Deliverable Report

Electrical Grid Service Catalogue for Water Electrolyser

(D1.1)

www.qualygrids.eu

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Abbreviations and Indices

Abbreviation	Explanation
AC	Alternating Current
ACE	Area Control Error
AGC	Automatic Generator Control
AWE	Alkaline Water Electrolysis
BRP	Balancing Responsible Party
BSP	Balancing Service Provider
CEP	Clean Energy Partnership
DER	Distributed Energy Resources
DSO	Distribution System Operator
DSR	Demand Side Response
ENTSO-E	European Network of Transmission System Operators for Electricity
EMS	Energy Management System
FC	Fuel Cell
FCR	Frequency Containment Reserve
FCR-D	Frequency Containment Reserve - Disturbance
FCR-N	Frequency Containment Reserve - Normal
aFRR	Automatic Frequency Restoration Reserve
mFRR	Manual Frequency Restoration Reserve
FHA	Aragon Hydrogen Foundation
FLECH	Flexibility Clearing House
FRCE	Frequency Restoration Control Error
FRR	Frequency Restoration Reserve
GB	Great Britain
HRS	Hydrogen Refuelling Station
IHT	Industrie Haute Technology
LFC	Load Frequency Control
NEL	New NEL Hydrogen AS
PAE	Pressurized Alkaline Electrolyser
PEM	Proton exchange membrane
PQ	Power Quality
PSC	Performance Score Calculation
P2G	Power to Gas
P2P	Peer-to-peer
RES	Renewable Energy Sources
RR	Replacement Reserve
SCADA	Supervisory Control And Data Acquisition
SO	System Operator
SOE	Solid Oxide Electrolysis
STOR	Short Term Operating Reserve
STU	Schedule Time Unit
TSO	Transmission System Operator
UCTE	Union for the Co-ordination of Transmission of Electricity
VGU	Virtual Generation Unit
VPP	Virtual Power Plant
WE	Water Electrolyser

1 Summary

Water electrolysers (WEs), as a type of flexible demand, can offer a variety of electrical grid services provided that such trials are both technically and economically feasible. This report, serving as the first deliverable of QualyGridS aims at identifying the technical feasibility of using WEs for electrical grid services by using a survey-based approach. The surveys are conducted from the grid service perspective and the WEs perspective respectively, in order to derive preliminary matchmaking between the technical requirements of grid services and the technical abilities of the WEs. Below, a short summary of key contributions (C), findings (F) and recommendations (R) of this study is given

C.1 A comprehensive introduction to existing and potential electrical grid services and peer-to-peer services in the context of Europe's electrical system.
C.2 An in-depth description of the technical requirements for existing electrical grid balancing service products in 8 surveyed countries, i.e. Denmark, France, Germany, Netherlands, Norway, Spain, Switzerland and UK.
C.3 An overview of pre-qualification requirements for electrical grid balancing services in eight surveyed countries and the USA.
C.4 An overview of past and ongoing activities of exploring the potential of using WEs to provide grid services in Europe.
C.5 A survey of the technical characteristics at different operation modes for MW class Alkaline and PEM WEs from three different manufacturers.
C.6 An identification of the technical feasibility of using electrolysers for different electrical grid services in the context of the survey.
F.1 The grid services and the corresponding technical requirements are different in the surveyed countries. The difference is small for countries in the same synchronous area, but can be big for countries in different synchronous areas.
F.2 The catalogue of grid services and the corresponding technical requirements are maintained by grid operators. Updates could be made on regular basis according to the grid needs, the request of harmonization at the EU level and other reasons.
F.3 Distribution grid services and peer-to-peer services are emerging as promising trials run by different stakeholders in Europe, but are not available yet as market-based services.
F.4 The details of pre-qualification requirements among countries are not given at the same level. Countries like UK whose demand for balancing resources is high provide more accessible information than countries that already have sufficient amount of certified balancing resources.
F.5 MW class Alkaline and PEM WEs are in principle able to meet the technical requirements of almost all kinds of existing grid services, although this can be significantly influenced by the design of the units, the corresponding control systems and the business feasibility, etc.
F.6 KW-scale WEs also have the high potential of offering grid services either through tailored demand response programs or through the existing market places. In the latter case, aggregation is necessary. However, how to test the qualification of an aggregation-based portfolio with many units for providing grid services (especially the most critical grid services like FCR/aFRR) remains an open issue.
R.1 Because only three WEs units are surveyed to characterize the dyanmic abilities of WEs, there is a risk that the survey results may deviate from the average performance of WEs. It is recommended to enrich this survey by collecting more information from different WEs suppliers and users.
R.2 The identified service potential for WEs represents a general indicator. Whenever it is needed, users of the results shall take this as a starting point to build a more specific case-dependent analysis, such as relating it to using one specific WE unit for one service in one country.

R.3 Aggregating a number of WEs in one portfolio to offer grid or other kinds of services is worthwhile to be further investigated, especially in a future context if hydrogen becomes one of the essential energy carriers and enables the use of a massive amount of FC vehicles and P2G plants.

R.4 The potential of using WEs to avoid/minimize curtailments of renewables is very high, especially when this is done for a local grid/community. Although this is not yet a market-based service, such kind of P2P service can emerge very fast and shall be further investigated from both technical and economic perspectives.

R.5 The standardized testing protocol to be developed for testing the potential of using WEs to provide grid services shall be designed based on a scientific approach that can balance the country/regional differences in the requirements of pre-qualification tests. The desired approach shall also take into account that the technical requirements and also the performance indicators of grid services may change from time to time.

2 Introduction

Electrical grid services refer to a range of services requested by electrical grid operators to maintain a reliable and balanced electrical power system. Grid services are used to address imbalances between supply and demand, maintain a proper flow and direction of electricity, and help the system recover after a power system event. Conventionally, grid services are known as ancillary services which are primarily provided to the grid operators by big generation units and large-scale industrial loads either as an obligation or through an ancillary service market that normally have both bilateral agreements and auctions. Small/medium scale units are often excluded by grid operators since grid services have specific requirements on capacity, ramping, duration, location and auxiliary units for measurement, communication and control etc. With the increasing penetration of intermittent renewables and distributed energy resources (DER), the demand for ancillary services is extended to manage the increased variability and uncertainty of generation at different voltage levels and to avoid or delay network reinforcement. At the same time, the importance of using various DER technologies to provide ancillary service is increasingly recognized and facilitated by improved market designs and regulations.

A flexible load which can respond to reference signals by turning up or down can offer the same grid services as a generator turning down or up respectively. Water electrolysers (WEs), in addition to producing hydrogen, may be regarded as flexible electrical loads. WEs can offer a variety of electrical grid services provided that such trials are both technically and economically feasible. The flexibility resides in the capacity of WEs to be connected/disconnected/regulated when requested to do so by electrical grid operators. Although WEs are today only rarely designed for, or included in grid service provision, the potential of using WEs to provide grids services has been widely studied and researched as well as initially demonstrated in pilot projects in the EU. Realizing this potential will not only provide the grid operators with more options but also introduce clear business opportunities and added values to WEs and the associated hydrogen industry.

As illustrated in Figure 2-1, the QualyGridS project aims to establish standardized testing protocols for WEs to perform electrical grid services. Existing electrical grid services are evaluated regarding their detailed technical and economical requirements considering a variety of regions and countries in EU, Switzerland and Norway. Attention is also given to new grid services and regulations in the pipeline for those services that seem most promising testing protocols will be elaborated.

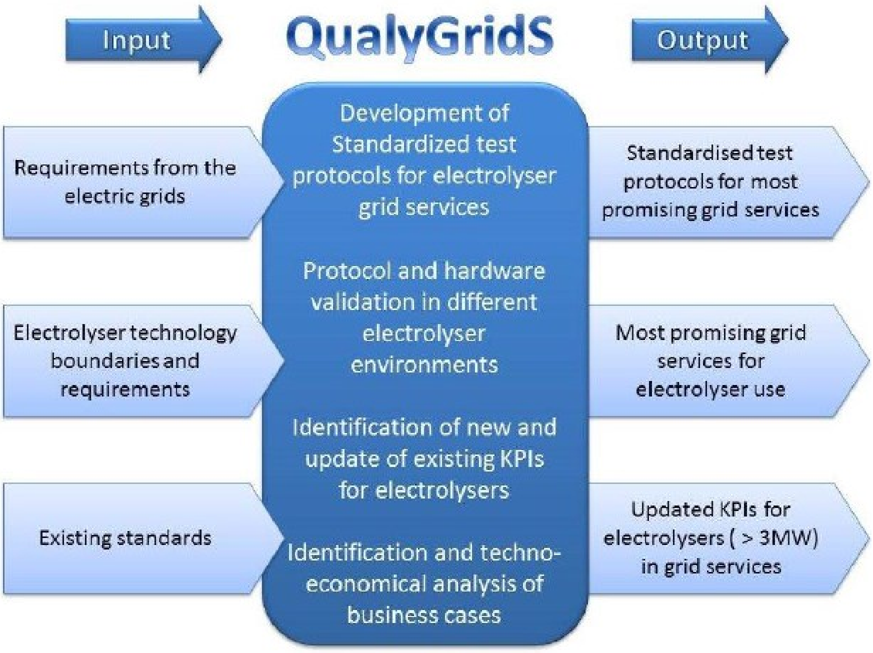

Figure 2-1: Concept of QualyGridS project with project inputs and expected outcomes

This report, serving as the first deliverable of QualyGridS aims at identifying the technical feasibility of using electrolyser for electrical grid services based on a preliminary matchmaking analysis that focuses on grid services requirements and the technical abilities of electrolysers. To achieve this target, three main studies were conducted.

In chapter 3, a comprehensive introduction to existing and potential electrical grid services and peer-to-peer services in the context of Europe's electrical system is given. Following this introduction, a review of electrical grid service requirements is presented for eight selected countries, i.e. Denmark, France, Germany, Netherlands, Norway, Spain, Switzerland and UK. The selected countries represent three synchronous areas, as shown in Figure 2-2. Each selected country is represented by at least one QualyGridS consortium member under the support of one member from the technical reference group, i.e., usually a grid company. This guarantees a high level of accuracy and temporal effectiveness of the information related to grid services that are presented in this report. In addition, the electricity sectors in the selected countries are relatively different, which results in different service catalogues and the associated technical requirements. For instance, countries like Denmark and Germany already have a high share of intermittent renewables and aim to achieve an extremely high level by 2050, therefore are in need of flexibility resources to address the associated challenges by offering grid services or other kinds of services; countries like Norway and Switzerland where there is a significant amount of hydro power, the need of flexibility is therefore not as much as Denmark and Germany; countries like UK and France are ahead of the other countries in terms of developing demand response solutions, which would provide a variety business potentials for WEs at different scales.

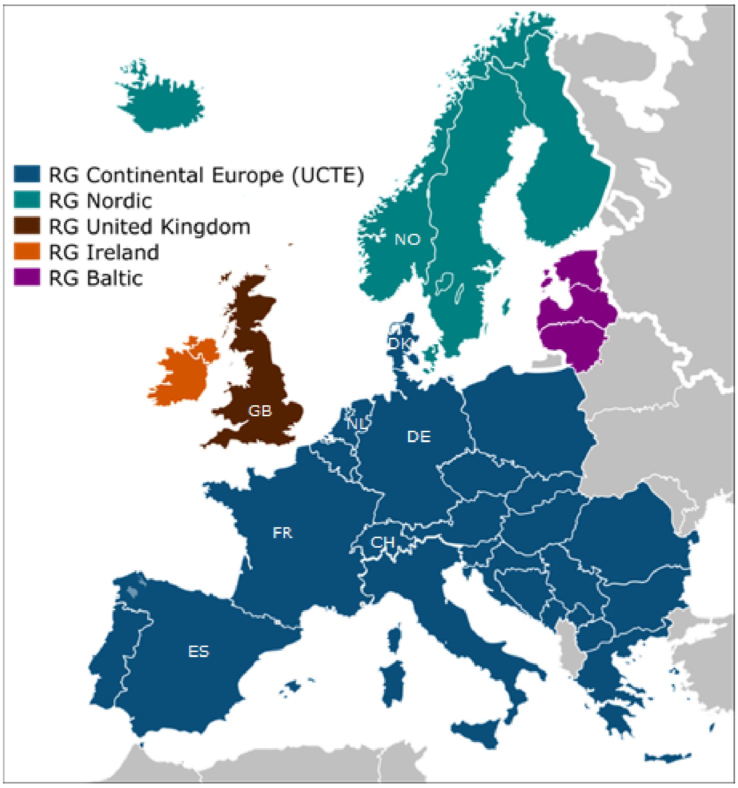

Figure 2-2: Countries (incl. selected EU member states, and Switzerland and Norway) for analyzing the technical requirements of various electrical grid services, the three investigated areas were: blue = UCTE, green = Nordic & brown = United Kingdom

Chapter 4 provides an overview of pre-qualification requirements for selected balancing services, i.e. FCR, aFRR, mFRR and RR, for the eight selected countries and two USA operators in PJM and California. Pre-qualification is a process whereby a grid operator makes an assessment of a service provider's ability against the technical requirements of targeted service. It is therefore a prerequisite for the participation in tendering procedures for services that are critically important, such as frequency control.

Chapter 5 firstly presents a state-of-the-art analysis of the technical abilities of different MW class WEs, i.e. Alkaline and PEM WEs, including an overview of recent project activities related to using WEs for grid services. Following this, the results achieved from a survey made for MW class WEs from three different manufacturers are given. The surveyed results cover the technical details at different operation modes of the surveyed units, therefore offering valuable information to support the work on identifying the most relevant services for WEs.

Concluding remarks and discussions are given in Chapter 6, and a number of surveyed information is included in the appendices.

3 Review of grid services and market structures

For a contemporary electric power system in Europe, as depicted in Figure 3-1 (in short called power system), electricity produced by bulk generators is transferred to end users through transmission and distribution networks, where grid operators are responsible for maintaining a safe and reliable power transfer from the production units to the end users. The power system is said to be vertically integrated. Normally, this combined responsibility is achieved through a number of integrated planning, operation and management functions (or services as termed in Figure 3-1. Some functions are either purchased through a market-based setup or procured based on obligations.

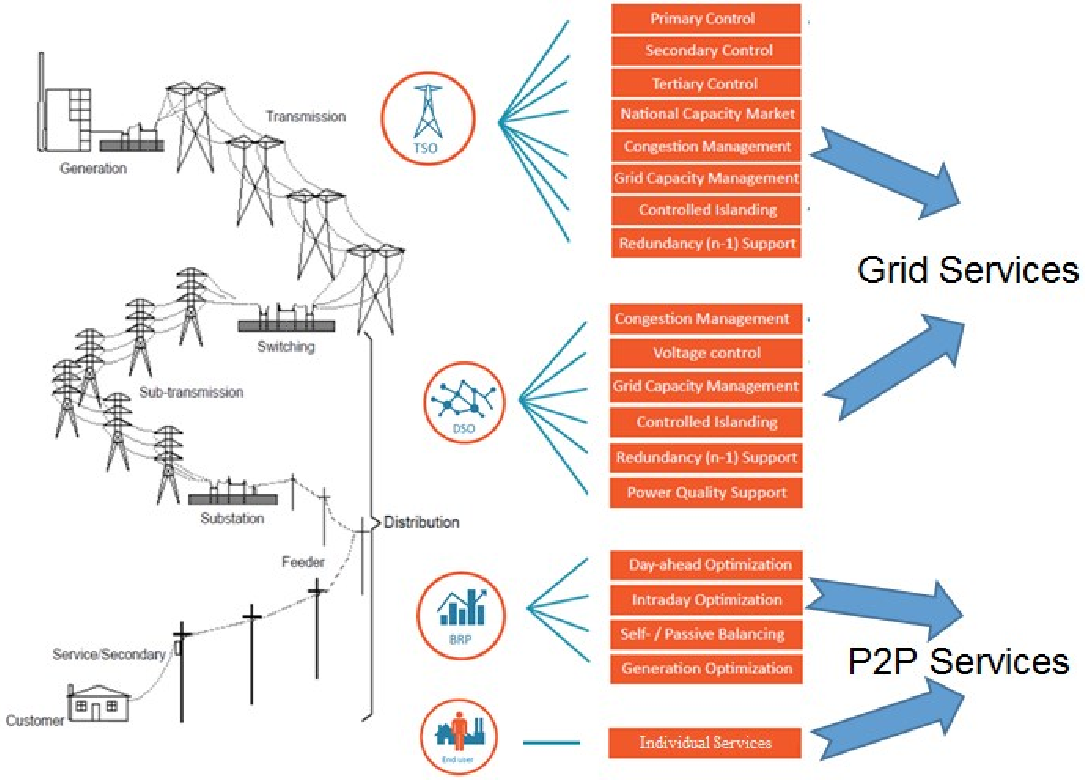

Figure 3-1: A schematic overview of services requested by grid operators & other stakeholders (e.g. BRP and end-users) in a modern power system, adapted from [1]

At the transmission level, many of these functions are referred as “ancillary services” (or grid services) and can be sourced by the Transmission System Operator (TSO) from an ancillary service provider (through a market) and are used to ensure that demand and supply are balanced in and near real time. These services normally include frequency response (to maintain system frequency with automatic/manual reserves, e.g. primary, secondary and tertiary); voltage control (by mandate or contracted reactive power support), capacity and congestion management (i.e. strategic reserves aim to increase the security of supply by organizing sufficient long-term peak and non-peak capacity), redundancy support (that provides emergency power, black-start capability and island capability). In Europe, using ancillary service market to maintain the security and reliability of the transmission grid has matured and allows for both public tendering and bilateral contracting. Today, new ancillary service products are being developed by individual TSOs from time to time to cope with emerging challenges led by the high penetration of intermittent renewables, such as inertia service and very fast reserve (to immediately respond to a power disturbance based on a supply-demand imbalance especially for grids with low inertia) and controlled islanding (to prevent supply interruption in a given grid section when a fault occurs in a section of the grid feeding into it).

Distribution System Operators (DSOs) responsible for a safe and reliable operation of the distribution network are also in need of a number of supporting functions to fulfil their obligation. Services requested by the DSO resemble to a large degree the services needed by the TSO, except that they are targeted to the local issues at medium/low voltage levels. Therefore, frequency support, a global service, is not needed by the DSO. Today, grid services for distribution networks are emerging because traditionally distribution systems are designed to operate passively. Existing service products are acquired through bilateral contracting. However, the techno-economic potential in obtaining grid services from distributed energy resources (DERs), third parties and end users (for increasing the flexibility of distribution network operation) is well-recognized by DSOs in Europe. Many pilot actions including developing a distribution grid ancillary service market have been tested and proved to be able to facilitate the integration of DERs.

In Europe the power system is deregulated and the power balance between consumption and production is to large extent facilitated through a liberalized electricity market. A major player on this market is a so-called balance responsible party (BRP), which may cover power sizes of the order GW and/or areas up to country size. The BRP may choose to further delegate to selected representatives/entities a local balance responsibility. Ahead of time a net balance is announced by the selected representative. The net balance need not amount to zero but deviations from the announced balance is penalized, e.g. by a proportional surcharge, the imbalance surcharge. BRPs and their selected representative announce their activity and balance based on forecasted production and consumption. A BRP may be an electricity producer, a major consumer, an electricity supplier, a trader or an aggregator involving more than one of these roles. BRPs are financially responsible for keeping their own position (sum of their production, consumption and trades) balanced over a given timeframe (the imbalance settlement period). Since BRPs rarely succeed maintaining a perfect balance between their forecasted generation/consumption and the real time value, trying to minimize the imbalance surcharges by coping with the shortage/surplus of energy is very necessary. This results in need of BRPs for additional flexibility options that can be used to improve key functions like day-ahead and intra-day trading, portfolio optimization and self-balancing etc.

Today, individual end-users/aggregators of end-users are also in need of services that can serve their individual needs. For instance, an owner of rooftop solar panels may need additional flexibility to consume the excessive power production to achieve a better economy. A wind farm owner might request flexible consumption/storage options to avoid being imposed curtailment. An aggregator of electric vehicles may need additional flexibility to meet his need of real-time balancing.

Services requested by BRPs and end-users are not considered as grid services (there are exceptions such as microgrids/islands/community-based power systems) because the requesters are rarely responsible for grid operation. In this report, the latter types of services are referred to as peer-to-peer (P2P) services where both parties, i.e., the service provider and the service receiver interact directly with each other without intermediation by a third-party (such as the grid operator). These types of services are currently emerging in different ways, following the transition of energy systems from centralized to a more decentralized system.

3.1 Overview of balancing services and market structures for the transmission grid

Balancing refers to the situation after markets have closed (gate closure) in which a TSO acts to ensure that demand is equal to supply, in and near real time. It is therefore the most important function that any TSO needs to have. In Europe, an important aspect of balancing is the approach to procuring various kind of balancing services from a balancing market, as illustrated in Figure 3-2.

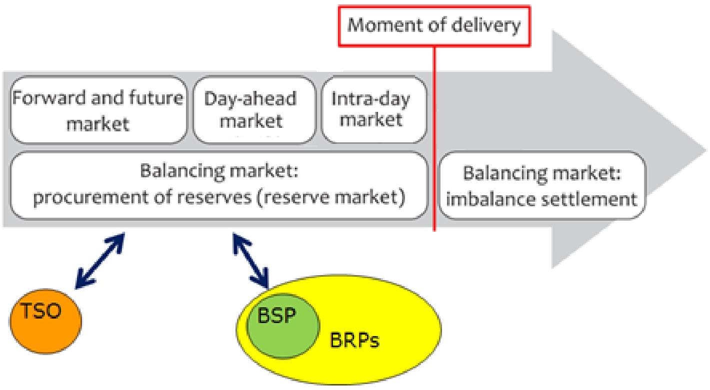

Figure 3-2: A schematic illustration of a typical balancing market setup in Europe

The balancing market normally consists of three main phases (balance planning, balancing service provision, and balance settlement) that concerns three main actors, i.e., the System Operator (SO) (normally a TSO), Balancing Service Providers (BSPs), and Balance Responsible Parties (BRPs). In the balance planning phase, BRPs submit energy schedules to the SO before delivery, stating planned energy generation and consumption for each schedule time unit (STU) within the day of delivery. In the balancing service provision phase, BSPs submit balancing service bids to the SO, which are procured by the SO in price order to secure the system balance. In the balance settlement phase, energy imbalances (schedule deviations) of BRPs and activated balancing energy are settled on a STU basis. BSPs who provided upward regulation receive the upward regulation price if marginal pricing is used, or the bid price in case of pay-as-bid pricing (euro/MWh). BSPs who provided downward regulation pay the downward regulation price, or the bid price. BRPs with a shortage pay the imbalance price for each MWh of deviation, and BRPs with a surplus receive the imbalance price[1].

Balancing services consist of two main types: balancing energy (the real-time adjustment of balancing resources to maintain the system balance) and balancing capacity (the contracted option to dispatch balancing energy during the contract period). Selected bids in the balancing capacity market are transferred to the balancing energy market. Furthermore, one can also differentiate between upward regulation and downward regulation, and between Frequency Containment Reserve (FCR), Frequency Regulation Reserve (FRR), and Replacement Reserve (RR), which vary in function and activation method. Efficient balancing markets ensure the security of supply at the least cost and can deliver environmental benefits by reducing the need for back-up generation.

Normally, balancing is understood as balance of active power on different time scales. There are also TSOs (such as National Grid in GB) who refer balancing services to comprehensive measures (including voltage control, redundancy support, etc.) applied to ensure the security and quality of electricity supply. Many ancillary services are designed to meet the purpose of balancing, therefore can also be understood as balancing services, although normally ancillary service products are procured from ancillary service market through tendering processes.

3.1.1 Grid services for frequency control

All modern electricity transmission systems are operated with alternating current (AC). The frequency of the current is a direct indicator for the total active power balancing in a synchronous area. The unbalance between generation and demand will result in a deviation from the Nominal Frequency. The gradient (the speed) of the frequency deviation is determined by the amount of kinetic energy stored and released by the synchronously connected rotating masses (Inertia) after a disturbance of the active power balance. To maintain a good quality of the frequency,

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[1] The imbalance settlement scheme implemented in different European countries can be different [41]; the philosophy behind them is similar as described here.

frequency control is developed as a set of services to ensure that the grid frequency stays within a specific range of the nominal frequency at any time. In Europe, a generic characterization of frequency control, as illustrated by Figure 3-3, is made by Network of Transmission System Operators for Electricity (ENTSO-E), where three frequency control services (FCR,FRR and RR) are operated in row at varying time scales for achieving different purposes [2].

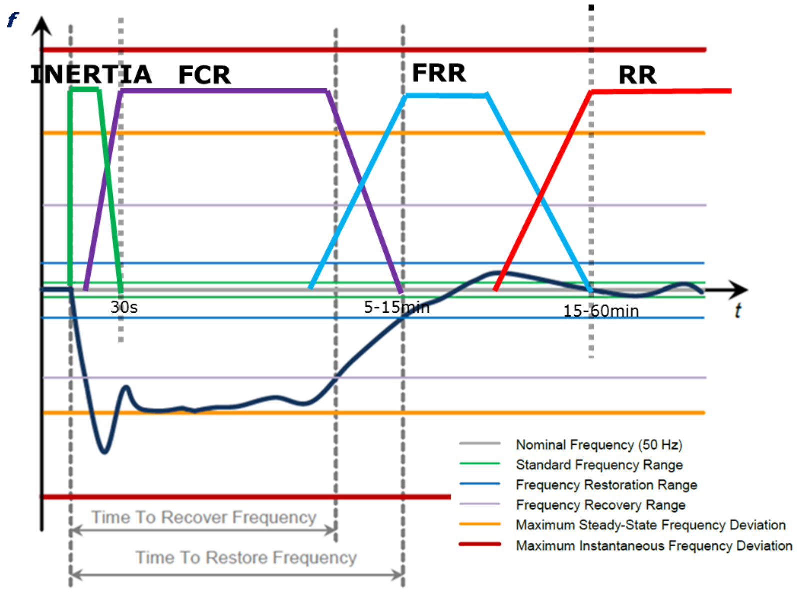


Figure 3-3: Frequency control services with approximate time scales

Frequency Containment Reserve (FCR), also referred as primary frequency reserve, is an automatic operating reserve designed to stabilize the power system frequency and make sure that the frequency will not further deviate from 50Hz. In many countries, FCR is mandatory for large capacity generators and is implemented using droop-based frequency controllers. These reserves have to be activated fast (typically within 30sec) and required to be online for a relatively short period (typically up to 15 minutes), the volume of the primary reserve is set by the ENTSO-E. The global reaction of FCR according to ENTSO-E regulations must be a symmetrical and linear activation with a total activation at a frequency deviation of ±200mHz [3]. However, in order to allow different types of flexibility (generation, demand, storage etc.) to participate in FCR, asymmetrical solutions (upwards/downwards) dedicated to specific frequency ranges (such as between -200mHz and -100mHz) are also implemented in some countries.

Frequency Restoration Reserve (FRR) is intended to replace FCR and restore the frequency to the target frequency, in Europe usually 50.00Hz. Two types of FRR are distinguished, i.e. automatic FRR (aFRR) and manual FRR (mFRR). aFRR is normally understood as the new terminology to replace secondary frequency reserve/load frequency control (LFC) and activated by using an electronic actuating signal/control set-point instructed by the TSO; while mFRR is often referred as fast tertiary frequency reserves that are dispatched remotely by TSOs through messages or phone calls. Both types of FRR are operating reserves used for restoring the power balance to the scheduled value and consequently the system frequency to the nominal value. Similar to FCR, the implementation of FRR also varies from country to country primarily due to historical reasons. Figure 3-4 presents an overview of ENTSO-E members that apply automatic Frequency Restoration Reserves. Regarding the technical requirements of FRR, there are differences on symmetrical/asymmetrical properties, activation time (normally between 30seconds and 15 minutes) and required duration, etc.

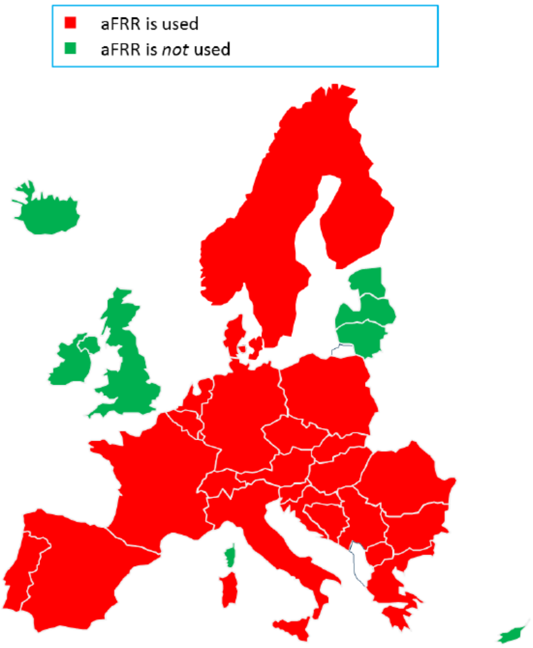


Figure 3-4: Overview of ENTSO-E members that apply automatic Frequency Restoration Reserves (aFRR) [4]

Replacement Reserve (RR), sometimes referred as slow tertiary reserves, is an optional manual reserve with an activation lead time normally exceeding 15minutes and may last up to hours. RR is used to restore the required level of operating reserves to be prepared for a further system imbalance.

In Table 3-1 an overview of the frequency control services applied in a number of selected EU member states together with Switzerland and Norway is given. It should be noted that terminologies like FCR, a/mFRR and RR are harmonized European terminologies to represent the fundamental principle of governing frequency control. Due to the structural differences among countries, the implementation of frequency control and the corresponding requirements can vary from country to country. The degree of this difference is normally small among countries within the same synchronous area, but can be significant among countries from different synchronous areas. For instance, FCR is often implemented as obligated primary control in the continental European system (UCTE); in Nordic area, FCR consists of two different services, i.e. FCR-D (f<49.90 Hz) and FCR-N (49.90<f<50.10 Hz), to provide frequency control to different conditions; in UK, in addition to Mandatory Frequency Response (MFR), the need FCR can be met by a combination of several additional service products i.e., Mandatory Frequency Response (MFR) Firm Frequency Reserve (FFR), Enhanced Frequency Reserve (EFR) and Frequency Control by Demand Management (FCDM). The implementation of aFRR (normally implemented by LFC) is another good example to show the divergence across synchronous areas. As a physical process computer that is implemented in the TSOs' control centre, LFC processes frequency restoration control error (FRCE) measurements and instructs LFC control signals through established communication links every 4-10s. On the continental Europe (UCTE), many LFC areas are defined with controller designed for each area, while in the Nordic synchronous area the four TSOs only apply one LFC controller for the entire synchronous area. Control wise, LFC control mode applied to UCTE is "Tie-line Bias Control" that each LFC controller controls its own FRCE and only indirectly the UCTE system frequency; while the LFC implemented in Nordic system directly impacts the Nordic system frequency.

Table 3-1 An overview of Frequency Control Services in selected EU member states and Switzerland and Norway

Country (Synchronous area)	**Frequency Control Services**			
	FCR	aFRR	mFRR	RR
CH (UCTE)	Primary control	Secondary control (LFC)	Tertiary control (positive and negative)	Tertiary control (negative)
DE(UCTE)	Primary control	Secondary control (LFC)	_	Tertiary control (minute reserve)
ES(UCTE)	Primary	Secondary (LFC)	-	Tertiary & interruptible loads
NL(UCTE)	Primary control	Regulating Reserve (contracted/non-contracted)	FAST tertiary control (reserve power balancing)	Slow Tertiary (Reserve power other purpose)
FR(UCTE)	FCR(Primary Reserve)	aFRR (Secondary reserve)	mFRR(Rapid reserve)	RR(Complementary reserve)&DSR-RR(Demand reserve)
DK-W(UCTE)	Primary reserve	aFRR(secondary reserve/LFC)	Manual reserve (regulating power)	-
DK-E(Nordic)	FCR-D/FCR-N	aFRR (Nordic LFC)	Manual reserve(regulating power)	-
NO(Nordic)	FCR-D/FCR-N	aFRR	Tertiary regulation (regulating power)	-
UK(United Kingdom)	MFR/FFR/FCDM/EFR	FFR/FCDM/EFR	Fast reserve	STOR/BM Start-up/Demand turn up

Although the requirements of different frequency control service products can be different, the shape of a standard balancing product is defined in Network Code Electricity Balancing article 29.5 as follow: “*The list of Standard Products for Balancing Capacity and Standard Products for Balancing Energy shall define at least the following standard characteristics of a bid by a fixed value or an appropriate range* [17]*:*

(a) Preparation Period: time required prior to start of delivery of the first MW;

(b) Ramping Period: time when the bid starts the physical activation, delivers the first MW and approaches the requested power of the TSO; expressed in seconds if the bid is not divisible and expressed in MW/s if the bid is divisible;

(c) Full Activation Time: the sum of Preparation Period and Ramping Period;

(d) Minimum and maximum quantity;

(e) Deactivation Period: the time from the start of physical deactivation of the unit until the full instruction MW has been delivered; expressed in seconds if the bid is not divisible and MW/s if the bid is divisible;

(f) Full Delivery Period: the sum of Ramping Period; Minimum and maximum duration of Delivery Period; and Deactivation Period;

(g) Validity Period: the period defined by a beginning time (hh:mm) and an ending time (hh:mm), when the bid could be activated. The Validity Period is at least the Full Delivery Period;

(h) Minimum and maximum Duration of Delivery Period: the period during which the bid delivers the requested MW.

(i) Mode of Activation: Manual/Automatic.”

This description of a standard balancing product could be illustrated by the hereafter figure,

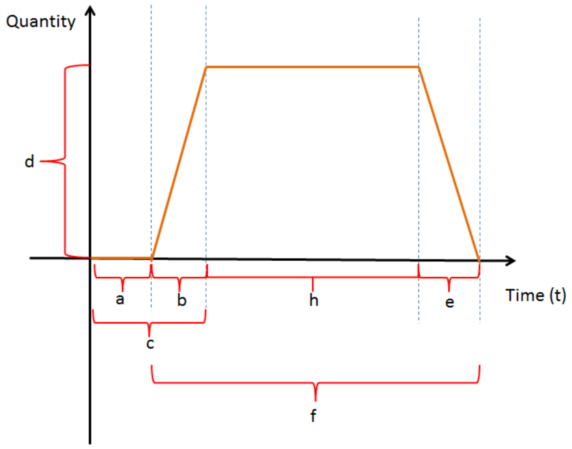


Figure 3-5: Standard description of any balancing product recommended by ENTSO-E

In Appendix-1, the characteristics of each frequency control service (i.e., FCR, aFRR, mFRR and RR) product implemented in the selected eight countries are provided in detail, together with a preliminary description of the methods for procurement/remuneration. Terminologies used by the TSOs to describe the frequency control services are slightly different from the standard characteristics due to the fact that harmonization of grid service description is an ongoing process. It is worth noting that in some cases, even the same terminology can be interpreted differently by different TSOs. For instance, the term “activation time” used by most TSOs refers to the preparation period, excluding the ramping period, while several TSOs refer the activation period as the “full activation time”. In practice, TSOs also implement several additional characteristics to better characterize a service product in order to meet their needs, such as,

(j) Dynamic/static: describes if a service is provided as a static fixed output or a continuous varying dynamic output. This term is only explicitly used by the TSO in UK, but implicitly used by many other TSOs.

(k) Symmetrical/asymmetrical: describes if the service product requires equal quantity of the service product at both upward and downward directions.

(l)Provider(s): specifies the technologies preferred to provide the corresponding service, such as generation, consumption, battery, etc. Today, technological portfolio developed as an aggregation of single/several different technologies is allowed by many TSOs to provide grid services as long as the aggregated performance is qualified.

Unlike the rest of the selected countries, services applied in UK for system balancing are more diversified as given in Appendix 1-5. Frequency control services defined by National Grid (i.e. the TSO in UK) primarily function as FCR and aFRR that react to frequency deviations at second level. Reserve products defined by National Grid complement the FCR and aFRR as slow operating reserves that can either restore frequency or replace fast operating reserves at time scales ranging from minutes to hours. Due to the decrease of balancing resources, several demand side services such as FCDM, STOR Runaway, and Demand turn up have been lately implemented to enable the use of demand side flexibility offered by individual or aggregation-based service providers. Meanwhile, the new frequency control service EFR that requires a very short response time (i.e. less than 1 second) is now market available for combating the decrease of system inertia.

System frequency is a continuously changing variable that is determined and controlled by the second-by-second (real time) balance between system demand and total generation in a synchronous area. Services products for frequency control therefore normally have no requirements on the service location. In contract, services, like voltage control and congestion management, which are used to address grid challenges in a specific area or location, the requirement on service location is often necessary.

3.1.2 Grid services for voltage control, congestion management, black start and other purposes

A transmission constraint arises where the system is unable to transmit the power supplied to the location of demand due to voltage issues or congestion at one or more parts of the transmission network. Voltage control and congestion management are two common services requested by the TSOs to address such problems.

Voltage control is accomplished by managing reactive power on an AC power system, wherein reactive power can be produced and absorbed by both generation and transmission equipment at specified service points. In Europe, the provision of reactive power is typically an obligation to large-scale generators (50MW in UK) implemented via grid code or is from other reactive power facilities (e.g. capacitors and Static Var Compensators) connected to the transmission network. In some countries like Denmark, reactive power reserve can be acquired through a market-based tendering process. However, because there are only a few power plants that are qualified, the competition is little.

Congestion management refers to avoiding the thermal overload of system components by reducing the amount of power transferred. The reason for network congestion is normally due to insufficient network capacity, therefore congestions can be observed at cross-border levels, national levels, transmission networks and distribution networks. Solutions to congestion management can be either implemented at the planning stage through grid reinforcement or implemented at the operational stage by optimally dispatching the regulatory capacity offered by service providers. Similar to voltage control, congestion management is also a location-dependent service. The corresponding requirements on capacity, service time window, ramp rate and reactive capabilities etc., therefore vary from case to case.

Black Start is an example of services commonly needed by all TSOs; it ensures the restoration of the grid after major incidents. A power plant is capable of black-start if it can go from idle to operational without requiring the injection of grid-connected electricity and if it fits well the operational sequences pre-designed by the TSOs.

Today, most TSOs base their choices of the units participating in these localized services via bilateral contracts. In addition to remunerating one-time expenses (IT implementation, technical adaptations to the unit) and operational expense, penalties are often applied in case the performances are not well met.

In addition to the above mentioned services, TSOs are often in need of tailored services to maintain their system security individually. In general, these services can be understood as additional dispatchable capacities applied to improve the reliability, the resilience and the economics of the transmission networks. For instance, the service “Compensation of active power losses” is a particular service procured by Swissgrid at 5MW bid structure to compensate for active power losses in the Swiss transmission grid.

3.1.3 Demand side response

By changing or shifting consumption, DSR is able to increase the system’s adequacy and to provide various kinds of grid services in an economic manner. It can act as a cost effective balancing resource, can lower the need for spinning reserves offered by conventional fossil fuel fired power plants, and can decrease the need for network capacity investments. DSR is conventionally offered by consumers – residential, commercial or industrial – with control signals and/or financial incentives to adjust their consumption at strategic times. Today, following the rapid deployment of distributed energy resources (DER), DSR can also be offered by prosumers who consume, produce and control their energy use.

In principle, services offered by DSR can be from an individual consumer or an aggregator. Aggregators pool many different loads of varying characteristics to increase the overall reliability and to break market entry barriers such as capacity requirements. They create one “pool” of aggregated controllable load, made up of many smaller consumer loads, and sell this as a single resource. As an alternative to developing a portfolio with diversified DER technologies, some aggregators choose to aggregate specific DER technologies such as electric vehicles or heat pumps in some countries where the market is booming.

In Europe, DSR has been through a moderate growth over the recent years as indicated by Figure 3-6. In countries like UK and France, several DSR programs have been made commercially active, while in Germany and the Nordics, the market is partially opening. A short summary of the DSR status and requirements of the surveyed countries are given in Appendix 2.

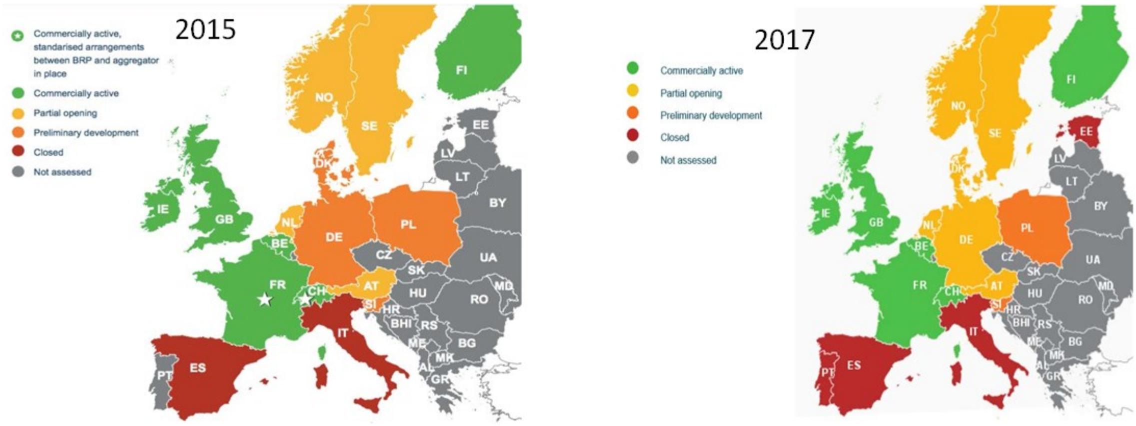


Figure 3-6: Mapping DSR to EU member states, Switzerland and Norway 2015-2017 [16]

Comparing to large-scale consumption units that are well used in almost all countries as interruptible loads to provide grid services, aggregation-based DSR still face many practical challenges. In UK the market model allows independent aggregators direct access to consumers for most ancillary services and capacity products, but they are unable to utilize the energy for wholesale market purposes. In Germany and the Nordics, they are in the process of discussing or establishing their own frameworks to enable independent aggregation. France is the only Member State in Europe, which has opened both the ancillary services markets and wholesale market to DSR and independent aggregators after a standardized framework put in place in 2013 [21].

In most countries, the grid service programs are mainly designed around the characteristics of generators, leading to a situation where only the largest consumption units are able to participate. Unless specified, this also implies DSR will be treated equally as the conventional generation technologies when they are applying for pre-qualification test in order to enter the grid service market.

3.2 Overview of services and market structures for the distribution grid

As illustrated in Figure 3-1, services requested by DSOs to a large degree resemble the services requested by the TSOs, except for that they are applied to address the local issues at medium/low voltage levels. These services as alternative solutions to the conventional planning and operation solutions can enhance the reliability and power quality of distribution network and increase the hosting capacity for RES in the existing distribution network. Ideally, distribution grid services can be offered by individual or an aggregation of flexibility-owners who are connected to the distribution grids. However, in Europe, grid services for distribution networks are not market-available yet because most of the distribution systems are designed to operate passively, i.e., to handle most of the distribution grid issues through reinforcement. In addition, how to address the existing regulating barriers through proper market design for the distribution system and how to optimally coordinate the use of flexibility by different stakeholders at different network levels are remaining common challenges. Today, distribution grid services are only being designed and trialled by pilot activities.

The Danish iPower project proposes five DSO services through active power control traded through a newly developed conceptual Flexibility Clearing House (FLECH) [22]. The goal of FLECH is to facilitate the trading of flexibility between different stakeholders (TSO, DSO, BRP and Aggregator, etc.) by providing them a common marketplace to exchange flexibility-based service products. The designed service trading platform, as illustrated in Figure 3-7, enables the use of flexibility for two types of DSO services: services for load management and services for voltage management [23].

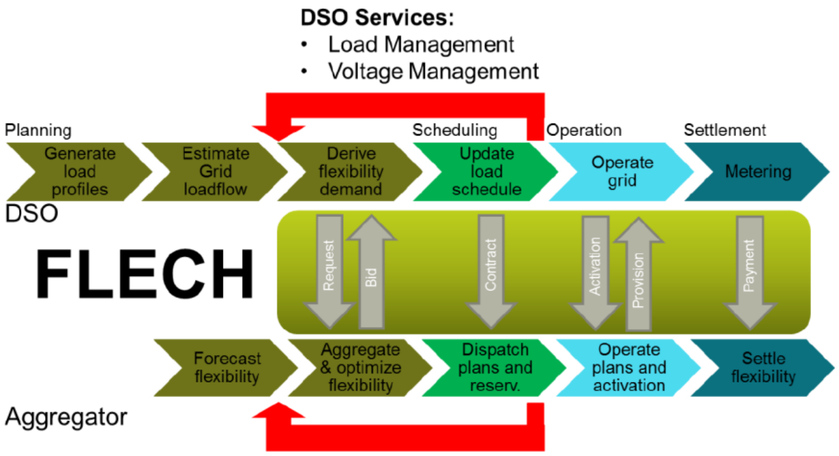


Figure 3-7: Overview of functional requirements of FLECH for DSO services

Services for load management include five different service products to address congestion or redundancy issues,

- PowerCut Planned: Used for handling predictable peak load for periodically daily issues in advance.
- PowerCut Urgent: Used for handling peak loads on an event basis.
- Power Reserve: Used when the system is operating in the reserve band of the feeder, and a fault in the system would require the utilization of the reserve band.
- PowerCap: Activated upon request to ensure that the capacity limits specified by the DSO are not violated.
- PowerMax: Same function as PowerCap, but activated through a planned schedule.

Services for voltage management include two service products to address the voltage issues,

- Voltage Support: Event-based voltage management through regulating active and reactive power.
- VARSupport: Reactive power reserve.

Similar to iPower, the EUFP-7 project IDE4L proposed two types of distribution services: an option based service, which is traded day ahead and requires activation by the system operator, and a scheduled service, designed for forecasted congestion, like for example during network maintenance work [24].

Normally, these capacity services requested by the DSOs need only static asymmetrical response to address local challenges. Therefore, technical requirements for DSO services are normally less harsh than the requirements for TSO services. This implies

- Capacity requirement is ranged from tens of KWs for LV up to several MWs for MV/HV networks.
- Activation time can be ranged from second scale for automatic solutions to hours for manual solutions.
- Duration time is dependent on the length of event, for instance the length of peak load moment is usually less than an hour, for fault-incurred contingencies the duration can be up to tens of hours, for voltage issues the duration is normally less than a few minutes.

Another type of service needed only by the DSOs is power quality (PQ) service. PQ is becoming more and more important at the distribution level due to the increasing presence of intermittent RES. Technical criteria for PQ characteristics are defined by the norm EN50160 [25], e.g. frequency, voltage magnitude variations, rapid voltage changes, supply voltage dips, short interruptions of supply voltage, long interruption of supply voltage, voltage unbalance, harmonics etc. Today, these PQ criteria are met either by obligatory grid code or by regulating the DSO assets such as tap changers. It is reasonable to believe, some of the PQ needs can be met by flexibility services, such as regulating the single-phase loads to address unbalance issues.

It is also worth noting that DSOs who operate grid-connected island systems can have dual identities. During the grid connected moments, these DSOs only require distribution grid services. In case of islanded operation, they have to fulfil the TSO obligations and acquire balancing services to balance the production and consumption for the islanded systems.

3.3 Overview of services for peer-to-peer operation

Peer-to-peer (P2P) is a decentralized architecture model whereby any two peers can interact to buy or sell resources and services directly with each other, without intermediation by a third-party. The internet and modern communication technologies have made a peer-to-peer approach to many things more tenable than ever before, such as P2P shopping with Ebay, P2P accommodation with Airbnb. As the number of prosumers grows in the energy system, P2P services between stakeholders who are none grid operators are being developed. This in principle allows electricity end-users to choose their preferred energy course and destination, enables agreements on own service terms such as price, offers a relatively fair market place to everyone since the capacity of generation/consumption is irrelevant.

Today, there are many P2P energy trading platforms developed and tested. The most notable ones include the Brooklyn microgrid [26], Vandebron platform [27] and Open Utility [28] etc. Brooklyn microgrid is a community microgrid with P2P energy market for local end users and local RES to freely choose each other within the community. The latter two platforms are launched in the Netherlands and UK, aiming to enable electricity end-users to freely select and prioritize electricity suppliers (can sometimes be prosumers who have excessive energy production) at national or international scales. As the name indicates, P2P energy trading is oriented towards energy products at the current stage. Correspondingly, the requirements on energy products/services consider primarily the availability and the amount of the energy to be traded.

Another kind of P2P service which has been applied for years is the one requested by BRPs. Since BRPs are financially responsible for their imbalances in the electricity market, maintaining a balanced operation portfolio 24/7 to avoid imbalance costs is one of their routine tasks. In an unbundled wholesale market places, BRPs may request services for

- Day-ahead portfolio optimization: that enables the BRP to optimally reduce its overall electricity purchase costs or to increase its revenue from selling electricity based on the forecast,
- Intraday portfolio optimization: that resembles day-ahead optimization, but the time frame is more close to real time.
- Self-balancing: is the reduction of imbalance by the BRP within its portfolio to avoid/reduce imbalance charges.
- Portfolio optimization: that optimizes the behavior of the BRP’s whole portfolio in order to increase the reliability and profitability of the portfolio.

Taking a wind farm owner as an example, balancing the wind power with cheaper flexibility options at different time scales ranged from 1 minute up to hours can help the wind farm owner to have a much stable performance; therefore reducing the risk of paying market-based balancing cost. In case of being curtailed, increase the local consumption capacity would not only help the wind farm to avoid curtailment but also provide better use of the produced energy. Requirements for these kinds of P2P services are normally dependent on the operational principles of BRPs for energy management and energy trading. In terms of portfolio balancing services, the requirements are much comparable to the requirements for balancing products in the balancing markets. In terms of capacity products, the requirements are therefore put on capacity size, activation time and duration time etc.

Traditionally, resources that can offer P2P services to the BRPs would normally become part of the BRP’s portfolio or a contractual partner. Recent transitions towards a common flexibility marketplace where flexibility aggregators, virtual power plants (VPPs), BRPs and grid operators can freely trade flexibility products at a much larger scale would be the key to enable the use of P2P services.

4 Pre-qualification of electrical grid services

4.1 An overview of pre-qualification process in EU, Switzerland and Norway

Pre-qualification is a process whereby a grid operator makes a assessment of a service provider's capability against the technical requirements of targeted service. It is therefore a prerequisite for the participation in tendering procedures for services that are critically important, such as frequency control. In principle, detailed pre-qualification testing procedures are well defined by the TSOs. Pre-qualification, in general, is initiated by potential service providers who have to make applications to the TSOs. Once all the required certificates, protocols and other documents are received by the TSO, pre-qualification tests will be arranged under framework/bilateral agreements.

Figure 4-1 presents an example of Pre-qualification tests for FCR in DK-West. For this test, applicants must meet the requirements from the following three aspects,

1. Measurement:

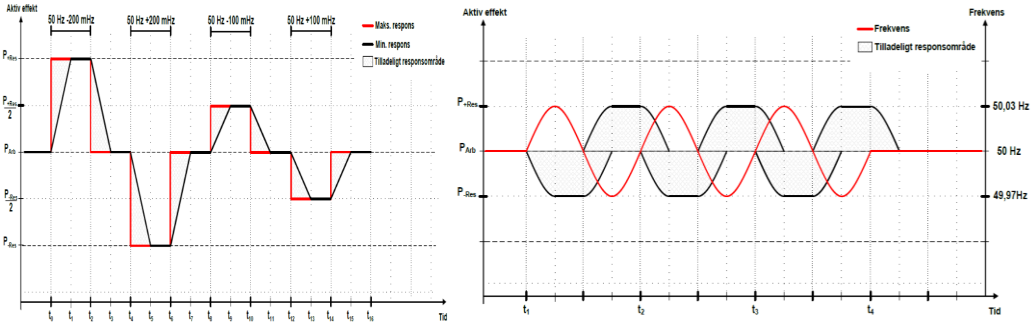
- Accuracy of frequency measurement must be better than 0.01mHz;
- Sensitivity of frequency measurement must be better than ±0.01mHz;
- SCADA resolution must be better than 1s;
- Performance has to be recorded for at least one week.

2. Communication:

- Online controllability from the TSO control center,

3. Controlled performance

- At least one test will be arranged to test the minimum and maximum capacity and ramping rates at different frequency thresholds;
- At least one test will be arranged to test the performance stability by signaling a continuous frequency profile;
- Response to the control/frequency test signals has to stay within the permissible range as illustrated in Figure 4-1 in order to pass the test.



Test af minimumskrav til respons for FCR (Primærregulering) i DK1.

Testforløb for stabilitetstest for anlæg i DK1

Figure 4-1: Prequalification test for FCR in DK-W [14]

Table 4-1 shows an overview of countries whose pre-qualification requirements for frequency control services are surveyed in this study. A brief explanation about the testing requirements for the surveyed services in the selected countries is given in Appendix 3. More detailed testing procedure is accessible from the homepages of individual TSOs.

In general, the testing profiles applied by the TSOs for frequency control services include both step signals and continuous signals. These signals are either practically measured (historical/real-time) or developed through simulations. Step signals are normally used to test performance characteristics such as accuracy, speed of response, response delay, ramping performance, deadband performance etc., within a very short period, therefore offering both the TSOs and the service providers a preliminary impression of the unit's technical performance. Continuous signals, normally a sequence of frequency signals or a sequence of set-points are used to test the sustainability of the unit's response within a longer duration. Assessment criteria regarding each performance characteristics are normally defined by formulas that are illustrated as permissible response ranges. In case the test is made for an aggregated portfolio of more than one unit to provide FCR or aFRR, documenting the performance of individual unit is normally requested by the TSOs. Although (aggregation-based) DSR programs are already commercially available in many European countries, they are often approved for mFRR or RR. In those cases, pre-qualification tests are either not necessary or carried out against the baseline that enables the grid operators to measure the performance of DSR.

Table 4-1 An overview of countries whose pre-qualification requirements for frequency control services are accessed as highlighted in green

Country	**Frequency Control Services**			
	FCR	aFRR	mFRR	RR
CH	Primary control	Secondary control (LFC)	Tertiary control (positive and negative reserve)	Tertiary control (negative reserve)
DE	Primary control	Secondary control (LFC)	–	Tertiary control (minute reserve)
ES	Primary	Secondary (LFC)	-	Tertiary & interruptible loads
NL	Primary control	Regulating Reserve	FAST tertiary control (Reserve Capacity and Emergency capacity)	Tertiary control (Reserve Capacity and Emergency capacity)
FR	FCR(Primary Reserve)	aFRR (Secondary reserve)	mFRR(Rapid reserve)	RR(Complementary reserve)&DSR-RR(Demand reserve)
DK-W	Primary reserve	aFRR(secondary reserve/LFC)	Manual reserve (regulating power)	–
DK-E	FCR-D/FCR-N	aFRR (Nordic LFC)	Manual reserve(regulating power)	–
NO	FCR-D/FCR-N	aFRR	Tertiary regulation (regulating power)	–
UK	FFR/FCDM/EFR	FFR/FCDM/EFR	Fast reserve	STOR/BM Start-up/Demand turn up

Today, requirements of pre-qualification tests in Europe, similar as the descriptions of frequency control services, are different from service to service and from country to country. For example, 15 standard testing signal profiles are defined by the TSO in UK to test the performance of any potential service providing technology through different combinations of these signals; while in many other countries, only a few testing profiles are defined by the TSOs. This difference results in the fact that technologies already approved by one TSO still need to be pre-qualified by other TSOs as long as the connection points change from one system to another. Another challenge faced by potential service providers is that the English version of pre-qualification requirements published by TSOs for international service providers is normally maintained much slower than the version made in the TSOs' native language (if it is not English). For new technology developers, the lack of harmonized testing procedures could result in a longer duration between technology ready and market ready.

4.2 Pre-qualification in USA

As a common approach to select the qualified resources for providing grid services, pre-qualification tests can be designed and implemented by grid operators in many different ways.

In PJM (the regional transmission organization that coordinates the movement of wholesale electricity in all or parts of 13 states and the District of Columbia in the USA), balancing resources are either regulated through regulation signals (i.e. measured ACE signals) or dispatched through dispatch signals (i.e. PJM calculated signals) in order to maintain the system balance [18].

Qualification tests in PJM include verifying the resource (1) providing regulation for the duration (40 minutes) of each test, (2) can achieve its full regulation testing range (symmetrical), (3) has set and held it’s regulation basepoint for the full duration of the test and (4) that no other resources within the testing fleet were in the regulation market during the testing period.

A resource may be certified only after it achieves three consecutive scores of 75% or above. The first of these tests can be a self-test with up to three self-administered tests may be performed on a resource each day, following the PJM Regulation test procedure. The remaining tests should be administered by PJM Dispatch. In addition, resources providing dispatchable energy and regulation service needs to provide testing at the low economic and high economic regulation limits, which is normally not required by the TSOs in Europe.

Test performed in PJM is evaluated based on compliance to the Performance Score Calculation (PSC) method designed by PJM. The method calculates an hourly performance score which reflects a regulation resource’s accuracy in increasing or decreasing its output to provide frequency regulation service in response to PJM’s dispatch signal. The unitless Performance Score (0-1) will be a weighted average of the performance score components as following

$$\substack{Performance\\Score}(t) = \max_{i=0\,to\,5min}\left[A * \substack{Delay\\Score}(t+i) + B * \substack{Correlation\\Score}(t+i)\right] + C * \substack{Precision\\Score}(t)$$

Where the delay score is calculated to quantify the delay in response between the regulation signal and the resource change in output; the correlation score is a statistical match that measures the degree of relationship between the two signals; and precision score calculates the difference in the energy provided versus the energy requested by the regulation signal while scaling for the number of samples. The component scalars A, B, and C are currently set equally with each at 1/3. Scoring equations for each component are calculated on a 10-second interval basis, then averaged over a 5 minute period to determine the composite performance score.

This scoring method applied currently uses all components in performance scoring captures resources performance effectively when resources are following the signal fairly well. However, it doesn’t do a good job during periods of poor performance. Improvements suggested in [19] propose an initial threshold evaluation on precision before scoring resources to better capture periods of poor performance, i.e. equations will stay status quo 1/3 accuracy +1/3 delay + 1/3 precision if precision score is higher than 75%, otherwise score interval as precision only (1/3*0 +1/3* 0 + 1/3 precision).

For DSR resources providing regulation, PJM requires DSR specify MW-value basepoint that they are regulating around and can fulfill the regulation range requirements without injecting energy into the power system.

In California, the testing procedures and requirements for different services are also documented in detail [20]. Description of the test procedures is similar to the ones implemented in Europe with requirements specified for service related performance characteristics. The time typically allocated to perform resource testing in one to two hours; the complete test time depends upon the type of service being tested, the type of resource being tested and the system conditions at the time of the test.

For non-generator resources participating in the regulation services, they will be tested full range (both upwards and downwards regulation) for at least one hour.

5 Electrolyser’s potential for providing electrical grid services

5.1 An overview of the current state of using electrolyser for electrical grid services

WE has the potential to play a key role in a future energy system based on two energy carriers: electricity and hydrogen. This is because the renewable energy sources, mainly wind and photovoltaics, can be easily coupled with WE processes producing clean and sustainable hydrogen. The state of the art of WE has been thoroughly assessed in the report “Development of Water Electrolysis in the European Union” released in February 2014 by the Fuel Cell and Hydrogen Joint Undertaking [29]. The Consortium will take this report as the basis to evaluate the potential capabilities of the WEs to provide electrical grid services taking into account the requirements defined in the prequalification procedures under consideration.

As QualyGridS project is focused on the grid services provision, there will be some certain characteristics that will be summarized in the following points, regarding the capability of the WEs of working under dynamic conditions as it is requested by this specific operation profile. There are different WE technologies available in the market at different size and TRL, namely alkaline, PEM, SOE or AEM. However, as the projects related to grid service provision are framed in the MW class, only alkaline and PEM technology can match these sizes at short and medium term.

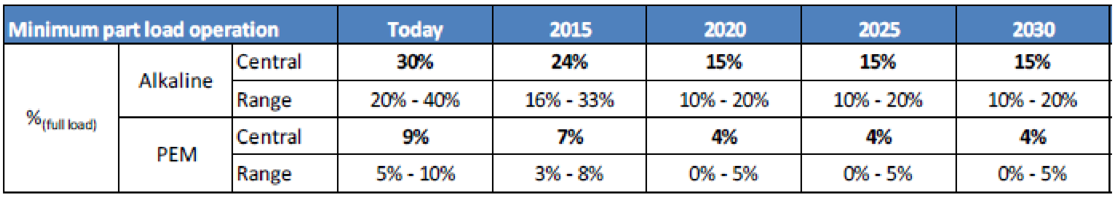
The dynamic characteristics of WEs which are relevant to provide grid services are the load flexibility and the response time under fast load changes (up/down). These parameters were introduced in the mentioned report “Development of Water Electrolysis in the European Union” but the information and trends shown have to be taken with caution as *“the manufacturers consulted indicated considerably uncertainty around both what these applications might be and what technical performance characteristics would be needed”.*

Load flexibility

The load flexibility is referred to the WE capability of being operated under a broad range of load. Higher load ranges involved that the WE can provide the grid service in a profitable way, as it can offer to the grid operator a higher amount of power range (MW). The maximal load is normally defined by the nominal load at that the WE is designed. Overloading approaches above 100% are not foreseen at MWs sizes as power electronics and BOP design capable of operation at higher loads (more than 100%) would seriously increase the capital expenditure.

The minimum load is defined by the operation conditions at which the WE can be operated under safe conditions. As it can be seen in the following table, both technologies can be operated at low loads, having more room for improvement in the case of alkaline technology. In any case, recent developments of alkaline suppliers have already achieved to decrease the low loads below 10%.

Table 5-1 Present and expected part load performance for Alkaline and PEM



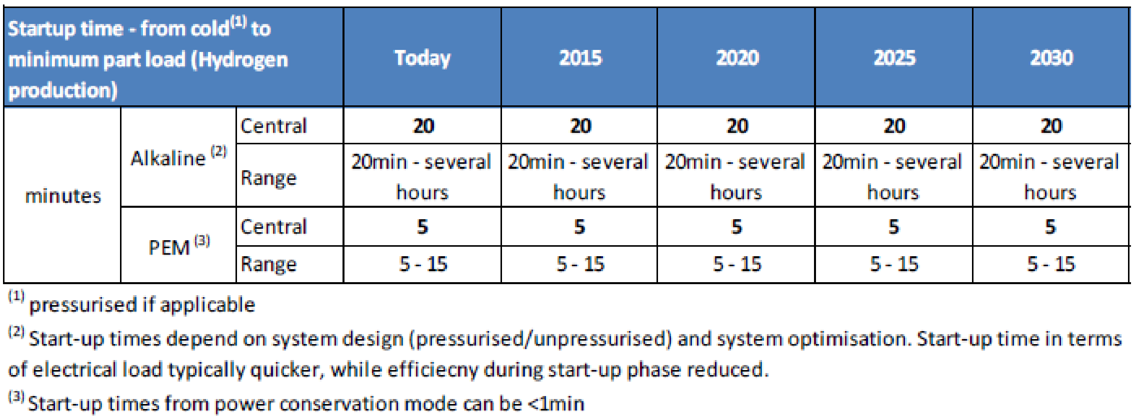
Minimum part load operation			Today	2015	2020	2025	2030
$\%_{\text{(full load)}}$	Alkaline	Central	**30%**	**24%**	**15%**	**15%**	**15%**
		Range	20% - 40%	16% - 33%	10% - 20%	10% - 20%	10% - 20%
	PEM	Central	**9%**	**7%**	**4%**	**4%**	**4%**
		Range	5% - 10%	3% - 8%	0% - 5%	0% - 5%	0% - 5%

Response time

The response time under fast load changes (up/down) is an important characteristic which WE has to fulfil in order to provide grid services. The response time can be defined in different values depending on the operation conditions taking into account the WE state, namely if the WE is at operation, ambient conditions or stand-by conditions (at pressure and operation temperature). Normally, the response time of the WE under operation conditions or stand-by state is defined by the capability of the power electronics to react to the fast set points as it is not stack limited. Therefore the response time of both technologies is in the range of few seconds.

The response time when the WE is at ambient conditions depends on the technology and unit size. Normally, PEM WEs need lower activation times than alkaline technologies and MWs WEs needs more time than KWs units for both technologies. In the following table, the response time of both technologies is defined.

Table 5-2 Present and expected startup performance for Alkaline and PEM



Startup time - from cold(1) to minimum part load (Hydrogen production)			Today	2015	2020	2025	2030
minutes	Alkaline (2)	Central	**20**	**20**	**20**	**20**	**20**
		Range	20min - several hours	20min - several hours	20min - several hours	20min - several hours	20min - several hours
	PEM (3)	Central	**5**	**5**	**5**	**5**	**5**
		Range	5 - 15	5 - 15	5 - 15	5 - 15	5 - 15

(1) pressurised if applicable

(2) Start-up times depend on system design (pressurised/unpressurised) and system optimisation. Start-up time in terms of electrical load typically quicker, while efficiecny during start-up phase reduced.

(3) Start-up times from power conservation mode can be <1min

On the other hand, it is worthy to mention that when a MW WE is erected in a certain application, the goal is to have this unit with high loads and capacity factors in order to maximize the profits from the hydrogen produced, considering the grid services provision as an extra income to boost the profitability of the whole plant. Therefore, MWs WEs rarely will be kept at ambient conditions without hydrogen production as it would be contrary to the customer profitability.

Table 5-3 presents the FCH-JU multi-annual work plan 2014-2020 road map for hydrogen production for energy storage and grid balancing; it gives an indication of the 2017 status and future trends in relation to key performance indicators [31]. The development targets indicate a strong focus on parameters of importance in grid balancing applications. It is important to mention that the parameters shown in the FCH-JU report and in the table 4-2 are not always well associated (i.e. KPI 6 “Cold start” ranges are not the same in both references), what it portrays the great uncertainty of the technical parameters and requirements of WE operating at dynamic conditions.

Table 5-3 Roadmap for electrolysis development under the FCH-JU platform

		2017	2020	2023
KPI 1	Energy consumption (kWh/kg) @ rated power	55@500 kg/day	52@1000+ kg/day	50@1000+ kg/day
KPI 2	CAPEX @ rated power including ancillary equipment and commissioning	3.7 MEUR/(t/d)	2.0 MEUR/(t/d)	1.5 MEUR/(t/d)
KPI 3	Efficiency degradation @ rated power considering 8000 h operation per year	2% per year	1.5% per year	<1% per year
KPI 4	Flexibility with a degradation < 2% year (refer to KPI 3)	5%-150% of nominal power	0%-200% of nominal power	0%-300% of nominal power
KPI 5	Hot start from min to max power (refer to KPI 4)	10 sec	2 sec	<1 sec
KPI 6	Cold start	2 minutes	30 sec	10 sec

Projects review

An investigation on the on-going/ finished (especially EU FP7/H2020) projects related to using WEs for a grid service in Europe is conducted. A short overview of these projects is summarized in Appendix 4. As the survey indicated, both alkaline and PEM WE are in principle capable of meeting the requirements that are necessary to operate on the investigated markets in terms of dynamic operation capabilities, although different factors such as capacity, flexibility, dynamic performance etc. would limit their grid performance.

Most of the projects take developing/demonstrating power to gas (P2G) as a basis. It therefore enables P2P services like avoiding wind power curtailment by consuming excessive wind power, improving the electricity market-based energy economy for intermittent generation through hydrogen-based energy storage, improving the overall system economy of local energy community etc. Alkaline WE, as a mature technology in the MW range for industrial applications, are often applied for these types of services. In any case, more projects integrating AWEs for energy applications have been launched in the last years.

In addition to P2G, the feasibility of using WEs for different kind of balancing services is being tested by several research activities. One of the most promising results is the ITM 300kW PEM plant that was tested for primary and secondary control services by multiple dynamic signal profiles, and got prequalified for secondary control service in Frankfurt [32]. Further investigations are therefore on testing the balancing service potential for MW class unit. These include examples like the H2020- H2Future project (2017-2021) and the Energiepark Mainz project (2015-). For H2Future, there will be a 26 month demonstration of a SIEMENS's PEM electrolysis 6MW power plant installed at the VOESTALPINE LINZ production site (Austria). After the pilot plant has been commissioned, the WE will be prequalified with the support of APG, the Austrian transmission operator, in order to provide grid-balancing services such as primary, secondary or tertiary reserves [33]. For the Energiepark Mainz project, a PEM electrolysis of 6.3 MW will be demonstrated to trade at the European Power Exchange, to participate at the market for secondary control reserve, and including the surplus of power of the connected wind farm (DE) [34]. Other projects like DEMO4Grid (2017-2022) will also demonstrate MW class AWE for grid balancing services where a 4 MW high pressure single stack WE provided by IHT will be installed at the MPREIS facilities in Innsbruck (Austria) [35]. The installation will be prequalified to provide grid services including primary, secondary and/or tertiary services.

Apart from Europe, there are relatively few demonstration projects on the integration of electrolytic hydrogen production systems with renewable energies. Most of the projects involve either autonomous systems isolated from the electric grid or systems consisting of microgrids. The renewable source is mainly photovoltaic although in some of them, wind energy or both are considered. The WEs are most frequently of the alkaline type working at atmospheric pressure and intermediate pressures (4–30 bar). A variety of electric powers (0.8–111 kW) and hydrogen storage procedures (compressed gas, liquid, and as metal hydrides) are considered [36].

Hydrogenics reports field experience with their HySTAT Alkaline electrolyser that provided frequency regulation by responding to real-time frequency regulation signals from the IESO (Independent Electricity System Operator) on a second-by-second basis. They also report that no significant degradation was seen after 10,000 On/Off cycles. The dynamic responsiveness of systems is stated to be 40-100% load [37].

In addition, the National Renewable Energy Laboratory (NREL) has also shown that both PEM and alkaline WE systems can ramp power up and down very quickly to accommodate the needs of grids with high penetration of renewable electricity installed. In addition, their ability to ramp quickly enables these WE systems to participate in grid ancillary services aimed at assuring a safe and reliability electrical grid. The 99.99+% purity levels of the hydrogen product from these WE systems can be used in a number of industries including; fuel cell electric vehicle refuelling, stored for use in stationary fuel cell applications, material handling refuelling (e.g., forklifts) and can be reacted with carbon dioxide to produce renewable hydrocarbon chains (e.g., methane), which can then take advantage of existing infrastructure. For example, the very early project named Wind2H_2 developed by the U.S NREL and Xcel Energy analysed several configurations for grid integration of hydrogen, photovoltaic, and wind systems [39]. The project includes a 10kW photovoltaic solar array, two wind turbines of 10 kW and 100 kW, two PEM WEs of 1.05 Nm^3/h each, an alkaline WE of 5.6 Nm^3/h, a hydrogen storage system in pressurized tanks (around of 1300 Nm^3 at 241 bar), and a 50kW hydrogen-fuelled internal combustion generator. With the aim of improving costs and efficiency, the performance of a complete renewable electrolysis system is evaluated, and particularly the operation of hydrogen technologies under variable power feeding regimes.

5.2 Characterization of electrolyser’s dynamic capability for providing grid services

In this sub-section, a summary of an internal survey conducted by the QualyGridS Consortium members is presented in Table 5-1. The survey intends to characterize MW class WEs’ dynamic capability at different operation modes. The presented information is based on three partners’ feedback.

The first feedback is based on the public final report of the project “Kompaktes 1 MW-PEM-Wasserelektrolyse-System – Regenerativer Wasserstoff für Mobilität und Energiespeicherung (KompElSys)” supported by “Nationales Innovationsprogramm Wasserstoff- und Brennstoffzellentechologie”, Germany, Nov. 2012-Sept. 2016. The electrolyser investigated is a PEM electrolyser system by Hydrogenics with a nominal power of 1 MW and a pressure of 30 bar. It is located in Hamburg-Reitbrook operated by Uniper. It was designed for P2G applications with hydrogen being fed into the natural gas grid, normally operating continuously. The tests were run before the final optimization of BOP (Balance of plant) components and control.

The second feedback is based on the information provided by ITM Power who develops integrated hydrogen energy solutions that are able to meet requirements for grid balancing and energy storage services, and for the production of clean fuel for transport, renewable heat and chemicals. Their HGas system brings together rapid response and self-pressurizing PEM water electrolysis into a fully integrated package, capable of addressing MW scale applications. It is designed specifically for P2G applications and capable of responding in 1 second, which makes it able to accommodate fluctuating power profiles, while generating hydrogen at pressures suitable for either direct injection into natural gas networks, or via methanation processes, without additional compression. The modular philosophy allows multi-MW units of WEs to be accommodated within standard ISO containers. Systems range from 60kW to multi-MW and can produce hydrogen at pressures up to 20bar or 80bar, depending on the chosen options.

Table 5-1 Surveyed technical performance of AWE and PEM WEs at different operation modes

Operation mode		**1 MW-PEM-Wasserelektrolyse-System**	**ITM Power PEM-Electrolyzer (HGas1000)**	**IHT HP AWE**
Constant operation	Consumed power (**at nominal power**)	Average 1075 kW, min 1050 kW, max 1100 kW (test 24hr)	1030 kW	4MW
	Fluctuation (**at nominal power**)	Variations lasting < 2 min	-	-
	Amount of H_2 produced (**at nominal power**)	213 ±4.5 Nm^3/hr H_2 (Fig.7 in [40])	432 kg/24hrs	800 Nm^3/h
	Efficiency (**at nominal power**)	Not mentioned	Typically up to 74%, however, the number of cells and stacks, as well as current density can be adjusted to meet the client’s operating requirements.	4,5-4,7 kWh/Nm^3 at stack level
	Restrictions(**at nominal power**)	Not mentioned	Not mentioned	-

	Consumed power (**at maximum power**)	1540 kW	ITM Power's systems are typically designed to operate between 20 – 100% of maximum available power and in some cases can operate down to a minimum of 10% of maximum power. The systems incorporate a product gas drier and therefore provide hydrogen at >99.999% across the whole range.	Up to 150% of nominal power
	Fluctuation (**at maximum power**)	±8kW, less than every 60 min short spike of -40 kW;		-
	Amount of H_2 produced (**at maximum power**)	292 ±9 Nm^3/h H_2 (Fig.9 in [40])		1200 Nm^3/h
	Efficiency(**at maximum power**)	Not mentioned		**-**
	Restrictions (e.g. due to overheating) (**at maximum power**)	In principle no restrictions, at least 6 hr operation possible (demonstrated)		**-**
	Consumed power (**at minimum power**)	282 kW		0.6MW
	Fluctuation (**at minimum power**)	±8kW (could also be 220kW, not clear from published data)		**-**
	Amount of H_2 produced (**at minimum power**)	-		**-**
	Efficiency(**at minimum power**)	60%-100%		**-**
	Restrictions (e.g. gas impurity) (**at minimum power**)	Gas purity		Gas purity
Long term stand-by operation	Power consumption in stand-by mode (i.e. system already at operating temperature)	Stand-by is designed as a transition state, therefore needs relatively high electrical power for keeping pressure and temperature.	Depends on the size of the system, but typically is <5% of the system's total consumption. ITM Power's systems enter different stand-by modes depending on how long the system is off for. Typically, when a system stops generating hydrogen, it enters a stand-by mode during which the water circulation pumps continuing to operate for up to 15 min. In this mode the power consumption is typically 5% of the system's total consumption. If the system was to be off for between 15 min to 1 hr, it enters a stand-by mode	Depends on the stand-by duration but in principle it is negligible for stand-by durations shorter than 8 hr.
	Fluctuations	Switching between 60 kW and 220 kW in intervals of several minutes to maintain temperature or constant 220 kW, depending on the control.		-

			during which the water circulation pumps are switched off. In this mode the power consumption would be <5% of the system's total consumption. Restart from either stand-by mode would be within 30 sec.	
	Does the unit switch to nominal load to keep the electrolyser at temperature? Time interval between these heating cycles, power profile and duration of these heating cycles.	Yes, dependent on the control.	No.	Not needed.
Cold state	Power consumption in cold stand-by mode	Not mentioned	Depends on the size of the system, but typically <1% of the system's total power consumption. If the system is off for longer than 1 hr, it would typically power down, entering an idle state and restart from cold.	Negligible. Just control system and safety sensors. (less than 0.25-0.3% total power)
	Start-up time from cold start mode to 100% power	Needs rather long time due to gas flushing, system architecture, safety concept; same for transition from operation to off (p. 78-80 in [40]). Hydrogen purge on startup to remove nitrogen inert gas for 25 min, takes even longer to reach acceptably low N_2 content for mobility use of hydrogen. No data of profile of system power consumption during startup available.	Depends on the size of the system, but typically 5 min. This is due to a series of system safety checks that are carried out before hydrogen generation begins.	Between 10-20 min.
	Production of usable hydrogen after startup profile	Not mentioned	100% of hydrogen generated is utilized, no hydrogen is vented.	-
	Efficiency consid-	Not mentioned	Not mentioned	-

	erations			
	How long should operation after startup be to achieve satisfying efficiency?	Not mentioned	Depends on the size of the system, but typically 10 min from cold start mode to reach maximum efficiency.	-
Dynamics	Power steps up	(See Fig 10 in [40]) 176 kW to 550kW in 17 sec; initial response time 1.5 sec; power fluctuations after reaching target value not more than during long term constant operation; ramp smooth but non-linear 1081 kW to 1234 kW (Fig. 13 in [40]) duration below time resolution of the figure; power fluctuations after reaching target value not more than during long term constant operation; fluctuations in hydrogen output	Dependent on PSU and whether signal is supplied by operator or ITM control system. Typically <1 sec response between minimum and maximum available power.	2 sec between signal and target load
	Power steps down	No information in the report, should be as fast or faster than power steps up	-	About 1-2 sec between signal and target load
	Transient response time	No information in the report	<1 sec	1 sec
	Time from standby to nominal power	(See Fig. 11 in [40]) 167 kW to 1072 kW in 32 sec; initial response time 2 sec; power fluctuations after reaching target value not more than during long term constant operation. (See Fig. 12 in [40]) 167 kW to 1513 kW in 46 sec; initial response time 2 sec; start H_2 output ramp delayed by approx. 6 sec, not exactly linear	30 sec	Response time is 2 sec
	Time for cold start to nominal power: initial response time after signal	Needs rather long time due to gas flushing, system architecture, safety	5 min. (including safety checks)	Answered above.

	for change is given, ramp speed, deviations from ramp, fluctuations after reaching target voltage; consider different steps to nominal power and max. power and intermediate	concept; same for transition from operation to off (Report p. 78-80). Hydrogen purge on startup to remove nitrogen inert gas for 25 min., takes even longer to reach acceptably low N_2 content for mobility use of hydrogen. Initial response time usually is 1.5-2 sec.		
	Repeatability	Not mentioned	Yes	-
Others		**1 MW-PEM-Wasserelektrolyse-System**	**ITM Power (HGas1000)**	**IHT HP AWE**
Precision of control	Deviations from linear ramp	Not mentioned	<5%	-
	Amount of exceeding the target power after ramp	Not mentioned	Not mentioned	-
	How long time to reach constant power;	Not mentioned	<1 sec	2 sec
	Can the control be such that the power is never below the required ramp and target value but only above?	Not mentioned	Yes	Yes
Availability and reliability	For how long can start state be operated with only small power deviations and no malfunction? (time scale 15min, 1h, 24 h, 1 week). Starting state could be nominal power or ½(Pmax-Pmin) or stand-by mode or cold state mode	Nominal power: 24hrs and more	Indefinitely in any mode (stand-by mode, cold start mode)	24 hrs 7 days
Measurement data	Total electrical power of the electrolyser system	Time resolution 1 sec	Time resolution 1 sec	Time resolution 1 sec
	Amount of hydrogen supplied to application	Desirable time resolution 1 s; otherwise integral value over at maximum 15 min.	Desirable time resolution 1 s; otherwise integral value over at maximum 15 min.	1 sec

	Quality of hydrogen supplied to application	Desirable time resolution 1 sec.	Desirable time resolution 1 sec.	1 sec
Desirable additional information	Total electrical power of the electrolyser module	Time resolution 1 sec	Time resolution 1 sec	1 sec
	Current-voltage of stack	Time resolution 1 sec	Time resolution 1 sec	1 sec
	Behaviour of other important components to determine what their specification is	Time resolution 1 sec	Time resolution 1 sec Note: the PLC control system of the plant is capable of recording the above information on 1 sec timescale, but typically records on a 10 sec timescale to reduce the volume of data generated.	1 sec

The project partner NEL responded to the survey in a more general way:

Recent generation of atmospheric alkaline WEs by NEL, specially developed for industrial market with the largest capacity per cell stack 485 Nm^3/h can sustain fast start and stop, and can be operated at as low as 10% of operation range. Also, they are very well known due to a high energy efficiency (3.8-4.4 kW/Nm^3) and long reliability (7-9 years between service intervals). The largest plant installed by NEL during the last 5 years was of 20 MW power. In addition, another generation of alkaline cell stacks was developed during the last years with focus on using them with intermittent load. These pressurized stacks (nominal pressure 15 bar) can be operated with response of below 2 seconds and with wide operation range from 5 to 100%. This NEL technology was demonstrated through several projects, including first *hydrogen* refueling station *(HRS)* in Reykjavik, clean energy partnership (CEP) Berlin HRS and during UTSIRA project where hydrogen society (wind-electricity-hydrogen generation-fuel cells/battery-end users) was created on an isolated island [30].

As the surveyed results indicate, although the technical characteristics of different MW class WE are not the same, they in general can satisfy the requirements of aFRR, mFRR and RR which require the time of response at a time scale from 30 seconds up to tens of minutes (e.g. requesting the electrolysis to move between stand-by mode and nominal operation mode), especially if the service requires static asymmetrical responses. Dynamic symmetrical response requested by FCR also in principle can be provided by both WE technologies. However, the control system for both WE plants may need to be revised in order to meet the service requirements. For instance, the requirement of FCR normally requires a droop-based linear response curve.

5.3 Service catalogue for electrolysers

The technical requirements of grid services in general include capacity, speed of action, ability of ramping, and ability of offering a reliable symmetrical/asymmetrical dynamic/non-dynamic response over designated service period. In the following Table 5-2, the level of potential of using WEs to provide different grid services is identified qualitatively based on a preliminary matchmaking analysis between the service requirements and the abilities of WEs.

The rating applied to indicate the service potential consists of four levels:
Low: This can be due to the technical viability is not demonstrated yet, or there might be some needs of major technical improvements for the WEs, or there are some big non-technical

barriers, such as the service is not market-based yet or does not offer clear remuneration schemes.

Medium: The technical viability might be already demonstrated, and there might be some needs of technical improvements for the WEs; however there are some big non-technical barriers, such as the service is not market-based yet or do not offer clear remuneration schemes.

High: The technical viability is already demonstrated, and there are clear remuneration schemes. Although there might still be some needs of technical improvements, there is a growing interest of using WEs to provide this service.

Very high: The technical viability is already demonstrated, and there are clear remuneration schemes. The service is designed for/welcomes flexible DER technologies like WEs. Although there might still be some needs of technical improvements, there is a growing interest of using WEs to provide this service.

It must be noted the abilities of a WE can be affected by the selected WE technology, its primary application and the associated control system, etc. For instance, the capacity of associated hydrogen storage (e.g. hydrogen tank, HRS and gas network) would to a large extent affect the length of the duration over which a WE can be regulated by the grid operator. If a single WE plant fails to pass the capacity threshold of a service, aggregating it with a number of other WEs or DERs is therefore a feasible approach to increase the overall capacity, where appropriate coordination/control schemes have to be developed to handle the management of multiple plants. In case WE, gas storage and FC are integrated as a whole, the system would be able to represent flexible bi-directional electrical energy storage with the potential of offering various kinds of grid services.

For TSO services, as explained in Section 5.1 and 5.2, WEs in principle can meet the requirements of different kinds of services, especially for those ones requiring only active power regulation. As service requirements for the DSOs and P2P are normally less critical than the requirements of TSO services, WEs naturally exhibit a high technical potential of offering active power services to these stakeholders. For location dependent/capacity oriented services like congestion management and capacity management, capacity requirement might be a barrier if these services are requested by the TSO. This capacity barrier is normally much lower in the distribution grid; therefore would not limit the potential of WEs providing such services. The potential of offering voltage control and PQ to the grid operators is much dependent on the ability of grid inverters of a WE plant, which has not been much considered by the current design of WEs. In special applications such as microgrids with high penetration of intermittent renewables, offering this service to local grid operator should be highly feasible if the design of grid inverters is improved. P2P services and DSR programs can be very much relevant for WEs, which have already been proved by live examples.

Aggregating a number of WEs in one portfolio to offer grid or other kinds of services is a notable way of enabling the use of WEs’ flexibility. By doing so, the technical barrier for an individual WE to provide services can be mitigated, since its technical ability in capacity, dynamic characteristic and availability, etc., will be supplemented by a number of other units. The benefits of aggregation are already demonstrated by a number of trials carried out in Europe for electric vehicles, households and other different kinds of flexible DER technologies. In a future context when hydrogen becomes one of the essential energy carriers, aggregating a massive amount of FC vehicles and P2G plants to offer grid services can be easily foreseen.

Table 5-2 Service catalogue for electrolysers

Service requester	**Service name**	**Requirements identified by most service requesters**	**Justification**	**WE potential**
TSO	FCR	Capacity ≥1MW, activation time ≤30s, duration ≥15 min, high ramping requirement, auto symmetrical and dynamic response.	Service designed for generator, normally requires very rapid auto symmetrical dynamic response. In UK, the required activation time for a new service so-called enhanced frequency control is less than 1s. Technically, WEs can meet the requirements if they are designed for such purpose, e.g. running the WEs at 50% load in order to meet the requirements on identical up/down regulation.	Medium
	aFRR	Capacity ≥ 1MW, activation time (second to 15 min) slower than FCR, duration ≥15 min, ramping requirement, auto/remote-controlled symmetrical/asymmetrical dynamic response.	Requires less critical dynamic characteristics than FCR, but higher capacity and longer duration. Technically viable for MW class WEs, provided some technical improvements are made. Use an aggregation-based portfolio to provide such service is feasible. The market might be dominated by generators and large loads.	High
	mFRR	Capacity ≥ several MW, activation ≤15, min duration ≥15 min (up to hours), no ramping requirement, manual controlled messaged-based asymmetrical dynamic/non-dynamic response.	Requires less critical dynamic characteristics than aFRR, but higher capacity and longer duration. Technically viable for MW class WEs, provided some technical improvements are made. Use an aggregation-based portfolio to provide such service is feasible. The market might be dominated by generators and large loads.	High
	RR	Capacity ≥ several MW, activation from 15min to hours, duration ≥15 min (up to hours), no ramping requirement, manual controlled messaged-based asymmetrical static response.	Requires slower response than mFRR, but can be higher capacity and longer duration. Technically viable for electrolysis.	High
	DSR	Requirements are case dependent, can to large extent resemble FCR, aFRR, mFRR and RR.	Tailored for demand to provide TSO services. For countries like UK, DSR is started to be used to provide different kinds of balancing services.	Very high
	Congestion management	Requirements can to certain degree resemble RR. Capacity requirement is normally high.	The remuneration scheme is usually not clear due to the service is very location dependent. This implies only a few large-case WEs sited in designated locations can provide this service.	Medium

	Capacity management	Requirements can to certain degree resemble RR. May also need storage-alike abilities for load shifting etc.	Normally acquired through TSO tailored DSR.	Medium
	Voltage control	Requires WEs to offer reactive power support.	Location dependent. Normally offered by designated large scale units. Remuneration scheme is not clear.	Low
DSO	Congestion management	Requirements can to certain degree resemble RR, but the capacity required will be much lower (e.g. tens of kWs to several MW) and location dependent.	Normally implemented through DSO tailored DSR, are relevant for both MW scale and kW scale WEs.	High
	Capacity management	Requirements can to certain degree resemble RR. May also need storage-alike abilities for load shifting etc.	Normally acquired through DSO tailored DSR.	High
	Voltage control	Requires location dependent WEs to offer reactive power support.	Can be relevant for WEs in microgrids, may require improved ability of grid inverters and the associated control logic.	Medium
	PQ	Location-based service, requirements depend on the specific criteria of PQ service, such as unbalance, voltage management etc.	For WEs, this may require improved ability of grid inverters and the associated control logic. It is possible that the grid operators include the PQ requirements in grid codes, so it is an obligation for WEs to meet the corresponding PQ requirements.	Low
BRP, P2P and other service requesters	Self-balancing	Depends on the requester's portfolio, SCADA and EMS systems etc. Requirements on the dynamic characteristics can be comparable to aFRR, mFRR, and RR when services are about self-balancing. Energy trading oriented energy management will need to consider characters related to unit commitment (e.g. capacity, start/stop time, must on/off duration) and optimal dispatch (e.g. the ability of being modulated).	Notable examples of using WEs to avoid wind curtailment, to improve the portfolio performance (e.g. an integrated wind-hydrogen system) exist. Today, this is one of the major applications for using WEs to support renewable integration.	Very high
	Portfolio optimization			
	Energy trading			

6 Conclusions and recommendations

The potential of using WEs to provide different services to the grid has been widely studied and researched as well as initially demonstrated by several pilot projects in the EU. This potential resides in the capacity of WEs to be operated as flexible loads to be connected and disconnected when demanded by various stakeholders. Thus, flexibility of WEs is defined as the modification of generation injection and/or consumption patterns in reaction to an external service signal in order to meet the specific functional needs of a stakeholder. Depending on its function, a service may have clear requirements on parameters like power capacity, duration, ramping rate, response time and location etc. Evaluating the feasibility of meeting these technical requirements of a service is a necessary step to enable the use of WEs' flexibility that befits both the electric power system and the owners of WEs and the associated hydrogen industry.

This report presents a compressive overview of the existing grid services and the corresponding technical requirements. Based on a preliminary matchmaking analysis made between service requirements and the technical characteristics of MW class WEs, WEs show a great potential of offering active power services to the TSOs, the DSOs and other stakeholders who may request P2P services. Readers of this report shall take the identified service potential as a general indicator rather than a determining factor for any case-dependent investigations due to a number of reasons. First of all, the grid services and the corresponding technical requirements can be different from country to country and from time to time. Secondly, the detailed technical characteristics are collected from three MW class WEs, there is a risk that the surveyed results deviate from the average performance of WEs. Thirdly, the technical abilities of a WE can be influenced by many other factors, e.g. its control system, its capacity and the way it is operated (individual vs. aggregated). Finally, the grid services requirements and the technical abilities of WEs may both evolve rapidly, a decision on using any specific WE technology for any specific service should be made based on timely information.

A detailed overview of the requirements of pre-qualification tests requested by TSOs in the eight surveyed countries for frequency control services is also presented in this study. The collected information, in particular the technical requirements of grid services and pre-qualification tests will support the a number of relevant activities to be conducted in QualyGridS, such as development of the first set of standardized testing protocols for WEs performing electrical grid services, and economic analysis for using WEs to provide services that will consider both the remuneration schemes in different countries and various hydrogen applications.

When to design standardized testing protocols for investigating WEs' ability of performing electrical grid services, one of the key points that should be kept in mind is that in a market-based environment, grid operators treat all service providing technologies in the same way. In other words, in order to be qualified for a grid service-oriented technology in the long run, WEs have to compete with other flexibility technologies in terms of technical capabilities and economic performance. In addition, the variation of grid service requirements from country to country shall also be taken into account. Taking the most strict existing pre-qualification test protocols for balancing services as a reference can be the first step towards developing standardized testing protocols. Alternatively, using a combination of different pre-qualification test protocols that represent different synchronous areas would offer a more comprehensive understanding of WEs' technical potential.

Currently, the duration of pre-qualification tests varies from short (i.e., a few minutes) to medium (i.e., up to two hours). The short-duration tests are normally made to exam one/several individual technical aspect(s). The medium-duration tests are conducted to test the sustainability. Reliability testing and durability testing which are used to assess the long term performance and degradation effects etc., of a service providing unit are not requested by grid operators during pre-qualification. This is because existing technologies (i.e., mostly generators) for grid services are well understood and re-qualification tests can be arranged by grid operators when necessary. However, for new technologies whose technical capability has not been fully proved yet, testing their durability and reliability would be quite necessary. The corresponding service signals can be derived from historical/live service signals or simulations that significantly resemble the real demand of services. Finally the standardized testing protocol shall be designed based on a scientific approach that can result in a proper balance between practicality and comprehensiveness.

7 Appendix

Appendix 1 Requirements of Frequency Control Services in selected EU member states and Switzerland and Norway

Appendix 1-1 Requirements of FCR in selected EU member states and Switzerland and Norway

Country (Synchronous area)	**FCR**							
	Capacity	Dynamic/Static	Symmetrical/Asymmetrical	Preparation time	Ramping	Duration	Provider(s)	Procurement/Remuneration
CH (UCTE)	≥1MW	Dynamic	Symmetrical	≤30s	Full capacity within 30s	≤15min	Generation/demand	Capacity (Pay-as-bid)
DE(UCTE)	≥1MW	Dynamic	Symmetrical	≤30s	Full capacity within 30s	≤15min	Generation	Capacity (Pay-as-bid, capacity price)
ES(UCTE)	All generators	Dynamic	Symmetrical	≤30s	-	≤15min	Generation	Obligatory (no remuneration)
NL(UCTE)	≥1MW	Dynamic	Symmetrical	≤30s	Full capacity within 30sec	≤15min	Generation	Mandatory for those with >5MW. Capacity. (Pay-as-bid, capacity price)
FR(UCTE)	≥1MW	Dynamic	Asymmetrical (adjustments up or down)	≤30s	Half capacity within 15s, full capacity within 30s	≥15min	Generation/Demand[1,2]	Mandatory provision by all new generation capacity >= 40MW (formerly 120 MW) connected to the transmission grid; Capcity
DK-W(UCTE)	≥0.3MW	Dynamic	Symmetrical	≤30s	Half capacity within 15s, full capacity within 30s	≤15min	Generation/Demand[1]	Capacity (marginal price) and energy(imbalance price)
DK-E(Nordic)	≥0.3MW (FCR-N and FCR-D)	Dynamic	FCR-N Symmetrical and FCR-D Asymmetrical	≤1min	150s, linearly to frequency deviation between 0 and 100mHz for FCR-N; first half 5s, second half 30s, inverse-linearly for FCR-D	≤15min	Generation/Demand[1]	Capacity (Pay-as-bid) and energy(imbalance price)
NO(Nordic)	≥1MW	Dynamic	Symmetrical	≤5s(FCR-N) 2-3min(FCR-N)	Full capacity within 30s for FCR-N	4/8/12 hour block for FCR-N, ≥1 hour for FCR-D	Generation/Demand[1]	Mandatory reservation for machines over 10 MW.

[1] Service provided by an aggregation-based portfolio is allowed.

[2] Demand participation is in experimental use since 2017.

Appendix 1-2 Requirements of aFRR in selected EU member states and Switzerland and Norway

Country (Synchronous area)	aFRR						
	Capacity	Symmetrical/Asymmetrical	Preparation time	Ramping	Duration	Provider(s)	Procurement/Remuneration
CH (UCTE)	≥5MW	Symmetrical	≤30s	The gradient must be 0.5% of the normal output per second	≥15min	Generation/Demand[1]	Capacity (Pay-as-bid) and energy
DE(UCTE)	≥5MW	Asymmetrical	≤5min	Full capacity within 15min	≥15min	Generation/Demand[1]	Capacity (Pay-as-bid) and energy
ES(UCTE)	All generators except for non-manageable	Symmetrical	≤100s	-	≤15min	Generation	Marginal price (Capacity and energy)
NL(UCTE)	≥4MW	Symmetrical	≥4s	≥7(%/min.)	≥15min	Generation	Regulating power, market-based energy price, contracted reserve receives a pay-as-bid capcity price
FR(UCTE)	≥1MW	Asymmetrical (adjustments up or down)	≤15min	-	-	Generation/Demand[1,2]	Compulsory contract for any new production site >120 MW, payments are according to capacity and energy.
DK-W(UCTE)	≥1MW	Symmetrical	-	Full capacity within 15min	-	Generation/Demand[1]	Monthly auction, Capacity (marginal price) and energy)
DK-E(Nordic)	≥1MW	Symmetrical	-	Full capacity within 5min	-	Generation/Demand[1]	Monthly auction, Capacity (marginal price) and energy
NO(Nordic)	≥5MW	-	120-210s	Set-point capacity within 120s(or 210s)	≤30min	Generation	Capacity (marginal price) and energy

[1] Service provided by an aggregation-based portfolio is allowed.

[2] Demand participation is in experimental use since 2017.

Appendix 1-3 Requirements of mFRR in selected EU member states and Switzerland and Norway

Country (Synchronous area)	**mFRR**						
	Capacity	Symmetrical/Asymmetrical	Preparation time	Ramping	Duration	Provider(s)	Procurement/Remuneration
CH (UCTE)	≥5MW	Asymmetrical	-	Full capacity within 15min for Fast energy(±);	-	Generation/Demand	weekly, daily, Pay-as-bid (capacity and energy)
DE(UCTE)	-	-	-	-	-	-	-
ES(UCTE)	-	-	-	-	-	-	-
NL(UCTE)	≥4MW	Asymmetrical	≤15min	-	≥15min	Generation/Demand[1]	Reserve power balancing, (energy price)
FR(UCTE)	≥10MW	Asymmetrical	≤13min	-	≥30min	Generation/Demand[1]	Tender-based capacity and energy
DK-W(UCTE)	≥10MW	Asymmetrical	≤15min	-	-	Generation/Demand[1]	Capacity (marginal price) and energy
DK-E(Nordic)	≥10MW	Asymmetrical	≤15min	-	-	Generation/Demand[1]	Capacity (marginal price) and energy
NO(Nordic)	≥10MW	Asymmetrical	≤15min	-	≥1hour	Generation/Demand[1]	Capacity (marginal price) and energy

[1] Service provided by an aggregation-based portfolio is allowed.

Appendix 1-4 Requirements of RR in selected EU member states and Switzerland and Norway

Country (Synchronous area)	RR						
	Capacity	Symmetrical/Asymmetrical	Preparation time	Ramping	Duration	Provider(s)	Procurement/Remuneration
CH (UCTE)	≥5MW	Asymmetrical, negative	-	within 20 min for Slow energy(-).	-	Generation/Demand[1]	Pay-as-bid (capacity and energy)
DE(UCTE)	≥5MW	Asymmetrical	≤15min	Full capacity within 15min	-	Generation/Demand[1]	Pay-as-bid (capacity and energy)
ES(UCTE)	All generators except for non-manageable	Symmetrical	≤15min		≤120min	Generation	Marginal price (energy)
NL(UCTE)	≥4MW	Asymmetrical	≥75min	-	≥60min	Generation/Demand[1]	Reserve Power Other purposes (energy price)
FR(UCTE)	≥10MW	Asymmetrical	30min	-	≥30min	Generation/Demand[1]	Tender-based, capacity and energy.
DK-W(UCTE)	-	-	-	-	-	-	-
DK-E(Nordic)	-	-	-	-	-	-	-
NO(Nordic)	-	-	-	-	-	-	-

[1] Service provided by an aggregation-based portfolio is allowed.

Appendix 1-5 Requirements of balancing products in UK

Function	**Products**	**Characteristics**							
		Short description	Capacity	Symmetrical/Asymmetrical	Preparation time	Ramping	Duration	Provider(s)	Procurement/Remuneration
Frequency control services	Mandatory frequency response (MFR)	Obligatory service for large generators to provide primary, secondary and high frequency response.	>=100MW(National Grid) >=30MW(Scottish Power) >=10MW(Scottish Hydro)	Symmetrical for primary response	≤10s for primary response	-	20s	Obligatory for large generators	Capacity and energy
				Symmetrical for secondary response	≤30s for secondary response	-	30min		
				Asymmetrical for high frequency response	≤10s for high frequency response	-	indefinitely		
	Firm Frequency Response (FFR)	designed to complement other sources of Frequency Response and delivers dynamic or non-dynamic firm availability for primary, secondary and high frequency response.	≥10MW	symmetrical	≤10s for primary and high frequency response, ≤30s for secondary response	-	≥30min	balancing mechanism (BM) units, dynamic and non BM, static and non BM, as well as aggregation based non BM, including generators, loads, and storage[1]	Monthly electronic tender process, different agreements for different kinds of providers.
	Frequency control by demand response(FCDM)	Relay-based automatic interruption at low frequency, i.e. 49.7Hz.	≥3MW	Asymmetrical	<=2s	-	≥30min	Demand[1]	Availability Fee (£/MW/h) is paid against the Metered Demand.
	Enhanced Frequency Response (EFR)	Dynamic, symmetric, combatting expected decrease in inertia	≥1MW	symmetrical	≤1s	Begin producing after 0.5s in proportion to frequency deviation	≥15min	balancing mechanism (BM) units, dynamic and non BM, static and non BM, as well as aggregation based non BM[1]	Tender
Reserve	Fast reserve	Combatting sudden unexpected changes in generation or demand as secondary frequency response	≥50MW	Asymmetrical	<=2min	in excess of 25MW/min	≥15min	Generators, loads, and storage[1]	Three possible tender periods: monthly, multi-month, long-term.. Multi-part payment structure, including Availability Fee (£/hr), (£/MWh) , utilization fee (£/MW/h) and holding fee (£/h).
	Short term operating reserve (STOR)	Function as tertiary reserve	≥3MW	Asymmetrical	- <=4 hour	-	≥2hour	Generators, loads, and storage[1]	Three tender rounds each year. Multi-part payment structure, including Availability Fee (£/hr), (£/MWh) , utilization fee (£/MW/h)

	BM Start-up	Made up of M Start Up and Hot Stand-by. Applied to generators that couldn't be made available in balancing mechanism timescales due to their technical characteristics and associated lead-times.	-	-	-	-	-	Generators	-
	STOR Runway	An opportunity for Demand Side providers to secure a contract for an envelope of volume which will then be grown in their portfolio within an agreed timeframe to be delivered as new STOR volume.	≥3MW	Asymmetrical	- <=4 hour	-	≥2hour	Loads[1]	-
	Enhanced optional STOR	Provision of a volume of an Enhanced Optional STOR Service from non-BM Providers on a trial basis for winter 2017. This service creates an opportunity for National Grid to access additional non-BM volume closer to the real time.	-	Asymmetrical	<=20min	-	-	Generators, loads, and storage[1]	-
	Demand turn up	Developed to allow demand side providers to increase demand (either through shifting consumption or reducing embedded generation) as an economic solution to managing excess renewable generation when demand for electricity is low (curtailment avoiding).	≥1MW	Asymmetrical -	<5 minutes	-	Specified time windows, Time windows. ~12h per day in summer	Loads/distributed generators[1]	- Two routes to market for Demand Turn Up providers in 2017: Fixed and Flexible.

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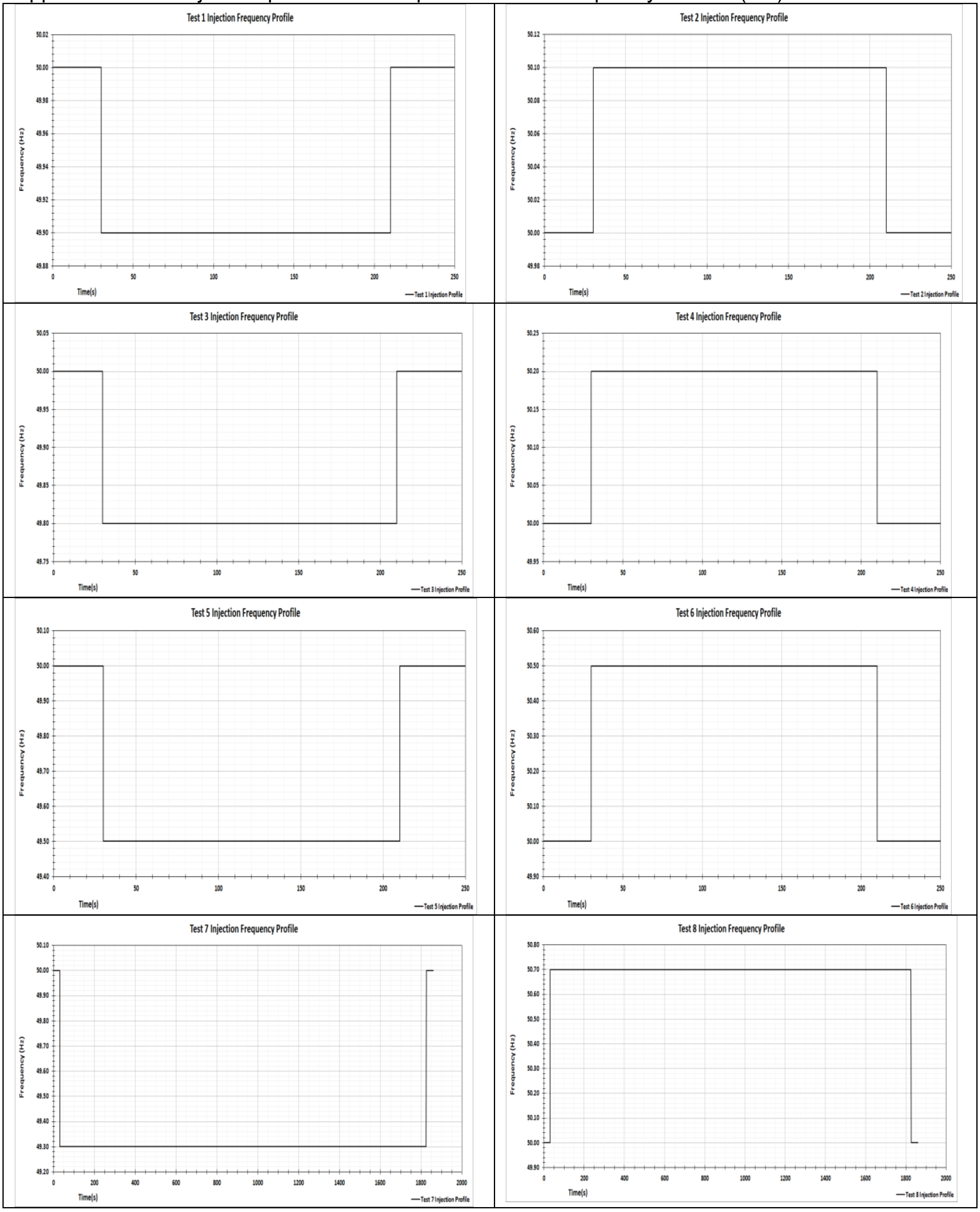
[1] Service provided by an aggregation-based portfolio is allowed.

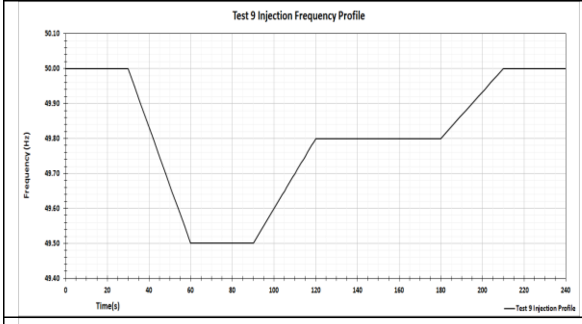
Appendix 2 Status and requirements of DSR in selected EU member states and Switzerland and Norway

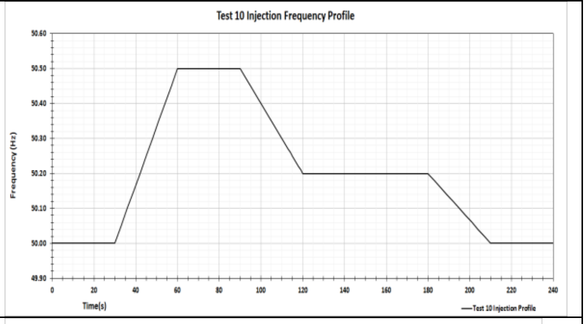
Country (Synchronous area)	DSR status	DSR (tailored) requirements
CH (UCTE)	Individual or aggregated DSR can act in a balancing group.	No tailored DSR programs, therefore DSR are treated the same as generation technologies when providing grid services
DE(UCTE)	In principle, individual or aggregated DSR allowed in Balancing markets, but the actual share is almost none due to entry barriers. There are DSR tailored programs like immediately and quickly interruptible loads.	Immediately interruptible load, 5-200MW, automatically activated by frequency deviation or remote control, activated within 350 milliseconds for frequency-deviation controlled, within 1second for remote control , maximum duration 32x15min,
		Quickly interruptible load, 5-200MW, remote control, activated within 15min, maximum duration 32x15min,
ES(UCTE)	DSR has access only to Interruptible Load Program.	Interruptible Mainland (automatic), minimum 5MW/90MW. Three execution methods (preparation-maximum duration): a) Instant-1hour; b) Fast 15min-1hour; c) hourly 2hour-1hour,
		Interruptible Islands (automatic), minimum 5MW. Five options: a) instant -1hour; b)5min-2hour; c)1hour-3hour; d) 2hour-8hour; e) 2hour-12 hours,
NL(UCTE)	Individual or aggregated DSR can act in balancing markets (secondary and tertiary Reserve). DSR can offer balancing services to BRPs.	No tailored DSR programs, therefore DSR are treated the same as generation technologies when providing grid services.
FR(UCTE)	Individual or aggregated DSR allowed in Balancing and ancillary markets. Tailored program such as DSR-RR is also available.	DSR-RR is a tender-based manual reserve, minimum 1MW, activation time less than 2 hour, duration up to 10 hours.
DK-W(UCTE)	Balancing regulation is generation-centric but not excluding DSR. DSR can be aggregated in a balancing group, therefore accessing balancing markets and ancillary services.	No tailored DSR programs, therefore DSR are treated the same as generation technologies when providing grid services.
DK-E(Nordic)		
NO(Nordic)	DSR can be aggregated in a balancing group, therefore accessing balancing markets and ancillary services.	No tailored DSR programs, therefore DSR are treated the same as generation technologies when providing grid services.
UK(United Kingdom)	Ancillary service market is open to DSR, also with several tailored programs.	FCDM for frequency control, STOR Runway, Demand turn up (requirements see Appendix 1-5)

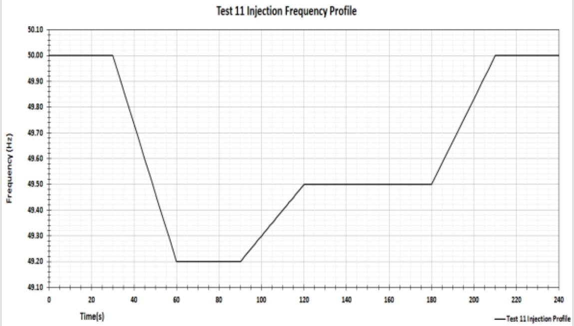
Appendix 3 Pre-qualification requirements for frequency control services in selected countries

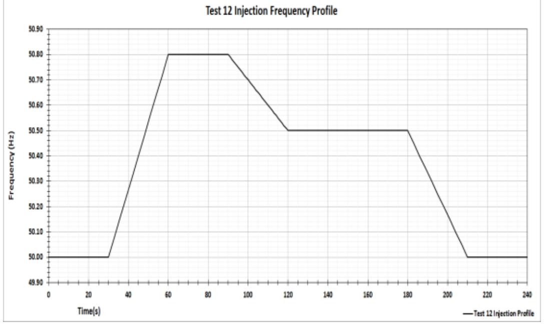
Appendix-3-1 15 Injection profiles for Prequalification of Frequency Control (UK)

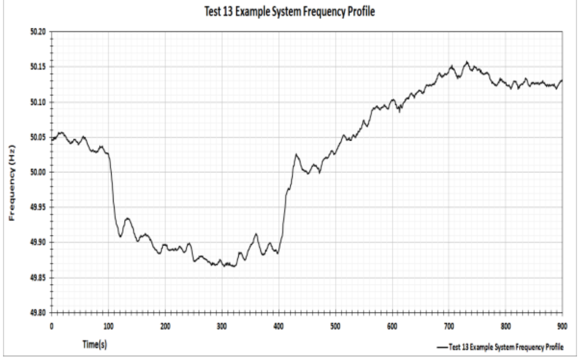


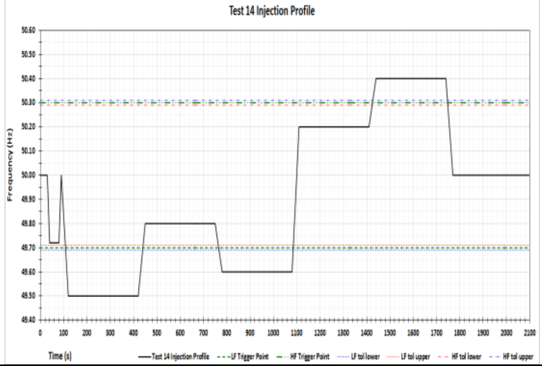


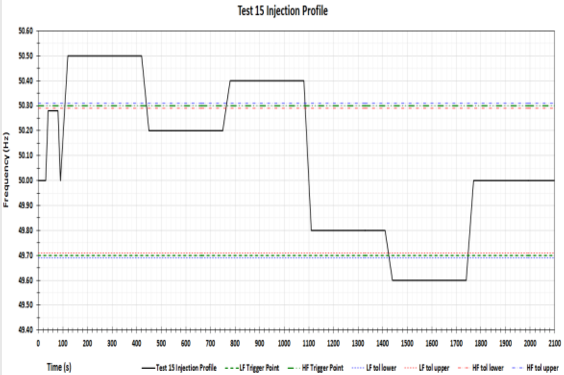






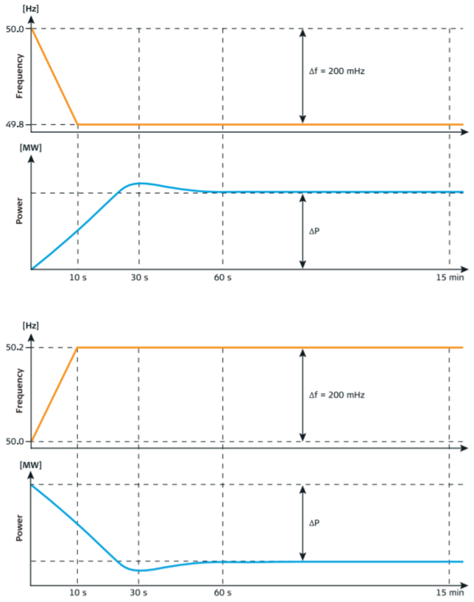
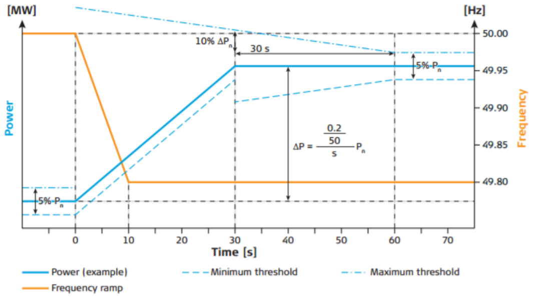
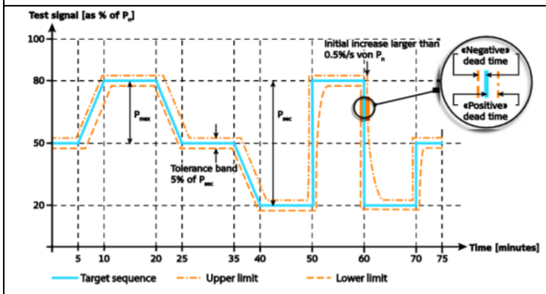






These 15 test signals are combined in different ways to test the performance of various technical characteristics, such as Speed of Response Delivery (T1-T8), Proportionality of Response (T1-T12), and Sustainability of Response (T7-T8 for dynamic services and T14-T15 for static services). Detailed requirements can be found in [5]-[7].

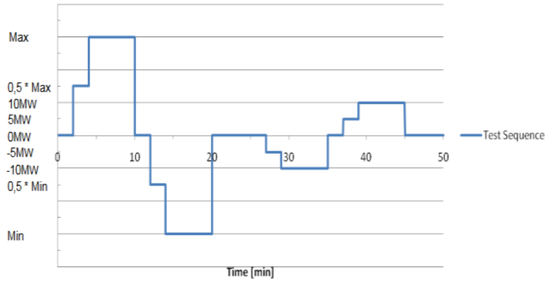
Appendix-3-2 Pre-qualification test Primary and Secondary Frequency Control (CH)

	 The test for Primary Frequency Control constitutes ideal testing signals indicated by left figure, with recorded performance characteristics must be within the tolerance limits indicated by the figure above.[8] Requirements for the technical setup include • Accuracy of the transformer: < 0.5 % (of the nominal value, where possible Class 0.1) • Metering time period: 100 ms • Recording period: ≤ 30 min • Nominal frequency: < 5 mHz
	Test signal with tolerance band for Secondary Frequency Control: Signal is issued by grid operator. The difference between the maximum and the minimum power should be at least 60 % of the nominal output Pn, must be greater than 10 MW and should be aligned with the secondary control power subsequently offered. An operating point at approx. 50 % nominal output can be selected as the start value.[9]

Appendix-3-3 Pre-qualification test Primary Reserve (TENNET for NL and DE)

Primary reserve	Testing signals are simulated to mimic the frequency variation. Detailed testing procedure is described in [10] for different operational conditions.

Appendix-3-4 Pre-qualification test FRR (NO)

	Testing signals are provided to test the response after an approved signal test that verifies the accuracy of communication channel. In addition to testing the desired response, there is a test to test the AGC responds properly to a simulated short loss of communication [11].

Appendix-3-5 Pre-qualification test (FR) [12]

FCR

Test 1:

- unit at max power ($P_{maximum\ groupe}$, maximum power notwithstanding the reserved power for FCR/FRRa)
- Injection of an artificial echelon of Δf = -200mHz for 15 minutes at the speed regulator

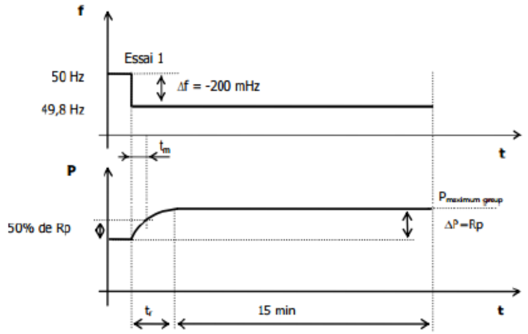


Figure 1

- t_m: time to obtain 50% of Rp
- t_r: time to obtain 95% of Rp

Test 2:

- unit at max power ($P_{maximum\ groupe}$, maximum power notwithstanding the reserved power for FCR/FRRa)
- Injection of an artificial echelon of Δf = +200mHz at the speed regulator

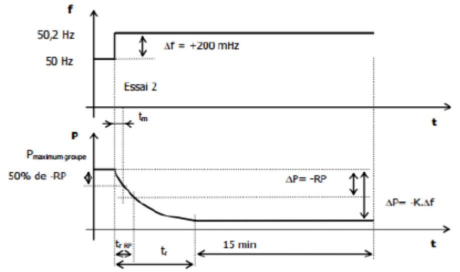


Figure 2

- t_m: time to obtain 50% of -Rp
- $t_{r\ RP}$: time to obtain -Rp
- t_r: time to obtain 95% of –K.Δf

with K: regulating energy of the group (MW/Hz)
Δf: echelon used

Test 3:

- unit at max power ($P_{maximum\ groupe}$, maximum power notwithstanding the reserved power for FCR/FRRa)
- Injection of an artificial echelon of -50mHz at the speed regulator

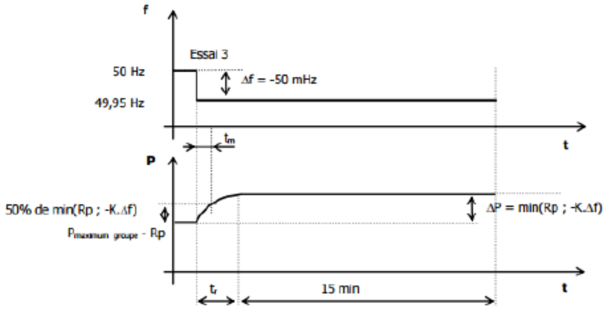


Figure 3

- tm: time to obtain 50% of min(Rp; –K.Δf)
- t_r: time to obtain 95% of min(Rp; –K.Δf)

Test 4:

- Same as test 3 with an echelon of Δf = -15mHz

Test 5:

unit at max power ($P_{maximum\ groupe}$, maximum power notwithstanding the reserved power for FCR/FRRa)

Injection of an artificial echelon of +50mHz at the speed regulator

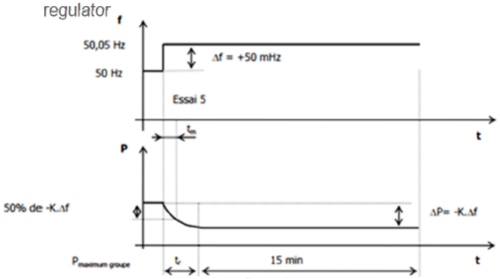


Figure 4

tm: time to obtain 50% of –K.Δf

t_r : time to obtain 95% of –K.Δf

Test 6:

Same as test 5 with an echelon of Δf =+15mHz

Test 7:

unit at min power ($P_{min\ groupe}$)

Injection of an artificial echelon of -50mHz at the speed regulator for 15 min

Compliance criteria:

Non oscillating waveform response

Time t_r < 30 sec. for all tests except test 2

Time t_r < 30+20 sec. for test 2 (if –K.Δf ≥ -RT)

Time t_m <15 sec.

For test 1: the variation ΔP=Rp maintained for 15 minutes (after t_r)

For tests 2 and 5: the variation ΔP= -K.Δf maintained for 15 minutes (after t_r)

For tests 3 and 7: the variation ΔP=min(Rp; -K.Δf) maintained for 15 minutes (after t_r)

For tests 4 and 6: the variation ΔP ≥ 0.005*K MW maintained 15 min (after t_r)

For tests 2, 3 and 5, the recordings must prove that regulating energy K measured = regulating energy preset within 5%.
The regulating energy K is calculated thanks to the test 2 and is equal to $\frac{(P-P_{co})}{(f_0-f)}\ ie. \frac{\Delta P}{\Delta f}$

aFRR

Test 1:

Group at its max power ($P_{maximum\ groupe}$) at which is subtracted the FRRa range 2*Pr

Artificial injection of a ramp for the parameter N from -1 to +1 (see figure 1) in 800 seconds and sustain the +1 level for 15 minutes

Test 2:

Group at its max power ($P_{maximum\ groupe}$)

Artificial injection of a ramp for the parameter N from +1 to -1 (see figure 1) in 800 seconds and sustain the -1 level for 15 minutes

Test 3:

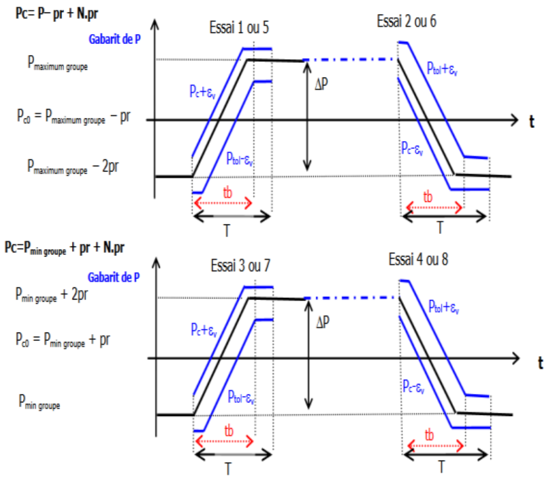
Group at its minimum power ($P_{min\ groupe}$)

Artificial injection of a ramp for the parameter N from -1 to +1 (see figure 1) in 800 seconds and sustain the +1 level for 15 minutes

Test 4:

Group at its minimum power ($P_{min\ groupe}$) at which is added the FRRa range 2*Pr

Artificial injection of a ramp for the parameter N from +1 to -1 (see figure 1) in 800 seconds and sustain the +1 level for 15 minutes



Test 5:

- Same as test 1 but with a variation time of 133s instead of 800s.

Test 6:

- Same as test 2 but with a variation time of 133s instead of 800s.

Test 7:

- Same as test 3 but with a variation time of 133s instead of 800s.

Test 8:

- Same as test 4 but with a variation time of 133s instead of 800s.

ε_v: uncertainty on the active power mesure, equal to max(1 MW ; 5% Pr)

tb: time response to attain the FFRa fully

T: time of the ramp augmented by 100s

P_{tol}: $P_c/(1+T_{max}*p)$ (Filtering the set point by a time constant)

Compliance criteria:

For each test:

- Non oscillating waveform response as shown is figure 1
- ΔP=2*Pr

For positive ramps (tests 1,3,5 and 7):

- The measured power must be within the [Pc+ ε_v;P_{tol} - ε_v] range at least 95% of the time
- Pc=P0 + N*Pr
- $P_{tol} = P_c/(1+T_{max}*p)$
- T max=20sec.
- ε_v = max(1 MW ; 5% Pr)

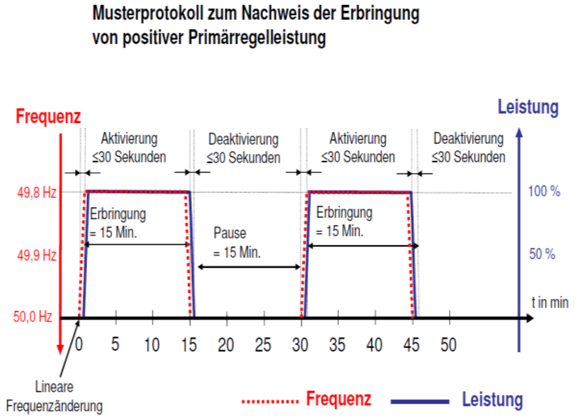
For negative ramps (tests 3,4,6 and 8):

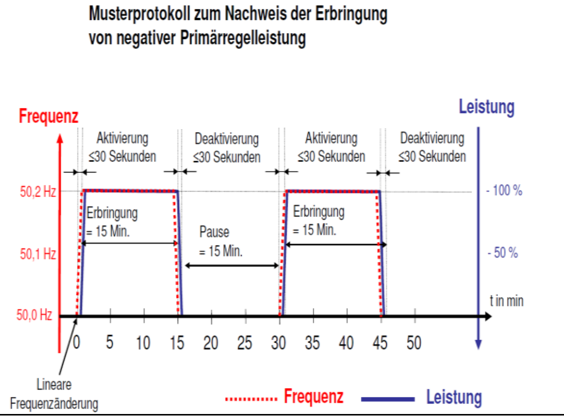
- The measured power must be within the [Pc- ε_v;P_{tol} +ε_v] range at least 95% of the time
- Pc=P0 + N*Pr
- $P_{tol} = P_c/(1+T_{max}*p)$
- T max=20sec.
- ε_v = max(1 MW ; 5% Pr)

The FFRa must be maintained for 15 minutes

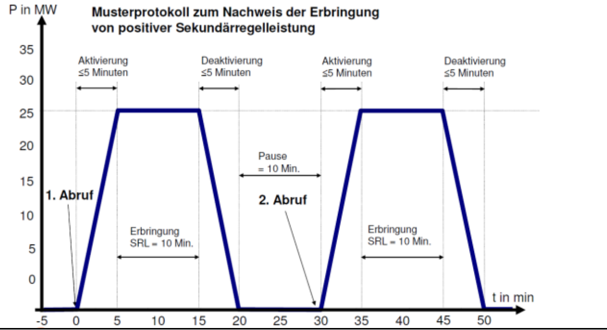
Appendix-3-6 Pre-qualification test (DE) [13]

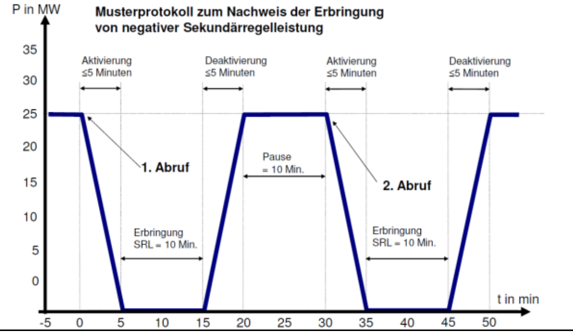
Primary control reserve



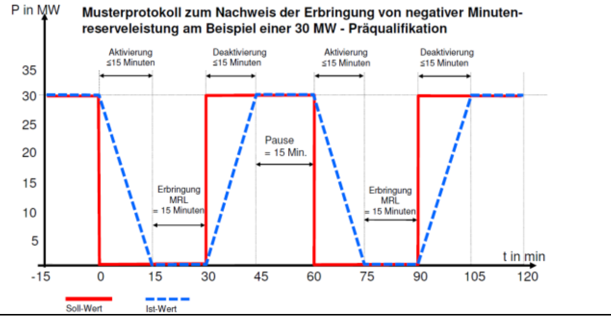


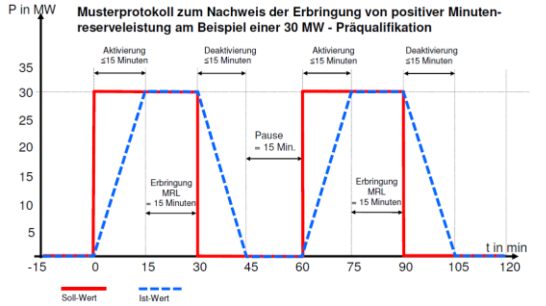
Secondary control reserve





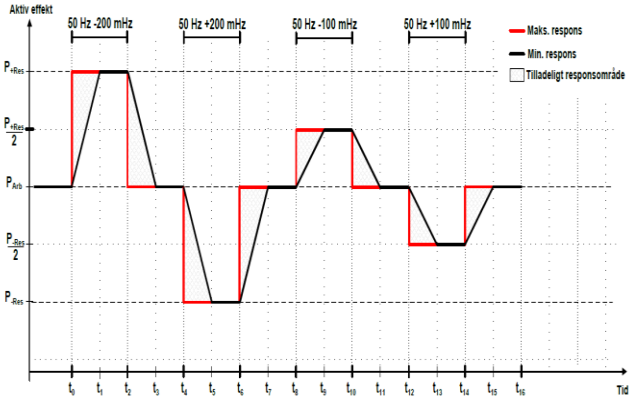
Tertiary control reserve (minute reserve)





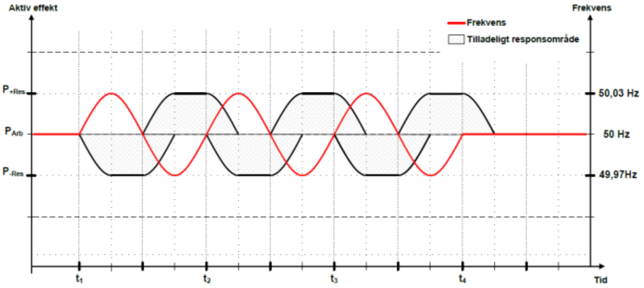
Appendix-3-7 Pre-qualification test (Denmark) [14][15]

FCR (DK-W)



Test af minimumskrav til respons for FCR (Primærregulering) i DK1.

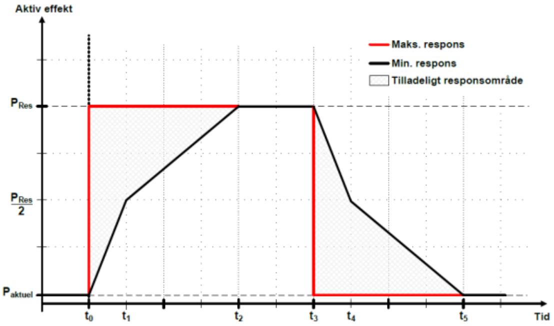
Tidsparametre	Tid
$t_0 - t_1$	Som specificeret i Figur 2
$t_1 - t_2$	15 min
$t_2 - t_3$	Som specificeret i Figur 2
$t_3 - t_4$	1 min
$t_4 - t_5$	Som specificeret i Figur 2
$t_5 - t_6$	15 min
$t_6 - t_7$	Som specificeret i Figur 2
$t_7 - t_8$	1 min
$t_8 - t_9$	Som specificeret i Figur 2
$t_9 - t_{10}$	15 min
$t_{10} - t_{11}$	Som specificeret i Figur 2
$t_{11} - t_{12}$	1 min
$T_{12} - t_{13}$	Som specificeret i Figur 2
$t_{13} - t_{14}$	15 min
$t_{14} - t_{15}$	Som specificeret i Figur 2
$t_{15} - t_{16}$	1 min



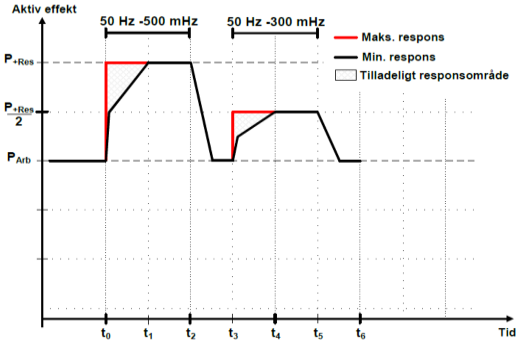
Testforløb for stabilitetstest for anlæg i DK1

Anlægstype	Tidsparametre	Periodetid	Testlængde (6 · Periodetid)
PPM	$t_0 - t_1$	10 s	60 s
	$t_1 - t_2$	15 s	90 s
	$t_2 - t_3$	25 s	150 s
Elkedler	$t_0 - t_1$	15 s	90 s
	$t_1 - t_2$	25 s	150 s
	$t_2 - t_3$	40 s	240 s
Diesel/gas-motoranlæg	$t_0 - t_1$	40 s	240 s
	$t_1 - t_2$	60 s	360 s
	$t_2 - t_3$	70 s	420 s
Kedelanlæg	$t_0 - t_1$	80 s	480 s
	$t_1 - t_2$	100 s	600 s
	$t_2 - t_3$	150 s	900 s

FCR-D(DK-E)



Responsforløb ved en tilfældig aktivering af FCR-D.

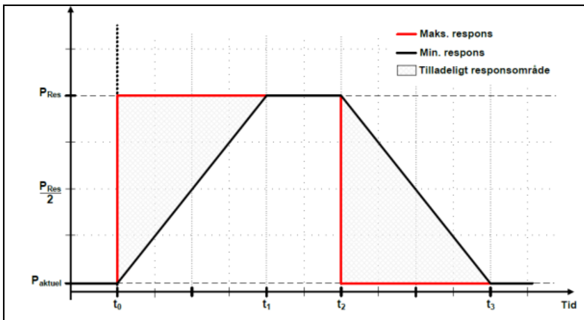


Test af minimumskrav til respons for FCR-D.

Tidsparametre	Tid
$t_0 - t_1$	< 5 s
$t_1 - t_2$	< 25 s
$t_2 - t_3$	Længden af frekvensubalancen, dog minimum 15 min
$t_3 - t_4$	< 5 s
$t_4 - t_5$	< 25 s

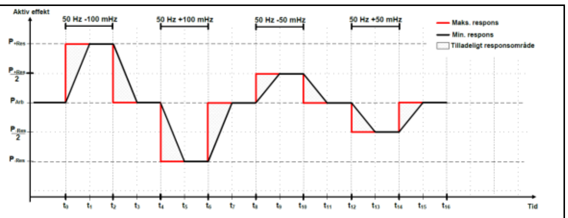
Tidsparametre	Tid
$t_0 - t_1$	Som specificeret i Figur 3
$t_1 - t_2$	15 min
$t_2 - t_3$	1 min
$t_3 - t_4$	Som specificeret i Figur 3
$t_4 - t_5$	5 min
$t_5 - t_6$	1 min

FCR-N(DK-E)



Responsforløb ved en tilfældig aktivering af FCR (FNR) i DK2.

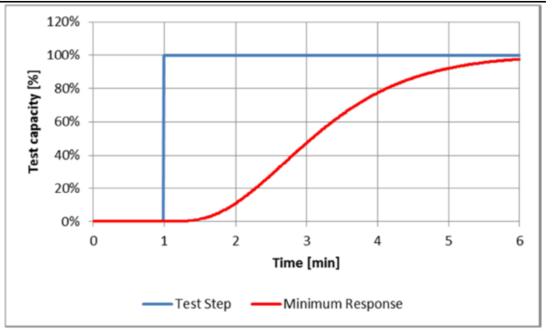
Tidsparametre	Tid
$t_0 - t_1$	150 s
$t_1 - t_2$	Længden af frekvensubalancen, dog minimum 15 min
$t_2 - t_3$	150 s



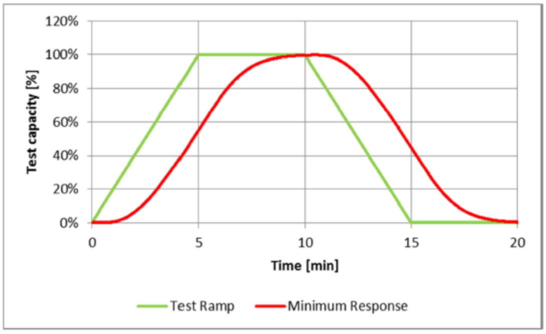
Test af minimumskrav til respons for FCR-N.

Tidsparametre	Tid
$t_0 - t_1$	Som specificeret i Figur 3
$t_1 - t_2$	15 min
$t_2 - t_3$	Som specificeret i Figur 3
$t_3 - t_4$	1 min
$t_4 - t_5$	Som specificeret i Figur 3
$t_5 - t_6$	15 min
$t_6 - t_7$	Som specificeret i Figur 3
$t_7 - t_8$	1 min
$t_8 - t_9$	Som specificeret i Figur 3
$t_9 - t_{10}$	5 min
$t_{10} - t_{11}$	Som specificeret i Figur 3
$t_{11} - t_{12}$	1 min
$T_{12} - t_{13}$	Som specificeret i Figur 3
$t_{13} - t_{14}$	5 min
$t_{14} - t_{15}$	Som specificeret i Figur 3
$t_{15} - t_{16}$	1 min

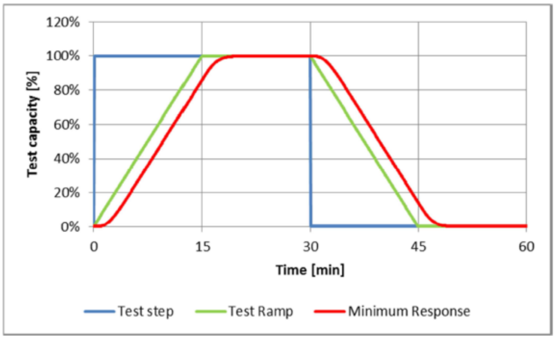
aFRR



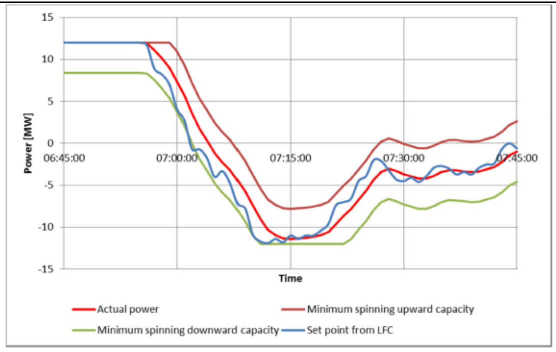
Example of minimum response when the unit/portfolio is tested against a step set-point change in DK2, where 90% of full activation has to be reached within 5 min



Example of requirements when the unit/portfolio is tested against a ramp in DK2, where the response between 20% and 80% shall be at maximum 135 seconds delayed from Test Ramp

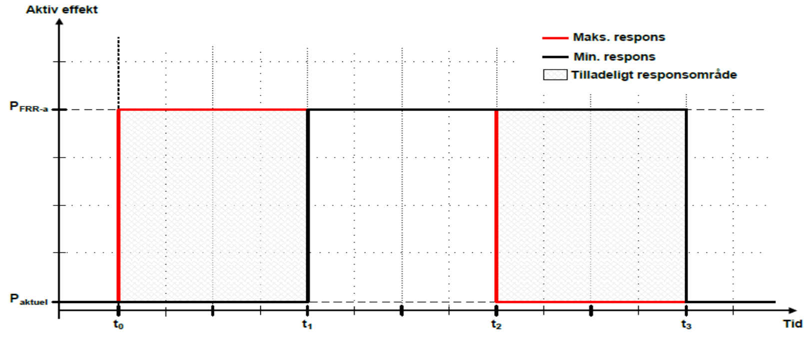


*Example of required response when the unit/portfolio is tested against a step **or** a ramp set-point change in DK1, where the response between 20% and 80% shall be at maximum 135 seconds delayed from Test Ramp values. 85% of full activation has to be reached within 15 min*



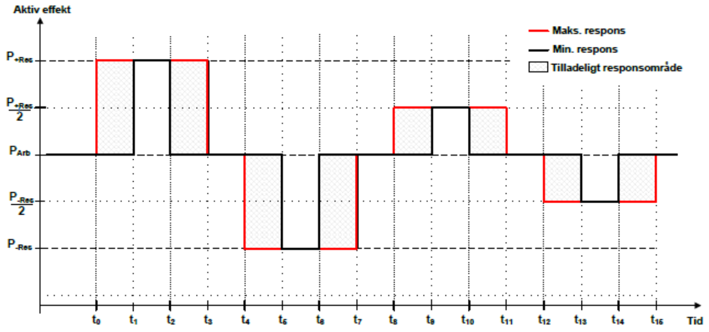
Example of a schedule for activation of FRR-A in DK2 from a capacity of +/- 12 MW.

FRR-M



Responsforløb ved en tilfældig aktivering af mFRR.

Tidsparametre	Tid
$t_0 - t_1$	< 15 min
$t_1 - t_2$	Ubegrænset
$t_2 - t_3$	< 15 min



Tidsparametre	Tid
$t_0 - t_1$	Som specificeret i Figur 1
$t_1 - t_2$	30 min
$t_2 - t_3$	Som specificeret i Figur 1
$t_3 - t_4$	1 min
$t_4 - t_5$	Som specificeret i Figur 1
$t_5 - t_6$	30 min
$t_6 - t_7$	Som specificeret i Figur 1
$t_7 - t_8$	1 min
$t_8 - t_9$	Som specificeret i Figur 1
$t_9 - t_{10}$	5 min
$t_{10} - t_{11}$	Som specificeret i Figur 1
$t_{11} - t_{12}$	1 min
$t_{12} - t_{13}$	Som specificeret i Figur 1
$t_{13} - t_{14}$	5 min
$t_{14} - t_{15}$	Som specificeret i Figur 1

Test af minimumskrav til respons for mFRR.

Appendix 4 An overview of project activities related to using WEs for grid services

Project name	Project type/location	Duration	Short description	Type of grid services	WE technology	Links for further information
H2Future	EU	2017-2021	Demonstration of a 6MW electrolysis power plant installed at the VOESTALPINE LINZ production site (Austria). After the pilot plant has been commissioned, the electrolyser will be prequalified with the support of APG, the Austrian transmission operator, in order to provide grid-balancing services such as primary, secondary or tertiary reserves while utilizing the commercial pools of VErBUND.	Balancing services such as primary, secondary or tertiary reserves	6MW PEM electrolyser	http://www.fch.europa.eu/project/hydrogen-meeting-future-needs-low-carbon-manufacturing-value-chains
DEMO4Grid	EU	2017-2022	Demonstration of 4MW Pressurized Alkaline Electrolyser for Grid Balancing Services	Balancing services.	Pressurized Alkaline Electrolyser (PAE)	http://www.fch.europa.eu/project/demonstration-4mw-pressurized-alkaline-electrolyser-grid-balancing-services
BALANCE	EU	2017-	Reversible electrolyser technology is expected to support the growth of wind and solar energy by providing grid balancing services.	Balancing services.	High temperature steam reversible electrolysers(multi-kW scale)	https://www.balance-project.org/
ECO	EU	2016-2019	develop and validate a highly efficient co-electrolysis process for conversion of excess renewable electricity into distributable and storable hydrocarbons via simultaneous electrolysis of steam and CO2 through SOEC.	conversion of excess renewable electricity into distributable and storable hydrocarbons.	simultaneous electrolysis of steam and CO2 through SOEC	http://www.fch.europa.eu/project/efficient-co-electrolyser-efficient-renewable-energy-storage-eco

ELY4OFF	EU	2016-2019	Development of an autonomous off-grid electrolysers as an energy storage or backup solution (e.g. replacing diesel engines)	Energy storage & Back up	50KW PEM electrolyser	http://www.fch.europa.eu/project/pem-electrolysers-operation-offgrid-renewable-installations-0
HPEM2GAS	EU	2016-2019	Demonstrating a 180-300 kW PEM electrolyser system in a power-to-gas field test; High Performance PEM Electrolyser for Cost-effective grid balancing applications.	P2G and grid balancing	180-300 kW PEM electrolyser	http://www.fch.europa.eu/project/high-performance-pem-electrolyzer-cost-effective-grid-balancing-applications
ELYntegration	EU	2016-2019	an operational environment reflecting different on-grid integration schemes using 635 kW wind and 100 kW photovoltaic power plants.	Balancing services at various time scales.	A high pressure AWE industrial prototype of 250 kW	http://www.fch.europa.eu/project/grid-integrated-multi-megawatt-high-pressure-alkaline-electrolysers-energy-applications
Towards solid oxide electrolysis plants in 2020	DK	2015-2017	Further improve performance and durability of SOEC cells and stacks targeting applications specifically for regulating the future Danish power system with a high amount of fluctuating renewable energies.	Balancing service for TSO on market basis (details to be investigated) (DK)	SOEC (cell and stack)	http://vbn.aau.dk/da/projects/towards-solid-oxide-electrolysis-plants-in-2020(ee9c4a78-48a6-4854-9dec-9714893eebbd).html
HyBalance	EU	2015-2020	Demonstrate large scale hydrogen production from wind power, electricity storage, grid balancing and supplying the industrial and the transportation sector with green hydrogen.	Balancing service for TSO on hourly basis (details to be investigated) (DK)	1MW PEM electrolysis plant	http://hybalance.eu/
Energiepark Mainz	DE	2015-	A community scale project. Electrolyser connected to wind park and grid. H2 Storage, Trailer, gas grid. Testing technical and economic aspects.	Trading at the European Power Exchange, offer secondary control reserve, (DE)	Siemens PEM 6.3MW	http://www.energiepark-mainz.de/en/
MHYRABEL	FR	2015-	Wind Power to hydrogen for mobility, electriciy, gas injection and heat	P2G, Power-to-Power, multiple grid services	PEM Steam elecrolysis	http://www.smartgrids-cre.fr/index.php?p=mhyrabel

GRHYD	FR	2014-2019	Power to hydrogen project hydrogen for injeciton in the gas grid or for CH4/H2 mobility	P2G, energy storage.	PEM	http://www.engie.com/en/innovation-energy-transition/digital-control-energy-efficiency/power-to-gas/the-grhyd-demonstration-project/
JUPITER 1000	FR	2014-2020	Demonstration of massive renewable energy storage into the transmission gas grid.	P2G, renewable power storage.	PEM (0,5 MW) and alkaline (0,5 MW)	http://www.jupiter1000.com/en/accueil.html
Thüga Frankfurt	EU	2013 - 2016	Test multiple dynamic balancing grid services. Demonstration of integration of power to gas in DSO networks. H2 feed in gas grid. Efficiency tested 77%.	Primary control reserve load profile of grid frequency variation; pre-qualification for secondary control market passed in 2015	ITM 300 kW PEM	https://www.szg-energiespeicher.de/no_cache/header/presse/presseinformationen/presseinformationen-detail/article/pressemitteilung-72.html
Audi e-gas	DE	2013-	Bio methane produced through P2G.	P2G	6MW Alkaline Hydrogenics	http://www.audi.com/corporate/en/corporate-responsibility/we-live-responsibility/product/audi-e-gas-project.html#fullwidthpar__ah_2
Falkenhagen EON	DE	2013-	P2G, feed to high pressure gas grid, using surplus local wind energy when it cannot be fed in grid.	P2G, wind curtailment	alkaline 2 MW, 360Nm3/h H2	http://www.powertogas.info/power-to-gas/pilotprojekte-im-ueberblick/windgas-falkenhagen/
KompElsys	DE	2012-2016	New generation PEM electrolyser installed in Hamburg Reitbrook, grid feed in. Technical feasibility for P2G	Electricity supply contract options.	Hydrogenics 1MW PEM	-
MYRTE	FR	2008-2017	PV + hydrogen (electrolyser and fuel cell) for peak shifting Experimentation of integration of a 650 kW solar plant on the electric grid.	PV output smoothing.	PEM electrolyser (200kW) and Fuel Cell (210kW)	http://myrte.univ-corse.fr/

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