Delivery of downward aFRR by wind farms

October 2015

This report is the result of a close cooperation between Windvision, Enercon, Eneco and Elia to set up a pilot project testing the technical ability of wind farms to provide aFRR services to the grid. The know-how and efforts introduced by all of the parties led to a successful completion of the pilot project.

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1 Executive summary

1.1. Introduction

The installed capacity of intermittent renewable energy resources (PV, wind,...) increased significantly over the last years. A further increase is expected in order to achieve the European climate and energy goals for 2020, reaching up to an expected installed capacity of over 8000 MW in Belgium by the end of 2019. The intermittent nature and limited predictability of these renewables represent additional challenges to balance the grid.

The sustainable integration of high volumes of intermittent renewables in the system requires these resources to provide flexibility to balance the generated and consumed electricity.

In the Belgian system the Balancing Responsible Parties are responsible for balancing their portfolio on a fifteen minute level[1]. In second instance Elia is responsible to resolve any residual imbalance in the system by means of activation of flexibility offered by market parties or by activation of pre-contracted reserve capacity.

In Belgium a large share of the pre-contracted reserve capacity for Frequency Containment Reserves (FCR, former primary reserves) and Automatic Frequency Restoration Reserves (aFRR, former secondary reserves) is provided by gas-fired power plants (CCGTs).

The market conditions for these CCGT units declined over the last years as these types of units often fall out of the North-West European (NWE) merit order, with, as a result, high must run costs for these units to provide FCR and aFRR. Therefore it is important to investigate whether other resources, that are running under such market conditions (i.e. with less running gas units), could ensure the provision of these types of reserves.

Windvision (Owner), Eneco (BRP), Enercon (Supplier of windfarms) and Elia (TSO) teamed up to perform a pilot project investigating the technical capability of wind farms to provide aFRR capacity. In order to gain as much experience as possible, it was decided to physically test the delivery of downward aFRR on a real wind farm. The pilot project took place on the Estinnes wind farm of WindVision. This wind farm has a nominal power of 81 MW and consists of 10 E-126 Enercon wind turbines of 7,5 MW each and one wind turbine of 6 MW. The existing systems of the wind farm were modified in order to allow aFRR delivery. Eneco is the BRP (Balancing Responsible Party) for the wind farm and performed the daily nomination of the available aFRR capacity on the wind farm.

The focus of the pilot project was mainly on the provision of downward aFRR capacity, as the provision of upward aFRR capacity would require continuous de-rating of the wind farm (significant loss of green certificates for the power producer, and finally a high cost of the service for the system).

1.2. Delivery of aFRR services by wind farms

There are some important differences between wind farms and conventional units for the delivery of aFRR services. The most important difference relates to the reference power as of which control capability is provided (baselining):

- Centralized (fossil) power plants deliver the aFRR set point from an ex-ante, producer defined, generation profile (power) of the unit. Hence the sum of the ex-ante defined power profile and the aFRR power profile provides the desired power infeed of the power plant.
- The infeed of a wind farm is defined by (limited predictable) wind conditions. In such case it is more difficult to define the desired power infeed of the wind farm in case of aFRR delivery. There are two mechanisms to perform the baselining on wind farms.

  Under the **Balancing control mechanism** the infeed of the wind farm is continuously derated to an ex-ante defined infeed level. The aFRR set point is then delivered from this ex-ante defined infeed level on. Main advantage of this scheme is its simplicity, whereas the drawbacks are a loss of renewable generation and continuous loss of green certificates (support scheme).

[1] According to art. 157 of the Belgian Federal Grid Code

Under the **Available Active Power (AAP) mechanism** an estimation of the baseline (i.e. the infeed of the wind farm in case there would be no delivery of ancillary services such as aFRR) is performed in real-time (e.g. every 4-5 seconds) on the basis of the wind conditions and technical characteristics of the wind farm.

This baseline (AAP) is then used as reference infeed from which the aFRR set point is delivered. The main advantage of this control scheme is that there is no need for continuous de-rating of the wind farm to provide downward aFRR (and hence no loss of green certificates). The drawbacks of the AAP mechanism are its complexity (calculation of the AAP, quality control of the AAP,...). **This pilot project investigates the AAP mechanism as it is more efficient since there is no need for continuous curtailment of renewable production for the delivery of downward control power.**

The main challenges of the **AAP mechanism** are:

- **Verification of the accuracy of aFRR delivery by wind farms:** the graph below shows that the combination of the AAP error (i.e. error on the estimated AAP) and the control error (i.e. whether the difference between the estimated AAP and the measured infeed equals the required aFRR set-point) determines the accuracy of the aFRR delivery. Within this pilot project some tests are developed to check this accuracy.

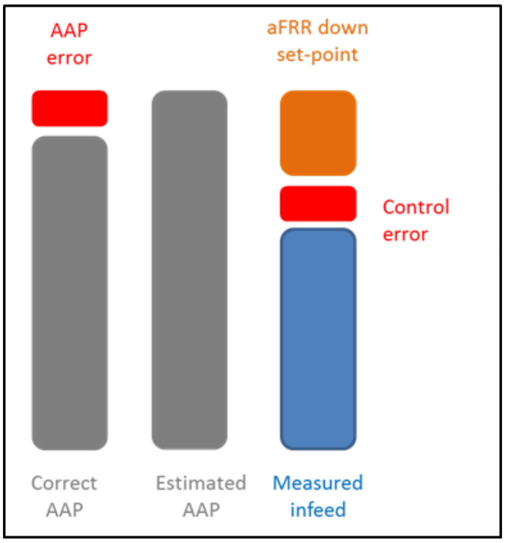

Figure 1: Difference between AAP error and control error for aFRR delivery by wind farms under the AAP mechanism

- **Accuracy of the AAP calculation under curtailed conditions ("wind farm effect"):** when curtailing a wind turbine, the downstream wind speed behind the turbine increases (i.e. less energy is withdrawn from the wind). Hence any wind turbine that is located behind this first wind turbine will face higher wind speeds and will therefore increase its infeed.

  In other words, whereas the first wind turbine is partially curtailed, the second wind turbine might produce relatively more (thereby partially offsetting the requested curtailment). This could lead to an overestimation of the AAP and hence under delivery of downward aFRR services.

  A test performed on the wind farm of Estinnes confirmed that this might be a potential issue, whereas other test on the wind farm do not clearly reveal this effect (under stable wind conditions). Under varying wind conditions the effect itself is difficult to measure.

From a market perspective the integration of wind farms in the current aFRR framework poses a number of challenges, a.o.:

- **Loss of green certificates**: A reduction of the output of wind farms for balancing purposes results –under the current Belgian support scheme- in a loss of green certificates (which are allocated on the basis of produced energy). The resulting opportunity cost therefore must be compensated within the balancing framework. This means that the support scheme has a non-negligible impact on the prices and competitiveness of aFRR capacity and/or aFRR balancing energy by wind farms.

- **The availability of wind farms** to provide aFRR capacity fully depends on wind conditions. Hence it is more difficult for wind farms to determine the aFRR capacity that can be offered (ex-ante) to the TSO. This can only be done on the basis of (imperfect) forecasting of wind conditions for the near future (one or two days ahead).

1.3. Pilot project test on the wind farm of Estinnes

The actual testing of aFRR delivery on the wind farm of Estinnes was split in two stages. In a first stage (initiation stage) tests were performed on the wind farm of Estinnes in order to perform a high level check on both the quality of the AAP calculation under curtailed and non-curtailed conditions as well as on the ability of the wind farm to control its output on the basis of an aFRR set point sent by Elia.

In a second stage (participation stage) the wind farm of Estinnes technically contributed to the Belgian aFRR balancing energy market for a period of around three months. The pilot project enabled to gain experience in delivering aFRR balancing energy on wind farms during all different stages of the aFRR framework (e.g. nomination quality, data exchange, reaction of the wind farm on the aFRR set point, settlement, AAP quality under curtailed and non-curtailed conditions,...).

Both in the initiation and participation stage the performance of the downward aFRR delivery by the wind farm of Estinnes was monitored. This performance was evaluated based on:

1. **AAP quality** (both under curtailed and non-curtailed conditions): the pilot project showed that the AAP quality for the Estinnes wind farm is good and therefore can act as a suitable reference power for aFRR delivery by wind farms. The graph below shows both the measured infeed (blue line), the estimated AAP (red line) and the AAP error (green line). The AAP error was, on average, limited to a few percentages of the actual measured feed in.

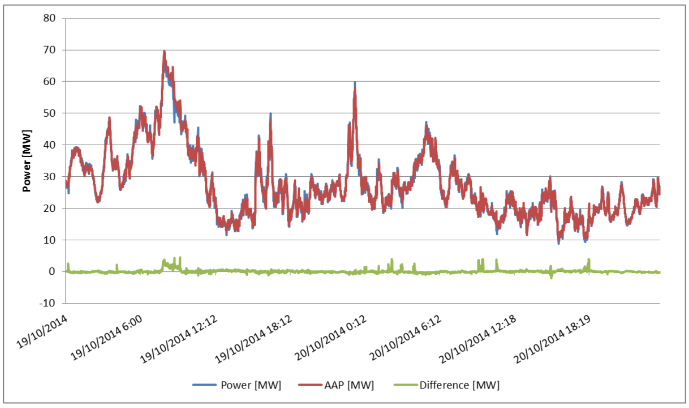

Figure 2: Illustration of AAP performance during a two day period in October 2014

Nevertheless some improvements for the AAP calculation of the Estinnes wind farm were identified:

- The value of the AAP throughout the startup of a turbine after an outage (e.g. a turbine could have been stopped due to the shade control implemented on the wind farm of Estinnes) wasn't modelled in the AAP, yielding error values for several minutes (cfr. a number of peaks of the AAP error in Figure 2).
- The turbines pitching behaviour for blade load control in high wind conditions should be taken into account more accurately in the AAP calculation.
- Furthermore a better AAP quality was observed for medium and high wind conditions than for low wind conditions.
- The calculation of the AAP is potentially affected by the requested curtailment (overestimation of the AAP) but the effect is limited (wind farm effect).

2. **Controllability of the wind farm:** as stated before, the accuracy of aFRR delivery is determined by the combination of the AAP error and the control error. During curtailment the output of the wind farm is controlled to the sum of the AAP signal and aFRR set point (negative sign for curtailment).

   The wind farm's capability to accurately control its power generation (i.e. having a low control error) is thus an important factor for accurate aFRR delivery. Tests performed on the basis of the balancing control mechanism (i.e. curtailment from an ex-ante defined constant output), showed that the Estinnes wind farm was able to deliver the required control set-point within a control error limited to 1% of the offered control capability band. This is shown by the left part of Figure 3, demonstrating the wind farm's ability to accurately deliver an aFRR set point (green line) from an ex-ante defined curtailed level (black line). The measured infeed is represented by the blue line, whereas the orange line represents the error.

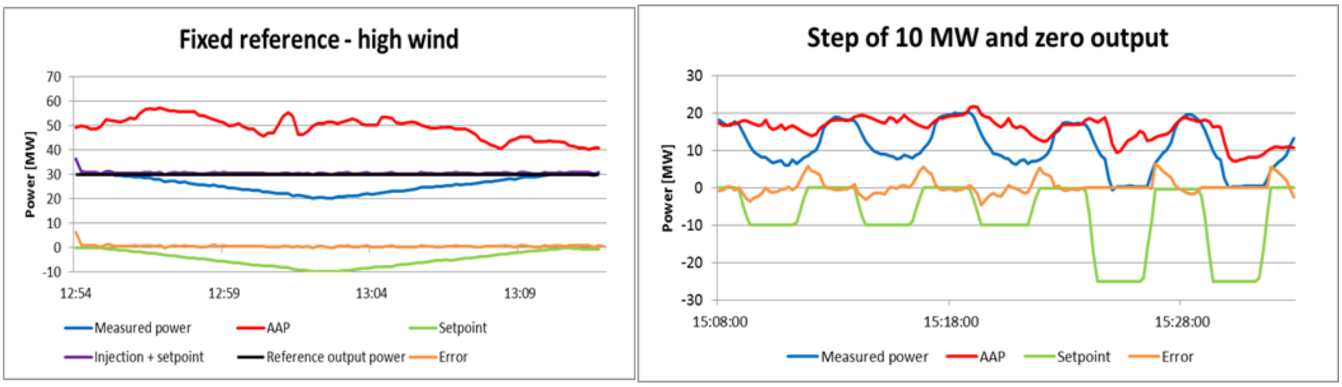

Figure 3: Illustration of AAP performance from a fixed reference and response to a step

The tests revealed that the wind farm of Estinnes has a very low minimum technical stable power and very high ramping capabilities (both upward and downward). The right part of Figure 3 shows the high flexibility of the wind farm by demonstrating its capability to provide a step response of 10 MW and curtail its output to zero. It also shows transient error peaks illustrating a.o. minimal changes in the wake effects inside the windfarm during curtailment.

Tests for the delivery of aFRR on the basis of the AAP mechanism (i.e. curtailment from the real-time calculated AAP value), showed that the Estinnes wind farm was able to deliver the required control set-point with a control error limited to 2-3% of the offered control capability band. The higher error for the AAP mechanism might be due to the dynamic behaviour of the AAP. This is shown in Figure 4, demonstrating the wind farm capability to provide a set point from the calculated AAP as a reference (red line). It can be noticed that the error is characterized by some fast, relatively limited, variations.

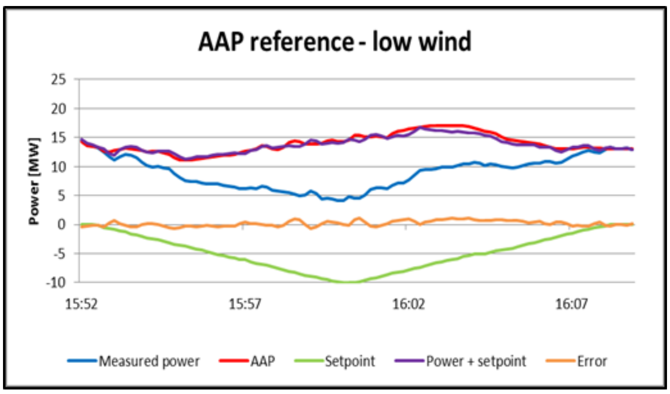

Figure 4: Curtailment of the wind farm from the AAP reference

Figure 5 shows an example of the performance of the Estinnes wind farm technically contributing to the delivery of downward aFRR to the Belgian system. In general the reaction of the wind farm to the aFRR set point is good, as is the quality of the AAP signal itself. Nevertheless it is difficult to verify whether the AAP is influenced by the aFRR set point under varying wind conditions.

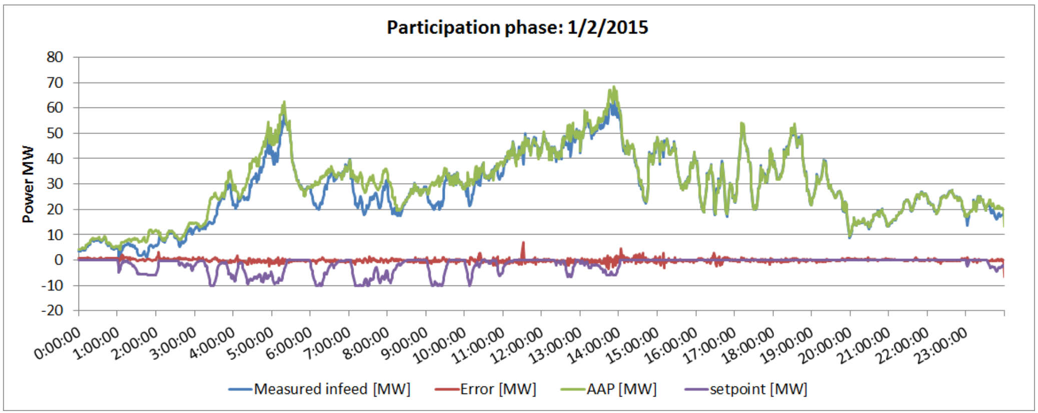

Figure 5: performance of Estinnes wind farm in delivery of aFRR (1/02/2015)

3. **aFRR nomination reliability:** during the participation phase the wind farm nominated the available aFRR volumes on different time horizons (week ahead, day ahead and intraday). Analysis showed that the wind farm was able to accurately nominate the available volumes, with increasing nomination reliability closer to real time. A performant nomination strategy should be able to accomplish a reliability of over 99% in the day-ahead time horizon.

In general the pilot revealed good potential for wind farms to participate in the aFRR market towards the future. In general the AAP method delivers promising results and the wind farm was able to curtail with a high degree of accuracy. A number of potential improvements which could add to a higher accuracy of aFRR delivery were identified. Given that the accurate calculation of the AAP is an active field of research, further improvements can be expected.

Finally we showed that, in case of performant nomination strategy, a nomination reliability of over 99% is feasible in the day-ahead time horizon.

1.4. Market analysis on the integration of aFRR by wind farms

In addition to a detailed technical analysis, a high-level market analysis was performed in the pilot project. The conclusions of the market analysis are:

- The need for continuous de-rating for the delivery of upward control power on a wind farm results in high opportunity losses (loss of green certificates, less energy sold on the market). Hence the focus in this pilot project is on the delivery of downward aFRR by wind farms.

- The current monthly procurement cycle and product duration of the aFRR capacity products act as a barrier for participation of wind farms. An evolution towards daily procurement (accurate forecasting capability of wind farms in D-1) and shorter duration of aFRR capacity products (optimally 4h – 8h blocks) will positively influence the participation of wind farms in the aFRR market.

  Nevertheless it must be emphasized that participation of wind farms in the downward aFRR capacity market requires the availability of the upward aFRR complement. Such complement might be difficult to find on 4h-8h level.

- The combination of the current pro-rata aFRR activation scheme and the energy based support schemes scheme significantly affects the possible competitiveness of wind farms in the aFRR markets.

  Elia activates all aFRR bids in a parallel and proportionate way (so called pro-rata activation). Such an activation mechanism requires a cap and floor on the aFRR energy prices to avoid inefficient activation of very expensive bids for relatively small imbalances. The floor (0€/MWh) does not allow wind farms to price in the loss of green certificates in the energy price of the downward aFRR bids.

This could be either resolved by moving to a merit order activation of aFRR (where bids are activated on the basis of price ranking) or by a change in the energy based support schemes.

The feasibility and consequences of the above required market changes to facilitate participation of wind farms in the aFRR market must be analysed in detail in the future. The analysis must also consider the requirements of the future Network Code on Electricity Balancing, fostering the integration and harmonization of the European balancing markets.

Finally the energy based support schemes for renewables results in significant differences in the aFRR activation cost structure compared to conventional units. These differences must be considered when setting up a control mechanism and an efficient incentive to ensure qualitative delivery of the service.

1.5. Pre-qualification requirements for providing aFRR services by wind farms

The pilot project shows that pre-qualification for wind farms to ensure qualitative aFRR delivery on the basis of the AAP method is highly complex as:

- The quality of the AAP calculation under both non-curtailed and curtailed (during regulation) conditions must be verified; and
- The ability of the wind farm to deliver a set-point as of the AAP must be verified.

The main difference with aFRR delivery by conventional units is that wind farms, under the AAP mechanism, deliver an aFRR set point as of the calculated AAP. Therefore if the AAP calculation is inaccurate, also the delivered aFRR will be inaccurate. Hence the quality of the delivered aFRR is determined by both the inaccuracy of the AAP calculation and the control error on the aFRR delivery from the calculated AAP. It is impossible to assess both aspects separately during curtailment (regulation) of the wind farm.

Furthermore Elia requires a highly reliable delivery of aFRR in the grid. Therefore the reliability of the nominated aFRR volumes by the wind farms must be very high (close to 100%).

The pilot provides more insights on potential aFRR pre-qualification tests for wind farms. Detailed technical requirements and targets must afterwards be defined in close collaboration with all stakeholders. Moreover the feasibility of the required market changes must be examined in more detail (in parallel with the requirements of the upcoming Network Code on Electricity Balancing).

1.6. Conclusion

The technical pilot project reveals a significant potential for wind farms to participate in the (downward) aFRR market. It is shown that wind farms are able to provide a significant amount of flexibility to the grid (high ramp rates, low minimum technical power requirements,...) and can offer these services in a reliable way (high reliability of nominated aFRR volumes).

The AAP method is a very promising mechanism to ensure efficient delivery of aFRR capacity by wind farms as it avoids the need for continuous downward curtailment. It is expected that, given the amount of ongoing research, the remaining observed issues regarding the AAP quality will be resolved in the future.

It was demonstrated that the current Belgian aFRR market design does not facilitate the stand-alone participation of wind farms in the aFRR market. The required changes are identified and must be analysed in more detail during the next years, in parallel with the implementation of the requirements of the upcoming Network Code on Electricity balancing (fostering the integration and harmonization of the European balancing markets).

Last the study focused on how to verify technical requirements that are needed to ensure a qualitative delivery of aFRR capacity by wind farms. These requirements and pre-qualification targets must be determined later on in close collaboration with all stakeholders.

The pilot project reveals, both from technical and market perspective, the required changes to be investigated in the future to enable wind farm participation in the aFRR markets in the future.

2 Glossary & abbreviations

AAP	Available Active Power
aFRR	Automatic Frequency Restoration Reserves
ARP	Access Responsible Parties
BRP	Balancing Responsible Parties
CCGT	Combined Cycle Gas Turbines
CHP	Combined Heat and Power
CIPU	Coordination of the Injection of Production Units
DC	Direct Current
ENTSO-E	European Network of Transmission System Operators for Electricity
FCR	Frequency Containment Reserves
FCU	Farm Control Unit
GC	Green Certificates
LFC	Load Frequency Containment
MADP	Mean Absolute Deviation Percent
mFRR	Manual Frequency Restoration Reserves
NWE	North-West European
NWS	Nacelle Wind Speed
RES	Renewable Energy Sources
RR	Replacement Reserves
SCADA	Supervisory Control and Data Acquisition
TSO	Transmission System Operator
WFPS	Wind Farm Power Station

3 Introduction

3.1. Context

The installed capacity of intermittent renewable energy resources (PV, wind,...) increased significantly over the last years. A further increase is expected in order to achieve the European climate and energy goals for 2020, reaching up to an expected installed capacity of over 8000 MW in Belgium by the end of 2019.

In electricity grids it is of vital importance to maintain the balance between electricity generation and consumption at all times in order to keep the system frequency within an acceptable range. The massive penetration of intermittent renewables results in an additional challenge for keeping this balance.

The reasons for this challenge are on the one hand that the generated power by these resources is mainly defined by weather conditions, regardless of the instantaneous demand for electricity (the energy based support schemes in place and the near zero marginal cost incentivize renewables to maximize their output). On the other hand the generation of these units has an intermittent character and can only be predicted up to a certain precision level.

In the past a large share of the flexibility to balance the system was delivered by centralized fossil power plants. In the future there will be periods where, depending on weather conditions, most of the energy will be produced by renewables (with less running fossil power plants).

In such cases it is important that the available resources in the system, including intermittent renewables, provide sufficient flexibility to balance the system. The sustainable integration of high volumes of intermittent renewables in the system requires these resources to provide their share of flexibility for the system to balance the generated and consumed electricity.

Conform art. 157 of the Belgian federal grid code, Balancing Responsible Parties (BRP[2]) are responsible for balancing their portfolio on a fifteen minute level in Belgium (by accessising market flexibility or by adjusting generation and/or consumption in their own portfolio). They can also support (under certain conditions) the balance of the Belgian LFC Block[3] up to real-time.

In second instance Elia is responsible for controlling the residual imbalances in the system. Therefore Elia utilizes on the one hand remaining flexibility in the system and on the other hand ex-ante procured reserve capacity. In Belgium a large share of this reserve capacity of Frequency Containment Reserves (FCR, former primary reserves) and Automatic Frequency Restoration Reserves (aFRR, former secondary reserves) is currently provided by gas-fired power plants (CCGTs).

The market conditions for these CCGT units declined over the last years as these types of units often fall out of the NWE merit order. This results in high must run costs for these units to provide FCR and aFRR (spinning reserves). Therefore it is important to investigate whether other resources that are in the merit order could ensure the provision of these types of reserves.

The diversification of aFRR resources is even more important as Elia estimates that the required aFRR needs will increase towards the future, whereas currently a large share of the resources providing this service (CCGTs,...) is being mothballed or decommissioned.

Windvision, Eneco, Enercon and Elia teamed up to perform a pilot project to investigate the technical capability of wind farms to provide aFRR capacity. In order to do so tests were performed on the wind farm of Estinnes.

The focus of the pilot project is mainly on the provision of downward aFRR capacity, as the provision of upward aFRR capacity would require continuous de-rating of the wind farm (significant loss of green certificates, and finally a high cost of the service for the system). It is considered that under the current energy based support scheme the delivery of upward aFRR by wind farms would only be economically interesting under extreme and very rare market conditions.

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[2] Balancing Responsible Parties in Belgium are also referred to as Access Responsible Parties (ARPs).

[3] The LFC Block is the area for which a TSO is responsible to regulate imbalances to zero and to dimension the required reserves.

In second instance a high level analysis on whether the Belgian aFRR market allows for the participation of wind farms in the aFRR market was performed, resulting in some recommendations for market changes. The feasibility and implementation of these recommendations must be considered in parallel with international developments in the balancing markets.

In this perspective the future European integration and harmonization of balancing markets, such as set forth by the Framework Guidelines of Electricity Balancing [1] and the draft Network Code on Electricity Balancing [2], will introduce significant changes in national balancing markets during the next years. On a regional level Elia and TenneT (Dutch TSO) performed a pilot project study [3] on the design of a common balancing market (including aFRR framework). In addition a joint qualitative comparison study between the Dutch, German and Belgian balancing market specifications [4] was performed. In a next stage the Dutch, German, Austrian and Belgian TSO created an Expert Group to discuss, amongst others, a target model for the aFRR framework. The yearly ancillary services survey of ENTSOe provides an overview of the current state of play of the European balancing markets [5].

Last an overview is provided of some required technical capabilities for wind farms to participate in the aFRR market. As further work the required changes in the aFRR balancing markets must analysed. Moreover a wide consultation of the required technical requirements for wind farms to participate in the aFRR market must be held.

3.2. Organization of the pilot project

This technical pilot project investigates the delivery of downward aFRR control power by wind farms. In order to gain as much experience as possible, it was decided to physically test this on a wind farm. The pilot project took place on the Estinnes wind farm of WindVision. This wind farm has a nominal power of 81 MW and consists of 10 E-126 Enercon [6] wind turbines of 7,5 MW each and one E-126 Enercon wind turbine of 6 MW.

The turbines are amongst the most powerful turbines on the market, with a rotor diameter of 127 metres and a total height of nearly 200 metres. The directly driven synchronous generator and innovative modular full-scale converter allow for a wide range of technical options for adaptation to the grid conditions and new requirements.

The grid management system of the Enercon wind turbines consists of a rectifier, DC link and modular inverter system. To ensure that the generated power is properly fed into the grid, voltage, current and frequency are constantly recorded at the point of reference and transmitted to the wind turbine control system. The reference point is located on the low-voltage side of the wind turbine transformer. The grid management system enables feeding the generated power into the grid in accordance with grid code requirements and allows for reliable and continuous turbine operation in grids with heavily fluctuating voltage or frequency.

The wind turbines, in cooperation with the installed SCADA System and the wind farm controller (SCADA FCU) may be modified to comply with new requirements, such as ancillary services and the delivery of control reserve as discussed in this report.

The Farm Control Unit (FCU) offers a platform for exact and rapid wind farm control by controlling the individual wind turbines and implementing a closed loop control on wind farm level. A number of tasks and regulations are already stipulated in the grid code requirements for wind farms. To meet these demands and assume the tasks, various interfaces are available for signal exchange between the utility and operator-owner.

Depending on the stipulated connection requirements, the FCU offers a solution for quick control purposes, with a response time down to less than 1s. Through the use of an ENERCON SCADA FCU, various control concepts for active and reactive power, voltage and the wind farm´s power factor are possible.

The wind farm from Estinnes was modified from its standard configuration to deliver aFRR in the framework of this technical pilot project.

The farm was constructed in 2010. The power curve of the E-126 wind turbines is shown in Figure 6. The wind farm itself is shown in Figure 7.

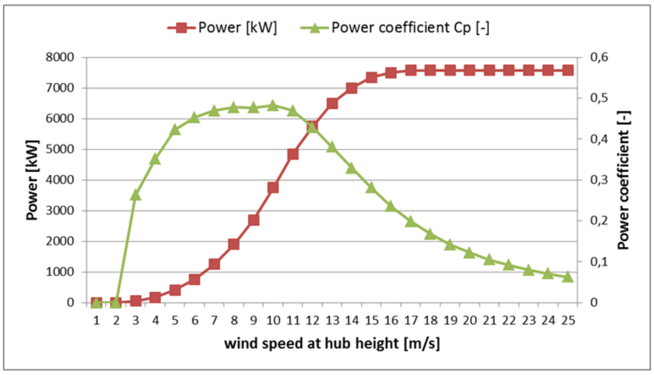


Figure 6: Power curve of Enercon E-126 wind turbine

Figure 7: The wind farm of Estinnes (source: Enercon, 2011)

The layout of the wind farm and the leading wind direction can be found in Figure 8.

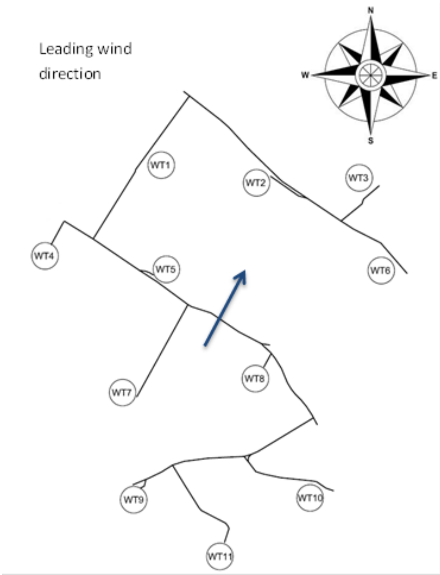


Figure 8: Lay-out of the wind farm of Estinnes and leading wind direction

During the pilot project no commercial aFRR service was delivered by the Estinnes wind farm to Elia. The main purpose was to test the technical feasibility for wind farms to provide downward aFRR.

This pilot project formulates the necessary conditions and changes that must be investigated to develop a commercial aFRR down service by wind farms in the future. Only for the framework of these tests the lost green certificates were compensated by Elia.

The pilot project was commonly performed by Windvision, Enercon, Eneco and Elia. The following paragraphs give a short overview of the roles of the different parties:

- **Windvision Belgium SA** is the owner, operator and developer of the wind farm of Estinnes. Windvision was involved in all aspects of the project, such as settlement of lost green certificates, forecasting of the volumes of aFRR capacity that could be delivered to Elia, providing technical information and data,...
- **Enercon GmbH** is the manufacturer of the wind turbines of Estinnes. Enercon provided technical assistance for enabling the wind turbines to perform the tests and provided turbine data. Enercon supported the parties in the interpretation of results and performed technical analysis where needed.
- **Eneco Energy Trade NL** is the Balancing Responsible Party of the wind farm of Estinnes. Within this project Eneco enabled to set up the downward aFRR framework and provided aFRR nominations to Elia.
- **Elia**, being the Belgian Transmission System Operator, has to ensure safe, secure and efficient operation of the Belgian grid. Elia performed a coordinating role within this pilot project and was mainly involved in setting up the framework for this test and in analysing the results.

The report is a joint effort of all involved parties in the pilot project.

3.3. Added value of the pilot project

In Belgium most of the aFRR capacity is delivered by gas-fired power plants (CCGT units). Market conditions for these units declined over the last years, resulting in high must run costs for these units to provide aFRR capacity to the TSO. Furthermore Elia estimates that the required needs of aFRR capacity will slightly increase [7] towards the future, whereas a share of resources currently providing this service to Elia announced mothballing or decommissioning.

Therefore it is important to investigate the diversification of aFRR resources. This pilot project is a first step to investigate technical aspects regarding the delivery of downward aFRR by windfarms to Elia (such as technical capability, forecasting, communication,...).

Whereas technically wind farms might also be capable of providing upward aFRR capacity, it was considered here that, under the current renewables support scheme, the continuous de-rating would result in a significant loss of green certificates. Hence the delivery of such service can only be economically interesting under extreme and very rare market conditions.

It is therefore expected that the delivery of downward aFRR capacity by wind farms must be complemented by the delivery of upward aFRR capacity by other resources (CCGT, CHP, biomass,...). The delivery of downward aFRR could lower the amount of must run units for aFRR as such units then should only deliver upward aFRR capacity instead of symmetrical upward and downward aFRR capacity bands..

The main goal of this pilot project is to allow both market parties and Elia to gain experience regarding the delivery of (downward) aFRR services on wind farms. The report provides answers on fundamental questions such as:

- Are wind farms technically capable to provide (downward) aFRR services to the TSO?
- What are the relevant differences between wind farms and conventional units for delivering aFRR services? How to overcome these differences?
- Does the Belgian aFRR market design enable participation of wind farms in the aFRR market? What are the required changes to enable this?
- What is the impact of the energy based renewable support schemes in place on the delivery of (downward) aFRR services by the TSO?
- How can wind farms participate in the aFRR reserve capacity market? How can they participate in the aFRR balancing energy market?
- Can a single wind farm nominate (ex-ante) a reliable amount of aFRR capacity to the TSO? How reliable is the nominated service?
- ...

In this pilot project the Estinnes wind farm technically contributed, for a period of about 3 months, to the delivery of aFRR in the Belgian aFRR market in order to answer the above mentioned questions. The results are shared within this report.

In order to facilitate future participation of wind farms in the aFRR market it is important to provide a set of technical requirements for future pre-qualification. During this pilot project Elia gained experience with the required technical aspects for a qualitative delivery of aFRR services by wind farms. An overview of these technical requirements is provided. The observed performance of the Estinnes wind farm is provided as an example.

The technical requirements and pre-qualification targets must be defined in close collaboration with all stakeholders. Hence at this stage only some considerations are formulated in the report, on the basis of the experience gained over the testing period.

3.4. Report structure

Chapter 4 first provides an overview of the actual Belgian aFRR market framework. A high level overview of literature on the delivery of control power by wind farms is provided in Chapter 0.

Chapter 6 focuses on the challenges for wind farms to provide downward aFRR. Differences between conventional units and wind farms are highlighted. The chapter provides more information on the calculation of the Available Active Power on the Estinnes wind farm, as well as the control mechanism used to deliver aFRR balancing energy. Furthermore the applied nomination strategy to define the ex-ante nominated aFRR volume for the Estinnes wind farm to Elia is described.

Chapter 7 provides an overview of the different tests for the provision of downward aFRR by the Estinnes wind farm, along with an analysis of the results. Chapter 8 performs a high level investigation on whether the actual Belgian aFRR market design enables participation of wind farms in this market. Some recommendations for market changes, to be further investigated in the future, are formulated.

Chapter 9 provides an overview of the required technical capabilities for wind farms to provide aFRR control power to the TSO. The observed performance of the Estinnes wind farm is provided as an example. The technical requirements and pre-qualification targets must be defined in close collaboration with all stakeholders.

4 Belgian aFRR market framework

4.1. Introduction to current aFRR framework

In Belgium the majority of the aFRR is delivered by CCGT plants. The main characteristics of the Belgian aFRR market design are summarized below.

A difference is made between the aFRR capacity market and the aFRR balancing energy market. Elia as a TSO performs an ex-ante procurement of aFRR capacity in order to secure the continuous availability of a minimum volume of aFRR balancing energy in the system. A market party providing aFRR capacity has the obligation to bid in (at least) the contracted volume of aFRR balancing energy bids. In this market the remuneration consists of a capacity fee [€/MW/h].

In the aFRR balancing energy market parties with pre-contracted aFRR capacity, as well as market parties without pre-contracted aFRR capacity, can bid in for aFRR balancing energy in day-ahead market. The remuneration in this market consists of a payment for activated aFRR energy [€/MWh].

4.1.1. aFRR capacity

As of 2015 Elia procures all the required aFRR capacity on a monthly basis. There is a combined procurement of FCR and aFRR capacity in order to minimize the total cost (linking between FCR and aFRR capacity bids is allowed).

The aFRR capacity is procured separately for peak and off-peak periods and for the upward and downward direction. Links can be introduced between peak and off-peak and upward and downward aFRR bids. Contracted capacity must be continuously available (100%). A day-ahead secondary market, where aFRR providers can bilaterally exchange aFRR obligations, enables the providers to accomplish this. Table 1 provides an overview of the Belgian aFRR capacity market.

Table 1: aFRR capacity characteristics

aFRR capacity product	Value
Procurement cycle	Monthly
Procurement lead time	Three - two weeks ahead of delivery period
Product characteristics	• Monthly product • Peak – long off-peak product • Upward and downward product
Full activation time	7,5 minutes
Response time	30 seconds
Linking of bids	Possible: • between upward and downward; • between peak and long-off-peak; aFRR capacity bids (as well as between FCR and aFRR capacity bids)
Availability requirement	100% availability required
Minimum bid size	1 MW
Maximum bid size	Not applicable (except for BRPs having no aFRR back-up units available (limit of 50 MW))
Provision by Elia	Portfolio based (list of prequalified aFRR units) Co-optimization of FCR and aFRR procurement (cost minimization for the combination of FCR and aFRR capacity)
Remuneration	Pay-as-bid
Secondary market	• Day-ahead bilateral secondary market • Exchange aFRR obligations on QH basis. • Gate closure time at 13h30 in D-1

Penalty for non-availability	Uniform penalty for all market parties; Designed to incentivize use of secondary market

Chapter 8 investigates whether the design of the actual aFRR capacity market facilitates the participation of wind farms in this market.

4.1.2. aFRR balancing energy

Contracted aFRR capacity bids have the obligation to offer at least the contracted aFRR capacity volume as aFRR energy bids in day-ahead (taking exchange of aFRR obligation on the secondary market into account). Also non-contracted providers are allowed to introduce aFRR energy bids in day-ahead[4].

Elia selects a maximum volume of 150 MW of the aFRR energy bids with the cheapest activation price (separately for upward and downward direction). These selected bids can either be pre-contracted or not. The non-selected aFRR energy bids automatically pre-qualify as non-contracted manual CIPU bids.

Elia performs pro-rata activation of the selected aFRR bids, as illustrated in Figure 9. In such mechanism all the selected aFRR bids are activated in parallel (proportional to their bid size), regardless of the related aFRR energy price. From a technical point of view such a mechanism allows for very high active ramp rates. In order to avoid excessive aFRR activation prices (pro-rata mechanism doesn't consider prices), Elia has put in place a cap and a floor for the aFRR energy price. The selection of a maximum amount of 150 MW of cheapest aFRR bids enables competition on the aFRR energy prices.

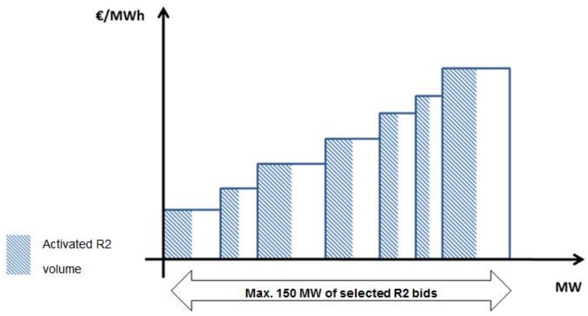


Figure 9: Illustration of aFRR activation

Table 2 provides a more detailed overview of the main characteristics of the aFRR balancing energy market.

Table 2: aFRR balancing energy characteristics

aFRR balancing energy	Value
Procurement mechanism	• Obligation for contracted aFRR capacity (via primary or secondary market) to bid in at least the contracted capacity as aFRR balancing energy bids; • Non-contracted providers can also introduce bids
Bidding process	Bidding process is unit based
Activation process	Portfolio based activation
Product resolution	15 minutes
Gate closure time for energy bids	Day before delivery (D-1) at 15h00
Remuneration	Pay-as-bid
Selection mechanism	Elia selects a maximum of 150 MW of the cheapest aFRR balancing energy bids in each direction (asymmetric selection).

[4] In case they have signed an aFRR general framework contract.

Pricing restrictions	Floor: 0 €/MWh Cap: +/- 100 €/MWh[5]
Minimum bid size	1 MW
Activation mechanism	Pro-rata activation
Activation cycle	New set point sent out every 4s – 5s
Required reaction	• The Elia activation signal respects the contractual ramp rate (determined by 7,5 minutes full activation time) • The aFRR provider must therefore follow in real-time the signal sent out by Elia (on 4s – 5s basis) • Verification on 10s basis
Activation signal	One aggregated delta power signal is sent out to the aFRR provider • Aggregated for upward and downward activation • Aggregated for all aFRR balancing energy bids The provider determines which resources to activate.
Compensation of BRP portfolio	The requested amount of activated aFRR balancing energy is compensated in the BRP perimeter (hence in case of perfect delivery there is no imbalance related to the delivery of aFRR balancing energy).

Chapter 8 investigates whether the design of the actual aFRR balancing energy market facilitates the participation of wind farms.

[5] Fuel cost of a 50% efficient gas unit [€/MWh_el] + 40 €/MWh

5 Literature study

5.1. Research on the participation of wind generation in ancillaries

Currently, with some exceptions, wind generation is not participating actively in the balancing of the electricity system[6]. In that sense, either technical requirements have not been studied or specified, or the technical and economic feasibility has not been demonstrated.

Given the expected increased penetration of variable RES (in particular wind) for the horizon 2020 and beyond, it is clear that the participation of wind generation in the ancillary services is required to keep a high level of security of supply.

The REserviceS project [8] provides a qualitative assessment of the capabilities of wind generation for providing frequency support, voltage support and system restoration, both for current (FCR, aFRR & mFRR, RR) as well as for possible new services (e.g. synthetic inertia, ramping margin, etc.). A qualitative assessment of the cost of the provision of such services is also presented in paragraph 8.2 of REserviceS project document.

Participation of wind generation in the provision of frequency control involves the need for a methodology that allows both for a reliable forecast of the volume of the service that can be offered and the correct measurement and settlement of the provided services. Two methods are investigated in [9] and [10] to enable the provision of control reserve from wind farms: **the balancing control mechanisms** (also referred to as planned power production mechanism) and **the available active power (AAP) mechanism**.

In the **balancing control mechanism** the wind farms are continuously curtailed to a scheduled power level that can be achieved with a high level of certainty (e.g. probabilistic forecast that in >99% of the cases it is expected that this power level will be achieved). The delivered amount of control power is then calculated as the difference between the scheduled set point and the actual feed-in of the wind farm.

In the **available active power (AAP) mechanism** the power level that could have been produced in case of the absence of the delivery of control power is calculated continuously (the so-called Available Active Power or AAP). Here the delivered amount of control power is calculated as the difference between the AAP and the actual feed-in of the wind farm.

The difference between these two methods is explained in more detail in section 6.1.

The **AAP mechanism** is more complex than the **balancing control mechanism** as it requires real-time state-of-the-art calculations of the AAP. The advantage however is that there is no need for continuous de-rating of the wind farms to provide control power.

Different methods for the computation of the AAP exist of which the “physical model” (combining data like wind turbine position in the wind farm, hub heights, rotor diameters, etc.) with historical time series of measured nacelle wind speed (NWS) and produced power measurements of every wind turbine yields the best performance. Such models are highly complex and still under development.

The method used for the calculation of the AAP in this pilot project is further elaborated in section 6.2.

5.2. International experiences and initiatives for controlling wind power production

In Belgium some wind farms already provide voltage support [MVAr] to Elia. Furthermore they also provide non-contracted manual CIPU balancing energy bids to Elia (manual Frequency Restoration Reserves, mFRR).

In Ireland, the grid code requires the installation of a Wind Farm Control System for controllable Wind Farm Power Station (WFPS) to allow for the provision of Active Power Control and Frequency

[6] In Belgium some wind farms already participate in the market of non pre-contracted manual CIPU bids (mFRR) and reactive power services.

Response [11]. Moreover, wind farms are obliged to deliver a qualitative calculation of the Available Active Power (AAP) to the TSO.

Under high wind conditions there is a possibility for the Irish TSOs to curtail wind production in order to make sure that a sufficient amount of the generated electricity is provided by synchronous generators. The reason is to maintain a certain level of system inertia (by synchronous generators) to safeguard safe operation of the system. The Irish DS3 program (“Delivering a Secure Sustainable Electricity System”) is set up to ensure a secure operation of the power system with increasing amounts of variable renewable generation. Studies will be performed to look in to the possibility to provide frequency regulation by dispatching the wind farms down.

More recently, in Denmark, Energinet.dk (the Danish TSO) changed its regulation to enable wind turbines to participate in the Scandinavian regulating power market. In [12] a test involving the bidding and provision of down-regulation reserve (manual regulating power or tertiary reserve) during one hour from a Danish wind turbine is presented. An approach on how to value the offered service is also presented.

In Germany, the purpose of the project “Regelenergie durch Windkraftanlagen” was to develop a proposal on how wind turbines can provide balancing. A project called “Regelenergie durch Windkraft und Photovoltaik” was subsequently initiated in 2014. Past initiatives involving the provision of power reserve include the project “Integration grosser Offshore-Wind parks in elektrische Versorgungssysteme” and WINDGRID (“Wind on the grid”) [13] where control strategies for wind farm cluster management were implemented (in Germany and Portugal) and evaluated with real field tests.

6 Delivery of aFRR services by wind farms

This chapter investigates the challenges for wind farms to provide aFRR services. Differences between wind farms and conventional units for the delivery of aFRR services are highlighted.

More information is provided on how the different aspects for providing downward aFRR control power on the Estinnes wind farm were implemented. This relates to the calculation of the Available Active Power (AAP) and the control mechanism for adjusting the output of the wind farm according to the aFRR set point.

Finally the applied nomination strategy in this pilot project, in order to determine ex-ante the volume of aFRR capacity that was offered by the Estinnes wind farm to Elia, is described.

6.1. Challenges for wind farms to provide aFRR

Determination of reference power

From a technical perspective there is a significant difference between the delivery of aFRR balancing energy by conventional units or wind farms.

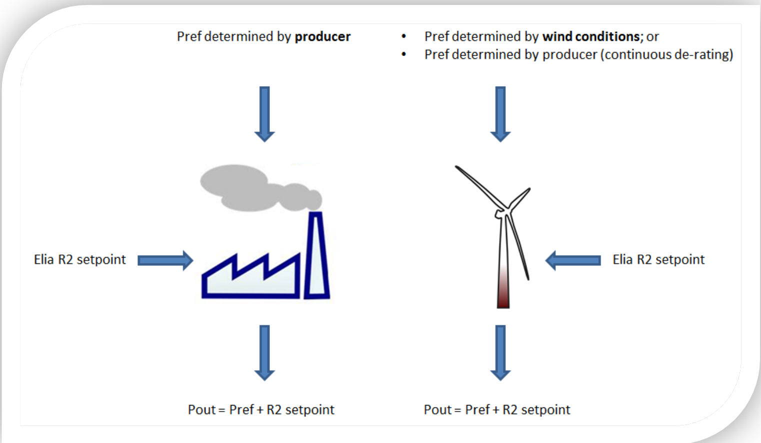


Figure 10: reference power for conventional units and wind farms

Whereas in case of a conventional unit the producer has control over the reference power (i.e. required production of the unit without aFRR activation), this is not the case for the wind farm, see Figure 10. Here the reference power is determined by variable and limited predictable wind conditions.

For the delivery of aFRR balancing energy the exact knowledge of the reference power is of key importance to calculate the desired output power (infeed) of the unit. For wind farms there are two ways to determine this reference power:

Balancing control mechanism: continuous de-rating of the wind farm

- The wind farm is curtailed to a reference power that is ex-ante determined by the producer on the basis of generation forecasts and uncertainty intervals:
    - E.g. if it is forecasted that there is a >99% probability that the production will exceed 50 MW, the reference power can be 50MW.
- This reference power then acts as the starting point as of which the aFRR balancing energy is activated;
- The level of curtailment depends on the requirements set by the TSO (required reliability of the service). An overestimation of the reference power (i.e. reference power exceeds the maximum output determined by wind conditions) results in an incorrect delivery of the aFRR service.

Available Active Power (AAP) mechanism: real-time calculation of reference power

- This methodology uses wind speed measurements, wind turbine blad angles, power curves of the wind turbines and/or physical models of the turbines to estimate in real-time the reference power (as if no control power would be delivered). This reference power is called the Available Active Power (AAP);
- Under this scheme there is no need for continuous de-rating; however the quality of the AAP calculation is vital. Errors on the AAP quality result in an incorrect delivery of the aFRR service: the output of the wind farm is determined as the sum of the AAP and the aFRR set point. Hence if the AAP is incorrect, per definition the wind farm does not provide correctly the requested aFRR service.

The functioning of both schemes is shown in the graphs below. Figure 11 shows the balancing control (de-rating) methodology. The production is curtailed ex-ante to the thick blue line (reference power). The aFRR down control energy (shaded area) is then delivered as of this point.

Figure 12 shows the AAP methodology. Here the downward aFRR energy is delivered from the simulated AAP (as of the dashed green line).

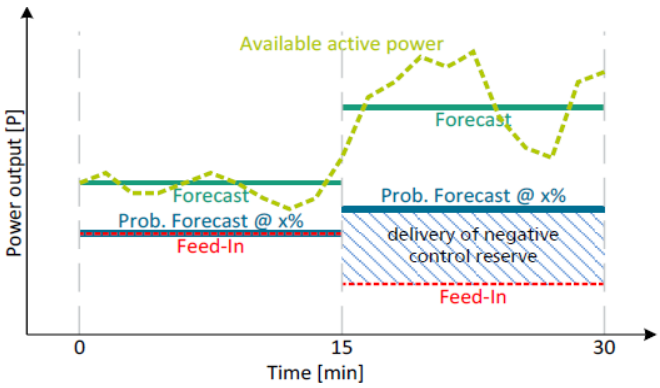


Figure 11: Balancing control mechanism; source: Jansen, M., Speckmann, M., "Wind turbine participation on control reserve markets", EWEA 2013, February 4-7 2013, Vienna, Austria [9].

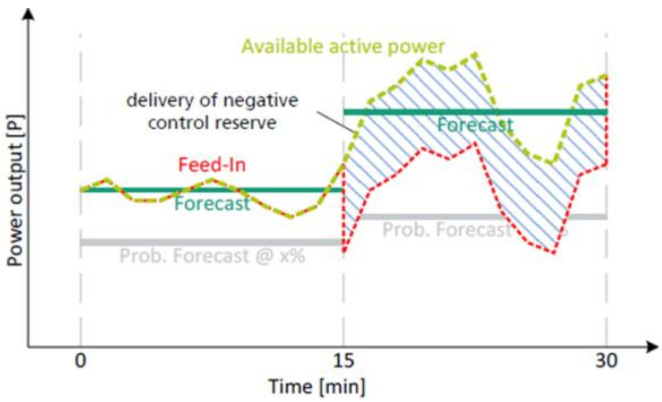


Figure 12: Available Active Power Mechanism ; source: Jansen, M., Speckmann, M., "Wind turbine participation on control reserve markets", EWEA 2013, February 4-7 2013, Vienna, Austria [9].

The **balancing control mechanism** is the least complex one. On the other hand it is clear that the continuous de-rating is not optimal from ecological (loss of renewable production) nor from economic (loss of green certificates / reduction of sold energy volumes) point of view. **Therefore the parties of this pilot project decided to test the method with the real-time calculation of the AAP (according to the AAP mechanism).**

On an international level there is a significant amount of research being performed on the qualitative determination of the AAP of wind farms. Therefore it can be expected that the quality of the AAP signal will further improve (e.g. account for wake effects, dynamic effects for changing wind conditions, technical availability of wind turbines,...). This justifies the choice for the latter methodology for this pilot project.

Influence of curtailment on AAP calculation: wind farm effect

One of the important aspects to analyse when controlling the output of a wind farm is the so-called "wind farm effect". When curtailing a wind turbine, the downstream wind speed (behind the turbine) increases (i.e. less energy is withdrawn from the wind). Hence any wind turbine that is located behind this first wind turbine will face higher wind speeds and will therefore increase its generation. In other words, whereas the first wind farm wind turbine is partially curtailed, the second wind turbine might produce relatively more (thereby partially offsetting the requested curtailment).

This is shown qualitatively (for illustrative purposes only) by the below figure. Whereas in uncurtailed conditions the wind speed drops with 2 m/s over the first wind turbine, in curtailed conditions (2 MW curtailment on first wind turbine), the wind speed only drops with 1 m/s. Therefore the produced output on the second wind turbine increases from 3 MW to 3,5 MW. Hence the first wind turbine is curtailed by 2 MW, whereas the second wind turbine increases its production with 0,5 MW. The total curtailed volume is therefore 1,5 MW (which is below the 2 MW requested curtailment).

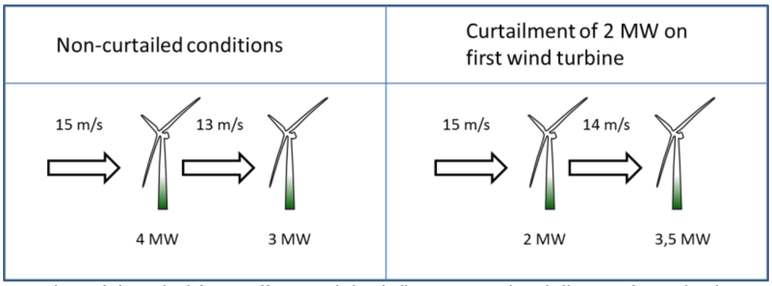


Figure 13: Illustration of the wind farm effect and the influence on the delivery of required curtailed volume

The wind farm effect can be due to:

- Internal wind farm effects, i.e. one turbine influencing another one; or
- External wind farm effects, i.e. one wind farm impacting wind conditions of another wind farm.

The external wind farm effect decreases with greater distances between the different wind farms.

The wind farm effect is specific for each individual wind farm. Whether or not (and to which extent) this effect influences the curtailment depends amongst others on:

1. the geographical lay-out of the wind farm(s);
2. the wind turbine model (blade design);
3. the wind conditions (wind direction); and
4. the algorithm used for the AAP calculation (physical model, power curve model, compensation for this effect,...).

For the delivery of downward aFRR on a wind farm, the higher wind conditions on some of the turbines caused by the wind farm effect (i.e. a result of curtailment of upstream turbines), might lead to an increase of AAP on these turbines. In such case the reference power for downward curtailment is slightly overestimated, potentially leading to insufficient curtailment.

This pilot project therefore elaborated some tests to analyse the presence of this phenomenon on a wind farm. On the basis of these results it can be concluded whether or not there is significant overestimation of the AAP under curtailed conditions. In case the results of these tests are negative, the AAP calculation must be adjusted to compensate for this effect.

Loss of green certificates

A reduction of the output of wind farms for balancing purposes results –under the current Belgian support scheme- in a loss of green certificates (which are allocated on the basis of produced energy). The resulting opportunity cost therefore must be compensated within the balancing framework. This means that the support scheme has a non-negligible impact on the prices of aFRR capacity and/or aFRR balancing energy. This is explained in more detail in Chapter 8.

This is the reason why this pilot project focuses on the delivery of downward aFRR by wind farms only. In case of downward delivery (with AAP methodology) there is no need for continuous de-rating of the output. Hence there is only a loss of green certificates in case of activation of aFRR balancing energy.

For upward aFRR by wind farms there is a need for continuous de-rating, resulting in very high costs due to the loss of green certificates. This in only viable in extreme and very rare market conditions.

Reliability of nominations

At this moment the aFRR capacity is mainly delivered by gas-fired units in Belgium. One of the advantages of these units is their ensured availability of primary energy (fuel) to deliver aFRR capacity.

The availability of wind farms to provide aFRR capacity fully depends on wind conditions. Hence it is more difficult for wind farms to determine the aFRR capacity that can be offered to the TSO. This can only be done on the basis of (imperfect) forecasting of future wind conditions.

TSOs require a reliable provision of reserve capacity (aFRR). Therefore the amount of aFRR capacity that can be offered by a wind farm to the TSO must be determined a.o. on the basis of uncertainty intervals; e.g. in >99% of the cases it is forecasted that the wind farm will be able to deliver a certain amount [MW] of aFRR capacity.

On the other hand one of the advantages of delivery of aFRR capacity by decentralized production units is the reduced risk of a loss of a significant amount of aFRR capacity (e.g. such as the case for a forced outage of a conventional unit delivering aFRR capacity). This of course depends also on the concentration of the aFRR services on different wind farms (e.g. risk of loss of wind production in case of offshore storms,...).

The performance of the wind forecasts has an important impact on the potential of aFRR capacity that can be offered to the TSO and on the reliability of the delivered aFRR service.

The reliability of the aFRR balancing energy nominations performed in this pilot project is discussed in Chapter 7.

Intermittent nature of production vs aFRR capacity product duration

Conventional units can deliver aFRR capacity over long continuous time periods (e.g. monthly products as in Belgium). Wind farms cannot provide such services as wind conditions continuously change. E.g. there is a very high probability that within a one month period there will be moments without wind.

In practice this means that wind farms would only be able to participate in the aFRR capacity market if

- they make part of a portfolio with other aFRR resources (conventional units, storage, biomass, CHPs,...) to be able to provide aFRR capacity over a long time period; or
- in case of transition towards short(er) duration of the aFRR capacity products (e.g. weekly or daily procurement).

This is discussed in more detail in Chapter 8.

Variations on the service

The delivery of aFRR down balancing energy by the wind farm of Estinnes, on the basis of the AAP mechanism, shows relatively more variations (short duration errors) than for the delivery of aFRR from a fix reference (balancing control mechanism). The reasons for this are multiple:

- Instantaneous wind conditions change continuously and in very short timeframes;
- The AAP calculation itself shows some deviations;
- Dynamic effects in case of wind farm control (wake effects, change in wind conditions behind the wind farm,...); and
- Imperfect interaction (e.g. reliable data transmission, signal lead time, cycle times, etc.) between the calculation of the AAP by the turbine controller, the centralized piloting by the wind farm controller and the data exchange with the Elia SCADA system.

It is expected that the variations on the delivery will be levelled out in case more wind farms simultaneously provide aFRR.

Pre-qualification requirements

Whereas for conventional fossil fired units the pre-qualification requirements for the aFRR service mainly focus on the controllability of the unit from the reference power defined by the producer, this is more complicated for the delivery of aFRR by wind farms via the AAP mechanism.

Indeed in such case the prequalification requirements should at least check:

- The ability of the wind farm to adjust its output on the basis of an external aFRR set-point;
- The quality of the AAP calculation both under normal conditions (i.e. without delivery of control power) and during the delivery of control power; and
- Whether there is structural overestimation of the AAP during curtailment (wind farm effect) or not.

The error on the delivery of aFRR balancing energy on a wind farm is the sum of the error on the AAP calculation and the error in providing the aFRR set point. This will result in more complex pre-qualification requirements for wind farms. Chapter 9 deals with this subject.

6.2. AAP calculation

The AAP, or Available Active Power, is used as an estimate for the reference power production of the wind farm in this project (i.e. the estimated power output of the wind farm as if no control power was delivered).

The AAP of the Estinnes wind farm is calculated for each turbine based on the measured power output and the pitching angle of the blades via a power/blade angle characteristic curve. These characteristics provide a relationship between the power output of the wind farm depending on the pitch angle of the blades and the wind speed (measured behind the blades)

In addition other technical parameters such as the instantaneous maximum technical output (e.g. reduced power due to maintenance,...) and availability of the turbine (e.g. due to outage) are taken into account for the calculation of the AAP.

The graph below shows how a change of pitch angle can be used to deliver aFRR balancing energy for a certain wind speed.

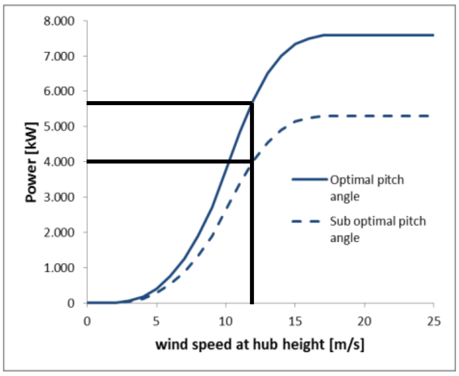


Figure 14: Illustration of curtailment by changing pitch angle

The aFRR set point by Elia is defined on a 4-5s level. Therefore it is important that the calculation of the AAP is also performed at a high frequency (in this pilot project also on a 4-5s level). The individual AAP values for the different turbines are aggregated to calculate the AAP of the entire wind farm.

The delivery of downward aFRR balancing energy is performed by pitching the blades away from the optimal blade angle in order to achieve the desired (reduced) output. In such case the actual blade angle and actual feed-in (under curtailed conditions) are used to estimate the power that would be produced at the optimum blade angle.

When asked to deliver a set point (aFRR balancing energy) the AAP will function as reference for the curtailment. This means that the desired output of the wind farm is determined by the sum of the AAP and the aFRR balancing energy set point defined by Elia.

The disadvantage of the current use of the power/blade angle characteristic curve to calculate the AAP is that wind farm effects (wake effects, overestimation of AAP during curtailment,...) are not fully incorporated.

The importance of these effects depends on the geographical lay-out of the wind farm. Hence they can be more or less outspoken for different wind farms. It is expected that the quality of the AAP calculation will further increase in the future and might even take these effects into account.

The location at which the AAP is calculated is also important. In this pilot project the AAP was calculated at turbine level (low voltage side of the transformer), whereas the measurement for the output of the wind farm was located at the grid side (high voltage side of the transformer). Hence in such case an adjustment must be applied to the calculated AAP in order to perform correct settlement (taking transformer losses into account).

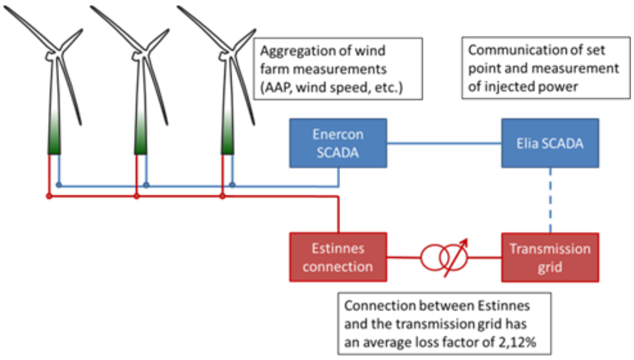


Figure 15: Measurement location

For this pilot project it was decided (for reasons of simplicity) to assume an average, constant loss factor of 2,12% between the location where the AAP was calculated and the measurement at the side of the Elia grid. However more detailed models could be applied in the future.

6.3. Control of the wind farm

This section provides more information on the control mechanism used in the Estinnes wind farm in order to provide aFRR balancing energy. As described above the AAP for the wind farm is calculated every 4-5 seconds.

The computation of the desired output of the wind farm (reference computation) is performed by calculating the sum of the AAP and the aFRR set point defined by Elia. The desired output of the wind farm is then compared with the measured output of the wind farm. The delta between these two metrics then provides the input signal for the control mechanism determining the required pitching of the blades. The closed-loop control ensures that the blade angle is changed accurately to achieve the desired output (the pitching angle of the blades is changed until the actual measured feed-in of the wind farm matches the desired power production).

As shown in the previous section the active power output of the wind farm can be changed by adjusting the blade angle of the turbines.

The control mechanism of the Estinnes wind farm was equipped with a dead band mechanism (no control for aFRR requests below 500 kW) as well as a delay and a filter in order to avoid unnecessarily pitching the blades for small changes in the desired output.

The control mechanism is designed to perform the same relative curtailment on each wind turbine compared to its original AAP value. Hence the aFRR set-point (delta power) for the wind farm is divided proportionally over the wind turbines on the basis of the AAP of the turbines.

6.4. Applied nomination strategy for aFRR capacity

The wind farm of Estinnes participated for a period of about three months in the Belgian aFRR balancing energy market. Therefore the wind farm had to provide day-ahead nominations (D-1) of the expected available downward aFRR volumes for the next day (D). Given the importance of the aFRR control for balancing, such nominations must be very reliable.

This section provides a high level description of the applied nomination strategy in this pilot project in order to guarantee such high reliability.

In order to gain as much experience as possible in this pilot project, nominations were also provided on week ahead level. As such the impact of the nomination horizon on the reliability of the aFRR nominations could be analysed in more detail (see paragraph 7.2.3).

The nomination process can be illustrated as follows:

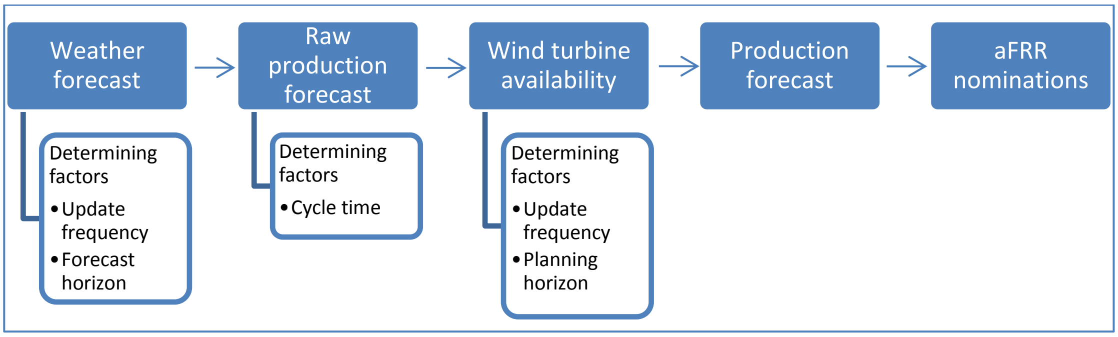


Figure 16: Illustration of the nomination process

The conjunction of the update frequency of the weather data and the turbines availability, the horizon of available data, and the cycle time needed to generate a production forecast, yields the limits of the available production data for efficient nomination.

More generally for wind energy producers in Belgium, a weather forecast is reliable one to two days ahead. Its predictability radically diminishes for the subsequent days of the forecast horizon depending on the season and punctual climate conditions. For this reason a week ahead forecast is unreliable and can only be used as an indication of the current clime conditions (stable or volatile) and their potential evolution (increasing or decreasing wind). If a clime condition is expected to remain stable, the forecast can be used with precaution and as such only for well evaluated purposes.

For the sake of the present research project, week-ahead nominations have been simulated. In order to do so quantitative and qualitative appraisals of the above mentioned elements have been made. However, as will be shown in Chapter 7.2.3, its added value is limited.

On the other hand, an efficient intraday forecast also has its requirements. Not only is a weather forecast with an adequate update frequency needed, but also the planning for turbine availability must be managed in an appropriate manner. Technologies are at hand, but will only be used by wind energy producers if the investment is justified.

The scheme used throughout this pilot project for the computation of the day-ahead aFRR nominations is illustrated in the following figure:

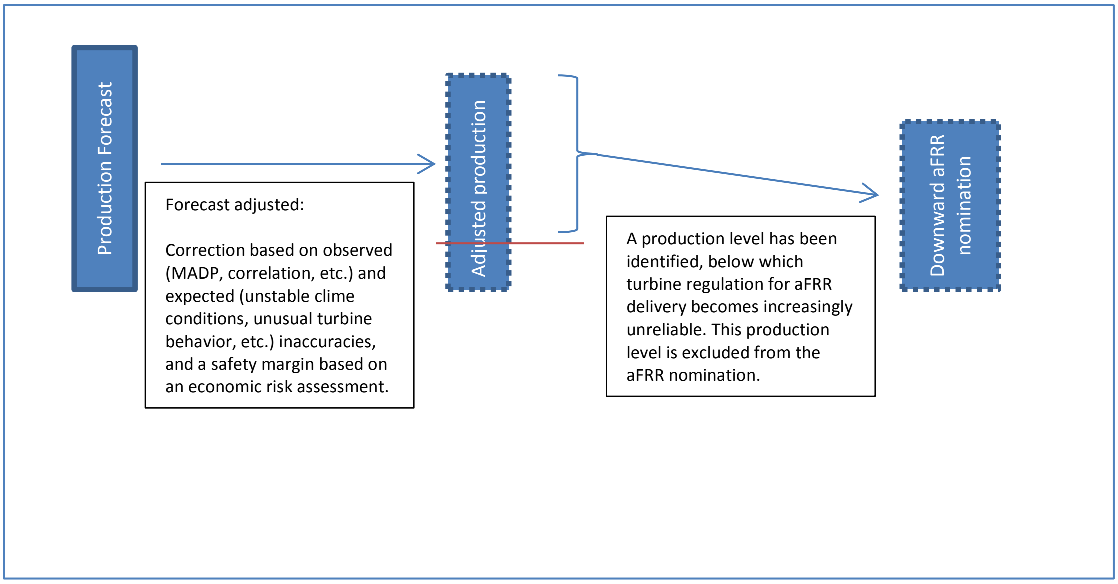


Figure 17: computation of the day-ahead aFRR nominations

The production forecast yielded by models is never perfect. As such, an adapted interpretation of this forecast may help to be more efficient in the targeted use of the forecast. A probabilistic approach to the inaccuracies and the risk related to unreliable nominations, depending on the targeted use of the forecast, yields an adjusted production forecast. In the case of aFRR delivery, a deterioration of the service quality has been observed when the turbines produce below a certain output level (Chapter 7). For this reason a dead band has been defined by WindVision and Enercon, below which no aFRR may be delivered. Applying this dead band to the adjusted production forecast yields the aFRR nominations.

The observed performance of the nomination strategy is further elaborated in paragraph 7.2.3. As a result the applied nomination strategy can allow for highly reliable nominations for a single wind farm (e.g. a day-ahead nomination reliability of >99% was observed during the test).

7 Pilot project tests on the wind farm of Estinnes

This section provides a description of the different tests that were performed on the wind farm of Estinnes for the provision of downward aFRR balancing energy.

In a first stage (**initiation stage**) some tests were performed on the wind farm of Estinnes in order to perform a high level check on both the quality of the AAP calculation under curtailed and non-curtailed conditions as well as on the ability of the wind farm to control its output on the basis of an aFRR set point by Elia.

In a second stage (**participation stage**) the wind farm of Estinnes technically contributed to the delivery of aFRR balancing energy in Belgium for a period of about three months. It was considered that such a testing period would be sufficient to gather information on the performance of aFRR delivery by the wind farm under different conditions. The pilot project enabled to gather experience of delivering aFRR balancing energy on wind farms in all different stages of the aFRR framework (e.g. nomination quality, data exchange, reaction of the wind farm on the aFRR set point, settlement, AAP quality under curtailed and non-curtailed conditions,...).

During the entire participation phase data was gathered on many parameters such as wind speed, wind direction, generation forecasts,... in order to enable ex-post analysis.

Both in the initiation and participation stage the performance of the downward aFRR delivery by the wind farm of Estinnes was monitored. This performance relates to:

1 AAP quality (both under curtailed and non-curtailed conditions): The performance can be considered bad if the AAP deviates strongly from the measured infeed;

2 Controllability of the wind farm: The response of the windfarm to the new set point during curtailment; and

3 aFRR nomination reliability: How accurately can the availability of the wind farm be forecasted.

This is illustrated in Figure 18. The underlying reason for imperfect delivery of aFRR balancing energy on wind farms can be due to (a combination of) the above three points. Hence it is very complex to analyse this performance.

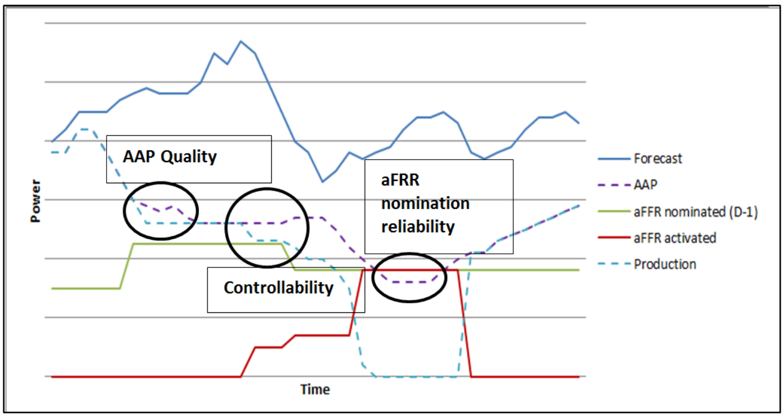


Figure 18: Illustration of possible performance issues

7.1. Initiation phase

7.1.1. Scope

As shown above it is relatively difficult to assess the full performance of aFRR delivery by wind farms. The goal of the initiation phase was to perform some high level tests in order to check the performance of the delivery of downward aFRR by the Estinnes wind farm before allowing the wind farm to contribute to the Belgian aFRR balancing energy market (participation phase).

The tests performed in the initiation phase were limited (non-exhaustive), but provided a first indication of the performance. Further performance checks during the participation phase are required to come up with statistically representative results.

The tests in the initiation phase were performed both under high and low wind conditions (characterized respectively by an output of the Estinnes wind farm below or above 30 MW). The nominal power of the Estinnes wind farm is 81 MW.

During the initiation phase test were performed on the Estinnes wind farm to check:

- The controllability of the wind farm (performance, ramp rate, minimum stable power,...);
- The AAP quality under curtailed and non-curtailed conditions; and
- The reaction of the wind farm on different types of set points (aFRR test sequence, step, ladder function).

The results for the different tests are summarized in the next paragraphs.

7.1.2. Test results

<u>AAP quality under non-curtailed conditions</u>

In a first test the quality of the AAP under non-curtailed conditions was verified by gathering 10 seconds data for September and October 2014 (both AAP value and measured infeed of the wind farm).

In Figure 19 a sample period of two days is shown, including low and high wind conditions. The blue line on the graph shows the injected power into the Elia grid, while the red line shows the estimated AAP of the wind farm. The error, shown in green, does not take into account the losses between the wind farm and the Elia measurement point. In general it can be concluded that the error is limited. Most of the errors (spikes) occur during periods characterized by high ramping conditions, or are caused by turbine start-up procedures, during which the AAP signal is inaccurately predicting the available power on the turbine during the period where the power output is still restricted[7] during the turbine start-up procedure (see paragraph 7.2.2). This technical issue has been recognized and might be resolved by software updates.

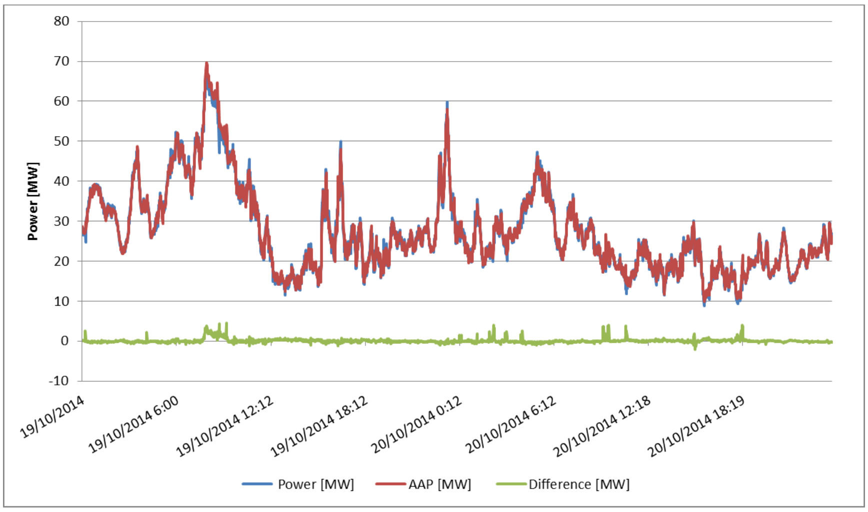


Figure 19: Performance of AAP for 19/10/2014 - 20/10/2014

The average value and the different percentiles (as a function of the measured power infeed of the wind farm) of the error on the AAP calculation for the September – October '14 period are shown in the Figure 20.

[7] The error peaks displayed in the graph below are mainly caused by planned wind turbine outages (such as shade control,…), yielding incorrect AAP signals throughout the turbines start-up procedures (see paragraph 7.2.2).

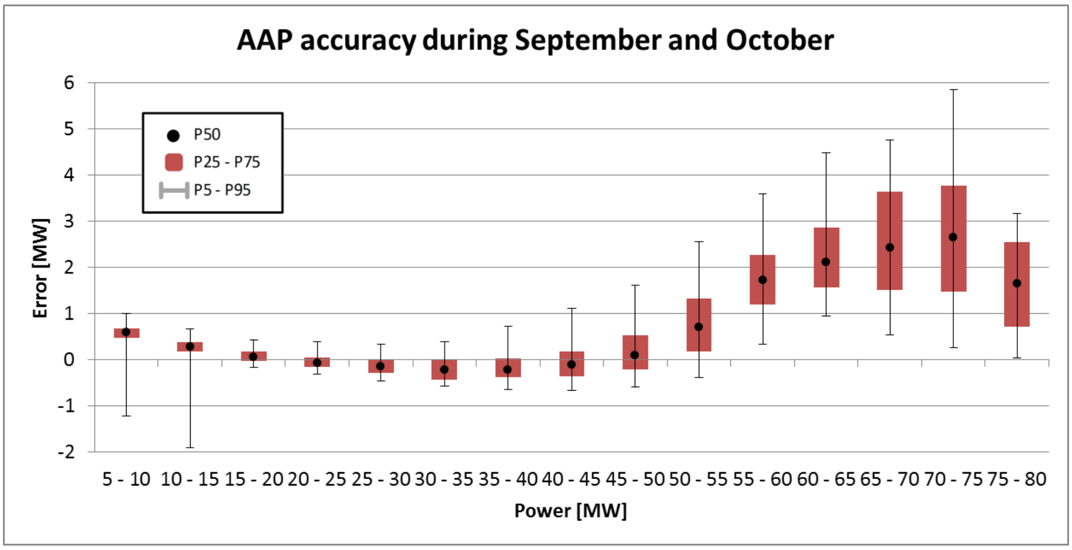


Figure 20: AAP accuracy during September and October 2014

The graph shows (per power infeed interval of 5 MW) the median of the AAP error (black dot, the 25- and 75-percentiles (red error bars) and the 5- and 95-percentiles of the AAP error. For the error calculation the loss factor is not taken into account, this was done to avoid a skewed result resulting from power dependant losses.

The error was calculated as the AAP minus the injected power. A positive error thus indicates an overestimation of the AAP, while a negative error is caused by an underestimation of the AAP. Should we take into account the loss factor, determined at an average of 2.12%, then we can expect the above graph shifting downwards.

We see that at low generation levels (e.g. 10-15 MW) the absolute AAP errors are low. Nevertheless the relative error, compared with the measured infeed, here is quite high (up to 20%). For high generation levels there appears to be a large spread between the 5- and 95-percentile.

The best performance of the AAP is between 20 and 35MW with very accurate performance, the spread between the 5^{th} and 95^{th} percentile is limited to 3-4% (compared to the measured infeed) and the median of the error is below 1%. For high wind conditions the relative error on the AAP calculation is between 5 and 7% for the P5 and P95.

As mentioned above, part of the AAP errors are due to turbine start-up procedures, during which the AAP signal is inaccurately predicting availability while the power output is still restricted (shade control,...).

The relatively higher errors at high wind conditions might be explained by following observation from the participation phase. At higher wind speeds in general the blades are pitched for reasons other than supplying reserve power (eg. blade load control). It was observed during the test that not all these effects were represented accurately in the AAP calculation. This technical issue has been recognized and will be resolved in future software updates.

The observed quality of the AAP under non-curtailed conditions is relatively good. It can be concluded that the AAP quality is superior for medium infeed values. Furthermore the performance of the AAP calculation will probably further improve towards the future, given the amount of ongoing research on this topic.

Controllability of the wind farm (balancing control mechanism)

In a second test the controllability of the wind farm is investigated by applying the balancing control mechanism (continuous de-rating of the wind farm). For this test the wind farm is ex-ante curtailed to a certain power level. Then the wind farm is requested to provide a standard aFRR test sequence as of this pre-defined power level, both for high and low wind conditions. The results of this test are shown below:

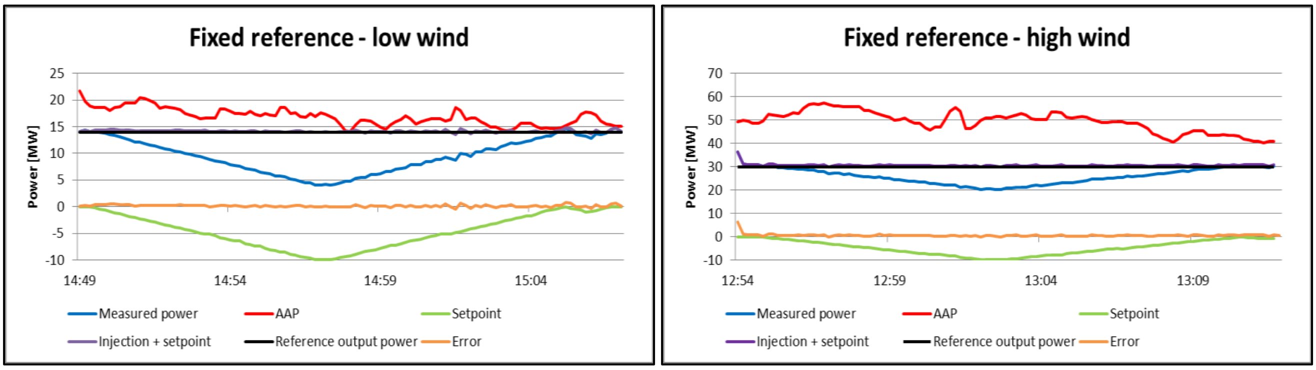


Figure 21: Controllability of the wind farm. The low wind conditions test was performed on 19/08/2014 and the high wind conditions test on 22/08/2014

Both for the high and low wind conditions the wind farm was asked to curtail to an ex-ante defined set point of respectively +/- 15 and 30 MW (black line in the graph above).

Then the wind farm was required to deliver the aFRR set-point (green line, delta power) from the ex-ante defined set point. The aFRR test sequence is a gradual curtailment of 10 MW over 7,5 minutes time period (i.e. Full Activation Time of aFRR in Belgium). Such curtailment was chosen to prove whether the wind farm of Estinnes could deliver the maximum allowed volume of 10 MW of aFRR in the participation phase (see later).

The measured output of the wind farm is described by the blue line in the above graph. The control error is given by the orange line in the above graph. Based on the above tests it can be concluded that the wind farm of Estinnes can be controlled very accurately, both under high and low wind conditions. The average observed control error is below 1.5% of the 10 MW regulation band, the standard deviation on the other hand was about 2%.

This test also confirms that the wind farm is able to respect the aFRR Full Activation Time for the pre-defined maximum contribution of 10 MW aFRR capacity in the participation phase.

Performance of aFRR delivery for the AAP mechanism

In this test the wind farm of Estinnes was requested to provide the downward aFRR test sequence from the AAP value itself instead from a pre-defined curtailed set point (AAP mechanism), both for high and low wind conditions.

Due to this change of reference, there are two kinds of errors: firstly, the control error (i.e. imperfect delivery of the set point from the estimated AAP) and secondly, the AAP error (i.e. the error on the estimated AAP as the reference for downward curtailment). It is very complex to separate both errors.

The results of the tests are summarized in Figure 22 (10 seconds data):

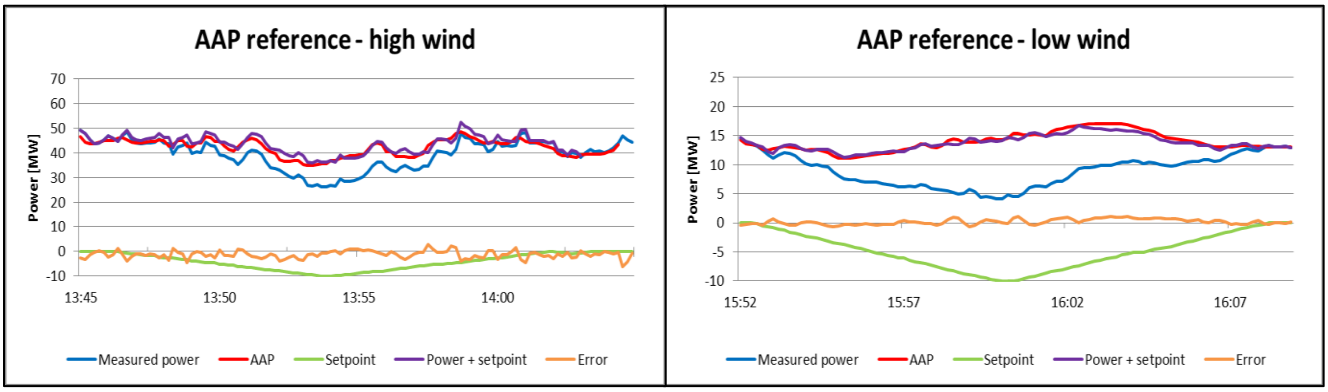


Figure 22: Performance of aFRR delivery for the AAP mechanism (10s data). The low wind conditions test was performed on 19/08/2014 and the high wind conditions test on 22/08/2014

The orange line shows that the use of the AAP mechanism introduces additional control errors compared to the balancing control mechanism. It is assumed that the underlying reasons are the following:

- some variations of the AAP signal are faster than the control capabilities of the wind farm itself. As a result the wind farm cannot perfectly control its power output to the sum of the AAP and the aFRR standard test set point; and
- whereas in the previous test the wind farm was controlled from a fixed reference value, the wind farm is controlled here as from a continuously changing reference value (wind conditions continuously change), which is more challenging.

Therefore some noise is introduced on the control accuracy of the wind farm. This could be levelled out in case more wind farms simultaneously provide aFRR. Furthermore there is also an error on the AAP calculation itself, which has an impact on the control performance under the AAP mechanism (not shown in the above graphs).

Regarding the AAP error it is important to notice in this test that towards the end of the curtailment the AAP converges naturally towards the measured infeed of the wind farm (meaning that the AAP value is correct at the end of the test). Therefore it can be concluded for the above tests that (in general) there is no significant structural influence of the downward curtailment on the estimated AAP values. Should there be a structural influence of curtailment on the AAP signal, then the AAP signal would sharply change at the beginning or end of a step signal. This is not the case as can be seen in e.g. Figure 22 and Figure 24.

This is important as a structural impact could indicate that the calculated AAP becomes incorrect during curtailment (a different set point, or test, could result in a different error and thus a different behaviour). In such case the AAP mechanism could not be applied, as the desired output, defined by the sum of the AAP and the aFRR set point would be incorrect. This would be e.g. problematic in case of overestimation of the AAP. In such case the curtailed volume will not be correctly delivered. Given the importance of this aspect, this is investigated in more detail in other tests.

The test shows that, although there is some noise on the control performance (especially for high wind conditions) on a 10-seconds level, the wind farms provide in general the requested amount of aFRR control power and energy.

The performance of these tests (10 seconds level) are summarized in the tables below. The percentages indicate the observed error divided by injected power plus the set point.

Table 3: performance during initiation tests based on 10 seconds data

	Low wind	High wind
Average error	1.33%	-2.78%
Standard deviation	3.32%	3.40%

In the actual aFRR qualification procedure the unit should be able to follow the predefined set point within an error margin of 7.5% of the contracted volume (10 MW was used during this test) on a 10 second basis (with the exclusion of the two most extreme values). The error on the delivery of aFRR services was bigger than 7.5% of the setpoint for 17 times in the low wind case and for 87 times in the high wind case, both during a 20 minute test

In order to filter the effect of the noise on the control error, the same analysis is performed on the basis of minute average values. It becomes clear that the performance in terms of standard deviation is better than for the 10 seconds metrics.

Table 4: Performance during initiation tests based on minute averages

	Low wind	High wind
Average error	1.33%	-2.78%
Standard deviation	2.56%	1.81%

When using the minute averages, we see that the average error on the delivery of aFRR services is bigger than 7.5% for 2 minutes for the low wind conditions and 15 minutes for the high wind conditions.

Nevertheless the results show that for the average one minute values the performance of the Estinnes wind farm remains acceptable as the majority of the power is correctly delivered (see Figure 23):

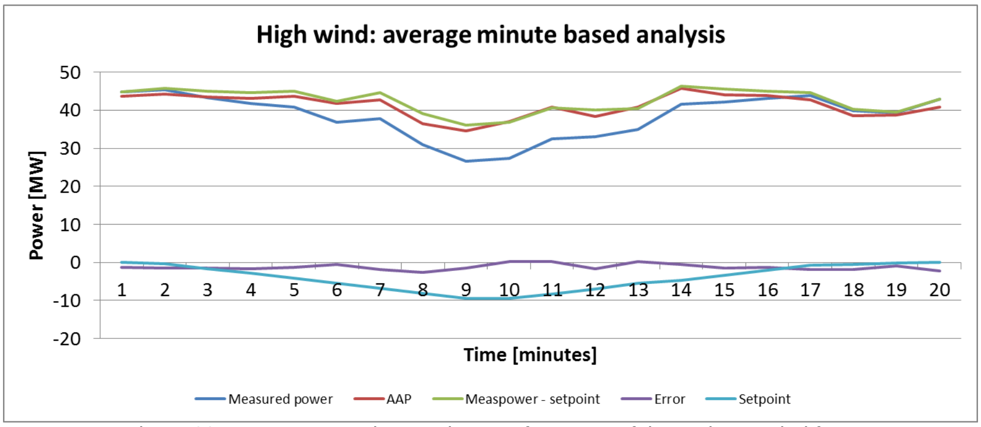


Figure 23: Average one minute values performance of the Estinnes wind farm

The above results show a promising potential for wind farms to provide aFRR services.

Reaction of the wind farm on a step

A test was performed in order to analyse the step response of a wind farm. The main goal of this test was to determine the ramp rate at which the wind farm can be controlled and whether the upward and downward ramp rates are more or less symmetric or not. Furthermore the minimum stable power of the wind farm was analysed.

All these aspects have an important impact on the maximum amount of downward aFRR capacity that can be delivered by the wind farm. Indeed the controllable ramp rate and minimum stable power define the maximum volume that can be curtailed within the full activation time of 7,5 minutes (Belgian aFRR product requirement).

Different tests were performed:

- Two test sequences with respectively a 10 MW and 30 MW step response; and
- A test sequence where the wind farm was asked to curtail to zero MW.

The results of these tests are shown in Figure 24:

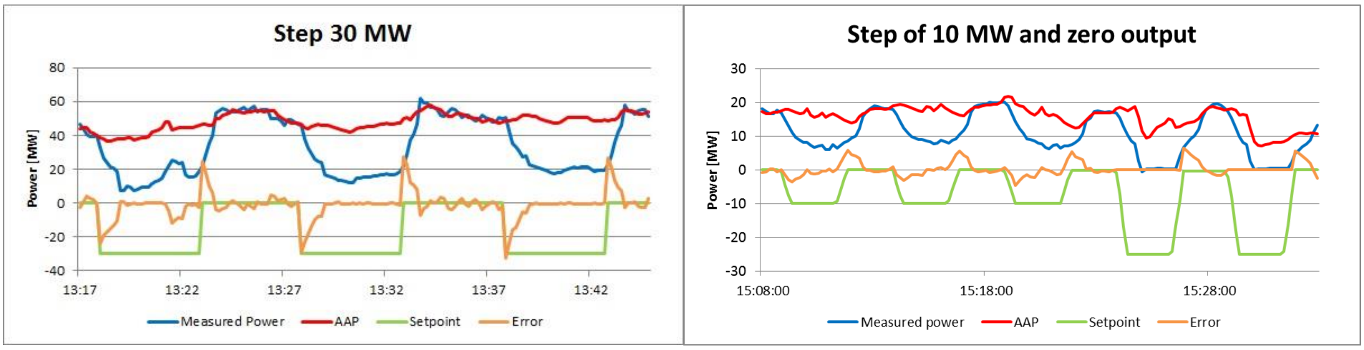


Figure 24: Response of the wind farm to a step

In general the response of the Estinnes wind farm on the steps is very good. The errors at the beginning and the end of the steps are due to the fact that the ramp rate of the wind farm is finite. The test sequence with the 30 MW steps shows on average a ramping time of about 1 minute for both the upward and downward step. This shows that the controllable ramp rate of the Estinnes wind farm is high (up to 30 MW/min) and that it is not a limiting factor for the delivery of downward aFRR.

The last test shows that the wind farms can be curtailed up to zero (no minimum stable power). However from the operational point of view it is preferred to keep a very low minimum power on each individual wind turbine. Nevertheless it can be concluded that even in such case the minimum stable power is very low (below 1 MW) for the entire wind farm.

Analysis shows that the upward and downward ramping period for the step response of the Estinnes wind farm are more or less symmetrical. It is however possible that, especially under low wind conditions, the upward ramping is slightly slower than the downward ramping. The performed test shows that this effect is limited for the Estinnes wind farm and hence no limiting factor.

During the above tests it appears that the AAP is not structurally affected by the requested downward regulation as the AAP and the measured power naturally converge at the end of the step response.

In case of regulation towards 0 MW the AAP is influenced by the downward regulation. This could be, amongst others, the result of two effects:

- Less accurate calculation of AAP at high curtailment (large deviation from standard working conditions);
- At very low power levels, the AAP calculation is based on the wind speed measured at the nacelle. Due to its measurement location, the wind speed's value is subject to both the turbulences generated by the rotor blades and the logic used to filter them out, rendering increasingly unreliable values at very high curtailment levels.

Impact of curtailment on the AAP calculation (wind farm effect)

In order to gain more in-depth insight on the behaviour of the AAP calculation under curtailed conditions, a test was set up where only half the wind farm (6 turbines) is curtailed, whereas the other half (5 turbines) is not curtailed. The split of the wind farm was empirically determined in such a way that it was expected that both parts would have similar behaviour (depending on wind direction and topography of the wind farm). The lay out of the wind farm can be found in **Error! Reference source not found.**. The analyses performed below are based on minute average observations.

The test is performed for high wind conditions. One part of the wind farm is requested to deliver 10 MW downward regulation with a ramp rate of about 4 MW/min. The park is then curtailed for 15 minutes and then ramps up again with the same ramp rate of 4 MW/min.

Figure 25 shows that the curtailed part of the wind farm correctly delivered the required volume compared to its estimated AAP.

The graph shows that after the curtailment the AAP and measured infeed do not perfectly correspond. The underlying reason is that as of minute 30 in the test some AAP data was not received any more for each of the individual wind turbines. It was observed that via linear interpolation the difference could already be reduced significantly[8].

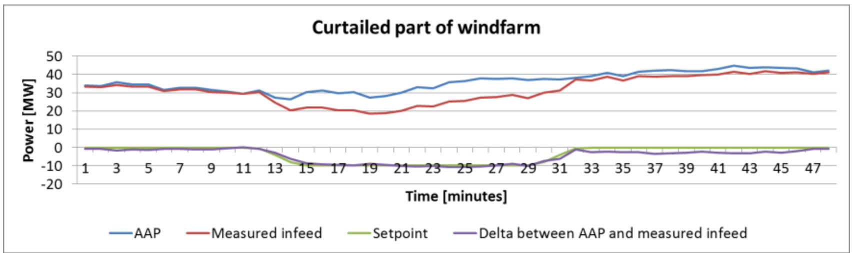


Figure 25: Difference between the measured power of the first half and the AAP second half of the windfarm

[8] During the initiation phase the issue of missing AAP data was observed. The reason for this missing data was a communication error between the Elia and Enercon SCADA. The issue was resolved before starting the participation phase.

The AAP and measured infeed of the non-curtailed part of the wind farm are shown below. As could be expected the AAP coincides well with the measured infeed. Also here the quality is slightly reduced after minute 30 in the test due to missing values of the AAP of the individual wind turbines (less data missing than for the curtailed part of the park).

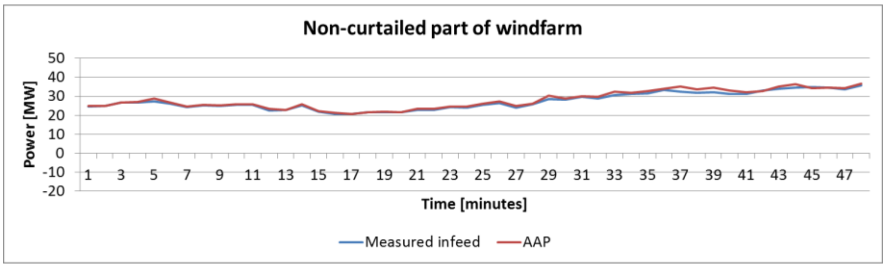


Figure 26: The AAP and measured infeed of the curtailed part of the wind farm

In this test it is possible to compare the measured infeed of the non-curtailed part of the wind farm with the AAP of the curtailed part of the wind farm. In theory the average AAP value per turbine of the curtailed part of the wind farm is expected to follow the same behaviour as the average infeed of the non-curtailed wind farms. If this would not be the case, this might give an indication that the AAP is corrupted during downward curtailment.

During the test the instantaneous wind speed for each individual wind turbine (behind the blades) was monitored. It was noticed that the average wind speed for the curtailed part of the wind farm was slightly above the average wind speed for the non-curtailed park. This is shown in the graph below:

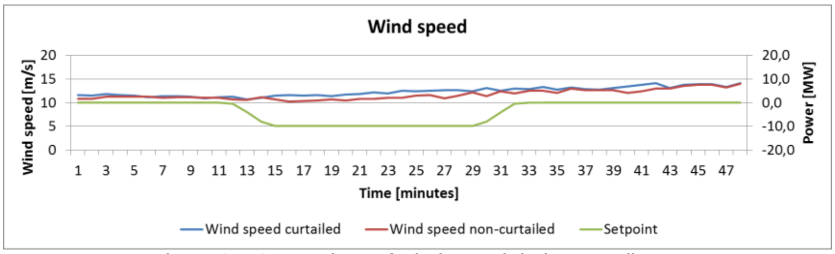


Figure 27: Comparison of wind speed during curtailment

Because less energy is taken from the wind, the drop in wind speed over the curtailed wind turbine is lower than for non-curtailled turbines. The expected effect is that the estimated AAP of the curtailed part is slightly overestimated during the curtailment (wind farm effect).

This could be analysed by comparing the average measured feed-in per turbine of the non-curtailed part of the wind farm with the average observed AAP of the turbines of the curtailed part of the wind farm.

Figure 28 shows that, although the AAP for the curtailed part is also slightly higher before and after the curtailment, the effect is more outspoken during curtailment. This leads to a situation where (a limited) part of the curtailed volume is not delivered due to overestimation of the AAP (wind farm effect). The effects seen here have been observed during individual events. More comprehensive statistical analysis is necessary in order to validate the results and resolve uncertainties surrounding their impact.

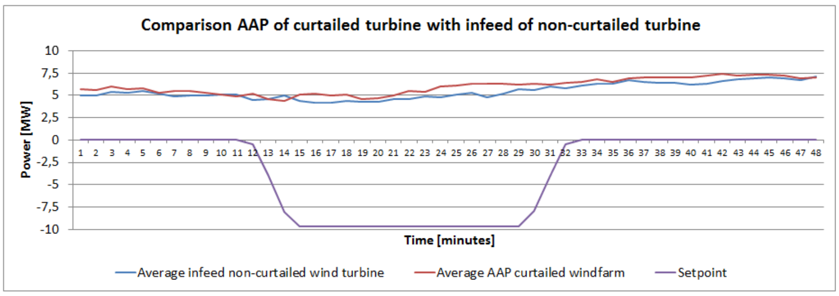


Figure 28: Comparison AAP of curtailed turbine with infeed of non-curtailed turbine

In order to quantify the effect the average AAP of the curtailed part of the wind farm (compensated for the loss factor between the measurement point of Elia and the infeed of the wind farm) and the average infeed of the non-curtailed part are calculated before, during and after curtailment:

Table 5: Illustration of AAP overestimation during curtailment

	Average AAP of curtailed wind turbine [MW]	Average measured power non-curtailed wind turbine [MW]	Delta per turbine (average for 6 curtailed turbines)[MW]	Delta for the entire curtailed part of the wind turbine (6 curtailed turbines) [MW]
Before curtailment	5,5	5,1	0,4	2,1
During curtailment	5,6	5,0	0,6	3,8
After curtailment	7,1	6,6	0,4	2,6

This results in a limited overestimation of the AAP of the curtailed part of +/- 1,4 MW (the average delta over the different phases) for a curtailment of 10 MW. Hence the AAP is slightly affected by the requested curtailed volume. It is expected that further improvements of the AAP calculation model and the implementation of physical AAP calculation models might resolve this issue towards the future.

In this pilot project two more straightforward tests were elaborated to identify the potential issue of overestimation of the AAP (wind farm effect) during curtailment:

1. **Option A:** this test calculates the curtailed volume as the difference between the slow component of the AAP (30 minutes rolling average) and the measured infeed. The rolling average of the AAP for a certain point in time is calculated by considering the values of the AAP fifteen minutes before and after the concerned point in time.

   In case of short periods of curtailment this methodology allows to filter out any overestimation of the AAP during the curtailment itself (30 minute rolling average value of AAP). Hence for curtailment during stable wind conditions (i.e. changes of AAP only related to curtailment) and for short curtailment periods (for long curtailment periods the effects are levelled out by the 30 minute average), the curtailed volume can then be determined as the difference between the slow AAP component and the measured infeed during curtailment. This value should be compared with the requested curtailment.

2. **Option B:** this test calculates the curtailed volume as the difference between the interpolated measurement before and after the curtailment.

   For this test the (5-minute) average infeed before and after curtailment is determined. Then an interpolation is performed between both during curtailment. In case the wind conditions are stable during the curtailment, the curtailed volume can then be determined by comparing the difference of the interpolated infeed (calculated) during curtailment and the measured infeed. This value should then be compared with the requested curtailment.

It must be highlighted that the results of these tests are only relevant under certain conditions:

1. Stable wind conditions during the test;
2. Curtailment periods of a few minutes; and
3. For AAP levels below the nominal power of the wind farm.

None of these tests delivers perfect results as it is inherent that wind conditions change during the test. However they provide interesting information on whether there is significant overestimation of the AAP during curtailment or not. In case of significant overestimation of the AAP, it is clear that changes are needed to the AAP calculation in order to perform aFRR down delivery via the AAP control mechanism.

Figure 29 provides three illustrative cases where both Option A and Option B are applied. In a first situation both for option A and B no overestimation of the AAP during curtailment is assumed (hence the total required curtailment volume is delivered). For the second case there is full overestimation of the AAP (overestimation equal to the required curtailment), so that in practice no curtailed volume is delivered. The third case assumes an overestimation of 30% of the AAP (hence delivery of 70% of the curtailed volume).

The graphs below show that for option A the overestimation of the AAP can clearly be recognized by:

1. Overestimation of the AAP before and after the curtailment (due to 30 minute rolling average values, starting fifteen minutes before and ending fifteen minutes after the actual AAP value);
2. The calculated reaction differing significantly from the required set point; and
3. The set point (measured infeed) being mirrored in the AAP calculation itself.

For option B the overestimation of the AAP can clearly be recognized by:

1. The calculated reaction differing significantly from the required set point;
2. The AAP value differing significantly from the interpolated infeed during curtailment; and
3. The set point (measured infeed) being mirrored in the AAP calculation itself.

The main advantage of the above tests is that they can be performed more easily than performing curtailment on a part of the wind farm and then comparing the AAP and measurement of both parts of the wind farm. Option A can be automated relatively easy, whereas this is more difficult for option B. Nevertheless the results of the option B test are easier to interprete. It must be emphasized that the below results are based on simulated data. As shown further on in the report the interpretation of these tests is slightly more difficult for real test data. The elaborated tests could be relevant as a prequalification procedure in the future.

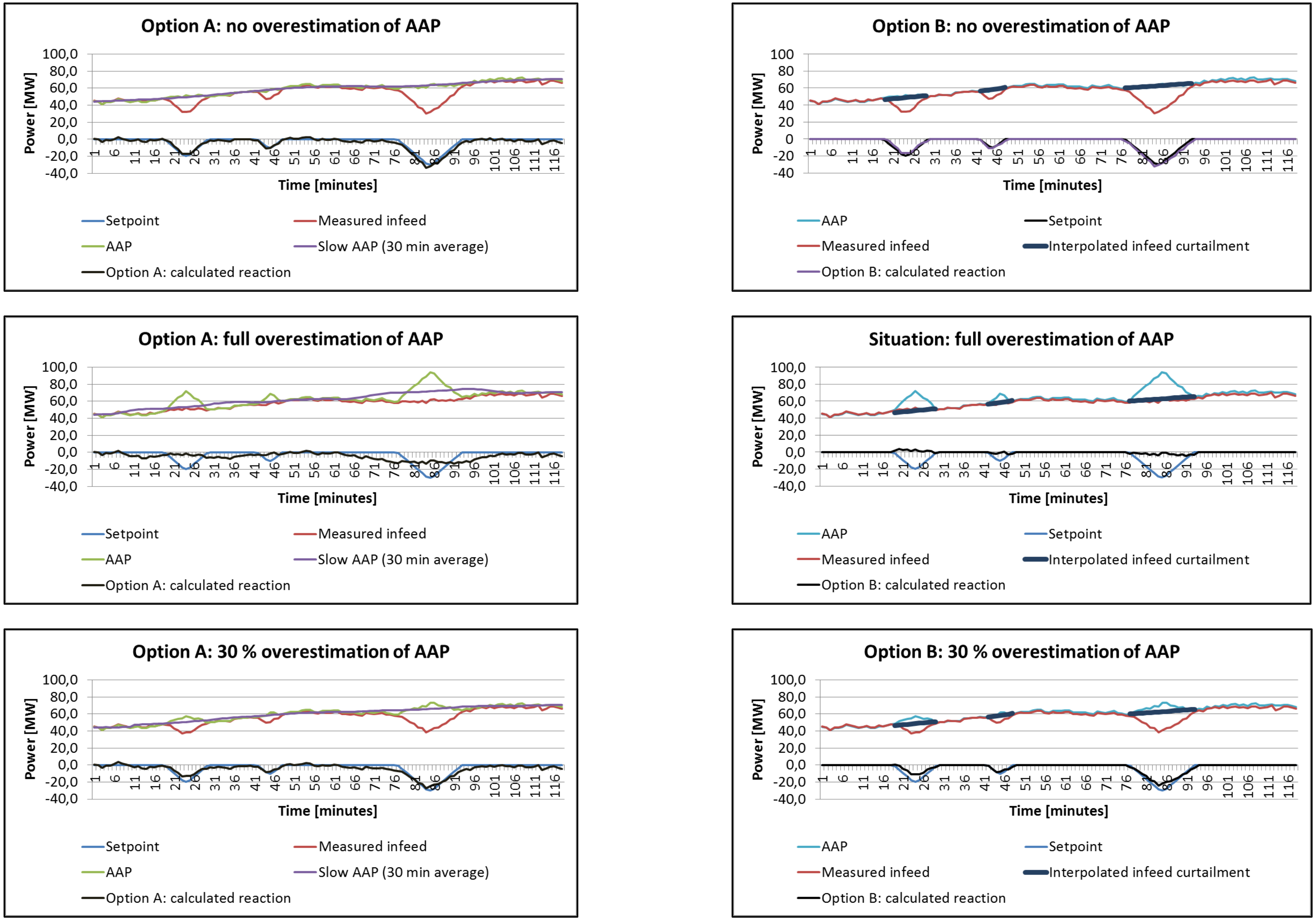


Figure 29: Illustrative examples of Option A and Option B to investigate potential overestimation of the AAP during curtailment.

In Figure 30 option B is applied for the 30 MW step tests of the initiation phase. The results indicate no significant structural overestimation of the AAP on the Estinnes wind farm for this test. As already mentioned before the results are more difficult to interpret due to changing wind conditions during the different tests:

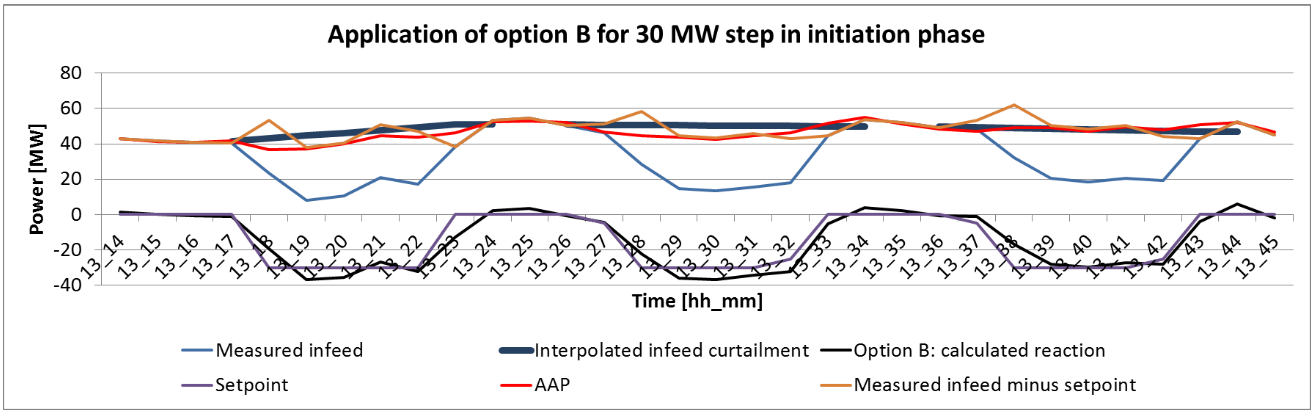


Figure 30: Illustration of option B for 30 MW step test in initiation phase

7.1.3. Conclusions of the initiation phase

The results of the initiation phase on the Estinnes wind farm are promising for future participation of wind farms in the (downward) aFRR markets. It was shown that wind farms can be controlled very accurately according to an aFRR test sequence.

The step response tests have shown the potential high flexibility available on wind farms. The controllable ramp rate of the Estinnes wind farm is relatively high and the minimum stable power very low.

The quality of the AAP calculation on the Estinnes wind farm in situations without curtailment is relatively good. A good quality of the AAP is fundamental to apply the AAP mechanism for the downward provision of aFRR on wind farms. The reason for this is that the desired output of the wind farm is defined as the sum of the AAP and the downward aFRR set point defined by Elia. An incorrect AAP would thus yield unsatisfactory results. The test performed in the initiation phase showed that the calculation of the AAP is potentially affected by the requested curtailment (overestimation of the AAP) but that the effect is limited. The effect was observed in one of the tests, whereas the results of the other tests do not provide evidence of structural overestimation.

Tests showed that the delivery of downward aFRR under the AAP mechanism introduces fast varying control errors in the system. This can be explained by the fact that the variations in the AAP can be faster than the control algorithm itself. Furthermore the errors present in the AAP calculation itself are also reflected here.

Nevertheless it can be concluded that, looking at e.g. one minute average values, the wind farm of Estinnes provided satisfactory downward aFRR reaction. The variations could be levelled out in case more wind farms simultaneously provide aFRR energy.

Finally it is expected that the quality of the AAP calculation will further improve, given the amount of research that is being performed on this subject. On this basis it was decided that the AAP mechanism is promising for the delivery of downward aFRR on wind farms. It was therefore also chosen to perform the AAP mechanism on the Estinnes wind farm during the second stage of the pilot project, the participation phase.

The observed results in the initiation phase only cover the performance of wind farms under a limited amount of specific conditions. Therefore it is important to continue to perform the tests also in the participation phase itself.

7.2. Participation phase

7.2.1. Scope

In the participation phase the wind farm of Estinnes contributed to the Belgian downward aFRR balancing energy market. As such the wind farm was activated together with the existing aFRR resources.

The wind farm of Estinnes was allowed to nominate either 0 MW (no aFRR nomination) or between 5 and 10 MW of downward aFRR in the system. The under limit of 5 MW was chosen in order to make sure that the effect of activation would be clearly visible for analysis. The upper limit was chosen to limit the impact of the pilot project on the balancing energy market.

During the test there was no contracted downward aFRR capacity on the Estinnes wind farm. Therefore the wind farm of Estinnes could nominate (in day-ahead) downward aFRR balancing energy bids in line with the forecasted generation of the wind farm (no obligation to nominate a fix volume of downward aFRR capacity to Elia).

During the participation phase Windvision communicated the available volume of downward aFRR, capped between 5 and 10 MW, to Eneco who then performed daily nomination of the available aFRR to Elia. The gate closure time for nominations for day D is 15h in day D-1.

The participation phase was organized in a way to minimize the impact on the market parties:

- The pilot project had no impact on the aFRR selection (see Chapter 4) as the downward aFRR volumes on the Estinnes wind farm were selected in addition to the normally selected downward aFRR volumes;
- There was no activation price defined for the downward aFRR activation on Estinnes. As such the presence of downward aFRR volumes on the Estinnes wind farm did not had an impact on the imbalance prices in case of activation;
- It is clear however that the presence of additional volumes of downward aFRR impacts the activated downward regulation volumes (Net Regulation Volume). This impact is limited given the maximum amount of 10 MW aFRR on the wind farm.

The requested activated downward aFRR volumes on the Estinnes wind farm were compensated in the perimeter of its BRP, being Eneco Energy Trade NL.

Only for the framework of this pilot project (no prerogative for any future arrangement) WindVision was compensated by Elia for the lost green certificates on the basis of the amount of verified activated downward aFRR energy. **For the development of a commercial aFRR down wind product it is clear that the loss of green certificates needs to be compensated in a different way.**

The downward aFRR volumes on the wind farm of Estinnes were directly activated by the Elia SCADA system (aFRR set point defined every 4 to 5 seconds).

The participation phase took place from mid December 2014 until the end of March 2015. The goals of the participation were the following:

- The longer duration of the participation phase allowed performing statistically more representative analysis of the quality of the AAP calculation under different operating conditions and the control performance of the wind farm. The quality is e.g. analysed in function of the measured infeed, in function of the wind direction, in function of the curtailed volume,...;
- The participation in the real aFRR framework allowed analysing **the reliability of the day-ahead nominations for available volumes of downward aFRR** on the Estinnes wind farm.
- It was investigated whether the nominated aFRR volumes were continuously available or not (e.g. not the case if the nominated volume of downward aFRR exceeds the actual infeed of the wind farm). To gain more experience, nominations were also requested on a week-ahead basis. Furthermore day-ahead nominations without the 5 to 10 MW constraints were gathered.
- The contribution of the Estinnes wind farm to the actual aFRR framework allowed identifying required changes to the Belgian aFRR framework to facilitate participation of wind farms in this market. This is analysed in more detail in chapter 8.

This chapter mainly focuses on the technical aspects of AAP quality, curtailment accuracy and reliability of performed aFRR nominations.

7.2.2. Observed issues

During the participation phase it was observed that the estimated AAP was sometimes structurally higher than the measured infeed of the wind farm for a period of some minutes.

Investigation revealed that this effect is due to wind turbines being stopped and then restarting, e.g. due to shade control, internal errors, wind turbines restarting, ... In such case the AAP already indicates full power directly from the start up, whereas the wind turbine needs several minutes to ramp up again. This technical issue has been recognized and will be resolved in future software updates.

This effect is illustrated in the graph below. An error occurs at 4:35, resulting in a sudden drop in injected power and AAP. After a few minutes the turbine would start up again, and thus generating a rapidly increasing AAP signal. However the ramp up of the turbine itself only starts some minutes later. During this period there is a significant difference between AAP and measured infeed. It is envisaged to resolve this issue by adjusting the AAP calculation mechanism in the future. It is believed that the effect of wind turbine errors or unavailability is wind farm related. Therefore a methodology was elaborated to filter such errors in order to come up with representative analysis of the performance of aFRR delivery without turbines in start-up procedure.

Therefore Elia and Enercon exchanged in real-time information on the number of turbines in start up phase. Each time a wind turbine was indicated in start up phase, a timeframe of 5 minutes before and 5 minutes after this instance was excluded from the performed analysis.

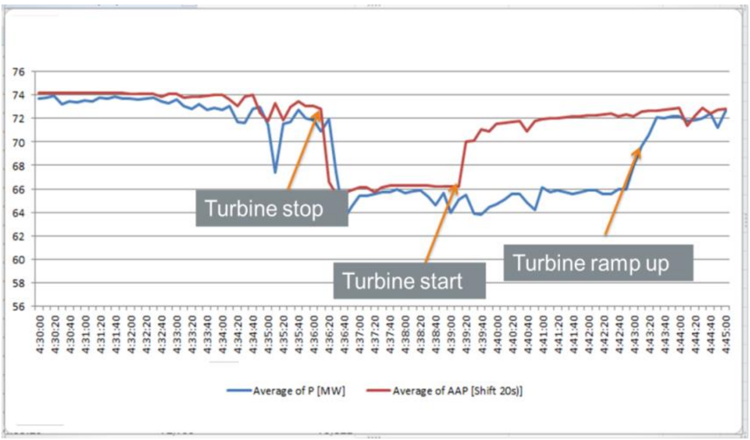


Figure 31: Illustration of a turbine in start up

7.2.3. Reliability of nominations

From a TSO perspective it is important that the nominated aFRR volumes are reliable in order to permanently have sufficient aFRR volumes at its disposal.

One of the goals of the participation phase therefore was to test the reliability of the ex-ante nominated aFRR volumes (see nomination strategy of paragraph 6.4) on wind farms. The related issue is that the actual amount of (downward) aFRR that can be delivered depends on the real-time wind conditions, which can only be forecasted up to a certain extent.

Under the actual mechanism Elia requires nominations for the aFRR volumes for day D before day D-1 15h00.

Chapter 8 investigates how much aFRR capacity a wind farm could theoretically offer to the TSO under different aFRR capacity procurement schemes. The main difference is that for the provision of aFRR capacity the procurement lead time is (depending on the system) longer (e.g. monthly procurement, weekly procurement). In addition the offered volumes must remain continuously available throughout the aFRR capacity product duration (e.g. same volumes for monthly off-peak and peak periods,...). These effects were not accounted for in the pilot project itself. Hence the nominated volumes of aFRR on the Estinnes wind farm could be different for each 15' period of day D.

During the participation phase Windvision, in cooperation with Eneco, was required to deliver following aFRR nomination data:

- Two different types of week ahead (W-1) nominations:
  - A firm (constant) aFRR volume for the entire week W;
  - Hourly blocks for the entire week W.
- Two different types of day-ahead (D-1) nominations:
  - Constrained case: hourly nominations submitted in D-1, either 0 MW (no aFRR delivery) or between 5 and 10 MW for day D. This nomination was used throughout the participation phase;
  - Un-constrained nominations: for these hourly D-1 nominations the windfarm could nominate any volume between 0 MW and its nominal power (81 MW). This data was only used for analysis in the pilot project.

This section investigates the reliability for aFRR nominations for different nomination time horizons (week ahead and day-ahead). In addition the volume that was offered under the different nomination time horizons was analysed. The considered period is 29/1/2015 until 25/3/2015. The offered volume can be put in perspective by comparing it with the actual feed-in of the wind farm. This shows the amount of flexibility the wind farm provided.

The reliability of the nominated aFRR volumes is determined by comparing the ex-ante nominated aFRR volume with the actual feed-in of the wind farm (compensated for any activated aFRR volume). In case the nominated aFRR volume exceeds the feed-in, the missing volume can be easily calculated (i.e. the amount of overestimation of the aFRR volume).

Table 6: Reliability of aFRR nomination

Volume of nominated aFRR	Average nominated aFRR down [MW]	Average infeed [MW]	% compared to feed-in	Reliability of nominated aFRR volumes
W-1: constant volume	0,3	17,6	1,6%	94,6%
W-1: hourly volume	3,9	17,6	22,1%	91,2%
D-1: constrained volume	2,2	17,6	12,5%	99,3%
D-1: unconstrained volume	6,1	17,6	34,7%	97,8%

Here it can be concluded that more volumes can be offered in a reliable way by allowing nominations for aFRR volumes closer to real-time. On a week-ahead basis already a certain share of the infeed can be offered in case the volume can vary on an hourly basis. However in such case the reliability is lower. As of day-ahead a significant aFRR volume can be offered with relatively high reliability.

Hence it would be beneficial for wind farms to move from day-ahead nomination of aFRR balancing energy volumes towards intraday nominations, both in terms of potential volumes to be offered as in terms of reliability.

Figure 33 provides an overview of the actual measured feed-in of the Estinnes wind farm and both the constrained (red line) and unconstrained (green line) day-ahead nominations.

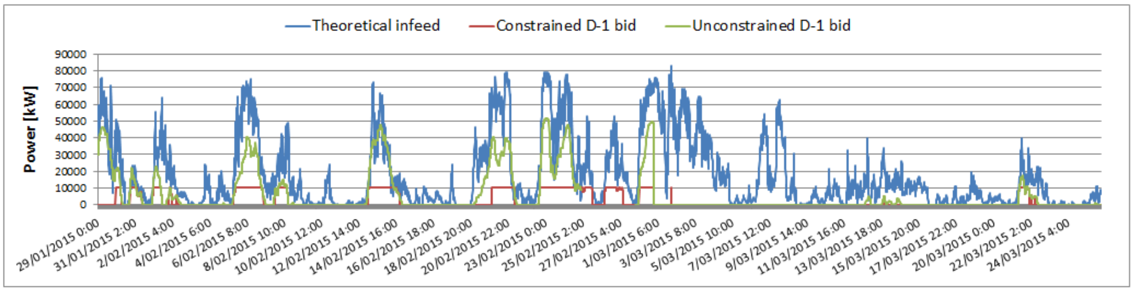


Figure 32: Comparison of measured feed-in and day-ahead nominations

Figure 33 shows the missing volumes of the nominated aFRR capacity for the unconstrained day-ahead nominations. The reliability of the constrained D-1 nominations is higher, as can be seen in the above graph.

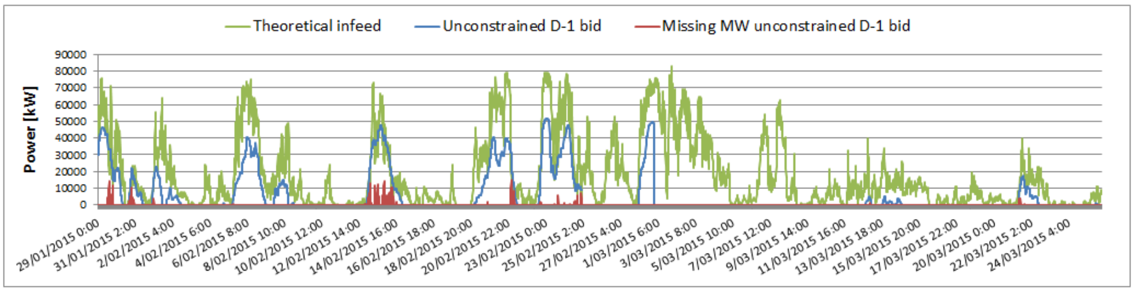


Figure 33: Missing volume of the nominated aFRR capacity for non-constrained day-ahead nominations.

Most of the nomination errors occur in case of changing wind conditions. Hence the reliability could be increased by adjusting the nomination strategy (see paragraph 6.4) for such cases. **It can be concluded that -in case of a performant nomination strategy- a nomination reliability of above 99% for an individual wind farm is feasible.**

7.2.4. AAP quality under non-curtailed conditions

Data and quality calculation

During the participation phase the AAP quality under non-curtailed conditions was assessed by comparing the measured infeed of the wind farm with its AAP. The error on the AAP is then calculated as the difference between the AAP and the injected power:

1. Error [MW] = AAP [MW] – Injected power [MW]

A positive error indicates overestimation of the AAP whereas a negative error indicates underestimation. The grid losses between the injection point and Elia's measurement are not taken into account, as the loss factor (considered as a constant value of 2,12% in this pilot project) itself depends on the infeed. Hence considereding a constant value of 2,12% could lead to skewed results.

The quality of the AAP signal was evaluated on both 10-seconds and one-minute average basis. The effect of wind farms in start up (see paragraph 7.2.2) was excluded.

AAP Quality under normal operating conditions

For the evaluation of the AAP quality, the same method as for the initiation phase (see paragraph 7.1.2) is applied. However here the relative error (i.e. error divided by measured infeed) is shown, whereas in the initiation phase the absolute error was shown.

The AAP performance is shown in function of the measured infeed of the wind farm (per interval of 5 MW). As such the quality of the AAP can be considered for different levels of generated power. Since the losses in the transformer were neglected, it is expected that the data points would be a little closer to zero (average value closer to zero) in reality.

Figure 34 allows to conclude that, due to the fact that the noise on the error is levelled out for the minute average values, the one-minute average results are slightly better. The average error nevertheless is the same for both cases.

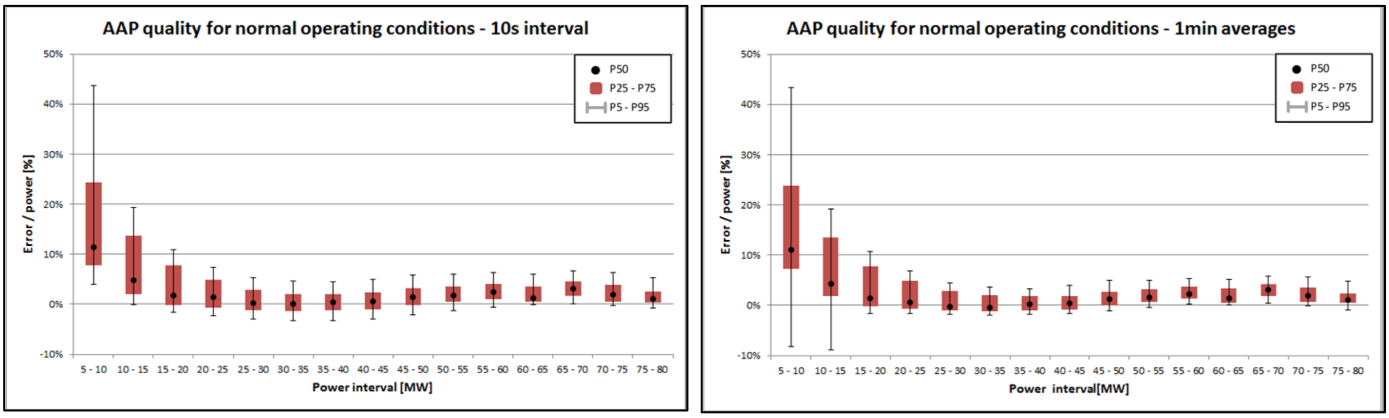


Figure 34: AAP quality under normal operating conditions for 10 seconds data and minute averages

Figure 35 shows the absolute AAP error in function of the measured infeed of the wind farm. This graph can be compared with the graph on the AAP quality in paragraph 7.1.2. The comparison between the initiation and participation phase reveals some differences, which can be attributed to the different treatment of turbine errors or unavailability (which were not excluded during the initiation phase) and to difference in wind conditions. Nevertheless the conclusions from the initiation phase remain valid for the participation phase.

The results show a (slight) overestimation of the AAP for low and high powers (in reality this would be a bit less due to the fact that the transformer losses are neglected). The absolute error increases slightly for higher generation infeed. The relative error is more or less constant as of a generation level of 25 – 30 MW. It slightly decreases towards higher infeed levels.

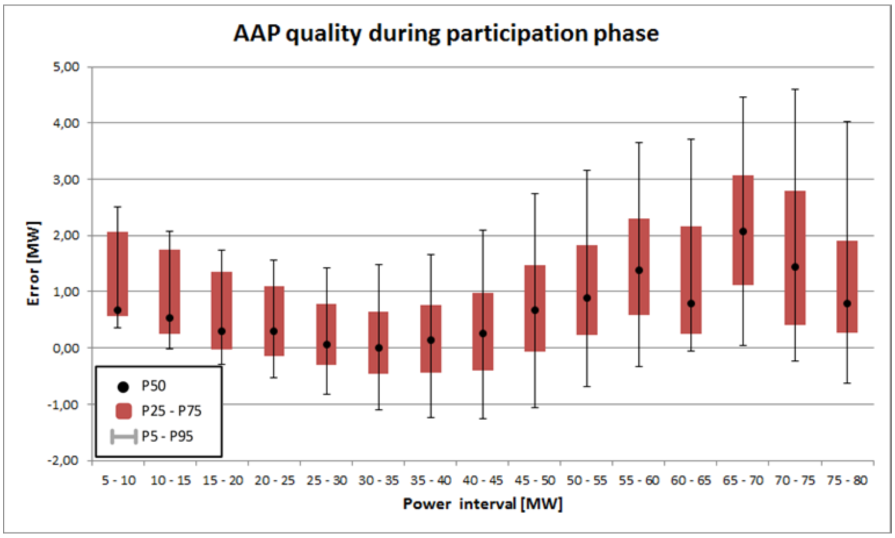


Figure 35: AAP quality during the participation phase 10 seconds data

As already explained in the initiation phase a possible explanation for the increase of absolute error for higher generation levels might be the fact that the AAP calculation method needs to be improved to account better for the effect of pitching the blades at high wind conditions, used to reduce the physical strain (blade load control).

In general we see that the AAP quality is lower in low power conditions, giving rise to large relative errors. In medium and high power conditions the relative error is limited, but the active available power estimation shows large deviations for the higher power levels.

It can be concluded that the AAP calculation is not perfect, but that the achieved performance shows potential for future participation of wind farms in the aFRR market via the AAP mechanism. Furthermore it is expected that the quality will further improve towards the future.

The low quality at low infeed levels indicates the potential need to define a minimum power below which wind farms cannot provide aFRR energy.

7.2.5. Wind farm control error under curtailed conditions

Data and quality calculation

During the participation phase the AAP quality (controllability of the wind farm) was assessed under curtailed conditions by comparing the injected power in the Elia grid minus the aFRR set point with the AAP of the wind farm. The error is then calculated as the difference between the AAP and the injected power minus the set point or:

Error [MW] = AAP [MW] – (Injected power [MW] – aFRR set point [MW])

In curtailed conditions the interpretation of the error is different than for non-curtailed conditions. The reason for this is that in curtailed situations, the wind farm is controlled to a generation infeed equal to the sum of the estimated AAP and the aFRR set point. Hence the error considered here is the **control error**. Figure 36 highlights the difference between the AAP error and the control error.

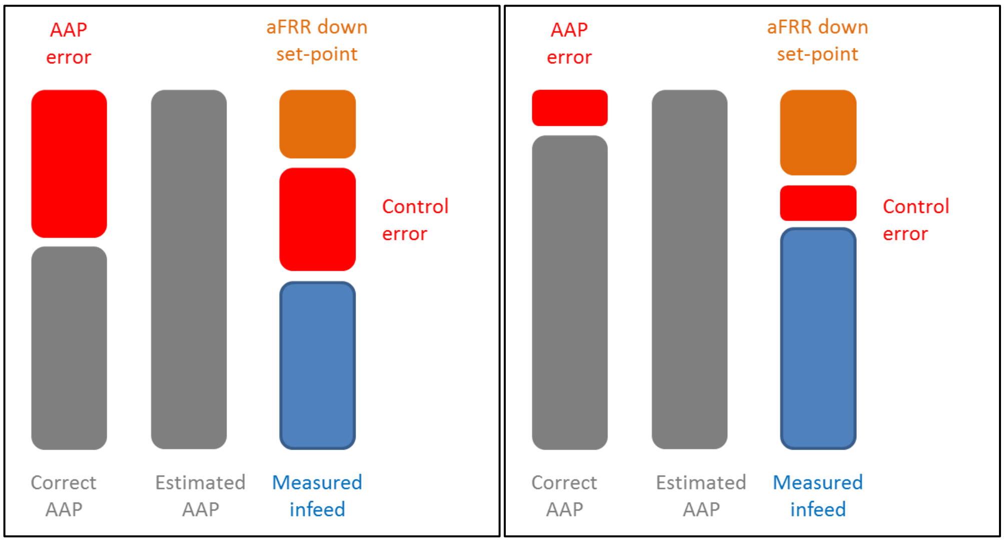


Figure 36: Difference between AAP error and control error

As shown in the left image above the control error can be influenced by the AAP error; the reason for this is that in this situation, for the control error to be zero, the wind farm should actually produce above the correct value of the AAP (physically impossible). In the right graph above the control error is not influenced by the AAP error. Furthermore it is clear that the control error can be zero, but that the actual performed curtailment can be incorrect due to an existing AAP error. Therefore the results in this paragraph must be analysed with care.

A positive error indicates that the calculated curtailed volume (AAP minus measured infeed) exceeds the downward aFRR set point. This can indicate following situations:

1. Overestimation of the AAP: in this case the calculated volume of curtailment is incorrect and hence overestimated. Although the calculated curtailed volume exceeds the requested downward aFRR delivery, in reality there might be insufficient or no curtailment performed at all;
2. Correct estimation of the AAP but the curtailed volume exceeded the requested curtailed volume (e.g. in case of a sudden increase of the AAP exceeding the control speed of the wind farm).

The above situations are shown in Figure 37, respectively on the left and right hand side:

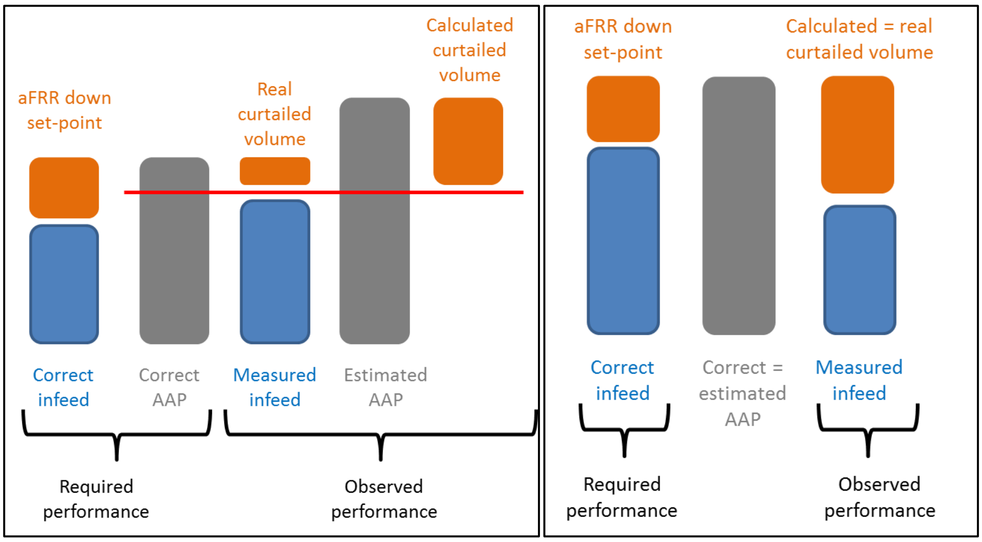


Figure 37: Illustration of AAP error

A negative error indicates that the calculated curtailed volume (AAP minus measured infeed) is less than the downward aFRR set point. This can indicate following situations:

1. Insufficient curtailment performed (e.g. in case of a sudden drop of the AAP faster than the control speed of the wind farm or in case of unsatisfactory behaviour of the control);
2. Insufficient wind available to deliver the required downward aFRR set point (hence AAP is lower than the downward aFRR set point). In such case the measured infeed of the wind farm is close to zero.

For the same reasons as stated above, also here the losses between the injection point and Elia's measurement are not taken into account. The analysis is performed both for a 10 seconds and average one minute value basis. Data including the start up of wind turbines was filtered out as in the previous sections.

Analysis of the control error of the wind farm

Figure 37 and Figure 38 show the control error observed on the Estinnes wind farm during curtailment. It must be noticed that the actual error on the curtailed volume is a combination of the AAP error and the control error. Hence the graphs below provide an estimation of the control capability of the wind farm (i.e. ability to deliver a set point compared to the estimated AAP) but do not provide a total overview of the quality of the delivered aFRR service. The second graph shows the controllability on 10s basis, whereas the first one is based on one-minute average values.

A poor quality of the control error at lower power levels is shown. This might be due to a lower reference AAP quality which leads to higher errors.

This again indicates that there might be a need to implement a minimum power below which wind farms cannot provide aFRR balancing energy.

For higher power levels the control error seems to be limited; looking at the minute average values, it is observed that the 5th- and 95th-percentile (of the error) are limited to 2% of the generated infeed, while the median control error is close to zero. These graphs allow to conclude that the Estinnes wind farm is able to accurately curtail from the AAP value at higher power levels.

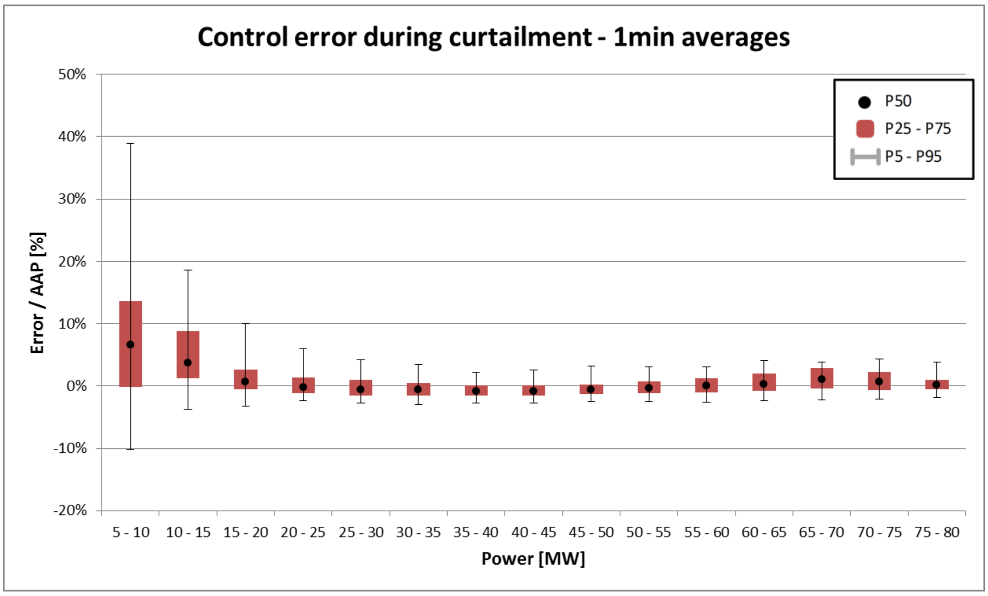


Figure 38: Control error during curtailment for the participation phase - 1 minute average

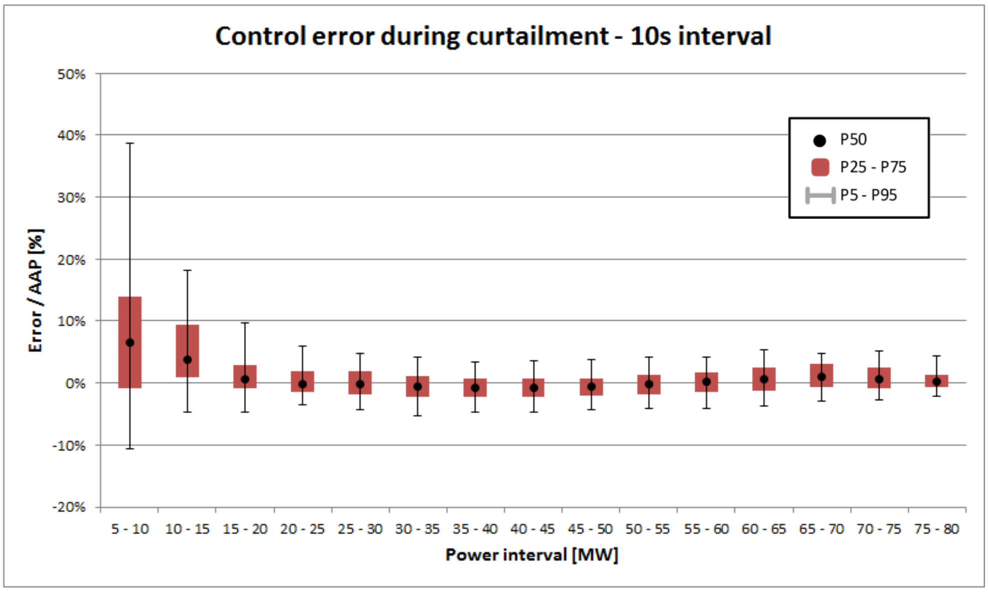


Figure 39: Control error during curtailment for the participation phase - 10 seconds data

Above it was explained that an overestimation of the AAP in general leads to a situation where insufficient downward control is performed. Such overestimation can occur due to the wind farm effect as explained in paragraphs 6.1 and 7.1.2. Therefore also in the participation phase it was tested whether there were signs of structural overestimation of the AAP. Here the Option A methodology, as elaborated in paragraph 7.1.2 is applied. The data for a three day period (30/1/2015 – 1/2/2015) is analysed on a daily basis.

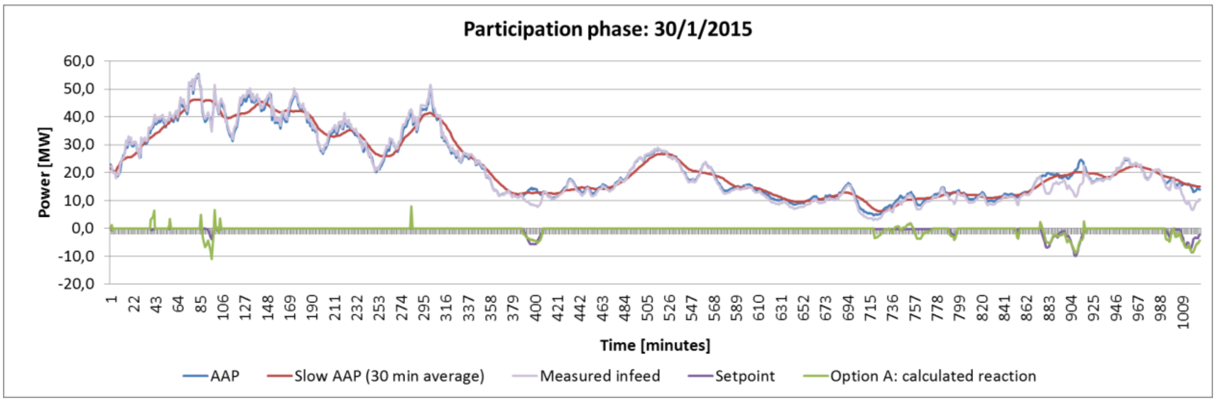


Figure 40: Performance on 30/01/2015

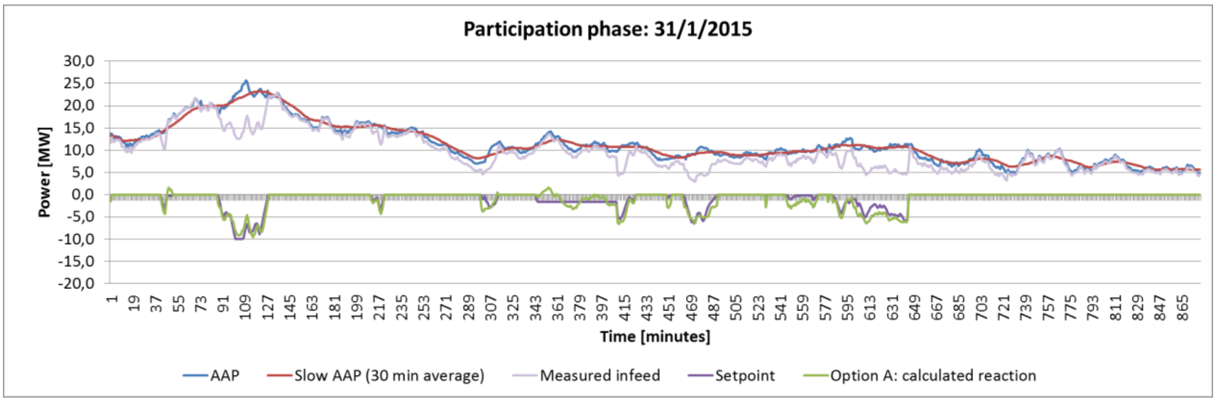


Figure 41: Performance on 31/01/2015

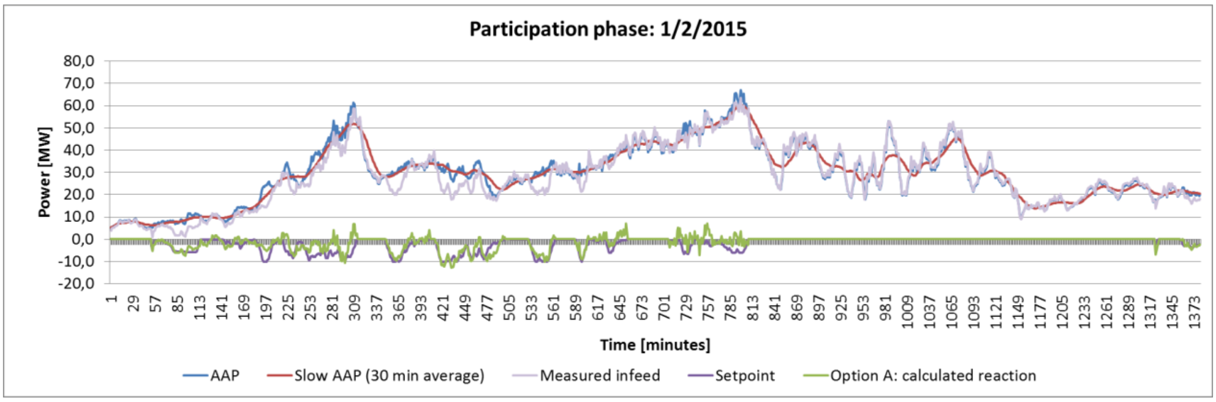


Figure 42: Performance on 01/02/2015

In the graphs above the Option A calculated reaction is only shown for the cases where an aFRR set point was sent. It is clear from the graphs that in general (under stable wind conditions) the calculated reaction (green line) corresponds well with the set point (purple line). This demonstrates that there is no or very little structural overestimation of the AAP under such circumstances. As noticed before, the Option A methodology to check overestimation of AAP is only valid under stable wind conditions. Under varying wind conditions this effect is more difficult to measure.

For the last day shown above (1/2/2015), Figure 5 shows that during the periods with varying wind conditions, the control error itself (such as defined above) remains limited.

On the basis of the above results it can be concluded that during periods with stable wind conditions (i.e. conditions for which the Option A test was elaborated), there is no proof of significant, structural overestimation of the AAP during periods of curtailment.

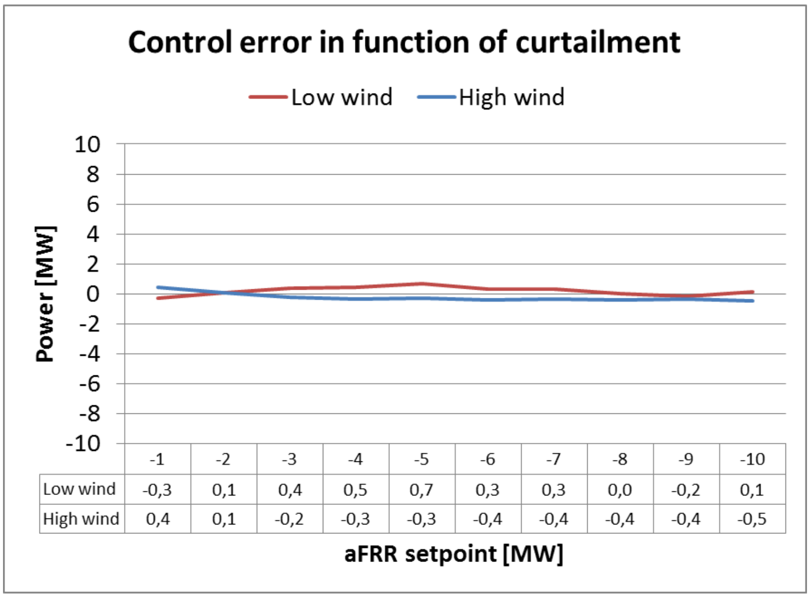
Influence of activated volume on quality

To determine whether the amount of curtailment (or MW of aFRR) has influence on the control error, the control error was analysed in function of the required curtailed volume.

In Figure 43 an AAP higher (lower) than 30 MW is considered as high (low) wind conditions in the graph below. The required activation is divided in ten intervals of 1 MW each.

A positive average control error in the graph below indicates that the calculated curtailment exceeds the required downward aFRR set point, indicating either overestimation of the AAP or too much volume curtailed. If the average control error is negative than we expect either under delivery of curtailed volume or insufficient wind available to perform the requested downward curtailment.

The graph below shows that the average control error is close to zero, regardless of the curtailed volume. It is important to consider that the average control error, especially for small curtailed volumes, can be relatively large. The below graph doesn't account for the transformer losses. Hence it is expected that there is –on average basis- a slight under delivery of the required curtailment (insufficient volume curtailed).



	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10
Low wind	-0,3	0,1	0,4	0,5	0,7	0,3	0,3	0,0	-0,2	0,1
High wind	0,4	0,1	-0,2	-0,3	-0,3	-0,4	-0,4	-0,4	-0,4	-0,5

Figure 43: control error in function of curtailment

7.2.6. Influence of wind direction on AAP quality / control error

During the participation phase it was analysed whether the AAP quality / control error was influenced by the wind direction. For this purpose the wind direction was monitored on a 10-minute average basis. Given that the previous tests showed worse performance of the AAP calculation for low generation infeed, only wind conditions which result in an injected power higher than 20 MW were taken into account. For this analysis no separation was made between curtailed and non-curtailed situations. On the basis of Figure 44 it is clear that in terms of occurrence we can focus on the 180-252° interval in terms of leading wind directions.

We investigated whether for these wind directions there was an influence on the AAP / control error quality. The same quality indicators were used as in the previous paragraph. Figure 45 shows the distribution of wind direction for powers higher than 20 MW. The green bars indicate an AAP / control error of less than 3% (compared to the measured infeed), red bars indicate an error higher than 7.5%.

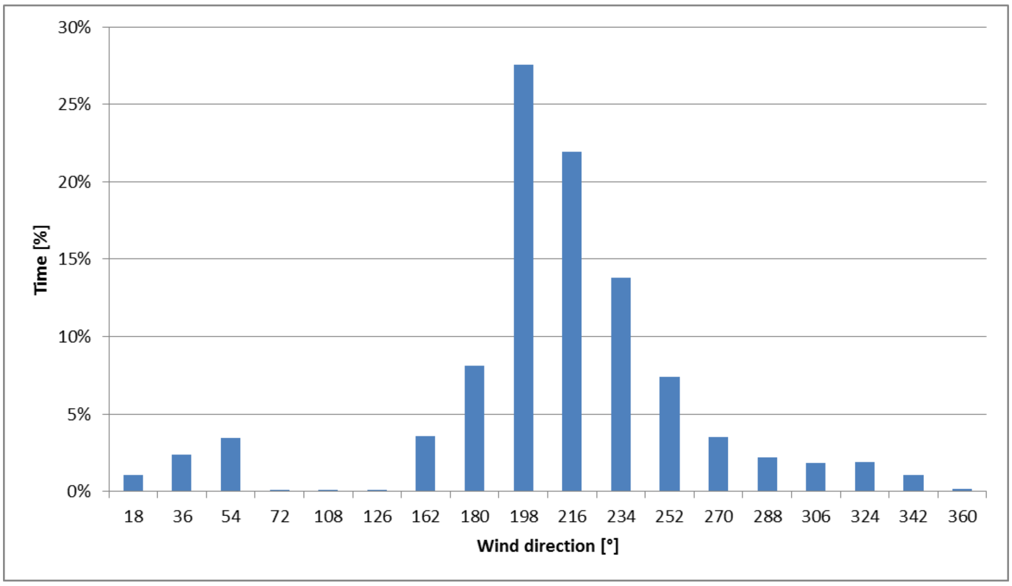


Figure 44: Leading wind direction for Estinnes wind farm

The graph shows that for the Estinnes wind farm the wind direction has limited influence on the AAP error / control error. The lay out of the wind farm can be found in **Error! Reference source not found.**. It is expected that this effect is wind farm specific. Therefore it could be of relevance for other wind farms. This effect can be tested by requiring a sufficiently long dataset of AAP and infeed data, covering all wind conditions.

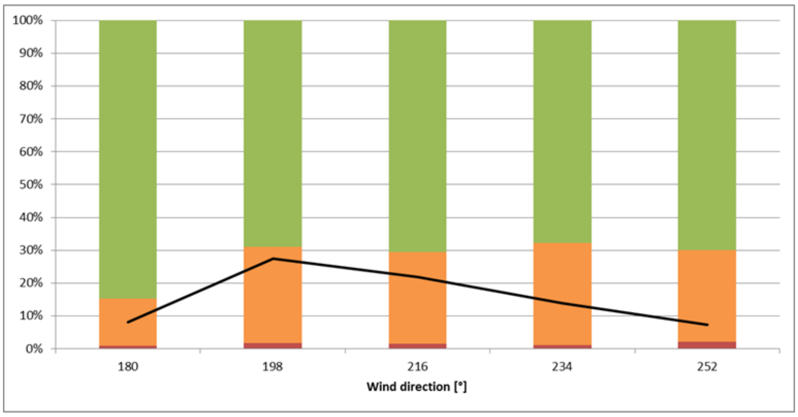


Figure 45: Illustration of AAP quality in function of the wind direction

7.2.7. Conclusions of the participation phase

The participation phase revealed good potential for wind farms to participate in the aFRR market towards the future.

In general it can be concluded that wind farms are able to provide reliable aFRR nominations (reliability >99%) as of the day-ahead timeframe. A transition towards intraday nominations would further increase the amount of aFRR balancing energy bids that could be offered by wind farms, as well as the reliability of these nominations.

The participation phase showed that the quality of the AAP calculation is not yet perfect and is undergoing active development. It also showed that the AAP quality must account for both wind farm specific effects (geography, wind directions, failing of wind turbines...) and general effects (data transmission, controller cycle speeds, grid losses…). Nevertheless the AAP quality is promising and expected to further increase towards the future given the amount of ongoing research.

The fact that the downward aFRR is delivered from a calculated reference (AAP) complicates the analysis of the aFRR activation quality. This was demonstrated by defining both an AAP error and a control error. Both are relevant to consider when discussing the aFRR activation quality (the AAP error can have an impact on the control error). It was shown that the control error is relatively limited for medium to high wind conditions.

Given the above it is clear that the approach followed in this pilot project (i.e. first assess the AAP error without curtailment, and then assess the control error under curtailed conditions) allows a fair idea of the overall aFRR activation quality.

The tests showed that both the AAP quality and control error were worse for low infeed levels. This indicates a potential need to either

- implement a minimum power below which no aFRR can be delivered in order to improve the quality of the service; or
- improve the AAP quality and control accuracy at low power levels.

The pilot project showed that over a three day observation period, there was no (or limited) sign of structural overestimation of the AAP. Hence it is expected that the wind farm effect is limited for the Estinnes wind farm. In case of transient wind conditions the results were less clear as it is possible that there is some overestimation of the AAP related to the required level of curtailment. It must be noted that this can also be related to changing wind conditions during the test.

The participation phase showed that the control error was little dependent of the curtailed volume itself (both for low and high wind conditions). When taking into account the loss factor between the connection point of the wind farm and the measurement point of Elia, a limited amount of under-delivery of required downward regulation is observed.

Finally it was shown that the wind direction has no or little impact on the AAP quality or control error for the Estinnes wind farm.

8 Market analysis

This chapter provides a high level analysis on whether the actual Belgian aFRR balancing capacity and energy market design allows for the participation of wind farms. Given the technical focus of this pilot project, not all market aspects are elaborated in detail. This could be done in a next step.

8.1. Product duration and procurement lead time

Paragraphs 6.4 (nomination strategy) and 7.2.3 (nomination reliability) already showed that the forecasts for wind production are reliable as of one or two days ahead. The reliability increases towards real-time. Hence it can be concluded that both:

- A short procurement lead time for aFRR capacity procurement (i.e. time between procurement and delivery); and
- Possibility for nominations of aFRR balancing energy bids close to real-time (e.g. intraday nominations) for non pre-contracted aFRR balancing energy bids,

are very important to facilitate the participation of wind farms in these markets.

The actual monthly duration of aFRR capacity products, along with the procurement lead time of about 2 weeks ahead, might be limiting factors for a stand-alone participation of a wind farm in the aFRR (down) capacity market.

This can be demonstrated by a simplified example. Here we assume the hypothetical case that the forecasting quality would be perfect in all time horizons (i.e. even month- or week-ahead the actual production per quarter hour can be perfectly forecasted). In such case we could suppose that (if we also neglect a minimum required power and assuming high ramp rates) in principle a wind farm could offer its entire forecasted production as downward aFRR balancing energy to the TSO.

The duration of (actual) aFRR capacity products however is relatively long. Hence the potential of downward aFRR capacity that wind farms can offer, without accessing the secondary market[9] to ensure continuous availability, is the minimum amount of the forecast volume throughout the duration of the aFRR capacity product. The underneath graph gives for an entire week an example of the volume of aFRR capacity that a wind farm could offer (thereby assuming a weekly aFRR capacity product).

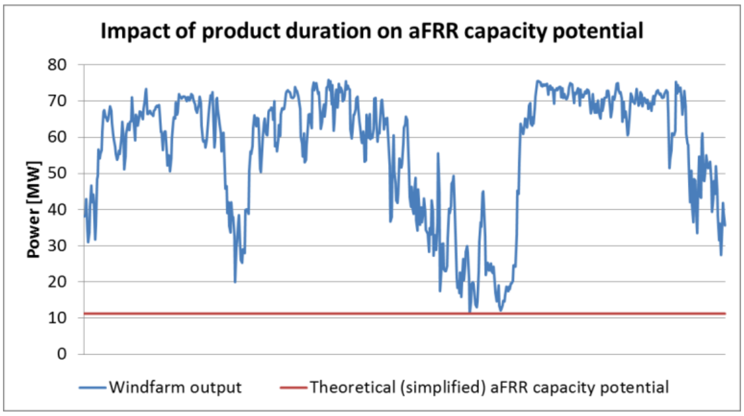


Figure 46: Impact of product duration on aFRR capacity potential

It is clear from the above graph that the wind farm could in principle contribute significantly more to the aFRR down markets if the duration of the aFRR capacity product would be shorter.

Table 7 below shows an overview of which share of the (simplified) theoretical downward aFRR capacity can be offered for different aFRR capacity product durations and product resolution (currently peak and long off-peak in Belgium). This exercise is performed for the wind farm of Estinnes for 2014. Given the potential difficulty of finding the complementary aFRR upward capacity for peak and long-offpeak (or even shorter) periods, also a base delivery is considered below. Indeed it is important to find the complementary upward aFRR volumes to develop an attractive aFRR stand alone (capacity) product. On the other hand it must be recognized that it is expected that the needs for downward regulation capacity will significantly increase towards the future (thereby potentially relieving this constraint).

[9] See description of the actual aFRR framework. The secondary market is a day-ahead market where aFRR providers can bilaterally exchange aFRR obligations.

The same exercise is performed for the aggregated Belgian offshore wind production such as published on the Elia website for 2014 (wind forecasting tool). The latter is investigated to check whether there are substantial differences between onshore and offshore wind farms regarding the potential to offer downward aFRR capacity.

As shown in Figure 46 above, these values are calculated on the basis of the minimum observed quarter hourly generation during the aFRR capacity product duration (= simplification). Hence, for an entire year the volume that can be offered in each of the periods (red line in graph above) is divided by the infeed during the same periods (blue line in the graph above) to obtain the values in the table. In reality significantly less capacity can be offered as a safety margin must be incorporated to compensate for forecasting errors. Moreover forecasts only become reliable two days until one day ahead (cfr. paragraph 6.4).

Table 7: Impact of product duration on aFRR capacity potential

	Product duration / product resolution	Base delivery	Peak & long-off-peak	8h blocks	4h blocks
Onshore wind farm	Month	0%	0%	1%	1%
	Week	2%	4%	5%	8%
	Day	**25%**	**34%**	**50%**	**65%**
BE aggregated offshore production	Month	0%	1%	1%	1%
	Week	3%	6%	7%	11%
	Day	**36%**	**47%**	**65%**	**78%**

It can be concluded that with the current monthly aFRR capacity product duration in Belgium there is almost no potential for stand-alone wind farm participation in the aFRR down capacity market as of today. For weekly product duration there is –at least in theory- a small potential for participation. Considering however that there is also the relatively large uncertainty on week-ahead forecasts (and an additional procurement lead time of some days), it is clear that also here the final potential on W-1 basis will be very low.

Only in case of daily procurement and short procurement lead times there is a high potential for wind farms to participate in the aFRR down capacity market (with relatively high certainty on forecasted infeed). There is no significant difference between onshore and offshore wind farms with respect to this matter.

In addition it can be concluded that an increase of product resolution from the current peak / long off-peak products towards 4 to 8 hour blocks would almost double the participation potential. Furthermore it is clear that a shorter procurement lead time results in better forecasting quality and therefore increases the participation potential.

Hence following changes must be further investigated to maximize potential participation of wind farms in the aFRR down capacity market:

- Procurement lead time: as short as possible (e.g. day-ahead);
- Product duration: as short as possible (daily);
- Product resolution: as high as possible (8 or 4 hour blocks).
- Improvements of forecasting quality (reliability of nominations).

The feasibility of the proposed changes (short procurement lead time, daily product duration, higher resolution) needs to be investigated further in the future. It is clear that these changes increase complexity and require –given the short time for procurement- very efficient processes and a reliable fall-back solutions in case of issues (e.g. insufficient aFRR capacity offered,...). These changes have to be investigated in parallel with the implementation of the Network Code on Electricity Balancing [2] that requires the implementation of a standardized and integrated European balancing market.

The aFRR balancing energy market is based on day-ahead nomination of aFRR energy bids and would therefore already allow today the participation of wind farms. As shown later in this chapter there are other issues however that block wind farm participation in this market.

Actually wind farms can however participate relatively easily in the Belgian balancing market under the form on non-contracted manual CIPU bids (nominations of bids allowed in intraday).

8.2. Cost structure / loss of green certificates

There is a significant difference in the cost structure for conventional units (CCGTs) and wind farms to provide aFRR capacity and balancing energy. Table 8 provides an overview for the cost structure for making available aFRR capacity:

Table 8: Cost structure for making available aFRR capacity

Cost structure for aFRR capacity	Conventional unit	Wind farm
Opportunity losses / costs for making units available	• Upward aFRR capacity: opportunity losses due to less volume sold on the market (if unit is in the money) • Upward / downward aFRR capacity: must run costs if unit is out of the money	• Upward aFRR capacity: loss of green certificates due to continuous de-rating, less energy sold to market • Downward aFRR capacity: no costs (no de-rating)
Other costs	Wear and tear, account for activation income, back-up costs,...	Wear and tear, account for activation income, back-up costs,...

It is clear that the inherent costs for making downward aFRR capacity on wind farms might significantly be lower than the cost for providing aFRR capacity on CCGT units.

On the other hand the cost for making upward aFRR capacity available on wind farms is very high. This cost will probably exceed the price of green certificates due to the de-rating and market opportunity losses. The delivery of upward aFRR capacity on wind farms is therefore not considered in this pilot project (although technically possible). This is only profitable in very extreme and rare market conditions.

Table 9 provides an overview for the cost structure for the activation of aFRR balancing energy:

Table 9: Cost structure for activating aFRR balancing energy

Cost structure for activating aFRR balancing energy	Conventional unit	Wind farm
Downward aFRR regulation	**In general cost reduction** Fuel saving, reduction of CO2 emission,... (Negative) impact on plant efficiency Opportunity losses (e.g. less steam output for CHP unit,...)	**In general cost increase** Loss of green certificates No cost reduction due to fuel saving
Upward aFRR regulation	**In general cost increase** Increased fuel consumption, more CO2 emission,... (Positive) impact on plant efficiency ...	**In general cost reduction** Recuperation of lost green certificates due to continuous de-rating No cost increase for fuel (being the available wind)

It can be concluded that the cost structure for activation aFRR balancing energy is structurally different for conventional units and wind farms.

As already indicated in Chapter 4 Elia performs pro-rata activation of aFRR balancing energy. This means that Elia activates all selected aFRR bids in parallel regardless their price. From a technical point of view this results in higher ramp rates due to parallel activation. In order to avoid excessive prices, there is a cap and a floor on the aFRR balancing energy prices:

- Downward activation: a floor of 0 €/MWh; and
- Upward activation: fuel costs of a 50% efficient gas unit + 40 €/MWh (~100 €/MWh).

The floor of 0 €/MWh does not allow to reflect the cost increase for downward aFRR regulation on wind farms (loss of green certificates). Therefore, under the current pro-rata aFRR scheme, the cost increase due to loss of green certificates needs to be priced in the aFRR down capacity price. This would significantly affect the competitiveness of wind farms on the downward aFRR capacity market. This is demonstrated by the following (simplified) example.

Under following assumptions:

- a MW of downward aFRR capacity is (fully) activated on average for 25% of the time;
- the price of a green certificate is about 65 €/MWh

the inherent downward aFRR capacity cost for a wind farm would be around 16 €/MW/h. This cost is relatively high compared to the cost for making aFRR (symmetric) capacity available on conventional units [see Elia website[10]]. For conventional units a significant share of the costs for delivering aFRR capacity to Elia is related to the must run costs (i.e. starting a gas unit up to minimum stable power in negative market conditions). However once this unit is running, the cost for providing upward and downward aFRR capacity is relatively low. Hence under the current support scheme and aFRR capacity market design the competitiveness of wind farms to provide downward aFRR capacity is relatively low.

Under the current framework the delivery of aFRR down capacity might be competitive under following conditions:

- Very negative clean spark spread and hence high must run costs for gas units. Delivery of downward aFRR capacity on wind farms in such situation could reduce the power at which conventional units must run to deliver aFRR capacity (Pmin + aFRR down capacity);
- In case sufficient aFRR down capacity by wind farms is available to reduce the number of must run conventional units:
    - E.g. instead of having 2 - 3 must run gas units delivering symmetrical aFRR, going to a situation where one must run delivers all upward aFRR and wind farms provide all downward aFRR capacity.

Lowering the floor on aFRR energy prices –so that costs related to the loss of green certificates can be integrated in the aFRR energy price- in the current pro-rata scheme is rather difficult as this would result in a situation where relatively cheap and very expensive aFRR down energy bids are activated at the same time (no competition). This would result in more extreme imbalance prices, also for relatively small imbalance volumes.

It can be concluded that the combination of the current energy based RES (Renewable Energy Sources) support scheme and a pro-rata activation scheme for aFRR, is a limiting factor for the participation of wind farms in the Belgian aFRR down markets (both aFRR balancing capacity and balancing energy markets).

A possible solution could be a transition towards a merit order activation scheme for aFRR as in such case aFRR bids are activated sequentially on the basis of increasing (decreasing) aFRR balancing energy prices for upward (downward) aFRR regulation. In such case cheaper aFRR balancing energy bids would be activated before the more expensive ones. This is illustrated by the graph below (left: pro-rata activation, right: merit order activation of aFRR). Under such mechanism the floor on the aFRR energy prices might be lowered.

[10] For conventional units the majority of the aFRR capacity costs are related to must run costs. These costs are shared for aFRR down and aFRR up and therefore cannot be looked at separately. More information on the purchasing of ancillary services can be found on http://www.elia.be/en/suppliers/purchasing-categories/energy-purchases/Ancillary-Services-Volumes-Prices

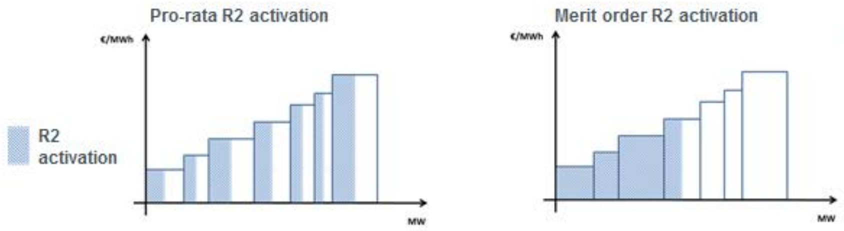


Figure 47: Illustration of pro rata and merit order aFRR activation

However it must be noted that the activation of aFRR occurs on the basis of an automated system. Due to the fact that there are many imbalance spikes in the system, there is always a risk for the activation of very expensive downward aFRR balancing energy bids (e.g. by wind). In such case the imbalance price could become very negative even for very small imbalances on a fifteen minutes level.

Hence in such case it must be discussed whether it is desirable to include the cost for the loss of green certificates in the aFRR energy price. It should also be further investigated whether this would not deteriorate the imbalance price incentives given to market parties (e.g. asymmetric incentives for having a long and short position). This is less a problem for manual bids on wind farms (where already today the loss of green certificates is included in the energy bid price) as such bids are only activated in case of persisting large imbalances (or a lack of cheaper flexibility available in the system).

The Network Code on Balancing requires the border-crossing exchange of aFRR balancing energy. This might require a harmonization of RES support schemes to create a level playing field for intermittent RES units to participate to the balancing markets.

8.3. Availability and activation check

The costs charged by Elia for missing FCR and aFRR capacity volumes are uniform for all involved market parties. The cost is determined in a way to incentivize the use of the secondary market to ensure that, in case of unavailable volumes, market parties exchange their obligation on the secondary market instead of paying the penalty to Elia. No change is required for the participation of wind farms to the aFRR capacity markets.

On the other hand the checks for activation quality might need to be reconsidered:

- As shown before the cost structure for activating aFRR balancing energy is fundamentally different for wind farms than for conventional units;
- Whereas conventional units can follow the aFRR set point very accurately (even on short time periods), the variability of wind conditions (and AAP calculation) makes this more difficult for wind farms. Hence it must be considered whether changes in the activation checks are required. The goal must be to give a proper incentive to reach an acceptable quality. A possible solution would be to check on minute basis instead of 10s basis.

8.4. Activation quality

One of the results of the pilot project was that aFRR delivery by wind farms on the basis of the AAP mechanism introduces some fast changing control errors (noise). The observed quality in this pilot project is promising for future participation of wind farms in the aFRR markets. It is believed that (in case a solution is found for the observed issues regarding AAP calculation) the impact of the participation of the Estinnes wind farm on the Belgian regulation quality would be limited. This might be different nevertheless for other wind farms.

It is therefore important to determine minimal technical requirements, setting a standard for acceptable activation quality. Given the expected improvements of the AAP quality, such standard could become stricter in time.

If there would be an impact of the delivery of downward aFRR by wind farms on the Belgian regulation quality, there might be a need to set a restriction to the concerned volume (or to increase the required amount of aFRR down capacity to compensate for the quality loss).

8.5. Conclusions of market analysis

The analysis showed that the Belgian aFRR market design does not facilitate the participation of wind farms in the aFRR balancing capacity and energy markets.

In first instance it was demonstrated that the monthly duration of the aFRR capacity product is too long to allow for stand-alone participation of wind farms in the aFRR capacity market. Moreover it would be beneficial for wind farms to increase the resolution of the aFRR capacity product from the current peak / long-off-peak products towards blocks of 4 to 8 hours. It must be noted that in such case also the upward complement of aFRR (conventional units,...) must be found on the same timeframe.

It was shown that the combination of the current energy based support scheme for renewables and the current aFRR pro-rata activation scheme significantly affects the competitiveness of wind farms in the aFRR markets.

A potential solution for this issue would be to move towards an aFRR merit order activation scheme where the floor on the aFRR energy prices could be lowered such that the loss of green certificates can be included in the aFRR balancing energy price. Nevertheless also for such solution there are some important questions to investigate:

1. The impact of having aFRR energy bids with very negative prices, that are activated on an automatic basis to cover a.o. sudden (and potentially short) imbalance peaks, might lead to very negative imbalance prices for small imbalance volumes. It must be discussed whether this is desirable and whether such mechanism might not deteriorate imbalance pricing incentive (e.g. lead to asymmetric incentives for short and long imbalance positions);
2. Will there be harmonization of RES support schemes on EU level given the further integration of EU energy and balancing markets?

Whereas the penalty design for missing aFRR capacity can remain unchanged in case of participation of wind farms in this market, there can be a need to re-design the penalties for imperfect activation given the significant difference in cost structure between conventional units (for which the penalty is designed today) and wind farms.

Depending on the quality of aFRR delivery by wind farms there might be a need to limit their total participation in the aFRR market or to increase procured volumes to maintain the current regulation quality. The first results of this pilot project, in combination with the significant amount of research being performed on the topic, are however promising to avoid such measures.

It is important to indicate that the above mentioned changes to facilitate stand-alone participation of wind farms in the aFRR market are significant and increase the market complexity. They should be further investigated in detail, in parallel with the requirements of the Network Code on Electricity Balancing [2], the next years before they can be implemented.

9 Pre-qualification requirements

In chapter 8 the required aFRR market design changes in order to facilitate the participation of wind farms in the aFRR (down) market were discussed. The pilot project shows that delivery of aFRR on the basis of the AAP mechanism is very promising for the future; especially as significant research is performed –both by wind turbine manufacturers and on academic level- to further increase the quality of the AAP calculation. A good AAP quality is of vital importance for qualitative delivery of aFRR to the TSO.

In order to facilitate the future participation of wind farms in aFRR it is also important to define, to the extent possible, the requirements for wind farms to participate in this service. This chapter therefore focuses on the required control capability of wind farms and specifications for the calculation of the AAP.

No targets for pre-qualification are defined within this technical pilot project as the scope of the pilot project was limited to testing the technical capabilities of wind farms to provide aFRR capacity and to perform a high-level market analysis. In first instance the feasibility of the required market changes (to enable commercial participation of wind farms in the aFRR market) has to be investigated, in parallel with the developments on European level with the implementation of the requirements of the Network Code on Electricity Balancing [2]. In a later stage the targets for technical pre-qualification must be determined in close collaboration with all market parties. The different paragraphs of this chapter refer to the observed performance of the Estinnes wind farm[11] where possible.

Furthermore targets for the minimum required AAP quality (both under curtailed and non-curtailed conditions) might be dynamic in the future as they could gradually become more strict given the ongoing research and progress on this topic.

The next paragraphs provide an overview of which technical aspects are important for a wind farm to be able to participate in the aFRR market in the future.

9.1. Minimum communication requirements

The wind farm should be able to communicate in real-time with the Elia operational systems (SCADA,...). Data is exchanged typically on a 1 to 10 seconds basis. It must be possible to exchange data[12] such as the AAP, the aFRR set-point, wind speed, technically available maximum power, status of aFRR controller,... on a real-time basis between the wind farm and Elia.

In case of the implementation of the AAP control mechanism it is also important that the wind farm is able to calculate and communicate an AAP calculation every 1 to 10 seconds (4s in this pilot).

9.2. Ramping capabilities

The Full Activation Time of aFRR in Belgium is 7,5 minutes. Hence in order to be able to deliver aFRR capacity, the wind farm should be able to respect at least following ramp rate:

$$\text{Ramp rate} = \frac{\text{Delivered aFRR capacity [MW]}}{7{,}5 \text{ minutes}}$$

On a European level however there are substantial differences for the full activation time of aFRR. Most common values for Continental Europe[13] are roughly between 5 and 10 minutes. The Network Code on Electricity Balancing strives for harmonization of balancing products during the next years. This includes a.o. harmonization of ramp rates of aFRR. The outcome of these discussions will therefore determine the minimum required ramp rate to participate in the aFRR framework towards the future. The requirement here sets a limit for the minimum aFRR ramp rate. It is possible that TSOs will also accept and activate higher ramp rates.

[11] Corrected for moments with turbine failure
[12] The following list is not exhaustive and because it is only the beginning of this technology as an ancillary service resource, the list of required data could still undergo significant changes.
[13] This indicates the current practice only. Towards the future it is possible that the Full Activation Time might even go to 1 or 2,5 minutes.

9.3. Reliability of aFRR nominations

A reliable delivery of nominated aFRR volumes is very important for a TSO (target is 100% reliability). For wind farms though there is always a risk that wind conditions might differ from the forecasted ones, leading to incorrect nominations.

The pilot project showed that for the constrained nominations (between 5 and 10 MW) an availability of 99,3% was achieved. For the uncapped nominations a reliability of 97,8% was achieved. Main cause of this lower availability was the reduced reliability in case of changing wind conditions. This could be resolved by improving the algorithm calculating the nominations.

Elia therefore considers that the reliability for aFRR nominations on wind farm level of above 99 – 99,5% should be achievable.

It is expected that the reliability of aFRR nominations on wind farms might even further increase towards the future as a result of continued improvements in forecasting accuracy, together with a potential evolution towards aFRR markets (nominations) closer to real-time and portfolio delivery of reserves.

A high reliability can also be achieved by performing deals on the day-ahead aFRR secondary market. The use of this market allows the transfer of obligations for aFRR delivery to other market parties.

9.4. Controllability of the wind farm

The controllability of the wind farm needs to be demonstrated ex-ante both for low and high wind conditions. The controllability is tested by requiring the wind farm (aggregated) to curtail to a fix power output and to deliver an aFRR test sequence as of that power output (balancing control mechanism). This test only focuses on control capability as the ex-ante curtailment excludes other uncertainties of the wind farm. The proposed test for pre-qualification can be similar to the tests performed on the wind farm of Estinnes in this pilot project.

Possible criteria to be used for pre-qualification are an average control error close to zero and only a very small number of deviations exceeding a tolerance band of X% of the pre-qualified and tested aFRR volume in the test sequence.

The Estinnes wind farm showed a very high accuracy both for high and low wind conditions, such as illustrated in paragraph 7.1.

In order to provide aFRR the wind farm must be able to perform closed loop control in order to accurately deliver the required aFRR set-point. Elia sends out an aFRR set-point only (i.e. delta power control, or desired output reduction), not the set-point of the entire generation of the wind farm (i.e. power output control). Hence the wind farm itself should still determine its own desired generation per turbine in order to deliver the required aFRR set-point sent by Elia.

9.5. AAP quality under non-curtailed conditions

As mentioned before a good AAP quality is of vital importance for a performant delivery of aFRR by wind farms under the AAP mechanism. Any error on the AAP signal automatically results in an error on the delivery of aFRR balancing energy. Therefore a proposal could be to investigate the AAP quality (without curtailment) over a representative time period (one to several months). It is important that the dataset comprises a representative amount of both low and high wind conditions for different wind directions.

Possible criteria to evaluate the AAP quality are:

- Average AAP calculation error must be close to zero;
- Most of the AAP calculation errors should be within a relatively small band around zero; and
- Only a limited amount of AAP calculation errors can be outside a wider band around zero.

The analysis of the AAP quality will be performed separately for high and low wind conditions. In case the relative AAP error is significant for low wind conditions, it can be decided to determine a minimum power below which the wind turbine cannot perform delivery of secondary control power. In such case the test values for this interval are discarded.

The observed AAP quality of the Estinnes wind farm under non-curtailed conditions can be found in paragraph 7.2.

In this pilot project a detailed analysis of the impact of the wind direction on the AAP quality was performed. It would however be highly complex to prequalify wind farms only for the delivery of aFRR balancing energy for certain wind conditions. Therefore it is proposed to only consider the overall AAP quality for different wind conditions. In such case a wind farm is either prequalified to deliver aFRR balancing energy for all wind directions or is not prequalified at all.

9.6. Investigation of AAP quality / control error under curtailment

Finally the wind farm should be capable of delivering an aFRR set-point from its AAP on (i.e. delta power control). Here it must also be investigated whether the quality of the AAP remains satisfactory in case of curtailed conditions. E.g. it would be unacceptable that a downward aFRR set-point would result in an overestimation of the AAP. In such case the wind farm would not deliver the correct amount of downward aFRR balancing energy.

The performance of the AAP calculation under curtailed conditions can be analysed by requiring consecutive periods with and without curtailment. In such cases it can be investigated whether the AAP and the measured infeed coincide before the start of the curtailment and naturally converge to each other at the end of the curtailment period. Furthermore the overestimation of the AAP can be tested for stable wind conditions by the tests elaborated in paragraph 7.1.2.

Furthermore the provision of measured wind speed data per wind turbine allows investigating the behaviour of the AAP under curtailed conditions.

The goal of such test is to:

1. check whether the AAP is influenced by the level of curtailment;
2. whether the transient effects remain acceptable in terms of amplitude and duration;
3. whether the wind farm can accurately provide aFRR from the AAP on (i.e. has a low control error).

The performance of the wind farm of Estinnes for such kind of tests can be found in paragraph 7.1 and 7.2.

9.7. Conclusions

In terms of further work the feasibility of the required market changes to enable the participation of wind farms in the aFRR market has to be investigated in parallel with the developments on European level with the implementation of an integrated European balancing market as a result of the Network Code on Electricity Balancing. The definition of technical requirements for wind farms to participate in the aFRR market and the targets for pre-qualification must be determined in close collaboration with all market parties. From a technical perspective at least following topics will be investigated:

- Reliability of aFRR nominations;
- Control accuracy of wind farms;
- Requirements for AAP quality and control error; and
- Impact of curtailment on AAP quality.

It must be noted that technical requirements related to AAP quality might become stricter in time given the significant amount of research that is being performed on algorithms for qualitative AAP calculation.

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