Grid support services by wind and solar PV: a review of system needs, technology options, economic benefits and suitable market mechanisms

Synthesis report of the REserviceS project

Agreement n.: IEE/11/814/SI2.616374
Duration: April 2012 – September 2014
Co-ordinator: European Wind Energy Association
Supported by: [Image]
Foreword

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The authors would like to gratefully acknowledge the inputs received from the project Advisory Board, as well as from the stakeholders received through interviews and stakeholder workshops.
# Table of contents

Executive summary.................................................................................................................. Error! Bookmark not defined.
Symbols and abbreviations........................................................................................................ Error! Bookmark not defined.

1 Introduction .......................................................................................................................... 16

2 System needs versus grid support services from wind and solar PV ........................................ 18
   2.1 Introduction ................................................................................................................... 18
   2.2 How do system needs change with increasing wind and solar (PV) penetration? .................. 20
       2.2.1 General trend – increasing needs at increasing penetration levels of VG .................... 20
       2.2.2 Regional differences in needs for services ............................................................... 27
       2.2.3 Methods of assessing system needs with VG are still evolving ................................. 29
   2.3 Recommended key services from wind and solar PV ....................................................... 30
   2.4 Services not addressed by the REserviceS project ........................................................ 32
   2.5 Specific high VG penetration issues at transmission respectively distribution level ............ 33
       2.5.1 Issues at transmission level .................................................................................... 33
       2.5.2 Issues of high VG levels at distribution level: .......................................................... 34
   2.6 Interaction of needs and services between transmission and distribution level ................. 35
   2.7 Cross-border issues of needs and services ...................................................................... 36
   2.8 Specific needs regarding wind and large scale offshore wind deployment .......................... 36
   2.9 Specific needs regarding distributed solar PV ................................................................. 37
       2.9.1 Specific needs at transmission level due to increased solar PV ................................. 39
       2.9.2 Issues and needs at distribution level with increasing solar PV .................................. 40
   2.10 Conclusions .................................................................................................................. 41

3 Capabilities of variable renewables as ancillary service providers ........................................ 42
   3.1 Introduction .................................................................................................................... 42
   3.2 Technical assessment of VG capabilities for service provision ........................................ 42
       3.2.1 Existing capabilities to provide frequency and voltage support .................................. 42
       3.2.2 System restoration support (SRS) from VG: present capabilities ............................... 46
       3.2.3 Recent technical developments of capabilities for system services ............................ 47
   3.3 Power system impact of services provided by VG .......................................................... 49
3.3.1 Frequency Control
3.3.2 Voltage Control
3.3.3 Provision of GSS with offshore wind plants
3.3.4 Impact of aggregation and short term forecasting on GSS provision
3.4 Techno-economic assessment of service provision (at generator level)
3.4.1 Comparing costs of providing grid support services with wind and solar PV
3.5 Challenges for enhancing capabilities and solutions
3.5.1 Enhanced frequency and voltage support with VG: challenges and solutions
3.5.2 System Restoration Support with VG: technical challenges and solutions
3.6 Conclusions
4 Economic benefits of variable renewable based services
4.1 Introduction
4.2 VG in frequency support
4.2.1 Assumptions in the simulations
4.2.2 Cost-benefit of using VG in frequency support
4.2.3 Cross-border sharing vs. VG in frequency support
4.2.4 Other options for frequency support
4.2.5 Impact of better forecasts on the provision of frequency support
4.3 Cost benefit of VG in voltage support
4.3.1 Cost-benefit of using VG to support voltage at high voltage levels
4.3.2 Cost-benefit of using VG to support voltage at low/medium voltage levels
4.3.3 Other options for voltage management
4.4 Cost-benefit of using VG for system restoration
4.5 The excessive cost of requiring capabilities from all generators
4.6 Conclusions
5 Market concepts (commercial frameworks)
5.1 Introduction
5.2 The electricity market – an overview and an interface to REserviceS
5.2.1 How do different market and procurement based mechanisms relate to each other?
5.2.2 Which markets segments for which services?
5.3 Ancillary services market in Europe in monetary terms ................................................................. 95
5.4 Relation between ancillary services and adequacy of generation ................................................. 98
5.5 Identification of best practices in different countries ................................................................. 99
5.6 Key market design/ product adaptations for solar PV and wind to offer on ancillary service markets ......................................................................................................................................... 102
5.6.1 Suitable product characteristics for frequency support services .............................................. 102
5.6.2 Suitable product characteristics for voltage support services .................................................. 105
5.6.3 Suitable procurement models enabling TSO / DSO coordination of grid support services .............. 105
5.7 Conclusions ........................................................................................................................................ 106
6 Knowledge gaps and needs for further research ............................................................................. 109
6.1 Introduction ........................................................................................................................................ 109
6.2 Knowledge gaps .............................................................................................................................. 109
6.2.1 System needs for ancillary services .............................................................................................. 109
6.2.2 Technology ..................................................................................................................................... 110
6.2.3 Markets/costs/economics ............................................................................................................. 112
6.3 R&D needs ...................................................................................................................................... 113
6.3.1 System needs ............................................................................................................................... 113
6.3.2 Technology .................................................................................................................................... 114
6.4 Conclusions ...................................................................................................................................... 115
7 Overall conclusions of the REservices project .................................................................................. 117
8 Literature references .......................................................................................................................... 118
9 List of REservices reports (deliverables) .......................................................................................... 121
   System needs for ancillary services ................................................................................................. 121
   Wind and PV ancillary services capabilities and costs ........................................................................ 121
   Wind and PV ancillary services in future systems – Case Studies .................................................... 121
   Recommendations for a future EU market for ancillary services ..................................................... 122
EXECUTIVE SUMMARY

The foreseen high shares of wind and solar PV in the European electricity supply bring fundamental changes in the way transmission and distribution network operators use grid support services (ancillary services) from generators to manage network frequency, network voltage and system restoration. These changes are twofold in the sense that (a) needs of power systems are changing and (b) the changing generation fleet with its specific technology characteristics changes the technical and economic opportunities of providing these services. The REserviceS study was set up to assess the provision of these grid support services by variable renewables (wind and solar PV) themselves, to contribute to the design of ancillary services market mechanisms that would enable the power systems in Europe to function safely, reliably and cost-efficiently with very high shares of variable renewables. The study – carried out by the REserviceS consortium including renewable energy industries, research institutes and DSOs - has focused on wind and solar PV because these are expected to jointly produce the lion’s share of renewable electricity production needed to reach the EU’s 2020 targets. Intermediate results of the study have been discussed with European TSOs/DSOs and policy makers and their feedback is integrated in the study findings.

In the first project stage, REserviceS analysed how system needs for services change in growing presence of VG and identified a key set of services that should be provided by VG (Work Package 2). In a second stage, a technical and economic assessment was made of the capabilities for providing this key set of grid support services by wind and solar PV of (WPs 3 and 4). The third stage of the project consisted of case studies looking at technical and economic impacts in transmission and distribution grids – simulating effects of massive deployment of services and assessing cost benefit aspects. In the last project stage, constituting the synthesis of these three main project stages, the findings have been integrated into this Synthesis report as well as in a separate Recommendations report. The integration of the project findings also included an initial exploration of procurement methods of frequency and voltage support services by TSOs and DSOs including possible market mechanisms, in the context of the further integration of the European electricity market. The study also helped to identify knowledge gaps and needs for further research in the area of provision of grid support services by variable generation.

System needs versus grid support services by wind and solar PV
REserviceS assessment of system needs in European power systems focused on frequency support and voltage support as the main ancillary services categories from wind and solar PV generation point of view. Frequency and voltage control constitute several services with different response times. With high shares of VG also new services will be needed to be provided by them, mainly faster responses as well as services/capabilities inherently provided by synchronous generation, for example mitigation of negative sequence voltages and damping of harmonics. Generally, the system needs for the identified ancillary services will increase with high shares of VG. Enhanced frequency support in the system is observed especially for manually activated system reserves (<15 min) FRR. VG may increase
the need for voltage support as online available reactive power sources, both steady state and dynamic, available to the system operator to manage network voltage will change. In any case, voltage profile management will become more complex with increasing shares of VG.

The needs for grid support services with VG depend on the power system studied (for example its size and robustness), and how VG is built in the system (for example its dispersion, penetration levels and technical characteristics). As grid support services come with a cost, requirements for generator capabilities and service provision should demand only what is needed by the system in order to avoid excessive system costs. Preparing for future systems with large share of VG thus requires studies and simulations for making well-founded estimates of the needs and technical requirements. A handicap for a comprehensive assessment is the absence of a common methodology to include for VG in estimating system needs for services as well as the limited information basis on combined effects of wind and solar PV. Thus, as the process used to assess system needs for grid support services with VG is still evolving, efforts to develop new tools are needed.

DSO/TSO interaction will be more and more important in the future with large shares of VG, as well as a further growing role for DSOs in the ongoing transition process in electricity networks. Data exchange and ability to control the multitude of small generation units should be organised. Governance on who is doing what needs to be established for coordinating frequency and voltage support, as well as restoration services.

**Technical capabilities of wind and solar PV as service providers**

Technology analysis of wind power and solar PV - validated in industry enquiries - confirms their technical and operational capabilities to provide grid support services for frequency, voltage and certain functions in system restoration assuming an adequate procedural and economic framework is present. The technical and operational functionalities required are either state-of-the-art of the existing hardware or can be implemented at a reasonable cost. The feasibility of providing services by enhanced plant capabilities is confirmed by TSOs, for example in Spain where voltage control by wind power plants on the specific transmission nodes leads to a significant improvement with fast response. The German and Spanish case studies within REserviceS demonstrate that letting the DSO use ancillary services from RE generation connected to its own system contributes to cost-efficient voltage management. Participation of VG in system restoration is not (yet) practice of today. Certain functionalities required are available in principle in VG technologies but their implementation in specific restoration strategies needs further investigation.

For wind power, potential technical enhancements for frequency and voltage support services include: faster and reliable communication (a.o. between wind farms and system operators’ control rooms), dedicated control tuned for delivering the required performances, estimation of available power/forecasting. Furthermore structural, mechanical and electrical design changes in wind turbines need to be implemented to take into account the changes in loading involved with grid service oriented operation. Specifically for offshore wind power service provision needs to consider the differences between connection technologies (HVAC or HVDC) as these have a fundamental impact on the
provision of voltage services and fast frequency support. AC connected offshore wind plants can provide active power reserve and frequency response (in all time domains: FCR, FRR, RR, FFR) in the same manner as onshore AC wind plant projects. Ancillary services can be augmented by aggregating multiple offshore wind plants or clusters of wind plants. Regional coordination of offshore wind plants in providing reactive power and voltage control at their respective onshore POC would strengthen system reliability. In the case of HVDC offshore grids, the onshore VSC HVDC can provide reactive power/ voltage ancillary services regardless of the offshore wind condition. Technical standards and Network Codes currently in preparation are important enablers of offshore wind ancillary services.

For solar PV potential enhancements of capabilities include: estimation of available power/forecasting, faster and reliable communication and control within the plant, control strategies for portfolios composed of numerous small and medium sized units, improving interoperability of different networks and enhancing compliance to a multitude of non-harmonised grid code requirements.

Thus, implementation of better and faster communication systems together with the development and implementation of more accurate forecast systems are essential required improvements for both wind and solar PV technologies. In general, aggregation of multiple VG power plants is desirable because this improves the performance when providing a service and reduces the relative implementation costs. Also both for wind and solar PV, control strategies should be tuned up and improved to obtain the maximum power performance and flexibility from VG. In this case, the precondition is to have clear and well-described requirements and procedures to integrate wind and solar PV as GSS providers. In this respect, poorly defined or non-existent technical specifications in grid codes or pre-qualification procedures that allow VG to provide GSS constitute a significant barrier to overcome in the future. This is exacerbated by the lack of standardisation and harmonisation of procedures across Europe. As a necessary precondition, a clear GSS roadmap should be established describing the required capabilities and services in due time along with a set of pre-qualification and procurement methods with proper attention to the characteristics of the sources.

Implementing enhanced capabilities will involve additional investment costs, and the deployment of the services will also involve costs. For both wind and solar PV the additional capex costs involved for enhanced provision are relatively low and – provided appropriate cost recovery/ market mechanisms are in place – their deployment should be commercially feasible. Only for small PV systems the impact of required communication components will result in high additional capex costs. In general, both for wind and PV, OPEX costs notably upward readiness cost represents the highest costs to make frequency services available.

**Economic benefits of grid support services by wind and solar PV**

The REserviceS simulations of power systems of various sizes across Europe and increasing share of VG (up to 50%) show it is beneficial to utilise variable generation in frequency reserves and that these system benefits increase with the share of variable generation. The benefits were calculated by comparing the overall operational costs of power generation with and without using VG for frequency
support. The largest benefits are observed in downward FCR and in automatic FRR. The operational benefits for the system operator in the simulations are higher than the cost of equipping all VG with the capability to participate in the frequency support, especially for wind power plants with their lower CAPEX costs (per MW) than residential PV. In the system simulations not all VG needed to participate in frequency support in order to achieve the economic benefits. In a sensitivity analysis the frequency response and its corresponding economic benefits remain adequate with a 25% fraction of the VG participating in frequency support services. Thus it should be sufficient to only equip a part of VG with capability for FCR and automatic FRR services. Cross-border sharing of frequency reserves creates similar benefits as VG, but there are additional benefits when both variable generation and cross-border sharing are utilised.

The REserviceS case studies analysing different MV/LV networks with different VG shares conclude that the cost/benefit ratio of voltage support from VG is very case specific and that provision of voltage support by VG should be compared with alternatives. As there will be a high number of locations where individual decisions need to be made from where voltage support will be sourced, there is a need for universal and robust methods to make the assessment with reproducible and comparable results. The findings from the case studies demonstrate that voltage control capabilities from VG are not likely to be always the best choice and therefore an across the board requirement may lead to excessive costs.

**Markets and commercial frameworks**

In today’s energy-only market, still dominated by synchronous generation, the contribution of ancillary services in the system costs and revenues to generators is very low compared to energy and capacity payments. As it is clear that VG can provide GSS and their utilisation can decrease operational costs of the power system, there should to be sufficient incentives to obtain these benefits along with the capability and availability requirements for VG. Currently, only a few markets (e.g. Ireland, GB system) provide arrangements for enhanced services where variable renewables are incentivised to participate. In future systems with high shares of VG the ancillary services part will increase, even if it still will be a smaller part of total system costs and revenues.

Not all generators in a system need to provide ancillary services to ensure safe system operation. Thus a mandatory request for ancillary services is often far from being cost-efficient. Market based remuneration on the other hand stimulates cost-reduction and incentivises the provision by plants providing the cheapest services, irrespective of whether these are VG or non-VG plants.

Detailed and clear specifications are of crucial importance for the participation of wind and solar PV in GSS provision. Without these, market participation and procurement of such services is delegated to incumbent generators with long-term contracts already in place. Requirements should be defined in close cooperation between the TSOs and VG industry via consultations, such as in Ireland.

To enable the provision of GSS by VG, a multi-level procurement process should be defined involving TSOs and DSOs, and generators connected to their networks. On the one hand, the participation of VG in a grid support services market - run by the TSO - could lead to violate constraints in the distribution
grid. On the other hand, by solving local issues (congestion or voltage management) with GSS provided by VG, DSOs’ actions could have repercussive effects on the transmission grid operation. Given the complexity of coordinating the respective tasks, a hierarchical definition of the supervision and control actions is necessary and a clear hierarchy of functions between TSO and DSOs should be established.

In order to enable full utilisation of the capabilities of VG for the provision of GSS, the design of markets and products should be adapted to take into account the characteristics of VG. Characteristics of ‘service’ products such as separation of bids up from downwards, inclusion of confidence intervals and aggregated bids and offers are fundamental for allowing wind and solar PV to participate cost-effectively in grid support services provision.

- As a first step, TSO should allow a certain amount of balancing power to be offered with a confidence tag stating the probability of the offered power.
- For smaller systems or for smaller portfolios of variable renewables, the minimum bid size is crucial for entering the market or not. Although low minimum bid sizes have the downside for the TSO that non-automated management of the portfolio of small bids can be highly complex, their advantage is that the increased competition in the market may reduce procurement costs.
- The time elapsed between the gate closure and the delivery of frequency support is crucial to allow for wind and PV cost-effective participation, and should be as short as possible. The longer the time between procurement and delivery the more room for forecast errors occurrence and less is the chance for VG to take part in the provision of services at reasonable costs.
- The products for reserve power provision by wind and solar PV should have short blocks of a few hours or even blocks of less than one hour, as VG is constrained in offering to the reserve market due to weather dependency, for example at night and/or at too low or too high wind. Furthermore future production can only be predicted with an accuracy that decreases with increasing forecast horizon, resulting in actual production deviating from forecast.
- All products should be split in upwards and downwards products. PV and wind would be able to offer downward reserves at relatively low costs. Apart from wind also other flexible resources and demand in the power system would benefit from such product design.
- In order to enable for cost-efficient offers with high certainty, solar PV and wind need to offer reserve products from aggregated portfolios of several PV and wind plants spread across wider areas. The general allowance to offer reserve products with portfolios would significantly facilitate the participation of renewables.

It might in general be valuable to evaluate the implementation of a reactive market approach that allows real-time balancing of the BRPs perimeters. Flexibilities of VG can then be used by the BRP manager in case they prove to be most cost-efficient. This would also reduce the need for reserve power for balancing by the TSO.
Voltage support services cause costs for the VG plant operator, and being valuable for the system operator (TSO, DSO), these services should be reimbursed with a fee that is fixed by a competitive process, e.g. regular bidding process, auctioning arrangement or contracting for short or long time horizons. The often taken approach of a tendering or auctioning process seems to be advisable as a possible option for remunerating voltage support services. An alternative option could be to require voltage support by the grid code and to compensate the cost incurred directly through the support policies. DSOs should then be enabled by a suitable regulatory framework to compensate VG systems directly through a fee or indirectly through lower connection or network tariffs to cover the additional capital costs of and additional losses due to the reactive power provision.

Knowledge gaps and needs for R&D
Streamlined and consistent R&D efforts will play a determining role in the timely and effective enhancement of VG in providing ancillary services. The REserviceS study defined several topics in the area of system needs assessment, VG technologies and market designs, where research efforts are needed to fill knowledge gaps, and to develop improved methods and solutions.

The identified research needs link with several other activities at European level from major stakeholders: ENTSO-E, the European Electricity Grid Initiative and the European Solar and Wind Industrial Initiatives.
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<tr>
<td>AS</td>
<td>Ancillary Services</td>
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<tr>
<td>BESS</td>
<td>Battery Energy Storage System</td>
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<td>CCGT</td>
<td>Closed Cycle Gas Turbine</td>
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<td>CHP</td>
<td>Combined Heat and Power Plant</td>
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<td>DC</td>
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<td>DFIG</td>
<td>Doubly Fed Induction Generator</td>
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<td>DG</td>
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<td>DS</td>
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<td>DSO</td>
<td>Distribution System Operator</td>
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<td>eBOP</td>
<td>Electric Balance of Plant</td>
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<td>ENTSO-E</td>
<td>European Network of Transmission System Operators for Electricity</td>
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<td>ETS</td>
<td>Emission Trading Scheme</td>
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<td>FACTS</td>
<td>Flexible AC Transmission Systems</td>
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<td>FCR</td>
<td>Frequency Containment Reserve</td>
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<td>FFR</td>
<td>Fast Frequency Response</td>
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<td>FRCI</td>
<td>Fast Reactive Current Injection</td>
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<td>FRR</td>
<td>Frequency Restoration Reserves</td>
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<td>SET plan</td>
<td>Strategic Energy Technology Plan</td>
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<td>SNSP</td>
<td>System Non-Synchronous Penetration</td>
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<td>System Restoration Support</td>
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<td>SSVC</td>
<td>Steady State Voltage Control</td>
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<td>SVC</td>
<td>Static Var Compensator</td>
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<td>VAR</td>
<td>Volt Ampere Reactive</td>
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<td>VG</td>
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<td>VRES</td>
<td>Variable Renewable Energy Source</td>
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<td>WT</td>
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1 INTRODUCTION

High shares of variable renewables such as wind and solar PV in the European electricity supply are causing fundamental changes in the provision of grid support services - notably frequency, voltage, system restoration - by the generators in the power system (so-called ancillary services). The setting for grid support services in the future European electricity systems is characterised by the following important developments:

- Fundamental changes in the generation mix, resulting in the disappearance of traditional providers of ancillary services and the entry of large numbers of decentralised renewable plants driven by environmental concerns, increased competitiveness of VG, geopolitics (e.g. fossil fuel scarcity and prices) and changing business cases for non-VG conventional plants;
- fundamental conceptual changes in electricity networks in Europe – more generation at lower voltage levels challenging the traditional hierarchic network structures;
- rapid developments in control and communication technologies with profound impact on control of generation plants (including VG) and management of electricity systems in general;
- continuous process of integration of electricity markets in Europe which will require new ancillary service markets; increased competition at the wholesale and retail levels, following the liberalisation, opening space for new market players and business models;
- in parallel with increased electrification of society, electricity consumers become more and more “prosumers” by installing DGs at their facility (house hold PV, industrial PV and CHP, etc.);
- increased inter-TSO cooperation and creation of over-arching network and market codes;
- transmission developments have not kept pace with the developments of renewable generation. All TSOs now have significant grid upgrade plans but many are delayed due to increased public opposition to major infrastructure developments and related consenting delays;

The REserviceS study has made a technical-economic assessment of the provision of grid support services – notably frequency support, voltage support and system restoration - by variable renewables (wind and solar PV) themselves. The study adds to existing reference knowledge and methods to establish costs and values for ancillary services that can be provided at large scale by wind power and solar PV - installed both at transmission and distribution level in the power system. The REserviceS project in this way strives to contribute to development of effective market-based approaches for ancillary services in a European context and more broadly to design of electricity market mechanisms that enable the power systems in Europe to function safely, reliably and cost-efficiently with very high shares of variable renewables.

The study has focused on wind and solar PV because these are expected to jointly produce the lion’s share of renewable electricity production needed to reach the EU’s 2020 targets. Moreover, many of
the study findings apply to other variable renewable energy sources e.g. marine energy sources, as the physical and economic principles are similar.

Research questions put forward and discussed in this report are structured along the five following themes:

- How do system needs develop for services (frequency, voltage and system restoration) when shares of VG are very high?
- Technical and economic aspects of capabilities of VG to provide the necessary services
- What are economic benefits of large scale provision of services with variable generation?
- What are suitable market conditions and commercial frameworks?
- Knowledge gaps and needs for R&D.

The input for addressing these topics has been generated in several stages of the project. Initially the system needs for services were analysed (Work Package 2). In a second stage a technical and economic assessment has been made of the provision by wind and solar PV of a defined set of grid support services (WPs 3 and 4). The third stage of the project investigated technical and economic impacts in power systems in scenarios with high share of VG by means of case studies – both in transmission (WP5) and distribution (WP6) networks. This synthesis report integrates the output of these activities in the logical structure as sketched above.

At the end of this report, a list is given of the ‘Deliverables’ containing the findings of all these WPs. Besides the simulations and analysis, the consortium also actively interacted with stakeholders (industry and network operators) during workshops1, through surveys and discussions with the Advisory board.

Policy recommendations have been formulated based on the REserviceS study (in a separate REserviceS report) towards the following relevant processes: EU Network Codes (RfG, balancing, DCC, operation etc.), the European Target Model and related (regional) market models, energy policy processes and scenarios, (Grid) infrastructure (e.g. ICT), energy regulation and SET Plan, R&D. The recommendations are put forward by the REserviceS consortium, consisting of wind and solar energy industry associations and industrial companies, knowledge institutes specialised in variable renewables energy markets and power system studies, as well as a European association of distribution system operators.

1 For more information, please consult: http://www.reservices-project.eu/events/

REserviceS D7.1 Synthesis report
2 System needs versus grid support services from wind and solar PV

2.1 Introduction

This chapter summarises the findings of the REserviceS project regarding system needs for grid support services, as well as what services are relevant from variable generation (VG) point of view (REserviceS D2.2). Specific issues at TS/DS level, cross border energy trading, and issues for wind and PV are discussed.

Ancillary services help to maintain integrity, stability, reliability and power quality or the power system, comprising both transmission system (TS) and distribution system (DS). Ancillary services, also called grid support services, can be provided by connected generators, controllable loads and/or network devices (like SVC/FACTS). Some services are set as mandatory requirements in Grid Codes and some services are being procured as needed by the system operators. Requirements as specified by network operators - in Grid Codes and other documents governing connection and operational contracts - define the capabilities of generators that are fundamentally needed for providing grid support services. The REServiceS project has been focusing on services from variable generation by renewable energy sources (VG).

System needs will be influenced by policy targets that anticipate a large share of generation from variable renewable generation. It is therefore important to assess system needs for grid support services for future systems. It is also necessary to do this well in advance to announce the anticipated changes to provide for regulatory stability, necessary to stimulate the needed investments into new power plants. The impact of VG will be seen as an increase in the system needs for support services, but they will also provide part of the services in future. There is a link between system needs for grid support services and the (technical) requirements for generators and services procured from them. Studies of system needs and value of services are needed in order to design the requirements as well as the volume, the level and structure of payments to the service providing generators. Ideally, remuneration should be relative to the value to the system and should reflect the long term cost of service provision. Study, so study results can be used when allocating costs and benefits between the consumers and the grid support service providers.

Power systems have in Europe two layers of system operators. Transmission system operators (TSO) and Distribution system operators (DSO). TSO’s operate the transmission system (TS) comprising (extra) high voltage transmission grid and interconnections to neighbouring TSOs. They also take care of the continuous balance of power demand and supply (frequency management) in addition to the reliability of the power system. DSOs sometimes operate the HV level, however they operate mostly the lower voltage levels – typically MV and LV - down to the consumer level. It has to be noted that a significant part of new VG is connected at DSO level.
Currently transmission connected generators are the main providers of grid support services to TSOs through contractual arrangement or markets. At distribution level, grid support services are not procured and not all services for TSO’s are even relevant to be delivered from generation connected at distribution level. However, it is possible that these will be required or offered in future, due to increased system needs, increasing share of distributed VG (also reducing the possibility to rely exclusively on large generation) new control and ICT technology and possible connection and reinforcement cost optimisation at distribution level. Thus both TSO’s and DSO’s are potential off-takers for grid support services offered by generators connected at transmission or distribution level – as far as allowed by the relevant energy regulator.

Today frequency control is handled by TSOs mainly with the help of generators connected to the transmission network. Frequency is a global load balance indicator in a synchronous power system, and can in theory be controlled from any location in the grid. Distributed generation at DS level can also participate in frequency control, and with the rising share of VG it will do so increasingly in the future.

In contrast to frequency, voltage is a local/regional quantity in power grids. Transmission and distribution systems both require voltage control that differs fundamentally at TS and DS levels. Active grid management for DS is increasing, moving from passive-only low voltage (LV) operation and partly passive medium voltage (MV) operation to more active LV/MV level operation.

By adding decentralised generation like VG, the whole picture changes especially at DS level. While today connection of prosumers and distributed VG in distribution grids is guaranteed in many countries, in the future the full access to the network may not be assured, and the generators may need to share the burden of connection and operation to a greater extent – either by financially participating in the strengthening of the distribution network, or by providing compensation of their impact on the system via new services. Grid management has to be set up in a more holistic way and both TSO and DSO need control at distribution level. Visibility (online data) and controllability of VG becomes important and there will also be more communication needs between TS and DS level. Furthermore, grid support services provision and their integration into the planning and operational stages of the distribution grids will reduce the need for grid reinforcements by enhancing the grid hosting capacity. The DSO’s will not rely only on grid extension anymore to ensure the power quality and connection of existing and new loads and distributed generators. A transition in role from network operators towards distribution system operators is currently happening (Figure 1).

Originally, grid support services were defined to be used by TSO’s, and ENTSO-E is currently striving to unify and harmonise them in Europe. Provision of services to the TSO from the distribution level is currently not standard practice and is not standardised. Furthermore grid support services for the distribution level have not really been defined, as they were singled out only after the introduction of the wholesale electricity markets and as such entrusted to the TSO responsibility. The fast increasing fleet of distributed variable generation connected at DS level could provide new services that could potentially significantly improve the operation of the DS. This is an ongoing transition in distribution...
systems, enabled by smart grid technologies and supported by massive world-wide research effort. Cooperation and information exchange between TSO and DSO are critical to minimise system investments, and operational costs.

**Figure 1.** Transmission and distribution systems traditionally built and how they are changing in future with local generation and smart grids.

### 2.2 How do system needs change with increasing wind and solar (PV) penetration?

#### 2.2.1 General trend – increasing needs at increasing penetration levels of VG

Quantified results on how renewables impact system needs for ancillary services are still limited, especially regarding combined impacts of wind and solar on system needs. The existing knowledge mainly stems from experience and estimates made in integration studies. However, other changes in frequency and voltage control have occurred in power systems, making it difficult to get direct information about how much the needs for frequency and voltage support have actually increased due to additions of wind and solar power. For example in Germany, the sharing of frequency restoration reserves between the four TSO areas has reduced the needed frequency support more than the growing wind and PV shares have increased it. Quantified impacts from a single generation technology like wind and solar (PV) are also difficult to extract from the system study results because system services are assessed simultaneously for the entire power system: all generation and load with the operational practices used.

The main impacts of VG are due to the increased variability (Figure 2), and uncertainty that will result in more balancing needs thus impacting frequency and voltage control needs. At increasing shares of
VG, the non-synchronous\(^2\) characteristics of VG generation become important, causing first the increasing need for services and as a second step the lack of sources to provide services from synchronous (non-VG) generation during high wind and sunny hours.

![Graph showing 2011, 2020 and 2030 ramping requirements in the EU 27 (MW)](source: EPIA, 2012)

**Figure 2.** Increasing ramping requirements of the net load in Europe, from EPIA and EWEA scenarios for the installed capacity of wind and PV

Distributed VG connected in DS also impacts system operation in ways not always perceived on the TS level (reverse power flows, line congestion, voltage profile management, impact on power losses, protection and control) thus causing new system needs in distribution systems. Impacts of inadequate system services have sometimes resulted in curtailments, even if the main reasons for curtailments so far have been a lack of transmission capacity and inflexibility of electricity spot markets to accommodate all VG during high wind/sunny hours. In Ireland curtailments have occurred due to concerns about low inertia.

\(^2\) Non-synchronous generation employs generation technology that does not rely on the synchronous generator and hence does not employ rotating masses in synchronism with the system frequency. Such generation does not exhibit some of the intrinsic network-stabilising properties like synchronous inertia.
Needs for frequency support services

The need for frequency related services increases with increasing penetration level of wind and solar. Experience of wind integration shows that when reaching penetration levels of 5-10%, an increase in the use of short term reserves is observed, especially for reserves activated on a 10-15 minute or longer time scale. Wind and solar PV, with small project size, do not impact contingency reserve requirements as large amounts of generation (>1-3 GW) will not trip of in seconds. However, in special extreme weather events large non-anticipated changes in generation can occur in an hour. Example is storm cases for wind (Twenties, 2013) or fog for solar PV (Figure 3).

![Figure 3: PV forecasting in high fog situation, an 8 GW deviation between the day ahead forecast and the real time projection. The open positions after the intraday gate closure time have to be cleared within the balancing market. Source: Elia Group, EPEX, 2014](image)

No significant frequency control impacts for services activated in less than 30 seconds have been observed to result from wind power variation. For solar PV, the morning and evening ramps will be challenging at larger penetration levels (>10%). This will necessitate planning the use of short term reserves and longer than RR services in interaction with the dispatch of plants on the day-ahead and intraday markets (IEA, 2014). Wind integration studies have aimed at quantifying the increase in short term reserves (usually the ones activated in 10-15 minutes, manual FRR), and the results show an increasing trend for increasing wind penetration. The results depend on what time scale of uncertainty is planned for when determining short term reserve needs. For wind up to 20 % share of yearly demand, the following results have been observed (Holttinen, et al. 2012):

- Preparing to respond to hourly and sub-hourly variations of wind power results in an increase of FRR services corresponding to 1-2 % of installed wind capacity. This is the extra reserve compared to a case without wind. This amount of extra reserve will cover the extreme cases during a year; most of the time the impact of wind on reserve requirements will not be that high.
- Allocating short term reserve to respond to unforeseen variations that could occur 4 hours ahead results in an increase corresponding to 5-10% of installed wind power capacity.
- Managing all day-ahead forecast errors with operating reserves will require an increase in maximal amount of services needed - corresponding to more than 15% of installed wind power capacity.

This shows that the operational practices used in a power system will impact the need of frequency support services: if dispatch decisions are updated frequently, the impact of wind (and solar PV) on reserve requirements will be smaller.

A more general indicator than VG penetration level in the power system is the system non-synchronous penetration (SNSP), as applied in Ireland. This is a useful measure for challenges in system inertia and frequency control. SNSP includes wind, solar PV and power flow from DC links, and gives the penetration relative to the load and the export capacities. Given the structure of generation and the share of VG in the power system, the required frequency response depends on system dynamics, and the response speed is not the only critical element which has to be taken into account. In Ireland a methodology has been used to determine the system needs in the DS3 project of the TSOs, with results reported in the D5.1 report.

In Germany, currently 20 GW of distributed generation installed capacity, including 17 GW of solar PV, cannot be controlled by grid operators. Large-scale distributed generation and conventional power plants were found to provide enough controllable capacity up to the year 2016 (Consentec & Ecofys, 2013), but there will be a growing need to control renewable energy generation for balancing reasons. Small PV plants in particular will be affected by this new requirement.

**Need for voltage support services**
Voltage control in the power system is traditionally performed with controlled reactive power injection or consumption and by changing the HV/MV transformer ratios using tap changers. With the reactive power consumption in the loads, the voltage drops at the end of long feeders can be significant and reactive power compensation is a technical solution to maintain voltage profile. Traditionally, the needed amounts of reactive power in the distribution network are provided from the transmission network. Due to the lack of generation resources in the distribution network, reactive power balancing usually did not happen there and all reactive needs were covered by reactive power provided by large generators on the HV side in the transmission network.

At high levels of generation in the distribution network, reverse power flows may occur in the DN towards upstream voltage levels up to the transmission system level. This phenomenon is often accompanied by voltage rises and may result in high compensation penalties for DSO’s when the power flows over the HV/MV substation are outside a predefined PQ-band. Using coordinated central control strategies at the MV level involving VG services, for instance, can contribute to the optimisation of reactive power exchange between HV and MV levels efficiently and hence reduce the reactive power compensation penalty for DSOs, while keeping the voltage values within required limits.
The need for voltage support services increases with higher penetration levels of VG. However as VG usually has reactive power capabilities (see Chapter 3), the increasing trend in the need is not straightforward. In cases where voltage control is provided by VG, the impact can be reversed to a positive impact. The main impacts are:

- Changes in voltage profiles will appear in the power system. To maintain the voltage profiles close to the optimal profiles, the voltage settings of the reactive power sources including large generators as well as network reactive power sources (e.g. tap changing transformers, capacitor/reactor banks and FACTS devices) will need to be recalculated.

- Installed reactive power sources, both static and dynamic, available to the system operator to manage voltage will fundamentally alter. The Ireland study for transmission level impacts (Eirgrid and Soni, 2012) concludes that to reach close to 40 % share of wind of yearly demand, enhanced sources of static and dynamic reactive power are needed – also from wind turbines. In particular, the necessary level of fast reactive current injection during and after transmission network faults (also called post-fault reactive current) will increase with the rising SNSP. This new type of grid support service will be needed to maintain the magnetic coupling of the rotating machines. The Ireland study also defined the system needs for AS products based on response time and proposed an allocation of services to the most likely providers.

- Dynamic reactive power support from network devices (e.g. FACTS, synchronous compensators, wind or PV power plants) during voltage disturbances could be used to mitigate most contingencies with a critical clearance time (CCT) less than 200 ms. Application of such mitigation strategies substantially improves transient stability by increasing the critical clearance time of the most onerous faults.

- VG can either decrease or increase grid losses depending on their location. Smaller amounts of VG sited near consumption usually help reducing grid losses, but VG becoming predominant increases grid losses. However, voltage support from VG can reduce losses (Twenties; REservices D6.2) and increase hosting capacity of the grid (delay grid reinforcements) (REservices D6.2).

- New, faster protection measures and enhanced fault-ride-through performances will be needed.

- The reactive power balance at the TSO/DSO interface is profoundly altered by the presence of distributed generators. During sunny or windy hours, the active load of a specific feeder can be partially or completely covered by the production of distributed generators. Feeder load could even be dominated by local generation, leading to reversed power flow at the HV/MV substation. However the need for reactive power still remains or increases due to the reactive behaviour of some loads and network components. This effect is aggravated by the increasing use of voltage measures using reactive power consumption DG capabilities to maintain the voltage profile at the LV and MV level. This “VAR aspiration” effect led to the
redefinition of PQ requirements at the TSO/DSO interface\(^3\) and new PQ requirements for generators connected close to the interface\(^4\).

**Need for system restoration services**

A third important category of ancillary services from generators are restoration services (for example recovering a system from black-out). Thus far, neither experience nor studies exist on how wind/PV would impact on system restoration, during an islanding situation or a black start. There is no evidence that wind and solar PV would increase the risk of black out. However, high shares of VG may bring power systems into types of situations where there is less experience with proper operational procedures while at the same time it is highly uncertain to which extent the traditional mechanisms and means for control of such situations would constitute a reliable solution. Retirement of conventional power plants will impact the ability of the system to restore. The risk of this conventional plants retirement and additions of variable renewables is not always considered as severe, for example in Spain where black start is performed by autonomous hydro power plants. In Denmark the Cell project (Energinet.dk, 2011) studied islanding in case of embedded VG, but did not take into account the possibilities of VG providing services.

When a power system is in island operation the survival of the island could be secured by activation of a power unit equipped with a voltage controller. High penetration of VG in the grid considerably changes the islanding scheme. Due to the problem of transient stability after islanding, a certain balance should be achieved between conventional units and renewable sources in the island. That may be a difficult task with high VG penetrations and, as a result, larger islands will be needed. A reduced number of conventional units in the system due to increased VG installed capacity may make it challenging to find a suitable island.

Recent investigations in Germany indicate that the restoration of the power system will be started with pumped storage and thermal plants– at least until 2033.\(^5\) According to the study a proven concept to integrate renewables in the restoration process does not exist, but it will be needed or at least it will be beneficial in the future.

To integrate renewable energy sources in system restoration the following is needed:

- The participating VG plants need to be controlled directly by the TSO;
- Partial curtailment of VG systems may be needed during reconnection;

\(^3\) ENTSO-E NC RIG, 2012
\(^4\) ENTSO-E NC for Demand Connection
\(^5\) dena-Studie Systemdienstleistung 2030, 2014

REserviceS D7.1 Synthesis report
• Provision of frequency and voltage support services;
• Training of responsible TSO and DSO staff, in particular with respect to interaction aspects for system restoration

**Power system needs beyond system services**
Variable generation will also have impacts other than those related to frequency and voltage support. These include the need for new grid infrastructure and the capacity and energy adequacy of a power system. There is a system security benefit from more installed indigenous power. However, the capacity value\(^6\) of wind and solar PV will depend on how much generation is available during times of peak demand. The impacts on grid infrastructure can be large, but as they are not related to ancillary services in operation of the system, they have not been discussed in the REserviceS project.

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\(^6\) Capacity value or credit per unit capacity (e.g. MW) of a generator is defined as the amount of additional load that can be served due to the addition of the generator, without affecting the level of security of supply.
2.2.2 Regional differences in needs for services

It is a challenge to define generic quantified system needs with VG. Quantitative results differ among systems due to the differences between the systems themselves. There are regional differences in power systems and the existence of multiple voltage levels means that each network will often have different characteristics. Power system resilience, its endurance and tolerance to changes, will influence how much extra services are needed when VG is added to the power system. Regarding balancing and frequency support, some power systems have more variable load and thus already operational measures and a more flexible generation fleet that is capable of managing variability. This existing flexibility in load and the generation fleet may be sufficient to accommodate larger amounts of VG.

The characteristics of power systems that impact the system needs with increasing share of VG are:

- **Operational practices** regarding both the timing of dispatch and timing of bidding of services as well as the use of advanced forecasting tools will influence how much system services are needed and available for bidding. If the dispatch time intervals are short (like 15 min instead of 1 hour) and they are dispatched shortly before delivery, the amount of imbalances in the system remaining to be used during the actual delivery interval will be shorter (Milligan et al, 2011).

- **Power system resilience** i.e. its flexibility and ability to endure changes which is characterised by the following aspects:
  - **AS needs from loads and generators**: The inherent variability and uncertainty of the load and maximum size of a generator tripping off will influence the needs for frequency support. If there is already a high need for services before installation of VG, the impact of VG will not be seen at lower shares of VG. Location of loads and generators will impact the voltage support needs. Location will also impact the reliability of the network connecting them, and how much VG can trip off due to network fault (causing a contingency event).
  - **Capability of sharing needs with neighbouring countries**: Using interconnection for balancing and frequency support can reduce the needs considerably for a single TSO area.
  - **Power system size and robustness characteristics**: For higher shares of VG the stability of power system can be impacted by VG. Each power system will have its predominant stability issues (IEA Wind, 2013). A smaller system size for example means that system inertia will become a crucial aspect.

- **Network strength and topology**: Network strength and topology primarily affect the needs for voltage control. They also influence how frequency support can be covered from a larger balancing area, reducing the need for services and also pooling in more services. For
example, bottlenecks in the grid (‘imperfect’ topology), create smaller areas that need to be balanced internally.

- **Diversity of voltage levels in DS:** The multiple voltage levels in a distribution network will often have different characteristics. Also urban and rural networks are different. In densely populated urban areas, load is spatially concentrated and often supplied from several locations with adequate reactive power sources, however many of the distribution lines are cabled. Rural demand on the other hand is spatially dispersed, weakly connected and chronically underfed with reactive power, leading to poor voltage profiles. The definition of voltage levels across power systems, high/medium/low voltage (HV, MV, LV) is not standardized (in particular MV⁷). Protection settings are dependent on voltage levels, and today even protection schemes can vary. The controllability of transformers (OLTC) also varies.

The way that VG is built in terms of location and technical characteristics also impacts the system needs for grid support and involves locational/regional aspects.

- Location of VG: is it built in a strong or weak grid, what are the electrical distances of units to DSO/TSO interface?
- Dispersion of VG units: The degree of concentration/dispersion in locations of VG determines the impact of wind and solar PV on the total variability and predictability of VG in the system.
- Enhanced technical capabilities of VG, and operational strategies of VG in critical high-VG share hours. This aspect is the central focus of REserviceS, and is addressed in detail in Chapter 3.

System needs will also be higher if not all generators providing services comply when asked to procure the service.

For frequency support services the main regional differences arise from the power system size (island systems like Ireland and UK versus the large Central Europe system), existing flexibility of non-VG generators, interconnectors and how they are used and operational practices like gate-closure times. For Ireland system inertia resp. rated-of-change-of-frequency (ROCOF) are issues, for the GB system this also may become an issue, but for the large Central European system it is not foreseen as an issue in the medium term.

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⁷ The International Electrotechnical Commission has classified the voltages into the following levels (IEC 60038): Low Voltage – up to 1000V; Medium Voltage - 1000V to 35kV; High Voltage - 35kV to 230 kV; Extra High Voltage - above 230 kV. But in practice each DSO has its own MV range (REserviceS D6.2)
For voltage support services the main regional differences are related to grid strength (short circuit levels and impedance), multiplicity of voltage levels, VG dispersion and distance to load, the difference between peak load and grid capacity, electrical distances to DSO/TSO interface, observability/controllability of transformers (OLTC) and other grid components such as lines. Also Grid Code requirements for reactive power provision and voltage bands imposed on different reactive power sources (e.g. defined leading/lagging cosφ, voltage level band etc.) are different across Europe.

The electrical distance of the VG plant to the DSO/TSO interface is important in how it can provide useful voltage support (Abele, 2013). In section 3.3.2 Voltage Control a ranking of reactive resources suitable for reactive balancing according to the electrical distance to the HV grid is presented.

2.2.3 Methods of assessing system needs with VG are still evolving

System operators have years of experience giving them good confidence in basic needs for system services. However, in future systems with large amounts of VG the current rules and study methods will not likely apply. Assessing system needs with VG and how much VG increases these needs is not straightforward as there are no generally applied rules/formulas for this purpose. The approaches differ among countries and require a lot of data/tools/new methods to include VG. On the other hand, simplified methods may lead to wrong estimates of the needs.

TSOs traditionally used deterministic rules for managing uncertainty. Managing increasing amounts of VG will mean that also development of methods for management of uncertainty is needed, as well as improved management of other elements like demand response. TSOs and regulators tend to strive to eliminate unnecessary risks, so any new methodologies need to be thoroughly tested and be proven to work even in rare events. Probabilistic reserve allocation has been tested by TSOs in Spain and Portugal, for daily allocation of reserve requirements, and has been used side by side with deterministic methods. So far regulators do not allow only probabilistic tools to be used. Assessing needs with stochastic tools and even having a possibility to make stochastic bids is identified as one of the long term options to integrate large shares of VG, even if at the moment such revolutionary new ways of operating power systems may be difficult to get approved. For example in Ireland, the TSO used the software tool Wilmar together with a probabilistic wind forecasting module (Anemos) to mimic the deterministic Reliability Constrained Unit Commitment tool RCUC\(^8\). The aim of European projects like AnemosPlus, UMBRELLA (www.umbrella-project.eu) and Garpur (www.garpur-project.eu) is to

\(^8\) A.F. Gubina, et al., 2008/9
explore new operational measures or tools to better integrate uncertainty management in the day to day operation of power systems.

There should be a link between the requirements for generator capabilities and system needs. Ideally legislation and requirements should not demand more than needed by the system. In practice system operators are defining the need and designing the requirements based on their experience of power system operation. But with the rise of variable, non-synchronous and decentralised generation, classical approaches could lead to inefficiencies in the requirements definitions. TSOs and DSOs have to rely more and more on detailed studies that take VG into account when estimating system needs which have to include the foreseen evolution of the network. For instance, Ireland has made a series of studies to investigate their future system needs with large amount of wind generation. Furthermore, EU-wide rules are difficult to define as system resilience varies a lot from one member state to another. There is still a long way to go towards a proper balance between harmonisation of rules and specifications encompassing all different national parameters. Another aspect for services and requirements for future systems is the need to minimise curtailment and to avoid costly and burdensome retrofitting of generators to enhance their capabilities.

It is not yet clear where the studies needed for future needs should be initiated. The current trend towards harmonisation of requirements means that - even if system needs are not the same everywhere - similar requirements can be demanded. There are currently statements in the ENTSO-E adequacy forecast report outlining the needs for energy and capacity. In the future TSOs could look at the whole range of system services for the next 3-4 years and ensure they are in place in time. However, the time frame needed to ask for new capabilities from new generators is longer than 5 years, and TSOs do not always have knowledge of how much VG will be developed 10 years ahead.

### 2.3 Recommended key services from wind and solar PV

To fulfil system needs there are different ancillary services products. The main services in use today are voltage and frequency control with different time scales and black start for system restoration. The main categories of frequency support, voltage support and restoration services were selected as starting point for system services provision from VG point of view. Power systems with large shares of VG will probably also need other services than in use today.

For frequency support services, the division proposed by ENTSO-E (ENTSO-E NC OS, 2012) has been chosen. New services to reflect future needs are fast frequency response and ramping margin for frequency support. In addition to voltage support for normal operation, fast reactive current injection during voltage dips and for post fault voltage control have been added. Regarding system restoration, basic black start services have been enhanced by islanding services (see Table 1 on the next page).
Table 1. Ancillary services categories relevant for VG provision of services (REserviceS D2.2).

<table>
<thead>
<tr>
<th>Frequency support</th>
<th>Voltage support</th>
<th>System restoration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Containment Reserve FCR (&lt;5, 10 or 30 sec)</td>
<td>Normal Operation: control of power factor, reactive power or voltage</td>
<td>Black start</td>
</tr>
<tr>
<td>Frequency Restoration Reserve FRR (&lt;15 min)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replacement Reserve RR (15 min to hours)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast frequency response (synthetic inertia) (&lt; 2s)</td>
<td>Fast reactive current injection</td>
<td>Islanding</td>
</tr>
<tr>
<td>Ramping margin (1, 3, 8 hours ahead)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Frequency control** – services related to the short-term balance of power and frequency of the power system; it includes automatic (primary/secondary) and manual (tertiary) frequency regulation and operational reserves. This is the main service provided by generators (online for automatic services and online or offline for longer term activated services). It can also be provided from flexible loads, and storage units.

- **Voltage control** – services required for maintaining the power system voltage within the prescribed bounds during normal operation and during disturbances by keeping the balance of generation and consumption of reactive power. Voltage control includes reactive power supply (injection or absorption) and can be provided by the dynamic sources (generators, synchronous compensators) and static sources such as capacitor banks, static voltage controllers and FACTS devices, including, Unified Power Flow Controller as well as network equipment like tap-changing transformers in the substations and loads. In the event of a disturbance to the system, dynamic reactive power response is required to maintain system stability. Network reinforcements and reconfiguration will impact on the voltage control needed.

- **System restoration** – services required to return the power system to normal operation after a blackout; from the generator point of view it includes mainly black start), and will in future also include islanding operation.

The technical specifications related to ancillary services are to a large extent based on the requirements for capabilities, described in national Grid Codes that will in future follow the ENTSO-E Network Code RfG (requirements for generators).
System restoration services from VG are not as acutely needed as frequency and voltage services, but there may be more needs in future. They are included in the project, but are not treated with as much detail as frequency and voltage support.

The selected services listed in Table 1 reflect current discussions and developments in the industry and TSO community at the onset of the REserviceS project. However, during the course of the project it appeared that current thinking in industry extends to defining other possible services that are needed in situations where functionalities traditionally inherently provided by synchronous generators are no longer present in the power system. These include the following:

- Mitigation of negative sequence voltages – in particular during unbalanced faults. Further research is needed to determine more precisely the needs depending on particular power system characteristics. This may result in the definition of services (like negative sequence reactive current injection) to be locally provided.
- Damping of low-order harmonics which are normally short-circuited in the windings of synchronous generators. A possible service that could be provided by inverter based VG is active filtering, based on local power system needs.
- Damping of power system (inter-area) oscillations, traditionally performed by PSS installed in synchronous generation. Further research is needed to assess the risk that these oscillations may change in future due to reduced rotating mass in the system and for example to which frequency range) a possible service by VG may tuned at.

2.4 Services not addressed by the REserviceS project
There are several other services that are provided by the system operator currently in use that are not included in Table 1 (not provided by generators):

- **Coordination of operating procedures between DSO and TSO:** loss of mains protection settings; capacity of the system to ride through high RoCoF events etc.

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9 Quitmann, et al., 2013

*REserviceS D7.1 Synthesis report*
- **Emergency control (EC) actions**: Maintenance and use of special equipment (e.g., power system stabilisers and dynamic braking resistors) to maintain a secure transmission system.

- **Dynamic Stability Management**: Offline studies for voltage, rotor angle or frequency stability.

Some existing system services can be handled with the already listed ancillary services, even if they are for a different purpose:

- **Congestion management**: Re-dispatch to prevent violations of the power flow Operational Security Limits (ENTSO-E OS NC). From generator point of view this service is technically similar to manually activated frequency support services. Even if not for balancing but for load flow management, TSOs could take these from manually activated Frequency Restoration reserve, for example if wind and solar were bidding to balancing markets (FRR manual). However, congestion management is a locally needed service whereas frequency support can usually be used from generators located in different parts of the system. This means that when using cluster control for frequency support, the local component should be kept to make use of Cluster capabilities for congestion management.

- **Grid loss compensation (GL)**: Compensating the transmission system losses. This is part of voltage control service.

Long term reserve planning is not included in the REserviceS work – in other words this is not considered as an ancillary service here. Variability of VG - meaning that VG capacity is not always available during times of high demand – has an impact on long term planning, because it influences power system resource adequacy and challenges the market design. Capacity markets constitute one of the options of income to generators to keep them on-line to provide power during short periods of high loads and low VG generation, in situations where energy-only markets and ancillary services markets would not give enough income.

### 2.5 Specific high VG penetration issues at transmission respectively distribution level

#### 2.5.1 Issues at transmission level

The main issues at transmission level arise from fewer thermal/hydro/nuclear power plants on-line, leading to high VG/high SNSP levels. This gives rise to even more need for frequency and voltage support and system inertia.

Frequency control and balancing is made more challenging with increased ramping needs (including also ramping up due to load picking up) when little non-VG generation is online. At higher VG penetration levels, provision of system inertia will be an issue for smaller islanded systems like Ireland and possibly for medium size interconnected systems like Great Britain and Nordic system. Cross-border sharing of frequency support (and intra-day trade) will help the balancing task. VG providing
frequency support services will help mitigate most of the issues, however the issues of fast response during faults and stability issues still need more work to confirm that notion.

For voltage control, the amount and the locational availability of reactive power in the system will change and VG provision of voltage support can mitigate most issues. However, the coordination of providing voltage support from small VG units still needs more work, as is the case for potential stability issues.

During rare occurrences of system restoration, the issue is adequacy of black-start units in the system. In systems with higher penetrations of VG, when there is not enough non-VG units in the system to cover the full load, VG could contribute to the restoration process. Probably this would be done first after some generation units have already started the restoration process. New processes limiting the variability inherent in their generation need to be created for VG to take part in the system restoration.

2.5.2 Issues of high VG levels at distribution level:

High levels of generation connected to distribution networks introduces complexity in the operation of distribution system and could create voltage disturbance and grid congestion at times of high VG generation and low local demand. Principal issues affecting the need for GSS at distribution level are:

- **Frequency control** – Requirements for generators connected at MV and LV levels may be different from those at HV level, affecting the extent of provision of different types of frequency support. Frequency control (on TSO demand) with generators or loads connected at the distribution level may also interfere with the distribution network operation.

- **Voltage control** – VG increases voltage variations and can lead to exceeding the acceptable voltage band. At the same time, reactive power control from VG can contribute to compensation of losses or can increase the hosting capacity of the distribution network without jeopardizing the security and the quality of the system, especially at MV network. Variation of generation level will lead to changing voltage profiles and needs more frequent assessment of voltage control.

- **Line congestion:** due to radial DS operation, some lines can get congested due to a surplus of generation over load in one node. In order to reduce line congestion, VG is usually curtailed with the optimisation algorithms also employing dynamic line rating and intelligent control.

- **Protection issues:** High amounts of VG lead to diminishing fault current in the systems and can have a negative effect on the protection schemes (unintentional islanding). To mitigate this issue, modification or reconfiguration of protection systems are required.

- **Intended islanding:** During a disturbance in the TS and subsequent interruption of supply from the HV side of the substation, the distribution feeder loads can remain supplied via a diesel generator. However, unlike the islands only supplied by schedulable generation, the uncertain and variable nature of the VG limits the reliability of supply in such an island.
Mitigation methods for the above VG issues include the implementation of distribution planning and operational tools. Practices for system planning and voltage profile simulations need to be further developed. These tools should include the use of services provided by advanced inverters, DFIGs and novel components in order to make the best of existing or future capabilities available at the distribution level.

In the case studies of REserviceS, solutions for DSO’s for enabling high shares of VG (high hosting capacity) were investigated. These solutions are mainly in the area of voltage control and congestion management, both at the level of the DSO and at generator level:

- With the increasing availability of voltage support and congestion management capabilities from distributed generators, the hosting capacity of a specific feeder can be increased without the need to reinforce the feeder.
- Central voltage control: Sending optimal voltage set points to generators connected to the HV and MV distribution networks (Steady State Voltage Control). The case studies show that Q-V control demands a large amount of reactive power to be effective. The need for reactive power decreases as the dispersion of the resources increases.

2.6 Interaction of needs and services between transmission and distribution level

Increase of VG means that generating capacity is increased in DSO networks and can even be decreased from the TSO networks. Consequently, DSOs start playing larger and larger role in coordination of VG and voltage control. Today in many countries already a transition phase is seen.

Governance of “who is doing what” needs to be established for DSO/TSO interaction in order to properly coordinate frequency and voltage support, as well as restoration services provided by VG. With the increasing availability of reactive power sources or consumers at the distribution level, the PQ and voltage coordination at the interface with the transmission network has to be redefined. Typical coordination tasks will involve the coordinated management of active and reactive power injections of VG at in the lower voltage levels.

The following topics of importance are identified:

- Organisation of data exchange: Real-time monitoring (visibility of distributed generation) and ability to control requires an effort for providing the communication to small renewables plants. This is relevant also for congestion management. Data exchange will be greatly expanded, and DSOs will also be more involved. The increasing need for data transfer between TSO/DSO is for instance covered by new requirements described in the ENTSOE operational security network code (ENTSO-E, 2012).
- As TSOs set the rules for frequency control they should also be responsible for overall coordination. Frequency support from generators at DS level by measuring frequency is straightforward but area control / centralised frequency control is less obvious. There can
be issues mainly in controls and communication and response times. Also there is an important task of coordination of information. For example, bids from DS level generators need to be checked by DSOs so that there are no conflicts if they are procured.

- For voltage control, DSOs play a large role. Voltage support requires coordination with TSOs, in case of embedded VG but also with FACTS and demand side. TSO’s activation of balancing reserves connected to the DSO network can cause problems in DSO’s networks. TSO needs to develop voltage control plans for normal operation and contingencies. As shown in WP6, fixing reactive power flow requirements at TSO/DSO connection points leads to inefficiencies for the transmission level. The TSO/DSO coordinated strategy must be considered and reflected in Network Codes. Letting TSO and DSOs manage reactive power in a coordinated manner at each connection point, improving cooperation and information exchange between TSO and DSO and empowering services from VG to DSO are critical to minimise system investments, and operational costs.

- Last but not least, it is evident that black start and islanding using support from VG where relevant require coordination at TSO/DSO level.

2.7 Cross-border issues of needs and services

VG impacts the need for cross border trade of ancillary services, mainly for the frequency related services because this trade can help in sharing/pooling together scarce resources. Cross-border trade enables providing services to a larger market covering several countries and TSOs.

Cross border trading of frequency support is beneficial for system operation and recommended. With increasing share of VG, the need for balancing resources increases. Cross border trade can help in two ways: by pooling-in more balancing resources and by reducing the total needs for services (reserve requirements). 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).

For voltage support, there can be cross border issues during events, like disappearance of reactive power due to network faults. Sharing voltage support cross border is not happening today. The need for it is not seen in the foreseeable future, and service provision is thus not recommended, at least at this stage.

2.8 Specific needs regarding wind and large scale offshore wind deployment

A significant difference in causing system needs between wind and solar PV integration is related to the size of units. Larger units have advantages in improving and simplifying communication systems
between TSOs. Larger wind power plants are connected to transmission networks, and the smaller solar PV plants are usually connected medium and lower voltage levels.

Compared to solar PV, combining wind power plants from larger and larger areas has a much stronger smoothing effect on power variability, which helps to diminish uncertainty and alleviates the additional need for services.

Increasing the plant size of wind generation is realised by centrally controlled wind farms and wind farm clusters, and by HVDC converters in the in case of offshore. Large offshore wind power plants with size up to 500-1000 MW represent large amounts of concentrated generation, connected to few onshore nodes. There are limits to the share of frequency support coming from one network node (max 10 %), therefore TSOs cannot fully rely on services coming only from offshore wind power plants.

For offshore wind, the choice of AC or DC connection has an impact on system needs. AC connected offshore wind plants can provide active power reserve and frequency response in the same manner as onshore AC wind plant projects, however there may be some issues related to providing services from a longer distance. Larger distance transmission brings higher losses and higher reactive power generated by the cable. Steady state voltage control (SSVC) can in general solved by the onshore installations (e.g. FACTS). Fault current injected during/after network faults (FRCI) needs to be addressed separately.

### 2.9 Specific needs regarding distributed solar PV

Some specific systems needs are caused by the intrinsic characteristics of the solar PV technology: modularity, inverter-based connection and variability.

Managing the short-term variability of solar PV and the impact of the grid interface technology will be somewhat similar to that of wind power and the subjects have been already covered by the previous sections. However it is important to note that the variability of solar PV systems can be considerable in partly cloudy weather and also with fog or snow.\(^\text{11}\)

When it comes to aggregation, the smoothing effect of solar PV will saturate quicker than the smoothing of wind variability – the fast variability due to clouds will smooth out to a bell-shape form of

\(^{10}\) Small wind turbines at household level in the lower voltage networks are still rare, and will not affect system needs in a foreseeable time.

\(^{11}\) Lorenz et al., 2009; Mills et al., 2011.
PV generation. When that has been reached, there are no more extra benefits of aggregating more PV inside an area. However adding a large area will smooth out the high and low intensity days, bringing less variability to the daily peak reached\(^\text{12}\). Aggregation throughout Europe will have some benefit in the morning and evening ramps, as there are a couple of hours of time difference in the rising and falling of sun inside Europe (Figure 4).

Figure 4. Example of smoothing effect of wind and PV generation in Europe (here including GB, Ireland, Nordic countries, France, Germany, Iberia and Italy). Source (IEA, 2014).

What makes PV really different from other generation technologies is its modularity. The range of applications starts from the small residential system connected at the low voltage level (a few kW) to large ground mounted installations connected at the high voltage level (a few hundred MW). The speed

\(^{12}\text{IEA, 2014}\)
at which numerous PV systems can be installed as well as the voltage level at which they are connected create new needs for the operation of power systems and the procurement of ancillary services.

2.9.1 Specific needs at transmission level due to increased solar PV

Significant factors affecting the operation of transmission grids in the presence of large amounts of solar PV are summarised below:

Need for increased controllability/observability

The need for data exchange and control strategies changes completely considering millions of units in comparison to the thousands of conventional non-VG units currently in activity in EU. To secure the network stability, a certain share of the generation capacity needs to be controllable. For instance, the ENTSO-E NC RfG\textsuperscript{13} will require that even a small unit (starting from 800 W) should be equipped with an on/off logic interface. This is not technically challenging at the unit level (even if there are associated costs with such requirements) but the challenge is in the control and communication infrastructures of such a large fleet. The increasing role of communication in power system operation raises also the question of cyber security.

Location of the installed capacity:

When providing services, the electrical distance to the transmission grid has an effect on the performance of the service provided. For frequency support services, electrical losses and possible interactions with the distribution grid operation will have an impact. However, the location will even be more important for voltage support services as reactive power cannot travel over long distances.

In addition, the growth of small PV systems is sometimes faster in specific communities or regions, leading to an uneven overall distribution of installations at the country level. This makes it particularly difficult for grid planners to plan and expand the infrastructure because where such “hotspots” will emerge is hard to predict. This unequal distribution leads to different needs in terms of services for different regions or even on a specific feeder. When designing the requirements and the framework for the procurement of ancillary services at the distribution level, the spatial distribution should also be taken into account to avoid cost inefficiencies which could be due to one-fits-all approach.

System impacts from improper settings of millions of small units

Due to the improper consideration of possible solar PV deployment trajectories in Europe, the disconnection settings for most of the distributed generation currently connected are in the range of

\textsuperscript{13} ENTSO-E, 2012
50.2 – 50.3 Hz for over-frequency and around 49.7 – 49.5 Hz for under-frequency. Knowing that the currently installed capacity of distributed generation corresponds to a multiple of the available primary control reserve, the risk of serious system disturbance due to an uncoordinated and massive disconnection of generation cannot be excluded anymore. It can be foreseen that the system balance might only be managed by the activation of large scale load shedding. The necessary amount of distributed generation which will have to be retrofitted by changing the frequency disconnection settings was analysed and recommendations for the implementation of two specific mitigation measures for the new installed capacity were set by ENTSO-E:\(^\text{14}\):

- No automatic disconnection in the frequency range from 47.5 Hz to 51.5 Hz shall take place. This should be implemented in all European countries as soon as possible.
- Automatic Reconnection after a severe frequency transient is permitted but specific logics are required in order to avoid reconnection during restoration phase and to guarantee a maximum total gradient of the PV power generation after the resynchronisation.

2.9.2 Issues and needs at distribution level with increasing solar PV

The narrow spatial distribution of single PV systems can lead to a high correlation of local irradiation conditions, as experienced for example in Germany, where local PV generation at times exceeds local load demand. As mentioned in section 2.5, reverse power flows occur toward upstream voltage levels, often accompanied by voltage rises. Consequently, the allowed voltage band of ±10% of the nominal voltage for less than 5% of the ten-minute average root-mean-square values over the course of one week (from power-quality standard EN 50160) is more often violated with PV than without PV.

To fulfil the voltage quality requirements DSOs have to take corrective actions when the local solar PV penetration gets too high. Typical measures encompass the replacement of transformers and the installation of additional lines in order to increase the local hosting capacity of the grid. Using the control capabilities of modern solar PV inverters (active and reactive power control) for local voltage support can reduce the necessity of such additional grid reinforcement measures. Currently, in addition to the conventional means of grid reinforcement, PV systems installed in Germany are required to support the local voltage by the provision of reactive power and active power curtailment.

High-penetration scenarios of solar PV will bring a demand for advanced control concepts to guarantee reliable and cost-efficient grid operation. PV systems must provide ancillary services based on multiple layers of control. Pure local-inverter control concepts can be used to mitigate local voltage rises and

\(^{14}\)ENTSO-E, 2013: The need for retrofitting the already installed capacity is currently being assessed by ENTSO-E building on the experience of ongoing retrofit plans in Italy and Germany.
so increase the hosting capacity of certain grid sections for further PV deployment. They will fail, however, in situations where coordinated power control is necessary (e.g., in cases of temporal congestions at higher voltage levels). This situation demands even more fully integrated approaches that consider local, decentralised, and central strategies, as well as their technical effectiveness and economic efficiency for all stakeholders.

The requirement of remote control raises additional questions regarding the security of the communication between generator and system operator and the information and communication technologies (ICT) standards used to enable this feature. These questions have yet to be sufficiently addressed.

2.10 Conclusions

The assessment of system needs in European power systems focused on frequency support and voltage support as the main ancillary services categories from wind and PV generation point of view. Frequency and voltage control constitute several services with different response times. With high shares of VG also new services will be needed to be provided by them, mainly faster responses as well as services that were inherently provided by retreating synchronous generation. Generally the system needs for these ancillary services will increase with high shares of VG. Enhanced frequency support in the system is observed especially for manually activated system reserves (<15 min) FRR. VG may increase the need for voltage support as online available reactive power sources, both steady state and dynamic, available to the system operator to manage network voltage will change. In any case, voltage profile management will become more complex with increasing shares of VG.

The needs for grid support services with VG depend on the power system studied (for example its size and robustness), and how VG is built in the system (for example its dispersion, penetration levels and technical characteristics). As grid support services come with a cost, ideally requirements for generator capabilities and service provision should demand only what is needed by the system. Preparing for future systems with large share of VG thus requires studies and simulations on which to base the requirements. A handicap for a comprehensive assessment is the absence of a common methodology to include for VG in estimating system needs for services as well as the limited information basis on combined effects of wind and solar PV. Thus, as the process used to assess system needs for grid support services with VG is still evolving, efforts to develop new tools are needed.

DSO/TSO interaction will be more and more important in the future with large shares of VG, as well as a further growing role for DSOs in the ongoing transition process in electricity networks. Data exchange and ability to control the multitude of small generation units should be organised. Governance on who is doing what needs to be established for coordinating frequency and voltage support, as well as restoration services.
3 CAPABILITIES OF VARIABLE RENEWABLES AS ANCILLARY SERVICE PROVIDERS

3.1 Introduction

This chapter deals with wind and solar PV capabilities to provide grid support services (GSS) in current and future VG dominated scenarios while presenting the techno-economic challenges for VG to play an active role supporting the power system.

The following aspects are discussed:

- **Capabilities**, presenting the existing capabilities to provide GSS with wind and solar PV, at power plant and aggregation levels.
- **Impact of GSS provided by VG at system level**, assessing how wind and solar PV could impact at different system levels (HV, MV, LV) and for different system sizes (small islanded systems, regional interconnected systems and at wide scale).
- **Techno-Economic Assessment of GSS provision**, presenting compared costs for providing GSS with wind and solar PV and assessing which functionalities are influencing mostly the overall costs.
- **Challenges and mitigation methods**, describing for each investigated GSS the technical challenges on the provision of GSS and possible mitigation methods to allow wind and solar PV to play an important role as service providers.

3.2 Technical assessment of VG capabilities for service provision

This section summarises the capabilities of VG to provide grid support services as defined in Chapter 2 (Table 1). Capabilities of wind and solar PV generation for frequency and voltage support are discussed in section 3.2.1. Capabilities for system restoration are discussed in section 3.2.2.

3.2.1 Existing capabilities to provide frequency and voltage support

An overview of the capabilities of wind and solar PV is given in Table 2. For each technology (wind, solar PV), level of aggregation (wind farm, cluster, single PV plant and portfolio) and plant size (small and medium scale - less than 500 kW - and large scale) a color scale represents the current and future possibilities for providing a specific GSS, divided in two different aspects: technical capabilities and procedures.
When single power plants or aggregation of plants are analysed, technical capabilities are rated against standards and grid codes\textsuperscript{15}. When service provision is analysed from the point of view of the System Operators' procedures or requirements, the ability of providing a service is compared against national grid code connection requirements, transmission codes, operational procedures, service's prequalification documents and various ENTSO-E Network Codes, constituting the procedural aspects and labeled as "Procedures".

The rating of technical aspects (represented with circles) makes a distinction between:

- capabilities for providing a specific service are already implemented (green);
- capabilities partially implemented - missing functionalities can be implemented at a reasonable cost (yellow);
- specific capabilities are not implemented and the implementation costs are an obstacle to availability in the near or medium-term future (red).

Regarding procedures (grid codes etc.) and technical requirements in general (triangle symbols) the rating distinguishes between:

- The provision of a specific grid support service and their requirements are well defined in general in grid/ network codes for a specific technology, (green);
- poorly defined capabilities/ requirements, meaning that grid/ network codes could be improved to facilitate renewable energy sources to provide a specific service.(yellow);
- The provision of the referred grid support service is not defined or even not possible due to the grid/ network code requirements (red).

Table 2 contains references to explanations in Table 3 about possible limitations or constraints to provide GSS with wind or solar PV. Table 3 also provides further references mainly to deliverables of the project and publications.

\textsuperscript{15} Grid codes in the EU differ regarding content and requirements for the VG, connected to the DS. A general overview of technical requirements regarding Ancillary Services in the national Grid codes, the overview of the practical issues and solutions with the integration of distributed renewable generation and the AS provision by them, as seen from the DSO perspective, has been investigated in the INCREASE project (http://www.project-increase.eu/).
### Table 2 Wind energy and solar PV capabilities for providing grid support services.

<table>
<thead>
<tr>
<th>Wind System Size</th>
<th>Solar PV System Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregation¹⁶</td>
<td>Small scale</td>
</tr>
<tr>
<td></td>
<td>Large scale</td>
</tr>
<tr>
<td>Tech. Procedures</td>
<td>Tech. Procedures</td>
</tr>
<tr>
<td>WF</td>
<td></td>
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<tr>
<td>FCR</td>
<td>▲ 3</td>
</tr>
<tr>
<td>FRR</td>
<td>▲ 3</td>
</tr>
<tr>
<td>RM</td>
<td>▲ 5</td>
</tr>
<tr>
<td>Voltage</td>
<td></td>
</tr>
<tr>
<td>SSVC</td>
<td>▲ 9</td>
</tr>
<tr>
<td>FRCI</td>
<td>▲ 6</td>
</tr>
</tbody>
</table>

| Aggregation¹⁷     |
| Tech. Procedures  |
| WF               | ▲ 8                  |
| FCR              | ▲ 8                  |
| FRR              | ▲ 8                  |
| RM               | ▲ 8                  |

**LEGEND**

- **Tech.** = Technical Aspects
- **Procedures** = Grid Code Requirements, prequalification procedures and Network Code Requirements, amongst other

- Green circle = Implemented
- Yellow square = Partially implemented/ implementable/ low cost or investment to enable the required capabilities.
- Red circle = Not implemented/ high cost to implement
- Green triangle = Well defined requirements/ specifications in most procedures at European level.
- Yellow triangle = Poorly defined requirements/ specifications or not addressed in most of the procedures.
- Red triangle = Not defined/ not possible due to requirements in all or most Procedures.

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¹⁶ Aggregation: The aggregation of multiple local wind power plants (WPP) jointly managed is usually referred as a Cluster; the same kind of aggregations but of PV plants are referred usually as Portfolio.

¹⁷ Idem
<table>
<thead>
<tr>
<th>Ref</th>
<th>service</th>
<th>Tech</th>
<th>Rationale and further references</th>
</tr>
</thead>
</table>
| 1   | FFR     | Wind | • disparity of wind turbine capabilities, lack of standardisation and unclear possible contribution.  
|     |         |      | • Uncertainty of impact on design loading and fatigue impact on wind turbine.  
|     |         |      | • No uniform reliable solution for detection of fast frequency deviations |
| 2   | FRCI    | Wind | Not yet considered as GSS. Depending on Type 3 / Type 4 control and detection methods to be improved [D3.1, p.36-38]; provision of negative sequence support to be improved [D3.1, p.38-39]. |
| 3   | FCR FRR RR | Wind | Most countries in Europe (except DK) do not allow provision due to lack of specific pre-qualification procedures (uncertainty in availability of primary source). Capabilities clearly defined in grid codes. |
| 4   | FFR     | Wind | Unclear or missing definition of specific behavior in most grid codes. |
| 5   | RM      | Wind & PV | Proposal described in the *Delivering a Secure Sustainable Electricity System (DS3)* Study by EirGrid and SONI in Ireland [D2.2, p.21; D2.1]. |
| 6   | FRCI    | Wind | Capability not properly defined in grid codes [D3.1, p.38, 63] |
| 8   | FCR, FRR, RR | Wind | The ENTSO-E Network Code for Energy Balancing mentions the “reserve providing group” [p.27] as the group or aggregation of units that can provide balancing services. But, besides that the tendency in the future will be to adopt or assimilate all ENTSO-E NCs at national level, the limitations imposed at power plant level to provide GSS (e.g. in national GC or ENTSO-E’s RfG) will not allow the provision at aggregation level anyway. |
| 9   | FFR, RM, SSVc, FRCI | Wind | Absence of specification for aggregation of power plant to provide the mentioned services. Some experience at research level performed by the Spanish TSO. |
| 10  | FCR, FFR, RR, FRR, RM | PV | The required communication system, sensor installation and control software implementation to manage small PV residential installations is a challenge in terms of costs. For all mentioned services besides FRR the availability of accurate forecasts is still an issue. For FRR and FCR improved frequency measurement techniques are required. [D4.1, p.81-83] |
| 11  | FRCI    | PV   | Very fast controlled response is a challenge for the converters, which would require improved control strategies. Also it is mandatory to recognise fault types for unbalanced faults by improving sensing and control. [D4.1, p.41-42] |
| 12  | FCR, FRR, RR, RM | PV | TSO requirements for Delta Active Power Control [D4.1, p.28] are unclear. Communication standards between DSOs, TSOs and PV systems to enable these services [D4.1, p.34] are absent. |
| 13  | FRCI    | PV   | Lacking specification of number of FRT occurrences in Grid codes [D4.1, p.83]. Grid codes do not define the detection procedure [D4.1, p.42] |
The overview above shows the ability of wind and solar PV for service provision today and in the near future. The main barriers to overcome in the future include:

- poorly defined or non-existent specifications in grid / network codes or pre-qualification procedures that allow VG to provide GSS;
- lack of standardisation and harmonisation of procedures across Europe;
- absence of possibility/permission for aggregation of dispersed VG to provide services;
- technical short-comings at control level and communication level to enable faster communications and responses at single plant and aggregation level.

Along with communication, a better visibility and controllability - mainly for PV systems - is required.

In future, more accurate forecast methods should reduce the uncertainty in management of VG.

### 3.2.2 System restoration support (SRS) from VG: present capabilities

A preliminary assessment of the capabilities has been made of wind and PV power technologies to participate in system restoration support (SRS), in situations such as:

- power system splitting into parts with multiple power plants including WPPs and PV systems supplying loads (islanding network operation);
- WPP or a PV system remaining the single source to supply a load (islanding WPP or PV system operation) or;
- black-out occurrence requiring black start capabilities.

As opposed to thermal plants wind plants or solar PV systems can restart very quickly and commence generation after a trip and if the power system is in operation again. Therefore Grid Codes currently do not require VG to trip to house load and do not require them to operate under this condition for a minimum time.
**Wind plant capabilities to provide system restoration support**

Islanding network operation is quite similar to the operation in a small power system with low system inertia and low short circuit ratio (SCR) at the POC. Generally modern wind turbines (Type 3 and 4)\(^{18}\) have successfully proven that they can operate reliably under such conditions and can be connected at locations that would not allow the stable connection of a thermal plant with a synchronous generator of a similar size. Furthermore wind turbines can change their active power output very quickly over a wide range and operate continuously at a low minimum generation level, typically exceeding the capabilities of larger thermal plants. Reactive power can be also provided in a highly dynamic way, especially from Type 3 and 4 wind turbines or additional WPP-components on eBOP-level (e.g. STATCOMs). These WPP features are desirable and even necessary capabilities in the context of SRS.

**Solar PV capabilities to provide system restoration support**

The PV industry has a long experience with standalone and island systems as solar PV power has first been used as a source of electricity for remote locations. Commercial products are available for island systems up to a few hundred kW. For these islands systems, small inverters (up to 10 kW) are clustered and act as a voltage source. The control is fast enough to ensure the stability of an island system and it starts even without batteries or a diesel generator. Currently some demo projects are exploring the same principles in the MW range\(^{19}\). These projects however are relying on other components such as flywheels to operate the system. Pure inverter based concepts for island systems in the MW range need further development. The capabilities used in large island systems could serve as a basis of capabilities for the provision of SRS by solar PV plants.

\section{3.2.3 Recent technical developments of capabilities for system services}

**Fast fault current provision from Type 3 wind turbines and its negative sequence component**

In the context of the industry consultations and developments regarding fast fault current contribution from wind turbines, the latest analyses and findings emphasise that Type 3 wind turbines (DFIG generator) have an intrinsic capability to provide a fast fault current component supporting fault detection and a negative sequence fault current component. This is due to the fact that the stator of the doubly-fed asynchronous machine is directly connected to the grid enabling an intrinsic response to voltage dips in general and to the negative sequence voltages during unbalanced faults. This response is mainly determined by the generator impedances. The

\(^{18}\) For a description of conversion concepts, please refer to D3.1, p.12-13.

\(^{19}\) Marble bar project, ABB, 2013

REserviceS D7.1 Synthesis report
negative sequence fault current component supports voltage stability as it counteracts the unbalanced voltages caused by an unbalanced fault and reduces over-voltages caused by excessive positive sequence reactive fault provision during unbalanced faults, which could lead to cascading over voltage trips and damaging equipment. Furthermore it supports system security as the negative sequence fault current component enables protection relays to identify the fault securely.

Integration of Battery Energy Storage Systems (BESS) in wind turbines
The integration of BESS into wind turbines (Hybrid WTsin20) is a recent technical development to improve the technical capabilities to make forecast based power production scheduling more reliable and to enhance a number the services to support power system frequency (FFR, FCR, FRR). Already relatively small BESS (e.g. in the range of ~10% rated capacity) can reduce forecast errors significantly and make power output better predictable. This helps to avoid balancing needs and costs, especially in the context of intraday scheduling / intraday trading in blocks of up to one hour. The shorter the trading intervals and gate closures time the more economically BESS can improve predictability. Additionally BESS strongly increases the reliability of a wind farm to provide FFR, FCR and FRR and contributes to system stability and security and especially reduces costs to provide an upward power reserve e.g. for FCR (no pre-curtailing). Rise times and settling times for active power changes to provide FFR and FCR can be further increased without applying more stress on the mechanical parts of the wind turbine. Extracting kinetic energy from the rotor to provide a FFR won’t be necessary then. BESS will provide enable an even more flexible FFR provision. Battery recharging can be stretched over minutes avoiding an active power reduction during the recovery phase, when mechanically energy from the rotor is used for FFR.

Integration of Battery Energy Storage Systems (BESS) in PV systems
The case study of Navarra in D6.2 presents a pilot project on integrating a Li-Ion BESS in an existing utility-scale PV installation in Europe. Similarly to wind turbines, the use of BESS can significantly reduce forecast errors and make power output better predictable and reliable. Results obtained from this pilot project evidenced that operation of BESS can reduce short-term maximum power output fluctuations from ~80% to ~20% in cloudy days, and from ~70% to ~35% in partially cloudy conditions.

The development of enhanced control systems and strategies (PV+BESS) can facilitate adaptation to different Grid Code requirements and to offering grid support services based on hourly PV production forecast, weather data, and electricity price estimation. This can be optimised in order to extend the lifetime of the BESS. Some strategies are proposed to determine

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20 Wind turbines integrating battery energy storage systems (BESS) are called by some manufacturers “Hybrid WTsin”

REserviceS D7.1 Synthesis report
nergy storage requirement for smoothing maximum power fluctuations below 2.5% per minute in a day-ahead basis. This can reduce the use of the BESS by more than 25% and hence extend its service life. Other studies results Error! Reference source not found.(based on real 5-s one year data from existing PV plants) indicate that the time during which short-term fluctuations exceed the maximum allowable ramp is very short; hence, possibilities exist for ancillary functions to be performed by BESS (such as frequency control or time shifting, enhanced voltage control) to maximise its value.

BESS for power system applications are known as a quite costly option to solve system needs and requirements. The analysis of economic and market aspects of VG with directly integrated BESS technologies was not in the scope of the REserviceS project and detailed analyses should be carried out in future research projects.

3.3 Power system impact of services provided by VG

This section addresses system impacts of services by VG, considering different system sizes, mix of sources and VG penetration levels.

3.3.1 Frequency Control

*Speed of response*

For wind power as well as solar PV, the critical characteristic for Frequency Containment Response will be the delay in the response. Simulations in the REserviceS case studies\(^\text{21}\) have shown that in situations with reduced system inertia, using all excess of VG for providing FCR could result in unstable frequency responses. This risk exists when high amounts of VG without inherent inertia have a too long delay in reacting to the deviation of system frequency e.g. caused by inadequate communication delays. If frequency is detected at the power plant/cluster level and the control signal needs to be transmitted in the regular power plant/cluster communication stream, the delay in the activation can get lengthy. In order to provide faster response, the frequency detection should take place at the turbine level or there should be much faster than regular communication available for the frequency response signals. Also FFR and/or a more intelligent response algorithm could conceivably mitigate oscillations, but this was not investigated in the case studies. Some measures may have to be taken even in situation of high system inertia if VG with long communication delays starts to contribute to

\(^\text{21}\) See REserviceS Deliverables D5.1 to D5.5
the FCR in large amounts in order to avoid or reduce those oscillations\textsuperscript{22}. In DC connected wind power plants (for example in future offshore grids) the frequency has to be detected on the AC side and the signal has to be communicated to the turbines through other means.

\textit{Ramping capabilities}

Whenever the ramping requirements of the power system are not met, generation needs to be re-dispatched and could cause the dispatch down of VG (together with increase of balancing cost). The precise impact on the ramping duty at a point in time will depend on the level of wind and PV generation but will also vary depending on the time horizon considered. Higher ramping capabilities are likely to be required as the time horizon extends due to increase in potential forecast error. For instance, based on the Ireland\textsuperscript{23} case study, the normalized change in wind output over 1-hour is relatively small, with 99.9\% of the variations between ± 15\% of installed capacity. Over a 12-hour period, the data shows that much larger variations can be expected; more than 1\% of 12-hour changes exceed 50\% of the installed capacity.

Novel operational policies and strategies are required to manage this issue successfully and to ensure that the demand can be met at all times. However, the results of the Irish case\textsuperscript{24} indicate that the nature of the portfolio will have a key impact on the capability of the system in respect of ramping services.

\textit{Amount of frequency response needed}

The Iberian case study\textsuperscript{25} shows that for FCR remaining acceptable in all dispatch situations (when analysed with a simple power-frequency model), it is not necessary that all VG participates in the frequency support. It was assumed that wind power plants had a relatively fast response after the frequency drop. Using just solar PV decreased the frequency excursions when VG participated in the FCR.

3.3.2 Voltage Control

Based on the analysis conducted on the case studies and the consulted literature, it would appear that there are significant efficiencies to be gained from a small increase in the dynamic reactive power response from VG as compared to the installation of alternative solutions (e.g. capacitor banks, FACTs, synchronous compensators, etc.). This is because VG plants are distributed across the power system,

\textsuperscript{22} See REserviceS Deliverable D5.3, p.35
\textsuperscript{23} See REserviceS Deliverable D5.1
\textsuperscript{24} See REserviceS Deliverable D5.1, p.13
\textsuperscript{25} See REserviceS Deliverable D5.3
both at transmission and distribution nodes. Alternative solutions could achieve the same effect but this would require a significant roll-out of these technologies in multiple locations in the system.

Enhancing dynamic voltage support during disturbances is required to increase system transient robustness in high instantaneous VG penetrations. Improving the response from VG units could mitigate some, if not all, of the issues.

**Voltage control at transmission level**

At high instantaneous SNSP levels transient stability of generators can be compromised due to a complex interaction between synchronous generator characteristics, VG penetration and their relative spatial distribution around the network. As there are fewer of the synchronous units online and the effective electrical distance and impedance between them increases, the synchronizing torque between the remaining synchronous units is reduced. The Irish case study has shown that, in the absence of mitigation strategies, when wind power plants only meet basic capabilities of dynamic reactive power production, reactive support would be insufficient to maintain the security of the power system at SNSP levels in excess of 60%.

**Voltage control at distribution level**

Distribution level case studies\(^{26}\) show the usefulness of giving the possibility for DSOs to utilize SSVC grid support services to actively manage their networks, which could bring a number of technical benefits\(^{27}\). However, the presence of VG modifies the voltage control criteria both in the HV/MV substation and along feeders because lines voltage profile is no longer decaying in monotonous way. In fact, due to active power injections, VG can increase node voltages beyond statutory limits. In addition, coordination of control parameters among several VG plants is challenging because controlled units will receive different voltage set-points due to their locations along the feeder with respect to the connection point. These set-points have to be calculated considering the underlying grid topology. The common practice is that all VG participates using the same set-point values resulting in voltage rise at the connection point of the feeder with the public grid.

The distribution level case studies analysed how new voltage control techniques solve these issues. Regarding the different options, it can be argued that local control strategies may be sufficiently efficient up to a certain increase of VG connected compared to a baseline (e.g. max. +28% in the Italian\(^{28}\) case study). Central control strategies are necessary when local voltage control does not give satisfactory results to fulfill the control criteria (EN50160) or when global benefits are considered.

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\(^{26}\) The Distribution case studies conducted within WP6 of REserviceS are summarized in deliverable D6.2

\(^{27}\) See REserviceS Deliverable D6.2, p.72.

\(^{28}\) See deliverable D6.2
Because of the resistive component of the network, the VG connected at the MV level of distribution network are facing voltage rise due to their active power injection, but they are still able to compensate it with the appropriate reactive power consumption. On the low voltage level the resistive component is higher, so, control of reactive power has relatively lower effect on voltage level. In such cases, reducing active power of the VG to control the voltage rise and keep the LV voltages within the secure band can become economically attractive.

**Voltage support by means of aggregation of VG**

The feasibility of voltage support provided by clusters among VG plants and the transmission grid has been demonstrated in Spain\(^{29}\) by the local TSO and is presented in D5.3. It is demonstrated that reactive power has been injected/absorbed in line with the TSO set-points and therefore according to the system needs. The influence of voltage control provided by the wind power plant on the HV grid has been significant - sudden changes of set-points have implied dynamic variations up to 3 kV on the 400 kV grid connection point. Other analyses\(^{30}\) of wide area voltage control in the transmission system have reported reductions of voltage deviation from 9 kV to <1 kV along a 400 kV transmission corridor. This leads to less curtailment due to voltage-related aspects and lowers overall system costs.

**Reactive power exchange at DSO/TSO interface**

The German and Spanish case studies have shown that a centrally coordinated control of SSVC services from PV plants in the MV grid can significantly reduce the reactive power flows at the DSO/TSO interface point (HV/MV substation). This is more efficient (and less costly) than fixing reactive power flow requirements with additional devices at this interface. However, central control is not always able to prevent an overrun of the reactive power values outside the PQ-bands at all times. The grid has a significant reactive power consumption (mainly leading power factor) during night times (low load) and because of power factor limitation (cosφ min=0.9) of the PV systems, central control is unable to minimize the reactive power consumption during times with low solar irradiation.

Nevertheless, it is not straightforward to generalise key results from the different case studies since there are strong dependencies attributed to network topology, impedance (R/X ratio), and load/generation distribution and location. For instance, high R/X ratios decrease the reactive power influence on voltage level.

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\(^{29}\) Arlaban et al. in *Voltage control by multiple wind power plants: field test results*, reviewed within D5.3 of REserviceS


REserviceS D7.1 Synthesis report
The electrical distance of the VG plant to the DSO/TSO interface is important for how it can provide useful voltage support\textsuperscript{31}. Figure 5 shows active resources suitable for reactive balancing according to the electrical distance to the HV grid. With the increasing numbers of VG units connected to DS at MV level, especially electrically close to the HV substations, they can provide reactive power balancing and voltage control in DS, as well as provide transmission system voltage control to the TSO. Reactive power from distributed VG units connected at distant MV nodes or at LV nodes can be used for local reactive power support or local voltage control\textsuperscript{32}. All VG units equipped with advanced inverters that can provide flexible reactive power support will reduce the amount of reactive power required from transmission-connected generation.

\textsuperscript{31} Abele, 2013

\textsuperscript{32} It is desirable that reactive sources suitable for reactive balancing of a distribution feeder have a very low impact on the voltage in the DS, regardless of their active or reactive power infeed. If the VG units are installed at the end of a long LV feeder, their injection of active and reactive power could cause severe over-voltages. So they need to be placed close to the feeder head, at the tap changer. Hence, units connected close to transformers with tap changers are the most suitable for reactive balancing task. Changing reactive power infeed in such unit, at the terminals changes terminal voltage, but this effect is mitigated by the tap change of the transformer that restores the voltage level. This way, the generating unit connected at LV level can inject reactive power without significantly affecting the voltage level or even causing overvoltage problems.

In HV networks, it can safely be assumed that reactive power $Q$ influences voltage $V$, while active power injection $P$ influences frequency $f$ only\textsuperscript{32}. On the other hand, in MV networks, the ratio of resistance component of the line impedance over reactance component is $R:X = 1:1$, so voltage control is still best performed with reactive power control. Deeply embedded sources can therefore be more suitable to control local voltage. Voltage control aims to keep the utility voltage within pre-set ranges. If the voltage is below the pre-set values, the VG unit will provide additional reactive power; if voltage is too high the VG unit can absorb some of reactive power which is in abundance.

In LV networks (400 V), the line has a strong resistive character (e.g. $R:X = 3.2:1$ in Holland), so reactive power control does not influence voltage enough anymore, while it leads to increased losses. On the other hand, due to the significant resistance character in LV network, active infeed influences the voltage level significantly. In LV networks, active power control is therefore needed to control the voltage rise due to active power injection. Due to increased losses incurred in LV network with voltage control using reactive power control, voltage control with active power is often more efficient. Voltage control with active power control in LV network may lead to income reduction for the VG unit. Reactive power voltage control of a generator (within certain limits) on the other hand does not pose additional operating costs to the VG unit.
The following is needed:\(^{\text{33}}\):

- From TSO’s: target values for the reactive power exchange.
- From DSO’s: VG units with short electrical distance to the TN, and suitable controller and ICT infrastructure.
- Appropriate oversizing of the VG inverter so that the required reactive power can be supplied even under maximum active power injection from the respective renewable source.

Opportunities to further enhance voltage control from distributed VG units can be achieved with adherence to the Voltage Standard (EN - 50160).

*Reactive power provision at no active power generation*

The majority of VG plants are capable to operate at a fixed reactive power level when not generating active power. In addition inverter-based VG is capable to provide dynamic voltage control. For solar PV plants using these capabilities is standard practice. Wind power plants on the other hand are typically equipped with these capabilities mainly because of the obligation imposed by grid codes but the

\(^{\text{33}}\) Abele, 2013

REServices D7.1 Synthesis report
functionalities are often not used by DSOs or TSOs. One of the reasons is the risk of negative interactions among the VG units, for example reactive power hunting where units are competing to control the voltage. Another allegation is the risk that the unit might interfere with the controls by the System Operator or will increase the reactive power needs at the TSO/DSO interface.

### 3.3.3 Provision of GSS with offshore wind plants

In the case of AC offshore networks, the useful effect of available wind power capabilities to provide frequency and voltage support is similar as for onshore networks. Cable length due to distances and the required reactive power compensation are issues that can be managed up to a certain distance. Here, the concentration of VG in a single or few connection points becomes an issue due to the variability of the source.

DC-connected wind plants impose new challenges to the system:

- large amounts of frequency decoupled concentrated power require fast communication infrastructure to remote measure and allocate set-points to provide frequency support;
- interactions between converters on weak grids with low available short circuit power

Nevertheless, the onshore VSC-HVDC station can provide reactive power, respectively voltage support services regardless of the offshore wind condition and GSS can be augmented by aggregating multiple offshore wind plants or clusters of wind plants\(^\text{34}\). Then the limitations are imposed by the converter stations onshore.

As described, the fundamental conditioning factors for offshore WPP installations to provide GSS are the implemented technology, the topological characteristics of the transmission grid and its connection to the shore, and the available operational strategies and operational procedures, which can enable a more efficient utilisation of the offshore wind, also cross-border. The implemented technology conditions how and who can provide a specific service:

- for frequency support, sophisticated communication methods are required to synchronise the offshore AC part of the grid connect by HVDC links to the shore in order to sense the frequency and provide the required support;
- for voltage support, the provider onshore is technology-dependent:

\(^{34}\) See REserviceS Deliverable D5.2, p.37.
in HVAC grids the support can be provided by wind turbine and/or other equipment (e.g. FACTS) as in usual onshore installations, limited by their technical capabilities and the grid characteristics;

- in HVDC grids the voltage support is provided by the converter stations onshore and limited to their capabilities, independently from generators.

### 3.3.4 Impact of aggregation and short term forecasting on GSS provision

The use of the smoothening effect of geographical dispersed wind and PV power production is one of the key factors to diminish the impact of wind and PV power variability on the provision of GSS. Moreover, it is shown that there is an almost linear relation between variability and predictability or forecast quality\(^{35}\).

Accurate forecasts are of vital importance for cost-efficient provision of GSS with VG since the availability of the prime mover is changing stochastically in time. It is important to recognise the need of different types of forecasts for different kinds of GSS. The most important time horizons for GSS are the short- and shortest-term forecasts (from day-ahead to minute scale). (Medium-term forecast are required to plan the operation of the grid at seasonal, week or for few days in advance, and only partly relevant for GSS).

Short-term forecasts are used for the day-head and intraday operation and the procurement of GSS. For services like voltage support however the shortest-term would be required, for time horizons lower than 15 minutes. However, there is no TSO's operational experience in this field and the R&D community is starting paying attention to this issue.

A further reduction of the uncertainty can be achieved by using probabilistic forecasting, allowing to reach confidence intervals similar to non-VG power plants. Therefore, the use of probabilistic forecasts - together with pre-qualification methods adapted to the characteristics of wind and PV power - is an essential enabler for efficient participation of VG in ancillary service provision.

**Forecast of wind generation**

Forecasting tools and techniques for wind energy have been developed since almost 20 years\(^{36}\). Nevertheless, the current and foreseeable future high penetration of increasingly concentrated installations of wind in the power system (i.e. large offshore wind farms and clusters) and the

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\(^{35}\) See REserviceS Deliverable D3.1, p.46-47

\(^{36}\) See Giebel et al., p.4
complexity of some weather physical conditions such as highly variable wind conditions and storm fronts make the forecasting task not trivial. For example, during storms large amounts of power are off the grid due to shut-down of the wind farms at cut-off wind speed.

Wind energy needs more accurate forecast methods in order to improve its integration and enabling participation in the provision of grid support services. In this direction, R&D activities are conducted to improve the performance (accuracy) of forecasts by means of ensemble forecasting and probabilistic solutions.

In any case, it is important to appropriately align market and operational rules with forecasting capabilities and time horizons.

**Forecast of solar PV generation**

Depending on the methodology used, solar PV forecasts can be generated for time horizons ranging from a few minutes to several days ahead (Table 4). Very short-term forecasts (0 to 6 hours head) perform best when they make use of measured data (solar PV plant, sky cameras or satellites), while numerical weather prediction models (NWP) become essential for forecast horizons beyond approximately six hours. The application of solar PV forecast will define the required time horizon and in consequence the method used. In the simulations performed in D4.1 these constraints were taken into account to create the simulation cases.

**Table 4 Characteristics of solar forecasting techniques** (IEA PVPS T14, 2013)

<table>
<thead>
<tr>
<th>Technique</th>
<th>Sampling rate</th>
<th>Spatial resolution</th>
<th>Spatial extent</th>
<th>Maximum Forecast horizon</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Persistence</td>
<td>High</td>
<td>One point</td>
<td>One point</td>
<td>Minutes</td>
<td>Reference</td>
</tr>
<tr>
<td>Whole Sky Imagery</td>
<td>30 sec</td>
<td>10 to 100 meters</td>
<td>Up to 3-8km radius</td>
<td>Dozen minutes</td>
<td>Ramps detection, frequency control</td>
</tr>
<tr>
<td>Geostationary satellite imagery</td>
<td>15 min</td>
<td>1 km</td>
<td>65° S – 65°N</td>
<td>5 days</td>
<td>Load following</td>
</tr>
<tr>
<td>Numerical weather prediction (NWP)</td>
<td>1 hour</td>
<td>2-50 km</td>
<td>Worldwide</td>
<td>10 days</td>
<td>Unit commitment, regional power prediction</td>
</tr>
</tbody>
</table>

37 See REserviceS Deliverable D3.1, p.44
38 See Cutululis, p.18
40 Ahlstrom et al., 2013
41 See REserviceS Deliverable D4.1, p.46
The field of PV forecasting is rapidly evolving. Current best approaches make use of both measured data and NWP models. Examples of this strategy include the use of NWP model outputs in stochastic learning models, or the use of measured data for post processing NWP models to correct systematic deviations between NWP model outputs and measured data.

The forecast accuracy depends on numerous parameters, such as local climate, forecast horizon and whether forecasts apply to a single point or cover a wide geographic area. For the latter, which is often the main interest of TSOs, higher accuracies can be achieved since random errors at distant locations tend to be largely uncorrelated and to partially cancel out.

This is achieved through up-scaling methods for which forecasts covering all systems are generated from forecasts for a limited number of representative systems. The physical approach with up-scaling has been applied for instance to generate PV forecasts over two balancing areas in Germany\textsuperscript{42}. Root mean square errors (RMSE) for intra-day and day-ahead forecasts of 3.9\% and 4.6\% respectively, have been achieved over a one year test period, where errors are defined as a percentage of the nominal installed PV power and include night-time values.

Compared to solar PV generation forecast, which is still a relatively new subject, GSS provision by PV is at its infancy. In absence of existing analyses about the influence of forecast accuracy on GSS provision by solar PV, the project needed to develop its own approach\textsuperscript{43} and model for the provision of reserve and its reliability using PV forecasts.

When PV system operators want to provide reserve (especially upward), significant costs can be incurred due to the uncertainty of future PV generation\textsuperscript{44}. Forecast is the determining factor for the costs of reserve provision. For instance, REservice\textsuperscript{S} analysis showed\textsuperscript{45} that an individual solar PV system located in Benelux would lose 60\% of its yearly production by offering day-ahead upward reserve for all days of the year. These losses could be reduced to 26 \% if the service is offered by a portfolio spread over an area of the size of the Benelux thanks to reduced forecast error. This demonstrates the importance of forecasting as enabler of GSS provision by PV.

Forecasting rapid solar ramp rates is also gaining attention among electricity system operators however did not yet received significant attention from the research community. Furthermore,

\textsuperscript{42} Lorenz E. et al., 2011
\textsuperscript{43} See REservice\textsuperscript{S} Deliverable D4.1, p.45
\textsuperscript{44} See REservice\textsuperscript{S} Deliverable D4.1, p.73
\textsuperscript{45} See REservice\textsuperscript{S} Deliverable D4.1, p.68

REservice\textsuperscript{S} D7.1 Synthesis report

58
probabilistic or ensemble forecasting could form the basis of GSS provision and other novel approaches for VG dominated system operation such as probabilistic unit commitment.

3.4 Techno-economic assessment of service provision (at generator level)

3.4.1 Comparing costs of providing grid support services with wind and solar PV

Table 5 provides an overview of the additional costs involved for enabling different services by technology and by system size and how challenging the implementation could be. This additional cost assessment is based on the REserviceS analysis\textsuperscript{46} backed up by industry interviews. The service costs are split in capability costs, readiness costs and provision costs. The colour scheme depicts to which extent the provision of a service (or set of services) is technically challenging in relation to the implementation costs. Green indicates that a service could be provided already at low additional cost, yellow indicates a moderate additional cost. In principle also the “not feasible” category (red dot) was foreseen, meaning that a service cannot be provided due to the lack of existing technical capabilities and that the implementation of such capabilities would be prohibitive due to high costs. However, the assessment did not result in the identification of services that would technically qualify unfeasible.

For frequency support services the readiness of upward reserve is quantified as the loss of generation that otherwise would be available, in case the generators were not providing services.

To correctly interpret the aggregation column it is necessary to keep into account that:

- communication costs for aggregation are additional costs on top of those needed to enable the services at WF or PV plant level;
- CAPEX-related costs regarding frequency support are considered as a fraction of the WF costs;
- Lost energy calculation considered on the upward readiness item is similar as for WF, but the energy loss is less due to the aggregation and the lower forecast error\textsuperscript{47} (between 8-10\% for WF and between 4-6\% for clusters/ aggregations);
- for SSVC costs considered at aggregation level there is need for extra communication equipment in order to coordinate the compensation at WF level.

\textsuperscript{46} Reservices Deliverables D3.1 and D4.1
\textsuperscript{47} D3.1, p.56
Table 5 Comparing costs for providing grid support services with wind and PV.

<table>
<thead>
<tr>
<th></th>
<th>Wind System Size</th>
<th>PV System Size</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WF</td>
<td>Aggregation</td>
<td>Small scale</td>
<td>Large scale</td>
<td>Aggregation</td>
</tr>
<tr>
<td>Communication costs for all services below</td>
<td>€</td>
<td>€</td>
<td>€ to €€</td>
<td>€</td>
<td>€</td>
</tr>
<tr>
<td>Technical challenge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investment&lt;sup&gt;48&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Readiness</td>
<td>Upward</td>
<td>€€ to €€€€€</td>
<td>€€ to €€€€€</td>
<td>€€€€€</td>
<td>€€€€€</td>
</tr>
<tr>
<td></td>
<td>Downward</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Provision</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SVC</td>
<td>Investment&lt;sup&gt;49&lt;/sup&gt;</td>
<td>€ to €€</td>
<td>€ to €€€</td>
<td>€</td>
<td>€</td>
</tr>
<tr>
<td>Readiness</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Provision</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>FRCI</td>
<td>Technical Challenge</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investment&lt;sup&gt;50&lt;/sup&gt;</td>
<td></td>
<td>&lt;€</td>
<td>n/a</td>
<td>&lt;€€</td>
<td>-</td>
</tr>
<tr>
<td>Readiness</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Provision</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**LEGEND**

- €€€€€ >20% of the system CAPEX for investments
- €€€€ <20% of the system CAPEX for investments
- €€€ -10% lost electricity share on the overall production
- €€ -5% insignificant
- € -1%
- n/a not applicable
- No technical challenges
- Technically challenging
- Not feasible

<sup>48</sup> additional investment costs to enable the provision of GSS, as considered in D3.1, p. 54-59 and D4.1, p.70-80

<sup>49</sup> Idem.

<sup>50</sup> Idem.

REserviceS D7.1 Synthesis report
Table 5 shows that - in terms of costs - the provision of all mentioned services with wind or solar PV is feasible. Additional investment costs range from 1% to 5%; only in small PV systems the impact of required communication components on the relative costs are high.

Readiness to provide upward reserves from VG necessitates that it is dispatched down from what is available. The corresponding financial loss depends on the market value of generation at the time. VG will be used for upward reserves only when market prices are relatively low and therefore this cost component is likely to be low. Assessment of this is made in Chapter 4.

A more in-depth listing of technical challenges is provided in the next subsection introducing the technical factors relevant for cost assessment. Besides the technical challenges, also regulatory and market-wise challenges have been identified.

### 3.5 Challenges for enhancing capabilities and solutions

#### 3.5.1 Enhanced frequency and voltage support with VG: challenges and solutions

Issues (problems, challenges, considerations, etc.) which significantly impact the cost of the provision of frequency and voltage support with wind and solar PV have been compiled from industry survey and discussions with other stakeholders. These have been reported in detail in the project deliverables D3.1 and D4.1. Summaries are presented in the tables below.

**Table 6. Wind: Communication systems related to grid support services**

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Possible Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faster remote controls for a plant and to change set-points, particularly for clusters</td>
<td>Implementation of faster communication technologies (OEM/DEV/SO)</td>
</tr>
<tr>
<td>Lack of clear &amp; complete technical specifications for communication systems</td>
<td>Improve technical specifications (Grid Codes) (SO)</td>
</tr>
<tr>
<td>Diversity of existing technical specifications</td>
<td>Development of International standards (OEM/DEV/SO)</td>
</tr>
</tbody>
</table>

**Table 7 Wind: Frequency support service capabilities grid support services, in general**

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Possible mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Providing the service in a cost-effective way</td>
<td>• Implementing forecasts (OEM/DEV/SO)</td>
</tr>
<tr>
<td></td>
<td>• Reduce LCOE/ LOCP (OEM/DEV/SO)</td>
</tr>
<tr>
<td></td>
<td>• Implementation / use of storage (OEM/DEV/R&amp;D/SO)</td>
</tr>
</tbody>
</table>
Limited forecast accuracy

- Improved forecast methods (OEM/DEV/R&D)
- Adopt market rules and operational schemes to available forecast performances.
- Implementation / use of storage (OEM/DEV/R&D)

Need for wind turbine redesign & recertification

- Lack of design feedback on operation beyond certified ranges
  - Including providing GSS as design load case in the certification process (OEM/REG)

Limitations of wind turbine control and actuation systems

- New control strategies/ systems required (OEM/R&D)

Unclear TSO requirements for Delta $\Delta P$51

- Improve specifications taking into account RES technology characteristics (OEM/R&D/SO).

Insufficient TSO/DSO coordination.

- TSO/DSO governance must be clarified taken into account the new paradigm imposed DG.

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Mitigation actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decrease uncertainty of investment costs related to FCR impact on the</td>
<td>• Make structural design adaptations (OEM/R&amp;D)</td>
</tr>
<tr>
<td>components’ life-time.</td>
<td>• Develop improved wind turbine controls (OEM)</td>
</tr>
<tr>
<td></td>
<td>• Add storage devices (OEM/R&amp;D/SO)</td>
</tr>
<tr>
<td>Measuring the frequency with sufficient high resolution</td>
<td>• Improvements on measuring techniques (R&amp;D/ OEM)</td>
</tr>
<tr>
<td></td>
<td>• Improved specification (OEM/R&amp;D/SO)</td>
</tr>
<tr>
<td>Deal with need for higher rating of auxiliary electrical/electronic systems</td>
<td>• Clear definition of the TSO regarding the need and requirements (SO).</td>
</tr>
<tr>
<td></td>
<td>• Implement the existing technology accordingly (OEM)</td>
</tr>
<tr>
<td>Not all large wind turbine types are capable of providing fast ramping</td>
<td>improved wind turbine design methods (OEM/R&amp;D)</td>
</tr>
<tr>
<td>Unstable controls at high penetration levels &amp; very low system inertia</td>
<td>• Improve controller structures to avoid inherent instabilities (OEM/R&amp;D)</td>
</tr>
<tr>
<td></td>
<td>• Minimise delay times by speeding up communications (OEM)</td>
</tr>
<tr>
<td></td>
<td>• Adaptive controller (settings) (OEM/R&amp;D)</td>
</tr>
</tbody>
</table>

Table 8 Wind: specific issues for capabilities for frequency services FCR, FRR, RR, RM

---

51 Refer to "Active Power Delta Control Mode" in REserviceS Deliverable D3.1, p.18

REserviceS D7.1 Synthesis report
| Increased wind turbine loading at low and high power (specifically for FRR) | Control and design adaptations (OEM) |
| Improve accuracy of short term forecast (specifically for RM) | Implement advanced forecast techniques (probabilistic, ensemble) to improve accuracy (R&D/ SO) |

**Table 9 Wind: frequency support services Fast Frequency Response (FFR)**

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Mitigation actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Deal with increased wind turbine wear and tear due to more frequent actuation of blade pitch systems</td>
<td>• Improved specifications of requirements in grid codes to enable accurate load cases definition (SO)</td>
</tr>
<tr>
<td>• Uncertainty of impact on design loading/ Fatigue impact on wind turbine</td>
<td>• Develop and implement improved frequency measurement method (OEM)</td>
</tr>
<tr>
<td>• Increased wind turbine mechanical loading at high ramp rates</td>
<td>• Design loads and structural design adaptations (OEM)</td>
</tr>
<tr>
<td>• Deal with increased wind turbine wear and tear due to more frequent actuation of blade pitch systems</td>
<td>• Clear definition of FFR by TSO (SO)</td>
</tr>
<tr>
<td>Enhanced loading of wind turbine electrical subsystems</td>
<td>Enhanced dimensioning of electrical equipment (OEM)</td>
</tr>
<tr>
<td>Quantify the interaction with power system</td>
<td>System studies (SO/R&amp;D)</td>
</tr>
<tr>
<td>Reliable detection of df/dt: accurate measuring and producing reference signal</td>
<td>Develop clear definition of FFR by TSO (SO)</td>
</tr>
<tr>
<td>Limited availability of the FFR functionality from manufacturers</td>
<td>Develop and implement improved frequency measurement method (OEM)</td>
</tr>
<tr>
<td>Additional investment costs due to re-certification</td>
<td>Develop clear definition of FFR by TSO (SO)</td>
</tr>
<tr>
<td></td>
<td>Implement appropriate cost recovery mechanisms</td>
</tr>
</tbody>
</table>
### Table 10 Wind: Voltage control services

<table>
<thead>
<tr>
<th>Challenges</th>
<th>mitigation</th>
</tr>
</thead>
</table>
| - Deal with high reactive power requirements for dimensioning of inverter.  
- Deal with design limitations of the inverter | - Oversizing of electrical equipment, especially at MV level (OEM/DEV)  
- Control improvements are required (OEM)  
- Use external devices (reactors, synchronous condensers, STATCOMS) (DEV) |
| - Enhanced mechanical loading at idling level when providing high Q for prolonged time | - Redesign (structural, mechanical) of wind turbine (OEM) |
| - Lacking requirements for negative sequence current provision | - System studies (SO)  
- Improvement of grid code requirements (SO)  
- Development of WT control methods (OEM) |
| - Parallel operation of plants in voltage control mode / Voltage stability, avoiding hunting phenomena and oscillations  
- Availability of wind turbines in the market with capability to provide SSVC/PQ without external additional equipment | - Clear definition and justification of the Grid Code requirements (SO)  
- Control strategies (OEM) |
| - Dealing with uncertainty about control behavior of wind turbine outside +/-5% of U rated | - Design of auxiliary equipment for over and under-voltages (OEM) |

See also: Communication.

### FRCI

<table>
<thead>
<tr>
<th>Challenges</th>
<th>mitigation</th>
</tr>
</thead>
</table>
| - Improved control on Type 4 wind turbines.  
- Very fast controlled response (Short rise times)  
- Recognise fault type for unbalanced faults  
- Complexity of FCRI according TSO specs with actual technology | - Sub-cycle rise times require complete new design/ Improve sensing and control  
- Develop tuning methods for controllers  
- Improve simulation methods and models |

The tables on the next pages present a summary of issues (problems, challenges, considerations, etc.) which have a significant impact on the cost of the provision of grid support services with solar PV.
Table 11 Services with solar PV: Communication hardware and controls

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Communication Hardware</strong></td>
<td>• The main cost driver is the hardware for communication infrastructure. To reduce costs the following solutions are needed:</td>
</tr>
<tr>
<td>• For FRR, RR, RM, fast communication hardware is needed for remote control of the system and to change set-points.</td>
<td>• Development /adoption of improved communication methods</td>
</tr>
<tr>
<td>• FCR, FFR and FRCI, SSVC is commonly an automatic response; however set-point changes could improve the behavior and might be needed. The communication software for rather rare set-point changes for the automatic response might however be less costly.</td>
<td>• Design of control systems and reliable communications between PV system controller and single inverters</td>
</tr>
<tr>
<td>• The communication hardware can be a significant cost factor in particular for smaller systems (% of CAPEX).</td>
<td>• Communication with TSO / obtaining set-points from TSO</td>
</tr>
<tr>
<td>• Cyber security is an important challenge and could be a cost driver.</td>
<td>• Communication standards between DSOs, TSOs and PV systems/portfolios</td>
</tr>
<tr>
<td>• The lack of communication standards for small generators and portfolios can be a cost driver</td>
<td></td>
</tr>
<tr>
<td>• Communication with TSO needs to be clarified. International standards would be useful.</td>
<td></td>
</tr>
<tr>
<td>• Better TSO-DSO coordination is needed.</td>
<td></td>
</tr>
</tbody>
</table>

<p>| Control software                                                          | Standards for portfolio controls and interfaces for several entities (TSO/DSO/markets participants/manufacturer/operator) can bring down the costs. |
| • Control software needs to be developed when larger portfolios need to be operated as a “swarm” to provide one service in particular FRR, RR or RM |                                                                                 |</p>
<table>
<thead>
<tr>
<th>Challenges</th>
<th>Mitigation</th>
</tr>
</thead>
</table>
| **FCR** | • Hardware:  
  - For small household systems temperature and irradiation sensors would be needed to calculate the available power. This is technically no challenge but relatively high costs compared to the system size.  
  - For larger systems this measurement equipment is in general already on site.  
  - Improved frequency measurements  
  - Software development for active gradient and delta control modes.  
  - Unclear TSO requirements for Delta P (especially regarding the availability and accuracy of Delta P) | • The costs for sensor installation and software developments need to be taken into account, but they are comparably low.  
• Better Delta P requirement definitions are needed. |
| **FRR and RR** | • Idem FCR: Sensor hardware  
  • Better power forecast or alternative proof methods can reduce the costs of lost power significantly. In particular intraday large improvements can be made: snow forecasting, cloud movement forecasting etc. Non-scheduled based proof methods could avoid high power losses.  
  • Market designs that favor conventional generation or do not allow aggregated bids from portfolios can largely increase the costs. | • Develop PV portfolio control strategies and software taking into account forecasts with confidence intervals  
• Market design adaptations that allows biddings by portfolios including PV |
| **RM** | • Power production forecast accuracy. In particular adapted evaluation tools for forecast accuracy for different time resolutions are needed. | • R&D in forecasting |
| **FFR** | • An additional battery bank can provide this service. Costs would however be high.  
• Alternatively the system is run down-regulated at all times. In this case there are high costs of lost power. | • Significant cost reductions for storage solutions could reduce the costs for this service. The cost of FFR provision will anyway be reduced by the decrease of PV LCOE. |
3.5.2 System Restoration Support with VG: technical challenges and solutions

General
Until now system restoration support services have not been systematically requested or considered for VG, and therefore the subject remained largely unexplored. Detailed requirements and technical specifications are absent in grid codes and standards, apart from some definitions in new grid codes. Consequently, wind turbines and solar PV systems are not specifically designed for the functionalities of islanding network operation, islanding WPP/PV system operation nor participation in black start, although some specific useful features are present (see section 3.2.2). For dedicated and reliable operation in system restoration schemes, major changes in their control systems would need to be applied, as a minimum. Any analysis regarding the technical capabilities of WPPs or PV systems to deliver SRS should start from the stochastic, hence not controllable or fully predictable nature of the wind or solar irradiation as the prime mover. In a critical situation of a blackout the reliability of supply

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52 ENTSO-E NC RIG Article 10, especially 10 (5), p.31 Error! Reference source not found.

REserviceS D7.1 Synthesis report
in terms of capability to unconditionally deliver the service is of massive importance. This needs sufficient information about the wind and solar conditions at the WPP or the solar PV system and a reliable forecast. By integrating storage into wind turbines or a WPP and solar PV systems the predictably and reliability of power production can be drastically increased, which would strongly improve the participation in SRS. Assuming that there is sufficient wind or sun to start up, there are additional physical limitations described below.

Islanding network operation
In general robustness against wide and fast frequency and voltage variations and stable operation at low short circuit ratios can become challenging and todays technologies’ capabilities would need to be enhanced even further. This may require changes in the controls and/or even re-dimensioning wind turbines and solar PV systems. Synchronisation and re-connection with other islanded networks or with the remaining power system has to be possible, too. This requires a function on WF or PV system level to receive information about the voltage in different network areas and to send commands to the WTs or the PV systems to alter the voltage or frequency to allow resynchronisation. During the whole process a signal interface to the system operator has to be maintained to interrupt and change the procedure at any time to guarantee a restoration.

Islanding WPP/PV system operation
Islanding WPP/PV system operation requires all the capabilities for islanding network operation but exceeds these even further. Today wind turbines are not designed as a stand-alone source of power supply to serve loads. Wind turbines synchronise themselves onto the “external” voltage of the power system at their POI. However, modern wind turbines comprising self-commutated semi-conductor switches (Type 3 or 4) are in principle able to generate their “own” symmetrical three-phase voltage system and act more like voltage source thus requiring major changes in their control systems at the minimum. But most of the required technical capabilities – as identified in the framework of functionalities – are technically feasible in modern wind turbines, both Type 3 and Type 4. Frequency control can become a challenge as wind and load may vary significantly. Storage at wind turbine or WPP is a measure to mitigate this challenge. An extreme scenario would be a trip to house load which would require the wind turbine operation at a very low loading level. It’s subject to further research and cooperation within the industry if trip to house load will bring significant benefits to system restoration.

For solar PV, already today full-inverter based concepts for island operation are commonly used in small power systems up to a few hundred kW, sometimes even without batteries. Commercial products exist also for island systems up to a few MW (such as mines) but in that case PV inverters have to be complemented by others devices such as flywheels and/or diesel generators to ensure the safe operation of the island system. The possibility to upscale a full inverter based concept to a MW range system and the hybrid concept (flywheels/genset/PV) to a few hundred MW needs further development.
**Black Start**

Black start capabilities are based on the ability to operate in islanding WPP/PV system. In order to black start a WPP or a PV system, it needs a reliable power source to supply all necessary auxiliaries including, in the case of wind, DC links to generate a three-phase voltage. Batteries in wind turbines or at WPP level or diesel gen sets on WPP level could be used as a reliable source of auxiliary power for such a SRS. In a critical grid situation like a blackout, the reliability of supply is of massive importance. Therefore, reliable participation of wind or PV power in the restoration process, at least as one of the main suppliers of the service, is a subject that needs much further investigation. A suggested approach for wind or PV power is not to constitute the first line of restoration by providing black start capability, but to contribute in later stages of the restoration process (Islanding Network Operation), when there are already other generators running.

### 3.6 Conclusions

Systematic investigation of wind power and solar PV technology, through analysis and validated in industry enquiries, confirms that they are technically capable to provide grid support services for frequency, voltage and system restoration assuming an adequate procedural and economic framework is present. The technical operational functionalities required are either state-of-the-art capabilities of the existing hardware or can be implemented at a reasonable cost. The feasibility of provision of services by enhanced plant capabilities is confirmed by TSOs, for example in Spain where voltage control by wind power plants on the specific transmission nodes leads to a significant improvement with fast response. The German and Spanish case studies within REserviceS demonstrate that letting the DSO use ancillary services from RE generation connected to its own system contributes to cost-efficient voltage management. Participation of VG in system restoration has not been considered until now. Certain functionalities required are available in principle but their implementation in specific restoration strategies needs further investigation.

For wind power, potential technical enhancements for frequency and voltage support services include: faster and reliable communication (a.o. between wind farms and system operators’ control rooms), dedicated control tuned for delivering the required performances, estimation of available power/forecasting. Furthermore, some structural, mechanical and electrical design changes in wind turbines need to be implemented to take into account the changes in mechanical load spectrum involved with grid service oriented operation. Specifically for offshore wind power service provision needs to consider the differences between connection technologies (HVAC or HVDC) as these have a fundamental impact on the provision of voltage services and fast frequency support. AC connected offshore wind plants can provide active power reserve and frequency response (in all time domains: FCR, FRR, RR, FFR) in the same manner as onshore AC wind plant projects. Ancillary services can be augmented by aggregating multiple offshore wind plants or clusters of wind plants. Regional coordination of offshore wind plants in providing reactive power and voltage control at their respective onshore POC would strengthen system reliability. In the case of HVDC offshore grids, the onshore VSC...
HVDC can provide reactive power/voltage ancillary services regardless of the offshore wind condition. Technical standards and Network Codes currently in preparation are important enablers of offshore wind ancillary services.

For solar PV, potential enhancements of capabilities include: estimation of available power/forecasting, faster and reliable communication and control within the plant, control strategies for portfolios composed of numerous small and medium sized units, improving interoperability of different networks and enhancing compliance to a multitude of non-harmonised grid code requirements.

Thus, implementation of better and faster communication systems together with the development and implementation of more accurate forecast systems are essential required improvements for both wind and solar PV technologies. In general, aggregation of multiple VG power plants is desirable because this improves the performance when providing a service and reduces the relative implementation costs. Also both for wind and solar PV, control strategies should be tuned up and improved to obtain the maximum power performance and flexibility from VG. In this case, the precondition is to have clear and well-described requirements and procedures to integrate wind and solar PV as GSS providers. In this respect, poorly defined or non-existent technical specifications in grid codes or pre-qualification procedures that allow VG to provide GSS constitute a significant barrier to overcome in the future. This is exacerbated by the lack of standardisation and harmonisation of procedures across Europe. As a necessary precondition, a clear GSS roadmap should be established describing the required capabilities and services in due time along with a set of pre-qualification and procurement methods with proper attention to the characteristics of the sources.

Implementing enhanced capabilities will involve additional investment costs, and the deployment of the services will also involve costs. For both wind and solar PV the additional capex costs involved for enhanced provision are relatively low and – provided appropriate cost recovery/market mechanisms are in place – their deployment should be commercially feasible. Only for small PV systems the impact of required communication components will result in high additional capex costs. In general, both for wind and PV, opex costs - notably upward readiness cost - represent the highest costs to make frequency services available.
4 Economic benefits of variable renewable based services

4.1 Introduction

Chapter 4 reports the economic benefits of providing frequency and voltage support services with VG as studied in the REserviceS project (Table 14). It will also briefly consider other options to provide the same services – options not necessarily investigated in the project.

Table 14. REserviceS case studies: purpose and geographic scope

<table>
<thead>
<tr>
<th>case study (deliverable)</th>
<th>Purpose</th>
<th>Geographic scope</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transmission case studies</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offshore (D5.1)</td>
<td>Implications of offshore wind energy.</td>
<td>Generic</td>
</tr>
<tr>
<td>Ireland (D5.2)</td>
<td>Lessons learnt from Irish TSO studies.</td>
<td>Ireland</td>
</tr>
<tr>
<td>Iberia (D5.3)</td>
<td>Economic value of VG in reserves with detailed unit data; frequency and voltage response on transmission level.</td>
<td>Iberia</td>
</tr>
<tr>
<td>Europe (D5.4)</td>
<td>Economic value of VG in reserves for a larger geographic scope; cross-border sharing of reserves.</td>
<td>Northern Europe</td>
</tr>
<tr>
<td><strong>Distribution case studies (D6.2)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>Different voltage control strategies of VG in LV and MV systems aimed at reducing HV/MV cross-border power flows and at connecting higher shares of VG while decreasing grid reinforcement investments and supporting grid stability.</td>
<td>South of Germany</td>
</tr>
<tr>
<td>Italy</td>
<td>Voltage control strategies of VG in LV systems aimed at supporting grid stability.</td>
<td>South of Italy</td>
</tr>
<tr>
<td>Spain</td>
<td>Voltage control strategies of VG aimed at supporting grid stability in MV and HV systems. Voltage and frequency control supported by VG at the MV level.</td>
<td>Central part of Spain</td>
</tr>
<tr>
<td>Portugal</td>
<td>Analysis of the impact of VG on grid stability and grid losses.</td>
<td>North of Portugal</td>
</tr>
</tbody>
</table>
The benefits are calculated as the reduction in the power system operational costs\textsuperscript{53} from the case where VG does not provide ancillary services. These annualised benefits are then compared with the annualised investments needed to have the capability in VG plants to reach those operational cost reductions. Hence, the cost-benefit comparisons in this section are between the capability costs and operational benefits (cost reductions). The assumed capability costs are based on the estimations made in the project (see Chapter 3 and REserviceS D3.1 and D4.1). The operational costs have been calculated without any regard to possible subsidies like feed-in tariffs. It was assumed that possible subsidies do not interfere with optimal unit commitment and dispatch.

4.2 VG in frequency support

4.2.1 Assumptions in the simulations

VG can participate in all forms of frequency support as described in Section 2.3. While VG does not intrinsically provide synchronous inertia, VG has the advantage of potentially very rapid response to frequency events as well as accurate performance.

As VG has no fuel costs and has to be curtailed in order to provide upward reserve, it is placed very low in the upward frequency reserve merit order. It is therefore used as upward reserve only at high levels of instantaneous VG penetration. On the other hand, VG can be allocated for downward frequency control without any loss of generation, but actually deploying the service would cause a loss of electricity without fuel costs. Normally this would not be cost effective. However, using VG for downward frequency support can decrease fuel use in conventional thermal plants because sourcing downward FCR from conventional thermal generators means that they must be online and generate above minimum load. These situations get increasingly more common with higher levels of VG.

Automatic FRR is used to correct random changes in the net load and therefore utilised almost continuously. Since utilisation of VG would cause loss of free electricity, VG is reserved for automatic FRR less often than for downward FCR. Manual FRR and RR would also require curtailing large amounts of VG and therefore it is likely to be useful only in periods of surplus generation.

\textsuperscript{53} Operational costs include fuel costs and other variable operation and maintenance costs. Unit start-up costs and restrictions, piecewise linear part-load efficiencies as well as wear and tear costs due to cycling are included. At transmission level losses are estimated endogenously and at distribution level the losses are included in the electricity demand.
Providing upward frequency support with VG requires pre-curtailing of generation. This can be cost effective for the system when it avoids start-ups or allows shut-downs of conventional power plants. In these cases the remuneration from the reserve markets should make up for the value of lost generation. Since upward FCR from thermal power plants is normally limited to 5-10% of the plant capacity, multiple units are needed to provide the total reserve required by the power system. Sometimes the only reason preventing a thermal unit from shutting down can be that its capacity is required for upward FCR. Using VG for upward FCR can release such thermal unit to shut down while the resulting energy gap can be filled by other fuel based generation running at partial load or by reduction of VG curtailments. Since the availability of VG is uncertain, headroom has to be considered in order to have high enough VG reliability for the provision of upward reserve from VG. Headroom means that more VG is curtailed than offered to the reserve market. The headroom could also be formulated dynamically utilizing the probability distribution of the VG forecast. In the Iberian and European case studies of REserviceS, headroom of 5% was used for wind power and headroom of 30% for PV.

VG can also provide symmetric frequency reserve (i.e. being able to provide the same amount of upward and downward reserve). In REserviceS automatic FRR has been assumed to be symmetric due to modelling limitations. The used model analysed only the allocation of automatic FRR and not the utilisation. When considering only allocation, it is necessary to force some curtailment to simulate the utilisation. This was achieved by forcing the automatic FRR to be symmetric. Units cannot therefore provide automatic FRR at full or at minimum load, because their output will be fluctuating around the dispatched value.

Unit commitment and economic dispatch model results are sensitive to the assumptions taken. The value of frequency response from VG can be highly sensitive to the available assets – e.g. pumped hydro or demand response can potentially provide low cost alternative to frequency support from VG. Both the Iberian and European case studies of REserviceS (D5.3 and D5.4) included some pumped hydro. Transmission constraints were expressed as net transfer capacities and the frequency response was studied with a simplified model. Utilizing full grid models to study dynamic stability could find issues in the use of VG for frequency support that have not been captured by the case studies of REserviceS.

4.2.2 Cost-benefit of using VG in frequency support

The Irish, Iberian and European case studies all showed clear benefits from wind / solar PV system services in the scenarios with higher shares of wind / solar PV. Figure 6 shows the annual benefits (reduction of total operating costs) from these studies. While the results from the different case studies are not directly comparable, the figure demonstrates clear benefits at higher penetration levels. In the Irish base case wind power is curtailed to stay below SNSP of 50% at all times and in the Irish enhanced case (EOC) to stay below 75% (Eirgrid, SONI and SEMO 2012). This difference yields considerable
benefits at higher penetration levels. The Iberian and European case studies have lower benefits, but they do not contain a limit to SNSP like the Irish case. The benefits are only due to VG replacing conventional generation in the frequency reserves FCR and automatic FRR. The European case study also demonstrated that the benefits of VG participation were quite similar to the benefits of sharing frequency support across borders. Doing both, VG participation and cross-border sharing, increased the benefits to some extent.

![Graph showing benefit of VG in frequency support in different case studies](image)

**Figure 6** The benefit (operational cost reduction) of VG in frequency support in the different case studies. The benefit is calculated as the decrease of annual operating costs of the power system when VG participates in AS compared to no AS from VG. For Europe also the benefit of cross-border sharing of frequency support is presented. (Ireland: EOC Enhanced Operating Capability has all variable generation with enhanced AS).

In Figure 7 the annual operational cost reductions are compared against the annualised investments required to make all new variable generators capable of frequency support. The scenario is from the Iberian case with variable generation producing 42% of the total generation. The left bar shows estimated investment costs to enable the participation of all VG assets in the reserves. The middle bar shows the benefits when each of the reserve categories are assessed separately and added together afterwards. The rightmost bar shows a case where VG has been able to participate in all reserves in the same model run. The difference between the middle and rightmost bars indicates that there are co-benefits when VG is participating in all frequency support services at once. In both cases, the benefits outweigh the annualised investment costs of wind power and lower cost PV categories. Due to small unit size, residential PV has higher costs especially per installed MW and is not a very cost effective source of frequency reserves.

*REserviceS D7.1 Synthesis report*
4.2.3 Cross-border sharing vs. VG in frequency support

The REserviceS European transmission case study also investigated the benefits of sharing of frequency support services across country borders. The results displayed that the benefits of VG in frequency support are similar to the benefits of cross-border sharing of frequency support (Figure 60). The sharing was allowed to the extent proposed in the new ENTSO-E Network Code for load frequency control (ENTSO-E 2013). The benefits of VG got slightly better than the benefits of sharing as the VG penetration increased. Utilising both at the same time created some additional benefits – especially at higher penetration levels.

4.2.4 Other options for frequency support

Frequency can be supported by other means other than power plants. Some of these other options may be more cost effective than utilizing VG, overall or in specific circumstances, but they were not studied in the REServiceS project. Other options for frequency support include:

- Demand response
- Lowering the minimum load capability of thermal plants
- Storage systems that are fast to respond or have an inertial mass
  - Flywheels: transferring the rotational kinetic energy stored in rotating masses into electricity
Batteries: change of charge/discharge

Table 15 shows typical full activation times for different technologies, which indicates the suitability of the technology for different frequency reserve purposes. The cost-benefit of VG should be compared with all these options also utilized in the model and can be a subject for further studies.

Table 15: Typical full activation times for different technologies

<table>
<thead>
<tr>
<th>Full activation time</th>
<th>Below 250 ms</th>
<th>5-15 s</th>
<th>Minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corresponding reserve products</td>
<td>No such product</td>
<td>FFR (2s), FCR</td>
<td>FRR, RR</td>
</tr>
<tr>
<td>Demand response</td>
<td>20 ms</td>
<td>⬠</td>
<td>⬠</td>
</tr>
<tr>
<td>Battery Li-ion</td>
<td>20 ms</td>
<td>⬠</td>
<td>⬠</td>
</tr>
<tr>
<td>Battery NaS</td>
<td>20 ms</td>
<td>⬠</td>
<td>⬠</td>
</tr>
<tr>
<td>Flywheel</td>
<td>Not possible</td>
<td>4s</td>
<td>⬠</td>
</tr>
<tr>
<td>Hydro</td>
<td>Not possible</td>
<td>15s (0.05-0.15 p.u.)</td>
<td>~1 min.</td>
</tr>
<tr>
<td>Pumped hydro</td>
<td>Not possible</td>
<td>15s (0.05-0.15 p.u.)</td>
<td>~1 min.</td>
</tr>
<tr>
<td>Online reciprocating engine</td>
<td>Not possible</td>
<td>15s (0.04 p.u.)</td>
<td>4 min.</td>
</tr>
<tr>
<td>Online open cycle gas turbine</td>
<td>Not possible</td>
<td>5-15s (0.05-0.2 p.u.)</td>
<td>10-20 min.</td>
</tr>
<tr>
<td>Online combined cycle gas turbine</td>
<td>Not possible</td>
<td>5s (0.05-0.01 p.u.)</td>
<td>10-25 min.</td>
</tr>
<tr>
<td>Online nuclear</td>
<td>Not possible</td>
<td>5s (0.02 p.u.)</td>
<td>20-100 min.</td>
</tr>
<tr>
<td>Online steam turbine</td>
<td>Not possible</td>
<td>5s (0.1 p.u.)</td>
<td>25-60 min.</td>
</tr>
<tr>
<td>Offline reciprocating engine</td>
<td>Not possible</td>
<td>Not possible</td>
<td>7 min. cold start to full power</td>
</tr>
<tr>
<td>Offline open cycle gas turbine</td>
<td>Not possible</td>
<td>Not possible</td>
<td>30 min. cold start to full power</td>
</tr>
<tr>
<td>Offline combined cycle gas turbine</td>
<td>Not possible</td>
<td>Not possible</td>
<td>30-60 min. hot start to full power</td>
</tr>
</tbody>
</table>

54 “Gas turbine” stands for heavy duty gas turbine, and hence not for aero-derivative gas turbine, the latter typically having significant better flexibility attributes such as fast start capability (5-10 min. cold start to full power, while not incurring cost penalties related to start stop cycles). Aero-derivative gas turbines are typically used for peaking applications and in flexible CHP solutions.”

REserviceS D7.1 Synthesis report
4.2.5 Impact of better forecasts on the provision of frequency support

Better or poorer variable generation forecasts would change the uncertainty related to the availability of frequency support in real time. When uncertainty increases, more headroom is required in order to provide certain amount of frequency support with high enough confidence level. The impact of this was investigated in the Iberian case study by doubling the headroom of wind power from 5% to 10% in the simulations. There was no quantifiable increase in the estimated operational costs of the power system.

Forecast accuracy is a function of the dispersion of the wind power assets under consideration. 5% headroom may be achievable for forecasts that aggregate a large number of wind power plants in a geographically large area. 10% headroom is currently a more realistic value when considering a single producer with a smaller portfolio of wind power plants. The impact of forecast quality for scheduling and balancing was not included in this sensitivity test.

Currently solar PV was not used for reserves, since wind power had smaller headroom and was therefore preferred by the model. However, if PV had better forecasts than wind power, there should be no fundamental difference and hence the same result should also apply to solar PV.

4.3 Cost benefit of VG in voltage support

Voltage control from variable generation requires additional CAPEX cost and causes some operational costs. On the other hand, VG voltage support may create benefits that outweigh the costs as exemplified by some of the case studies. However, many of the items can be currently difficult to amortize for the wind power/PV operators, especially when it comes to dynamic voltage or frequency support from VG (i.e. P droop function required mitigate the “50.2 Hz risk”). Furthermore, operational impacts are highly case specific and require detailed analysis. However, the cost benefit analysis should include at least the following aspects:

Investment costs:
- Investments for traditional grid reinforcement (substations, cables, surface rehabilitation, etc.)
- Reactive power resources (VG adaption, FACTS devices, etc.)

Operational costs:
- DSO and VG operation & maintenance
- ICT operation & maintenance
- Outages impact and VG curtailment
- Active power losses
Possible Benefits:

- Operation & maintenance costs reduction
- Deferred distribution capacity investments
- Active power losses reduction
- Outages reduction
- Curtailment of VG reduction
- CO2 emissions and reduced fossil fuel usage reduction
- Air pollution (particulate matters, NOx, SO2) reduction

When a CBA is performed, a system approach must be adopted in order to consider global costs and cost allocation among participants. Moreover, external benefits and costs may be important when concluding about the suitability of different solutions. The best solution is not the same everywhere and it may change as the system changes. Therefore more flexible planning taking different options systematically into account would be beneficial.

4.3.1 Cost-benefit of using VG to support voltage at high voltage levels

The REserviceS cases studies reported in D5.1, D5.2, and D5.3 have shown that today’s wind turbine technology can provide suitable voltage control services, within its design limits and capability range. The literature on cost/benefits of utilizing VG to control transmission level voltage is sparse and we can only present two examples related to the case studies in the REserviceS project.

According to Sáiz-Marín et al.\textsuperscript{55}, for a 488 MW cluster (comprising of 15 geographically distributed wind power plants), the plant owner CAPEX for implementing a wide-area steady state voltage control can be around €1.5M. The greatest cost impact corresponds to cluster level regulators and weather forecasting system. The impact on energy production is also estimated to be relatively low and is associated with installation and start-up of software and equipment at plant/cluster level, and the required time for On-Load Tap Changing (OLTC) increased maintenance. The estimated OPEX impact for providing steady state voltage control is relatively low, around 1\% of CAPEX.
Recent literature\textsuperscript{55} has shown that the provision of steady state voltage control leads to an increase in active power losses within the plants’ internal grid, and any common grid connection infrastructure (where applicable, e.g. in Spain). These additional losses are borne by the plant owner. The analysis in Sáiz-Marín et al.\textsuperscript{55} presents a case of an aggregation of several wind power plant (514 MW) connected to the same point within the transmission grid (similar to the case presented in D5.3), where aggregated annual power losses increase 736 MWh in comparison with a base case (without provision of voltage control). The cost of such additional losses for the plant owner for this particular case has been estimated around €60k per annum (based on Spanish regulatory rules and market).

The Irish case study reported in REserviceS D5.1 presented a comparison between 2010 (real) and 2020 (simulated) scenarios of available reactive power within the grid. When reactive power from wind plants is not included there is a noticeable reduction in the availability of synchronous reactive power across the year. When wind is included (and assumed to provide a reactive power capability in line with the current Grid Code), the available reactive power on the 2020 scenario increases, but it is still below the levels of the 2010 scenario. However, if wind power plants provide an enhanced reactive power capability (i.e. full reactive power range across the full active power output range), the reactive power capability is very similar to the 2010 level.

Compared to other providers of the Dynamic Reactive Power service, enhanced operation capability-enabled wind generation exhibits a favourable, almost 25\% lower cost structure when remunerated per capability. When remunerated dispatch-dependent it exhibits on-par costs. Annual payments are shown in Table 16 for each €1m spent on System Services, normalised to installed capacity (i.e. € per MW installed).

Table 16  Illustrative annual AS payments (per MW installed), for Dynamic Reactive Power service by provider type, (Eirgrid 2012)

<table>
<thead>
<tr>
<th>Dynamic Reactive Power</th>
<th>Enhanced wind power plant</th>
<th>CCGT</th>
<th>OCGT</th>
<th>Coal</th>
<th>Pumped storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capability (€/MW installed)</td>
<td>15</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>22</td>
</tr>
<tr>
<td>Dispatch-Dependent (€/MW installed)</td>
<td>27</td>
<td>19</td>
<td>2</td>
<td>29</td>
<td>26</td>
</tr>
</tbody>
</table>

4.3.2  Cost-benefit of using VG to support voltage at low/medium voltage levels

The provision of voltage support by reactive power consumption/production from distributed generation is helpful to maintain the voltage profile within acceptable limits, regardless of the way the

\textsuperscript{55}  E. Sáiz-Marín, et al. 2014

REserviceS D7.1 Synthesis report
reactive power is absorbed or generated (e.g., using statcom, automatic power regulators,...). Consequently, the hosting capacity of the distribution network can be increased without jeopardizing the security and the quality of the system.

Applying autonomous voltage control strategies at LV level by setting the operation points of solar PV inverters as well as the OLTC of MV/LV transformer could significantly mitigate the voltage raises caused by high solar PV feed-in and hence improve the steady state voltage stability. The investments costs for grid reinforcements can be substantially decreased by using such solar PV based ancillary services. Furthermore, this kind of local control approach does not require any ICT infrastructure, which makes it more suitable for the application in LV grids with numerous solar PV systems. The operational costs for the DSO, however, might be slightly increased by applying these control approaches (grid losses, maintenance). Exemplary results confirming the above are offered in Figure 8 on the next page.

![Figure 8 Total net present value of investigated local control strategies for a LV feeder in South of Germany, [D6.2]](image)

Another strategy would be to provide reactive power compensation with VG in order to decrease the line losses, by keeping the load power factor as close as possible to one. However, in that case the increase of hosting capacity would be limited. Thus the DSO has to make a choice between increasing the hosting capacity, and optimising losses.

Because of its strong dependency on the case characteristics, the effectiveness of voltage control from wind and solar energy must be assessed on a case-by-case basis. Numerical results highly depend on characteristic impedance, network topology, and load/generation distribution and location. The CBAs in REserviceS case studies show that the implementation of advanced voltage control techniques provided by VG can give benefits to the electrical system by:

REserviceS D7.1 Synthesis report
• increasing the grid hosting capacity for higher shares of VG;
• reducing the risk of VG curtailment;
• reducing the operation costs and grid reinforcement costs;
• reducing network losses and reverse power flows;
• enabling further applications linked to the implementation of a bi-directional communication network and enabling the participation of VG in ensuring grid stability and reliability and power supply, by providing grid support services like voltage and frequency control;
• improving quality of power supply.

4.3.3 Other options for voltage management

This section compares the costs and benefits of voltage management by VG with other, mainly network-based, options. For each alternative, a brief technical description is provided together with some cost implications.

Methodologically, each possible technology used for voltage and reactive power control should have been evaluated independently to determine specific cost/benefit ratio. However, the purpose of the investigations in the REserviceS demonstration cases was to establish the costs of VG-provided services and not the exact cost/benefit ratio of other options for voltage management. Therefore the information presented here is not based on well-defined comparative cases, but rather on literary sources.

The Irish DS3 program\textsuperscript{56} evaluated two alternatives to enable the operation of the system at 75\% SNSP instead of 50\% SNSP. Both scenarios were designed to resolve the four fundamental challenges identified: inertia/RoCoF, ramping, reactive power, and transient stability. The investigation focused on a scenario with enhanced capabilities from generators including wind power, but also contained an alternative network investment scenario. The network investment scenario was deemed to be a more costly alternative (1206 M€) in comparison to the enhanced generator capabilities scenarios (535 €M). No other possible configurations were investigated.

The network scenario assumed no enhancements to wind power generation – it utilised only network devices and new enhanced OGCTs (exclusively for System Operational purposes) to deliver the required ancillary services:

\textsuperscript{56} Eirgrid 2012, REservices D5.1

REserviceS D7.1 Synthesis report
- A number of dedicated synchronous compensators with flywheels to provide inertia and reactive support at various locations on the system.
- Approximately 400 MW of new OCGTs, which are required to provide ramping margin. It is assumed that these OCGTs will also be capable of operating in synchronous compensation mode.
- A significant number of STATCOMs distributed around the system to provide voltage control.

Table 17 shows the necessary investment cost breakdown for each of the scenarios (DNV KEMA 2012). Only the capital investments costs are taken into account.

**Table 17. Total capital costs for Generation and Network investment scenarios (DNV KEMA 2012)**

<table>
<thead>
<tr>
<th>Option</th>
<th>Capital Cost (€/MW or €/Mvar)</th>
<th>Volume (MW or Mvar)</th>
<th>Total cost (€m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enhanced Wind (incremental cost)</td>
<td>€139,000</td>
<td>1300</td>
<td>€181m</td>
</tr>
<tr>
<td>Enhanced New CCGT</td>
<td>€30,000</td>
<td>450</td>
<td>€14m</td>
</tr>
<tr>
<td>Improve Existing CCGTs</td>
<td>€122,000</td>
<td>2000</td>
<td>€244m</td>
</tr>
<tr>
<td>Enhanced OCGT (incremental cost)</td>
<td>€74,000</td>
<td>400</td>
<td>€30m</td>
</tr>
<tr>
<td>Sync Comp conversion</td>
<td>€63,000</td>
<td>200</td>
<td>€13m</td>
</tr>
<tr>
<td>STATCOM (total cost)</td>
<td>€109,000</td>
<td>500</td>
<td>€55m</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td><strong>€535m</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Option</th>
<th>Capital Cost (€/MW or €/Mvar)</th>
<th>Volume (MW or Mvar)</th>
<th>Total cost (€m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synch Comp / Flywheel</td>
<td>€766,000</td>
<td>840</td>
<td>€643m</td>
</tr>
<tr>
<td>Enhanced OCGTs - Strategic Reserve</td>
<td>€724,000</td>
<td>400</td>
<td>€320m</td>
</tr>
<tr>
<td>Batteries</td>
<td>€829,000</td>
<td>0</td>
<td>€303m</td>
</tr>
<tr>
<td>STATCOM</td>
<td>€109,000</td>
<td>2,500</td>
<td>€1,206m</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td><strong>€1,206m</strong></td>
</tr>
</tbody>
</table>

Table 17 demonstrates how the extent of availability of different options can be case specific (e.g. upgradable existing CCGTs, possibilities for converting retiring units to synchronous compensators). Furthermore, the need for steady state voltage control (SSVC) and fast reactive current injection (FRCI)
is localised as the penetration levels of variable renewables develop unevenly and the strength of the existing grid varies.

As a consequence each case has a selection of relevant technology choices that need to be compared while considering the current and future needs. In addition to renewables the choices include:

- **FACTS devices** (e.g. capacitor/reactor banks, Static Var Compensators (SVC), STATCOMs in conjunction with storage, Unified Power Flow Controllers). With the help of power electronics, these devices use stored energy or active power from the network to inject reactive power into the grid to control voltage.

- Static VAr Compensators (SVCs) use power electronics to provide fast acting reactive power compensation, and provide smoother and more precise control than mechanically switched compensation. If the power system load is capacitive (leading), the SVC individually switches thyristor-controlled reactors to consume reactive power from the system (lowering the system voltage). If the power system load is inductive (lagging), in capacitor banks to increase the system voltage (these can also be switched by thyristors for smoother control and more flexibility). The automated switching ability of SVCs provides near instantaneous response to changes in system voltage. SVC solutions are effective for mitigating undamped voltage oscillations and preventing voltage collapse. However, SVCs can only produce a reduced VAR output during low voltage, which makes them less effective for mitigating violation of certain voltage limits immediately following fault recovery. Their cost are about half of that of the STATCOM, Figure 9.

- **STATCOMs** also use power electronics to provide fast acting reactive power compensation. They are inverters based on forced-commutated switches (with full, continuous control of the reactive power). STATCOMs are about twice as expensive as SVCs, but are generally considered to have better characteristics. When the system voltage drops sufficiently to force the STATCOM output to its ceiling, its maximum reactive power output will not be affected by the voltage magnitude. Therefore, it exhibits constant current characteristics even when the voltage is very low. In contrast the SVC's reactive output is proportional to the square of the voltage magnitude. This makes the provided reactive power decrease rapidly when voltage decreases, thus reducing its stability. Therefore STATCOMs are better than SVCs for managing post-disturbance undervoltage conditions, and can improve power quality against dips and flicker\textsuperscript{57}. However, they may not be as effective as SVCs at damping voltage oscillations\textsuperscript{58}. Wind plant DFIG or inverter as well as PV inverter can provide similar voltage stabilizing behaviour for a lower price than a STATCOM\textsuperscript{59}.

\textsuperscript{57} Xiao-Ping Z. et al., 2006.
\textsuperscript{58} Holger M. et al., 2011.
\textsuperscript{59} Okedu K.E., 2010
- Tap changing transformers (OLTC) are the primary control solution in distribution grids, that can shift the ratio between high and low side in a series of discrete steps. In conjunction with a locally connected VG, a tap changing transformer could in principle help the source in MV network to maintain the node voltage while injecting reactive power. However, the presence of generation connected to MV/LV feeders makes OLTC control unreliable as the overall load is influenced not only by passive loads but also by generation. In order to benefit from OLTC, it is not possible to rely only on measurement at the HV/MV transformer level anymore; OLTC must be combined with some advanced voltage control system by measurements within the MV and LV grid to get a better knowledge about the actual grid state. The main cost implication lies in the need for extra measurement points and for the grid monitoring communication infrastructure along the MV/LV grids (Smartgrid concepts). As shown in D6.2, Report on the evaluation and conclusion of the DSO case studies, the use of OLTC in voltage control leads to a significant decrease of grid reinforcement costs. However, additional operational costs, such as equipment maintenance (for OLTC applications), additional network losses and active power feed-in curtailment may also be a consequence. The application of OLTC shows the highest saving potential with a reduction potential of about 50% of the total NPV compared to pure grid reinforcement.

- Synchronous condensers (large rotating synchronous machines not connected to a turbine) manage power factor compensation via a voltage regulator that allows the unit to either generate or absorb reactive power in a continuously adjustable manner. They are typically of lower capacity, more expensive, slower and less reliable than SVCs. Some fossil fuel generators are converted to synchronous condenser mode in their later lives, by decoupling the turbines and synchronising the condensers using small motors. With a help of excitation control of the rotor, they are able to use active power from the network and inject reactive power in it. However, the winding losses of synchronous condensers tend to make them expensive to operate, particularly in support of variable generation. As shown in Figure 9, cost-wise they are similar to the SVCs. In contrast to VG voltage support, the location of Synchronous Condensers is already either in the substations or as in the case of converted plants at a well-connected central location, providing a cost-effective voltage support at the HV, rarely running into line congestion issues of VG connected at MV and LV level.
In alternative voltage management schemes, the issue of scale has an impact on cost. For instance, several medium size SVCs cost less than many smaller SVCs for the same MVAr rating.

### 4.4 Cost-benefit of using VG for system restoration

The cost-effectiveness of services by VG for participating in system restoration has not been investigated in REserviceS. Irrespective of the technical capabilities to be developed and functionalities to be deployed during in a system restoration event (see Chapter 3), the issue of unavailability of the primary resource for VG dominates the technical and economic discussion. A primary aspect for further research is how to design cost-effective system restoration strategies for scenario’s with very high shares of VG.

- Large-scale participation of VG in system restoration is hardly imaginable without involvement of energy storage installed in/nearby the participating VG plants.
- During the restoration sequence, different small island ‘local’ networks need to re-synchronise with each other and for this purpose the appropriate system stabilising capability need to be present in the participating VG plant.

Both aspects involve additional CAPEX to VG plants. These costs as well as potential benefits for system operators and plant operators will be most likely very case specific. Ongoing research projects will provide more insights in these aspects.

### 4.5 The excessive cost of requiring capabilities from all generators

The capability to provide either frequency or voltage support from variable generation comes with a cost. Therefore, it is important to assess whether the expenditure of this cost is justifiable in all cases. In the end, electricity consumers will pay the bill and a reasonable balance has to be struck between adequacy, stability, power quality and costs. This section does not include comprehensive analysis about all these factors, but it does provide indication about the need for ancillary service capabilities in VG.

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60 Uijlings W., 2013
61 Begovic M., 2013.
In the Iberian case with 42% of annual energy from VG (scenario VG42) the frequency response remained adequate when only 25% of wind power participated in the frequency reserve. At the same time the economic benefits remained the same. The current cost to equip all wind generation with frequency response capabilities is visible in Figure 7. According to the model results, only a fraction of those investments would be needed. The cost to equip solar PV is even higher mainly due to the smaller size of the systems. There is a large difference in equipping PV with frequency response capabilities depending on the size category (roof-top, commercial and utility-scale). According to the model results, while the frequency response when solar PV is participating in the FCR is somewhat better (smaller frequency excursion), solar PV is not needed to maintain frequency. These results are current estimates and they are bound to change as experience and technology matures. The frequency response model was simple and as such not capable of capturing all aspects related to frequency and no aspects related to voltage.

It is more difficult to assess whether uniform voltage support capabilities should be required from all VG. As the REserviceS case studies analysing voltage control demonstrated, the costs and benefits are very case specific. The findings from the case studies demonstrate that voltage control capabilities from VG are not likely to be always the best choice and therefore an across the board requirement may lead to excessive costs.

4.6 Conclusions

The REserviceS simulations of power systems of various sizes across Europe and increasing share of VG (up to 50%) show it is beneficial to utilise variable generation in frequency reserves and that these system benefits increase with the share of variable generation. The benefits were calculated by comparing the overall operational costs of power generation with and without using VG for frequency support. The largest benefits are observed in the downward FCR and in the automatic FRR. The operational benefits for the system operator in the simulations are higher than the cost of equipping all VG with the capability to participate in the frequency support, especially for wind power plants with their lower capex costs (per MW) than residential PV. In the system simulations not all VG needed to participate in the frequency support in order to achieve the economic benefits. In a sensitivity analysis the frequency response and its corresponding economic benefits remain adequate with a 25 % fraction of the VG participating in frequency support services. Thus it should be sufficient to only equip a part of VG with capability for FCR and automatic FRR services. Cross-border sharing of frequency reserves creates similar benefits as VG, but there are additional benefits when both variable generation and cross-border sharing are utilised.

The REserviceS case studies analyzing different MV/LV networks with different VG shares conclude that the cost/benefit ratio of voltage support from VG is very case specific and that provision of voltage support by VG should be compared with alternatives. As there will be a high number of locations where individual decisions need to be made from where voltage support will be sourced, there is a need for universal and robust methods to make the assessment with reproducible and comparable results. The
findings from the case studies demonstrate that voltage control capabilities from VG are not likely to be always the best choice and therefore an across the board requirement may lead to excessive costs.
5 Market concepts (commercial frameworks)

5.1 Introduction

This chapter addresses possible market concepts and other commercial frameworks for an efficient and cost-efficient deployment of grid support services in systems with high shares of variable renewables. The discussion attempts to provide answers to the following questions:

- Is a market based system to be preferred or are there other possible set-ups – considering that the market itself is not the goal but the least cost service provision? In this context it is important to clarify that “market-based” does not necessarily equate to a pool of bids and offers. Bilateral contracts are also “market-based” mechanisms. One alternative to “market-based mechanisms” is “command and control”, which would imply mandatory, possibly non-remunerated provision.

- What general market designs are possible?

- Are solar PV and wind already offering services on some markets and how was this realised?

- What are the main barriers for VG to offer their services? Can simple changes be made to surmount these or are deeper market design adaptations necessary?

- Are market based mechanisms a possible option for services provided for distribution system operation?

5.2 The electricity market – an overview and an interface to REserviceS

Before discussing electricity markets and in particular markets for ancillary services, it is important to develop a uniform understanding of the most common terms used.

In this document the term electricity market is used whenever markets are considered to be used for the procurement of electricity services (reactive and active power both upward and downward) irrespective of whether they are traded on the spot market as standard product, over the counter in bilateral agreements or as balancing power to the system operator.

Electricity markets are split into active and reactive power markets. The reason for this is the fact that in all European electricity markets active and reactive power are also traded in separate systems. Reactive power management is either a requirement or traded in bilateral agreements between a power plant and a TSO/DSO or tendered by the system operator for rather long-term provision. In none of the European countries reactive power is traded on a standardised platform with monthly, weekly or even daily offerings.

The beginning of this section focuses on market designs for active power. Then, different concepts and products on these markets are described.
Self and central dispatch electricity markets
Two major categories can be distinguished for market designs for active power:

- **Market with central dispatch**: In a centrally dispatched market the TSO dispatches all plants, based on the different market offers or technology costs, to provide generation and demand balance, external transfers, reserve provision and transmission constraint management. Thus, in central dispatch systems balancing, congestion management and reserve procurement are performed simultaneously in an integrated process.

- **Self-dispatch market**: Self-dispatch is an arrangement where generators determine a desired dispatch position for themselves based on their own economic criteria to provide commercial independence within a market. The dispatch determination may or may not have a requirement to have a balanced position with demand. Deviations from the nominated dispatch are charged to the market participant as imbalance fees.

Most markets in Europe are self-dispatch markets as shown in Figure 10. Central dispatch can be found in Ireland, Italy, Slovakia, Latvia, Poland and Greece.

The choice between a self-dispatch or central dispatch model is often closely linked to the level of intervention by a TSO that is needed to guarantee system stability. Each power system has a unique mixture of features. Some features affect the level of intervention a TSO needs to have on the market-based schedule to form the operational schedule. Where there is significant intervention, system operation tends to move from the self-dispatch model to a more central dispatch model in order to optimise electricity market operation and transmission system operation and thus ensure economic efficiency.

Various stakeholders argue that a central dispatch model is not compatible with a European target model. The European target model is also the reason why this report focuses on self-dispatch electricity markets.

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62 Soni and EirGrid, 2012
63 ENTSO-E, 2014
64 Eurelectric, 2013
65 EFET, 2014
Self-dispatch market organisation

For the basic processes of self-dispatch power markets the different products can be best illustrated by using the time frames in which electricity is traded:

- The **electrical supply market** is designed to match generation and consumption as well as possible by allowing producers and consumers of electricity to trade. The market therefore comprises all electricity trade before the actual point of delivery. The electricity can be traded in two different forms:
  - **Trading over-the-counter (OTC)**: On the OTC non-standardised products are traded bilaterally between two parties. Virtually any kind of product can be designed as long as the two parties agree to it.
  - **Exchange market trading**: On the exchange market standardised products are traded anonymously on an exchange platform that collects offers and bids and matches these at the resulting market prices. The exchange market typically encompasses the future market, the day-ahead and intra-day market. On all three platforms several standard products can be traded. The number of products is limited mainly in order to maintain sufficiently high liquidity (sufficiently large number of offers and bids).
The balancing market is designed and operated by the TSO or a market operator\textsuperscript{66} with the goal to balance the power system in real-time. Thus if the generation does not meet the demand in real time because e.g. the pre-balancing markets did not fully clear, production and demand forecasts were wrong, or power plant outages etc., the excess or shortage of power needs to be absorbed by the balancing market. For this purpose the balancing market has different products which in general correspond to manual FRR and RR.\textsuperscript{67} Increasingly also FCR and automatic FRR are considered for bid based markets.

The different products on these markets and the time frames are illustrated in Figure 11. The market participants can trade on the exchange markets until gate closure time. In general there is a forward market that allows buying and selling electricity up to years before the actual delivery, a day-ahead and an intra-day market. Also OTC positions have to be forwarded to the TSO and therefore have to be handed in before gate closure time.

At the same time the TSO procures balancing service from the market participants, which then are activated after or within the GCT or in real time. This depends on whether a reactive or pro-active the self-dispatch market design is in place as explained below.

\textsuperscript{66} Czech Republic, Slovakia, Austria, Slovenia, Italy, Romania and Ireland – (Europex, 2012)

\textsuperscript{67} FCR, FRR, RR are standard products proposed by ENTSO-E in the NC OS operational reserves report, 2012. Different TSOs however have a variety of different products to procure balancing power.
As already indicated in Figure 11 within the self-dispatch markets we can distinguish further between pro-active and reactive\(^68\) and electricity markets.

- **Pro-active balancing markets;** in this market design the TSOs are taking over the balancing responsibility from the market in an early stage (e.g. 1 hour before delivery time). TSOs are performing imbalance forecasts and try to anticipate on important imbalances by activating slow balancing energy products\(^69\)

- **Reactive balancing markets;** in this kind of markets TSOs incentivise market players to restore the balance of their perimeter even in real-time. Therefore balancing actions by TSOs

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\(^{68}\) The term reactive market design should not be mistaken for a market on which reactive power is traded. The word reactive rather tries to capture that the market participants themselves have strong incentives to react to imbalances in their parameter.

\(^{69}\) ELIA, 2013

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**Figure 11:** Different time frames and process on a self-dispatch market (own illustration based on [5])

**Two different self-dispatch market types**

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consist in activation of fast reserves with short activation durations. Consequently replacement reserves are rarely used by TSOs in re-active balancing markets\(^{70}\).

In a stronger grid the TSOs can more easily rely on market players to take part of the responsibility in balancing. Some studies indicate that reactive market designs allow a deeper integration of renewables in the balancing process. This is because the balancing is shifted to real-time and thus renewables can still react to potential forecast errors. In pro-active markets the reserve are often contracted longer ahead and need to be held available for any moment. This by nature excludes renewables from these markets\(^{71}\). The Nordic market is a pro-active market, but still has a balancing market that only closes 45 min before delivery, where VG can also bid. The market design is thus a more complex issue and how to make the rules in a way to enable VG participation needs further studies.

**Markets for reactive power for voltage support**

In view of appropriate market designs for reactive power procurement the following two differences between active and reactive power should be highlighted:

- Reactive power should be supplied close to the point of demand. Otherwise the effect is limited and furthermore on the way to the point of demand reactive power congests the power lines limiting the capacity to transport active power. In particular the possibilities to provide reactive power from lower voltage level to higher voltage levels are limited.

- The demand for reactive power is relatively low compared to the demand for active power in a power system. Furthermore some generators can offer reactive power at very low costs.

These reasons limit the number of possible offers for reactive power demand. Furthermore the costs for the implementation of trading platforms of standard reactive power products and the trading transaction costs might not be justified by the traded volume.

On the other hand, the need for reactive power and the need to diversify reactive power sources grows with the increased penetration level of renewables in particular because the market share of conventional power plant that traditionally delivered reactive power steadily decreases. Thus, reactive power is often either asked as a mandatory service by the TSO or is tendered rather long-term by the TSO - typically on annual basis.

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\(^{70}\) ELIA 2013  
\(^{71}\) McDonald & SWECO, 2013  
RESserviceS D7.1 Synthesis report
5.2.1 How do different market and procurement based mechanisms relate to each other?

Relation between the pre-balancing electricity market and the balancing market

Different contingencies lead to imbalances that need to be dealt with by the balancing market. A significant part of the imbalances is due to inherent market design inefficiencies. Thus, even though the general goal is to design the pre-balancing market in such a way that the remaining imbalances at the point of delivery are minimal, it is not possible to completely eliminate the occurrence of imbalances. The main reasons are:

- Gate closure time (GCT):
  - The pre-balancing market closes at a defined time before the actual electricity delivery in order to allow the TSO to take all taken positions into account and to take reactive measures in case of mismatches. In the remaining time between the GCT and the delivery any change in production and demand (e.g. due to a power plant outage) cannot be put to the market any more.
  - Insufficient market liquidity in particular on the intra-day market;
  - During the intraday when the forecasts are adapted, market participants might want to put these changes on the market.

- Standardised products:
  - The creation of standard products increases liquidity but at the same time the products will not perfectly match the production and generation profile in particular of renewable energy plants. The mismatch results in an imbalance.

- Strategic over- or under-nomination:
  - The market participant needs to pay for imbalances in his position, if the sum of the power consumed, traded and produced is not equal to zero. If he assumes that the fee for imbalances is a lower cost than the cost for balancing the portfolio on the pre-balancing market, he will keep this “strategic” imbalance. Also, if the penalties are not symmetric (paying more for up-regulation than down-regulation or vice versa) it also may be cost effective to offer bids that overestimate (or underestimate) the generation level.

All these possible market driven imbalances need to be balanced by the TSO which needs to procure the necessary upward or downward power on the balancing market. Thus, the better the pre-balancing market clears, the lower are the needs for balancing power.

Therefore a better market integration of renewables in the pre-balancing market can have a similar or even higher positive impact on the overall costs for balancing the power system. It is however beneficial to improve the design of the balancing power market also, to allow all possible flexibility to bid on these markets.

*REserviceS D7.1 Synthesis report*
5.2.2 Which markets segments for which services?

For frequency support services the balancing market is very important. As discussed above it is however possible to also facilitate the integration of renewables in the pre-balancing market – OTC or exchange market trading – which can reduce the needed balancing power. The integration of VG in the pre-balancing market could be improved by shortening gate closure times to allow the traders to take better forecast into account or to allow intentional diversion from the nominated power as in the reactive power market model (see above). Balancing market participation was studied in WP3 and WP4 of REserviceS in detail, and the impact of providing the faster response automatic services (FCR and automatic FRR) were studied in WP5.

Voltage support services need a separate discussion. The only market based arrangements for reactive power service are auction systems in which the long-term provision of reactive power is tendered. Sometimes there are fixed reimbursements for reactive power provision for all generators. Often however, reactive power support is a mandatory non-reimbursed service. The main reasons are that:

- Voltage support services are needed locally and the quality of the service depends on the (grid-) distance of the providing power plant. Therefore the number of potential bidders would be limited and the creation of standard products is difficult.
- The costs for voltage support services are significantly lower than the costs for flexible active power provision, which lowers the interest for both the providing and the requesting party to integrate the provision in a market-base process.

5.3 Ancillary services market in Europe in monetary terms

Grid support services represent a small part of today’s market for generators in terms of revenues. The international comparison of ancillary services done in Ireland in the context of the DS3 program estimated that in today’s European markets on average ancillary services payments represent less than 5% - often between 2-3% - of the total revenues earned by an electricity producers from energy-only markets. An exception is Spain where the annual cost of system services in 2010 was €593.8M, representing 10.8% of total revenues in the national electricity market.

In UK in 2011, ancillary services represented 1.9% of the total sales of electricity, or around £547 million. Around 78% of these are commercial services that assist the system operator in meeting its obligations and which were negotiated between the generators and the system operator either through a market competition, the balancing mechanism or a bilateral negotiation. 18.5% were mandatory services consisting in mandatory frequency response (~10%) and reactive power (~8.5%).
In Ireland system services are procured by the TSOs using direct contracts with generators on regulated rates (Table 18). In the current arrangements about €55 Million is paid to generators to provide system services representing about 2% of the market total market turnover of €2 900 Million.

In the Nordic system the Regulating power market (balancing market) operated by the four TSOs has had a volume of about 4 TWh yearly (total for up- and down-regulation). This is 1-2% of the volume in Elspot (the day-ahead market) (Nordpool, 2014, NordReg, 2014).

A summary of the Irish wholesale market payments is shown in
Table 18: Ancillary services rates paid in Ireland. Source: KEMA, 2011

<table>
<thead>
<tr>
<th>Payment Parameters and Rates</th>
<th>EirGrid</th>
<th>SONI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Operating Reserve</td>
<td>€2.22 / MWh</td>
<td>£1.95/ MWh</td>
</tr>
<tr>
<td>Secondary Operating Reserve</td>
<td>€2.13 / MWh</td>
<td>£1.87/ MWh</td>
</tr>
<tr>
<td>Tertiary Operating Reserve 1</td>
<td>€1.76 / MWh</td>
<td>£1.55/ MWh</td>
</tr>
<tr>
<td>Tertiary Operating Reserve 2</td>
<td>€0.88 / MWh</td>
<td>£0.77/ MWh</td>
</tr>
<tr>
<td>Replacement (Synchronised) Reserved</td>
<td>€0.20 / MWh</td>
<td>£0.18/ MWh</td>
</tr>
<tr>
<td>Replacement Reserve (De-Synchronised)</td>
<td>€0.51 / MWh</td>
<td>£0.45/ MWh</td>
</tr>
</tbody>
</table>
Table 19: Irish Electricity Market Summary

<table>
<thead>
<tr>
<th></th>
<th>M €</th>
<th>% Market</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wholesale Market</td>
<td>2 900</td>
<td>100%</td>
</tr>
<tr>
<td>Capacity</td>
<td>530</td>
<td>18%</td>
</tr>
<tr>
<td>Imperfections</td>
<td>180</td>
<td>6%</td>
</tr>
<tr>
<td>Market Operation</td>
<td>25</td>
<td>1%</td>
</tr>
<tr>
<td>Services</td>
<td>55</td>
<td>2%</td>
</tr>
<tr>
<td>Energy</td>
<td>2 100</td>
<td>73%</td>
</tr>
</tbody>
</table>

5.4 Relation between ancillary services and adequacy of generation

The generation fleet providing ancillary services is depending on the future generation mix and how generation adequacy is managed. During times of low wind and low solar irradiation and without sufficient storage capacity and only limited demand side management, non-VG (conventional) generation will have to provide electricity and therefore needs to be maintained as a sort of “back-up” generation to guarantee power system generation adequacy. Due to shorter generation times non-VG power plants might not be able to recover their costs from an energy-only market. This is not only a threat to new investments but also larger utilities in particular with large share of thermal power plants claim that existing plants become unprofitable and need to be dismantled.

The availability of flexible system resources for provision of ancillary services should not be confused with the availability of sufficient capacity to provide energy to fulfil load under regimes of low wind and solar generation. Power markets often include various incentive schemes for the deployment of generation (and including renewable energy) and active loads which help to balance variable renewable energy. These incentive schemes include the EU ETS market, which can help to deploy low-carbon flexible gas fired generation, and incentive schemes for CHP, which can help to deploy flexible solutions for energy efficient CHP. Typically, under higher deployment rates of wind and solar, revenues of the balance of generation from energy-only markets significantly decline and hence do not provide sufficient level playing field for investments in the balance of generation. Many markets have capacity markets which provide opportunity to the balance of generation making them whole. Policy makers and regulators will need to assess optimal incentive schemes to drive deployment of generation and active loads which can help meeting energy and environmental targets, and to help integrating and balancing of variable renewable energy. These incentive schemes can be complementary to markets for ancillary services, but do not replace the need for well-functioning markets for ancillary services.
5.5 Identification of best practices in different countries

REserviceS case studies and research allowed identifying certain good practices and market rules that facilitate the provision of ancillary services from wind and solar PV. In addition, the cases of Belgium, Germany and the Nordic market provide examples of market arrangements that lower barriers for the participation of load and generation offering flexibility to support grid operation. Belgian and Nordic TSO market arrangements for balancing close to delivery time allow maximising flexibility from wind and solar PV generators. Markets in the UK and Ireland show enhanced transparency in technical requirements, procurement rules and reporting ancillary services use and payments.

Also, in Germany new players’ entry to the market is facilitated by clearly defined standard products, which are transparently contracted via a balancing service market platform.

In Italy a public consultation\textsuperscript{72} has been conducted in 2013 on three innovating procurement models representing three different pathways of coordinating the procurement of GSS for TSO and DSO operations (extended central dispatch; local DSO dispatch; scheduled program at TSO/DSO interface). Even if the models are not directly adaptable to other national or regional situation, they constitute a good example of new approaches for a multi-level and coordinated procurement by TSO and DSO of GSS provided by VG connected to the distribution level. The findings of this consultation should be considered when developing innovative procurement strategies.

Prospective plans from TSOs to enhance participation of VG in ancillary services provision are reinforcing the aforementioned examples. Germany is currently demonstrating the possibility to provide balancing power by wind energy and by virtual power plants with several renewable energy technologies. However, there is no plan to move these demonstration projects to the real market yet. The bid ladder proposed in Belgium and the Nordic balancing market are interesting instruments that would allow step-wise integration of renewables in the reserve power markets through VG-friendly rules such as:

a) offers until short before real-time
b) small minimum bid sizes
c) unavailability is penalised via standard imbalance fees.

\textsuperscript{72} AEEG, 2013.
**Frequency support services**

From REserviceS analysis and best practices, market design mechanisms for frequency support services should allow for the following:

- **Market-based remunerated provision:** The existence of TSO needs for different frequency support services, differing in activation time, length of provision, accuracy, etc. indicate the need for arrangements that ensure that services are provided cost-efficiently. A mandatory provision across all generators would mean that all assets may not be utilised efficiently at all times. In addition, generators providing such services would incur costs of design capabilities and delivery provision that otherwise would be included in the price of electricity. Last, frequency support services are fundamentally based on control of active power, being the basic commodity of the electricity market, with a set price which guarantees competition between participants and determines cost-efficient provision.

- **Clear technical requirements, prequalification procedures and procurement rules:** Detailed and clear specifications are of crucial importance for the participation of wind and solar PV in ancillary services provision. Without these, market participation and procurement of such services is delegated to incumbent generators with long-term contracts already in place. Real-time measurements of active power with high resolution (less than a minute) for verification of compliance may be limiting smaller VG to provide services. Aggregation of bids will be an important option in future and may also need new measures for procurement rules, for example allowing part of the providers’ response to be estimated inside an aggregated bid. As a best practice, requirements should be defined in close cooperation between the TSOs and possible service providers, including variable energy generators, via consultations, such as in Ireland.

- **Procurement gate closure times close to delivery:** The time elapsed between the gate closure and the delivery of frequency support is crucial to allow for cost-effective participation by wind and solar PV. The longer the time between procurement and delivery the more room for forecast errors occurrence and the less chance for VG to take part in the provision of services at reasonable costs.

- **Split of bids between upwards and downwards frequency support provision:** On the balancing markets, there is often a distinction made between symmetrical and asymmetrical products. Symmetrical products require both upward and downward power bids to be provided simultaneously. Asymmetrical products allow upward and downward bids to be offered separately. For VG, demand response but also CHPs it is often crucial to have the choice to either offer upward or downward demand. Participation of VG in reserves can reduce the overall need to curtail VG.

- **Aggregation of bids and offers:** Some balancing products in some markets can only be offered with single unit commitment. Allowing offers from a portfolio of aggregated units does not only give more flexibility to the providing parties, but also allows for the aggregation of very small units for relatively large offers. Aggregated offers also reduce variability and forecast errors from VG, hence increasing firmness of products. The aggregation could also be left with the TSO, which will then assess the uncertainty in the fully aggregated portfolio. This can further reduce the need for a margin.
**Cross-border exchange of services:** There is already experience of cross border trade of services in the balancing market (FRR manual) from the Nordic Regulating Power market. This exchange of services allows for greater geographical areas to be clustered lowering the needs for frequency support services by sharing resources across borders. In the Central European system the need for Frequency Containment Reserve is allocated between the countries.

**Voltage support services**
Voltage support services are more complex when it comes to procurement and market rules facilitating wind and solar PV participation. Reactive power has to be provided close to the point of demand. This limits the possible offers to generators located near the point where the service is required. When this service is mandatory for all generators connected to the grid, irrespectively of the location where the support is needed, and within certain reactive power set-points\(^73\), this causes investment costs (readiness costs) potentially to be stranded as the power system might not need such amount of reactive power.

The analysis performed by REserviceS identified as best practices for voltage support services:

- **Remunerated service provision:** In only a few countries analysed this practice is applied through a combination of full market-based tender processes and bilateral arrangements between generators, especially above certain capacity threshold (e.g. >100MW in GB), and TSOs. In most countries this service is mandatory without remuneration, but in Spain bonus and penalties are applied to generators not able to maintain a certain power factor that the TSO requires (TWENTIES, 2012).

- **Remuneration based on capability and utilisation:** TSOs recognising that the provision of voltage support is a combination of capability and utilisation get the most cost-efficient services from VG. In Ireland, remuneration is solely based on the capability of a reactive power range (in MVar) that can be provided across the full range of power active output (Maximum Generation – Minimum Generation) irrespective of the dispatched output from the generator. In GB, Default Payment Arrangements between generators and the TSO remunerate the Obligatory Reactive Power Service (ORPS) according to utilisation on a £/MVarh basis but an Enhanced Reactive Power Services (ERPS)\(^74\) rewards the provision of

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\(^73\) Strbac G., 2005

\(^74\) Enhanced Reactive Power Service is the provision of Voltage support which exceeds the minimum technical requirement of Obligatory Reactive Power Service (including Synchronous Compensation) or Reactive Power Capability from any other Plant or Apparatus which can generate or absorb Reactive Power (including Static Compensation equipment) that isn't required to provide the Obligatory Reactive Power Service. [http://www2.nationalgrid.com/UK/Services/Balancing-services/Reactive-power-services/Enhanced-Reactive-Power-Service/](http://www2.nationalgrid.com/UK/Services/Balancing-services/Reactive-power-services/Enhanced-Reactive-Power-Service/)
voltage support that exceeds the minimum technical requirement of the ORPS based on an available capability price (£/MVAr) and/or a synchronised capability price (£/MVAr) and/or a utilisation price (£/MVArh). In the latest reactive power market tender for contracts commencing on April 2014, power park modules and DC converters were allowed to bid for such ERPS.

- **Absorption or injection or reactive power differentiation:** Voltage support from generators is location specific, hence their capability and provision of voltage support either through injection or absorption of reactive power shall be distinguished (e.g. France).

- **DSO participation in the provision of services:** In France, the TSO operates compensation devices and in some cases reactors on its own network and compensation devices are connected on the MV bus bars of primary substation. They are operated by DSO within an agreement with the TSO. Only the first one is considered an AS and is subject to payment. Actual delivery of service is periodically checked. In the case studies analysed by REserviceS at distribution level in Spain and Germany, active participation of DSOs in managing voltage services in coordination with TSOs resulted in more efficient and less costly power system operation.

- **Aggregation and coordination of units for voltage support services:** Power systems allowing for aggregation of VG and coordinated approaches for voltage support by reactive power consumption or absorption, yield clear benefits to system operation such as reducing power losses or increasing DG hosting capacity. Coordinated control can be done locally by the DSO up to a central penetration rate, or centrally by TSOs when local control does not bring satisfactory results. When aggregating units, location, size of portfolio, regional spread and forecast horizon are key parameters to determine the optimum control strategy.

### 5.6 Key market design/ product adaptations for solar PV and wind to offer on ancillary service markets

#### 5.6.1 Suitable product characteristics for frequency support services

In the following the main dimensions of relevance for a frequency support product by renewable energies are discussed.

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75 http://www2.nationalgrid.com/WorkArea/DownloadAsset.aspx?id=28894
The contracting time before delivery of reserved products for frequency support needs to be shortened: tenders on daily or even shorter basis.

As there is a gate closure time for day-ahead and intraday trading also the procurement of reserve power products needs to be fixed at a certain point in time before delivery. The TSO needs this time buffer as a safety margin if the offer for reserve products is not sufficiently high and to allow for planning the operation of the reserve products once these are contracted. This time buffer is in general very different for the different “standard” products of FFR, FCR, FRR and in the different balancing zones depending on the technical situation, the need for demand, the communication hardware in place etc. Often the FCR is contracted with a far longer lead time as the technical pre-qualification requirements are significantly higher (often annual tendering), while in some market regions manual FRR/RR is procured on a daily or even more regular basis.

For the participation of RES in frequency support, smaller portfolios and a frequent tendering for shorter time frames is favorable. The uncertainty of VG influences how much can be offered and uncertainty decreases with shorter time horizons. Therefore tenders on e.g. daily or even shorter basis are a prerequisite for their participation.

Time for service provision availability should be small: preferably 1 hour or less.

Frequency support products are often requested in the form of a fixed band for relatively long time periods. In some markets and for some products (typically FFR) the products need to be hold ready during one year at any time. As output from VG varies, it can offer bids only when the time frame is sufficiently short. In particular PV power is only available during daytime.

The general recommendation is to reduce the product length significantly. For the automatically activated reserves, FCR and FRR, procuring part of the services with shorter markets, like used in Nordic countries today, is one option to open the possibility for VG.

Upwards and downward reserve products should be separated

For technical or economic reasons some plants and loads are either operated at maximum available power/load or are switched off/disconnected. This is also the case for most renewable energy sources that receive financial support. As the financial support is in general relatively high, the plants are operated at the maximum available power.

Other plants are either switched off or operated at full power and can therefore only provide upward or downward but not both services. E.g. a heat driven CHP plant usually runs at full power for heat production or is maintained at minimum load in order to avoid shutting down for a short period. It can therefore during certain hours only provide downward reserve and during others only upward reserve.

While some plants can be flexibly operated upward and downward as they can economically be run at partial load, other plants and consumption only can provide flexibility in one direction – either upward or downward – as e.g. technical requirements or other connected process request operation at full load or zero load operation.
**Allowing portfolio offers**

Allowing offers by portfolios of wind and PV (and/or other generation and demand) facilitate offers by PV and wind for the following reasons:

- Single PV systems and wind farms are often too small to allow offers above the minimum bid size.
- The forecast accuracy for larger and wide spread portfolios can be significantly higher from which both the bidder but also the contracting TSO would benefit. Of course it is important to discuss in how far the area across which the portfolio is split needs to be limited in order to have balancing power provisions where it is needed, how the TSO can have visibility of where the balancing power is provided within the portfolio and how the TSO can also steer balancing power provision in line with locational needs.
- Larger portfolios allow benefits from economy of scale.

**Reducing the minimum bid size**

For various products on the different national balancing markets the minimum bid size was historically designed for large central generation in order to limit the market settlement effort, the contracting effort, the control effort, etc. At the same time high minimum bid sizes often exclude renewables but also demand flexibility from participating in these markets.

**Confidence interval considerations for availability considerations**

Reserve power contracting is often based on the idea that the reserve power needs to be available with 100% probability. This already ignores the fact that also conventional power plants have unplanned outage probability and therefore also conventional power cannot offer reserve power with 100% certainty. For weather dependent renewables it is evident that future production has to be based on weather predictions and that the actual production might divert from the forecast.

If renewables are supposed to participate in balancing markets it is necessary that the balancing products are contracted taking into account potential unavailability. TSOs therefore should investigate in how far e.g. the concept of confidence intervals for future production can be integrated into reserve power contracting.

**Consideration of implementing a re-active market design**

As described above it might in general be valuable to evaluate the implementation of a reactive market approach that allows real-time balancing of the BRPs perimeters. Flexibilities of VG can then be used by the BRP manager in case they prove to be most cost-efficient. This would also reduce the need for reserve power for balancing by the TSO.
5.6.2 Suitable product characteristics for voltage support services

Voltage support services are like any other GSS valuable to the power system operator and incur cost for the power plant operator, therefore they should be reimbursed with a fee that is fixed by a competitive process, irrespective of whether this organized in a regular bidding process or an auctioning arrangement, whether the contracting is done for short time horizons like days to month or for longer time horizons up to several years.

The often taken approach of a tendering or auctioning process seems to be advisable as a possible option for remunerating voltage support services:

- 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.

As VG development is supported by policies which are increasingly incentivizing power systems integration, an alternative option could be to require voltage support by the grid code and to compensate the cost incurred directly through the support policies. This could be realised for instance by increasing slightly the valorisation of the fed in electricity or by reducing the connection cost. In countries such as Italy and Germany all distributed generation is requested to provide reactive power. To avoid tendering or an auctioning process with a few market participants only, a flexible regulatory framework should be established allowing DSOs to compensate VG systems directly through a fee or indirectly through lower connection or network tariffs to cover the additional capital costs of and additional losses due to the reactive power provision.

5.6.3 Suitable procurement models enabling TSO / DSO coordination of grid support services

To enable the provision of GSS by VG, a multi-level procurement process should be defined involving TSOs and DSOs, and generators connected to their networks. On the one hand, the participation of VG in a grid support services market - run by the TSO - could lead to violate constraints in the distribution grid. On the other hand, by solving local issues (congestion or voltage management) with GSS provided by VG, DSOs’ actions could have repercussive effects on the transmission grid operation. Given the
complexity of coordinating each tasks, a hierarchical definition of the supervision and control actions is necessary and a clear hierarchy of functions between TSO and DSOs has to be established\textsuperscript{76}.

5.7 Conclusions

In today’s energy-only market, predominantly dominated by synchronous generation, the contribution of ancillary services in the system costs and revenues to generators is very low compared to energy and capacity payments. As it is clear that VG can provide GSS and their utilisation can decrease operational costs of the power system, there should to be sufficient incentives to obtain these benefits along with the capability and availability requirements for VG. Currently, only a few markets (e.g. Ireland, GB system) provide arrangements for enhanced services where variable renewables are incentivised to participate. In future systems with high shares of VG, the ancillary services part will increase, even if it will remain a smaller part of total system costs and revenues.

Not all generators in a system need to provide ancillary services to ensure safe system operation. Thus, a mandatory request for ancillary services is often far from being cost-efficient. Market based remuneration on the other hand stimulates cost-reduction and incentivises the provision by plants providing the cheapest services, irrespective of whether these are renewable or conventional plants.

Detailed and clear specifications are of crucial importance for the participation of wind and solar PV in GSS provision. Without these, market participation and procurement of such services is delegated to incumbent generators with long-term contracts already in place. Requirements should be defined in close cooperation between the network operators and VG industry via consultations, such as in Ireland.

To enable the provision of GSS by VG, a multi-level procurement process should be defined involving TSOs and DSOs, and generators connected to their networks. On the one hand, the participation of VG in a grid support services market - run by the TSO - could lead to violate constraints in the distribution grid. On the other hand, by solving local issues (congestion or voltage management) with GSS provided by VG, DSOs’ actions could have repercussive effects on the transmission grid operation. Given the complexity of coordinating each tasks, a hierarchical definition of the supervision and control actions is necessary and a clear hierarchy of functions between TSO and DSOs has to be established.

In order to enable full utilisation of the capabilities of VG for the provision of GSS, the design of markets and products should be adapted to take into account the characteristics of VG. Characteristics of

\textsuperscript{76} Delfanti et al., 2014
‘service’ products such as separation of bids up from downwards, inclusion of confidence intervals and aggregated bids and offers are fundamental for allowing wind and solar PV to participate cost-effectively in grid support services provision.

- As a first step, the TSO should allow a certain amount of balancing power to be offered with a confidence tag stating the probability of the offered power.

- For smaller systems or for smaller portfolios of variable renewables, the minimum bid size is crucial for entering the market or not. Although low minimum bid sizes have the downside for the TSO that non-automated management of the portfolio of small bids can be highly complex, their advantage is that the increased competition in the market may reduce procurement costs.

- The time elapsed between the gate closure and the delivery of frequency support is crucial to allow for wind and PV cost-effective participation, and should be as short as possible. The longer the time between procurement and delivery, the more room for forecast errors occurrence and the chance for VG to take part in the provision of services at reasonable costs becomes lower.

- The products for reserve power provision by wind and solar PV should have short blocks of a few hours or even blocks of less than one hour, as VG is constrained in offering to the reserve market due to weather dependency, for example at night and/or at too low or too high wind. Furthermore, future production can only be predicted with an accuracy that decreases with increasing forecast horizon, resulting in actual production deviating from forecast.

- All products should be split in upwards and downwards products. PV and wind would be able to offer downward reserves at relatively low costs. Apart from wind also other flexible resources and demand in the power system would benefit from such product design.

- In order to enable cost-efficient offers with high certainty, solar PV and wind need to offer reserve products from aggregated portfolios of several PV and wind plants spread across wider areas. The general allowance to offer reserve products with portfolios would significantly facilitate the participation of renewables.

- It might in general be valuable to evaluate the implementation of a reactive market approach that allows real-time balancing of the BRPs perimeters. Flexibilities of VG can then be used by the BRP manager in case they prove to be most cost-efficient. This would also reduce the need for reserve power for balancing by the TSO.

Voltage support services incur costs for the VG plant operator and, being of value for the system operator (TSO, DSO), they should be reimbursed with a fee that is fixed by a competitive process, e.g. regular bidding process, auctioning arrangement or contracting for short or long time horizons. The often taken approach of a tendering or auctioning process seems to be advisable as a possible option for remunerating voltage support services. An alternative option could be to require voltage support by the grid code and to compensate the cost incurred directly through the support policies. DSOs should then be enabled by a suitable regulatory framework to compensate VG systems directly through a fee.
or indirectly through lower connection or network tariffs to cover the additional capital costs of and additional losses due to the reactive power provision.
6 KNOWLEDGE GAPS AND NEEDS FOR FURTHER RESEARCH

6.1 Introduction

This chapter identifies knowledge gaps and future R&D needs based on the aspects presented in the previous chapters, complemented by literature sources. The identified knowledge gaps were compared against a survey addressed to the project partners and the REserviceS Advisory Board.

The structure of the chapter follows the main structure of this report. The principal areas where knowledge gaps and needs for future R&D are identified include:

- Power system needs;
- Wind and solar PV technologies;
- Aspects related to economics (costs and benefits);
- Electricity market design.

6.2 Knowledge gaps

6.2.1 System needs for ancillary services

Assessing the system needs for ancillary services is a task that TSO’s deal with routinely and have an important experience with. With power systems shifting towards high penetration level of VG, the tools and methodologies used in assessing the system (operator) needs for services require adaptations. An important aspect is the development of methodologies for taking into account the impact of uncertainty associated with VG on the system needs, as well as development of new tools and strategies for operation of systems with uncertainties.

Wind and solar PV are now mainly considered in studies related to system and network planning, i.e. TYNDP plans and so on. Especially the combined effects of wind and solar PV in terms of AS is an area that needs more knowledge.

Similarly, there is a need of investigating the need and opportunity of new AS delivered by VG, such as Quitmann:

- Phase imbalance – negative sequence provision
- Harmonics content – active filtering
- System oscillations – power oscillation damping
Situations with low inertia would benefit from very fast frequency response as demonstrated by REserviceS WP5. While thermal power plants are limited in the time scale of hundreds of milliseconds, VG can react in that time scale. It may be worth considering a frequency response product that is even faster than the 2 second FFR proposed in Ireland.

The definition of those services, as well as their impact on the power system needs to be investigated, leading to the need of developing methods and tools power system models able to capture different operational time scales, i.e. models focusing on electromechanical dynamics (20 ms ... 30s), focusing on system balancing (5 min ... 24h), focusing on frequency quality for services such as FCR and FRR (s ... min), for power system with high variability. This need is highlighted in the ENTSO-E R&D Roadmap (R&D roadmap milestones 7 and 8).

Another area where knowledge gaps were identified is in enhancing the TSO/DSO interaction, with several points standing out:

- Increased observability of the distribution systems for transmission network management;
- Ancillary services provided through DSO and aggregators;
- Demonstration of power load control mechanisms at TSO and DSO levels;
- Improved defense and restoration plans;
- Integration of demand side management at DSO level into TSO operation;
- Mandatory requirements versus remunerated services? R&D needed to determine suitable assessment method at DSO level.

6.2.2 Technology

As explained in Chapter 3 and further substantiated in Faiella, 2013\textsuperscript{77} and Kreutzkamp, 2013\textsuperscript{78} both wind and solar PV are today technically capable of providing frequency and voltage support, as well as for part of the functionalities required in system restoration. For frequency and voltage support, no critical technical gaps preventing them from supplying these services were found. However, there are several issues that require a better understanding and in depth investigation.

\textsuperscript{77} Faiella, 2013
\textsuperscript{78} Kreutzkamp, 2013

REserviceS D7.1 Synthesis report
**Wind**

Wind turbines are designed for specific load cases, as prescribed in international standards (e.g. IEC 61400-1 for onshore wind turbines and IEC 61400-3 for offshore wind turbines). Some of the proposed ancillary services would require wind turbines to operate in dynamic regimes that were not specifically accounted for in the design. Therefore, there is a need of studying and better understanding the potential impact that AS operation modes could have on the wind turbine design (structural, mechanical, electrical, control and protection).

Control plays a crucial role in the capability of wind power to deliver AS with the required performances, i.e. response time, firmness of response, etc. There is a clear need for further development of advanced control strategies that are focused on AS delivery, especially at wind farm/cluster level. Traditionally, wind power control is optimised at wind turbine level. However, the grid code requirements are typically defined at the point of common coupling, requiring an additional control level, i.e. at wind farm/cluster level, that will optimise the overall wind farm/cluster performance, by, for example, calculating and distributing individual wind turbine set-points that take into account the interaction between wind turbines. This way, the overall wind farm/cluster performance can be optimised.

Fast and reliable communication are crucial in delivering fast services like FCR and FFR especially at wind farm/cluster level, necessary for being able to deliver a coordinated, optimised and centralised response. Requirements and standards for the communication systems are not established, further work being needed in defining them. Furthermore, most of the communications systems used in wind farms today are proprietary systems that are not inter-compatible within the industrial community.

From an operational point of view, an improvement of the accuracy of estimation of the possible (available) power – when operating in de-rated mode – is needed. This estimation needs to be reliable and accurate so that the confidence in the ability of wind power to deliver AS when needed and with the expected volume is increased.

The development of offshore wind power, especially in Northern Europe, implies connecting wind power using HVDC technology. This could lead to the development of a full scale offshore grid with DC that would connect to (and operate in-between) the onshore AC grids. To this end, there is a clear need of better understanding of the technical requirements and the control strategies for wind power operating in hybrid AC and DC multi-terminal networks.

The possibility of including VG in the restoration process of the power system level is a subject that is receiving increased attention. However, the issue is at a very incipient stage and there is an important need for more knowledge regarding the technical requirements and operational practices for wind to be included in restoration processes.
Solar PV
Any type of frequency support provided by PV technology requires active power dermalment or additional dispatchable power, meaning storage, or to operate PV systems below the MPP (a sort of fixed curtailment). In all cases there is still lack of concrete knowledge and experience as regards the feasibility of frequency support. Moreover the economic impact of applying the different options for PV based frequency support needs further investigation (considering also the extra devices and respective OPEX). The subject has been studied mostly with help of simulations, however no real study cases of wider scale exist that can provide a secure benchmark for replicating the results. Considering the complexity of the subject (dynamics of the PV technology, the local specificities and the different costs related and their volatility), further in-depth investigation is a huge task. However, with continuously increasing PV and VG penetration R&D efforts also with a TSO perspective (besides the DSO) are more than justified. This would additionally involve feasibility studies for storage solutions, aggregation techniques, optimum spread of DG, complementarities of wind and PV and annual impact on the profitability of PV when down regulated should take place at local and wider scale.

Although different methods and techniques have already been technically assessed in terms of capability in different countries and under different requirements, there is still experience to be gained as regards the cost-benefit mainly by real system operation.

Static voltage support by reactive power provision is already included as technical requirement in different grid codes, however the actual effects of reactive power provision on the grid voltage depend very strongly on the specificities of the feeder and the load pattern. Furthermore, depending on the system size, other solutions (such as STATCOM) have shown more benefits, meaning that there is still need for further analysis to provide more insight in possible cost-effective control strategies and to reduce the knowledge gaps.

This would include a more detailed economic assessment for optimally dimensioning the inverter to increase reactive power availability (CAPEX and losses).

Just like for wind power, research is needed into possible contributions of “solar PV in system restoration especially for scenarios with high VG penetration. In addition to ongoing research on the technical feasibility of black start service with high shares of PV (storage and other VG), the economical aspect need more in-depth investigation. Regarding islanding in particular, the behavior of the inverter (especially the self-commutated) during the fault and the current detection methods of islanding used by the inverters (introducing disturbances) are issues to be further examined.
dedicated cluster on market designs. In the REserviceS project, several knowledge gaps regarding market design and cost reductions were identified:

- Studies regarding coupling of energy and ancillary service procurement at European level
- Bottom-up engineering assessment needed to improve the estimates about current costs and cost reduction potentials.
- Design of markets and products that take into account the characteristics of variable renewables, including optimisation of gate closure times in relation to the service providing assets and the power system needs (e.g. uncertainty of VG, start-up times of thermal power plants, inertia of the power system)
- Large scale market models able to capture the complex market interactions across Europe, including the cross-border interactions
- Need of detailed and clear specifications for the participation of wind and solar PV in ancillary service provision
- Interplay between ancillary service markets, energy markets and possible capacity markets. How to mitigate issues in different time scales without causing unintended consequences in other time scales?
- To what extent and in what manner localised rules should be applied? It is clear that e.g. the power system in the island of Ireland is very different from central European power system in many ways.

6.3 R&D needs

In order to facilitate the integration of VG into the power system maintaining (or even increase) the stable, reliable and adequate operation of the power system, several R&D needs were identified. The proposed R&D needs are compared against other known R&D agendas, such as ENTSO-E R&D Roadmap [9], the Strategic Research Agenda published by TP Wind⁷⁹ and the Research and Innovation Roadmap of the European Electricity Grids Initiative⁸⁰.

6.3.1 System needs

Several research subjects were identified:

⁷⁹ Europex, 2012
⁸⁰ AEEG, 2013
• Development of methods and tools for power system (transmission and distribution level) planning able to include the stochastic nature of VG using probabilistic approaches. This is well in-line with the present research agendas, being included in the ENTSO-E R&D Roadmap. This aspect is, at present, included to some extent in research initiative such as the GARPUR project\textsuperscript{81}, but the subject is large and should be included in future R&D initiatives.

• Role of VG in system restoration services. This subject is partially investigated in ongoing research initiatives such as iTESLA project\textsuperscript{82}, however, given the very early stage of investigation, the issue should be part of further research efforts.

• Definition (technical and economic) of new system services and study their impact on the system. At the present, most of the attention is directed towards enhancing the capability of VG to provide ancillary services. However, those services are mainly the traditional ones, deriving from the needs of a power system dominated by synchronous generators. While this is very understandable and cautious, the need of looking at new services – that will derive from the traditional ones, but also include completely new ones such as the ones mentioned in the knowledge gaps part – should be a R&D priority.

• Common methodology for system needs of ancillary services with large amounts of VG

• Optimisation strategies for AS provision from portfolio of ML/LV systems (PV and small wind farms).

6.3.2 Technology

As presented in Chapter 3, both wind and solar PV technologies are able to provide ancillary services today. To this end, the main research needs are directed towards enhancing those capabilities and/or improving the economics of it. This research need has also been identified in the TPWind strategic research agenda. In the following, an overview of the identified research needs, presented relative to the ancillary services considered, is given.

Frequency

In general for frequency support:

• Reduce hardware-additional-costs / research on cost-benefit

• Develop enhanced communication techniques and standards to align with the system requirements

\textsuperscript{81} \url{www.garpur-project.eu}  
\textsuperscript{82} \url{www.itesla-project.eu}
• Develop necessary supportive software (for communication)
• Develop PV portfolio control strategies
• Develop necessary software for forecasting techniques (considering confidence intervals)

**FCR:**
• Develop software for facilitating control modes

**FRR, RR, RM:**
• Develop enhanced day ahead and intraday forecasting strategies

**Voltage**
Normal operation (Static voltage support):
• Assess under CBA criteria night-time reactive power provision and adequate design changes

**FRCI:**
• Develop new software and necessary hardware for faster response
• Assess the need and the benefits to apply FRCI in the LV

**System restoration**
The capability of wind and solar PV to control both frequency and voltage means that they could participate in system restoration services. However, there are several aspects that need to be investigated, also highlighted in the ENTSO-E R&D Roadmap:
• Control requirements and settings for VG to participate in system restoration
• Operational procedures for VG to participate in system restoration
• Quantification and mitigation of the uncertainties of VG operation in case of system restoration
• Participation of HVDC connected offshore wind power in system restoration processes

Development of tools for system restoration including forecasting of wind and solar PV

### 6.4 Conclusions
Several aspects with knowledge gaps were identified and, consequently, translated into research needs. As a general remark, streamlined and consistent R&D efforts will play a determining role in the timely and effective enhancement of VG in providing ancillary services.

These identified research needs link with several other activities at European level:
- ENTSO-E R&D Roadmap 2013 – 2022, published in 2013, that evaluates Europe’s energy policy goals (as defined in the so-called EU “20-20-20” targets and in the European Commission’s Energy Roadmap 2050) and describes the challenges and opportunities they represent for TSOs. Additionally, it focuses on the development of the pan-European transmission grid and completion of the IEM.

- The Strategic Research Agenda of the Wind Technology Platform, published in March 2014, that highlights the R&R engagements necessary to achieve reduction of the cost of energy, onshore and offshore, over the next 20 years

- European Electricity Grid Initiative Research and Innovation Roadmap 2013 – 2022, published in March 2014, that presents the common TSO and DSO views regarding the R&I and knowledge needs for the electricity grids of the future.
7 OVERALL CONCLUSIONS OF THE RESERVICES PROJECT

The REserviceS project has made an assessment of the provision of grid support services in future power systems with high shares of variable generation (VG). It focused on service provision by wind and solar PV. The objective was to contribute to conceptual thinking about electricity market mechanisms enabling an adequate, cost-effective and financially feasible participation of variable generation in frequency and voltage support in European transmission and distribution systems.

An analysis was made of system needs for grid support services for frequency and voltage management when shares of renewables become very high. Based on a selected set of frequency and voltage services, an in depth analysis has been made about existing capabilities in the wind and solar PV technologies. An assessment of technical issues as well as challenges for enhanced service provision has been made as well. An inventory of the costs (CAPEX and OPEX) has been made for both technologies – especially in view of cost estimates when deploying frequency and voltage services in an enhanced way when system needs increase due to higher shares of VG. As the existing information and knowledge on a possible participation of VG in system restoration is still very limited, the project has not looked into detail in this subject, and mainly formulated some recommendations for future work.

Case studies involving simulations and economic analysis in different transmission and distribution network scenarios with high shares of VG have been performed, providing insights in technical challenges of massive deployment of services and economic benefits for the power systems as well. It appeared that performing cost benefit analysis in distribution networks is highly case specific and making generalised conclusions for voltage services was not really possible. The project did not address in depth the potential of VG connected at distribution level to provide flexibility, not only for congestion management but also for balancing the system. This alternative should be further investigated in order to set the required coordination amongst TSOs and DSOs to enable it.

An assessment of current electricity market characteristics and trends in Europe, focusing on opportunities for ancillary services, together with the specific characteristics of large scale deployed VG enabled to identify suitable market and product characteristics for frequency support services by wind and solar PV. While various pre-conditions and possibilities could be identified for frequency support services by VG connected at TS level, it appeared not possible in the project to address these aspects in as much detail for voltage services especially at DS level as well as for TSO/DSO coordination, as this subject appears to be highly complex and requires further studies.

Finally, based on an internal survey in the consortium as well as in the Project Advisory Board, an inventory has been made of needs for further R&D effort, in the area of power systems, solar PV and wind technologies, and market design.
8 LITERATURE REFERENCES

Chapter 2


[4] ENTSO-E NC for Demand Connection


Chapter 3


[40] Ahlstrom et al., Knowledge Is Power. IEEE power & energy magazine. Issue NOV/DEC 2013, p.45-52


Chapter 4


Chapter 5


[72] AEEG, DCO 354/2013/R/eel “Possible models for the procurement of innovative ancillary services from RES and DG plants”. http://www.autorita.energia.it/allegati/docs/13/354-13all.pdf (Italian only). 2013

[7] Siemens, “Siemens Reactive Power at No Wind - Support the grid even when the wind is not blowing”.


[76] Delfanti and al, “The new role of DSOs: Ancillary services from RES towards a local dispatch”. CIRED Workshop, June 2014

Chapter 6

[77-78] REserviceS D4.1 ‘Technical capabilities of solar PV to deliver grid support services’.


9 LIST OF RESERVICES REPORTS (DELIVERABLES)

System needs for ancillary services
D2.2 Ancillary services: technical specifications, system needs and costs
D2.1 System needs for ancillary services: table
D2.3 Ancillary services costs for different services and different conventional generators
D2.3 Annex: template for costs table

Wind and PV ancillary services capabilities and costs
D3.1 Capabilities and costs for ancillary services provision by wind power plants
D3.1 Annexes: questionnaire, interview questions, grid code parameters
D4.1 Capabilities and costs for ancillary services provision by PV systems
D4.2 Annex: overview of costs and cost models

Wind and PV ancillary services in future systems – Case Studies

- Transmission level: European, Iberia, Ireland, Offshore
  D5.1 Onshore wind supporting the Irish grid – Ireland case study
  D5.2 Offshore wind providing grid support services – Offshore case study
  D5.3 Grid support services at the Iberian Peninsula – Iberia case study
  D5.4 European case study – Frequency reserves from wind power and PV in a large footprint
  D5.5 Full evaluation and conclusions of the transmission system case studies

- Distribution level: Germany, Italy, Spain (2), Portugal
  D6.1 Distribution case study scenarios – definition and assessment procedures
  D6.2 Provision of ancillary services by wind and solar PV to the Spanish, Italian, Portuguese and German market

REserviceS D7.1 Synthesis report
Recommendations for a future EU market for ancillary services
D7.1 Full Synthesis Report

D7.2 Full Recommendations

Final Publication

D8.9 Final Publication