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Review

Frequency Support Markets and Wind Power Integration

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Abstract: Europe's initiative to reduce the emissions of harmful gases has significantly increased the integration of renewable sources into power networks, particularly wind power. Variable renewable sources pose challenges to sustain the balance between generation and demand. Thus, the need for ancillary services to cope with this problem has increased. In this regard, the integration of larger shares of wind generation would have a clear system benefit when wind generators are able to provide these ancillary services. This would also have implications for electricity markets, enabling these services from wind power plants. This article gives an overview of several European markets for frequency support (FS) services, also referred to as FS markets . It identifies the changes in national regulations of 10 European countries to standardize these services based on the ENTSO-E guidelines. However, most of the countries still use their national service definitions, which presents a problem for researchers to understand the national regulations in relation to the ENTSO-E guidelines. This article provides a classification of the national FS services under the definitions of the ENTSO-E guidelines to facilitate research on this topic. Furthermore, it highlights the main requirements for the market practices that would encourage the participation of wind power generation in the provision of these services. An estimation of the economic benefits for wind producers from the provision of FS services is provided as well to show a possible outcome if changes are not made in national policies.

Keywords: ancillary services; frequency support; markets; wind participation; standardisation

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1. Introduction

European countries aim to reduce the emissions of harmful gases into the atmosphere. This has caused a significant increase in power generation from renewable resources, in particular wind. The variability of these resources makes the prediction of their availability at a given moment of time challenging. This is one of the reasons for the increased need for balancing generation and demand and the need for ancillary services. Moreover, the integration of wind power into power systems in Europe dictates to markets and operators to facilitate wind power participation in the provision of these ancillary services [1].

European countries already have markets and other mechanisms for the procurement of ancillary services [2] with different definitions and regulations. The drawback of these procurement mechanisms is that they are designed and based on conventional generation. This limits or, in some cases, disables the participation of wind power in the procurement of these services [3].

In the 'Energy Roadmap 2050', the European Commission identified the challenge and need to reconsider the structure of current energy markets [4]. This initiated the development of a European common framework for frequency support markets, allowing the participation of wind power and cross-border interaction. Furthermore, the participation of wind power plants in the provision of ancillary services has been shown to be valuable for the wind power producers and the system [5].

One of the most important steps to implement the common framework is to standardize different national frequency support services. With the entry of ENTSO-E's Electricity Balancing Guideline in 2017 [6], member TSOs were obligated to update their frequency support services in the following two years.

In terms of the participation of wind in frequency support markets, a lot of research has been conducted. However, the research on this topic usually centres around the current national mechanisms of one or a very small number of countries [7,8], without presenting the evolution of the frequency support services to accommodate wind power participation.

The objectives of this article are to give an overview of several European markets for FS services with different structures and link ENTSO-E nomenclature with national definitions. The research identifies the changes in national regulations to standardize these services based on the ENTSO-E guidelines. Moreover, it highlights the main requirements to encourage the participation of wind power generation and to what extent the selected countries have adapted these requirements to facilitate its participation in FS services. An estimation of the economic benefits for wind producers from the provision of FS services is provided as well to show a possible outcome if further changes are not made in national practices.

2. Materials and Methods

The first step in performing this study was to select the countries that would enter the research process. Taking all European countries into consideration would lead to repeating a lot of information. Therefore, 10 countries were selected based on their characteristics, such that different FS market mechanisms are represented. The countries were selected so that there is a representation of Continental Europe countries, such as Belgium and Germany, peninsular countries, such as Spain and Portugal, island countries, such as Great Britain and Ireland, and the Nordic countries Sweden, Norway, Denmark and Finland since they have one of the leading power markets in Europe.

The second step involved the collection of the necessary data for every country and the regulations of ENTSO-E before and after 2017 when the Electricity Balancing Guideline was implemented [6]. Data were collected from the TSOs' online databases and through their websites, as they have both historic and updated data. For part of the information, the ENTSO-E Transparency Platform was also used [9].

The third step was to identify the important parameters for wind power participation in the FS markets. This was important so that the FS services can be classified in a way that the services updates can be seen through these parameters. Representing the data this way, the facilitation of wind power participation, or the lack thereof, can be more easily detected. Finally, the collected data were classified under the parameters important for wind power participation. In addition, the different national terms for the FS services were matched to the ENTSO-E terms to provide a standardisation of the national terminologies.

3. Definition of Ancillary Services for Frequency Support

Before 2019, all countries had their own definitions and requirements for ancillary services for FS. For the countries in ENTSO-E Continental Europe Regional Group (referred to as CE block), the UCTE classification is used, and it is provided in the Continental Europe Operation Handbook [10], which also sets the requirements for the member countries. The Nordic countries have different definitions and requirements for the ancillary services that are given in the System Operation Agreement. Additionally, Great Britain and the Island of Ireland have different definitions, whose ancillary services definitions and requirements are given in their national procurement guidelines.

A step to unify and standardise the different ancillary services in the European countries is the classification by ENTSO-E. In 2017, ENTSO-E's Electricity Balancing Guideline was introduced [6], which obligated member TSOs to update and harmonise their balancing reserves in the following two years. The classification proposed in this guideline can be

seen as an updated version of the UCTE classification. Moreover, both classifications and the correlation between them are given.

UCTE and ENTSO-E Definitions

The classification and definitions of ancillary services for FS, according to UCTE, are given in [10]. The ancillary services for FS are divided into primary, secondary and tertiary reserves. The classification and definitions of ancillary services for FS by ENTSO-E are given in [6] . They consist of the Frequency Containment Reserve (FCR), Frequency Restoration Reserve (FRR) and Replacement Reserve (RR). FCR is activated automatically, while FRR can be activated automatically and manually (FRR-A and FRR-M), and finally, RR is activated manually.

Primary reserves are activated within seconds after a disturbance, and they bring the frequency to a quasi-stationary state. Primary reserves are released by the speed regulators of generating units before a frequency deviation higher than 20 mHz of the nominal frequency. The full activation of primary reserves starts at a deviation of 200 mHz. The total primary reserve for the UCTE area is 3000 MW, which is defined as the power deviation of the reference incident.

Secondary reserves are activated within minutes to bring the frequency from quasi-stationary to its nominal value. Secondary reserves are released by the AGC of each control area. The method for calculating the amount of primary and secondary reserves is given in [10].

Tertiary reserves should be activated 15 min after the incident. They are used to replace the secondary reserves. The amount of tertiary reserves should be enough to cover the loss of the largest amount of power in the control area.

The ENTSO-E equivalent of a primary reserve is the Frequency Containment Reserve (FCR). This is the automatically activated response to frequency changes increasingly released with time over a period of some seconds. The reserve should be maintained for up to 15 min before switching off. The need is assessed collectively at a synchronous area level, and the procurement responsibility is shared amongst TSOs.

The ENTSO-E equivalent of the secondary reserve is the FRR-A, whereas FRR-M and RR are equivalent to the tertiary reserve. For some countries, such as Belgium, Germany and the Nordic countries, there is only FRR-M.

The activation of FRR is central and modifies the active power outputs of the reserve, providing units in the period of seconds up to typically 15 min after an incident.

RR is activated manually, at the TSO control centre, with an activation time from 15 min to hours. These reserves are activated in the case of observed or expected sustained activation of FRR and in the absence of a market response.

4. Frequency Support Markets

Depending on the country regulations, the ancillary services for FS are either mandatory or procured through market arrangements. The procurement of these services is a task of the TSO.

In the following section, the different ancillary services for FS are given for continental, peninsular and island countries, namely Belgium, Germany, France, Denmark, Finland, Norway, Sweden, Great Britain, Island of Ireland, Portugal and Spain. The focus is on the services provided by generating units, the methods of procurement and the remuneration processes. Part of this research has been presented in [11].

The terms for ancillary services for FS are presented as defined on a national level and classified under the ENTSO-E terminology.

4.1. Belgium

The TSO of Belgium, responsible for obtaining the ancillary services for FS, is Elia.

4.1.1. Ancillary Services for Frequency Support

The ancillary services for FS in Belgium consist of primary (R1; FCR), secondary (R2; aFRR) and tertiary (R3, mFRR) reserves [12].

Elia procures different types of products at different frequency deviations that constitute the required FCR. The FCR products are currently both symmetrical and asymmetrical. The different products and volumes are presented in more detail in [13]. As of July 2020, this service include only the symmetrical FCR 200mHz [13].

Currently, the aFRR service can only be activated by large power plants connected to Elia's grid, which are managed by Balancing Responsible Parties. In [14], Elia describes in detail the proposed changes of the aFRR service.

The new design of the mFRR product was scheduled to be implemented as of February 2020. The details are provided in [15].

4.1.2. Procurement and Remuneration

The FCR procurement process is currently a weekly process that involves two steps: local procurement and regional procurement (through the Regional Procurement Platform Regelleistung). From July 2020, this service is procured only through the Regional Procurement Platform [13].

Elia remunerates providers of FCR only for the reservation of the contracted primary control power. The calculation is conducted on a monthly basis based on the unit prices (EUR/MW/h) obtained in the local FCR auction and EUR/MW in the regional auction. No remuneration is provided for the energy supplied (upward or downward) [13].

Currently, the aFRR is procured by weekly tenders. With the new design note, Elia aims to go from weekly to daily procurement to facilitate the participation of demand responses, RES and DRs [14]. The suppliers of aFRR have to able to bid for 4-h blocks.

The settlement of aFRR is conducted for both reserved capacity and activated energy on a monthly basis. The remuneration equals the product of the reservation price in EUR/MW/h, the volume of aFRR reserved in MW and the number of corresponding hours of the delivery period concerned. A penalty is applied for any contracted MW that has not been delivered for both up and down regulation [13].

The settlement of the activated energy is based on pay-as-bid. The aim is to change to a pay-as-cleared settlement once the merit order activation is implemented and a more liquid aFRR market is established [13].

The mFRR reserved volume was procured by monthly tenders. As of 2020, Elia will transition towards daily procurement of mFRR [15]. With the introduction of the new mFRR product design in February 2020, the settlement methodology for the balancing energy is defined as pay-as-clear.

4.2. Germany

The German transmission grid is managed by four TSOs: 50Hertz, Amprion, TenneT DE and TransnetBW. The ancillary services are procured in close cooperation between the four TSOs, thus minimising the overall amount needed. Since 2011, the German TSOs have procured their ancillary services in an open control power market [16].

4.2.1. Ancillary Services for Frequency Support

The ancillary services for FS in Germany consist of primary (FCR), secondary (aFRR) and minute reserves (mFRR) [17].

The FCR demand is determined on a European level, according to ENTSO-E guidelines. Currently, the tender for FCR supports symmetrical products only [18].

For the determination of the required capacity of aFRR and mFRR, the German TSOs use a common dimensioning methodology. Since 9 December 2019, the required balancing capacity is dimensioned dynamically for every 4-h block [16].

4.2.2. Procurement and Remuneration

The tenders for the procurement of reserves are organized by means of a shared IT-platform developed by the German TSOs [19]. The tendering calendar for each reserve is provided on this platform.

As of 1 July 2019, the tender submission period for FCR is one calendar day. The tenders close on working days D-2. In the FCR tenders, participants from Belgium, Netherlands, France, Switzerland and Austria can join the tender in addition to the German units [18].

The tender and assignment of aFRR is given on the platform for each calendar day. Currently, aFRR is procured through weekly tenders. As of 2019, the aFRR is procured in a joint tender with Austria [20].

The tenders for mFRR are organized daily, and the products are offered in upward or downward directions [21].

The settlement procedures and the details for each product are provided in the Description of the System Balancing and Control Reserve Market [22]. The document is currently only available in German.

4.3. Iberia

The Iberian region is formed by Portugal and Spain. In 2001, a memorandum was signed by both countries to set up the base for a Common Electricity Market (MIBEL). Its start was postponed until 2007, when the Market Operator started operating as an extension of the existent one in Spain [23]. Even though Spain and Portugal have a common electricity market, the ancillary services are procured on a national level.

4.3.1. Portugal

The TSO of Portugal, responsible for obtaining the ancillary services for FS, is REN.

4.3.2. Ancillary Services for Frequency Support

The ancillary services for FS in Portugal consist of primary (FCR), secondary (aFRR) and regulating tertiary reserves (mFRR).

4.3.3. Procurement and Remuneration

The FCR in Portugal is a mandatory service provided by generators [24]. This service is not remunerated.

The aFRR and mFRR services are procured via market arrangements. The aFRR market is open the day before delivery, and the requirements for downward and upward aFRR are posted by REN. They are posted for every market time unit of the delivery day, which is one hour. The offers have to be sent for both upward and downward aFRR. The contracted parties are remunerated for both reserved capacity and used energy. The payment for the capacity is based on marginal pricing [24].

The mFRR is procured on delivery day. The requirements for mFRR depend on the demand-supply situation for every hour, and the amount that needs to be contracted is calculated by REN. If in real-time the aFRR does not suffice for the system needs, REN uses mFRR and RR to compensate aFRR. The needed reserve is assigned from a merit order list. The payment is based on a marginal price for each market time unit for both upward and downward directions separately. In case there is a reserve that has been contracted and does not follow the merit order list, the payment is conducted based on a pay-as-bid price, and the offer is not considered in the marginal price formation of the tertiary reserve market [24].

4.3.4. Spain

The TSO of Spain, responsible for obtaining the ancillary services for FS, is REE.

4.3.5. Ancillary Services for Frequency Support

The ancillary services in Spain are known as system adjustment services and follow the regulations in [25]. The ancillary services for FS consist of primary (FCR), secondary (aFRR) and tertiary regulations (mFRR), deviation management (RR) and additional upward reserve [25].

Since 2018, Spain has already been implementing changes in the ancillary services for FS, according to the new Electricity Balancing Guideline proposed by ENTSO-E. Changes have been proposed for the aFRR [26], mFRR [27], RR services and the additional upward reserve. The new operational procedures can be found in Spanish in [25].

With the new changes, as of November 2019, the additional upward reserve is no longer procured. If an additional reserve is needed, it will be resolved with the help of other products in real-time [28].

The deviation management product was the equivalent of RR. It has been officially changed to RR in December 2019 [25]. Some characteristics have been kept temporarily until the product fully evolves to match the ENTSO-E recommendations.

4.3.6. Procurement and Remuneration

The FCR in Spain, similarly to Portugal, is a non-remunerated mandatory service and the aFRR, mFRR, and RR services and additional upward reserve are procured via market arrangements.

The requirements for aFRR reserves in both upward and downward directions are published by REE every day for every hour of the next day. The bids submitted by the suppliers are assigned based on the criterion of minimum cost and paid according to the marginal price of the aFRR regulation band for every hour. The remuneration process consists of two payments: availability (aFRR capacity) and (aFRR energy) [25]. The used energy in real-time is then remunerated at the marginal price of the mFRR energy necessary to replace the net energy usage of aFRR in both upward and downward directions [25].

For mFRR, the bidding in both upward and downward directions is mandatory for the units that are licensed for the provision of this service. The bids are selected based on the minimum cost. The payments are conducted for used energy at a marginal price for upward and downward directions [25].

Based on the new operational procedure, the procurement of RR is set to be conducted through a common European platform, where REE has to submit the system needs and the bids for RR for both up and down regulation. The bids are selected based on the marginal price. The payments are conducted at a marginal price for upward and downward directions [25] .

4.4. Nordic Synchronous System

The Nordic synchronous system is formed by the subsystems of Norway, Sweden, Finland and East Denmark. The subsystem of West Denmark is part of the CE block. The TSOs of these subsystems, Statnett from Norway, Svenska Krafnät from Sweden, Fingrid from Finland and Energinet.dk from Denmark, have to cooperate following the terms of the Nordic System Operation Agreement (SOA) [29].

4.4.1. Ancillary Services for Frequency Support

The ancillary services for FS for the Nordic synchronous system are given in [29]. In the SOA before the changes made in 2019, the ancillary services for FS consisted of frequency-controlled normal operation reserve (FCR-N), frequency-controlled disturbance reserve (FCR-D), fast and slow active disturbance reserves, fast active forecast and fast active counter-trading reserve. The first two reserves fall under the definition for FCR, and the other reserves form the mFRR. The requirements for the aFRR are now included in SOA. The updated SOA, specifically the Annex on Load-Frequency Control and Reserves [30], includes the updated definitions of these services following the guideline of ENTSO-E.

4.4.2. Procurement and Remuneration

For East Denmark, Energinet.dk obtains the FCR in collaboration with the Swedish TSO Svenska Krafnät. The bids are collected in a process consisting of two auctions [31]. The first one runs two days before the delivery day and the second one runs the day before the delivery day. The procurement of the FCR capacity is then organized by each TSO before the delivery hour. The FCR reserves can also be traded bilaterally between the Nordic TSOs. The remuneration of the FCR-N reserves involves two payments, the capacity payment, based on the pay-as-bid price, and the activation payment, which is the payment for supplied energy with the regulating power price for upward or downward regulation. The remuneration of the FCR-D reserves has only capacity payments based on the pay-as-bid price. The supplied energy volumes are settled as imbalances. For West Denmark, the FCR consists of and is requested as an upward and downward regulation reserve depending on the system's need. Energinet has the obligation of supplying a share proportionate to the generation in West Denmark relative to the total generation in the CE area. This share is determined once a year. The procurement is conducted through a daily auction. The payment is only for reserved capacity at a marginal price for up and down regulation separately.

Fingrid obtains the FCR through yearly and hourly markets, the Russian and Estonian HVDC links and the other Nordic countries [32]. In the yearly market, the amount is bought in total. The price is fixed throughout the year and is set according to the most expensive bid that has been approved for the yearly market. In the hourly market, a reserve owner can participate by making a separate agreement with Fingrid. The owners of reserves can submit daily offers for their reserve capacity. The price of the remuneration is based on the most expensive bid used for each hour separately. Participants in the yearly market can also participate in the hourly market if they have completed their obligation from the yearly market [33].

The FCR-N in Norway is procured through daily and weekly auctions and the FCR-D only through daily auctions [34]. The remuneration process involves a capacity payment, paid at a marginal price, and an activated energy payment based on the frequency measurements and by the market price for the activated mFRR. In special circumstances (local grid conditions that result in higher marginal price), the capacity payment is conducted by the pay-as-bid price.

In Eastern Denmark, the suppliers of aFRR must be capable of delivering a full response within 5 min with a profile matching the requirements of the Nordic aFRR market. In Western Denmark, the suppliers of aFRR must be able to deliver a full response within 15 min . Energinet procures aFRR supply ability for both East and Western Denmark on a monthly basis, one month at a time. The products are only symmetrical and remunerated on a pay-as-bid basis. West Denmark has requirements for the aFRR reserve as part of the CE block. The aFRR is still procured as a combined, symmetrical upward and downward regulation. The frequency of procurement depends on the system's needs and the remuneration process is conducted on a pay-as-bid basis [31].

In Sweden, the suppliers of aFRR get paid with pay-as-bid for the reserved capacity. The remuneration for activated energy is calculated based on frequency measurements and the price of activated mFRR [35].

In Finland, aFRR is procured through hourly auctions, currently only for partial hours of the day. The remuneration is conducted for up and down regulation separately. The reserved capacity is remunerated based on the bid price and the activated energy based on the price of the activated mFRR [33].

In Norway, aFRR is procured through weekly auctions. The remuneration for reserved capacity is conducted based on the marginal price or pay-as-bid in special circumstances. The remuneration for activated energy is based on the price of activated mFRR [34].

Energinet obtains mFRR with long-term contracts. For the period from 2011 to 2015, there was an agreement with one supplier for all mFRR, and from 2016–2020, it was bought from five suppliers. If more mFRR is needed, Eneginet buys it through the Regulating

Power Market (daily auctions). The remuneration of the balancing energy is conducted at a marginal price. In West Denmark, the requirement for the mFRR from [10] is procured through a daily auction. The mFRR is activated according to the lowest price. The balancing energy is remunerated according to the marginal price. The mFRR is procured for up and down regulation separately [31] .

In Sweden, in addition to the requirement for mFRR stated in the SOA, Svenska Krafnät procures additional mFRR for imbalances, congestions and other grid issues through the Regulating Power Market. The activated mFRR is remunerated at a marginal price [35].

Fingrid obtains the needed mFRR through the Regulating Power Market. The remuneration is conducted for activated energy based on the marginal price for each hour. This is conducted separately for up and down regulation [31] .

In Norway, the mFRR is procured through weekly and yearly auctions, and both production and load sides can participate [34]. The remuneration process includes capacity payment at a marginal price and in special circumstances at a pay-as-bid price. The remuneration is adjusted based on the maximum duration of continuous activation and the rest periods between activations.

4.5. Island of Ireland

The ancillary services in the Republic of Ireland and Northern Ireland are procured in the same market. It is run by SEMO, which is the Single Electricity Market Operator for the island of Ireland. The TSO of the Republic of Ireland is EirGrid, and Northern Ireland's is SONI.

4.5.1. Ancillary Services for Frequency Support

The definitions of each ancillary services are provided in the Grid Codes of both the Republic of Ireland and Northern Ireland [36,37]. The ancillary services for FS in Ireland are referred to as operating reserves and consist of: the primary operating reserve (POR, ENTSO-E equivalent FCR), the secondary operating reserve (SOR, ENTSO-E equivalent FRR-A), the tertiary operating reserve 1 (TOR 1, ENTSO-E equivalent FRR-M), the tertiary operating reserve 2 (TOR 2, ENTSO-E equivalent FRR-M) and the replacement reserve (RR, ENTSO-E equivalent RR).

The DS3 program was initiated in 2011 to develop solutions to the challenges of operating the electricity system securely while achieving the 2020 renewable electricity targets [38]. The DS3 program proposes new services and refined definitions of some of the existing ancillary services. The DS3 program takes into account not only the ancillary services for FS but also the voltage support ancillary services. The new proposed ancillary services are the Synchronous Inertial Response (SIR), Fast Post-Fault Active Power Recovery (FPFAPR), Dynamic Reactive Response (DR), Fast Frequency Response (FFR) and Ramping Margin (RM). From the existing services, minor modifications are proposed for the replacement reserve and the steady-state reactive power.

The harmonised all-island arrangements have been brought into operation for ancillary services on the 1 February 2010. These arrangements have been replaced by the DS3 System Services as of 1 October 2016 [39].

The latest changes to the DS3 System Services Protocol Document have been introduced for consultation in April 2020 and can be found in [40,41].

4.5.2. Procurement and Remuneration

The TSOs procure ancillary services for FS by means of contracts. The remunerating process is conducted by a payment with set tariffs, determined for each following year. The prices for the 1 October to the 30 September for each year are provided in [42].

4.6. Great Britain

The ancillary services in Great Britain are procured by National Grid ESO.

4.6.1. Ancillary Services for Frequency Support

The ancillary services are defined in the Connection Condition (CC.8) of the Grid Code of the UK [43]. They consist of mandatory and commercial ancillary services. The mandatory ancillary services include the Mandatory Frequency Response (MFR) [44]. The commercial ancillary services include the Firm Frequency Response (FFR), Fast Reserve (FR) and Short-Term Operating Reserve (STOR) [44]. In terms of the ENTSO-E terminology, the MFR and FFR fall under FCR, FR falls under FRR-A, and STOR under FRR-M and RR. In continuation, the national terminology will be used to better explain the different services and their procurement and remuneration processes.

4.6.2. Procurement and Remuneration

The ancillary services can be provided by balancing mechanism (BM) providers who have a contract with the National Grid ESO and non-BM providers who do not have this contract.

MFR is mandatory for large generators, and FFR, FR and STOR are procured by market arrangements [45]. The remuneration for MFR consists of two payments: availability and activated energy [46].

FFR is procured through a monthly tender [45]. The tests for procurement through weekly tenders began in June 2019. The remuneration process consists of multiple payments, although most providers tender only for availability and nomination. Multiple payments consist of availability, nomination, window initiation, tender window revision and response energy payment. The specifications of each payment are explained in [47].

FR is procured by monthly tenders [45]. The remuneration of FR consists of availability, nomination and utilisation payments [48].

STOR is procured through a competitive tender three times a year [45]. The remuneration process involves an availability payment and an activated energy payment or only an optional availability payment for non-balancing mechanism providers [49].

5. Important Market Parameters for Wind Power Operators

The main critical requirements for wind power operators to be able to participate in the procurement of FS services have already been analysed in [5] and include:

- Procurement rules and remuneration: The different FS services, in terms of activation time and how long the service is provided, show that TSOs must organize a cost-efficient way of procuring and remunerating the services. The reserves cannot be used efficiently at all times if there is a mandatory provision for all generators.
- Gate closing time: With the intermittent nature of wind as a source of energy, the gate closing time is essential for the cost-effective provision of FS services from wind. A short closing time from the point of submitting an offer to the moment of service provision would mean a more accurate forecast of the wind power and the amount of needed reserves.
- Minimum offer: If the market allows smaller power offers, this would improve the possibility of offering part of the foreseen power to the FS market. Moreover, bidding from smaller wind power plants would also be facilitated.

Additional important parameters for the wind power operators are the activation time and the possibility of offering reserves separately for upward and downward regulation. The activation time enters these parameters as a result of the wind intermittency. If the service has to be provided for an extended period of time, wind generators may not be able to deliver the requested reserves. Regulating in an upward direction can mean lower generation of wind power than what is available. Furthermore, the possibility to separate the offers for downward and upward regulation enables a more economic provision for the wind operators, as downward regulation prices are always lower than spot prices.

6. ENTSO-E Standardisation

The harmonisation of the ancillary services for FS of all countries according to the ENTSO-E classification has been conducted in separate tables for FCR (Tables 1 and 2), FRR-A (Tables 3 and 4) and FRR-M and RR (Tables 5 and 6). In most of the countries, FRR-M and RR services are defined as one type of reserve; thus, the third table includes both services.

The tables present several important parameters, namely which ancillary services of the countries fall under the particular type according to ENTSO-E, the procurement arrangements, the gate closing times and the minimum offers.

Table 1. Summary of FCR services unified under the ENTSO-E classification, including Nordic countries, Ireland and Great Britain.

Parameters	Denmark	Finland	Norway	Sweden	Ireland	Great Britain
Reserve type	Frequency-controlled normal operation reserve (FNR, now FCR-N) Frequency-controlled disturbance operation reserve (FDR, now FCR-D)				Primary operating reserve Secondary operating reserve	Mandatory frequency response Firm Frequency Response (dynamic and static)
Procurement arrangement	Two-day auctions	Yearly and day-ahead markets	Day-ahead and weekly auctions	Weekly and day-ahead auctions	Bilateral contracts	Firm Frequency Response-monthly tenders
Gate closing time	Day before at 15:00	Yearly market-day before by 18:00, Hourly market-day before 18:30	Day-ahead: by 19:00, Weekly: weekdays by Friday 13:00, weekend by Thursday 13:00	-	-	On business day 1 before the month by 17:00
Minimum offer	DK1: 0.1 MW	FCR-N 0.1 MW; FCR-D 1 MW	Less than 1 MW	Less than 1 MW	-	-

Table 2. Summary of FCR services unified under ENTSO-E classification, including Belgium, Germany, Spain and Portugal.

Parameters	Belgium	Germany	Spain	Portugal
Reserve type	Primary reserve	Primary control reserve	Primary control reserve	Primary control reserve
Procurement arrangement	General framework, short-term auction or long-term tender	Market auctions, weekly call for tender	Mandatory	Mandatory
Gate closing time	-	Every week by Tuesday at 15:00	-	-
Minimum offer	1 MW	1 MW	1.5% of nominal power	-

Table 3. Summary of FRR-A services unified under the ENTSO-E classification, including Nordic countries, Ireland and Great Britain.

Parameters	Denmark	Finland	Norway	Sweden	Ireland	Great Britain
Reserve type	Automatic FRR (still developing)				Tertiary operating reserve 1 Tertiary operating reserve 2	Fast reserve
Procurement arrangement	Through market arrangements	Hourly market	Weekly market	-	Bilateral contracts	Monthly tenders (single and multiple)
Gate closing time	DK2: two-day and day ahead auctions with Svenska Krafnät	Hourly market, day before by 18:30	Weekly by Thursday 13:00	-	-	On business day 1 before the month by 17:00
Minimum offer	-	5 MW	5 MW	5 MW	-	Minimum delivery volume 50 MW

Table 4. Summary of FRR-A services unified under the ENTSO-E classification, including Belgium, Germany, Spain and Portugal.

Parameters	Belgium	Germany	Spain	Portugal
Reserve type	Secondary reserve	Secondary control reserve	Secondary control reserve	Secondary control reserve
Procurement arrangement	General framework, short-term auction or long-term tender	Weekly auctions	Day-ahead market	Day-ahead market
Gate closing time	Day before delivery day by 15:00	Before Wednesday every week	At 16:00 daily	In the period of 19:00–19:45
Minimum offer	1 MW	5 MW	10 MW	-

Table 5. Summary of FRR-M and RR services unified under the ENTSO-E classification, including Nordic countries, Ireland and Great Britain.

Parameters	Denmark	Finland	Norway	Sweden	Ireland	Great Britain
Reserve type	FRR-m: Fast and slow active disturbance reserve (FADR and SADR) Fast active forecast reserve (FAFR) Fast active counter trading reserve (FACTR) RR : does not exist				Replacement reserve	Short-Term Operating Reserve (STOR)
Procurement arrangement	Through long-term contracts; Daily auctions if needed	Long-term bilateral contracts and Nord Pool Regulating Power Market	Weekly and yearly auctions	Nord Pool Regulating Power Market	Bilateral contracts	Three tender rounds per year

Table 5. *Cont.*

Parameters	Denmark	Finland	Norway	Sweden	Ireland	Great Britain
Gate closing time	DK1: Prior to delivery month for monthly offers	45 min before delivery hour	Weekly by Friday 14:00; Yearly auctions are announced	45 min	15 min notice before dispatch	-
Minimum offer	10 MW	10 MW	10 MW	10 MW	-	3 MW

Table 6. Summary of FRR-M and RR services unified under the ENTSO-E classification, including Belgium, Germany, Spain and Portugal.

Parameters	Belgium	Germany	Spain	Portugal
Reserve type	Tertiary reserve	Minute reserve	Tertiary control reserve	Tertiary control reserve
Procurement arrangement	Short-term auction or long-term tender; Standard contracts	Daily auctions	Intraday market	Intraday market
Gate closing time	Day before delivery day by 14:00 [15]	At 12:00 daily	25 min before delivery hour	50 min before delivery hour
Minimum offer	1 MW	5 MW	10 MW	-

7. Possible Role of Wind Power in Future Frequency Support Markets

7.1. Frequency Support Responsibility of Wind Power Generators

The provision of frequency support is still mostly provided by conventional generators, as current market arrangements are still in transition to accommodate wind generators. Some countries' FS markets already have the conditions to allow wind generators to participate, while other countries' FS markets are still not developed to a stage where they can let wind power generators participate.

The European Wind Energy Association (EWEA) has conducted a survey to provide an overview of FS responsibility, including cost implications, of wind power generators in the EU countries [50]. The summary of this survey is given in Table 7.

In roughly half of the considered countries, the wind generators are responsible for FS , and they are not treated differently to other generators. The provision of FS services is allowed for wind generators, but this is not occurring practically due to the market conditions that are restricting their participation. Even when wind generators are allowed to provide FS services, it is mostly for RR.

However, steps to include wind generators in FS markets are being made. The German TSO 50Hertz has allowed wind farms to participate in the FS market as of the 17 February 2016 [51]. In Spain, the legislation that lays out the criteria for renewable generation to participate in FS was implemented in February 2016 [52]. Denmark has a promising example of wind power participation in FS markets [50], and in Belgium, there are successful results from the pilot project for the delivery of FS services by wind generators [53].

Table 7. Frequency support responsibility of wind power generators according to EWEA's survey.

Country	Are Wind Generators Responsible for FS?	Are They Treated Differently to Other Generators?	Is Provision of FS Services Allowed?
Belgium	Yes	No	Yes
Germany	Partly	N/A	Partly (only RR)
France	No	N/A	No
Spain	Yes	No	Yes
Portugal	No	N/A	N/A
Denmark	Yes	No	Yes
Finland	Yes	No	Yes
Norway	N/A	N/A	N/A
Sweden	Yes	No	Yes
Ireland	No	No	N/A
UK	Yes	No	Yes

7.2. Estimation of Wind Power Participation in FRR-M and RR Markets

The estimation of wind power participation in FS markets was conducted based on the collected FRR-M market data for 2017. The objective of this estimation is to showcase the outcome for the wind producers under unchanged market mechanisms.

In the estimation, the low scenario of wind power capacity for 2030 was used, as presented in [53]. A rough estimation was made for three different markets: the Spanish, the Nordic and the Portuguese markets [54]. It is assumed that 25% of the total wind power will participate in the FS market and produce on average 3000 MWh per MW. The estimation was conducted for two cases: a minimum and a maximum case. The results of both cases are presented in Figure 1.

For the minimum case, the assumptions are that the volume of the markets stays the same as in 2017 in the FRR-M/RR markets. Wind only takes part in downward regulation and will get a 5% share of all bids accepted for the year. In this case, the wind power producers active in the FRR-M/RR market would sell 2–6% of their yearly generation to balancing markets in the different countries: 6% in Spain, 2% in Nordic countries and 3% in Portugal.

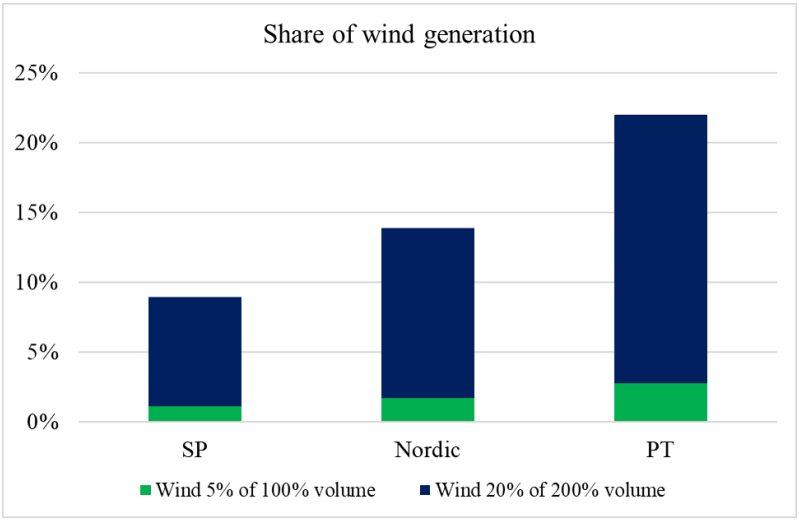

Figure 1. Share of wind generation in FRR-M/RR markets , assuming market volumes of 2017 and double that and 5–20% share of wind power producers in the markets (original figure).

For the maximum case, the assumptions are that the volume of the FRR-M/RR markets is doubled and wind power producers would get a 20% market share, selling both down and up regulation. In this case, the wind power producers active in the market would sell 9–22% of their yearly generation to FRR-M/RR markets in the different countries: 9% in Spain, 14% in Nordic countries and 22% in Portugal.

Assuming a price range, decrease/increase of 80%/120% of prices in 2017, the possible future income for wind power producers from FRR-M/RR market participation is estimated. For the Nordic countries, it would be between 600 EUR/MW/annually (down regulation only, 5% market share) and 14,000 EUR/MW/annually (both up and down regulation, with double market volume and 20 % market share); for Portugal, twice as high; for Spain, 400 EUR/MW/annually to 16,000 EUR/MW/annually. This income would be associated with some less income from the spot market. The difference of spot price and up/down regulation is 2–5/3–5 EUR/MWh in Nordic countries and 8–10/15–23 EUR/MWh in Iberia, respectively. The spot and up/down regulation prices and the difference between them for the countries of the Nordic region, the total Nordic region, Spain and Portugal are given in Figure 2.

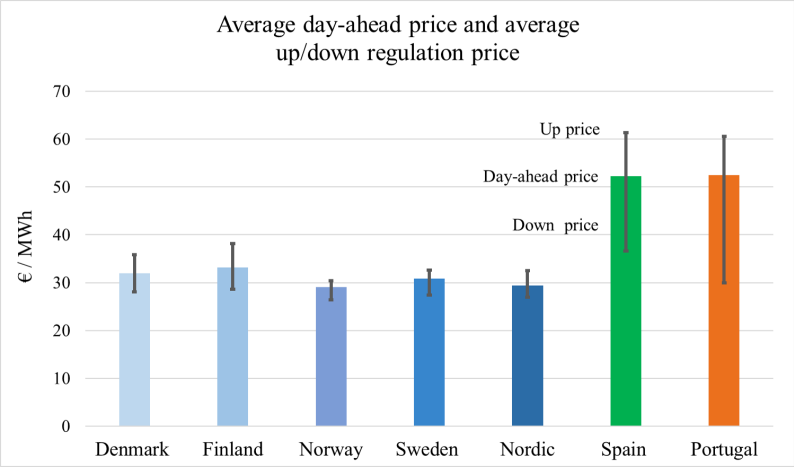

Figure 2. Average spot price and average up/down regulation price for 2017 (original figure).

For down regulation, providers would get paid less than the spot price so this would not bring extra income for wind power producers, unless forced to operate in curtailed mode.

8. Discussion

The provision of ancillary services for FS from wind power operators can be facilitated by adopting and synchronising the best market practices for each service based on the parameters mentioned in Section 5. Thus, the countries should strive to implement markets with small minimum offers and short gate-closing times. This would also enable the integration of these markets into one shared European market. Moreover, the recommendations for facilitating wind power provision of ancillary services in the markets are provided based on the best already implemented practices.

For FCR, the countries where this service is mandatory should consider changing to market-based procurement. Good examples to follow, in terms of procurement method, are the day-ahead markets in Finland and Norway. The gate-closing times of both markets are less than 12 h before delivery. In terms of the minimum offer, the case in Denmark and Finland shows that the offers can go as low as 0.1 MW.

For FRR-A, most of the countries have day-ahead markets with short gate-closing times and small minimum offers. However, these parameters are different in each country. A great practice to follow for FRR-A is the Belgian market. This example shows that the gate-closing time can be less than 12 h before delivery, and the minimum offer can go as low as 1 MW.

For FRR-M and RR, all countries except the Island of Ireland have market-based procurement. Two great examples are the Spanish intraday market, with a gate-closing time of 25 min, and the Nordic Regulating Power Market, with a gate-closing time of 45 min. Both markets have a minimum offer of 10 MW; however, the case of Belgium shows that the minimum offer can go as low as 1 MW.

The simplified estimation of current market volumes for FRR-M/RR gave cases with possible market volumes and incomes. The results show that with past market volumes and assuming down regulation participation only from wind power plants, the share of energy sold as well as extra income is modest. With higher market volumes and shares of wind power, the volumes and income could become significant. Extra income would also come from FRR-A. The overall outcome of this estimation is that following current procurement mechanisms, wind operators do not have a sufficient economic incentive to participate in the FS markets.

9. Conclusions

The performed analysis of FS services for 10 European countries gives a clear overview of the definitions and procurement practices of these countries. The presented tables in this article help identify the services of each country under the ENTSO-E classification and the parameters important for wind participation. This is of great relevance for analysing how neighbouring countries perform under the same task. Furthermore, the study presents the national strategies the countries have undertaken to harmonise these services according to the ENTSO-E guidelines. This is the first step towards unifying different FS services and markets, as well as opening a path for the participation of wind in these services.

The estimation of the economic benefits for wind power participants in the FRR-M/RR markets show the very low outcome for the wind operators with the current FS services definitions and procurement mechanisms. This opens the path for further research of different market practices that would result in more benefits for wind operators.

The adjustments should be made taking into account gate-closing times, minimum offers, activation times and the ability to participate in upward and downward regulation separately.

The best current market practices are emphasised in this article and are intended to serve as a recommendation for the changes that would facilitate FS provision from wind power generation.

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Abbreviations

The following abbreviations are used in this manuscript:

AGC	Automatic Generation Control
CREG	Commission for Regulation of Electricity and Gas
DR	Dynamic Reactive Response
DS	Distribution system
DSO	Distribution System Operator
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
FCR	Frequency Containment Reserve
FFR	Fast Frequency Response
FPFAPR	Fast Post-fault Active Power Recovery
FRR	Frequency Restoration Reserve
FS	Frequency Support
LP	Linear Programming
RR	Replacement Reserve
SIR	Synchronous Inertial Response
TS	Transmission system
TSO	Transmission System Operator
UCTE	The Union for the Co-ordination of Transmission of Electricity

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