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Review

Strategies for Continuous Balancing in Future Power Systems with High Wind and Solar Shares

Henrik Nordström [1,*], Lennart Söder [1,*], Damian Flynn [2], Julia Matevosyan [3], Juha Kiviluoma [4], Hannele Holttinen [5], Til Kristian Vrana [6], Adriaan van der Welle [7], Germán Morales-España [7], Danny Pudjianto [8], Goran Strbac [8], Jan Dobschinski [9], Ana Estanqueiro [10], Hugo Algarvio [10], Sergio Martín Martínez [11], Emilio Gómez Lázaro [11] and Bri-Mathias Hodge [12]

1 Division of Electric Power & Energy Systems, KTH Royal Institute of Technology, 10044 Stockholm, Sweden
2 School of Electrical and Electronic Engineering, University College Dublin, D04 V1W8 Dublin, Ireland; damian.flynn@ucd.ie
3 Energy Systems Integration Group, Reston, VA 20195, USA; julia@esig.energy
4 VTT Technical Research Centre of Finland, 02044 Espoo, Finland; juha.kiviluoma@vtt.fi
5 Recognis Oy, 01530 Vantaa, Finland; hannele.holttinen@recognis.fi
6 SINTEF Energi, 7034 Trondheim, Norway; vrana@alumni.ntnu.no
7 Netherlands Organisation for Applied Research (TNO), 2597 AK Den Haag, The Netherlands; adriaan.vanderwelle@tno.nl (A.v.d.W.); german.morales@tno.nl (G.M.-E.)
8 Department of Electrical and Electronic Engineering, Imperial College London, London SW7 2AZ, UK; d.pudjianto@imperial.ac.uk (D.P.); g.strbac@imperial.ac.uk (G.S.)
9 Fraunhofer Institute for Energy Economics and Energy System Technology (IEE), 34117 Kassel, Germany; jan.dobschinski@iee.fraunhofer.de
10 Laboratório Nacional de Energia e Geologia, 1649-038 Lisbon, Portugal; ana.estanqueiro@lneg.pt (A.E.); hugo.algarvio@lneg.pt (H.A.)
11 Renewable Energy Research Institute, Department of Electrical, Electronic, Automatic and Communications Engineering of ETSII-AB, Universidad de Castilla-La Mancha, 02071 Albacete, Spain; sergio.martin@uclm.es (S.M.M.); emilio.gomez@uclm.es (E.G.L.)
12 National Renewable Energy Laboratory, Golden, CO 80401, USA; bri.mathias.hodge@nrel.gov
* Correspondence: hnordstr@kth.se (H.N.); lsod@kth.se (L.S.); Tel.: +46-733211997 (H.N.); +46-87908906 (L.S.)

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Abstract: The use of wind power has grown strongly in recent years and is expected to continue to increase in the coming decades. Solar power is also expected to increase significantly. In a power system, a continuous balance is maintained between total production and demand. This balancing is currently mainly managed with conventional power plants, but with larger amounts of wind and solar power, other sources will also be needed. Interesting possibilities include continuous control of wind and solar power, battery storage, electric vehicles, hydrogen production, and other demand resources with flexibility potential. The aim of this article is to describe and compare the different challenges and future possibilities in six systems concerning how to keep a continuous balance in the future with significantly larger amounts of variable renewable power production. A realistic understanding of how these systems plan to handle continuous balancing is central to effectively develop a carbon-dioxide-free electricity system of the future. The systems included in the overview are the Nordic synchronous area, the island of Ireland, the Iberian Peninsula, Texas (ERCOT), the central European system, and Great Britain.

Keywords: balancing services; continuous balancing; frequency control; renewable power system; wind power; solar power

1. Introduction

The world's total annual electricity consumption in 2021 was around 28 466 TWh, of which around 1862 TWh (6.5%) was served by wind power, and 1033 TWh (3.6%) was served by solar power [1]. However, the share of these variable renewable energy (VRE) sources has increased significantly in the last few years. The average yearly growth rate of installed wind power capacity in the years 2011–2021 was 14.1%, while installed solar power capacity increased by 27.9% per year. In this article, the studied countries are among the frontrunners in VRE integration, serving on average more than 20% of total production with wind power in 2021 in their respective system [1–3]. In the IEA future Net Zero system report, the result is that on a global level, by 2050, "solar PV and wind together account for almost half of electricity supply" [4]. By 2050, the electricity supply is also expected to significantly increase, as society becomes increasingly decarbonized. With such a high global share of VRE generation, and considering the variability of VRE resources, this certainly means that in some areas/countries, during some hours, the power system must be able to operate at close to 100% VRE generation, in order to minimize wind and solar curtailments.

One of the main challenges with operating the power system at a very high share of VRE generation is that the continuous balance between production and consumption must be maintained in a reliable and economic manner. At very high shares of VRE, power systems will have to be operated at low levels of inertia [5], while imbalances likely will be larger and more frequently occurring, due to the uncertainty and variability of VRE generation, see, e.g., [6–8]. Historically, the continuous balance has been maintained by generators adjusting their output according to the power systems' needs. However, along with the increasing share of VRE generation, there is a parallel development toward more flexible demand resources being available, which can contribute to continuous balancing. These resources include electric vehicles, electric heating systems, batteries, hydrogen production, and demand-side management (both larger consumers, e.g., industries and data centers, and smaller consumers, e.g., households). VRE generation also can contribute to maintaining the continuous balance, in different ways, e.g., [9,10].

The aim of this article is to provide an overview of the challenges and proposed solutions regarding how to efficiently maintain a continuous balance in systems targeting significantly larger amounts of VRE generation. The article studies six different power systems, summarizing the current mechanisms for continuous balancing, current and future challenges that the systems face, and how they plan to tackle these challenges. The six systems are then compared and some general conclusions are drawn. The purpose of this article is to create a deeper understanding among researchers and decision makers regarding the challenges and solutions to continuous balancing at a very high share of VRE generation.

The remainder of this article continues as follows. In Section 2, an overview of power system balancing and related activities, services, mechanisms, and technologies is given. In Section 3, we provide detailed descriptions of how continuous balancing is currently handled, and how future challenges related to continuous balancing will be tackled, in six different systems targeting a significantly increased share of VRE. In Section 4, we summarize the current setups, proposed changes, and future challenges in these six systems, and discuss differences and similarities. In Section 5, we make some concluding remarks regarding how to efficiently maintain continuous balance in power systems with high VRE shares.

2. Power System Balancing—Overview

In a power system, there is always an instantaneous balance between the electric power supplied and consumed. The task of continuous balancing in a power system refers to supplying the demanded power at every time instant. Poor balancing can lead to large frequency changes or transmission line overloading. If the frequency deviates too much from the nominal level (50 Hz in Europe and 60 Hz in North America), or the flow over a transmission line becomes too high, control systems may be triggered. This, in turn, will lead to all demanded power not being supplied. The challenge with continuous balancing is that all components and their operational status in a power system are not predictable and controllable. In order to retain the continuous balance in a power system, a combination of power system planning, efficient handling of margins, equipment's inherent physical reactions, automated controls, and manual instructions are used.

In Section 2.1, the three general activities performed to keep a continuous balance in power systems are described. How the combination of these three activities is performed forms the balancing principles of a power system. To perform some of these activities in practice, the system needs certain balancing services. Section 2.2 provides an overview of the purpose and technical characteristics of the most common categories of balancing services. In Section 2.3, an overview of different mechanisms used to ensure the availability of balancing services is given. Finally, Section 2.4 describes how the characteristics of different technologies make them suitable, or not, for providing different types of balancing services.

2.1. Balancing Principles

Strategies used to keep the continuous balance vary between countries and regions in the world. Generally, there are three main types of balancing activities performed at different time frames and at different spatial resolutions in a power system. The combination of these balancing activities forms the balancing principles of a power system. These balancing activities are:

Frequency balancing: Frequency balancing refers to keeping the frequency close to nominal in a synchronous system. The synchronous system is balanced if the frequency is close to the nominal level, with small variations within a certain band being acceptable. The rationale behind frequency balancing is that some power system components are designed to be operated at nominal frequency, and frequency deviations may impact or damage these components. Frequency deviations occur when the rotational energy of synchronous machines increases, or decreases, as the immediate reaction to handle a mismatch between power production and consumption. This mismatch is then compensated by some units having automatic controls changing their power setpoint, which will stabilize the frequency. After a while, frequency is restored by a combination of slower automatic controls and manual actions to change units' power setpoints.

Power balancing: Power balancing refers to keeping the sum of produced and imported power equal to the sum of consumed and exported power in a certain balancing area. A balancing area is a region operated by one transmission system operator (TSO) (commonly known as Independent System Operator (ISO) in the US and Electricity System Operator (ESO) in Great Britain; however, we use the term TSO here when referring to the entity responsible for balancing the power system in real time), and, commonly, a synchronous system consists of many balancing areas. The rationale behind power balancing is to consider transmission constraints within a synchronous system by using resources in the correct location to balance out deviations within dispatch intervals. In each balancing area, power balancing is performed by both proactively and reactively applying a combination of automatic controls and manual actions to change generator power setpoints to mitigate the area control error (ACE). The ACE is calculated as the difference between measured and planned flows to/from the area (ΔP), added with a "frequency bias" term to consider the activation of resources used for frequency balancing based on the regulating strength (K) of frequency reserves in the balancing area and the frequency deviation (Δf) [11]. The ACE of a balancing area is calculated according to (1). When the ACE is close to zero, a balancing area is balanced. Just as for frequency, smaller variations within a certain band are deemed acceptable and, hence, automatic or manual actions are not taken.

$$\mathrm{ACE} = \Delta\mathrm{P} + \mathrm{K}\Delta\mathrm{f}, \quad (1)$$

Energy balancing: Energy balancing refers to power system planning where the anticipated energy demanded in a certain time interval is matched against the anticipated energy supplied. Energy balancing is commonly performed in markets such as day-ahead markets, intraday markets, and real-time markets. These markets vary in the duration of the planning intervals, planning horizon, and spatial resolution. Although power systems are planned to be balanced for certain time intervals in these markets, there remains a need to have more resources to keep the continuous balance. This need is caused by both uncertainties, such as imperfect forecasts of VRE generation unit outages, as well as by imperfect markets not fully considering the variability of VRE generation/demand and ramp restrictions of units in power system planning. This paper focuses on how to keep a continuous balance after energy balancing is performed, and when referring to "continuous balancing", the balancing performed after energy balancing is intended from that time on. However, the features of energy balancing impact the need for additional resources for continuous balancing, and energy balancing can thus not be neglected. With energy balancing being performed closer to real time and for shorter time intervals, the anticipated conditions for which energy balancing is performed will be more similar to actual conditions. Hence, there will be a reduced need for reserves to perform frequency and power balancing.

2.2. Common Services Contributing to Continuous Balancing

There are a number of services contributing to keeping the continuous balance in power systems by both frequency balancing and power balancing. The types of services, their names, and their requirements are often specific for each TSO and depend on the system's characteristics. Some services are procured through markets, while others are not remunerated. Here, we list a number of common types of services used to keep the continuous balance and describe the purpose of each service. The different types of service are categorized according to the EU SysFlex project [12]. The ability to provide services related to voltage control may influence if a technology is used to provide balancing services. However, this paper focuses solely on services directly used for continuous balancing. Figure 1 shows the approximate time frame within which the different categories of balancing services discussed in this section, as well as energy balancing, contribute to keeping the continuous balance in power systems.

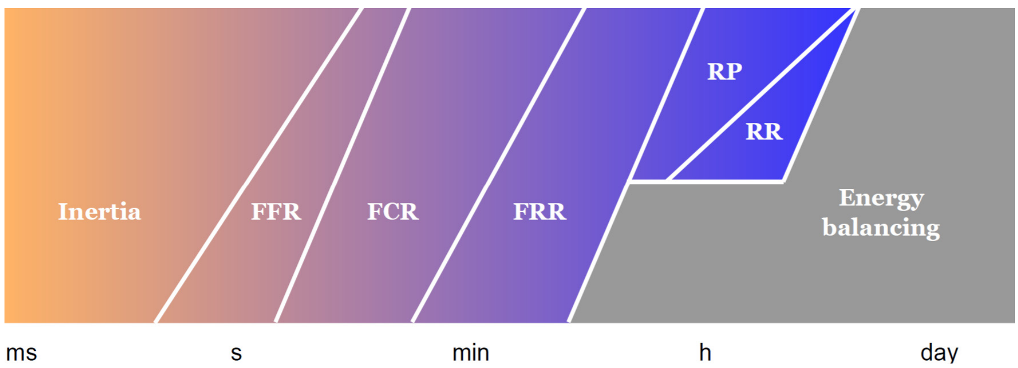

Figure 1. Approximate time frames of different balancing services (in color), as well as energy balancing (in gray). The balancing services in the figure are Fast frequency response (FFR), Frequency containment reserves (FCR), Frequency restoration reserves (FRR), Ramping products (RP), and Replacement reserves (RR). Modified after [13].

Inertial response: In a power system context, inertia is the rotational energy stored in spinning directly grid-connected electrical machines. When a mismatch between production and consumption occurs, the immediate initial reaction will be an increase or decrease in this rotational energy leading to a change in frequency. This is defined as the inertial response of a power system [12]. High inertia resists changes in frequency, and gives other services more time to respond to compensate for the mismatch between production and consumption. With high shares of conventional (so-called grid-following) inverter-based resources, the inertia from spinning machines is reduced. This inertia reduction could impose challenges related to frequency stability in power systems if the size of the largest disturbance is not reduced [5]. Recently, a new class of inverter-based resource controls has emerged (so-called grid-forming), which can allow the nearly instantaneous injection of active power in response to a mismatch between production and consumption in the direction resisting changes in frequency. While grid-following inverters assume that frequency and voltage are regulated by synchronous machines and, hence, follow the grid, grid-forming inverters aim to, by the use of advanced controls, provide services traditionally provided by synchronous machines. Provided that a sufficient energy buffer is available behind an inverter, these grid-forming resources can then support the grid in the inertial time frame, similar to spinning machines. If a grid-forming inverter is controlled with a "virtual synchronous machine philosophy", this technology is known as synthetic inertia.

Fast frequency response: With lower inertia levels, the frequency will change more rapidly following the occurrence of a mismatch between production and consumption. To give other services more time to compensate for this mismatch, fast frequency response services are used. Fast frequency response can be defined as "power injected to, or absorbed from, the grid in response to changes in measured or observed frequency during the arresting phase of a frequency excursion event to improve the frequency nadir or initial rate-of-change of frequency" [14]. Fast frequency response services generally react in a time frame faster than 2 s, and can include both existing services from synchronous resources as well as services from new fast-acting non-synchronous resources [12]. In systems with high inertia, there is no need to distinguish between fast frequency response and frequency containment reserves, due to frequency containment reserves having sufficient time to react to frequency deviations [14].

Frequency containment reserves: Frequency containment reserves have the main objective to compensate for a mismatch between production and consumption to stabilize the frequency [12]. Frequency containment reserves shall stabilize the frequency at a stationary level in a synchronous system in a time frame of 5–30 s after a mismatch between production and consumption. However, frequency containment reserves do not aim to restore the frequency to its nominal value. Frequency containment reserves react to frequency deviations in a few seconds within a certain frequency range. Sufficient frequency containment reserves should be available to stabilize the frequency at a level within an acceptable range in the case of a dimensioning incident (a dimensioning incident refers to the loss of the largest single component in a synchronous system in terms of active power).

Frequency restoration reserves: Frequency restoration reserves are used to keep the ACE toward zero in a balancing area and to restore the frequency to its nominal value [12]. Frequency restoration reserves may be activated in parallel with frequency containment reserves, and it is thus important that the frequency restoration reserves do not impair the frequency containment reserves. Frequency restoration reserves are commonly based on automatic generation control (AGC) using either the frequency deviation or the ACE as a setpoint. The full activation time of frequency restoration reserves generally varies within a time frame from 30 s to 15 min [12]. Frequency restoration reserves can also be manually activated.

Replacement reserves: Replacement reserves are used to replace fast frequency response, frequency containment reserves, and frequency restoration reserves when the system is in a balanced situation, to prepare these services to be activated again [12]. Replacement reserves may also be used as a complement to frequency restoration reserves when restoring the frequency after a larger disturbance. Replacement reserves generally act in a time frame from 15 to 60 min after a disturbance [12]. Replacement reserves are most often activated manually by a TSO when activation of frequency restoration reserves is either expected (scheduled activation of replacement reserves) or observed (direct activation of replacement reserves). Replacement reserves are generally a slower balancing service operating during a longer time frame compared to frequency restoration reserves.

Ramping products: Ramping products are online resources being able to decrease or increase the active power output over a specific time horizon for a certain time duration, to maintain supply, and demand balance in the case of net load ramps [12]. These net load ramps can both be unforeseen (such as unforecasted wind and solar production) or predictable (such as sunrise and sunset). Some ramping products act in time frames shorter than 15 min, while others act in longer time frames between 1 and 8 h. The motivation behind holding ramping products varies between time frames, whereby, in some systems, ramping products are needed to ensure the availability of certain technical capabilities not provided by shorter time frame balancing services. In other systems, ramping products are instead used to deal with market design failures, as the markets used for energy balancing fail to bring conventional generation online in sufficient time for it to deal with the net load ramps.

2.3. How to Achieve Sufficient Balancing Services?

Given the portfolio of balancing services available in a power system, it is the task of TSOs to determine how much of each balancing service must be available to keep the continuous balance in a reliable manner. The criterion for how to determine the sufficient volumes varies between TSOs, and includes both static (for a longer time frame, e.g., a year), as well as dynamic dimensioning methods (for a shorter time frame, e.g., a day). Before the real-time operation, TSOs must then acquire the needed balancing services. The process of acquiring balancing services can either be an independent process or a process in co-optimization with other parts of the short-term power system operation planning, such as clearing the day-ahead market. To ensure sufficient balancing services will be available, TSOs rely on different mechanisms to incentivize, or oblige, market actors to provide balancing services. Some common mechanisms are as follows:

Grid codes: in some systems, there are regulations, called grid codes, which make it compulsory for a power plant owner to keep certain margins, or to offer certain services, to be allowed to be connected to the transmission network.

Cost remuneration: an alternative mechanism is to require a technology to keep certain margins and have control systems available, but the technology is economically compensated, as it cannot be operated in a cost-optimal way from the owner's perspective.

Tender system—capacity: This implies a system where the TSO procures the availability of a certain balancing service in a market. Owners of various technologies are then free to provide offers in this market, based on the costs of keeping sufficient margins and having control systems available. The least-cost offers will be accepted until the TSO's needs are met. The market players who had their offer accepted then need to plan their real-time dispatch, such that the balancing service, can be activated if given a certain trigger signal.

Tender system—energy: This means that the TSO procures the activation of a certain balancing service in a market. Owners of various technologies are then free to provide offers in this market, based on the cost of changing their output level, such that the balancing service is provided. The least-cost offers will be accepted until the TSO's needs are met. The market players who had their offer accepted then need to increase or decrease their output in a manner that complies with the technical regulations of the specific balancing service.

2.4. Technology Options for Continuous Balancing

Technologies that are able to provide continuous balancing services can be categorized into generation, demand, electrical storage, and transmission. They must have a reaction time suitable for the particular balancing service. They have upward and/or downward capacity limits, which means that they must keep a margin, in order to be controllable in upward or downward directions. Most technologies have relevant ramp rate restrictions, i.e., how fast the technology can change its output. There is also a need for an observation and control system to execute balancing based on local signals (frequency and/or voltage), as well as communication systems that can trigger not only locally measured balancing commands, but also can enable new setpoints for the local controls.

Figure 2 shows the potential of different technologies to provide intra-hour balancing services. A notable difference is that while the synchronously connected generators (four top rows) provide physical inertia, they also tend to be slower in starting up, or in ramping from minimum load to full capacity, than inverter and resistor loads. From the synchronously connected machines, hydro power plants stand out, since they are not restricted by the thermal stresses that turbine plants must manage. Hydro power still has limits, since valves need to be opened, and water flows need to be managed. Electric motor-driven applications (synchronous and non-synchronous) can ramp their consumption fast depending on the processes these motors are driving. Fuel cells and electrolyzers are other groups with somewhat slower ramping and start-up capabilities. Their limitations are caused by the management of gas and liquid flows, as well as thermal stresses. These limitations are technology-specific, as there are many different fuel cell and electrolyzer types.

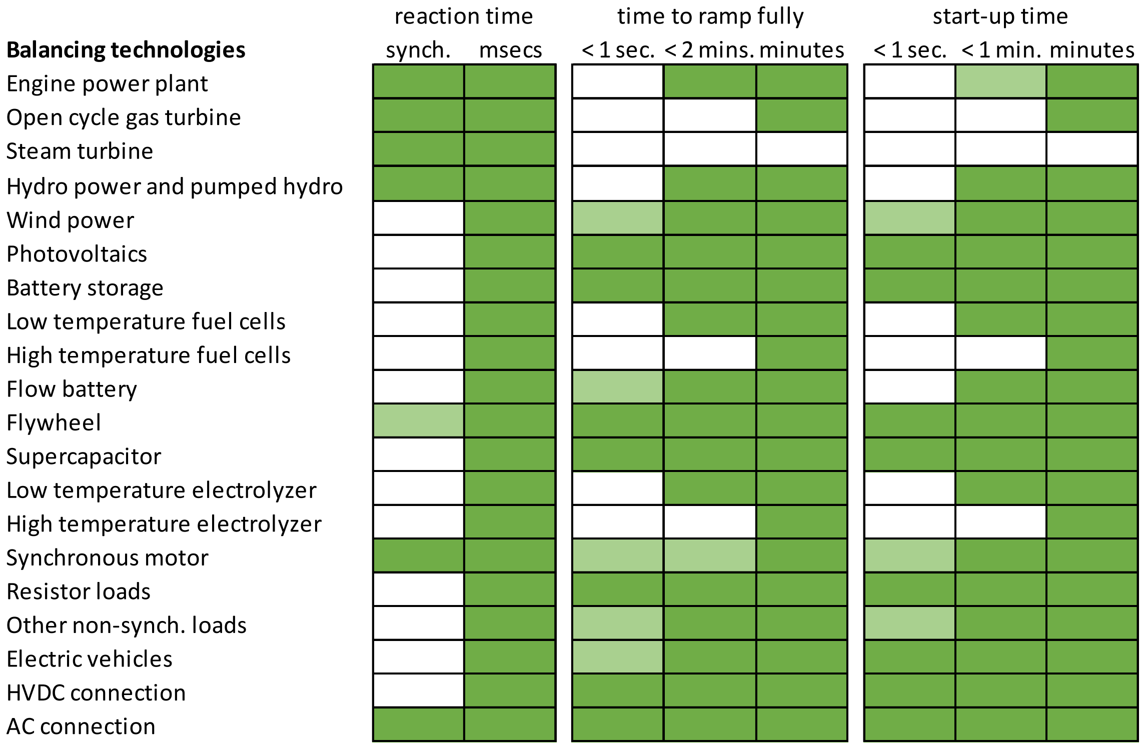

Figure 2. Potential performance of different technologies that can participate in the continuous balancing of power systems. Reaction time is the time for initial response for units in operation, while start-up time refers to the time it takes to start up an offline unit. Lighter green indicates a dependency on a specific technology, while darker green indicates capability in prevalent technologies. The figure is a rough compilation of the work in [15–20].

3. Continuous Balancing in Power Systems Targeting a High VRE Share

The overall aim of this paper is to provide an overview of different proposals regarding how to efficiently handle continuous balancing in power systems targeting a significantly higher share of renewable power in the future. The challenges and solutions vary across systems. In this section, a detailed description of the current setup to keep continuous balance, as well as future changes to cope with higher shares of renewable power, is given for six different systems across Europe and the United States. For each system, an overview of today's power system is first given. This is followed by an overview of future outlooks to understand the scope of current continuous balancing challenges and how these may change in the future. Then, today's balancing principles are described to understand the core strategy to keep continuous balance in the systems. Planned and potential changes to the balancing principles are also discussed. This is followed by an overview of today's set of balancing services in each system, describing the technological details, the dimensioning process, and how a TSO ensures that sufficient balancing services are available. Planned and potential changes to the balancing services following an increasing share of renewable power are discussed. Finally, the main technologies providing balancing services are described, and the potential provision of balancing services from other technologies in the future is discussed. Each system's subsection follows the structure below:

System:

Today: the power system today.
Future: future scenario with increasing VRE share.

Balancing principles:

Today: today's principles used to keep a continuous balance.
Future: planned changes to the balancing principles acknowledged by the TSO(s).
Potential: potential changes to the balancing principles that could contribute to keeping the continuous balance, not yet acknowledged by the TSO(s).

Balancing services:

Today: today's balancing services, how the needed volumes are determined, and how they are acquired.
Future: future balancing services, both regarding changes in the setup of today's balancing services as well as changes to the portfolio of balancing services.

Balancing technologies:

Today: the main technologies contributing to continuous balancing today.
Future: future technologies that may contribute to the balancing.

3.1. Nordic Synchronous Area

3.1.1. System

The Nordic synchronous system consists of Finland (operated under the TSO Fingrid), Norway (operated under the TSO Statnett), Sweden (operated under the TSO Svenska kraftnät), and Eastern Denmark (operated under the TSO Energinet). In total, there are eleven balancing areas in the Nordic synchronous system, one in Finland, five in Norway, four in Sweden, and one in Eastern Denmark.

Today: In Sweden, a bit more than 40% of the electricity is produced by hydro power, mainly located in northern Sweden. Nuclear power in southern Sweden contributed to about 30% of the electricity produced and wind power contributed with nearly 20% in 2021 [21]. In Norway, hydro power is the main source of electricity production, contributing over 90% of the produced electricity in 2021. Wind power production was contributing about 5% of the yearly electricity produced during the same year [22]. In Finland, the share of wind power production is increasing, having a share of 14% of the total electricity demand in 2022. Hydro power contributes about 15% and nuclear power contributes nearly 40%. Biofuels and fossil fuels contribute about 30% [23]. The new nuclear reactor Olkiluoto 3 with a capacity of 1600 MW is currently (March 2023) being started up [24]. In Denmark, the share of wind and solar power exceeded 60% of the yearly electricity production in 2021. The remaining electricity was produced from waste, biofuels, and fossil fuels [25]. In 2020, the total Nordic electricity consumption was around 400 TWh [26]. The consumption is mainly located in the southern parts of the system while a large share of the production is located in the northern parts. Thus, limited transmission capacity has led to transmission bottlenecks being a frequently recurring issue, leading to significant electricity price gradients from north to south.

Future: A scenario for the decarbonization of the Nordic region in the year 2040 is presented in [26]. In this scenario, the installed VRE capacity increases from 24 GW in 2020 to 123 GW in 2040. The total electricity consumption is expected to increase by about 65% from the year 2020 to 2040, mainly due to the electrification of the industrial and transport sectors. A lot of the increased electricity consumption will be power-to-x, mostly power-to-hydrogen for fossil-free steel production. The main increase in consumption will be in the northern parts of the Nordic region. To meet the increased electricity demand, a large expansion of onshore wind power in Sweden and Finland as well as offshore wind power in all Nordic countries is expected until the year 2040. In Sweden, there is a target of 100% renewable electricity production by the year 2040, although this is not a clear date for full nuclear power decommissioning. However, the new Swedish government has expressed a willingness to change this target from "100% renewable electricity" to "100% fossil-free electricity". In Finland, a net zero target for 2035 has already been set, at which time the electricity sector will need to be carbon-free.

3.1.2. Balancing Principles

Today: The main energy balancing is performed in the day-ahead market cleared with hourly resolution at 12:00 D-1. Each balance responsible party (BRP) has the responsibility to not deviate from the hourly energy bid in the day-ahead market. Forecast errors can be corrected in the intraday market, which closes 45 min before the operating hour. The intraday markets allow for bids with a duration time of 15, 30, or 60 min. After the closure of the intraday market, system operators' frequency and power balancing keep the continuous balance. BRPs should bid all available flexibility to the mFRR (Regulating power) market instead of correcting their own imbalances, to avoid cross-balancing and only balance the system net imbalance. All automatic balancing services have up to now been used for frequency balancing. Power balancing is performed manually; proactively, by telling generating units to ramp at different times around hour shifts to avoid large instantaneous imbalances, and, reactively, by asking for up-/down-regulation in the case of observed power imbalances.

Future: The energy balancing will have a major change as the market time unit will change to 15 min within a few years' time. This means the day-ahead market will be cleared with a quarter-hourly resolution and BRPs will be responsible to follow a quarter-hourly schedule. As the temporal granularity of energy balancing becomes finer, it is likely that the need for frequency balancing and power balancing in normal operations will be reduced. Moreover, some services currently focusing on frequency balancing will instead be used for power balancing. The purpose behind this change is that it will clarify where in the synchronous system reserves are needed and, hence, activation of reserves will not violate transmission constraints. Power balancing is also expected to be a proactive balancing activity based on the anticipated ACE.

Potential: A potential change to the balancing principles is the intraday market being open closer to real time, with products of finer temporal granularity being traded. This would mean more imbalances will be handled in the energy balancing stage, hence reducing the need for balancing service. Such a change can be especially useful to handle deterministic imbalances, caused by the ramping of units when changing their output between trading periods.

3.1.3. Inertial Response

Today: There is no market nor remuneration for inertial response in the Nordic power system today. According to the System Operation Guideline (SOGL) article 39.3, a method to determine the minimum level of inertia in a synchronous area should be developed if all TSOs acknowledge there is a need for it [27]. The Nordic TSOs do not see a need for this in the foreseeable future [28]. Inertia is monitored and, in cases of low inertia, the largest unit(s) online has been asked to operate at a lower level of generation to make sure that an N-1 fault will not cause a too high rate-of-change-of-frequency (RoCoF).

Future: There are currently no clear plans of introducing inertia as a balancing service in the Nordic system. However, remuneration for the provision of inertia during hours FFR is activated is discussed, with the argument that lack of rotational energy becomes a cost for the TSO during such hours. Then, inertia providers contribute to reducing these costs and should thus be remunerated for them.

3.1.4. Fast Frequency Response

Today: A fast frequency response service named Fast Frequency Reserve (FFR) was introduced in the Nordic power system in 2020. FFR is used at times of low rotational energy to counteract rapid frequency change in the case of contingencies [29]. There are different variants of FFR classified as the same fast frequency response service in terms of trigger frequency, activation time, and support duration [29]. The remuneration is the same independent of which the variant is provided. FFR is procured in national markets organized by each TSO, but the procured volume depends on the total Nordic need. There is currently no need for FFR during winter in the Nordic region. In Sweden, FFR is procured from a static merit order list two times per week for each hour based on anticipated system conditions. The remuneration is based on marginal pricing. In Norway, FFR is split into two different services. One service covers all nights and weekends in the summer season, and the other being deployed on demand for every week of the summer. In Finland, Fingrid procures FFR from a national hourly market where bids for the hours of the next day are submitted on the previous evening. The price of the reserve capacity is determined separately for each hour on the basis of the most expensive accepted bid. The Balancing Service Provider (BSP) may also submit a combination bid for FFR and Frequency Containment Reserve for Disturbances Upwards (FCR-D Up). This enables flexible bidding for reserve capacity that is suitable for both balancing services. The capacity of a combination bid may be used for procuring either FFR or FCR-D Up. In addition, reserve capacity that participates in the Yearly Market of FCR-D Up can be offered to the FFR market. In Denmark, FFR is procured in an hourly market for the next day, just as in Finland. The Danish FFR market closes after the day-ahead market [29].

Future: FFR is currently under development and work is being conducted to improve the technical requirements of the balancing service. For instance, the deactivation of significantly larger volumes of FFR could potentially lead to frequency stability issues if all FFRs have the same duration. This could be the case if wind power is the main provider of FFR, as the FFR variant with a shorter duration fits wind power better than the one with a longer duration. The aim is also to have a common Nordic FFR market in the future.

3.1.5. Frequency Containment Reserves

Today: There are two types of frequency containment reserves in the Nordic system: the symmetrical balancing service Frequency Containment Reserve-Normal (FCR-N), used in the frequency range 50 ± 0.1 Hz, and the asymmetrical balancing services Frequency Containment Reserve-Disturbance up/down (FCR-D up/down), used in the frequency ranges 49.5–49.9 Hz/50.1–50.5 Hz [29]. FCR are Nordic balancing services, dimensionally based on the Nordic need; however, it is procured separately in the Finnish, Norwegian, and Swedish/Danish markets. The TSOs are allowed to procure one-third of the FCR capacity from another Nordic market. Remuneration for providing FCR capacity is provided through the pay-as-bid principle in the Swedish/Danish market, while marginal pricing is applied in the Finnish and Norwegian markets.

Future: There are plans to change the technical requirements for FCR services to allow more technologies (for example, VRE generation and demand-side flexibility) to provide FCR [29]. There is a strive toward reaching a common Nordic FCR market. To reach this objective, the TSOs must first adjust the technical requirements for FCR so the FCR services are similar for all Nordic countries. The Swedish/Danish FCR markets also plan on implementing the marginal pricing of FCR capacity, which would make the market attractive for more actors [30]. However, these FCR markets suffer from high market concentration and the Swedish and Danish TSOs must first increase competition in their markets before applying marginal pricing.

3.1.6. Frequency Restoration Reserves

Today: Frequency restoration reserves are provided through two common Nordic balancing services. Automatic Frequency Restoration Reserves (aFRR) are activated automatically based on frequency deviations. Manual Frequency Restoration Reserves (mFRR) are activated manually by the TSOs [29]. Both FRR services are asymmetrical; i.e., it is possible to provide only up-regulation or down-regulation. The activation of mFRR is performed in the balancing energy market, maintained by the four Nordic TSOs. BSPs can submit bids until 45 min before the operation hour; mFRR bids are then activated in real time based on identified system needs according to a merit order list. The most expensive activated up-regulating bid determines the up-regulating price and the cheapest activated down-regulating bid determines the down-regulation price for each hour. In the case of congestion, the regulating price may differ between balancing areas. The energy provided from FCR-N, aFRR, and mFRR then gets remunerated based on the regulating power prices. A provider of mFRR capacity is obliged to submit bids to the balancing energy market according to a certain volume. A provider of aFRR capacity is obliged to have a certain capacity available to automatically react to frequency deviations. The needed capacity (i.e., available bids) for both FRR services is currently set based on national levels with static methods. Since December 2022, aFRR capacity is procured in a common Nordic market where the aFRR capacity providers are remunerated according to marginal pricing [31]. A common Nordic mFRR capacity market is targeted for the near future, with the first step being national capacity markets being set up during the second half of 2023 [32]. As of right now, it is the responsibility of each TSO to contract sufficient mFRR capacity. To allocate FRR capacity in an optimal way for the Nordic capacity markets, new reserve dimensioning methods have been developed [33].

Future: In the coming years, it is planned that energy from aFRR and mFRR will be activated in the pan-European platforms MARI (for mFRR) [34], and PICASSO (for aFRR) [35]. In these platforms, aFRR and mFRR standard products will be activated in a least-cost order throughout a majority of the European countries (33 TSOs participate in the MARI project, 30 TSOs in PICASSO). The platforms will function such that all TSOs communicate the balancing needs in their balancing area, the available transmission capacities between balancing areas, and the costs, volumes, and locations of available balancing services. This is then fed into an optimization problem where the balancing needs are met in the least-cost manner, while transmission limitations are respected. For aFRR, this optimization will be run every 4th second, where the balancing needs are based on the measured ACE in each balancing area. This also means that a marginal price for aFRR energy in each balancing area is calculated every 4th second with PICASSO. Similarly, MARI will find the cost-optimal mFRR activation every 15th minute. The balancing need in MARI will be based on TSOs' forecasted need for balancing energy in each of their respective balancing areas. To connect to the European energy activation platforms, work is currently being conducted within the project "Nordic Balancing Model" [36]. The project contains the following steps, where the first step has already (March 2023) been implemented:

1. Introduce a common Nordic aFRR capacity market.
2. Introduce an automated common Nordic mFRR energy activation market.
3. Introduce 15 min imbalance settlement period.
4. Introduce a common Nordic mFRR capacity market.
5. Connect to the European mFRR energy activation market MARI.
6. Connect to the European aFRR energy activation market PICASSO.

The Nordic TSOs have set up guidelines for a common dimensioning methodology of FRR services that will use cross-zonal transfer capacity in a manner such that the FRR capacities needed are minimized [37]. At the moment, work is also being conducted on dynamic dimensioning the FRR services. This means the FRR capacities needed will be determined more frequently based on anticipated operating conditions.

3.1.7. Replacement Reserves

Today: mFRR also serves as the replacement reserve in the Nordic synchronous area as of right now. The new methodology for FRR dimensioning states that mFRR capacity in each control area (the Nordic control areas are Sweden, Finland, Norway, and Eastern Denmark) must be sufficient to handle the reference incident considering transmission limitations within the control area. Currently, the TSOs handle this by contracted reserves that always bid into the market. For instance, the Swedish TSO has a contracted 'disturbance reserve' of 1350 MW (mainly gas turbines) [38]. The Swedish and Finnish TSOs also hold 'strategic power reserves' that are used for peak load hours [39]. However, these are not considered replacement reserves as they are used to avoid deficits rather than to replace some other resource.

Future: With the new FRR dimensioning methodology in [37], it is likely that replacement reserves will be shared between control areas to a larger extent by reserving cross-zonal capacity for the exchange of reserves.

3.1.8. Ramping Products

Today: Currently, there is no market for ramping products in the Nordic power system. Noteworthy is also the presence of a 'time-shift regulation', where TSOs make agreement with units to not ramp at the same hour shifts. However, there is no official market for such services.

Future: The Nordic system is becoming increasingly interconnected with Europe through HVDC interconnections. In addition, the amount of controllable, and potentially price-sensitive, demand is expected to heavily increase, mainly through electrolyzers producing hydrogen for the industry. This development may lead to a lot more resource ramping at shifts in trading periods, which will cause large imbalances, as alleviated in [40]. To handle such deterministic imbalances, short-duration ramping products could potentially give incentives for resources to counteract the imbalances.

3.1.9. Balancing Technologies

Today: In Sweden, balancing services are today mainly provided by hydro power [41]. Demand-side flexibility and battery storage provide the FFR. Nuclear plants provide significant inertia but do not provide any other balancing services. In Norway, both balancing and inertia are provided mainly by hydro power. Only small shares of inertia come from other sources such as synchronous condensers or the Mongstad gas power plant. FFR is provided by industrial loads. In Finland, about 80% of the mFRR comes from hydro power, and the rest, mainly from thermal power plants—wind power also contributes a little. For the aFRR, hydro power is the sole provider. FRR, in 2022, was provided by mainly storage, and also demand (24%). FCR-N has been mostly procured from hydro power; however, storage has bid and provided up to half in the hourly market since 2021. For the disturbance reserves, FCR-D demand is dominating both hourly and yearly markets and storage is increasing its share [42]. In Denmark, combined heat and power plants provide a large share of the balancing services. This leads to seasonal variations in the amount of available balancing services, as the availability greatly depends on the heat demand [43].

Future: In Sweden, many new balancing technologies are currently being introduced in the power system. If balancing services do not have to be provided from hydro power, it would mean that there is less need to keep generation margins in hydro power, and hydro power can contribute to balance out daily/weekly variations in VRE generation to a larger extent. Flexible hydrogen production, energy storage facilities, and demand-side response are technologies expected to increase their contributions to balancing [30]. As an example, the company Tibber is pre-qualified to provide balancing services through the controlled charging of electric vehicles [44]. Other examples are controlled electric heating [45] and battery storage [46], having the potential to contribute to the balancing. There is an increasing interest from VRE resources to contribute with down-regulating balancing services, while the pre-qualified volumes are rather small today [41]. In Norway, the hydro-dominated generation mix has large balancing capabilities, somewhat reducing the need to utilize other sources compared to other countries. However, the large electric vehicle fleet, which is currently considered for local grid congestion management, could also provide balancing services. Down-regulating wind power is also an option, just as in Sweden. The Skagerrak 4 HVDC system is providing balancing services (FCR and aFRR) from Norway to (West-) Denmark, but not yet to Norway, even though it could be a future option [47]. Virtual inertia provision through HVDC has been investigated in research but not in use or planned [48]. In Finland, the trend in 2021–2022 has been toward more demand and storage participation, and wind power is expected to play a larger role in the future. In Denmark, the TSO makes a distinction between balancing technologies contributing in periods of high and low VRE generation, respectively [43]. At high VRE generation, VRE technologies, power-to-x, and battery charging will contribute to keeping the continuous balance. At low VRE generation, conventional power plants and battery discharging will instead play an important role. In both cases, the demand side, including flexible heat pumps and electric boilers, is expected to provide balancing services.

3.2. The Island of Ireland

3.2.1. System

The island of Ireland's synchronous system consists of the Republic of Ireland and Northern Ireland with limited ac interconnection. Each jurisdiction has its own TSO, but the island is effectively operated as a single joint system, as part of the single electricity market (SEM).

Today: In the Republic of Ireland, approx. 40% of electricity is produced by renewables, with the majority supplied by wind generation (35%), supported by hydro (2%) and CHP and bioenergy (3%). The remaining generation is mostly provided by gas-fired generation (48%), along with coal-fired power plants (8%) and oil-fired plants (2%) [49,50]. Peat-based power plants have recently been subject to early retirement, while there is no nuclear generation on the island, and there are no future plans for such technology. For Northern Ireland, the generation mix is similar, although there is a small, but increasing, contribution from solar PV. Consequently, the renewable energy contribution is 38% (33% wind, 1% solar PV, 4% biomass, CHP, and hydro), with gas-fired (51%) and coal-fired (11%) power plants being the other main contributors [49]. There are also 2 HVDC interconnectors to Great Britain, one in the Republic of Ireland and one in Northern Ireland, with a net export across the island of approx. 2% of annual energy. For stability reasons, based on extensive offline analysis, and the adoption of online monitoring tools, the instantaneous contribution from non-synchronous sources (wind, solar PV, and HVDC) is currently limited to 75% of demand. This is known as the system non-synchronous penetration (SNSP) limit. Against a peak system demand of 7 GW, and annual consumption of 39 GWh, much of the load is located along the east coast of the island, notably Dublin. However, with much of the wind generation located toward the west coast, network constraints (5%, 754 GWh in 2022) and system stability concerns (4%, 526 GWh) contribute to approx. 9% (1280 GWh) annual wind curtailment. Approx. 4% (6 GWh) of solar PV generation in Northern Ireland is also curtailed due to system stability concerns [51].

Future: Both the Republic of Ireland and Northern Ireland have targets of 80% renewable electricity by 2030, with full decarbonization of the entire energy system being targeted for 2050 [52,53]. For the Republic of Ireland, a major focus is being placed on both offshore wind generation (only 25 MW at present) and solar PV, along with further development of onshore wind generation. In Northern Ireland, onshore wind and solar PV are likely to be preferred, although strong interest in offshore wind is emerging (probably after 2030). Electricity demand is expected to increase by 37% (median estimate) by 2031 across the island, partly due to the electrification of the heating and transport sectors, but largely due to continuing growth in the number of data centers being built. At present, data centers consume approx. 15% of demand in the Republic of Ireland, but this may increase to 28% (median) by 2031 [54]. Most of this new demand will likely be located on the east coast of the island, but the development of offshore wind in the Irish Sea (to the east of Ireland) will tend to reduce some of the network impacts. Increased ac interconnection between the two jurisdictions is anticipated by 2025, which will reduce the risk of a "system split". The subsequent reduction in the number of regional constraints should enable more cost-efficient generation dispatches. Increased HVDC interconnection with Great Britain, and also France, is further anticipated in the next few years, providing significantly increased import/export opportunities during times of renewable generation scarcity/surplus. Indeed, the 80% renewables target for 2030 implies that at certain times, the available wind and solar PV generation will greatly exceed the indigenous demand, while, at other times, the reverse will be true. This means that maintaining system stability, avoiding excessive renewables curtailment, reducing network constraints, etc., will be major operational challenges [55].

3.2.2. Balancing Principles

Today: As with other systems, the main energy balancing is achieved in the day-ahead market, supported by an intraday market (operating up to 1 h before real time) and a balancing market. A long-term schedule (LTS), up to 30 h ahead, with a resolution of 30 min, is revised every 4–6 h based on an updated renewable forecast (or other contingencies). Prior to the UK leaving the European Union, initial day-ahead schedules for the European market recognized HVDC interconnector flows between the island of Ireland and Great Britain. Nevertheless, at present, this is not the case. (When the Celtic HVDC interconnector between Ireland and France is completed, expected in 2026, full market integration will again become available.) For the interim, the initial daily long-term schedules are conservative and indicative only, but more optimal day-ahead capacity arrangements are in development. A real-time (intraday) unit commitment (RTC) is performed every 15 min with a horizon of 4 h, resolution of 15 min, and lead time of 30 min. A real-time economic dispatch (RTD) is performed every 5 min with a 1 h horizon, resolution of 5 min, and lead time of 10 min. In real time, generators operate on a governor droop characteristic, typically set at 4%, and with a frequency deadband of less than 15 mHz.

Future: As the island of Ireland's power system pushes toward higher shares of renewables, there is concern that an energy-only market will be inefficient, as the generation schedules may need to be modified to fully recognize network and stability-related constraints. Consequently, reviews are ongoing concerning better coordination between energy, capacity, and system services markets, while also considering the impact of, for example, network tariffs, network losses, and oversupply issues. In addition, when the Celtic interconnector to France becomes operational, full compliance with EU electricity market network codes will be required, including integration with the intraday and balancing markets. In particular, fundamental changes relating to self-dispatch and ex post pricing will be required to integrate with PICASSO (exchange of automatic frequency restoration reserves), TERRE (Exchange platform for replacement reserves), and MARI (exchange of manually activated restoration reserves).

Potential: Increased use of probabilistic and stochastic scheduling methods for energy balancing are methods that can be useful in the future, although the implementation of such methods is not planned as of today.

3.2.3. Inertial Response

Today: Due to the synchronously isolated nature of the all-Ireland system, and the large size (MW) of generator infeeds/outfeeds relative to the system size, generator trips are of major concern. A static inertial floor (currently 23 GWs) constraint is imposed, linked to a maximum RoCoF constraint. Synchronous generators are not explicitly remunerated for providing an inertial response, but a synchronous inertial response (SIR) system service was introduced in 2018. This system service rewards generators based on the ratio of their stored rotational energy (MWs) to their minimum stable generation level, and the SNSP level [56]. It follows that generators are financially motivated based on regulated tariffs to reduce their minimum generation level. During times of low demand and/or high renewables production, more conventional units (providing an inertial response) can then be "squeezed" online to meet inertial floor requirements, while reducing the need for renewables curtailment. Non-synchronous sources are not eligible here, but synchronous condensers are particularly incentivized, since they can provide an inertial response, while they appear as a small load to the system.

Future: Trials are ongoing to increase the RoCoF requirement from 0.5 to 1 Hz/s, which would relax the inertial requirement. However, HVDC interconnection with France in the next few years will potentially increase the size of the largest infeed/outfeed (from

500/530 to 700 MW) and increase the inertial requirement. Low-carbon inertia services (LCIS) are to be procured by the respective TSOs, with regional target zones specified, including a synchronous inertial response capability, based on pay-as-clear principles [57]. It is intended that the inertial floor threshold will be gradually lowered, along with the required number of online large synchronous generators. In tandem, the all-island inertia requirement will be split into separate Republic of Ireland and Northern Ireland inertial requirements. However, on slightly longer timescales, with increased ac north–south interconnection anticipated, the regional requirements will likely be altered.

Potential: Beyond 2030, the aim is for the island system to be capable of operating at 100% SNSP [55], implying a system based on wind and solar PV generation, and HVDC imports/exports. Synchronous condensers are likely to be critical here, but grid-forming, and other technologies may also be considered eligible [58].

3.2.4. Fast Frequency Response

Today: A fast frequency reserve (FFR) system service was introduced in 2018 to support the system speed of response following the tripping of a large generator. The default system service requires a response within 2 s lasting for 8 s, with constraints imposed on the depth and duration of the energy recovery period. Availability payments are made based on a regulated tariff and the sustained magnitude of the response. Faster (than default) responses, a high trigger frequency, performance reliability, and a non-stepped response are all further rewarded [56]. Increased payments can also be achieved if a provider can provide a continuous response from the fast frequency time frame to the tertiary-1 contingency reserve time frame, i.e., from 2 s to 5 min. The payment also increases if the response is available under scarcity conditions (higher SNSP levels). Subject to completing a qualification trials process, synchronous and non-synchronous technologies are eligible.

Future: Low-carbon inertia services are being developed, which may affect the need for existing system services. The increased growth in battery energy storage systems (BESS) is improving the frequency response capabilities of the system, despite an increasing wind and solar PV energy share, which will feed into reviews of the availability tariffs. Locational scalars can also be introduced as being necessary to support regional needs, while solar PV and hybrid power plants are likely to be considered eligible providers.

3.2.5. Frequency Containment Reserves

Today: Regulating and contingency reserve requirements are currently combined as a primary and secondary operating reserve. The regulating reserve ensures that the system frequency is normally maintained within the range of 49.8 to 50.2 Hz, with a minimum regulating reserve capability defined for each jurisdiction. The contingency reserve requirement operates in the time frames of 5–15 s (primary) and 15–90 s (secondary), with the objective of containing the system frequency following an imbalance. The reserve requirements are dynamic, being based upon a fraction (currently 75%) of the largest all-island infeed. Within each jurisdiction, a minimum share of the primary reserve must come from regulating sources, i.e., synchronous generators. Similar to FFR, payments are based upon a regulated availability tariff, with scarcity, performance, locational, and enhanced delivery scalars also applicable. Until 2021, 100 MW of negative ramping reserve (associated with the tripping of a large load or outfeed) was required across the island, but this has now been reduced to a static 50 MW requirement in Northern Ireland only following successful trials.

Future: As part of ensuring alignment with the European network code for system operation, upward and downward reserve policies will be more clearly defined (also including fast frequency reserve and restoration reserve). In addition, the fraction of the largest infeed/outfeed to be covered will change from 75% to potentially 100% [59]. Consequently, a new frequency regulation system service may be explicitly required. Trials are ongoing regarding preferable frequency response controls for battery energy storage systems, recognizing the transition to a high-renewable (non-synchronous) power system. This may also impact the regulating reserve requirements. In addition, negative reserve requirements in Northern Ireland should be removed, with the assumption, based on previous trials, that wind generation can rapidly reduce its output, as required, to mitigate high-frequency events.

3.2.6. Frequency Restoration Reserves

Today: The tertiary-1 and tertiary-2 operating reserves operate in time frames of 90 s–5 min, and 5–20 min, with the objective of restoring the system frequency to the nominal value. They are achieved by a combination of automatic and manual actions, and the dynamic reserve requirement is based on 100% of the largest all-island infeed. Payment arrangements are similar to the frequency containment reserve, except that continuous provision and enhanced delivery do not apply to tertiary-2. In addition to the above, volume-capped payment long-term arrangements are also possible. These are targeted at high-availability battery energy storage, which covers all five system services from fast frequency to tertiary-2 time frames (2 s to 20 min), and include overfrequency capability.

Future: A review process is underway regarding all reserve system services, ranging from fast frequency to ramping products. This review relates to balancing service definitions, financial arrangements, forecasting methodologies, etc., and promoting opportunities from non-traditional sources, e.g., demand response, battery energy storage, and non-synchronous generation [60]. It is anticipated that a day-ahead auction framework for (some/all) reserve services will be established in 2025, supported by long-term procurement procedures for balancing services not considered appropriate for daily auctions. In addition, later coupling with the European reserve market in 2026/2027, following the completion of the Celtic HVDC interconnector between Ireland and France, is also planned.

3.2.7. Replacement Reserves

Today: Replacement reserves are manually dispatched, and predominantly provided by open cycle gas turbines, along with dispatchable aggregated generating units (AGUs) in Northern Ireland. AGUs represent a number of individual diesel gensets offering their combined capacity. At all times, the combined output of OCGTs (and AGUs) in each jurisdiction must be less than a defined threshold to ensure sufficient regional replacement reserve. The thresholds in each region are fixed, but they may be updated based on the availability of individual units and transmission-related constraints.

Future: As above, for future plans for frequency restoration reserve.

3.2.8. Ramping Products

Today: Sub-hourly timescales maximum ramp rates, currently 10 MW/min combined, are imposed on the HVDC interconnectors to reduce consequential "balancing" impacts on other generators. On longer timescales, due to potential renewable (wind) forecast errors, sufficient dispatchable generation and demand capacity is maintained. Three system services have been defined (ramping margin 1, 3, and 8), with an increase in generator output (or decrease in demand) to be delivered within a specified time frame (1 h, 3 h, and 8 h), and to be sustained for a specified time frame (2 h, 5 h, and 8 h). As before, availability payments apply based on regulated tariffs, with scarcity, locational, and performance scalars applicable.

Future: Given the increased number of HVDC interconnectors (from 2 to 4) by 2030, and the emergence of several large offshore wind farms by the end of the decade, much higher interconnector ramp rates are likely to be required (perhaps 40 MW/min combined) [59].

Potential: The existing ramping products are mostly associated with uncertainties relating to wind generation forecast errors. However, ambitious solar PV generation targets have been specified for 2030. Although the timing of upward and downward ramps in aggregated solar PV output is quite predictable, there may well be a future need to define a specific solar PV ramping system service.

3.2.9. Balancing Technologies

Today: Traditionally, the inertial response and all categories of reserve were mostly provided by fossil-fuel (gas and coal)-fired synchronous generators. Pumped storage plants were also a highly valued contributor to frequency containment and restoration reserve requirements. In more recent years, HVDC interconnectors, battery storage, and (perhaps aggregated) demand-side units provide non-regulating or partially regulating reserve. Wind generation is eligible to provide fast frequency reserve, primary, secondary, and tertiary-1 frequency containment reserve, but, of course, this may not often be attractive to provide, while wind generation also provides negative ramping reserve.

Future: The latest Climate Action Plan for Ireland [52] states that reserve requirements should be fully provided by zero-carbon technology by the end of 2023 and that the procurement of reserve services from carbon sources should be phased out by the end of 2027. It is also targeted that the all-island system will be able to operate securely with three, or less, large conventional (synchronous) generation units [59], further confirming that system services should come from elsewhere. In parallel, low-carbon inertia services are being defined, with a focus on an inertial contribution, reactive power support, and fault current contribution [57]. It is anticipated that synchronous condensers will be a dominant technology here, but grid-forming-based solutions may also emerge later. The latest Climate Action Plan further requires that 20–30% of the demand should be flexible by 2030, with a particular focus on large energy users, including data centers. Moreover, anticipated strong growth in electric vehicle charging, heat pump loads, and hydrogen production are highly relevant. Dynamic "green electricity tariffs", akin to real-time pricing, are also proposed to encourage demand consumption to better follow wind and solar PV variability.

3.3. Iberian Peninsula

3.3.1. System

The Iberian Peninsula system consists of Portugal and Spain's peninsular territories except for non-continental insular territories. The Iberian power systems are part of the European Transmission Network, although weakly interconnected with France, through the Pyrenees. Both countries agreed and operate the Iberian Market of Electricity (MIBEL), which manages spot, derivatives, and bilateral markets. Portugal has an installed capacity of 19.2 GW (~50% non-dispatchable) and a peak demand of 9.9 GW. Spain has an installed capacity of 113.7 GW (~42% non-dispatchable) and a peak demand of 45.4 GW. Ancillary services are independent in each country and managed by their respective national TSO. Notwithstanding that, system services can be traded between the Portuguese and Spanish TSO. For continuous balancing, both TSOs use the "Cross Border Balancing Exchange" mechanism to trade reserves.

Today: In Portugal, the main contributions to the energy mix are wind power with yearly generation shares of above 27%, and hydro and combined cycle (CC) with single yearly contributions between 20% and 30%, led by combined cycle gas turbines (CCGT) in dry years, and by hydro power in wet years. In recent years, the solar PV reached in Portugal was 7% of overall generation. In Spain, there is a very varied oversized generation mix with the main contribution to production coming from CC, wind, and nuclear energy with 23%, 22%, and 21% of overall production, respectively [61]. An important increase has occurred for photovoltaic energy, which currently reaches 10%. Spain exported 7.6% of the energy generated in 2022, despite the limited interconnection capacity.

Future: The Portuguese National Energy and Climate Plan (NECP) has the goal of significantly increasing the renewables' share in the electric sector to 87% by 2030, by increasing the installed capacity by 2030 of wind (from 5.6 to 9.3 GW), solar PV (from 1.7 to 9.0 GW), hydro (from 7.1 to 8.7 GW, of which 4.1 GW will be PHS—pump hydro storage), and biomass (from 0.4 to 0.5 GW) [62]. All coal power plants have already been decommissioned, with CCGT being the only non-renewable power plants in use in the Portuguese continental territory since 2021. The objectives set by Spanish NECP 2021–2030 are to reach 74% renewable energy in electricity generation in 2030, and 100% renewable in 2050 [63]. In the case of renewables, solar PV shows a higher expected growth target, with 339%. Therefore, it will play an essential role. Thermoelectric solar power has an expected growth target of 217%, but this variation is because it starts from a very low level of installed capacity. As for wind power, the target is 50 GW, so growth of 80% is expected by 2030. CC plants are expected to play a key role in the energy transition. In relation to coal, the objective is decarbonization in 2030, although it does not rule out the operation of those that undertake investments to comply with the community framework. Nuclear will be another technology that will begin to be progressively dismantled, although there is still much uncertainty about the date of closure of nuclear power plants in Spain, as well as the extension of their useful life. The plan takes into account the closure of four of the seven nuclear reactors by 2030, and estimates the closure of the other three by 2035. Furthermore, both countries will increase their cross-border transmission capacity from 3.2 to 4.2 GW.

3.3.2. Balancing Principles

Today: For continuous balancing, Portugal considers the traditional European frequency reserves: Frequency Containment Reserves (FCR), automatic Frequency Restoration Reserves (aFRR), manual Frequency Restoration Reserves (mFRR), and Replacement Reserves (RR) [64]. In Spain, the balancing markets are divided into two groups according to the time horizon. In the day ahead, the reserve of additional power to be uploaded for that program and aFRR power regulation are established. Intraday markets include the resolution of technical restrictions for the intraday and real-time market, aFRR and mFRR reserves, and RR. The resolution has recently been proposed to be adapted to 15 min for the implementation of the mFRR (MARI) platform. Thus, national terms and conditions in day-ahead markets have a compatible resolution that can be set to 15, 30, 45, and 60 min. The resolution of intraday products is set to 15 min.

Future: final testing and connection to the MARI platform will be developed by the end of the year.

Potential: potential changes to the balancing principles include the intraday market moving closer to real time, closing 15 min ahead of real-time operation as implemented/discussed in other European countries.

3.3.3. Inertial Response

Today: there is no market nor remuneration for inertial response in the Portuguese and Spanish power systems today.

Future: There are still no plans for introducing inertia as a balancing service in the Iberian power system in the short term. However, with the actual course of the fast pace of transition to a near 100% renewable electric power sector in Iberia, this situation changes, especially due to the crescent scarcity of classic (physical) inertia.

3.3.4. Fast Frequency Response

Today: There is no market for fast frequency response in the Spanish power system. In Portugal, those reserves are compulsorily provided by conventional power plants, e.g., hydro.

Future: There are no plans for fast frequency response markets in the Iberian power systems in the short term. Similar to inertia, the fast transition to a near-renewable power system will, expectably, dictate the need to set up such a market.

3.3.5. Frequency Containment Reserves

Today: FCR is a mandatory and non-remunerated system service for all that have technically capable generators connected to the grid (wind and solar power are excluded from this requirement) [65]. This means actors must either provide the service themselves, or contract it from a third party. The FCR requirements for generators are 5% and 1.5% of the nominal power in stable conditions, in Portugal and Spain, respectively. As Portugal and Spain are part of the synchronous grid of continental Europe, generators contribute with their reserved FCR capacity to the required 3000 MW of positive and negative FCR ready to be activated in continental Europe.

Future: There are no plans of changing the FCR mechanism in the Iberian power system at midterm. Similar to the case of fast frequency response, the pace of transition to a near-renewable power system will, expectably, dictate the need to start setting up such a market in the future. Additionally, it will be desirable to normalize the Iberian FCR services.

3.3.6. Frequency Restoration Reserves

Today: The Portuguese TSO requires an asymmetrical aFRR power band where the upwards capacity doubles the downwards capacity. Historically, in Portugal, the aFRR power band is more used for up-regulation than down-regulation. Thus, concerning ENTSO-E suggestions, the Portuguese TSO increases the upwards capacity of the aFRR until 60%, and reduces its downwards capacity until 40% [66]. In Portugal, the TSO allows the participation of all technically capable generators in hourly auctions of aFRR capacity. They are remunerated based on the marginal prices of the hourly auction. Generators have to be capable of providing both down-regulation and up-regulation, bidding an up capacity that has to double the down capacity [65,66]. Due to the lack of competition in the Portuguese aFRR market, the CCGTs and hydro power plants that provide aFRR have had the price of their aFRR energy defined by the regulator. The energy of mFRR is obtained by considering an hourly auction-based separate procurement of both up and down-regulation on marginal markets. Players participating in mFRR may support it for one hour [65]. So, replacement reserves are used to solve frequency disturbances for more than one hour. RRs can be activated in 15 min and continue active for long periods. In Spain, aFRR is procured via a pay-as-clear day-ahead market for the availability and utilization of energy. In mFRR, two types of assignments are distinguished. A scheduled assignment made 15 min before the quarter-hourly delivery period (96 gates), and a direct assignment, made at any time, for the corresponding delivery period and the following one with a variable duration between 16 and 30 min.

Future: Similar to the efficient FRR activation to be used by Nordic power systems (MARI and PICASSO). Additionally, it will be desirable to normalize the Iberian FRR services.

3.3.7. Replacement Reserves

Today: In Portugal, RRs have been approved in the regulator Directive No. 19/2022 [67]. RRs have been operational since 2022 and are supported by demand-side players with at least 4 MW of flexible demand. Their available capacity is remunerated through yearly marginal auctions. RRs' energy is obtained considering an hourly auction-based procurement of both up and down-regulation on marginal markets, with an equal price equal both for up and down-regulations. In Spain, the RR service is defined as the maximum variation in power generation that a generating or pump storage unit can experience in 15 min. A gate closure for this service's day-ahead market with the TSO is 11:00 p.m. However, when capacity is committed in other intraday markets, the bids in this market can be modified up to 60 min prior to delivery, and up to 25 min prior to delivery, when Cross Border Balancing using Tertiary Reserves (BALIT) is not in effect.

Future: To be defined in accordance with the future trading of inertia, FCR, and FRR for ~100% electric power systems. Additionally, it will be desirable to normalize the Iberian RRs services.

3.3.8. Ramping Products

Today: There are no ramping products in Portugal or Spain.

Future: There are currently no plans of introducing ramping products in the Spanish power system. In the near future, it is expected (and desirable) that Portugal introduces ramping trading and allows its renewable plants to participate in this market/trading mechanism.

3.3.9. Balancing Technologies

Today: In Portugal, the most active technologies by volume in the Balancing Markets are hydro power (with and without pumping) and CCGTs for both upward and downward actions. VRE technologies, such as wind and solar PV, are not allowed to participate in balancing markets. In Spain, wind has the second biggest share of downward volumes and is fourth in upwards [68]. Solar power (PV and thermal) has started to participate with symbolic volume in RR.

Future: Storage technologies are taken into consideration as the primary contribution in the future, in addition to considering their growth in the contribution of VRE generation to the balancing markets. According to the Spanish strategy, storage capacity will be around 20 GW in 2030 and 30 GW in 2050, taking into account both large-scale and distributed storage. Due to their maturity, pumped-storage hydro power plants or batteries are worth mentioning as technologies in Spanish NECP objectives with 9.4 and 2.5 GW, respectively. These are particularly relevant due to their use in self-consumption systems and electric mobility. Furthermore, it is important to consider their widespread deployment through hybridization with renewable energy production facilities. Thermal storage systems connected to solar thermal power plants are also significant in this regard. In addition, renewable hydrogen is also given consideration, and it will be crucial in bringing down emissions in industries that are challenging to decarbonize. In Portugal, with the foreseeable end of Feed-in-tariffs (FITs) between 2024 and 2025, it is expected that VRE technologies will be allowed to participate in balancing markets. Moreover, it is expected that balancing services will be harmonized with Spain.

3.4. Texas (ERCOT)

3.4.1. System

The Texas Interconnection, operated by the Electric Reliability Council of Texas (ERCOT), is one of the three interconnections in the United States (U.S.). ERCOT represents about 90% of the load in the state of Texas, serving more than 26 million customers. ERCOT is not synchronized with the rest of the U.S. power system and it has very limited HVDC connections to neighboring power systems, with total capacity equal to only 1.5% of peak load.

Today: In ERCOT annually, more than 43% of electricity is currently produced by natural gas, nearly 25% from wind, nearly 17% from coal-fired generation, 10% nuclear, and with solar PV production at around 5% [69]. ERCOT is a summer peaking system with peak demand of 80 GW. The demand is primarily located in the central and eastern parts of the state, while wind and solar resource areas are in the west and northwest (Texas Panhandle). Weak grid issues and steady-state voltage stability concerns due to long-distance power transfer frequently lead to binding transmission constraints from this renewable-rich region [69].

Future: Texas does not currently have any unfulfilled renewable energy goals, and all renewable energy generation installations occur on an economic basis. Solar PV installations, in particular, are increasing rapidly in the ERCOT territory, with a majority of utility-scale plants being planned in west Texas, away from the traditional load centers. This spatial mismatch between future generation and load is anticipated to exacerbate some of the weak grid and stability issues that ERCOT is currently experiencing due to the majority of installed wind power being located in the Texas Panhandle. Energy storage, primarily in the form of Li-ion batteries, has also been increasing rapidly over the previous five years. This experience has led ERCOT to be a leader among the U.S.'s TSOs in some of the balancing services described below.

3.4.2. Balancing Principles

Today: Much like many of the other systems previously described, ERCOT relies primarily on a day-ahead market for hourly unit commitment, with a five-minute real-time economic dispatch used for balancing purposes. The five-minute economic dispatch leads to most of the imbalances being handled in the energy balancing stage. ERCOT ancillary service markets traditionally consist of regulation up and down, responsive reserves, and non-spinning reserves, with some more recent changes described in the following sections. ERCOT ancillary services are co-optimized with energy in the day-ahead market.

Future: There do not seem to be any indications that the current structure will change dramatically in the near future.

3.4.3. Inertial Response

Today: In ERCOT today, inertia is primarily provided by conventional synchronous generators, such as coal and gas-fired units. An additional build-out of newly combined cycle generation in the 2014–2015 time frame resulted in an inertia increase, despite wind and solar build-outs and coal generation retirements. This is because a combined cycle generator provides a 1.5 times higher inertial contribution, compared to a coal-fired generator of the same size. The inertia additions and retirements between the years 2013 and 2020 are shown in Figure 3.

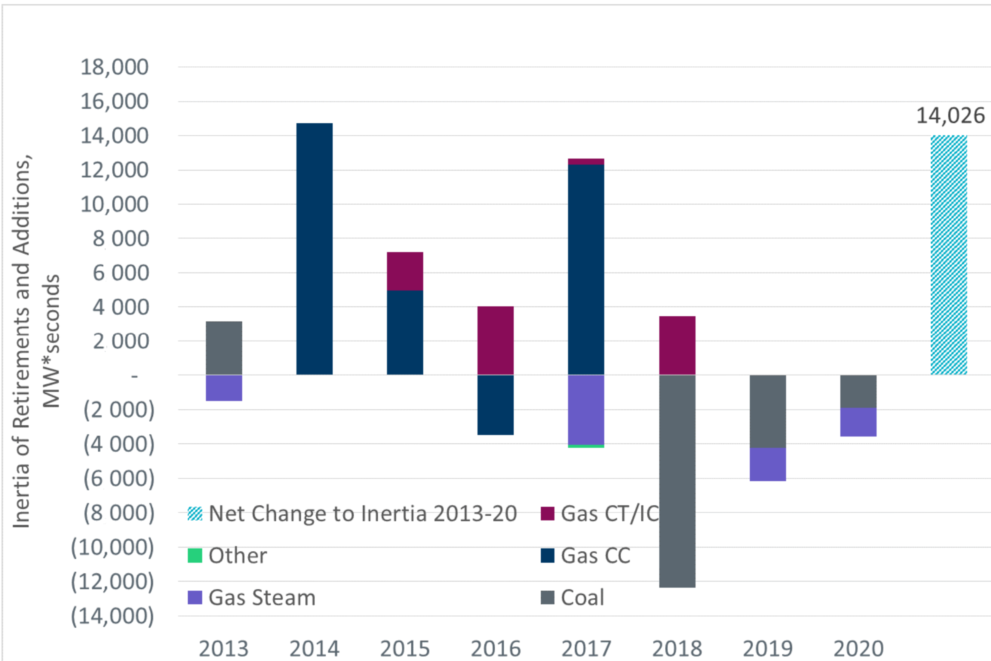

Figure 3. Changes in synchronous inertia from synchronous generation retirements, mothballing, and additions in ECROT (approximately 11,600 MW of capacity retired or mothballed (primarily coal and gas-steam) and 9300 MW of capacity was added (primarily combined cycle and combustion turbines) between 2013 and 2020.

ERCOT has determined an inertia floor, so-called critical inertia at 100 GWs [70]. This level of inertia allows sufficient time for existing frequency control methods to arrest the frequency above the first stage of the underfrequency load shedding trigger after the loss of 2800 MW due to a simultaneous trip of the two largest nuclear units (a dimensioning incident in ERCOT). If inertia gets close to this minimum, the system operator will start additional synchronous generators to bring inertia to the desired level. This inertia floor has not yet been encountered in real-time operations. In 2019, a new FFR service was approved (see details below). This service was fully implemented in the ERCOT systems by October 2022. Once fully subscribed, the critical inertia level in ERCOT can be reduced to 90 GWs due to the increased speed of frequency response.

Future: If the inertia floor will bind more often, ERCOT may consider the implementation of an inertia service market, since operator actions to bring inertia back up to the critical inertia level will lead to out-of-market actions (when additional generators are brought) and will negatively impact real-time market prices. It is possible that with time and continued synchronous generator retirements, regional pockets of critical inertia will need to be determined. Additionally, ERCOT is currently considering the addition of six synchronous condensers in the Texas Panhandle, primarily to improve system strength. The benefits of synchronous condensers for improved inertia levels will also be considered. ERCOT currently has more than 7 GW of utility-scale batteries in the interconnection queue with signed interconnection agreements and financial commitments, and will consider the benefits of requiring/incentivizing grid-forming capabilities from these resources.

3.4.4. Fast Frequency Response

Today: Since 1996, ERCOT has had a type of fast frequency response from load resources (i.e., large industrial loads) with underfrequency relays. These resources provide a full response within 0.5 s of the frequency dropping to 59.7 Hz (60 Hz is the nominal frequency in North America). This service was implemented as a part of a frequency containment reserve (called Responsive Reserve Service (RRS)), and load resources are paid the same price as generators providing RRS. Currently, up to 60% of RRS can be provided by load resources with underfrequency relays. A new FFR service was recently implemented as another subservice of RRS. A resource providing FFR is required to provide a full response within 0.25 s after the frequency reaches 59.85 Hz. The response should be sustained for 15 min or until the frequency recovers back to normal, whichever is shorter. Resources providing FFR are paid the same price as load resources and generators providing frequency containment. The price is determined in the day-ahead market, which applies to all balancing services procured in the day-ahead co-optimization of energy and ancillary services. There is currently a 450 MW limit for FFR capacity, set to avoid overfrequency conditions due to the FFR response after a large generator trip in low inertia conditions.

Future: It is expected that gradually resources will qualify and subscribe for the provision of FFR. As mentioned above, the full subscription of FFR will allow a reduction in the critical inertia level. In the future, the limit for FFR may potentially need to be reevaluated, given the changing inertial conditions.

3.4.5. Frequency Containment Reserves

Today: ERCOT ensures the sufficiency of frequency containment reserve through the procurement of necessary amounts of RRS. RRS requirements are determined dynamically based on the expected inertia conditions, and sufficiency is monitored in real time [70]. Up to 60% of RRS can be provided from load resources. There is a maximum on how much RRS can be provided from FFR and the minimum amount of RRS that should come from resources providing RRS through droop response. Requirements for RRS take the efficiency of faster resources into account. This allows the overall reduction in the required RRS based on inertia conditions and the number of faster resources providing RRS. Additionally, all generators in ERCOT (including wind, solar, and battery storage) are required to have a frequency containment capability enabled with a 17 mHz deadband and maximum 5% droop, and must provide a frequency response during disturbances, if they have headroom/legroom. This provides an additional frequency containment safety net for the ERCOT grid, considering that it is not synchronously interconnected with the rest of the U.S. Note that capacity reservation is not required unless a resource is providing RRS.

Future: For the past two years, the provision of RRS from batteries through droop-type response has increased dramatically. While synchronous generators are providing frequency containment with a 4–5% droop, batteries can provide frequency response with as low as a 1% droop. ERCOT is currently investigating if there are any reliability issues with larger amounts of batteries responding with a 1% droop, or if there are locational limitations, especially in weak grid areas with high concentrations of IBR.

3.4.6. Frequency Restoration Reserves

Today: Frequency restoration reserves (called Regulation in ERCOT) are deployed through the automatic generation control (AGC) system every 4 s based on an ACE calculation for the entire interconnection. Regulation reserve requirements are sized based on the 95th percentile of historically observed (in the past 2 years) 5 min net load variability, and adjusted to account for variability from newly installed wind and solar resources. The reserve amounts vary based on month and time of day. A portion of the Regulation reserve is provided by batteries as the so-called Fast Responding Regulation (FRR). Resources providing FRR receive a separate deployment signal from AGC and respond with full capacity for deeper frequency events ($\pm$0.9 Hz deviation from nominal frequency), based on local frequency measurement, within 1 s.

Future: no significant changes are currently anticipated for the Regulation service.

3.4.7. Replacement Reserves

Today: Replacement reserves (called Non-Spinning Reserve in ERCOT) are primarily provided from the offline capacity of units with start-up times of up to 30 min. A large fraction of these reserves is currently provided by quick-start combustion turbines with start-up times of 10 min. Reserves are dimensioned based on the 85th to 95th percentile of historically observed (in the past 3 years) 6 h ahead hourly net load forecast errors, and adjusted to account for forecast uncertainty from newly installed wind and solar resources. The procured reserve amounts vary based on the month and time of day. ERCOT selects a higher percentile of net load forecast error during times with the risk of high net load ramps.

Future: the methodology for the Non-Spinning Reserve may change in the future with the introduction of the ERCOT Contingency Reserve Service.

3.4.8. Ramping Products

Today: A new service called the ERCOT Contingency Reserve Service (ECRS) has recently been introduced [71]. ECRS is provided from capacity that can be deployed within 10 min after receiving the deployment instruction and can be sustained at a specified level for two consecutive hours. ECRS may be deployed to help restore frequency to 60 Hz within 10 min of significant frequency deviation, provide energy upon detection of insufficient capacity to follow net load ramps, provide energy to avoid or during an energy emergency, and provide backup for Regulation Up. ECRS requirements are dimensioned based on the sum of capacity needed to recover frequency following a large unit trip and the capacity needed to support sustained net load ramps. The latter component is determined based on historically observed 30 min ahead net load forecast errors. Higher amounts are procured during times when the periods of net load risk are the highest.

Future: This reserve has just recently been introduced. Adjustments to the methodology determining the amounts of this reserve may be made in the future.

3.4.9. Balancing Technologies

Today: All requirements for balancing services are defined in a technology-agnostic manner. However, due to the specifications of some services, these can only be provided by resources with the required capabilities. For example, FFR can only be provided with resources capable of providing a full response within 0.25 s, which makes batteries prime candidates for this service. Inverter-based resources theoretically can participate in any of these services; however, it requires capacity reservation and will result in a loss of revenue from the energy market for wind and solar resources. Conventional synchronous generators can provide any of the existing services except for FFR. The new ECRS service is more suitable for quick-start units and faster ramping generation. Shorter-duration batteries cannot participate in ECRS due to stringent duration requirements.

Future: As the build-out of IBRs continues in ERCOT, it is possible that in the future, it will make economic sense for wind and solar to participate in balancing services. Additionally, a number of hybrid projects are being built (primarily batteries co-located with solar plants). These hybrid resources are likely to optimize the revenue they can make from the combination of energy and balancing service markets.

3.5. Central European System

3.5.1. System

In general, the electrical grid of continental Europe, formerly known as the UCTE grid, is the largest synchronous grid in the world. In the present section, the focus lies on the central part of the continental European grid with a specific focus on the national grids of Germany and the Netherlands.

Today: In Germany in 2022, the net installed electricity generation amounts to about 225 GW, of which around 65% can be assigned to VRE (~5 GW hydro run-of-river, ~9.5 GW biomass, ~58 GW wind onshore, ~8 GW wind offshore, and ~66 GW PV) [72]. In the same year, about 49.8% (~244 TWh) of the public net electricity generation came from VRE technologies. Half of this was provided by wind energy, representing the largest share in the German energy mix. Regarding the conventional generation, the largest share (~22%) comes from lignite followed by hard coal (~11%) and fossil gas (~9%). It is worth noting that the large VRE share and missing storage systems have a high impact on the German balancing mechanism. In the Netherlands, the final electricity demand in 2021 amounted to 117 GW [73]. The gross installed electricity generation in 2021 was about 47 GW of which about 48% was VRE (14.9 GW solar PV, 5.3 GW wind onshore, and 2.5 GW wind offshore). VRE production was about 24% of total electricity production in 2021 [74]. Installed VRE capacity increased from 22.7 GW in 2021 toward 27.5 GW by the end of 2022 (18.8 GW solar PV, 6.2 GW wind onshore, and 2.5 GW wind offshore) [75].

Future: Despite a stronger focus on energy efficiency and saving, the German government assumes an increased demand for electricity of around 750 TWh up to 2030 (484 TWh in 2022), due to the electrification of industrial processes, heat generation, and transport. Eighty percent of this should be provided by VRE in 2030. To meet this targeted goal, large expansions of wind (up to 115 GW onshore and 30 GW offshore) and solar (up to 215 GW) energy are aimed. Moreover, the nuclear phase-out should be implemented by April 2023, as well as the coal phase-out by 2038. Consequently, the challenges for research and development of innovative balancing mechanisms will further increase. Given the current Dutch national emission reduction goal of at least −55% by 2030 compared to 1990, the shares of VRE, as well as electricity demand due to electrification, are likely to increase very significantly. Recent scenarios from network operators for 2024 national investment plans envisage that solar-PV increases to 42–76 GW in 2030, wind offshore to 21.5 GW, and wind onshore to 8–10 GW [76]. Electricity demand is estimated to increase to 170–233 TWh by 2030. This will have a major impact on the demand for flexibility in the balancing market.

3.5.2. Balancing Principles

Today: The energy balancing process within the German control zones corresponds to the day-ahead and intraday trading activities performed by BRPs, as described for the Nordic system. A difference is that there is only one price zone over Germany. Moreover, there is a further redispatch process that supports trading activities with a focus on clearing grid congestions close to real time. Before October 2021, only large conventional power plants > 10 MW were used within the redispatch process. The remaining congestions (often caused by wind power in the northern part of Germany) were solved by an additional "emergency" feed-in management, which mainly reduced the feed-in of wind turbines in real time. These reductions have to be balanced by further reserve power within the continuous balancing process [77]. The German continuous balancing process is based on a multi-stage mechanism that essentially takes the standard European services FCR, aFRR, and mFRR services into account. For some years, the four German TSOs have been cooperating within the so-called "Netzregelverbund" with the aim of (1) cost-optimizing aFRR and mFRR, (2) a joint reserve dimensioning, and (3) a joint tendering process for reserve power. This process led to a significant reduction in operated reserve power compared to individual balancing processes within the four control zones [6]. Besides FCR, aFRR, and mFRR, the German TSOs are able to use further measures in the case of particularly high imbalances. These include, in particular, the exchange of emergency reserves with other TSOs, the use of interruptible loads, or the execution of trading transactions for the system balance. These additional measures are selected based on the current availability. The dimensioning of the required emergency reserve power plant capacity is based on a yearly system analysis that has to be carried out by the German TSOs, and that is stipulated by the German Netzreserveverordnung [78].

The Netherlands consists of one control area. Following market coupling, day-ahead and intraday markets are organized and cleared in the same way as in other continental European countries such as Germany. It also means that a portfolio-based self-dispatching model is applied, which implies that market participants are responsible for the unit commitment and dispatch of aggregated generation and demand facilities. This allows market participants to decide for themselves which power plants are reserved for the provision of energy and which for the provision of reserve capacity. The process after the closure of the intraday market is different though; the TSO applies a reactive activation strategy that incentivizes BRPs to help to restore the system balance and activates balancing energy only to counteract residual imbalances in real time. Consequently, the TSO gives market participants a great deal of flexibility to adjust energy programs right up until close to real time in order to limit the need for the TSO to activate balancing ('passive balancing'). To this aim, the TSO publishes information about the system balance (balance-delta, activated amount of balancing energy, and pricing information of activated bids) on a real-time basis, in order to stimulate market participants to also react in real time to reduce the system imbalance. The balance-delta represents the sum of the reaction required by frequency control from BSPs (by means of the frequency-capacity regulation) [79], and is published every minute (with a 2 min delay) on the website of TSO TenneT. This helps BSPs with commitments in light of coupled heat- or process-driven production or demand to provide their flexibility in real time to the balancing market, without having to bind themselves contractually ahead of time [80]. BSPs are thus allowed to make balancing energy bids without a capacity contract (called 'free bids'). In addition, BRPs are being paid (assuming positive imbalance prices) for deviating from their day-ahead portfolio schedules and increasing their imbalance as long as this reduces the overall system imbalance. An imbalance is usually settled with single imbalance prices, which are independent of the direction of the imbalance. This means that a negative imbalance (less production or greater consumption than planned) is not penalized more than a positive imbalance [81]. However, in case the imbalance within one settlement period changes from positive to negative (or vice versa), a single imbalance price would provide adverse incentives. Hence, dual imbalance pricing is applied when both upward and downward reserves are activated.

Future: Since October 2021, the process redispatch 2.0 has been in operation, which obliges all generation systems (also VRE generation) with capacities > 100 kW to participate within the redispatch. One aim of this updated process is to reduce the expensive real-time down-regulations, leading to additional reserve power that is only needed for the balancing of these down-regulations. The redispatch 2.0 process is still in the starting phase; i.e., further reductions in VRE-induced reserve requirements will be expected. Moreover, more intensive European cooperation within IGCC, PICASSO, MARI, and joint FCR bidding processes, as well as further bilateral cooperation between neighboring countries, will have significant impacts on the central European balancing processes.

Potential: The EU regulator ACER wants to divide Germany into several electricity price zones to better reflect the physical realities of the regional electricity grid. A possible configuration is currently still under discussion. However, its implementation will have an enormous influence on the development of the German generation and consumption landscape and, thus, also on the balancing mechanism. Moreover, there are still some German projects with a focus on the utilization of flexibilities of smaller-scale generation and load facilities, such as heat pumps, PV-storage systems, and electric vehicles. Such flexibilities should be usable within the extended process redispatch 3.0, leading to further reductions in reserve power. The development of a secure and data protection-compliant IT infrastructure, of established automatable processes to control millions of facilities, and of attractive incentive systems or markets is currently the big challenge. Moreover, movement of the intraday market GCT closer to real time would lead to a further reduction in the need for balancing services.

3.5.3. Inertial Response

Today: The inertial response is an inherent property of the electricity supply system. In Germany, there are no market-based procurements of such a balancing service. This holds for nearly all countries in continental Europe, except for Italy, Romania, and Slovenia [82].

Future: On the one hand, there are several studies analyzing the impact of a decreasing inertial response on system security due to the decommissioning of conventional power. However, on the other hand, there are many promising studies evaluating the potential of inverter-based VRE technologies to an provide initial response. Additional markets for inertial response services are currently not in discussion in Germany.

3.5.4. Fast Frequency Response

Today: In Germany, there are no explicit balancing services between inertial response and frequency containment reserves. This holds for nearly all countries in continental Europe, except for Italy, Romania, and Slovenia [82].

Future: Currently there are no specific plans to establish dimensioning processes and markets for FFR services. With a focus on a general decrease in the initial response and a further installation of VRE, FFR services will presumably gain in importance. Battery Energy Storage Systems (BESS) have shown potential to provide FFR in the future.

3.5.5. Frequency Containment Reserves

Today: As in many other countries, FCR is the first German balancing power that is automatically activated in the case of a deviation of the grid frequency. In order to ensure a rapid effect and to keep the contribution by each involved unit as low as possible, the FCR is activated unselectively (pro-rata) and in solidarity with the entire network system. In accordance with the regulations of the SOGL, an FCR of ±3000 MW must currently be available for the continental European synchronous network [27]. In 2022, about 555 MW FCR was tendered in Germany [83]. For France, the Netherlands, and Belgium, respectively, 489 MW, 116 MW, and 86 MW of FCR balancing capacity were procured. FCR, but also aFRR and mFRR services, is traded on the Internet platform www.regelleistung.net (accessed on 4 May 2023) hosted by the four German TSOs. It should be noted that TSOs from Belgium, France, Netherlands, Austria, Switzerland, West Denmark, Slovenia, and Germany jointly tender FCRs on this platform. Participation in the platform is not mandatory since it is a voluntary TSO cooperation, outside of the scope of Regulation (EU) 2017/2195 [84]. It is worth noting that each country has to order a core share in their home country. In 2022, the core share amounted to 167 MW in Germany, 147 MW in France, 35 MW in the Netherlands, and 26 MW in Belgium [85]. Since 2020, the auction of FCR takes place every day with a gate closure time at D-1, 8 am. The duration of the FCR services is 4 h. FCR is a symmetric service. The minimum offer size for FCR is 1 MW. The remuneration is based on marginal pricing allocation, with one settlement price per MW for the awarded bids for the balancing service duration of 4 h. Settlement prices may differ though for the core share to be procured in the home country and the share that can be procured cross-border. In Germany, an installed generation capacity of about 7 GW (mostly hydro) has been prequalified for the provision of FCR.

Future: Currently the FCR market in Germany is sufficiently liquid; i.e., there is no negative impact on the security of supply. Moreover, several large battery storage systems are currently under construction. It is expected that these systems will place additional offers at the FCR market, which could lead to a potential extended export volume of FCR in the case of low prices and, hence, to lower local marginal prices in Germany.

3.5.6. Frequency Restoration Reserves

Today: As in other continental European countries, the German FRR services include the automatically activated aFRR, as well as the mFRR that has to be activated manually. Both services are asymmetric and traded via the Internet platform www.regelleistung.net (accessed on 4 May 2023) across the four German control areas. In 2020, the balancing energy market was introduced in addition to the balancing capacity market with a separate procurement of balancing capacity and balancing energy. At the end of the tendering of balancing capacity, the reserve providers can adjust the accepted bids and/or can offer new bids. This results in a new merit order list (MOL) for the TSOs to call up after each Gate Closure Time (GCT) at the balancing energy market. The minimum offer capacity is 1 MW for both balancing services. The GCTs on the balancing capacity market are every day D-1 9 am for aFRR and D-1 10 am for mFRR. The GCT of the subsequent balancing energy market is each day 25 min before the start of delivery for both FRR services. Regarding the balancing capacity market, there are six time slices with balancing service lengths of 4 h. The FRR activation is primarily cost-optimal according to the merit order list. The products are described in detail at www.regelleistung.net (accessed on 4 May 2023). Regarding aFRR, there is a joint tender process between Germany and Austria with the aim of cost-optimization of aFRR operation. In 2022, three major innovations were implemented: (1) the German TSO joined PICASSO and MARI for aFRR and mFRR cost-optimization, respectively; (2) the balancing service duration on the balancing energy market was reduced to 15 min; and (3) the remuneration of all FRR services was implemented as pay-as-cleared. With respect to the dimensioning of aFRR and mFRR, there are fewer requirements from ENTSO-E. In 2019, the German TSOs revised the procedure for determining the need for FRR in order to be able to adapt the FRR needs to the present situation. The previous static dimensioning method, which was used to determine a reserve capacity requirement that was constant over a longer period of time (in practice one quarter), was replaced by a dynamic dimensioning method [86]. The dimensioning is designed in such a way that the German TSOs will always be able to correct imbalances caused in Germany, independently.

In the Netherlands, the standard balancing energy services aFRR and mFRR are in place. TSO TenneT NL requested a derogation for joining both the PICASSO platform for aFRR and the MARI platform for mFRR until July 2024 since the replacement of the current EMS/SCADA is a prerequisite to connect to these platforms. The derogation was granted by the Dutch national regulatory agency (NRA). Hence, FRR procurement and the activation of balancing energy still take place nationally. For the national scheme, BSPs that produce or consume more than 60 MW are obliged to bid their capacity of available production/consumption flexibility to TSO TenneT on a day-ahead basis. Bidding is voluntary for market participants with generation and demand facilities smaller than 60 MW. The minimum bid sizes for aFRR and mFRR capacity are 1 MW and 20 MW, respectively. The corresponding full activation times are 5 and 15 min, respectively. The affiliate can adjust the magnitude (by a minimum of 1 MW) as well as the price of his energy bid until an hour before the imbalance settlement period (ISP) of 15 min, to which the adjustments pertain [79]. The bids are ranked on a local merit order list given price and direction. Bids to regulate downward are depicted on the left side of the bid ladder, and bids to regulate upward on the right. The position of the bid on the bid ladder determines whether the TSO calls the bid. Contracted BSPs receive capacity compensation for making capacity available, and if activated, the marginal energy price. Generators, demand-side response, batteries, pump storage, and distributed generation can be BSP. Concerning FRR dimensioning, following [27], both deterministic and probabilistic dimensioning methods are allowed, and the required FRR capacity is determined based upon the method that shows the highest capacity requirement.

Future: Since the go-live of PICASSO and MARI was recently (in the second half of 2022), there is still potential for further improvements, also with a focus on the first-time connection of other countries. The German dynamic dimensioning process is currently based exclusively on daily properties. This means that, in particular, the imbalances in the previous weeks and periods of the previous year (reference periods) have an impact on the dynamic dimensioning results. Deviations from the tendered quantities and the actual requirements are always possible, since the tendered quantities must take into account all expected balance deviations, but the imbalances in the reference periods can vary greatly. With the future planned consideration of external influencing factors such as wind and solar power in addition to the daily properties, the tendered control reserve should fit the needs even better in the future. Improvements in the platforms are applicable to all countries that join the platforms. For the Netherlands, it is expected that the largest reference incident for deterministic dimensioning of upward aFRR will increase from the current 1.3 to 2 GW by 2030 [87]. This relates to the new 2 GW cables for the connection of offshore wind parks to the onshore grid. For downward aFRR, based upon the application of the probabilistic dimensioning method, TSO TenneT deems an increase to 1.8 GW possible.

3.5.7. Replacement Reserves

Today: In continental Europe, in addition to the FCR, aFRR, and mFRR, there are often additional replacement reserves (RR) in operation. These are not taken into account in Germany. Given the reactive TSO activation strategy, which rests upon a relatively large proportion of fast reserves (mainly automatic FRR) with a shorter activation time before provision than replacement reserves (RR), RR is also not in place in the Netherlands.

Future: There are currently no German plans for establishing additional RR or to join international cooperation such as the Trans European Replacement Reserves Exchange (TERRE). The Netherlands does also not intend to join the voluntary European TERRE platform for RR.

3.5.8. Ramping Products

Today: Currently, a ramping reserve is not a requirement in the German power system. Larger imbalances, such as during the solar eclipse in 2015, can be handled with the available operating generation and demand capacity [88]. The full activation time (FAT) with the associated ramping requirement is part of the standard balancing market services for aFRR, mFRR, and RR. The FATs for standard aFRR, mFRR, and RR services are 5 min (by 18 December 2024), 12.5 min, and 30 min, respectively [89–91]. In the Netherlands, the TSO publishes information about the system balance on a real-time basis in order to stimulate BSPs to also react in real time to reduce the system imbalance and to achieve fast ramping. BSPs are thus allowed to make balancing energy bids without a capacity contract (called 'free bids').

Future: With focus on the growing electrification of the transport and heat sectors, simultaneous vehicle charging and the operation of heat pumps is likely. This is due to similar user behavior or electricity price-driven incentives. If not coordinated properly, this could lead to an increase in imbalances requiring special ramping products for peak times. This fact becomes even more important if controllable generation is missing. In case the FATs of one or more standard balancing energy services are deemed insufficient for fast enough ramping, a TSO may consider defining a specific balancing service. Specific balancing services must comply with the requirements of Article 26 of EC Regulation 2017/1295 [84]. Among others, a TSO needs to demonstrate 'that standard services are not sufficient to ensure operational security and to maintain the system balance efficiently or a demonstration that some balancing resources cannot participate in the balancing market through standard services'.

3.5.9. Balancing Technologies

Today: As required in SOGL, providers of reserve power must go through a prequalification process proving their technical ability for the reliable provision of the different reserve services. In addition to technical competence, a proper provision of the reserve services under operational conditions, as well as the economic performance of the potential provider, must be guaranteed. In Germany, the following balancing service-specific volumes have been prequalified (as of January 2023): FCR ~7 GW, aFRR ± ~24 GW, and mFRR ± 32 GW [92]. By far the largest share of all prequalified reserves is hydro power. Regarding FCR, battery storage systems are second. Regarding the FRR services, hydro is followed by natural gas, biomass, and brown coal. For the Netherlands, no prequalified installed capacity volumes are reported. TSO TenneT states though that there are currently around 25 BSPs accredited, and around 100 BRPs, of which around 40 serve connections. There is also considerable and increasing interest from market participants with VRE (mainly wind farms) and batteries to participate in the FCR and aFRR markets [93]. The aggregation of diverse sources including VRE and demand response is allowed. Several pilots have been carried out to enable the participation of smaller-scale assets, VRE technologies, and demand response in the provision of aFRR. This included the participation of wind turbines, batteries, solar parks, CHPs, heat pumps, and electric vehicles. Following the pilots, four of the seven pilot partners were prequalified as BSP at the time the report was published (July 2021) [94].

Future: In Germany, there are several large battery storage systems under construction. Such systems are economically very attractive to provide FCR and already have a comparable high market share in the German FCR market. With a focus on the lack of gas, and also on the planned coal phaseout by 2038, both these technologies will definitely leave the reserve market in the future. Moreover, it is difficult to estimate when wind turbines and PV will enter the FRR markets in Germany. Both technologies have already passed prequalification tests successfully, but, currently, it is not economically attractive for them compared to other trading options.

3.6. Great Britain

3.6.1. System

The Great Britain synchronous system includes Scotland, England, and Wales. The system is operated by National Grid Electricity System Operator, here referred to as the TSO, responsible for maintaining system balancing.

Today: In 2022, fossil fuels, mainly gas, contributed to around 43.7% of electricity generation, while renewables (solar, wind, and hydro) 34.9%, and others, including nuclear, 22.7%. GB's net export was about 1.3% [95]. The GB system has 6 GW of interconnector capacity to Northern Ireland, the Republic of Ireland, France, the Netherlands, and Belgium, where the energy and balancing services can be exchanged.

Future: The ambition is to fully decarbonize electricity by 2035 by replacing fossil fuels with renewables and other low-carbon technologies such as hydrogen-based power plants, and nuclear, with some continued use of fossil gas but with carbon capture and storage. By 2050, the target is to achieve net-zero emissions across all energy sectors. Electrification and hydrogen applications will be deployed to decarbonize heat, transport, and other sectors. A substantial increase in electricity load is expected, the electricity load (currently around 300 TWh yearly demand) will be doubled by 2050, requiring more than 100 GW of variable renewable sources to meet this demand. It is envisaged that renewables will meet more than 70% of energy demand [96]. In addition, it is expected that the total capacity of interconnectors will increase to 12–20 GW, allowing a higher volume of energy and balancing services exchanges between GB and Europe.

3.6.2. Balancing Principles

Today: Under a self-dispatch system, buyers and sellers of electricity contracts ahead of time balance their positions in the forward, day-ahead, and intraday markets up to gate closure (currently 30 min ahead in real time). Their anticipated physical behaviors and contractual positions are communicated to the TSO. After the gate closure, the TSO is responsible for maintaining the system balance in real time by accepting the "bids" or "offers" in the Balancing Mechanism (BM) considering the detailed technical capabilities of BM Units (BMU). A bid is a price to consume more or generate less; an offer is a price to consume less or generate more electricity. The operation of the BM relies on the information exchanges between the TSO and BMUs, which happen in real time. The processes must comply with the Balancing and Settlement Code (BSC). Every half hour, the BM opens to new bids and offers.

Future: Demand for balancing services has increased substantially over the last ten years, driven by the increased capacity of variable RES connected to the GB system. In 2012, the average imbalance was only about 5% of national demand, while today, the balancing services regularly exceed 50% of national demand [97]. At present, the balancing relies mainly on gas power stations. This leads to a big concern that the cost of balancing will increase as electricity production from gas power stations is further displaced by renewable energy and gas prices are high, recently driven by the war in Ukraine. The future will require a more smart and flexible system that makes the best use of all energy and flexibility resources from different scales and technologies to support system balancing most efficiently and economically. The role and value of aggregated small/medium-scale distributed flexibility resources, especially from distributed generation, co-generation, flexible loads, and energy storages (such as electric vehicles, batteries, and thermal storage) to support the TSO and Distribution System Operator (DSO) systems, have started to be recognized. A more coordinated approach requiring more intensive interaction between TSO and DSO is needed to maximize the whole-system benefits of those flexibility assets. Stronger integration between gas and electricity system operation has also been recognized, leading to the joint recommendation from Ofgem and BEIS to create an independent Future System Operator (FSO) [98]. The FSO will be responsible for operating, strategic network planning, long-term forecasting, and developing a market strategy for gas (leading to hydrogen) and electricity systems to maximize their integration.

Potential: Most of the solutions proposed to address the future challenges are still based on a conventional centralized, coordinated approach, as the TSO or FSO will be responsible for balancing the national energy system. The increased share of flexibility provided at distribution levels may require some balancing actions to be distributed and autonomously exercised. These actions will be based on combined local and national system signals to inform the right operating decisions taken by individual balancing units. Machine learning algorithms and appropriate control or market signals could be developed to relieve the burden of centralized control for energy system balancing in different time scales [99].

3.6.3. Inertial Response

Today: The inertia in GB is provided by kinetic energy stored in the spinning part of synchronous machines, most of them thermal plants from gas, nuclear, and coal. Renewables such as wind and solar do not synchronize with the grid in a way that provides inertia. Inertia service is not paid, but TSO may need to synchronize marginal generators, e.g., through contractual services or BM, to provide system inertia. As thermal generators must operate above the Minimum Stable Generation level, the cost of providing inertia can be high, and the "unwanted energy" may lead to renewable curtailment if the system does not have sufficient demand.

Future: New approaches have been trialed based on modifying existing, or building new, assets, to provide stability (inertia) services using less energy (or not produce electricity), simultaneously enabling reduced carbon emissions. This new approach allows more renewable generation to operate, ensuring system stability at a lower cost [100]. Emerging technologies such as grid-forming inverters can also support system stability and will be an integral technology as the system may run with 100% inverter-based generation technologies.

3.6.4. Fast Frequency Response

Today: There are mandatory and market-based frequency response services. All large power stations connected to the transmission network must provide Mandatory Frequency Response (MFR) capability as a condition of their Generation License to comply with the grid code [101]. Today, MFR is mainly provided by gas-fired power stations. MFR aims to maintain the frequency within statutory (±0.5 Hz) and operation limits (±0.2 Hz) by automatically adjusting the active power output in response to a frequency change according to droop characteristics. The primary response is provided within 10 s of an event, which can be sustained for a further 20 s. Other MFR services include (i) secondary response available within 30 s of an event and can be sustained for a further 30 min; and (ii) high-frequency response to reduce excess generation by reducing generation or increasing load—the service should be provided within 10 s of an event and can be sustained indefinitely. In addition to MFR, the Firm Frequency Response market creates opportunities for providers to offer their frequency response services to the TSO through a monthly tendering process. The Firm Frequency Response service can be dynamic or non-dynamic.

Future: The TSO will invite more wind participation, and has signaled solar generators for their future involvement in providing frequency response services. The contribution of battery energy storage systems (BESS) to provide fast or enhanced frequency response services also increases as it becomes the main revenue source for BESS.

3.6.5. Frequency Containment Reserves

Today: Dynamic Containment (DC) is a fast-acting post-fault market-based service to contain frequency within the statutory range of ±0.5 Hz in the event of a sudden demand or in-feed loss [102]. The service delivers quickly and proportionally to frequency but is only active when there is a frequency excursion (±0.2 Hz). A small linear delivery is considered between 0.015 and 0.2 Hz.

Future: Emerging technologies including smart appliances, smart EVs and Vehicle-to-Grid (V2G), and active buildings can provide fast responses to constrain frequency drift in addition to conventional solutions. Smart energy systems will dynamically differentiate the essential and non-essential loads and interrupt the supply of non-essential loads to respond against large frequency drops.

3.6.6. Frequency Restoration Reserves

Today: Dynamic Moderation (DM) is a market-based balancing service aiming to keep frequency within operational limits [103]. The service manages sudden imbalances between demand and generation, such as a wind forecast error, by responding swiftly when frequency moves toward the edge of the operational range. DM is a pre-fault service, with a speed of response of 1 s and a delivery range between ±0.1 and 0.2 Hz. Besides DM, there is also the Dynamic Regulation (DR) service, a pre-fault service designed to slowly correct continuous but small deviations in frequency. The aim is to regulate frequency around 50 Hz continually. DR's speed of response is 10 s with a delivery range between ± 0.015 and 0.2 Hz.

Future: As the imbalance increases, driven by variability in renewable output, technologies that operate by following renewable output, such as electrolyzers, are ideal to be developed in addition to BESS and demand response technologies, as discussed previously. The need for hydrogen and electricity integration has been recognized [104], and the UK government has doubled the hydrogen production target to 10 GW by 2030, with 50% from electrolyzers.

3.6.7. Replacement Reserves

Today: Fast reserve and short-term operating reserve (STOR) are market-based balancing services used to increase generation output or reduce consumption from demand sources to control frequency changes due to uncertainty in generation or demand [105]. To be eligible for providing fast reserve, the active power delivery must start within two minutes after the dispatch instruction, have a delivery rate of more than 25 MW/minute, and the service should be sustainable for a minimum of 15 min. While the response requirement for STOR is slower, i.e., 20 min, it should be sustainable for a longer period, i.e., a minimum of two hours with a recovery period of not more than 20 h. The minimum offer is 3 MW but can be aggregated from multiple sites.

Future: again, the role of demand response and energy storage technologies, including smart appliances and smart heating systems, is expected to increase to supplement the conventional operation reserve providers at the transmission level.

3.6.8. Ramping Products

Today: There are no specific ramping products in GB, as the ramping capability requirements are already considered and met in other balancing services. However, a ramping limitation is imposed on the interconnector to limit the impact on balancing capability requirements, as defined in the Grid Code (GC0154) [106].

Future: As GB is more interconnected to Europe with HVDC and the expected increase in battery storage or inverters, more resources are open for ramping services that can be procured to meet the system's needs. Other emerging technologies, such as electrolyzers and fuel cells, can also quickly change their electricity load or production, which is ideal for ramping services.

3.6.9. Balancing Technologies

Today: In GB, gas power stations and electricity storage (pumped hydro and battery storage) are the main providers of balancing services. There are also industrial and aggregated flexible load services, but they are still relatively small. Most balancing service providers are connected to the transmission network, directly controlled and visible by the TSO.

Future: More balancing services will come from distributed flexibility resources. Emerging technologies include smart appliances, smart homes/buildings, and smart EVs. All these technologies will provide more resources in the future to solve the increased balancing issues in different time frames more cost-effectively. In addition, the decarbonization of heat and transport sectors aligned with electricity decarbonization will create a stronger coupling between electricity, heat, and gas systems, allowing the exchange of flexibility across those energy vectors. This will enrich the range of flexibility technologies that can be used for system balancing. For example, excess renewable energy can be converted and stored in hydrogen, or otherwise curtailed. Hydrogen storage offers low-cost and low-losses bulk energy storage. Similarly, smart heating systems with heat storage can also provide flexibility to modulate heat-led electricity load to improve electricity system balancing.

4. Summary and Discussion

The challenges and solutions to continuous balancing at a high share of VRE in the six different systems from Section 3 are here summarized and discussed. A brief summary of the six systems, including the expected increase in VRE generation, future challenges with continuous balancing, measures to cope with these challenges, and today's and tomorrow's technologies used for continuous balancing, is provided in Table 1.

As can be seen in Table 1, the size of the studied systems, in terms of yearly electricity demand, varies from a relatively small system in Ireland to a very large system in Central Europe. The Nordic, Iberian, Texas, and British power systems are of relatively comparable size. However, the Iberian system is synchronously connected to the central European system, and hence they share the same challenges related to frequency balancing. All studied systems already have a significant share of VRE generation today, and except for Texas, emission reduction targets will drive an increase in VRE capacity in the coming 10–20 years. For all these systems, VRE is either expected to serve at least twice as large a share of the electricity demand as of today, or the installed VRE capacity is expected to at least increase threefold. In Texas, economic incentives are expected to drive a significant increase, especially in PV installations.

From Table 1, and the detailed descriptions in Section 3, it is clear that the challenges related to continuous balancing at a high share of VRE vary widely across the six systems. The reasons behind these variations can mainly be summarized by differences in system size, the technologies used/available in the system, as well as the established balancing principles of the system. Ireland and Texas represent systems that have already adopted a wide range of measures, such as introducing an inertia floor to ensure frequency stability, as they directly face the challenge of how best to cope with even larger shares of non-synchronous generation. The two systems share in common that the dimensioning incident is large in comparison to the size (inertia) of the system. Both systems are "centrally operated", with five-minute resolution real-time economic dispatch. This allows the uncertainty and variability associated with VRE generation to mainly be handled in the energy balancing stage. Hence, the main focus when designing balancing services is to incentivize as many resources as possible to handle disturbances and to incentivize the provision of inertial support. Of the six systems studied, Ireland and Texas currently face the largest challenge in maintaining a continuous balance, with the balancing mechanisms designed such that available assets can usefully contribute. In Great Britain, the main current concern relates to the increasing balancing costs following larger imbalances, given that most balancing is provided by gas-fired power stations. Low inertia levels have driven the curtailment of VRE generation, while large generators are mandated to provide a frequency response. In the presence of gas-fired power stations, these measures, in combination with markets for balancing services, have been sufficient for ensuring a continuous balance. However, being able to maintain a continuous balance, without relying as much on gas-fired power stations, at higher shares of VRE, is keenly acknowledged. This situation has strong similarities with the challenges currently faced by Ireland and Texas. In those systems, balancing principles and balancing services must be designed, as far as possible, for (all) available technologies to contribute. The Nordic, Iberian, and central European power systems currently do not face the same degree of challenges in keeping a continuous balance as the above systems. The Nordic system has introduced a fast frequency response service for frequency stability concerns, but no inertia floor has been implemented (deemed not to be needed). Due to the large size (and hence high inertia levels) of the continental European power system, minimum inertia levels, or fast frequency response services, are not needed, as frequency stability is not a major concern. Instead, the main challenge is to maintain the continuous balance in a cost-efficient manner as the electricity demand and VRE generation increase. Larger VRE generation capacity will increase the need for resources to maintain the continuous balance, as forecast errors and variability will lead to more frequent and larger imbalances. In Germany, VRE generation may also drive an increasing need for re-dispatch, to handle intra-zonal grid congestion, which, in turn, increases the need for reserves. The pan-European balancing energy activation platforms, MARI and PICASSO, should ensure the cost-optimal activation of balancing energy across continental Europe. Much current focus is directed toward making the existing balancing services compliant with the balancing services in these platforms. Meanwhile, balancing services must also be designed so that more technologies are eligible to provide low-cost balancing services.

Regarding technologies used for the provision of balancing services, hydro power currently plays an important role in systems with such resources. The expectation is that it will continue to do so. However, hydro power also plays an important role in energy balancing, and the provision of balancing services from non-hydro resources can increase hydro flexibility in the energy balancing stage. Systems with limited (or no) hydro resources mostly rely on fossil-fueled power plants for continuous balancing at present. So, as fossil-fueled power plants are gradually displaced (by renewables), there is also a question in terms of what will provide the balancing services in the future. The expectation is that flexibility on the demand side will provide a large share, especially in combination with storage technologies. The responsive loads could be large, e.g., industrial loads, flexible electrolyzers for hydrogen production, and data centers, as well as smaller distributed resources, e.g., EVs charging, battery storage, and heat pumps. Furthermore, hybrid resources, such as VRE generation in combination with storage, are expected to play an important future role. In Texas, loads incorporating an underfrequency relay have long since contributed to balancing services, while a specific regulation service for batteries has also been introduced. In the Irish system, ambitious targets for demand-side flexibility have been set out, with one specific focus being on large energy users, such as data centers. In Germany, large-scale battery storage is expected to play a key role in phasing out fossil-fueled generators. In the Netherlands, demand-side flexibility is stimulated through real-time communication of the balance-delta. In Great Britain, the need for TSO-DSO coordination is being discussed to ensure that full advantage from distributed flexible resources is achieved. VRE technologies are expected to increasingly contribute to balancing services, mainly in terms of down-regulating power and fast frequency response. In Spain, wind power is already the dominant down-regulating technology. The first step toward a larger contribution from VRE is to make such resources eligible for providing balancing services by designing the services to be technology agnostic, as in Texas. Both in the Nordic region and in Ireland, the frameworks for existing balancing services are being reviewed. In Portugal, it is expected that VRE resources will be allowed to provide balancing services in the coming years. In the Netherlands, the aFRR pilot projects have increased the participation of VRE technologies in continuous balancing. Meanwhile, the focus in Germany is on involving VRE generation as part of the re-dispatch process for the management of intra-zonal congestion. For VRE generation, it may be more economically viable to provide up-regulation following an increased buildout of VRE capacity. However, some systems, such as Ireland and Great Britain, see the need for VRE technologies contributing to balancing services. Hence, these systems are mandating VRE resources to be capable of providing certain reserves and system services. These requirements should be pursued through regulatory frameworks. Finally, to handle inertia scarcity at very high VRE generation shares, grid-forming inverter technologies are mentioned as a key solution in Texas, Ireland, and Great Britain. Fast frequency response from wind power and HVDC interconnectors are solutions being investigated in both the Nordic and the Irish power systems. In Texas and Ireland, synchronous condensers represent a potential alternative option to ensure sufficient inertia levels are maintained as synchronous generators are gradually being displaced. For the Irish power system, specific low-carbon inertia services are in the process of being procured by the TSOs.

Table 1. Summarizes the balancing challenges in the six different systems.

System	Current Yearly Demand	Expected VRE Increase	Main Future Challenge with Continuous Balancing	Measures to Cope with Balancing Challenges	Technologies for Balancing Today	Potential Future Balancing Technologies
Nordic synchronous area	~400 TWh	From 24 GW (23.5% of installed capacity) installed in 2020 to 123 GW (60.6% of installed capacity) in 2040.	Supporting Europe with balancing resources from hydro power, while VRE capacity increases fivefold and electricity demand is doubled.	Energy balancing with 15 min market time unit. Change technical requirements to make more technologies eligible for providing balancing services. Harmonize the balancing services with Europe for optimal activation of balancing energy. Defining the need for resources to ensure stable operations of own system with FFR and FCR-D products.	Mainly hydro power in Norway, Finland, and Sweden. Some thermal capacity in Finland and Sweden. Demand-side flexibility for FFR.	Flexible demand with storage such as EVs, batteries, district heating with thermal storage, and electrolyzers with hydrogen storage. VRE providing down-regulation services. Synthetic inertia from wind power and HVDC.
Island of Ireland	~40 TWh	From serving ~35% of electricity today to 80% in 2030.	Ensuring stable operation of the system at a higher system non-synchronous penetration level of 95% to enable increased VRE contribution and further HVDC interconnection.	Real-time unit commitment and five-minute real-time economic dispatch for energy balancing against close to real-time conditions. Lowering the inertia floor to reduce the need for online synchronous generators, and, instead, procuring low-carbon inertia services to support, for example, FFR. Reviewing arrangements for balancing services to make more technologies eligible to provide the services. Reviewing ramping products to handle wind forecast errors. Allowing higher ramp rates for HVDC interconnectors.	Traditionally gas- and coal-fired generators, as well as pumped hydro. HVDC interconnectors, batteries, and demand side beginning to contribute more.	Wind (and solar PV) power will contribute to a larger degree. Reserve requirements to be provided from zero-carbon technologies by 2023, including synchronous condensers and perhaps grid-forming inverters. Between 20 and 30% of demand should be flexible by 2030, supported by dynamic pricing, with a focus on data centers, but also EVs, heat pumps, and, perhaps, hydrogen production.

Table 1. *Cont.*

System	Current Yearly Demand	Expected VRE Increase	Main Future Challenge with Continuous Balancing	Measures to Cope with Balancing Challenges	Technologies for Balancing Today	Potential Future Balancing Technologies
ERCOT (Texas)	~390 TWh	Serving ~30% of electricity today, and expected to increase, although no formal target is set.	Ensuring stable operation of the power system with a high share of VRE while a spatial mismatch between generation and demand leads to binding transmission constraints.	Five-minute economic dispatch for energy balancing with near real-time conditions, co-optimized with procurement of balancing services. New FFR service to reduce inertia floor and allow higher share of VRE. Allowing loads (without droop-type response) to provide fast-acting balancing services to a large extent. Specific FRR service suitable for batteries Defining all balancing services in a technology-agnostic manner.	Demand side. Synchronous fossil-fuel fired generation. Batteries are contributing increasingly.	Synchronous condensers close to VRE generation are considered for inertia provision. Batteries will increase and they can provide all balancing services. Discussions of incentivizing grid-forming capabilities. VRE technologies can provide all balancing services, and it may make more economic sense with increased buildout. Specifically for hybrid resources such as PV co-located with battery storage.
Iberian peninsula	~300 TWh	From serving ~34% of electricity today to 87% in 2030 in Portugal. From 32% today to 74% in 2030 and 100% in 2050 in Spain.	Participating in the pan-European balancing platforms, while increasing shares of VRE may require balancing service provision from new technologies.	Normalize the Iberian balancing services such that they comply with the setup in other European countries. Cost-optimal activation of balancing energy through MARI and PICASSO, including 15 min resolution intraday market. Allowing VRE to provide balancing services (in Portugal).	Hydro (with and without pumped storage). Combined-cycle gas turbines. Wind power (in Spain). Thermal power. Solar (PV and thermal) starting to contribute in Spain.	Pumped hydro is expected to increase. VRE contributing more in Spain and will be allowed to contribute in Portugal. Batteries in households and EVs. Hybrid plants, e.g., solar thermal and thermal storage, or solar PV and batteries.

Table 1. *Cont.*

System	Current Yearly Demand	Expected VRE Increase	Main Future Challenge with Continuous Balancing	Measures to Cope with Balancing Challenges	Technologies for Balancing Today	Potential Future Balancing Technologies
Central Europe	>1200 TWh *	From 122 GW today to 360 GW in 2030 in Germany. From ~23 GW today to 71.5–107.5 GW in 2030 in the Netherlands.	Reducing costs of reserves following issues with increasing share of VRE. In Germany, the main issue is reserves needed to handle intra-zonal congestion. In the Netherlands, required aFRR capacity will increase toward 200 MW in 2030. The challenge remains to properly incentivize BRPs to keep system imbalance costs at a reasonable level.	Making smaller non-conventional generators participating in re-dispatch to manage German intra-zonal grid congestions. Dynamic dimensioning of frequency restoration reserves. Real-time communication of system balance-delta to give BRPs in the Netherlands incentive to reduce the system imbalance (not only their own imbalance). Pan-European platforms MARI and PICASSO will lead to cost-optimized reserve activation considering inter-zonal transmission limitations.	Hydro power, mainly in Germany. Batteries (for FCR) and conventional thermal generators (for FRR). Mainly gas-fired generation in the Netherlands. Some VRE and storage are prequalified to provide aFRR. Aggregated capacities of pre-qualified technologies are not published in the Netherlands	Large-scale battery storage in Germany. Distributed flexible resources such as heat pumps, EVs, and combines PV/storage. Coal- and gas-fired units are expected to be phased out from German reserve market. All sorts of resources are eligible to become BSPs in Europe generally.
Great Britain	~300 TWh	From serving 34.9% of demand today to 70% of demand in 2035. Expecting 100 GW additional capacity to be installed by 2035.	Keeping the costs of keeping continuous balance at a reasonable level when moving toward a zero-emission future.	Increasing TSO-DSO coordination as well as sector coupling with FSO role. Develop approaches to meet desired inertia levels without curtailing VRE. Mandatory frequency response (MFR) for large generators according to grid code; wind and solar power not participating today but have been signaled about future participation. Markets for balancing services in addition to MFR to give storage and demand-side flexibility incentives to contribute.	Mainly gas-fired power stations. Pumped hydro. Battery storage. Small share of demand response.	Variable and dispatchable renewable resources, as well as distributed flexible resources, are expected to replace the role of fossil-fuel-fired power plants. The latter include smart household appliances, batteries EVs, and buildings. Stronger sector coupling between electricity, heat, and gas will enable flexible hydrogen or heat storage. Grid-forming technologies for system stability when moving toward lower inertia levels.

* Aggregated electricity demand just in Belgium, France, Germany, and the Netherlands, in 2021.

5. Conclusions

To conclude, strategies for continuous balancing in power systems have been studied by describing the challenges and solutions implemented today, and anticipated in the future, for six different systems across Europe and the United States. All the studied systems are expecting to achieve very large shares of VRE generation within the coming decades. In detail, the potential future development of these systems, in terms of underlying characteristics, balancing principles, service arrangements, and the technologies used for continuous balancing, was described for each system. Various challenges and solutions to continuous balancing were then compared and discussed across the six systems. Subsequently, some important conclusions can be stated. Firstly, the challenges faced by the different systems, and the solutions adopted, vary quite noticeably. This indicates that there is no "one-solution-fits-all" approach to continuous balancing at high VRE shares. Instead, the challenges depend critically on the size of the system and its interconnection opportunities, the technologies available, and the underlying balancing principles. Secondly, for systems performing energy balancing with fine temporal granularity close to real time (such as Ireland and Texas), the major challenge for continuous balancing relates to frequency balancing at low inertia levels. For the other systems considered, the main focus, instead, relates to operating the system in the most cost-efficient manner. Of course, questions around cost, and attribution of cost, are also highly important in Ireland and Texas. Thirdly, there is a strive toward involving more technologies in contributing to continuous balancing. This is especially important for the systems where fossil-fuel-fired generation provides much of the existing (and historical) balancing services. Demand-side flexibility, VRE generation, and storage technologies, such as batteries, are expected to contribute to a much larger extent in the future. However, those measures, already taken and/or planned, to stimulate these technologies to participate in providing balancing services vary largely. Hence, it is highly likely that the different (and other) systems could benefit greatly from each other's experiences. This makes it important to understand the motivations behind the approaches taken and the decisions made. Finally, grid-forming technologies and synchronous condensers will likely play an important role for systems that, at times, will operate at (or near) 100% non-synchronous generation. Hence, it is important to develop mechanisms to stimulate investments in such resources, while also being agnostic to other, as yet unforeseen, technology solutions.

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