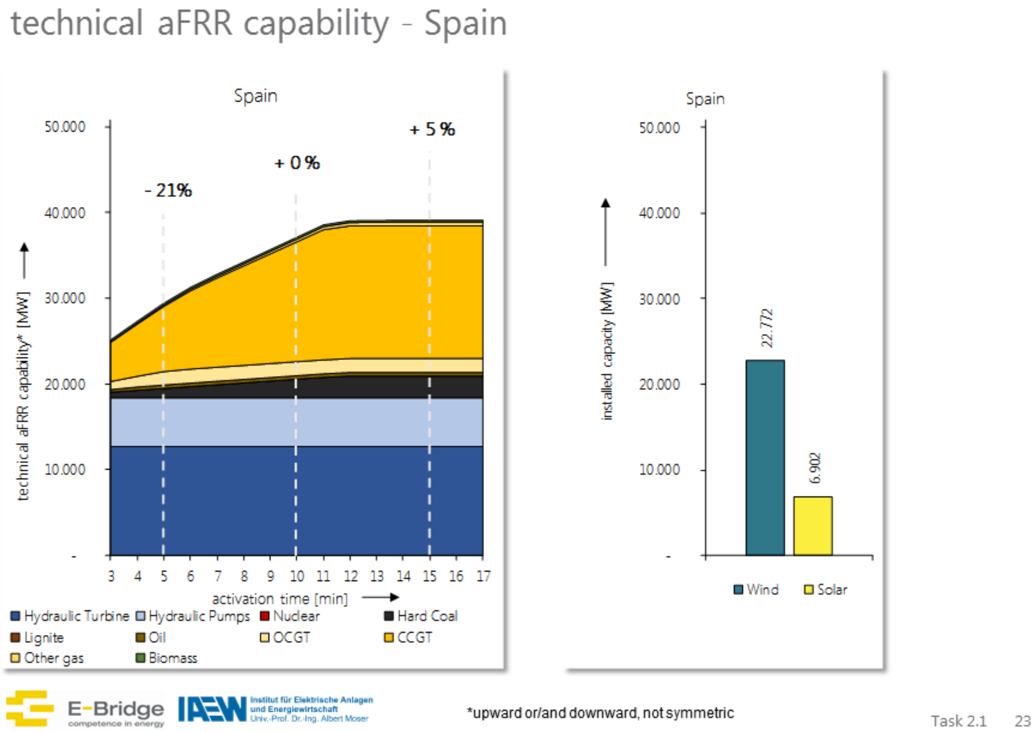


Figure 47: technical aFRR capability in Spain

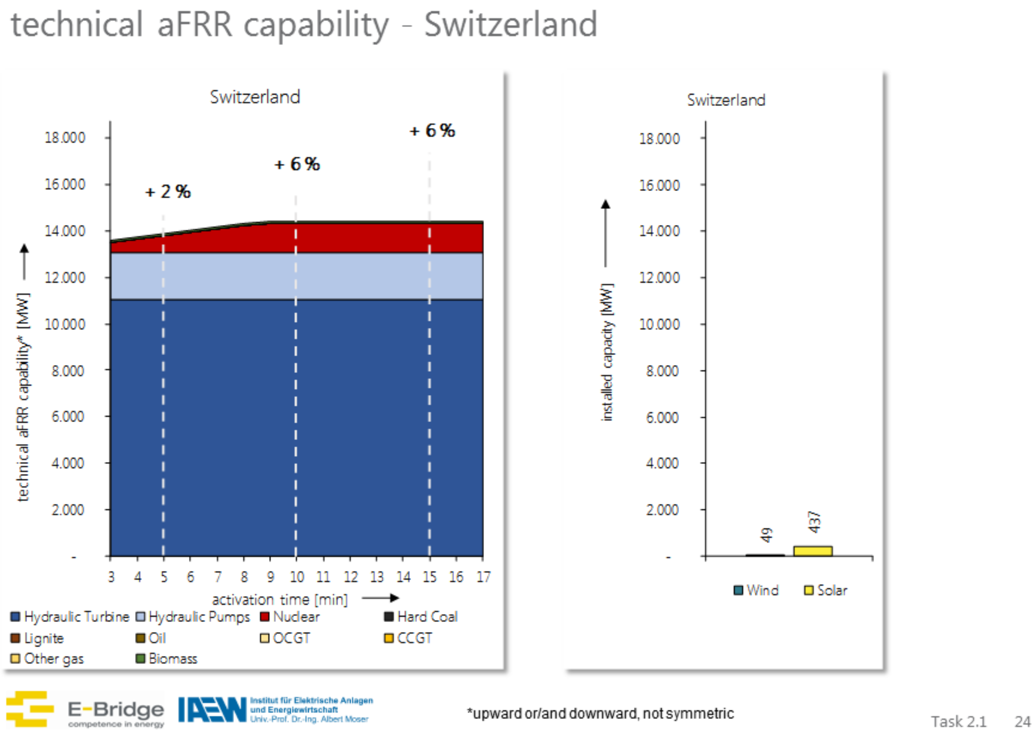


Figure 48: technical aFRR capability in Switzerland

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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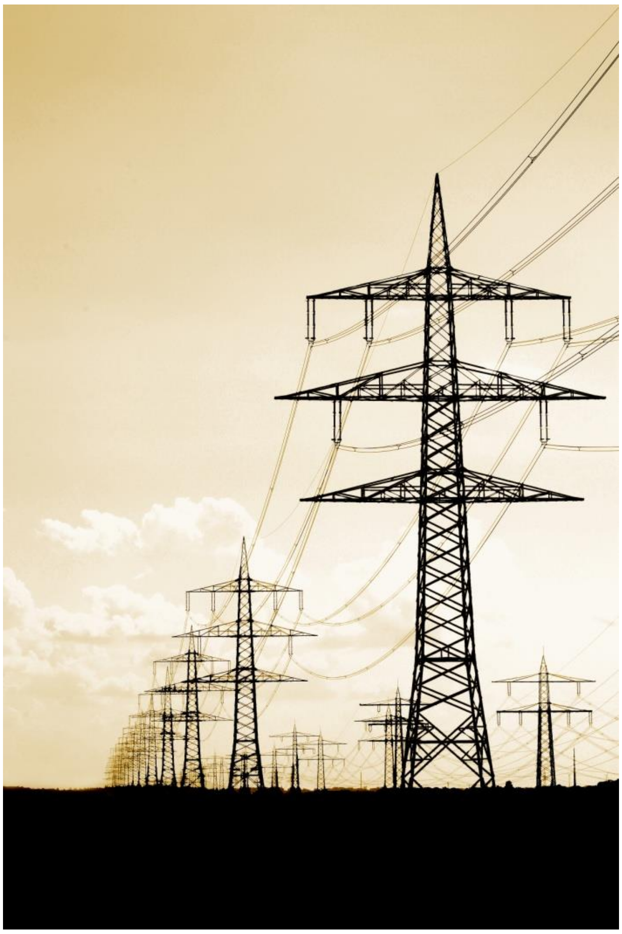

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