D5.3 Iberian test case

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In the revision Chapter 5.1 has been updated with new model results. Accordingly discussion and conclusions have been modified to reflect the lower benefits of VG participation in the frequency reserves.

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(REserviceS, Deliverable D5.3, Iberian case)
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LIST OF ABBREVIATIONS

AGC  Automatic Generation Control
CE   Central Europe (regional group of ENTSO-E)
ENTSO-E European Network of Transmission System Operators for Electricity
FCR  Frequency Containment Reserve (primary reserve)
FFR  Fast Frequency Response
FRR  Frequency Restoration Reserve (secondary reserve)
FRCI Fast Reactive Current Injection
VG   Variable Generation (wind power and PV)
RM   Ramping Margin
RR   Replacement Reserve (tertiary reserve)
RoCoF Rate of Change of Frequency
RoCE Rest of Central Europe (Central Europe without Iberian Peninsula)
RR   Replacement Reserve
SNSP System Non-Synchronous Penetration
SSVC Steady State Voltage Control
TSO  Transmission System Operator
UC   Unit Commitment
WP5  Work Package 5 of the REserviceS project

DEFINITIONS

Frequency nadir Lowest frequency value between a fault and a recovery
WILMAR Unit commitment and dispatch model used in the study
SUMMARY

The Iberian case study in the REserviceS project has studied the provision of ancillary services from wind power and PV (variable generation). The case study informs about the services at the transmission level in a medium size power system with limited interconnection to the central European system. For frequency related ancillary services a unit commitment and dispatch model (WILMAR) was used to evaluate the economic benefits of having and using the capability from variable generation to provide frequency reserves. In addition, a set of one year of hourly dispatches was further evaluated in a frequency response model, which simulated a post-fault frequency response of the Iberian power system linked to the Central European power system. Existing studies on voltage control by wind power plants in Spain are also reported as evidence for provision of ancillary services for voltage management on transmission level.

Using variable generation to provide frequency reserves and response can yield considerable cost savings in power system operations:

- At the current level of wind power and PV in Iberia, with a combined share at around 21% of annual energy, the simulations show a level of operational benefits that could justify additional investments to make some VG units capable of providing frequency reserves.
- At 32% share, the operational benefits are shown to be high enough to justify equipping all VG units with the frequency response capability.
- At 42% annual energy penetration of variable generation, the simulations show benefits of variable generation in providing frequency reserves and response to be much higher than the annualised investment costs.

However, the results also show that it is not necessary to have all VG units capable of providing frequency reserves.

The frequency response with wind power and PV is demonstrated to be good and in some situations even better than with conventional power plants. Since Iberia is synchronously connected with central Europe, the inertia in the system was adequate in the simulated cases and as a consequence frequency remained within limits and or the rate of change of the frequency was not too fast. Furthermore, the response would be adequate also if only a portion of the installed variable generation capacity was capable of providing the frequency reserves. However, the frequency response model was not based on a full power system model and further studies are required to rule out e.g. interregional oscillations.

A review of experience and project results provided by the Iberian transmission system operators has revealed that wind power plants in the Iberian Peninsula have been demonstrated to perform an adequate dynamic voltage control based on monitoring voltage set-points. The impact of voltage control by wind power plants on the specific transmission nodes has been significant and response from wind power plants has been fast and suitable for local system voltage management by the TSO. No oscillations or instabilities were identified in the reported studies. At low wind power production levels (10-20 % of rated power), a significant reduction in the capacity of generation/absorption of reactive power was noticed if power factor set-points were used, and it is recommended to use reactive power set-points instead.
1. INTRODUCTION

This report is part of the REserviceS EU project (http://www.reservices-project.eu/), studying how ancillary services could be attained from wind and solar power plants. As the penetration levels of variable renewables increase, there is need for more services for frequency and voltage support. If wind and solar can provide these services in a cost effective way, it will reduce the number of conventional power plants required by the power system during high wind and solar hours, thus reducing the need for variable generation curtailments.

The purpose of the case studies in the REserviceS work package 5 (WP5) is to assess – from technical and economic point of view - how the ancillary services from variable renewables can be used in transmission system, together with ancillary services available from conventional generation. This case study looks at the Iberian power system (Spain and Portugal); In the project there are complementing case studies for a small system (Ireland), and for a larger system, covering a large part of Europe (based on the TWENTIES EU project). The Iberian system study will bridge the gap between the results of the Irish case (reference D5.1) and the European case reference D5.4. It can improve the confidence in the applicability of the results from the European case. It will also be possible to assess the validity of the results by comparing against current operating experiences in the Iberian system which already has a considerable wind power and solar PV penetration. The validation is made by running a scenario based on the year 2012 in WILMAR and comparing with real experience on the Iberian system. Results from the past studies on ancillary services provision by renewables made in the Spanish and Portuguese power systems have been collected in chapter 2 regarding both impacts on balancing and frequency control and voltage control (results for active grid management by clustered wind farms tested in Spain).

The aim of this case study was to analyse the following:

- Reservation of different power plants for primary and secondary frequency control (Frequency Containment Reserve FCR and Frequency Restoration Reserve FRR - automatically activated part);
- The use of power plants for tertiary frequency control (manual FRR and Replacement Reserve RR) including the possible contribution from wind and solar power;
- The impacts of cross border reserve sharing;
- Amount of inertia in the system, compared against requirements for inertia.

In addition to the frequency related results, a review of Spanish voltage support tests by clustered wind farms was made.

The simulations were performed using the WILMAR planning tool. WILMAR is a unit commitment and dispatch (market simulator) model that can be used to determine the hourly energy balance from conventional generators and from wind and solar generation. The model was required to procure necessary reserves also for intra-hour operation (fast reserves for FCR and automatic FRR); and thus the approach can calculate the ancillary services costs due to uncertainty in wind power, solar PV, and electricity demand while ensuring a desired level of generation reliability.

The work in the WP5 of the project is based on the results from the previous work packages:

- WP2: pointed out the frequency and voltage support services with highest relevance and need for further study. WP2 also provided availability and costs of ancillary services from conventional power.
• WPs 3 and 4: provided availability and costs of ancillary services from wind and solar PV. Possibilities for providing frequency response from wind turbines and PV was based on WP3 and WP4.

• WP6: case studies provide information on the feasibility of using the services from distribution level generators in total system / transmission level simulations. This case study assumes that wind and PV ancillary services can be used as optimised by the WILMAR tool.

Input data for the WILMAR planning tool for conventional generators were based on literature sources and network constraints within Iberia estimated from the publicly available grid data. Time series data on wind power, solar PV and electricity demand were collected from TSOs (transmission system operators) and other sources which are specified in Section 3.2. Year 2012 time series data was used in the simulations as profile data. Using more years would decrease the uncertainty of the results, but the initial set of simulations took all time allocated for the case study so this was not feasible. Due to lack of time series forecast data for PV, the analysis for the utilisation of tertiary reserves (manually activated FRR and RR) was made in a case with wind power only.

Since there are only small amounts of network constraints within the Iberian system, the impacts of cross border reserve sharing were not studied in this case study. Cross border reserve sharing is studied in the European case.

While the provision of the frequency control services is based on the WILMAR simulations, the adequacy of the frequency response is verified with a model built with Matlab/Simulink (sections 3.5 and 5.2).
2. SURVEY OF EXISTING IBERIAN RESEARCH ABOUT VARIABLE GENERATION IN ANCILLARY SERVICES

Spain and Portugal are both among systems operated with the highest penetration levels of variable generation (VG) in the world. The penetration levels exceed 20 % of yearly electricity consumption from VG, and wind power is the majority of this (20 % of annual consumption in Portugal and 18 % in Spain in 2012 (REN 2013 and REE 2013)). In Spain the installed power capacity from renewable sources adds up to 30 GW, out of which 20 GW are from wind generation.

To manage high penetration of variable generation, the system operators of both countries have access to on-line generation data from most of the wind and large solar plants, and use wind power/PV forecasting in their control room operations. They have implemented fault-ride-through requirements in the Grid Code. They have also required retrofits to "older" plants, to ensure that large amounts of wind and PV power plants will not trip in cases of short disturbances in the grid.

In Spain, curtailments of wind power due to inability to maintain power balancing have occurred since 2008 (when penetration exceeded 10 %) and they have slowly been increasing (0.5 % of total wind generation curtailed due to excess generation in the system during off-peak hours in 2010, with >16 % penetration). Retrofits of Fault-ride-through capabilities were required by Grid code published in 2007. As a consequence, preventive production curtailments have not been required since 2008 due to the lack of fault ride through capability of wind power plants (Holttinen et al, 2011). In Portugal, wind power has been providing close to all load during some hours without the need of curtailments, due to access to flexible hydro power and the possibility to export to Spain (Ribeiro, 2012).

2.1. Frequency support

Experience on system reserves for frequency management in the various time domains has been reported for Spain in (Gil et al, 2009):

- The amount of wind on the system has no impact on the calculation of primary reserve requirements. This is because the variability of aggregated wind capacity in 30 s time scale is limited; larger variations that could occur due to voltage dips have been mitigated by fault-ride-through capability of the turbines.
- Secondary (automatic, AGC) and tertiary (manually activated) reserves have been moderately impacted by wind power.
- The largest impact of wind has been an increase in the manually activated frequency control (Frequency restoration reserve FRR, in Spain called “running reserve”) that operates in a time frame that is shorter than connecting new thermal power plants to the grid.
- Reserve allocation has so far been made based on a simple rule summing up possible deviations from largest outage, load deviation and wind deviation: 2 % of anticipated load level and 85 % of possible forecast error from wind is added to largest unit (1100 MW). Dynamic reserve allocation based on probabilistic forecasts of wind has been tested and is currently being used in parallel by the system operator REE. The first results reported in (Gil et al, 2009) show that the dynamic reserve allocation has provided enough reserves, and has been lower than the more simple rule-based method currently in use.

Wind generation is not (yet) providing reserves in Spain. A new upward reserve market to cover wind power forecast errors and other deviations has been operational since May 2012. It contracts balancing reserves in advance without impacting the day-ahead market and incentivizes flexible CCGTs to participate in the balancing by remaining hot, but offline.
In the TWENTIES project a demonstration SYSERWIND was made to prove that it is technically feasible to provide active-power control by an aggregation of wind power plants. A total of 15 wind power plants took part in the demonstration, providing secondary control according to the rules of the system operator REE. A +/- 20 MW regulation band was provided, with a central point at 100 MW using 7 wind power plants. Currently power plants need to make day-ahead bids for this service. For wind power this would mean considerable amounts of spilled energy. It was therefore concluded that wind energy would need a short term market – almost in real time – or to offer these upward reserves only once wind generation has been curtailed due to technical constraints, or being able just to offer downward reserve.

TWENTIES project also estimated economic benefits. FCR provision from wind power plants was evaluated for the Spanish system. Updating the wind parks with the desired technology for FCR provision was estimated to incur a cost of around 3000 €/MW. In the REserviceS deliverable 4.1 similar cost for clusters of wind power plants was estimated at 1000 €/MW and for individual turbines at 7000 €/MW. Updating the whole Spanish wind fleet by 2020 would incur an annualised investment cost of 5.1 M€/year, compared to the annual cost savings estimated at around 83 M€. (TWENTIES 2013). The simulations for a 2020 scenario for Spain (with almost 35 GW of wind power) showed a 1.1% reduction in system operational costs when using active power control by wind power plants. Most of the obtained cost savings are explained by the usage of wind generation to provide downward reserve instead of conventional thermal generation. Wind down reserve accounted for 11.8% of total down reserve requirements. There was also benefit from lower upreserve requirements during peak hours. The benefits would increase at higher levels of wind power, when there are more curtailment needs. With 38 GW wind the reduction of operational costs was estimated to be more than 6 %. Benefits would also increase in cases when reserve’s constraints highly influence the resulting generation scheduling (Twenties, 2013).

In Portugal wind power is already taken into account when reserves are allocated. “The 6 hours ahead forecast error for wind power can be 20% of the produced energy. However, the error is lower (around 10 %) when wind power is producing at high levels. Because of that the reserve requirement/allocation has been increased by 10% of predicted wind power. That is managed by existing hydro and thermal power plants, and occasionally by reducing import from Spain” (Ribeiro, 2012). Also dynamic reserve allocation has been tested in Portugal. In a demonstration by INESC for system operator REN they found days where the suggested reserve was high compared to the deterministic rules (Bessa et al., 2012) and also days where the suggested reserve in one direction was quite low compared to deterministic rules (Bessa et al., 2012b). Results depend on the rules used by the TSO and the resulting risk levels. If simple rules are used that allow higher risk and thus less reserve, it can be expected that the reserve from the dynamic tool is always higher. Usually a static rule will produce reserve allocation where the risk will be different for different days whereas a dynamic probabilistic reserve setting is based on holding the risk constant. A further evolution would consider the value at risk, but this is often difficult to estimate.
2.2. Voltage support

Regarding voltage control, requirements of (steady state) reactive power exist in many countries. Previous experience from Spain and Portugal shows that in some cases requiring or incentivizing constant reactive power or power factor does not support the system in all events. Due to this, less rigid rules have been implemented (RD 1565/2010). In Spain requirements are set for power factor control which for units larger than 10 MW can be changed by REE if values other than a power factor of 1 are more beneficial for the network.

Demonstration of coordinated voltage control from wind power plants in the TWENTIES project is presented in more detail in the following section.

2.3. Voltage control field tests with clustered wind power plants

Due to high share of variable renewables, the Spanish TSO has proposed new procedures for wind generation to provide dynamic voltage control. At present, variable renewable generation provide only reactive power factor control within values pre-set by the regulation, which can be modified by the TSO for power plants larger than 10 MW, when necessary. As a result, managing the grid voltage profile is becoming increasingly difficult, especially during off-peak hours. In order to enable increasing wind penetration levels in a safe, reliable manner, the Spanish TSO is studying the implementation in the near future of new requirements to supply voltage control. In such new requirement, the TSO sends voltage set-points at a transmission substation level in real-time and the variable renewable installations have to modify their reactive power production in proportion to the difference between the actual voltage and the set-point, according to the proposed revision of Operating Procedure PO 12.2.

In order to verify the performance of the new proposal for voltage control and its impact on system stability, the Spanish TSO proposed a series of field test campaigns at certain nodes of the transmission system (Arlabán et al. 2011 and Arlabán et al. 2012).

One of these tests was performed in the 400-kV node of the Morella substation (located in in South East Spain, illustrated in Figure 1), comprising of 9 wind farm hubs connecting to this node with an overall capacity of 395 MW owned by Acciona Energía, each one composed of wind turbines with doubly fed induction generators (DFIG) technology.
In the business as usual case of the Morella 400-kV node, apart from the pre-set power factor maintained by each wind power plant, the only real voltage control means is based on the discrete tap changing of the main power transformer. The tested voltage control functionalities demonstrated the wind power plants capabilities to enhance the controllability of the voltage profile at the transmission node as well as to provide dynamic voltage support (adaptable according to system needs), which are not available through the discrete tap changing scheme. These benefits have been acknowledged by the Spanish TSO (Arlabán et al. 2011 and Arlabán et al. 2012).

Figure 2 shows a transition from low to medium active power generation obtained during one of the tests performed at the Morella node with a fixed voltage set point. The following has to be remarked:

- Measured voltage remains always in allowable limits (note that voltage controllers are based on proportional control and therefore there is always a steady state voltage error);
- When active power generation decreases the reactive power generation also decreases almost down to zero, and so the measured voltage raises (increasing voltage error). The wind power plant voltage controller sent power factor set points instead of reactive power set points to the wind turbines. When medium and high active power rates are produced then the voltage error diminishes. With reactive power set points voltage controllability would have existed even in low active power generation periods, since the wind turbines were capable of providing reactive power even with zero active power generation.
- No oscillations or malfunction of voltage controllers located at substations have been identified.
Figure 2. Detail of active power, reactive power and voltage measurements (Arlabán et al. 2011)

Figure 3 shows a change in reactive power generation and the resulting change in the measured voltage. It takes less than 20s to achieve a steady state voltage following a voltage set point change.
Results obtained during these field tests have been regarded as highly satisfactory by both the Spanish TSO and Acciona Energía; the actual capability of the wind power plants to perform a dynamic voltage control based on monitoring of the voltage set-points has been verified. Reactive power has been injected/absorbed in line with the set-points and therefore according to the system needs. The influence of voltage regulation provided by the wind power plant on the high voltage grid has been significant - sudden changes of set-points have implied variations up to 3 kV on the 400-kV substation Morella. Besides, the wind power plants response has been fast and suitable for system operation.

No oscillations or instabilities have been identified regardless the values of control parameters considered, the voltage control mode (power factor or dynamic voltage control) or inconsistent regulatory objectives for wind power plants that regulate the same node of the transmission system. As power factor set points were sent to the wind turbines, when active power production was low (below 10-20% of total power output) a significant reduction in the capacity of generation/absorption of reactive power was noticed. However, with reactive power set-points (instead of power factor set-points) and the actual reactive power capabilities, voltage controllability would have existed even at low active power generation periods.
3. METHODS AND MAIN ASSUMPTIONS FOR EVALUATING FREQUENCY SUPPORT

The WILMAR planning tool is used to determine the hourly energy balance from conventional generators and from wind and solar generation (variable generation, VG). The approach will compare a case where VG is not participating in some of the frequency related reserves to case where they can participate. This comparison will reveal the economic benefits of using VG in frequency related reserves. In order to perform a cost-benefit analysis, also the additional investment costs to enable VG to participate in the frequency response need to be evaluated. In this report these costs are based on the REserviceS deliverables D3.1 and D4.1.

WILMAR procures reserves based on time series. In order to check the adequacy of the frequency response of these reserves after a fault, a separate Frequency Response Model is used (described in section 3.5). It uses the dispatch from WILMAR as input. Especially during situations where the inertia is low and hence a high share of the response comes from VG, it will be important to assess the frequency response. Since Iberia is part of the same synchronous area with ENTSO-E Central Europe (CE), the frequency response is assessed mainly in conjunction with the rest of the CE. As a consequence, most of the inertia and FCR response will come from the larger CE system. However, some results are also displayed for situations considering Iberia as an island. While not a very realistic setting, this gives some understanding for the frequency response from VG in synchronous power systems that are larger than Ireland, but smaller than CE.

3.1. WILMAR model

WILMAR is a stochastic unit commitment and dispatch tool well suited for analysing dispatch in power systems with high amounts of VG (Meibom et al 2011). Main characteristics of WILMAR:

- Bottom-up detail about the power plants (ramping, start-up costs, and efficiency losses of part-load operation)
- A time-horizon of 36-hours and rolls forward as new information comes available
- Simulation is normally run for one year at a time
- Possibility to aggregate units
- Possibility to run in either deterministic or stochastic mode
- Possibility to model district heating
- To model procurement of reserves including dynamic reserve allocation for tertiary frequency support reserves
- The reserves consist of primary (FCR), secondary (automatic FRR) and tertiary (manual FRR and RR) reserves and it is possible to select in which of these wind power and/or PV can participate. WILMAR model was modified to link with a frequency response model presented in the section 3.5.
- Ramping margin (RM) is also listed as a frequency ancillary service of interest in the REserviceS project, but for the most part it was not possible to analyse it in this case study. Part of ramping margin (RM) is implicitly included in the tertiary reserves of WILMAR. When VG can be curtailed and adjusted below its available generation for economic reasons, curtailment can happen in order to ensure sufficient ramping capability in the system. This contains only the portion of the ramping margin that is visible in the single point forecasts available for this study. However, more ramping margin would be required to include uncertainty about the ramping events at a desired
level of reliability. Data for this was not available and therefore could not be modelled as a reserve requirement.

### 3.2. Data and assumptions in the simulations

In the Iberian case study, the following assumptions were taken to have reasonable accuracy in the results while trying to keep the model calculation time at a reasonable level:

- 6 model regions in Spain and one model region to present Portugal with network constraints estimated from the publicly available grid data (Figure 4)
- All thermal units as separate units (not aggregated)
- VG aggregated in the regions
- Hydro power units with some aggregation
  - Each region has one reservoir
  - Each region has 4-7 aggregated units
- Most units in the system had a piece-wise linear efficiency, which is important when assessing the benefit of VG replacing conventional generation that would be operating at partial loads.
- All scenarios had dynamic tertiary reserve allocation and static primary and secondary reserve allocation as explained below.
- Most scenarios were run without forecasts (either single-point or stochastic) due to lack of PV forecast data.
- The wind only scenario (without any PV) was modelled with short-term (four hours) load and wind forecast errors in order to capture the cost of utilizing the balancing market / tertiary reserves to correct the forecast errors arising after the closure of the last intra-day market. The used forecasts were single point forecasts and did not include a stochastic tree.
Figure 4. Model regions for Spain and Portugal with net transfer capacities between the regions

Multiple sources were used to collect the time series for the Portuguese\(^1\) and Spanish\(^2\) systems, using 2012’s data as profile.

As VG has forecast uncertainty, it has to be made more reliable in order to provide upward reserves with high enough confidence. This can be achieved by dispatching VG below a desired reliability level in the forecast distribution. The forecast uncertainty changes over time, but there was no data to estimate the required reliability level. Therefore, a static multiplier was used based on the REserviceS deliverables D3.1 and D4.1. Based on the D3.1, the uncertainty of wind power in providing reserves meant that for each MW of procured upward reserve, 1.05 MWh generation was lost using the provision mechanism presented in Chapter 4 for of the D3.1. Based on the D4.1, the uncertainty of PV in providing reserves meant that for each MW of procured upward reserve, 1.3 MWh generation was lost. The range in D4.1 was 1.3 – 1.6. The lower number was selected, since the uncertainty is normally low in Spain due to frequent clear skies. PV will provide reserves mostly during days with high generation.

Basic power plant data (installed capacities, used fuel and technology type) was based on data received from Acciona and supplemented with data from the Platts World Electric Power Plants Database, September 2011 (see Figure 5). The start-up costs including wear and tear were estimated from NREL/APTECH data (Kumar et al. 2012). Piece-wise linear efficiency curves for thermal units and hydro power units were derived from two sources (Kirby 2007, Lew et al. 2012).

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\(^1\) Load, hydro production and inflows, import-export from (REN 2013); Irradiation from (MERRA 2013); Reservoir levels from (SNIRH 2013).

\(^2\) Load, hydro production, import-export from (REE 2013); Reservoir levels and Inflows from (Embalses 2013); Irradiation from (MERRA 2013).

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Conventional generators were constrained by minimum load factors, minimum shut-down times and operation times based on the power plant technology database at VTT. The same database was also used to derive the maximum efficiency of each power plant considering the vintage of the plant. In these scenarios it was assumed that fuel prices were as in Table 1 and the CO₂ price was 25 €/tCO₂. More unit data is in Annex I.

Table 1. *Fuel prices in the scenarios*

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<td>Fuel oil</td>
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<td>Light oil</td>
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<td>Natural gas</td>
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<tr>
<td>Uranium</td>
<td>5.4</td>
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<td>Wood waste</td>
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Figure 5. *Capacities of different power plants in the scenario Iberia base. Note: Portugal has an additional Wood Waste power plant with 84MW capacity.*
3.3. Method and assumptions for manual FRR and RR / Tertiary reserve

WILMAR model was run in deterministic mode, but with reserve allocation calculated dynamically. It was assumed that the intra-day markets balance most of the forecast uncertainty and only what remains after the markets have closed is in the realm of ancillary services or balancing power market. It was calculated how much different reserves are required for this remaining uncertainty (see below). WILMAR was subsequently constrained to procure those reserves. The utilization of the reserves was included only in the wind only case study due to lack of short-term PV forecast data. PV generation uncertainty is pronounced on cloudy days and this could not be reasonably estimated within the case study.

There is a delay between the gate closure of the markets and the real time operations. The length of the delay impacts how much uncertainty the reserves have to account for. Therefore, two different levels of uncertainty were analysed corresponding to four hour ahead and one hour ahead gate closures.

Tertiary reserve requirements due to load, wind and PV forecast errors were combined to get the tertiary reserve allocation for each hour. Combination was made as geometric sum of the three components:

\[
Tertiary \ reserve \ requirement_{\text{hour}} = \sqrt{\text{load}_{\text{hour}}^2 + \text{Wind}_{\text{hour}}^2 + \text{PV}_{\text{hour}}^2}
\]

The tertiary reserve requirement for each component tried to capture a sufficient portion of the forecast distribution. As similar data was not available for all components, different assumptions were taken. For load component 2% of the realized load was used (as reported in deterministic reserve setting in Spain from REE in Gil et al, 2009).

- The wind component in the reserve allocation was dynamic: it was based on the wind power output for a particular hour as well as on the forecast error distribution for that output level. Since the time horizon was rather short, it was feasible to use a two hour persistence forecast as a proxy for the four hour ahead forecast (as was done in NREL and GE 2010). One hour persistence forecast was used for the one hour forecast directly, since meteorological models do not improve a forecast this short. The forecast error was scaled to match with realised forecast errors in Spain (Figure 6).

- The reserve requirement component from PV was scaled according to the realized production level. The reserve requirement was scaled to be three times the standard deviation. As Iberian data was not available, the standard deviation was based on another study from the US (WestConnect in NREL and GE 2010 study). The study had a standard deviation for one hour, which was used for our one hour forecast. The study did not have a standard deviation for the four hour forecast, so an average between the one hour and the day-ahead forecast error standard deviations was taken.

\[3\] NOTE about calculation of the wind power induced reserve component: First, historical wind generation data from Spain was used to estimate the persistence forecast error distribution at five different generation levels (<0.1 p.u., <0.3 p.u., <0.5 p.u., <0.7 p.u. and >0.7 p.u.). Next, the reserve requirement based on the 99th percentile of the forecast error distribution was scaled to an average of 9% for the four hour ahead forecast and 6% for the one hour ahead forecast in order to follow Iberian values in Figure 6. The values in Figure 6 are average error values in relation to average generation level. This corresponds roughly to extreme values when the point of comparison is installed capacity. Extreme values in relation to installed capacity is a good proxy for the uncertainty that reserves should cover (mean error relative to installed capacity is about a third of mean error relative to average production. Extreme errors are about three times as much as average values. Thus the numbers would be divided by three and multiplied by three – cancelling each other).
Figure 6. The improvement of wind power forecasts in Spain over time. Source: REE.

Table 2. Reserve allocation in WILMAR: levels of forecast error uncertainty assumed for one and four hours ahead.

<table>
<thead>
<tr>
<th></th>
<th>One hour ahead uncertainty</th>
<th>Four hours ahead uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>2% of load level</td>
<td>2% of load level</td>
</tr>
<tr>
<td>Wind</td>
<td>On average 6% of wind generation (depending on generation level,</td>
<td>On average 9% of wind generation (depending on generation level,</td>
</tr>
<tr>
<td></td>
<td>from 3.4–10.0 %)</td>
<td>from 3.8–12.6 %)</td>
</tr>
<tr>
<td>Solar</td>
<td>6.7% of generation level, for generating hours, zero for hours</td>
<td>8.7% of generation level, for generating hours, zero for hours</td>
</tr>
<tr>
<td></td>
<td>with no generation.</td>
<td>with no generation.</td>
</tr>
</tbody>
</table>

3.4. Method and assumptions for FCR and automatic FRR requirements

When providing automatic FRR (in practice AGC), power plants need to be able to move upward and downward the procured amount. For all providing units, including VG, there has to be enough headroom to provide both directions. When VG is used, additional generation is lost due to uncertainty as described in section 3.2.

The total FCR in Iberia has to be at least 1026 MW (Table 3), which is the share of Iberian primary reserve in the whole CE. Wind and PV can provide upward FCR when they have been dispatched down and downward FCR when they are generating. Due to uncertainty, additional generation hast
to be shed when providing upward FCR as described in section 3.2. The model required upward and downward FCR separately.

In most simulations FCR and automatic FRR were provided in three hour blocks in order to make it easier for wind and PV to participate. A sensitivity run using one hour blocks was made in order to see the benefits of reserve products with higher resolution. Table 3 shows the requirements for FCR and FRR in the Iberian case. Unlike RR, FCR and FRR capacity cannot be traded between regions.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SP_CN</td>
<td>106.2</td>
<td>106.2</td>
<td>170</td>
</tr>
<tr>
<td>SP_NE</td>
<td>113.51</td>
<td>113.51</td>
<td>125</td>
</tr>
<tr>
<td>SP_NW</td>
<td>222.44</td>
<td>222.44</td>
<td>175</td>
</tr>
<tr>
<td>SP_SE</td>
<td>269.94</td>
<td>269.94</td>
<td>290</td>
</tr>
<tr>
<td>SP_SW</td>
<td>130.29</td>
<td>130.29</td>
<td>135</td>
</tr>
<tr>
<td>PT</td>
<td>183.41</td>
<td>183.41</td>
<td>200</td>
</tr>
<tr>
<td>Total</td>
<td>1025.79</td>
<td>1025.79</td>
<td>1095</td>
</tr>
</tbody>
</table>

### 3.5. Frequency Response Model

The Frequency Response Model takes as input the hourly results from WILMAR and will output the dynamic response in the system frequency in case a large trip off of conventional power plant occurs (N-1 or N-2 contingencies that the system should be prepared for).

The model was developed for Matlab/Simulink and is primarily based on Andersson (2012). The model contains primary control (FCR), AGC (secondary control, automatic part of the FRR), rotating mass loads, frequency-dependent loads, grid response (system inertia) as well as power plant turbine dynamics and control. Power plants are divided into five categories: hydroelectric, single steam cycle, reheated steam cycle, wind and PV.

It is assumed that since WILMAR is using net transfer capacities for transmission between regions and countries, there is enough capacity in the transmission lines to handle the power flows resulting from the contingency events. Therefore, the transmission limits are not taken into account in the frequency response model. As the inertia of the system gets very low at high levels of wind and PV, there could be dynamic impacts leading to instability between e.g. Iberia and rest of CE. These impacts need to be assessed in the future with a power flow model.

Fixed production values from the rest of synchronous CE (Rest of Europe, RoCE) are imported to the model. The RoCE was modelled with highly aggregated dispatch time series distinguishing wind, PV, hydro, nuclear and other thermal generation. The system inertia is much higher when considering also RoCE. It was assumed that there is 1700 MW of capacity in FCR in RoCE. It’s possible to choose whether PV and Wind are part of the FCR from RoCE.

It was assumed that the largest trip in the Iberian system at times of high wind and PV generation would be 650 MW, which is half of the NTC between France and Spain. There are two geographically independent connections between France and Spain. The largest unit in Iberia is a 1 GW nuclear unit, but it is assumed that it will generate at minimum load when the inertia is low. Using the same trip size (650 MW) for the whole year analysis makes the results more comparable. Larger trips are separately considered for the dispatch with the highest downward frequency excursion (nadir).

In Bossanyi (2013) delta-control was assumed when dispatching wind generation down in order to allow a reserve margin for upward response. For real wind turbines, the blade pitching speed is
limited due to structural design limitations. In the study, the full response time was assumed as 10s \((\text{based on } \text{REserviceS} \ D3.1)\), with the power output trending linearly. In the base case all wind turbines had a delay of 1s. If simulating an island operation of Iberia, this resulted in oscillations which were quite large in some occasions. In reality the delay will differ depending on the turbine and controller type. To get a more realistic response, wind power capacity in FCR was arbitrarily divided into four groups, each one of them with a different communication delay, but averaging in the base case at 1 s (using 0.75 s, 0.9 s, 1.1 s and 1.25s). PV units do not have ramp limitations and may have shorter communication delays (default 500ms based on \(\text{REserviceS} \ D4.1\)).

All steam cycle turbines were modelled without re-heaters, according to Sucena Paiva (2007). While most units in Iberia probably have a re-heater, it was assumed that in the situations where the frequency response might be weak, dispatching units with best response characteristics, i.e. without re-heaters, would be preferred. Hydroelectric control and dynamics were modelled using Schmidt and Papaioannou (2013) as a reference. Below, in Table 4, we present the main blocks, with their units and default values.

Table 4. The main blocks in the frequency response model with default values.

<table>
<thead>
<tr>
<th>Simple Cycle Steam Units</th>
<th>Reheated Cycle Steam Units</th>
<th>Hydroelectric Units</th>
<th>Wind Units</th>
<th>PV Units</th>
<th>Primary Control</th>
<th>AGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\frac{1}{Ts.s+1})</td>
<td>(\frac{1}{Tt.s+1})</td>
<td>(\frac{1}{Tr.s+1})</td>
<td>(\frac{1}{Tp.s+1})</td>
<td>(\frac{1}{Comm\ Delay})</td>
<td>(\frac{1}{K1})</td>
<td>(\frac{1}{K2})</td>
</tr>
<tr>
<td>Steam Valve</td>
<td>Steam Turbine</td>
<td>Steam Turbine and Reheater</td>
<td>Permanent Droop</td>
<td>Pilot Valve</td>
<td>Transient Droop</td>
<td>Turbine</td>
</tr>
<tr>
<td>Regulator</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- \(a)\) \(T_t = 0.1\) s
- \(b)\) \(f_{HP} = 0.3\)
- \(c)\) \(T_t = 7\) s
- \(d)\) \(T_t = 0.4\) s
- \(e)\) \(R_p = [-Hz/MW]\)
- \(f)\) \(R_t = 0.4\) p.u.
- \(g)\) \(T_p = 0.02\) p.u.
- \(h)\) \(T_r = 12\) s
- \(i)\) \(T_W = 1\) s
- \(j)\) \(Share = [0; 1]\)
- \(k)\) \(C.\ Delay = [s]\)
- \(l)\) \(Ramp = 10\) s
- \(m)\) \(C.\ Delay = 0.5\) s
- \(n)\) \(K_1: \text{ Full response in } \Delta 0.2\) Hz
- \(o)\) \(K_2: \text{ Full response in } \Delta 0.2\) Hz
- \(p)\) \(T_n = 120\) s
- \(q)\) \(C_p = 0.17\)
Where,

a) $Tt$: Servomotor time constant;
b) $f_{HP}$: fraction of steam that goes into the High Pressure level;
c) $Tt2$: Reheater time constant;
d) $Tt1$: Servomotor time constant;
e) $Rp$: Permanent Droop;
f) $Rt$: Transient Droop;
g) $Tp$: Pilot valve and servomotor time constant;
h) $Tr$: Reset time/dashpot time constant;
i) $TW$: Water starting time constant;
j) $Share$: Share of wind parks with given delay;
k), m) $C.\ Delay$: communication delay;
l) $Ramp$: blade pitching limits;
n), o) $Kx$: relative to the Droop R ($Kx = -1/R$);
p) $Tn$: Parameter of the Proportional Integral Controller (time constant);
q) $Cp$: Parameter of the Proportional Integral Controller (gain).

Results obtained from the model will allow us to partially access the stability of the system considering the high levels of renewable penetration. The Rate of Change of Frequency (RoCoF) and the lowest level of frequency (nadir) during the ancillary response are evaluated. Inter-area dynamics may be important (mainly since the interconnections between Iberia and France are quite small in relation to system sizes) but a power flow model would be needed to assess possible inter-regional oscillations.

RoCoF was measured in Hz/s, taking in account the first 500ms from the tripping time, as in Creighton et al. (2013), however we didn’t consider a moving average, as the worst RoCoF in the Matlab/Simulink model was always right after the fault. The frequency nadir was simply the lowest frequency value in the simulation.

The frequency response model results allowed us to compare what kind of units are providing FCR and FRR (conventional, wind, photovoltaic), inertia values for the whole simulated system, as well as nadir and RoCoF values for each hour of the year. Total FCR and FRR imported from RoCE into the Iberian Peninsula gives an indication of the flow increase over the transmission lines during an event. Results from the simulation can be found in Chapter 5.
4. SIMULATED SCENARIOS AND CASES

4.1. Scenarios with different VG penetration levels

The main scenario simulated has the same wind and solar penetration levels as the European case study: about 42% of yearly energy from variable generation (28.5% from wind, 13.7% from solar using the same penetrations as in the EPIA 2012 study Connecting the Sun). Table 5 shows the main scenario (VG42) and the other scenarios, which include:

- 50% penetration case, keeping the same ratio between wind power and PV as in the main scenario
- 32% penetration case, halfway between 2012 and 42% scenario, to estimate the value of ancillary services from VG at lower penetration level
- 21% penetration case, corresponding to 2012 levels, was used to have a further data point and also to validate with existing experience
- scenario with only wind to compare with the Ireland case study and to estimate the value of utilizing manual FRR and RR
- scenario with a larger amount of PV

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Wind penetration</th>
<th>PV penetration</th>
<th>Total VG penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>VG42</td>
<td>28.5%</td>
<td>13.7%</td>
<td>42.2%</td>
</tr>
<tr>
<td>VG42 Wind only</td>
<td>42.2%</td>
<td>0%</td>
<td>42.2%</td>
</tr>
<tr>
<td>VG42 High PV</td>
<td>23.4%</td>
<td>18.9%</td>
<td>42.3%</td>
</tr>
<tr>
<td>VG50</td>
<td>33.2%</td>
<td>16.4%</td>
<td>49.6%</td>
</tr>
<tr>
<td>VG32</td>
<td>23.4%</td>
<td>8.1%</td>
<td>31.5%</td>
</tr>
<tr>
<td>VG21</td>
<td>18.3%</td>
<td>2.5%</td>
<td>20.8%</td>
</tr>
</tbody>
</table>

All scenarios use hourly time series profiles for load, hydro, wind and PV from year 2012. Load has not been scaled. Assuming a higher load in the future while keeping the installed VG at the same level would decrease the penetration and alleviate the impact of VG.

Figure 7 shows the differences in the residual demand duration curve for the analysed scenarios. In scenarios with at least 42% VG annual penetration, the residual demand is below zero for 60-300 hours and below 10 GW for 1000-1800 hours.
In order to calculate the benefits of VG ancillary services, two cases are simulated for each scenario: one where VG can provide frequency related reserves and one where they cannot. The difference in the operational costs between the cases is the benefit that VG in frequency reserves brings. The scenarios will also reveal when and how much VG will be used to provide reserves.

4.1. Cases with different configurations for availability of ancillary services

While scenarios provide estimates on the value of VG in frequency related reserves, further cases are required to break down the benefits between different reserves and to perform some sensitivity analysis. Only in the VG42 scenario all cases were analysed. In the rest of the scenarios only ‘NNN’ and ‘YYY’ cases were modelled. Base case (‘NNN’) was simulated without wind and solar providing services, using reserve allocation of four hours ahead. A number of other cases were performed, where the participation of VG was allowed to smaller or greater extent as can be seen from the Table 6.

---

4 In the case name first letter Y or N (Yes or No) refers to upward FCR, second letter to downward FCR and the third letter to automatic FRR.
Table 6. Analysed cases in the VG42 scenario. In the case name first letter refers to FCR, second letter to automatic FRR, and the third letter to manual FRR / RR.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Wind upward FCR</th>
<th>Wind downward FCR</th>
<th>Wind FRR</th>
<th>PV upward FCR</th>
<th>PV downward FCR</th>
<th>PV FRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>NNN</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>YYY</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>YYN</td>
<td>Yes</td>
<td>Yes</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>YNN</td>
<td>Yes</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NYN</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>Wind YYY</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wind 25%</td>
<td>25 %</td>
<td>25 %</td>
<td>25 %</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
5. RESULTS FOR FREQUENCY SUPPORT SERVICES

This chapter first looks at the economic results – value and benefit from VG providing system services. Then some results from the frequency response model are presented, displaying the adequacy of the frequency response with low inertia and high amounts of VG in the primary reserve.

5.1. Cost-benefit of using VG in frequency reserves

To analyse the cost-benefit of VG in frequency response, all relevant costs and benefits need to be accounted for. Costs include investment costs (capability) and operational costs (readiness and utilisation). These are based on the REserviceS deliverables D3.1 and D4.1. Investment cost was annualised in order to compare with the annual operational costs and benefits. The investment was annualised with an annuity factor of 0.10 (corresponding to a 20 year investment with an 8 % interest). Whenever VG provides upward reserve, it needs to be dispatched down. This will result in lost energy, which entails a cost equal to the value of the otherwise generated electricity. The cost of lost energy is implicitly included by the WILMAR model. At the same time, all the benefits are also included through reduced operating cost in the rest of the power system. Since VG is assumed to have no operational cost, down dispatch happens only when there is a net benefit equal or greater than zero.

The investment to provide for one reserve category enables also provision of other reserve categories. Therefore the cost/benefit is evaluated for all the frequency support services together in this chapter.

The operational cost of the power system varied between the different scenarios mainly in relation to the amount of zero cost generation from VG (Figure 8). From operational cost perspective ‘VG42’ has a better mix of PV and wind than ‘VG42 high PV’, where PV is 18.9% of annual energy instead of 13.7% (and wind decreased accordingly). ‘VG42 wind only’ is more costly, since the correlation with PV and daily demand profile is a valuable addition. The operating costs of the ‘VG42 wind only’ did not noticeably change when the four hour ahead single point forecasts were changed to a case with perfect foresight (as in the other scenarios). For each scenario, the benefits from the VG frequency reserves are calculated as the cost reduction in comparison to this NNN case.
The operational benefit of ancillary services from variable generation can be seen in Figure 9. Results show increasing benefits with increasing VG penetration level. In VG42 scenario the benefit is over 250 M€ per year, which is 3.4 % of total operational costs of the power system. The scenarios with smaller share of VG (21 % scenario corresponding to the current level in Iberia as well as the 32 % scenario) show relatively small benefits. All other scenarios also show considerable benefits.

A sensitivity where only 25 % of the wind power capacity was able to participate in the reserves gave the same economic benefit as the case where all wind and PV were participating. Also according to the frequency response studies in the section 5, it is not necessary to have the capability in the categories with higher investment costs. For example residential and commercial PV, which account for 25 % of PV capacity, accounted for 73 % of the additional investment costs.
In Figure 10 the annual operational cost reductions are compared against the annualized 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 column shows estimated investment costs to enable the participation of VG in the reserves. The middle column shows the benefits when each of the reserve categories are assessed separately and added together afterwards. The rightmost column 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 columns indicates that there are co-benefits when VG is participating in all frequency support services at once. In both cases, the benefits outweigh the annualized 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.

It can be seen that highest benefits come from procuring either downward reserve (downward FCR) or reserve that requires both downward and upward room (automatic FRR). Upward FCR is small in the 42% scenario, but could get higher in the 50% scenario since there would be more opportunities due to increased curtailment. However, this was not tested. There was no benefit when procuring VG to manual FRR/RR and therefore it is not separated in Figure 10.

There was an additional increase in the benefit when the model allowed VG to provide for all reserve categories (‘together’) in comparison if the model allowed VG to participate in only one reserve category. A conventional power plant operating near minimum load can provide both primary and secondary reserve at maximum capability, which is usually 5-10% of the unit capacity, because the response is required in certain time frame and there are limitations how much power plants can ramp in seconds (primary) and in minutes (secondary). Therefore, only when neither primary nor secondary reserve was needed from that unit, it was possible to shut the unit down.

Switching from the three hour reserve block size to one hour blocks increased the benefit slightly. However, even a small benefit in relative terms may be worthwhile since the total cost to operate large power systems is very large.
The bulk of the benefits come from the reduced fuel costs resulting from the decreased use of natural gas (Figure 11). Use of coal and nuclear increased because there was more flexibility available in the system. Coal and natural gas had similar variable costs in the model runs – coal had somewhat cheaper fuel cost, but had a higher start-up cost than combined cycle natural gas.

![Figure 11. The change in power generation from the NNN case to the YYY case in the VG42 scenario](image)

A further benefit from AS provision from VG is reduced VG curtailments as well as increased utilization of nuclear (Figure 12). In the High PV scenario curtailments were higher due to less beneficial match between load and VG. When VG was allowed to provide reserves, wind power was curtailed more, since it was able to provide reserves with less energy loss compared to PV. However, at times when there was plenty of surplus VG available, it did not matter to the model which one it curtailed. Therefore the relation between wind and PV curtailments is not a firm result. In the VG21 NNN case, corresponding to 2012 wind power and PV generation data, the curtailments due to ‘surplus’ energy were of similar magnitude (0.11 %) as in the realised data (section 2 referenced a 0.5 % curtailment for wind power). The curtailment was increased in the VG21 YYY case (to 0.34 %), which indicates that there was economic benefit to utilize VG for ancillary services in some occasions. The benefit comes when fuel consuming power plants can be shut down for periods of several hours and the fuel savings can justify the additional start-up costs.
When VG was able to participate in the provision of upward FCR (Figure 13), it replaced conventional generation especially during those hours when there was surplus generation. The model reserved VG for downward FCR relentlessly (Figure 14). The reason is that procuring the downward reserve from VG did not cost anything to the model and there was no upper limit in the provision of the reserve. Utilization would have cost, but this was not assessed in the modelling framework. Figure 15 displays which power sources were used to provide automatic FRR (AGC) in different cases.

In studied cases, the WILMAR model was able to procure enough replacement reserves almost at all times without additional cost. There was enough capacity online plus fast start units to take care of the increased reserve needs. Therefore, the model runs where it was possible to procure RR from VG did not provide measurable benefits and accordingly that case is not displayed in the figures as it did not practically differ from the 'NNN' case.
Figure 13. Annual procurement of upward FCR in different cases of the VG42 scenario. Y-axis is a sum of hourly capacity procurements of the year; therefore the unit is TWh/h.

Figure 14. Annual procurement of downward FCR in different cases of the VG42 scenario. Y-axis is a sum of hourly capacity procurements of the year; therefore the unit is TWh/h.
Figure 15. *Annual procurement of automatic FRR in different cases in the VG42 scenario. Y-axis is a sum of hourly capacity procurements of the year; therefore the unit is TWh/h.*

It was not possible to analyse the utilization of manual FRR / RR in the scenarios with PV generation, since we did not have a good source for PV forecast time series. Therefore the utilization of these reserves was examined only in the wind power only scenario. The forecast error of wind power was combined with load forecast errors. Power plants were able to participate in the real time balancing only if they were committed to be online or there was enough time to start them up (with lead time of four hours).

There was a benefit for utilizing wind power for the tertiary reserves (manual FRR / RR services), but it was not very large for the total power system (0.3–0.6% of total cost; 0.6% when wind power was not allowed in other reserve categories and 0.3% when wind power was allowed also in FCR and automatic FRR). It was assumed that intraday markets had taken care of most of the forecast errors and that tertiary reserves handled only what remained four hours before to real time. However, the benefits were smaller than expected and the small size of the benefits could not be explained. Therefore the results are inconclusive about the use of VG for manual FRR / RR.

5.2. Adequacy of the frequency response

The main concerns regarding the use of VG in FCR are the frequency nadir (the lowest point in the frequency after a fault), the RoCoF (the rate of the change of frequency) and the stability of the response. This section shows the results of the frequency response simulations to address those concerns.

5.2.1. Main results

Figure 16 below relates the frequency nadir with the system inertia, taking in account the amount of VG contributing for FCR, for a full year run (8772 dispatch situations) with Iberia connected to RoCE using the VG42 scenario and the YYY case. Therefore all the sub-figures use the same dispatch and have the same operating costs. The sub-figures demonstrate that the maximum drop in the frequency is small when VG is participating in the reserves (hot colour dots in the lower left). This is caused by the...
fast up-ramp of the down dispatched VG after a fault. The best response is achieved in Figure 5 [a], where the communication delay is smallest (0.2s$_{avg}$). When increasing the average communication delay to 1s$_{avg}$ (Figure 16 [b]), the nadirs with VG shift higher. When the contribution from VG is limited (2.5GW of wind and 1GW of PV), as seen in Figure 2 [c], the frequency nadirs shift even more, but are still very good.

The implications of a high Rate of Change of Frequency (RoCoF) in a system are still being discussed. One possible threshold is due to protection relays set often at 0.5 Hz/s (as in Creighton et al. 2013). RoCoF larger than this could threaten system stability. First 500ms after the fault were used to calculate the RoCoF. Below, in Figure 17, one can see the relation between the RoCoF and inertia, taking in account the amount of VG in the FCR. The RoCoF is clearly low enough in all cases.

In the Figure 17 [a], one can see the effects of VG with a short communication delay. RoCoF is better when more VG is participating in the FCR, since the response from VG is faster than the 500 ms window used to calculate the RoCoF. The response in Figure 17 [b], which has 1s$_{avg}$ of communication delay, is very similar to Figure 17 [c] where VG does not participate in the reserves. With a 1s$_{avg}$ delay, VG did not actuate within the 500 ms window used to calculate the RoCoF and the response is therefore all inertia and to smaller extent conventional units in FCR. While the response is similar, there is a difference in the tail of the plots. When VG is not allowed to provide reserves, more conventional units are online during high VG events, and the resulting higher inertia decreases the RoCoF.
Below, in Figure 18, the frequency excursion at frequency nadir is displayed as a function of inertia, this time for three scenarios where VG was allowed to participate in the reserves. The Wind 100% is based on the VG42 scenario, but PV was not allowed to participate in the reserves. The case was simulated, because the frequency response from PV is more expensive and therefore it could make sense to use only wind turbines for this purpose. In Wind 25% only 25% of the wind turbines have the frequency response capability. Those turbines are down dispatched first.

![Figure 18](image1.png)

*Figure 18. Frequency excursions at nadir as a function of inertia and VG FCR contribution over a full year*

In the Wind 25% scenario, represented in Figure 18 [b], there aren’t significant differences compared to the Wind 100% scenario (Figure 18 [a]). Some small changes in periods with high reserve contribution from wind are seen: there is a slight shift toward higher frequency nadir values, since the VG contribution is not as high. The reason is that there were only few episodes where the 25% of capacity limitation had constrained the dispatch in WILMAR.

For the High PV scenario (Figure 18 [c]) we observe an increase of events with a VG contribution to the ancillary services (with, as expected, more PV than wind). These events show a further improvement in the frequency nadir, since PV was assumed not to have ramp rate limitations.

5.2.2. **Some sensitivity analysis**

The frequency nadir stays within limits of ±0.2 Hz even when the trip size is considerably increased (Figure 19). This assumed average response of 0.2 s from VG.
Islanded systems have less inertia to support the frequency drop. There is a stability risk when high amounts of VG have a communication delay in reacting to the frequency change. We have therefore simulated a case with Iberian Peninsula as an island to give insight into possible stability issues in smaller systems with less inertia.

In low inertia situations using all surplus VG for FCR resulted in an unstable frequency response. In order to mitigate this effect, two main methods were studied: reducing the delay times and limiting the amount of VG participating in the response. Also a more intelligent response algorithm could conceivably mitigate the oscillations, but this was not studied. In the islanded scenario, just reducing the delay time wasn’t enough for stabilizing the system. It was also necessary to limit the VG participation – in here we used 10% of the available surplus. Below, in Figure 20 [a], one can see the effects of various communication delays for the VG frequency response limited to 10%. Comparing it to Figure 20 [b], a case including RoCE and the same 10% limit to the use of VG, one can see how the oscillations are eliminated by the extra inertia in the system. Also, as expected, the frequency nadir is much higher.

Some measures may have to be taken even in high inertia power systems, if VG with long communication delays starts to contribute to the FCR in large amounts. In Figure 20 [c], all available surplus VG is used in the FCR in the case with RoCE and with a delay averaging at 2 seconds, there is considerable oscillation.
The hour simulated above is the one with highest wind and PV contribution (10\textsuperscript{th} of June, 14:00). The use of different technologies for the reserve within the hour can be seen in Table 7. In the islanded scenario, the VG contribution is limited to 10\% of the available surplus. Hydro power was not scheduled for the reserves at all.

Table 7. Values for the parameters behind the Figure 20 [a] and [b]

<table>
<thead>
<tr>
<th></th>
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<td>326.4</td>
<td>625.2</td>
<td>45.1</td>
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5.2.3. Inertia in the Iberian system

Figure 21 below presents the duration curve for the inertia (not including RoCE) in different scenarios. Using VG in FCR and FRR (YYY cases) results in an inertia decrease compared to the NNN cases, explained by the shutdown of some of the conventional units. The decrease would be higher, but the replacement of coal with combined cycle units makes up for part of the difference. The increase of VG (comparing blue line of VG42 YYY with the red line of VG50 YYY) results in a relatively small increase of inertia for the same reason.
Figure 21. **Duration curve of the inertia in Iberia only in different scenarios**

The yearly inertial difference between the VG42 NNN and YYY cases is represented in Figure 22 [a]. The hot-coloured areas represent an increase of inertia from NNN to YYY, while the cold ones represent a decrease.

![Figure 22](image-url)  
**Figure 22.** **Hourly inertia difference between two cases. Days of the year on x-axis.**

The decreased values observed in Figure 22 [a] are expected. With the participation of VG in the FCR and FRR, conventional power-plants are allowed to shutdown, decreasing the system inertia. These happen mostly before the peak load hours, where the extra VG can handle the demand. It is also interesting to mention that not always we observe a decrease in inertia. Some days in August have higher inertia for the YYY case. This happens due to the different characteristics of the power-plants. VG contribution allows the coal power plants, which have a higher start-up cost, to shut down. At the same time, the model will use combined cycle units more. However, the assumed inertial constant for the combined cycle units is almost twice the coal (8.5 s compared to 4.5 s). Therefore, an increase of the system inertia for certain hours is observed.

In Figure 22 [b] the High PV scenario has more asynchronous generation during the summer days and therefore less inertia. As there is less wind generation, windy periods see an increase in inertia.

**5.2.4. Simple short-circuit current analysis**

In order to evaluate the first-order magnitude of short-circuit currents a highly simplified approach was taken. Since the reactances of the grid’s elements weren’t available, a simple constant converting MW\_online to kA\_SC was applied for the three different types of generators for a three-phase short-circuit:
- Type 4 (full converter): $1 \text{kA}_{SC}/\text{MW}_{online}$ for all of the online PV and half of the online Wind;
- Type 3 (DFIG): $3 \text{kA}_{SC}/\text{MW}_{online}$ for half of the Wind;
- Synchronous Generators: $5 \text{kA}_{SC}/\text{MW}_{online}$ for all conventional units.

The assessment was made individually for each region. Full year dispatch time series were analysed to find the maximum and minimum values. It was considered that the short-circuit power ($S_{SC}$) for RoCE and the other regions was much higher than the $S_{SC}$ of the region being evaluated, resulting in a short-circuit impedance extremely low ($Z_{SC} = 1/S_{SC}$). Hence being considered a node with infinite power, it was discarded from the calculations. This will gives us a small error in excess, putting the results on the safe side. The values obtained can be seen in Figure 23.

![Figure 23. Short-circuit currents in the model regions in the different scenarios / cases](image)

In Figure 23 [a] the maximum values of the $I_{SC}$ are presented. The $I_{SCmax}$ is dependent on the type of generators online and the total online capacity. For high amounts of VG (VG42 and VG50 scenarios) YYY is slightly higher, or equal, as the NNN cases. If the switches are dimensioned with a reasonable failsafe margin, then they should have a cut-out power high enough to avoid the electrical arch. For the other cases (VG21 and VG32), the NNN case has higher $I_{SCmax}$ than the YYY ones, meaning that the current switches are well dimensioned for the use of VG in the reserves.

However, comparing the VG21 with the VG42 case, in most regions we observe an increase in the $I_{SCmax}$. The cut-out capacity of the protective relays should follow the trend of increased VG in order to keep the grid’s elements safe.

Regarding the $I_{SCmin}$, presented in Figure 23 [b], further studies are advised to obtain a better understanding of the effects of the disturbances in the generators and loads. A change in the system operation method from NNN to YYY might need a decrease in the relays’ sensibility (decrease of $I_{SCmin}$ from NNN cases to YYY cases), while long term, it appears that most of the regions have an adequate protection, since the $I_{SCmin}$ decreases with the increase of VG operating in the system’s reserves.
6. DISCUSSION

The unit commitment and dispatch modelling made for the Iberian case study contains significant sources of uncertainty as will be discussed below. As a consequence, the numeric results should not be taken as accurate estimates. However, while exploring the sensitivity of the model, all results indicated that there would be considerable cost savings from utilizing wind power and PV for frequency reserves especially at higher penetration levels. The same result is corroborated by the TWENTIES project Iberian case simulations.

The simulations gave clear economic benefits for a power system providing primary and secondary control (FCR and automatic FRR services) with wind power and PV. The economic benefits for tertiary reserves (manual FRR/RR services) were not easy to capture from the simulations. In the ‘VG42 Wind only’ scenario using four hour ahead forecasts, there was a small benefit when comparing a case without wind power providing any reserves to a case where wind power was allowed to provide manual FRR/RR (0.6 % of total cost). When comparing a case where wind power was allowed to provide all frequency reserve categories to a case where it was allowed to provide FCR and automatic FRR, but not manual FRR/RR, the benefit was reduced to 0.3 % of total cost. The small size of the benefit could not be explained. This area needs further research.

Using VG for frequency response decreases fuel use in thermal power plants and gives the possibility of shutting down more conventional power plants at times of high wind and solar penetration. The economic benefit can be highly sensitive to the assumptions taken. We observed that increasing the cost of starting combined cycle units would strongly reduce the benefit of VG in frequency response. With the assumptions we used (Kumar et al. 2012) it was considerably less costly to start-up combined cycle plants in comparison to steam power plants. The start-up cost estimates are based on a large database of actual unit data, but Kumar et al. have published estimates only from the lower range of the dataset. A consequence was that combined cycle plants were shut down quite often. If there is nothing cost effective to shut down during periods of low power prices, the benefit of replacing conventional generation with VG would be much less both for FCR and automatic FRR.

The investment costs estimated in the previous REserviceS deliverables are current estimates based on current costs and technologies. As this is a new field those estimates have a large uncertainty and future improvements can decrease the costs considerably.
7. CONCLUSIONS

Aim of this study was to see how much variable generation (wind and solar PV) would participate in the frequency related ancillary services at high variable generation (VG) penetration levels in a power system that resembles the Iberian Peninsula with respect to system size, generation mix and interconnection to a stronger system. All three frequency related reserve categories (FCR, FRR, and RR) were analysed. Economic results are very promising especially at high shares of VG showing an annual benefit larger than the annualised investment cost. Also curtailment of VG was considerably reduced. At the same time, the adequacy of the frequency response with VG was good.

The WILMAR planning tool was used to determine the hourly energy balance with generation from conventional units as well as wind power and PV. WILMAR minimized operational costs while respecting the constraints to include enough reserves in different reserve categories. For manual FRR and RR (tertiary frequency control), the WILMAR model can also evaluate the utilisation of the reserves. However, this requires time series of forecast data. Forecast time series were not available for PV and therefore this part of cost-benefit analysis was made for the scenario with wind power only.

The economic benefits of using VG in frequency related reserves were calculated by comparing a case where VG was not participating in some of the frequency related reserves to a case where VG did participate. The results display from which sources FCR (primary) and automatic FRR (secondary) frequency control is procured and how VG would participate, if it were optimally scheduled to do so. The results also display the adequacy of the response using the WILMAR dispatch and a separate frequency response model.

At higher VG penetration levels (at least from 42 % of annual energy onwards) the power system wide economic benefits of using VG in frequency response were sufficient to cover the extra investment costs of all wind power units and most PV units. The annual benefits were clearly higher than the annualised investment costs when VG was producing 50 % of the annual electricity consumption. However, a scenario with only 25% of wind power participating in the frequency reserves was also calculated. This scenario showed similar benefits and frequency response as the scenario where all VGs were participating in the frequency reserves. As a consequence, it is likely that already at the 32 % level (or lower) it is economic to equip a portion of the units with frequency response capability.

Currently there are two broad primary frequency response categories: hydro and thermal. Thermal units in general provide a swift and stable response, while hydro has a less desirable initial response (with a small initial reduction, since the opening of the admission valve creates a brief decrease in the water pressure). Adding wind and PV creates a third category, which is typically utilized when the inertia is low, since only then there is surplus VG available. For wind power and PV, the critical characteristic will be the delay in the response, since these units do not provide inherent inertia.

The results of the frequency response simulations demonstrated that the frequency response remained adequate at system level when provided mainly from VG. The speed of the response from VG was demonstrated to be a factor of critical importance. With a short communication delay for VG, the frequency nadir was even higher than with conventional power plants. Also the RoCoF was inside the acceptable limits by a large margin. The frequency response could be less efficient in power systems with very low inertia, but this was not observed in the Iberian case. However, there could
be a need to tune the response from VG in order to prevent possible oscillations, if large amounts of VG participate in the primary response.

Regarding voltage control, the field tests reported in Section 2.3 verify the capability of the wind power plants to perform a dynamic voltage control based on monitoring voltage set-points. The influence of voltage control by wind power plants has been significant and response from wind power plants has been fast and suitable for local voltage management by the TSO. No oscillations or instabilities were identified. At low wind power production levels (10-20 % of rated power), a significant reduction in the capacity of generation/absorption of reactive power was noticed when power factor set-points were used, and it is recommended to use reactive power set-points instead.
8. REFERENCES


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Gil, A., de la Torre, M., Rivas, R. 2010. Influence of wind energy forecast in deterministic and probabilistic sizing of reserves. 9th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, October, 2010, Quebec, Canada.


### Annex I. Some assumptions about generation technologies

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<th>Type</th>
<th>Vintage</th>
<th>Installed cap. (MW) per</th>
<th>Min. load</th>
<th>Minimum (hours)</th>
<th>Costs</th>
<th>Startup</th>
<th>Losses</th>
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