TKI Wind op Zee

Ancillary services from offshore windfarms in the Netherlands

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Introduction

In the framework of the intended reduction of LCOE of offshore wind energy by 40% in 2020, one of the options identified for further research is focusing on increasing revenues by wind farms from the delivery of ancillary services to the electricity grid. Therefore the TKI Wind op Zee has commissioned, through the Netherlands Enterprise Agency, this study to assess the technical and economic potential for ancillary services in the Dutch context and related to offshore wind farms. The study provides an overview of the possible ancillary services, an indication of the value of these services and the required developments in the wind farms and their deployment of ancillary services in the Dutch power system. The indicative time horizon for future developments is 2023. The results of the study includes a high level R&D and innovation roadmap targeted at implementation of these services.

The study essentially builds on published information, research results and market information. Opinions and interpretations of the author have been checked by interviews with principal stakeholders: transmission network operators (Tennet, ENTSO-E), and wind farms operators.

The report is divided into four parts:

- Chapter 1 introduces principles of ancillary services in power systems in general and in the context of the Dutch power system including the applicable regulations and grid codes
- Chapter 2 discusses possible provision of ancillary systems by offshore wind farms, addressing technical capabilities, operational aspects and costs;
- Chapter 3 assesses the potential and of ancillary services by offshore wind farms in the context of the characteristics of the electricity market in the Netherlands;
- Chapter 4 summarizes a roadmap for R&D efforts to enable efficient deployment of ancillary services by offshore wind farms. Details on the proposed research themes are described in a separate document (presentation).

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1 Possible ancillary services and general network and market context

1.1 General introduction on ancillary services

Network operators need a variety of system services for a secure and reliable operation of the electrical power system. Generators (as well as flexible loads, and other network connected devices) can provide these ancillary services (AS). As offshore wind farms are connected to the HV level, this report limits to ancillary services to the network managed by the Dutch operator (Tennet)[1].

At present, offshore wind is exempted from AS delivery in most European countries[2] including The Netherlands [1]. However, it is foreseen that offshore wind power as a significant generation source will participate under defined conditions and terms.
The technical and economical modalities of AS provision - especially in competition with conventional plants and considering the present high cost of offshore wind power - strongly depends on the rules and practices in the power market, which are rapidly changing today (par. 1.4).

This study focuses on services[3] identified in the European REserviceS project [2] as possible and relevant for being procured from renewable generation in the area of frequency support , voltage support and system restoration:

- **Frequency services** support the balancing actions by the TSO in different time frames (from seconds to hours). Frequency services have a system wide effect, and thus are relevant for exchange across country borders – be it over land or over sea.
- **Voltage services** support maintaining the required voltage profile and the management of voltage stability in the network. Voltage support generally is delivered in the form of reactive power[4] exchange between the device (generator or other) and the network. Unlike frequency services, voltage services through reactive power serve localized network needs.
- **System restoration services** include actions of power plants to assist the reestablishment of normal operation of the power system after the occurrence of a black-out in the network. They include participation in black-start procedures and possibly islanding operation in combination with loads.

[1] The MV and LV level (distribution network) have their specific Ancillary Services

[2] Exceptions are France and GB

[3] Other possible services include congestion management etc. The present study focuses on the ones that are considered most relevant in the Dutch context

[4] Reactive power (VARs) is required to maintain the voltage to deliver active power (watts) through transmission lines.

Technical and operational requirements for power plant capabilities, functionalities and performances related to AS delivery are formulated in Network Codes[5] or Grid Codes (par. 1.4).

The system of remuneration for AS – especially for frequency services - is complex a.o. because of the multitude and diversity of possible AS 'products' and moreover because of the changing market conditions in the framework of harmonization in the internal European energy market.

Important factors of change in power system needs of AS due to high share of renewable generation – in this case offshore wind farms as identified in previous studies at the international level [2], [3] include:

- The additional uncertainty in the power system due to the variability of (offshore) wind increases balancing reserve requirements[6] in different time scales, especially at low levels of on-line traditional synchronous generation (gas, coal etc. plants).
- The replacement of synchronous generation – as traditional providers of ancillary services - by non-synchronous[7] variable renewables such as offshore wind power changes the amount and locational availability of reactive power in the network, and necessitates additional reactive power management from all network assets, power plants, including variable renewables.
- Increasing occurrences of low levels of synchronous generation on-line (because of replacement by non-synchronous generation), for example during moments of high wind, combined with low electricity demand, reduces system inertia[8], and may require additional fast frequency support (e.g. synthetic inertia).

Consequently, the role and share of ancillary services (reactive power and frequency services) from offshore wind farms in the future as conventional generation is being replaced will grow, not only in terms of larger amounts of services, but also in new 'enhanced' services to be developed by TSO's. The REserviceS simulations show that allowing wind power to participate in frequency reserves in the central European power systems – including the Netherlands [11] - brings considerable economic benefits, and more so with increase of the share of wind power in the demand.

However, the future role of renewables as AS providers in most European power systems – including the Netherlands - is unclear as the 'traditional' market and framework conditions are still geared

[5] The presently developed European Network Code Requirements for all Generators (NC RfG) of ENTSO-E [33] is the guiding document for national Grid Codes with requirements for capabilities of offshore wind farms connected via HV AC (paragraph 1.5.1).

[6] A survey and quantification of additional reserve requirements is given in the IEA Task 25 report [3]

[7] non-synchronous: rotational speed of the generator and thus 'generator frequency' is de-coupled from the network frequency.

[8] System inertia is an essential part of the power system response to frequency events, its magnitude being proportional to the system's resilience to a sudden frequency change.

towards the traditional providers of these services, and are not yet allowing an optimal and cost–efficient deployment of the capabilities of the renewable generators (see further Chapter 3).

1.2 Ancillary services in the Dutch context

This section introduces the various ancillary services frequency support, voltage support and system restoration to the needs of the Dutch TSO TenneT, focusing on those services where offshore wind may contribute. The overview demonstrates (a) that there is a system of AS, (b) offshore wind farms hardly participate in the services now; (c) more services than the existing ones may be needed in future.

1.2.1 Frequency services

Frequency services consist of reserve provision in different time frames to help the balancing action of the TSO to control the system frequency. The reserves are listed in Table 1 and subdivided into[9] primary, secondary and tertiary reserves. Basically the action of the generator in each of the reserve types is holding and delivering capacity and/or energy for up and/or downwards support of the frequency.

In the framework of market integration in Europe, a uniform definition of the reserves listed in Table 1 and their corresponding characteristics throughout Europe is still in the making[10]. The present lack of EU –wide uniformity in framework conditions of the reserves is still hampering cross-border exchange of services. The Dutch TSO is involved in several harmonisation efforts (see par. 1.3.3).

In the Netherlands, frequency services are supplied to the TSO via an organised market. As stated before, wind farms in The Netherlands are not yet participating in this market of reserve provision. The possibilities are discussed in par.3.2.2

RESERVE	NL term	ENTSO-E	Time scale	description
Primary control reserve (PCR)	**Primaire Regeling**	Frequency Containment Reserve FCR	seconds	starts automatically within seconds after a frequency 'disturbance' and is carried out as joint action of all generators contracted for that purpose
Secondary control Reserve (SCR)	**Regelvermogen**	Frequency Restoration ReserveFRR	< 15 minutes	replaces the primary control reserves after minutes; activation can be automatic or manually.
Tertiary control Reserve (TCR)	Reservevermogen	Replacement Reserve RR	15 min to hours	replaces the secondary control by re-scheduling of generation; activation is manually

Table 1 Types of control reserve where offshore wind farms may participate

[9] Apart from that, the NL also has Noodvermogen – however for several reasons not interesting for provision by RES.

[10] Subject of work of the ENTSO-E Working Group Ancillary Services (www.entsoe.eu)

Recent publications [2], [4] describe enhanced types of frequency service that in future may become relevant with large shares of variable renewables. One of those is Fast Frequency Response, to support the system frequency in very short time frame (below 5 seconds), relevant in situations when sources for system inertia may become significantly reduced[11]. System operators in Continental Europe (Tennet, ENTSO-E) indicate that this only becomes relevant for the Netherlands in a far future[12], as Netherlands is embedded in the large European interconnected system where the need for additional inertia support above the synchronous rotating masses inertia is still far away. In this study, the subject is addressed in the framework of long-term R&D (Chapter 4).

1.2.2 Voltage services

Control of the system voltage profile by voltage services is tightly connected to reactive power control[13]. The voltage control services are then needed to ensure that adequate voltage support is maintained and that sufficient reactive power is present in the relevant electrical regions to ensure voltage stability. For convenience, the relevant service is called Steady-state Reactive Power/Voltage Control (SSVC) [2]. The voltage service provider – in casu offshore wind connected via HV platform - is controlling the onshore voltage node profile during normal network operation to a target value or within a target range injects or absorbs reactive power.

Unlike energy for balancing and reserves, reactive power is not a tradable commodity[14]. The capability for generators (or other network assets) to provide reactive power is prescribed in the applicable Grid Code. Beside these Grid Code requirements the system operator may procure (augmented) voltage services, against a remuneration.

At present, the Dutch TSO presently is procuring reactive power services from generators, including wind farms, via bilateral contracts.

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[11] With an increasing penetration of non-synchronous generation in the system (e.g. through increasing converter connected generation like wind and PV) there will be an increasing need for capabilities from generators to supply very fast frequency response. This is already included in several present national Grid Codes as well as in the ENTSO-E NC RfG. A possible technical implementation could consist of additional increase in active power (MW) output from a wind turbine following a frequency event that is available within 2 seconds of the start of the event and is sustained for at least 15 seconds – based on the immediate release of the kinetic energy stored in the rotor.

[12] Communication Tennet

[13] Voltage can be controlled through voltage control, reactive power control, power factor control or by a combination of two of these, so they are often referred to as voltage/reactive power control.

[14] Reactive power is not a (tradable) commodity and in the end is always lost. It has to be paid for by the TSO but these costs cannot be recovered unlike the costs for active power services.

The REserviceS study [2] describes a type of enhanced voltage service that in future may become relevant with very large shares of variable renewables, namely Fast Reactive Current Injection (FRCI) during network faults. The 'standard' capability for wind farms to do so will be included in the Grid Code (see par.1.4). The possible procurement of an enhanced FRCI on a commercial basis from wind farms remains to be explored (see Chapter 4).

1.2.3 System restoration services

System restoration services are included in this review because in future they may be also called upon from offshore wind farms [2]. A relevant service, black-start, is used in the power system restoration phase, defined[15] as "a set of actions implemented after a disturbance with large-scale consequences to bring the system from emergency or blackout system state back to normal state". Presently, wind farms are not providing this service, as TSOs have even higher demands for reliability than during normal operation and will avoid any components adding uncertainty. This means that for wind, uncertainty and variability during this time should be fully mitigated (for example by adding local storage) in order to be suitable/ eligible for this service provision.

The Dutch TSO is presently not considering involvement of wind farms in black start[16].

1.3 Offshore wind power in the Dutch power system context

The evaluation of the possibilities of ancillary services from OWFs needs to consider a broad spectrum of aspects of the power system. Of primordial importance for ancillary service provision is (a) the share of offshore in the total generation mix and (b) how offshore wind farms are connected to the transmission network.

1.3.1 Development of offshore wind power in the Dutch generation mix

The generation mix and its likely development in time determines in principle all potential[17] participants in ancillary services provision: from slow coal power plants to distributed variable generation. The type of plant (gas, coal, wind) influences its flexibility and costs of service provision. The projections for the period are summarized in Table 2.

	2015	2020	2023	2030
(A) Total generation capacity (GW)	28.5	33.0	36.5	>>50.0
(B) Installed capacity offshore wind (GW)	0.35	2.05	4.5	16.0
(C) Share of offshore wind capacity in mix (%) C = B/A	1.2	6	12	>30

[15] ENTSO-E Operational Handbook, Policy 5, Appendix

[16] Communication Tennet

[17] Potential : because renewables are not yet participating in most of the applicable services.

(D) Energy penetration (%)	1%	7	16	>50

Table 2 Projections for development of generation capacity in The Netherlands and offshore wind capacity until 2030.

The numbers in Table 2 use following assumptions:
- The development of total generation capacity is based on [6] and [7]. The total generation capacity for 2030 is only an indicative value;
- The development of offshore wind will follow assumptions of the Energie-akkoord; the number for 2030 is based on 'prudent' expectations by NWEA [9]
- The energy penetration is calculated based on demand assumptions [6]

Assessing these numbers in perspective of AS brings forward a number of observations, positioned in time windows of characteristic mile-stone years in the Dutch energy policy (now, 2020, 2023, 2030). In the period up to 2020 offshore wind will remain a relatively small fraction of the total generation mix and will – depending on specific service - be a marginal player in this time frame, against the role of gas and coal plant. At the same time, the market mechanisms relevant for AS may change substantially in the frame of European integration of energy markets in favour for cost-effective deployment by offshore wind farms.

The period between 2020 and 2023 can be considered as a transition to significant wind penetration levels, where the relative position of offshore wind as AS provider increases significantly.

a) The situation after 2023 should probably be considered in a different way compared to the periods before with respect to the position of offshore wind as AS provider. The development of offshore wind may – unlike the period before – sustainably incorporate trends that will influence AS provision:
b) connection of wind farms to HV DC offshore grid – resulting in different technical performances of service delivery (see par. 1.4);
c) technical advances in control and wind power forecasting;
d) substantial role of energy storage and flexible demand in the system;
e) substantially lower LCOE of offshore wind (after successful results of present efforts like TKI WOZ), affecting the competitive position towards other service providers18; changed (lower) feed-in tariffs.
f) very high instantaneous SNSP19 ratio's – and consequently substantially changed needs for AS (inertia, new forms of voltage support) [2]

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18 For example due to the reduced opportunity costs

19 SNSP is a measure of the non-synchronous generation on the system in an instant. It is a ratio of the real-time MW generation from wind / solar PV and HVDC imports to demand plus HVDC exports.

g) changed position of thermal generation (higher costs of AS provision due to lower capacity factors, more cycling, higher number of occurrences of minimal generation.
h) Completion of the internal electricity market in Europe – including implementation of target harmonised market rules facilitating cross border exchange of services (see par. 1.4.2).

Preparing for these developments should be driving long-term research (see Chapter 4).

1.3.2 Connection of offshore wind to the Dutch electricity grid

The Dutch system operator TenneT has been appointed to roll out the offshore grid to connect the planned 3.5 GW offshore wind capacity described in par. 1.3.1 [8]. In the period up to 2023, offshore wind will be built in clusters of 700 MW, each connected to a central HV platform installed by Tennet [6] as illustrated in Figure 1. The choice has been made for a HV AC, motivated by its lower costs considering the relatively small distances to shore (appr. 20 km) and the fact that the HV AC platforms are less bulky than platforms for HV DC equipment [8]. The wind farms in the clusters will be interconnected at 66 kV voltage[20]. Each wind farm will be connected to the platform with up to 5 cables at 66 kV. The connection from each platform to shore is via HVAC - 220 kV line (double/redundant).

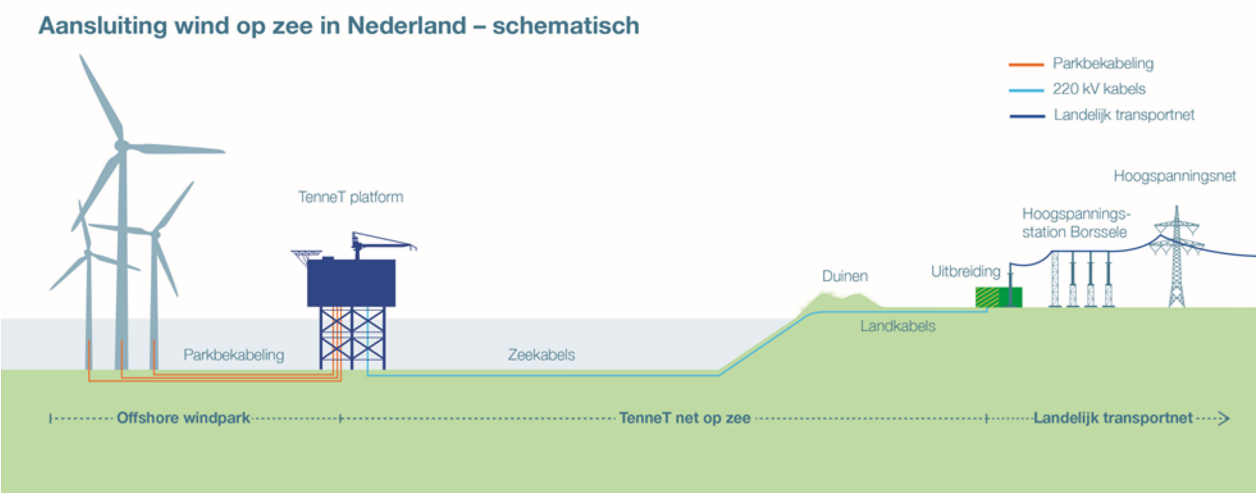

Figure 1 Connection of offshore wind farms schematically (TenneT)

Further expansions of offshore wind beyond the presently planned 4.5 GW farther from shore will probably connect to a (meshed international) HV DC offshore grid. Such an offshore grid – combining the functions of electricity trade and connection of offshore wind power - is the natural vehicle for transporting frequency services [1]. HV DC technology implies specific approaches regarding ancillary services (Chapter 2).

[20] Verbal communication of Tennet March 2015

1.3.3 International context, exchange of services with EU member states

Opportunities of cross-border *frequency reserve provision* with offshore wind farms need to be investigated in the perspective of the broadening European power market. On the other hand, *voltage services* by nature are managed at the local (regional level) and the need for cross-border exchange of service provision is not seen in the foreseeable future[21], at least at this stage.

An important issue is the large disparity between EU member states in service definition and the lack of consistency in the design of balancing markets [1]. On a positive note, several initiatives under the 'European impetus' – where also the Netherlands participates - are ongoing to couple markets and harmonise practices including the RSCI's[22][12].

Cross border trading of frequency support is beneficial for system operation and reduces overall system costs of power generation [2]. Cross border trade can help in two ways to mitigate the additional balancing needs with increasing share of VG: (a) by pooling-in more balancing resources enhancing competition [13] and (b) by reducing the total needs for reserves. Cross border sharing of frequency reserves as well as trading in real-time balancing markets (FRR manual) works already in some places, like the Nordic market – even across two synchronous systems (West-Denmark and Nordic system).

A precondition for cross-border exchange of frequency services is sufficient availability of transmission capacity at the interconnectors. This should not really constitute a major issue – at least on the short and medium term - as The Netherlands is quite well interconnected with several countries: Belgium (AC), Germany (AC), Norway (DC), UK (DC)[23] and in a few years also with Denmark (DC). The AC interconnectors are treated as regular transmission lines, provide access to traded services with neighbouring systems.

Thus, offshore wind plants within the Dutch power system – and interconnected with the European system - can exchange frequency services system-wide, provided proper rules and conditions among TSO's will be available.

The benefits of such exchange of reserves, along with the participation of renewables in reserve provision have been investigated in REserviceS [11]. EU wide model based market simulations at high shares of renewables[24] showed that enabling participation of (offshore) wind power in frequency

[21] However, voltage services may become cross-border for example as a part of defense plan against large voltage collapse managed by system operators, especially in the light of occurrences of high SNSP levels.

[22] RSCI: Regional System operation coordination initiative

[23] In GB, DC interconnector operators are also required to provide reactive power and frequency response as mandatory services under the Mandatory Services Agreement (MSA) between the TSO and the interconnection owner

[24] Up to annual shares of 50% of total electricity demand

reserves substantially reduces curtailment of wind power and significantly reduces the overall cost of generation. These benefits increase with increasing penetration of renewables.

1.4 Technical and operational specifications of AS

The practical aspects of AS delivery – including generator aspects, system operation aspects and market design aspects are described / regulated through various international codes presently being developed in the European Network Code process [15].

1.4.1 Offshore Network Code

Grid Code requirements for connection are harmonised through European Network Code process, which also drives the national Grid Code applicable for offshore wind farms in the Netherlands. The systematic of the European Network Codes drafted by ENTSO-E distinguishes between AC and DC connected offshore wind farms. The requirements for AC connected wind turbines[25] are formulated in the NC RfG [33], whereas requirements for DC connected offshore wind farms are formulated in the NC HVDC [16].

The present Electricity Law in the Netherlands including regulations and grid code requirements is not applicable outside the 12 nm zone, hence not for the foreseen offshore wind farms to be connected to the TenneT platforms. Therefore, TenneT[26] is presently in the process of making preparations for an Offshore Network Code, in agreement with the above described trend in Europe, whereby the system operator will also be able to call upon variable renewables – and thus offshore wind farms – for providing AS. Prior to adoption of the NC RfG[27] as formal European legal document, Tennet is preparing[28] this Offshore Network Code. This process will include a consultation with the stakeholders. In this way, TenneT intends to provide clarity on the technical requirements and general conditions for connection sufficient long time before the opening of the subsidy tender. The drafting of the Offshore Network Code for the Netherlands also involves the elaboration of specific requirements and values where the NC RfG does not provide exhaustive specifications.

Unlike the foreseen AC connections, offshore wind farms connected to HV DC networks will have to comply with technical requirements from the HV DC Network Code [16]. This Network Code sets out the rules and requirements that will cover High Voltage Direct Current technology[29],[30].

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[25] relevant for the offshore wind developments in NL to be connected to the TenneT platforms until 2023

[26] In agreement with the Minister of Economic Affairs and the regulator ACM

[27] According to communication with ENTSO-e, the ENTSO-E document is in the stage of comitology at the moment of this report (May 2015). In the possible earliest case of adoption before Summer 2015, the NC RfG becomes applicable/enforceable for new generation from 1 January 2016.

[28] Information from TenneT in March 2015. The document seen is a preliminary draft.

[29] Just like the NC RfG, the NC HV DC is still in the process of consultation, and will only be applicable in the course of 2016 at the earliest.

[30] The NC HVDC covers HVDC connections between different parts of Europe, as well as specifying the connection rules applying to the generators, which are connected to the main electricity systems via HVDC lines [17].

As mentioned in par. 1.3.2, HV DC technology is envisaged for future meshed offshore grids. Except for offshore interconnectors (for example the interconnectors from NL to Norway, UK and DK) HV DC technology is not expected to be deployed specifically for offshore wind farm connection in The Netherlands before 2020.

However, in the perspective of the huge far offshore resources potentially connectable to a meshed international HV DC grid, it is recommended to investigate specific technical aspects of ancillary service provision of HV DC connected wind farms (Chapter 4).

1.4.2 Network Codes for system operation and for market design

Beside technical requirements, and of no less importance, other boundary conditions for AS provision by offshore wind farms are related to power system operation aspects and power market design characteristics.
European Network Codes that will be of specific relevance for shaping the ancillary services to be provided by offshore wind farms are listed in Table 3 These Network Codes, once entering in force, will impact the practices of the TSOs, the design of the international market for ancillary services, and the related national regulatory aspects.

Network Code	Principal contents and objective	
Operational Security	Sets out the framework for maintaining a secure interconnected European electricity transmission system. It contains the common, legally binding principles and rules for operating electricity transmission networks, which all TSOs must follow.	SYSTEM OPERATION CODES
Operational Planning and Security	Introduces a set of rules, which all TSOs must adhere to in order to ensure the smooth operation of electricity transmission systems at both a national and European level. It will ensure that TSOs work more closely together and will implement a common approach to assessing the operational security of the European transmission grid. As such, it aims to enhance the security of electricity supply across Europe.	
Load Frequency Control & Reserve	Contains significant technical detail related to cooperation between TSOs, and to rules for how parties providing reserves and TSOs will interact. The principal benefit of the NC LFCR comes from setting out a single set of rules in a transparent manner.	
Capacity Allocation & Congestion Management	Sets out the rules that will enable a transition from the current system, in which there are different rules for electricity market participants in different countries or regions, to a single set of electricity market rules applied across Europe.	MARKET CODES
Energy balancing	Will promote greater integration, coordination and harmonisation of electricity balancing rules in order to make it easier to trade resources. This will allow TSOS to use the resources available more effectively, bring down costs and enhance security of supply. A key part of the NC EB is that it creates a level playing field for all potential providers of balancing services, including demand side response and variable sources (like wind and solar power) by introducing standardised rules. Anyone will be able to offer balancing services with the most cost effective offers selected by the TSOs. The NC EB will encourage a greater number of parties to offer balancing services, which will create larger and more competitive balancing markets.	

Table 3 European Network Codes of relevance for Ancillary Service Delivery by offshore wind farms (www.networkcodes.entso.eu)

2 Capabilities of offshore wind farms for AS

2.1 Studies and experiments

This chapter addresses technical and operational capabilities relevant for assessing the technical and economic feasibility of providing ancillary services with offshore wind farms. Technical capabilities of wind turbines and wind farms for frequency and voltage services have been assessed in several studies, see further below. In addition, practical examples have demonstrated the technical and operational capabilities as well. However, wind farms are not yet participating as full-fledged AS providers – mostly because of limitative conditions due to present market design and regulatory frameworks. Specific capabilities for AS delivery[31] are not driving wind turbine selection by project developers in The Netherlands. Also, in The Netherlands, wind farms both onshore and offshore are exempted from frequency service provision. Therefore, practical demonstration of service provision is only available in experiments, mostly onshore. A reference project in this respect was the European FP7 TWENTIES project [18], [26] where coordinated provision of voltage control and secondary reserve by wind farms connected to the transmission network was tested and successfully demonstrated.

Furthermore ongoing projects should be mentioned, testing ancillary services with onshore wind farms.

- In the 122 MW onshore wind farm Zuidlob, NUON is testing provision of frequency and reactive power provision;
- In the 77 MW onshore wind farm in Estinnes the Belgian TSO Elia is testing provision of downward secondary frequency services [21];
- In Germany the TSO is testing the provision of negative tertiary reserve provision with regionally distributed onshore wind farms [28].

The EU-project REserviceS [2] assessed the technical and operational state-of-art possibilities of wind farms taking into account existing specifications in grid codes, standards, technical literature, validated by practical experience in case studies, and found that in general for the investigated voltage and frequency services the necessary capabilities are already incorporated in existing wind turbine technology or can be installed if required. Actually, the consequences of deploying certain capabilities – especially for providing enhanced services - is mainly a question of additional CAPEX costs which in the case of frequency services are moderate. For several services, a full assessment of capabilities is not possible because a proper TSO specification in grid codes or otherwise is yet available (par. 1.4).

More specific findings relevant for offshore wind farms are explained separately for frequency and voltage services. There it is also explained how capabilities for voltage services and fast frequency

[31] Beyond the usual requirements in the Grid Code – verified with a couple of project developers in the frame of this study

support need to consider the differences between technologies (HVAC or HVDC) for connection to the transmission network.

2.1.1 Capabilities for Frequency services (reserves)

The inherent control capabilities of wind turbines presently used in offshore wind farms are not different from onshore wind farms and support the provision of the different forms of frequency support as listed in par. 1.2[32]. For these services, essential technical wind farm capabilities include active power control, frequency sensing, wind power forecasting and communication.

When offshore wind farms are connected however to DC networks (which is an issue in future), the frequency decoupled power source requires fast communication infrastructure in order to remotely measure and allocate set-points to provide frequency support. Consequently advanced communication methods are required to synchronise the offshore AC part of the grid connected by HVDC links to the shore in order to sense the frequency and provide the reserve [30].

In addition to technical capabilities, operational aspects need to be considered in the deployment of system reserves with offshore wind power:

- **Forecasting in combination with clustering:** An inherent challenge of wind power plants in delivering frequency reserves as specified in present rules is the variability of the primary source, which is increasing the forecast uncertainty[33]. The forecast error can be reduced significantly by using the prediction for a geographically spread cluster of wind farms. A further reduction of the forecast uncertainty can be achieved by using probabilistic intraday forecast methods [21], allowing to obtain confidence intervals similar to those of conventional power plants.
- **Adapted proof of wind power reserves:** Application of current proof methods used for conventional plants (schedule) cause losses in wind farms when providing negative control reserve [23]. Therefore, an adapted proof method[34] 'Available Active Power' is presently being tested in Germany[35] enabling minimizing losses due to down-regulation of wind turbines during downward reserve provision. Combining this method with the use of probabilistic intraday forecast enables wind farms to provide cost-effective control reserve at reliability levels acceptable for TSOs [21].

2.1.2 Capabilities for voltage support

Steady state and dynamic voltage support capabilities to provide voltage support services are present in wind turbines used for OWF. The minimum capability for providing reactive power in a controllable way is determined by the grid code requirements. Augmenting the ability (for example over minimum

32 Delivering frequency services (reserves) on a sustained basis may require minor technical adaptations – mostly related to control, communication and additional type/project certification assessments [2]

33 The relationship between predictability (forecast error) of wind power and variability is nearly linear [24]

34 Developed in the project Regelenergie durch Windenergie anlagen [23]

35 The available active power is the power that would have been produced if the wind farms had not been down-regulated

Grid Code requirements) is possible by oversizing the converters and/or installing additional equipment like STATCOM devices. A specific issue concerns extension of reactive power provision down to zero active power as specified in the ENTSO NC RfG [33] and can imply additional wind turbine CAPEX costs, depending on the technology (Type 3 or Type 4 wind turbines[36]). Especially relevant for the future offshore wind farms in The Netherlands, voltage services can be further augmented by regional coordination of wind farms in providing reactive power and voltage control at their respective onshore point of connection [30]. The feasibility of such coordinated voltage support provided by (onshore) wind farm clusters has been demonstrated in Spain by the local TSO [26].

In the case of offshore wind farms connected to HVDC offshore grids, the onshore VSC HVDC converter – within its design limits can provide reactive power/voltage ancillary services regardless of the offshore wind conditions [31].

Furthermore, tools are available for economic design of coordinated voltage support. A possibly useful tool specifically aimed at offshore wind farm clusters has been developed in the European FP7 research project ClusterDesign[37].

The capability for the possible future service Fast Reactive Current Injection (FRCI) during network faults (i.e. during fault-ride-through), is in principle present in offshore wind turbines, because of the current Grid Code Requirements. Costs[38] to provide a possible enhanced FRCI are depending on the wind turbine conversion technology and the grid code requirements imposed.

2.1.3 Capabilities for system restoration support

Capabilities of wind power technology to participate in system restoration (black start, islanding), are largely unexplored until now [2]. REserviceS has found that for black start, most of the required technical capabilities are in principle technically feasible in modern wind turbines and wind power plants [30]. The critical issue of availability of wind (possible power production) and hence reliability of service delivery can raise significant challenges and requires further R&D into suitable methods to ensure the availability of the service.

Islanding network operation is quite similar to the operation in a small power system with low system inertia and low short-circuit ratio at the point of connection. Generally modern wind turbines (Type 3 and 4) have successfully proven that they can operate reliably under such conditions and technically

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[36] Type 3 wind turbines have DFIG Generator and are partly converter based. Type 4 wind turbines have full-scale converter[27] which provides inherently full scope reactive power capabilities.

[37] www.cluster-design.eu

[38] For very fast provision of a controlled response, technical challenges include the development of accurate voltage sensing, recognition of fault types and appropriate tuning of controllers. An important issue here is the need to develop a proper TSO specification that is based on a thorough quantification of the need for the fast reactive current in-feed, as well as on system stability studies about impacts of various in-feed strategies [20]

can provide grid support in an even better way than larger thermal. Adaptations in standard control systems would be necessary as a minimum to enable islanding operation.

2.2 Cost of ancillary service provision with offshore wind farms

Relevant costs in this respect are the additional costs for OWF project developers/operators for sustained deployment of the respective AS. From plant operators view, these costs are to be considered in cost/benefit analysis in perspective with the potential revenues from service delivery. Reference is made to the cost assessment by REserviceS [2] by means of a basic cost structure, consisting of (a) cost for ability/capability (investment): focused on additional CAPEX cost for enabling sustained deployment of services (b) readiness (cost for capacity reserved, opportunity cost loosing energy that cannot be sold) and (c) Utilisation costs (actual provision of the services). Costs were assessed by interviewing OEM, plant operators [30] segregated in wind turbine, wind farm and wind cluster level.

For frequency services, the review showed that additional CAPEX cost are mainly related to sensing, communication infrastructure, control and possibly to additional structural design assessment (certification) due to changed mechanical load spectrum. These additional relative cost are quite low compared to project capex costs [2], [30], in the order of magnitude 1-2 % for onshore wind, and in the case of offshore projects would be negligible. On the other hand the opportunity costs for frequency services can be quite high – depending on the specific frequency service, and on the features of the frequency service market and specific products (see chapter 3). In fact, the deployment costs in the present market framework is prohibitive for the participation in most reserves except for downward SCR and TCR (see par.3.2.2).

For voltage services, the relevant costs are additional costs for installing and operating coordinated voltage control[39]. The literature on cost/benefits of utilizing wind power to control transmission level voltage is sparse. Orienting figures are given from a case study in the REserviceS project. The plant owner CAPEX for implementing a wide-area steady state voltage control in an onshore 488 MW wind project comprising of 15 geographically distributed wind power plants amounts to around €1.5M, involving cluster level regulators and a weather forecasting system [32]. The estimated OPEX impact for providing steady state voltage control is relatively low, around 1% of CAPEX.

The assessment of REserviceS of costs for enhanced (new) services showed that these are quite low, both for FFR and FRCI, but this would need to be confirmed by more in depth analysis, once TSO specifications for such services would be available.

Finally for system restoration services, no sources have been found [30] to enable a proper estimation.

[39] Assuming that reactive power capability on wind turbine level is standard installed following Grid Code requirements

2.3 Conclusions : existing capabilities offshore and bottlenecks

Technically there are no bottlenecks for delivery of existing frequency and voltage services with state-of-the-art OWF technology. Control methods and devices for all existing frequency and voltage services are available and proven at wind turbine and even at cluster level.

Costs for frequency services are mainly consisting of opportunity costs and depend strongly on market features. These costs can be mitigated – from the side of the wind farm operator in a given market framework - by using methods reducing forecast uncertainty such as probabilistic intraday forecasting and clustered forecasting. The cost of voltage services mainly depend on dimensioning of the electrical equipment and costs for regionally coordinated provision.

Capabilities for future enhanced frequency services (Fast Frequency Response, synthetic inertia) have been developed as well by several wind turbine manufacturers, however the main issue here is the absence of a proper TSO (Grid Code) specification for a response that would be adequate from system point of view. Similarly, for the provision of FRCI as an ancillary service, capabilities are existing in wind turbine technology, but also here a proper TSO specification is still missing.

service	Technology development	TSO Specifications required for
Frequency Containment Primary control reserve (FCR)	Wind turbine structural design may need adaptations to take into account increased mechanical loading of a sustained delivery of FCR.	active control mode of wind farms .
	Improved methods for defining and sensing system frequency at wind turbine and plant level, especially with respect to higher measurement resolution	
Secondary and Tertiary Control Reserve (FRR and RR)	In addition to the wind turbine design challenges of FCR, improved forecasting methods and pooling wind farms into clusters	Proofing method for reserve provision
	Reliable methods to estimate available active power as input for active power control in wind farms.	
Fast Frequency Reserve (FFR)	Reliable methods to detect and measure system frequency deviations at wind turbine and plant level, as well as for fast and reliable communication between plant and network operator.	Specification of wind power plant control response to enable adequate design specifications for the wind turbine and control technologies.
Steady State Voltage Control (SSVC)	cost reduction of equipment and operational strategies for regional coordinated provision	Aggregated reactive power provision
Fast reactive current injection (FRCI)	Not yet considered as ancillary service (except Ireland). Topics for improvement are control and sensing.	wind power plant control response to enable adequate design specifications for the wind turbine and control technologies

Table 4 Summary of recommended further developments of capabilities for frequency and voltage services [30]

3 Value of ancillary services by Dutch offshore wind farms

3.1 Introduction

This Chapter explores economic aspects of deployment of frequency and voltage services by offshore wind farms in the Dutch context in the time period up to 2023. The assessment identifies services attractive for OWF operators, identifies possible market barriers and addresses possible revenues for wind farm operators.

Frequency services in The Netherlands are traded in an organised market, whereas voltage services are dealt with in a different "market" environment, i.e. in individual contracts between TSO and operators. Hence, specific assessment approaches apply for frequency and voltage services, and the findings are presented in different paragraphs.

3.2 Potential for frequency services with Dutch offshore wind farms

3.2.1 Approach

The potential[40] for frequency service products to be delivered by offshore wind turbines is primarily driven by market design. The effects of the (rapidly changing) market design features on any chosen indicator for the potential (prices, quantities) are strongly non-linear and a quantitative assessment requires sophisticated modeling which is not possible within the frame of the present study. An interesting analysis of the market interactions regarding ancillary services from offshore wind farms in the German market has recently been reported in the frame of the FLOW project Dynamic Power Management [28]. The study includes references to market design features of the Dutch power market, and these have been taken on board in this chapter. It would be recommended to apply a similar analysis method to the offshore wind potential frequency service delivery in The Netherlands.

Given the above limitations, the present study focuses to a more overall assessment consisting of the following steps:

- scoring of Dutch market conditions with respect to key-features facilitating service provision by wind power;
- general assessment of feasibility of various frequency services and identification of key services;
- qualitative discussion of the economic potential for the most attractive services and a rough estimation of revenues for operators;
- discussion of effects of removing barriers the deployment of ancillary services (summary – recommended changes in the market

3.2.2 Key enabling design features in the Dutch power market

Market design features relevant for frequency services (reserve provision) historically developed in function of traditional generation (thermal, with synchronous generators). Inherent characteristics of

[40] Amount of services, economic value etc.

the natural wind source (variable, non dispatchable), affecting its reliability, hamper the operation of (offshore) wind power as service provider in a system designed for participation mainly by dispatchable generation. The REserviceS project recommended possible market features for an efficient deployment of ancillary services with renewables, based on analysis, case studies and inventory of best practices [2]. Recommended product and market features favouring the participation [2] are summarized in Table 5. Market simulations in REserviceS showed that participation of offshore wind power (radially connected) in FCR and automatic FRR is not technically necessary at high shares of renewables and does not bring significant economic benefits. Market design features for the different forms of reserve in the Netherlands based on market data for the year 2015 are summarized in Table 6.

Market Feature	definition	Desirable value
Product length	Period of time during which the service has to be delivered within a fixed band	As short as possible, preferably one hour or less. Procuring part of the automatically activated reserves (FCR, FRR) with shorter markets.
Separate upward and downward reserve	The possibility to make separate (asymmetrical) bids distinguishing between up and downward reserve	As upwards reserve with wind is costly because it involves loss of costly energy, the framework should allow separation (e.g. participation in negative reserve only)
Contracting time	Time period between gate closure and delivery	The uncertainty of RES influences how much can be offered and decreases with shorter time horizons. Tenders on daily basis of shorter are prerequisite for participation, enabling accurate forecast
Allowing portfolio offers	Possibility to combine bids from different generators	Enabling offshore wind plants to offer above minimum bid size and to increase forecast accuracy
Minimum bid size	Minimum amount of MW that should be offered	As low as possible, typically a few MW at most
Confidence intervals for availability	Quantified reliability/ availability indices of the offered reserve based on forecast uncertainties	Enabling the offer to be accompanied with confidence intervals tags.

Table 5 Key market design features favouring participation of wind power in frequency services [2]

Market feature	FCR (PCR)	FRR (SCR)		RR (TCR)	
	Primaire regeling	Regelvermogen		Reservevermogen	
Contract option	**capacity**	**capacity**	**energy**	**capacity**	**energy**
Contracting time	1 week	1 year	1 hour	1 year	**15 min**
Up and down separated	no	no	yes	no	**yes**
Product length	1 week	months	15 min	months	**15 min**
Minimum bid size (MW)	1	4	4	20	**20**
Confidence intervals	no	no		no	
Appr. market size 2015(up and down)	110 MW	300 MW		2400 MW	

Table 6 Market design features of various forms of control reserve in the Netherlands (2015). The green highlighted columns indicate potentially interesting services (downward). Ref. ENTSO-E, TenneT

A comparison of the desirable features and the current features in the Dutch power market shows:

- Market framework conditions in The Netherlands already today would be suitable for participation of offshore wind farms in negative secondary and tertiary control reserve (energy). Prequalification of wind farms / wind turbines for participation in reserve provision is not necessary in The Netherlands. Proofing of reserve provision based on Available Active Power brings further advantages of participation (par. 2.1.1), but needs to be implemented in the applicable regulations.
- The participation of wind farms in capacity contracts for secondary and tertiary control reserve would under present conditions only be possible for example in a flexible portfolio with conventional plants [28]. Decoupling up and downwards bids is presently being considered in the Netherlands, as well as a reduced contracting time. If so, wind farms could also participate in the capacity market without need for doing this in portfolio.
- With the possible introduction of an energy-only frequency control market, several of the described market issues (barriers, see Table 7) will be obsolete [28]

Frequency service		rating	barriers	Enabling activities
Primary control reserve		🔴	Symmetric product Long contracting time Long product length	The technical need for participation of offshore wind in PCR is not demonstrated and macro-economic benefits are marginal.
Secondary Control reserve	capacity	🟡	Symmetric product Long contracting time	Barriers are being addressed by TenneT [28]
	energy	🟢	Acceptance of adapted proof method	Adapted proof method to be implemented in TSO practice
Tertiary control reserve	capacity	🟡	Symmetric product Long contracting time Large minimum bid size	Barriers are being addressed by TenneT
	energy	🟢	Acceptance of adapted proof method	Adapted proof methods to be implemented in TSO practice
Fast Frequency Reserve		🔴	Not yet investigated	Not yet investigated

Table 7 Rating of frequency services in the Dutch Market context (green=OK; yellow=maybe soon OK; red=not ok)

3.2.3 Economic potential

In the present Dutch market framework conditions, the already existing attractive options are provision of frequency services for negative secondary (manual) and negative tertiary control reserve. Moreover the prospects for participating in capacity contracts seems possible in a near future [28].

REVENUES FROM FREQUENCY SERVICES

A model exercise enabling detailed assessment of revenues for wind farm operators is outside the scope of this study. Results of existing analysis in the Netherlands – for example from project developers - have not been available for this study. A high level estimation of the revenues therefore is based on recent numbers from the assessment of the market for ancillary services in Germany in the Dynamic Power Management study [28] where different wind power penetration scenarios were simulated, and the effect of implementing different product characteristics, market reactions, feed-in tariffs etc. was modelled. The (forecast) modelling showed that (offshore) wind farm operators in Germany can obtain revenues for tertiary provision in the order of 5000 - 6000 €/MW. It remains to be demonstrated however, in how far these values apply for the market in the Netherlands. A coarse estimation, assuming annual revenues from the energy market at ca. 600 000 €/MW[41], shows that the above revenues from the control reserve market are in the order 1-1.5% of the energy market earnings. This estimate matches the findings of an international comparison of ancillary services carried out in the frame of the DS3 programme in Ireland[42] [35].

Thus, at the level of project developers, the potential revenues from participation in frequency reserves are low, at least when compared to the earnings from the energy market and present incentive scheme, but should still contribute to the project's business case.

Nevertheless, it is recommended to make a more detailed assessment of revenues for operators with an analysis that investigates the effects of different market design features, using proper market analysis tools. Possible income from cross-border trading of frequency services for example to Germany and Belgium could be analysed as well.

BENEFITS AT SYSTEM LEVEL

The REserviceS project analysed the potential benefits of providing frequency services (FCR, FRR and RR) at system level, in terms of reduced wind power curtailment and reduced system overall cost of power generation in a system spanning a large part of Continental Europe and thus including the Netherlands [11]. The results showed that:

- Participation of renewables in frequency reserves (FCR, FRR, RR) reduces overall annual system cost - in a situation of 50% share of renewables this amounts to 2% for the Netherlands

[41] Assuming 4000 full load hours and a market price of 150 €/MWh

[42] where it was found in general that in today's European market on average ancillary services represent less than 5% of the total revenues earned by wind energy producers (mainly onshore) from energy markets.

- Wind power curtailments can be significantly reduced by letting renewables participate in system reserves.
- However, the benefits can be obtained without participation of offshore wind in FCR and (automatic) FRR

The system benefits become more prominent the higher the share of renewables in the annual electricity demand becomes.

Following these conclusions, from system point of view, it is economically justified for OWF in the Netherlands to at least should participate in the slower reserves (negative RR – tertiary reserves). Participation in faster reserves should not be a priority on the short term. Benefits of participation in (negative) FCR and FRR should be further investigated to prepare for future higher penetrations of variable renewables in the Dutch system.

3.3 Potential for voltage services

In The Netherlands, reactive power for voltage management to cater for locational needs in the HV grid is purchased by the TSO via an annual tender. The tendered amount of reactive power is being determined in an analysis including a forecast for future locational needs. The contracting does not distinguish between RES and other generators: all parties in a certain area considered to be capable of covering the needs in a particular area are invited for participation. The participation of wind in this respect is not yet significant: in 2015 one wind farm was contracted in the Netherlands[43]. More parties since have shown interest in providing reactive power with wind farms, and may become future service provider. The remuneration system includes three possible options: (a) Fixed annual fee independent of number of calls; (b) Hourly fee per call; (c) Combination of both.

Provision of voltage support involves investments in capability of offshore wind power plants to enable offering reactive power to cater for the TSO reactive power needs in the onshore transmission network (see par. 2.2). REserviceS [2] based on survey of possibilities and inventory of best practice recommends that there should be a reimbursement for voltage support services by renewables with a fee that is fixed by a competitive process - possibly a regular bidding process or an auctioning arrangement. The contracting could be done for short time horizons like days to months or for longer time horizons up to several years.

A non-remunerated mandatory band as part of the grid code requirements could be complemented with payment for additional voltage support to grid operation, provided such costs are recognized by the regulator and recoverable by the network operator.

[43] Communication Tennet

A tendering or auctioning process could be an option for remunerating voltage support services where:

- The need for reactive power is analysed and studied by the TSO and a forecast for future locational needs is established.
- Based on the investigation a tender for reactive power within a certain perimeter is published or an auctioning system is started to receive the lowest cost reactive power provision.
- The best offer (or best offers) is awarded with a fixed reimbursement for the reactive power provided to the system and a minimum off-take guarantee to ensure investments security.

These enabling features are in principle fulfilled by the method deployed by the TSO in the Netherlands. In this respect, the system operator promotes as much competition as possible by preparing for a 'flexibility platform' where all types of AS both frequency and voltage will be traded[44].

More importantly, a specific issue in the context of the configuration of wind farms connected to the five foreseen TenneT platforms is how to procure reactive power in a coordinated way from the various connected wind farms within the clusters, and adjusted to the onshore reactive power needs. As the procurement methods influence the technical set-up of the wide-area coordinated voltage control of the offshore wind farms, the topic of reactive power procurement methods deserves in depth investigation.

Concluding: Any additional investment made by project developers for voltage support services in principle could be reimbursed by participation in the reactive power tenders from the TSO. In this respect, in principle there is no additional revenue for project developers from those services, as this should be considered a cost-neutral operation. On the other hand, a coordinated voltage support from offshore wind power generation connected to the platforms could be beneficial both for the TSO and the OWF operators. The size and economic consequences including financial benefits for the various stakeholders from such an undertaking should be subject to further R&D.

3.4 Summary market potential and revenues

Ancillary services from offshore wind plants are much needed for the power system. However, even massively deployed in favourable power market conditions, AS will not constitute a major source of additional income for offshore wind farm operators. Revenues from frequency services will not represent much more than 1% of the income from the energy market. This relative income will increase with decreasing feed-in and market premium in future.

For voltage support, the planned coordinated approach of connecting all wind farms to standard HV platforms, provides the opportunity for setting-up a suitable coordinated provision method for

[44] Communication Tennet

reactive power. The economic benefits will follow from the chosen approach, and remain unexplored in this moment.

The deployment of ancillary services will yield system benefits (overall reduction of the cost of power generation) and thus increased deployment of frequency services by OWF will increase social welfare. Estimations have been made at EU level within the REserviceS project. It would make sense to make more detailed estimations for the specific foreseen wind energy scenarios in the Netherlands.

Finally, the economic benefits from new 'enhanced' services such as fast frequency and voltage are very dependent on the TSO viewpoint on the specific design of services and remain to be investigated. At least, these services are not needed from OWF on the short term.

4 High-level R&D roadmap

4.1 General

This section identifies R&D needs and research questions based on needs formulated by the stakeholders (wind industry, TSO's, research community) in various forums and sketches a high level roadmap for R&D into ancillary services provision by offshore wind farms in The Netherlands.

Industry needs:

- The REserviceS project with extensive stakeholder involvement; the project formulated knowledge gaps and research needs in the areas of system needs, technology and markets [2]
- the Strategic Research Agenda of TP Wind [36] lays out objectives and priorities for research on ancillary services from wind power in the chapter on wind integration .

TSO needs:

- the ENTSO-E R&D Roadmap and the related implementation plans [37] [38] ,
- interviews with TenneT during this project.

Furthermore, through the assessment of the subject in the frame of this study, relevant topics for R&D have been identified as well.

4.2 Scope of R&D in AS from OWF

This report structures themes for R&D in three main areas: wind (OWF) technology, system integration and markets.

For the area of **OWF technology**, the scope includes:

- improving control methods and design features at turbine, wind farm and cluster level for coordinated frequency and voltage support.
- Reducing costs and increasing reliability of AS provision by OWF.
- Exploration of role of OWF in system restoration and in HV DC networks.

For the area of **system integration**, the scope includes:
- Experimental verification of reliable and cost-effective deployment of frequency and voltage services.
- Study the impact of enhanced frequency and voltage services to optimize secure system operation at high shares of OWF

For the area of **markets**, the scope includes:
- Quantification of macro-economic benefits of AS provision by OWF.
- Market designs and investigate procurement methods to facilitate AS provision by OWF.

The status, bottlenecks and R&D targets are formulated in the areas of OWF technology, system integration and markets, in the Table 8, Table 9 and Table 10. The three areas are the main building blocks of the R&D roadmap proposed to accompany a gradual implementation of ancillary services along the implementation of the foreseen offshore wind farm development in The Netherlands in the coming decade. Zooming in on further details, the principal research themes and topics within are described in a separate document, delivered together with this report.

4.3 Research stakeholders

Principal stakeholders are TSOs, wind industry (OEM, project developers), R&D institutes and knowledge &service providers (consultants etc.). TSOs are the natural lead takers in the areas of system integration and markets. The wind industry is lead taker in the area of OWF technology:

4.4 Timeframe

The proposed research topics as listed in a separate document have been assigned to different time frames (periods of 3 years). Details are given in a separate document.

	OWF Technology
Status:	Present wind turbine capabilities technically are suitable for participation in system reserves, and for provision of reactive power. OWF in principle are allowed to participate in AS but do not because of non-existing business case and in some cases due to market rules. Practical implementation of existing AS for the planned AC connected 4.5 GW OWF is not yet defined. The possibilities of OWF in system restoration processes are hardly explored. OWF in The Netherlands will not be HV DC connected in the coming years, and different methods for AS delivery will apply because of DC technology features and shared role in AS provision with onshore converters.
Bottlenecks:	Implementing ancillary services by OWF on the short term in the Netherlands is limited/prevented by existing market design, costs and reliability issues. Lack of experience with coordinated provision of frequency and voltage services. Lack of knowledge on possibilities in system restoration. Lack of knowledge how to share AS provision task in HV DC Grids with the converter stations.
R&D Target:	Improving control methods and design features at turbine, wind farm and cluster level for coordinated frequency and voltage support. Reducing costs and increasing reliability of AS provision by OWF. Exploration of role of OWF in system restoration and in HV DC networks.

Table 8 Status, bottlenecks and R&D target for area OWF technology

	System integration
Status:	There is substantial experience with system integration of wind power, but the share of wind power in the system is still quite low in NL. In the near future, system operators face retreat of conventional generation and thus of principal AS providers. TSO expects OWF to participate as active generation (instead of negative load) providing flexibility and supporting Security of Supply through AS provision.
Bottlenecks:	Lack of visibility and predictability of wind farms to the system operator. Lack of experience with operation of wind farms as AS provider especially in system reserves. The system impacts of high share of OWF providing enhanced ancillary services (fast frequency, enhanced voltage support) are insufficiently investigated.
R&D Target:	Experimental verification of reliable and cost-effective deployment of frequency (FRR, RR) and voltage services, including demonstrated predictability and plant observability. Enhance knowledge about impact of increased flexibility of OWF by enhanced AS (e.g. fast frequency and fast voltage) on secure operation of the power system.

Table 9 Status, bottlenecks, and R&D target for area System Integration

	Markets
Status:	Present market design for frequency in the Netherlands is traditionally customized to AS provision by conventional, but is in transition under European pressure. An organised market is available for frequency services, with several features suitable for participation of offshore wind (negative TCR). Procurement of reactive power is local (no EU context) and dealt with in individual contracts. For enhanced services (e.g. fast frequency and reactive power), only mandatory grid code requirements are available.
Bottlenecks:	Lack of specific knowledge on macro-economic benefit of frequency services of the presently planned configuration of OWF for the coming years. Absence of clear commercial/procurement framework for coordinated reactive power provision by the planned OWF clusters. Absence of commercial framework may delay development of enhanced AS (fast frequency and voltage) from OWF.
R&D Target:	Quantification of macro-economic benefits of AS provision by OWF. Market designs and procurement methods to facilitate AS provision by OWF.

Table 10 Status, bottlenecks and R&D target for area 'Market'.

5 Summary, conclusions and recommendations

This study has assessed the provision of ancillary services by offshore wind farms in The Netherlands based on a review of literature, stakeholder viewpoints and own analysis. The international perspective is integrated in this review by incorporating findings of the European REserviceS project which collected EU wide TSO, OEM and project developer inputs.

5.1 Possible as, costs, developments and bottlenecks

Technically there are no bottlenecks for delivery of existing frequency and voltage services with state-of-the-art OWF technology. Control methods and devices for all existing frequency and voltage services are available and proven at wind turbine, wind farm and cluster level. Capabilities for future enhanced frequency services (Fast Frequency Response, synthetic inertia) have been developed as well by several wind turbine manufacturers, however the main issue here is the absence of a proper TSO (Grid Code) specification for a response that would be adequate from system point of view. Similarly, for the provision of FRCI as an ancillary service, capabilities are existing in wind turbine technology, but also here a proper TSO specification is absent.

Possible AS from OWF in the Dutch context are depending on power system needs and economic factors. The Dutch power system being embedded in a large interconnected system, frequency services have to be regarded in a European context, also because of the developments in the European power market rules governing national provision practices and economics for system reserves. Present power market features offer participation in negative secondary and tertiary reserves as immediate opportunities for economically feasible frequency AS to. Furthermore, international assessment indicates that from system point of view and even at very high shares of renewables (up to 50% at in Continental Europe), not all generators need to participate in fast services, and participation of offshore wind farms in the fast services (FCR, FRRa) does not bring significant economic welfare.

Costs for frequency AS are mainly consisting of opportunity costs (value of not produced/sold energy) and depend strongly on power market features. These costs can be mitigated – from the side of the wind farm operator in a given market framework - by using operational methods reducing losses and reducing forecast uncertainty. Lack of practical experience with such methods is a bottleneck. The additional relative CAPEX cost for OWF participation in frequency services are low.

For voltage support, the planned coordinated approach of connecting all offshore wind farms to the standard HV TenneT platforms provides the opportunity for setting-up a suitable regionally coordinated provision method for reactive power. The need for the reactive power from OWF is depending on the regional reactive power need, and is being supplied by competing providers, chosen by a tender procedure. The opportunities for OWF will follow from procurement methods and coordinated provision, and remain unexplored in this moment, which is a bottleneck to be solved. The cost of voltage services mainly depend on dimensioning of the electrical equipment and costs for clustered (regionally coordinated) provision and are considered to be relatively low.

Concluding, in the near future the possible services for OWF include participation in negative reserves (SCR and TCR) as well as coordinated provision of reactive power. Participation in system restoration as well as in new services remains to be investigated.

5.2 Value of as and implementation potential

Even massively deployed in favourable power market conditions, AS will remain a small source of additional income for offshore wind farm operators, but the amounts in absolute terms will certainly be sizable and growing Under present market conditions in the Netherlands, revenues from frequency services will not represent much more than 1% of income from energy market. This relative income will probably increase with decreasing feed-in and market premium in future. Regarding reactive power, the income will depend on the procurement method chosen, but will mainly have to be considered as a cost recovery.

Estimation of the total value of AS by OWF is complex and needs adequate market models to take account of spectrum of market parameters, hence is outside the scope of the present study. The deployment of ancillary services will yield system benefits (overall reduction of the cost of power generation) and thus increased deployment of frequency services by OWF will increase social welfare. Estimations have been made at EU level within the REserviceS project, and indicate substantial annual system cost [45] reduction due to participation in frequency AS by wind power (onshore + offshore) for NL at a future high share of renewables (42% at EU level). It is recommended to make more detailed estimations for the specific foreseen wind energy scenarios in the Netherlands to make a more careful judgement of the possible contribution from offshore wind only.

Finally, the economic benefits from new ‘enhanced’ services such as fast frequency and voltage are very dependent on the TSO viewpoint on the specific design of services and remain to be investigated. At least, these services are not needed from OWF on the short term.

5.3 R&d roadmap

This study provides high level roadmap structuring identified R&D needs in three areas (I) OWF technology (II) System Integration (III) Markets. In each of the areas, R&D targets are formulated, as well as a range of research topics, indicating a proposed timing (short, medium and long-term).

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