19th June 2010

Simon Bartlett
Chairperson, E S Cornwall Scholarship Advisory Committee

Dear Mr Bartlett,

Re: ES Cornwall Scholarship – Fifth Quarterly Report

Please find enclosed my fifth quarterly report during my tenure of the E S Cornwall Memorial Scholarship, as required by the scholarship rules.

During the first quarter of 2010, I have been working for National Grid in the United Kingdom. My primary responsibilities during this quarter included power system studies, analysis of generation scenarios for the year 2050, and involvement in the fundamental review of Great Britain's transmission planning criteria. Additionally, I was able to visit the Spanish TNSP Red Eléctrica, a major central London substation, and participate in the grid code compliance testing of an offshore wind farm. The report documents my impressions from each of these activities.

I welcome feedback or questions from the committee or other interested parties on anything I have discussed in my report.

Yours faithfully,

Jonathan Dennis

Enclosures:

- E S Cornwall Scholarship 2008-2010 – Jonathan Dennis – Fifth Quarterly Report

ES Cornwall Scholarship 2008-2010
Jonathan Dennis

Fifth Quarterly Report

Introduction 1
Strategic Network Investment Power System Studies 2
2050 Generation Scenarios 2
Visit to Red Eléctrica de España 3
Visit to St John's Wood 400kV GIS Substation 6
Full Converter Wind Farm Grid Code Compliance Testing 7
Fundamental Review of GB Network Planning and Operation Criteria 10
Next Quarter 11
Acknowledgements 11
Detailed Notes from my visit to Red Eléctrica de España 12

Introduction

I am using my tenure of the E S Cornwall Memorial Scholarship principally to gain experience in the measures being applied internationally by transmission companies to manage three significant complicating aspects of large centralised renewable generation, being:

- variability of renewable power generation over time,
- low inertia, poor fault ride through capability, and
- remote location necessitating long distance radial connections.

As previously indicated, my overwhelming impression since commencing the scholarship is that the obstacles to the increased use of renewable generation are multi-faceted, and that the technical difficulties listed above must be considered alongside the political, regulatory, and commercial challenges. I have therefore sought to investigate and report on all of the transmission related obstacles to increased use of renewable generation.

This is the fifth of six quarterly reports required by the scholarship guidelines and relates to the first quarter of 2010. During this time I have continued my employment with National Grid, in their UK electrical transmission network investment planning team.

My primary responsibilities during this quarter have included power system studies, analysis of generation scenarios for the year 2050, and involvement in the fundamental review of Great Britain's transmission planning criteria. Additionally, I have been able to visit the Spanish TNSP Red Eléctrica and a major central London substation, and participate in the grid code compliance testing of an offshore wind farm. This report documents my impressions from each of these activities.

Strategic Network Investment Power System Studies

Throughout January I was involved in performing power system studies to assess the options available to facilitate the connection of new wind generation in central Wales. For the purposes of the study wind generation was treated no differently from any other generation. However, I found it very interesting to perform power system studies on such a large and interconnected network. In particular, I found the following aspects quite novel:

- The comparatively large number of contingencies to study (around 40 for my study)
- The ability to tap quad-boost transformers to alter the sharing of power between parallel flow paths
- Using the GB transmission planning standard's guidance for establishing the baseline generation background to study. Since there are ~300 significantly sized generators in Great Britain it would be practically impossible and unnecessarily onerous to ensure the transmission network could support every possible way in which the generation could be dispatched to meet demand. The GB planning criteria therefore defines a procedure by which a typical 'planned transfer' condition is developed. This procedure utilises a generation ranking order and deterministic rules regarding the level to which different types of generation are scaled. The planned transfer condition and sensitivities around this are used as the basis for planning studies.

In this case, the network reinforcement option that I was responsible for studying was found to be inferior to an alternative option being studied by another engineer. In retrospect, the reinforcement option I was studying had a critical flaw, in that it did not address one of the key contingencies. By their own admission, this deficiency should have been obvious to the senior engineers who conceived the option. This emphasised to me how easy it is for even experienced engineers to inadvertently overlook issues when dealing with such a large and interconnected system.

2050 Generation Scenarios

Another interesting piece of work a senior colleague and I performed this quarter involved providing assistance to the UK's Department of Energy and Climate Change (DECC) in understanding the implications of a number generation scenarios they had developed. The scenarios were intended to reflect the range of possible generation backgrounds that could exist in

the UK in the year 2050. DECC developed the scenarios by identifying possible future locations for different types of generation and investigating the rate at which new generation could be constructed. Some of the scenarios were heavily skewed towards a particular fuel type (i.e. nuclear or renewable) whilst others were more blended.

We attempted to study the high level implications for the transmission network. Unsurprisingly, the implications of the different scenarios were quite varied, but there were also a number of general consequences:

- The increased presence of intermittent wind generation meant that a greater proportion of the network would only be significantly utilised under particular wind conditions (i.e. the general utilisation of the network is likely to be much lower than it presently is).
- Similarly, the flows on the network were much more variable than at present, making the use of quad-boost transformers inadequate to manage the sharing of flows between parallel flow paths. The greater use of HVDC (perhaps back-to-back) might become necessary to manage this variability.
- A very considerable amount (20-30GW+) of additional interconnection with Europe was identified as being necessary in several of the scenarios, although it was difficult to then know how to assume that the interconnection would behave in different situations and how to factor this into the design of the onshore transmission system. For example, whether all of the interconnectors would behave uniformly and whether the interconnectors could be relied upon to supply power to the UK when wind generation was low. A likely consequence of this is that transmission planning in the UK and throughout Europe is going to increasingly involve the study of weather patterns and market behaviours, and planning teams will therefore need to acquire expertise in these areas.

Visit to Red Eléctrica de España

In early February, fellow ES Cornwall Scholars Reena Kwong, Nick Craig and I were able to visit Red Eléctrica de España (REE), the Spanish Transmission System Operator. The visit included a tour of their control facilities and meetings with a number of their engineers. For reference, Spain has a typical peak demand of around 40-45GW and a typical minimum demand of around 20-25GW. Although Spain is part of the synchronous European power system, we were surprised to learn that they presently only have 600-1400MW of interconnection with France (the available capacity varies with system conditions), 1500MW with Portugal, and 600-900MW with Morocco. Both of the later connections are to relatively small power systems with no onward interconnections, and so these connections do not contribute much additional security. Plans are in place to increase the capacity of interconnection with both France and Portugal.

At the time of our visit, over 18.5GW of wind generation capability and 3.5GW of solar generation capacity had been connected to REE's network, with an additional 1-2GW of intermittent generation being installed each year. During our visit, we observed a new record high output from wind generation, of 11.8GW. There have been recent instances where wind generation has supplied over 50% of demand. As far as I am aware, this proportion of wind generation is much greater than in any other region in the world. Spain is therefore a proving ground for the significant integration of renewable intermittent generation, and provides an opportunity for other countries to learn from their experience.

An extended account of our visit is appended to the end of this report. The most notable observations from our visit are summarised below:

- The key to Spain's successful integration of intermittent generation to date is the 4000-5000MW of pumped hydro generation which is spread fairly evenly across central Spain. By strategically utilising this generation, Spain have managed to allow their nuclear generation to continue operating while largely avoiding the need to constrain wind generation offline – even during periods of high wind generation and low demand. However, as the installed capacity of wind generation keeps increasing the capacity of the pumped hydro is becoming inadequate to avoid constraining wind generation for more of the time, resulting in wind being constrained offline more frequently. There are government incentives to encourage the development of more pumped hydro generation.
- Until 2005 there was no fault-ride-through requirement for wind turbines. Consequently, during system faults (when the voltage can briefly drop to a very low level), significant volumes of wind generation could suddenly trip, posing a risk to system security. The problem became so significant that when new requirements were brought into force in 2005 the Spanish government agreed to apply them retrospectively. This forced the majority of the existing fleet of wind turbines to be retrofitted with additional equipment in order to comply with the new requirement. In neighbouring Portugal there is still no fault ride through requirement. Late last year REE observed the sudden disconnection of 1500MW of wind generation in Portugal during a system fault.
- The low fault contribution of most intermittent generation is causing system fault levels to decrease generally, and especially during high-wind low-demand situations. In response, REE now ensure that at least one protection scheme on each item of plant is differential/unit scheme and are working with the distribution companies they supply to help them to ensure the ongoing effectiveness of their overcurrent relays.
- Given Spain's synchronous interconnection with Europe and significant volumes of hydro and nuclear generation, REE do not anticipate any problems with system inertia on their continental power system. However REE are also responsible for the Canary Islands, an island system where they envisage that wind generation may soon supply up to 90% of off-peak demand. REE are considering the use of synthetic inertia but have experienced problems with full-scale converters maintaining synchronism in weak networks.

- REE have recently proposed new requirements for yet to be constructed wind generation. The draft grid code includes firm requirements for voltage control, response to system frequency changes, and resilience to off-nominal steady state voltage and frequency conditions. The proposed code also prescribes the ability to ride through faults where the terminal voltage can drop to 0.0pu voltage (the previous requirement was 0.20pu, but with the reduction in system fault levels the minimum voltages seen during faults have also been decreasing). In general, the requirements being applied to intermittent generation are becoming increasingly similar to that which applies to conventional generation.
- REE has established a renewable energy control centre to help manage the 640 wind farms (plus other intermittent renewable generators). Its main functions are to aggregate data from all of the individual wind farms, forecast future generation, assess the power system's ability to cope with the anticipated generation (including any loss of infeed following system faults), and if necessary, to issue constraints to generators.
- REE has a relatively cautious approach to novel transmission technologies (especially when compared to National Grid). Presently there is an existing EdF phase-shift transformer on one of the interconnectors to France, and REE are in the process of installing two phase-shift transformers of their own. REE's only use of FACTS is a research project studying the effectiveness of a flow controller on the 120kV network. After serious public opposition to a new overhead AC interconnector to France, HVDC (line commutated, 2000MW) is going to be used for the new link. A smaller HVDC scheme will also be used to connect an island to the mainland.
- REE are implementing an extensive capital program driven largely by load growth, the development of high speed railways, and the growth of intermittent generation (RES). From 2008 to 2016 REE plan to construct:

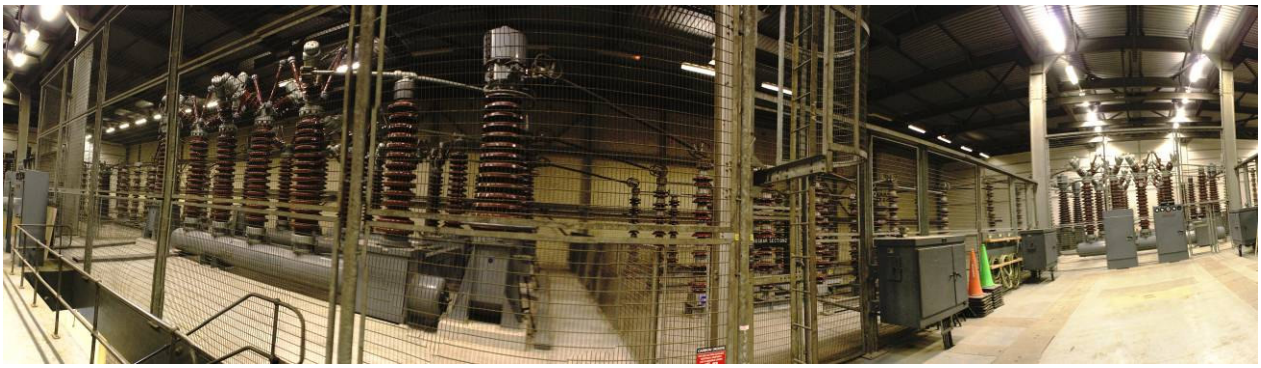
	Whole planned infrastructure			Specific infrastructure planned to integrate RES		
Lines and cables	**Total**	**400kV**	**220kV**	**Total**	**400kV**	**220kV**
New ones [km]	12656	7488	5168	4465	3504	961
Refitting [km]	8308	3850	4458	1730		
Substations	**Total**	**400kV**	**220kV**	**Total**	**400kV**	**220kV**
New bays	3476	1163	2313			
New substations	399	106	293	39	20	19
Extension of substations	405	76	329	59	18	41
Transformers	**Total**	**400 / 220 kV**	**400 / 132 kV**	**Total**	**400 / 220 kV**	**400 / 132 kV**
Additional capacity [MVA]	68540	52450	16090	5305	3500	1805

Reactances and Capacitors	**Total**	**400kV**	**220kV**
[MVAR]	3900	2800	1100

Visit to St John's Wood 400kV GIS Substation

In January I was able to visit St John's Wood substation, a major substation supplying central London. It consists of 132kV, 275kV and 400kV switchyards, two Static VAr Compensators, eight supergrid transformers and several sub-275kV transformers. It is presently supplied by 3x400kV and 4x275kV circuits (all cables).

The 132kV and 275kV switchyards have been present at the site for a considerable time. They formerly adjoined a power station, but this has long since closed. These switchyards both use air insulated switchgear, but unlike many Australian substations, are housed inside buildings. It was particularly interesting to observe the air-blast circuit breakers used in the 275kV yard. Because of the very high cost of circuit breakers at the time the switchyard was originally constructed, the switchyard is configured in a four-cornered mesh arrangement, with multiple connections to each corner. A photograph of one corner of the 275kV mesh is shown below:



Two Areva SVCs were installed in the early 1990's to manage voltage instability in the London area. Although adjacent to each other, the two SVCs are completely independent of each other and connect to opposite corners of the 275kV mesh.

Given a strong increase in demand in London throughout the 1990's, it was deemed necessary to connect a third 400kV circuit to the substation and install additional transformers. This in turn necessitated the construction of a 400kV switching station. Given the very limited space available onsite and the very expensive cost of land surrounding the substation (there are literally luxury apartments across the road from and overlooking the substation), gas insulated switchgear was utilised. This enabled the new 18-bay 400kV switchyard to occupy a similar footprint as the existing 275kV 4-corner mesh. A photograph of the switchyard is included below.

The personnel on site explained some of the additional concerns with using full GIS, including the need to prove and then monitor SF_6 gas pressures in chambers adjacent to any chambers being worked on during maintenance. Monitoring and minimising the leakage of SF_6 is another major concern, but has not been a significant issue to date.

To facilitate the additional 400kV circuit into St John's Wood a 3 metre wide, 20km long tunnel was bored from St John's Wood to a nearby 400kV substation. The installation of a remotely controllable monorail inside the tunnel allows for the condition of the cable to be inspected remotely, and for personnel to be transported to the scene of any maintenance. An additional cable tunnel will soon be bored to another adjoining substation to facilitate the installation of a fourth 400kV circuit into St John's Wood.

Full Converter Wind Farm Grid Code Compliance Testing

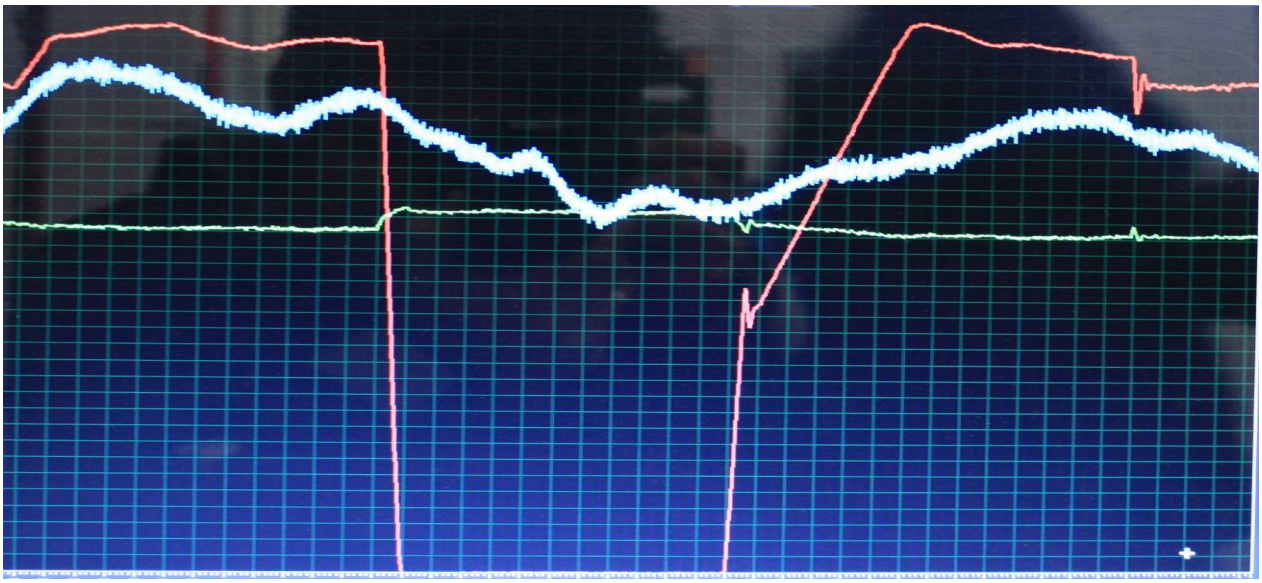
In February I was able to attend the final grid-code compliance testing of a new offshore wind farm. A photograph of the wind farm (taken from the shoreline) is included below:

The wind farm had already been operational for some time. However, during its initial compliance testing the wind farm had experienced some glitches with its frequency response controller – a problem that had since been corrected but needed to be verified by National Grid. The testing involved simulating a wide variety of power system frequency conditions and monitoring the response of the wind farm. Because some of the tests required the wind farm to significantly reduce its output, the tests could only be performed when it was sufficiently windy that the wind farm would be operating near its rated capacity. As such, the testing was re-scheduled several times, trying to align it with a forecast for good wind. When the testing did eventually go ahead one evening, part way through the battery of tests the wind dropped and testing had to be suspended. After a while, since the wind had not increased again and the wind forecast was for it to keep decreasing in strength, arrangements were made to attempt to complete the testing during a short window of high-wind forecast for the following week. Then, just before we started to pack up our equipment the wind increased in strength again and remained sufficiently strong for long enough that the testing was able to be completed after all. This experience highlighted to me the somewhat unpredictable nature of wind (even at short timeframes with detailed wind forecasts) and the consequent difficulty in trying to plan around the wind's availability.

The wind farm is the first in the UK to use full converter (type D) turbines. Full converter turbines utilise four-quadrant power converters rated for the full output of the turbine. The converters therefore entirely decouple each turbine from the grid. This decoupling enables the turbine to rotate at whatever rate facilitates maximum energy extraction from the wind. The power converter on each turbine responds almost instantly to instructions from the central wind farm controller, with the turbine blades then rotating over the next couple of seconds to ensure that the power generated by the turbine is approximately equal to the power being extracted from the turbine by the power converter. Any mismatch in the power produced by the turbine and extracted by the power converter will cause the turbine to change its rate of rotation. This configuration makes it possible for the wind-farm to almost instantly adopt any power output level and power factor requested of it, subject to the power available in the wind. It also allows for sudden variations in the in the wind speed to be absorbed in the mass of the turbine rotor, whilst the power converters regulate the flow of power into the grid.

While I was already expecting the wind farm to be very responsive, it was still very impressive to witness a large generator almost instantly adopting any power output level and power factor. The only exception to this was when the wind-farm was increasing its output after being forced to operate at a level significantly lower than the power available in the wind. The representative from the wind turbine supplier indicated that this was due to a lack of confidence in the estimated level of wind power presently available, and the need to not significantly overshoot this level. Were the power converters to extract significantly more power from the turbines than they could recoup from the wind, the speed of rotation could drop to a speed at which energy extraction from the wind would be far less effective, causing the power recouped from the wind to drop further

still and eventually causing the wind farm to suddenly drop to zero output. The representative explained that significant R&D was continuing into better equipment and techniques to estimate the level of available wind power, and that with greater confidence in this estimate the rate at which the power level was allowed to increase could be accelerated. An example photograph of the power-output level trace is shown in the figure below. The axes have been deliberately obscured to respect customer confidentiality. The red trace is the MW output of the wind farm, which is responding to a simulated system frequency change (unfortunately not shown). The thick white trace shows the variation in the actual system frequency while the thin white trace shows the voltage at the wind farm terminals.



In the long-term, it is expected that a significant proportion of the wind turbines installed in the UK will be similarly based on a full-converter design. Therefore, National Grid is considering how the controllability of full-converter turbines could be utilised to support the transmission network/power system. For example, developers in Great Britain have been advised that the GB Grid Code will be modified in coming years to require that offshore wind farms developed from 2015 onwards will be required to support 'synthetic inertia', whereby the power-converters on each turbine respond to frequency variations in a fashion that emulates the response of a conventional generator. National Grid is still refining the details of this new requirement. Using wind-turbines to provide an inertial surge of power when the frequency falls can reduce the rotational speed of the turbine blades outside of the optimal range for power extraction and lead to a net reduction in energy production over time. Additionally, while the characteristic of the inertial response of conventional generation is driven by physics, it is recognised that the power converters could be programmed to respond with any characteristic. The design of the synthetic inertia requirement is therefore seeking to find the most effective balance between an immediate inertial response and the power available in available in longer timeframes, and the optimal response characteristic. The use of synthetic inertia is considered to be essential in ensuring that the GB power system can continue to be operated securely as the proportion of conventional generation decreases.

Perhaps more relevant to Australia in the near to medium term, the controllability of full-converter based turbines could also be used to dampen oscillations in the power system and improve power quality (essentially acting as a STATCOM/SVC). The controller of the wind farm I observed already had the provision for a utility provided signal to be modulated onto the power output. If the amount of response normally required from the wind farm was slight (i.e. if a significant response was only required following contingencies), then using it in this fashion wouldn't affect the energy output of the wind farm. Such an approach could potentially provide an ancillary revenue stream to the wind farm developer, while cost-effectively increasing system security and/or raising stability-driven network constraints. Because the power converters directly control the power output of each turbine, they could be more effective at dampening power oscillations than SVCs, which can only influence the amount power consumed by local loads by raising and lowering the voltage.

Whilst it is possible for full-converter turbines to provide STATCOM/SVC services regardless of the wind level, they presently cannot alter their real power production/consumption (e.g. for oscillation damping) when the wind in slight. However, the world's largest supplier wind turbine power converters (Converteam) has recently announced that they are developing a power converter solution which incorporates energy storage and would enable this service to be provided continuously.

Fundamental Review of GB Network Planning and Operation Criteria

A common transmission planning and operational criteria is used throughout Great Britain, called the National Electricity Transmission System Security and Quality of Supply Standard (NETS SQSS). In 2008, a fundamental review of the standard was initiated to take account of the significant changes expected to occur in coming years, including:

- UK government plans to deliver policy that facilitates investment in approximately 35GW of new renewable generation in the UK between now and 2020.
    - The location of this generation will mean that significant network reinforcement is needed, perhaps including the development of interconnected offshore transmission networks.
    - Much of this renewable generation will be intermittent in nature, and the impact of this intermittency needs to be reflected in the SQSS.
- It is expected that new nuclear power stations will want to use generating units that are larger than presently accounted for in the SQSS.
- There are significant new interconnections to external systems under construction and more are planned. Interconnectors can result in large changes in flows within short timescales across the transmission system, and this needs to be taken account of in the planning process.

Earlier this year, the SQSS review committee decided to document the progress to date and consult the broader industry on various proposals to change the SQSS. I was given responsibility for liaising with the different working groups and helping to produce the consultation report. This work provided an excellent opportunity to better understand:

- the rationale behind different criteria in the SQSS,
- alternative ideas for how the transmission network should be planned/developed,
- the multi-faceted impact of the changes which are expected to occur.

In the second quarter of 2010 my responsibilities on this project were expanded to include membership of a special working group established to urgently resolve the outstanding issue of how to consider intermittent generation when planning the capacity of the main transmission network.

Given that this work continued beyond the first quarter of 2010 and was my sole focus in the second quarter of 2010, it is my intention to report on this work in more detail in my next quarterly report.

Next Quarter

The second quarter of 2010 will be my final quarter on the ES Cornwall Scholarship. In addition to my involvement in the development of Great Britain's revised planning criteria it will include a visit to the Finnish transmission operator Fingrid to learn about their internationally respected approach to asset management and a couple of shifts in National Grid's control room to learn about GB power system operations.

Acknowledgements

I would like to gratefully acknowledge the assistance and patience of those NGET colleagues with whom I worked during the quarter: Jo Zhou, Richard Proctor, Beehun Tan, Hardeep Garcha, Mark Perry, Duncan Hughes, Paul Plumptre, and Chris Humphries.

I would also like to thank David Alvira, Olivia Pilar Infantes Morales, and Miguel de la Torre from Red Eléctrica de España for taking the time to meet with Nick, Reena and I, and for the assistance of David Bones in organising the visit.

Soli Deo Gloria – to God alone be the glory.

Detailed Notes from my visit to Red Eléctrica de España

February 5, 2010 meeting with:

- David Alvira, Network Planning & Development
- Olivia Pilar Infantes Morales, Market Operation Department
- Miguel de la Torre, Electricity Control Centre Department

Local Conditions

Peak demand is approximately 48GW, minimum demand around 20GW.

Interconnectors:

Presently

Maximum exchange capacity presently (MW)		
	export	import
France	600	1400
Portugal	1500	1500
Morocco	900	600

In the mid term (~2015) rising to:

Forecasted maximum exchange capacity (MW)		
	export	import
France *	2800	3000
Portugal	3000	3000
Morocco	900	600

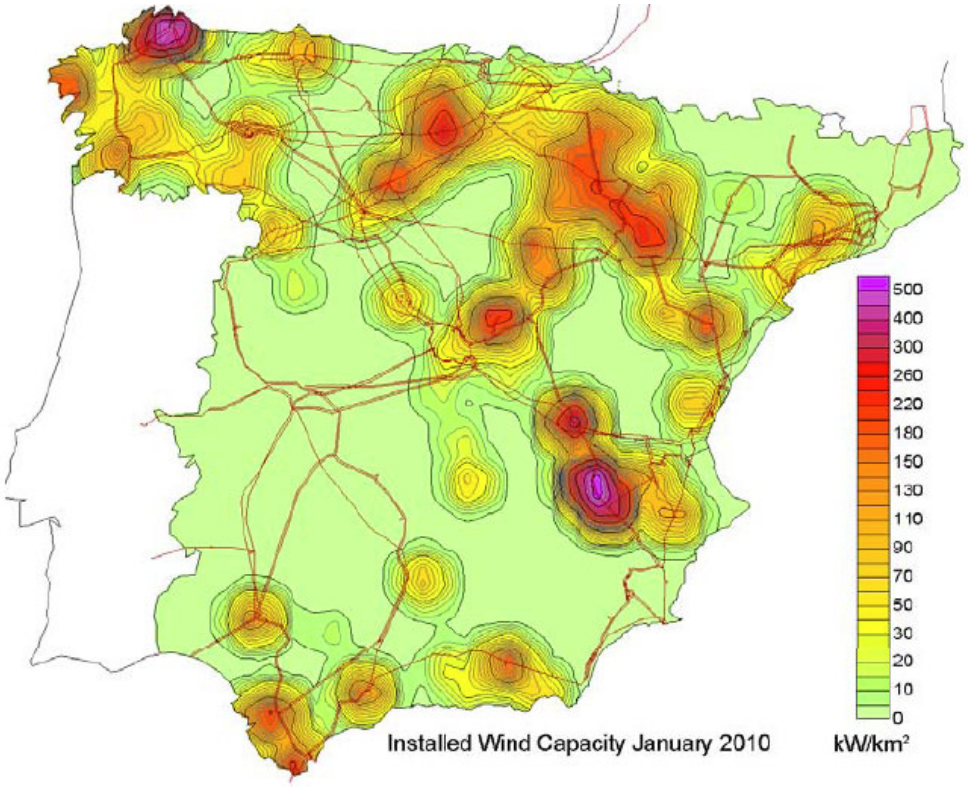
Interconnector to France possibly rising to +/- 4GW by 2020

Significant pumped hydro:

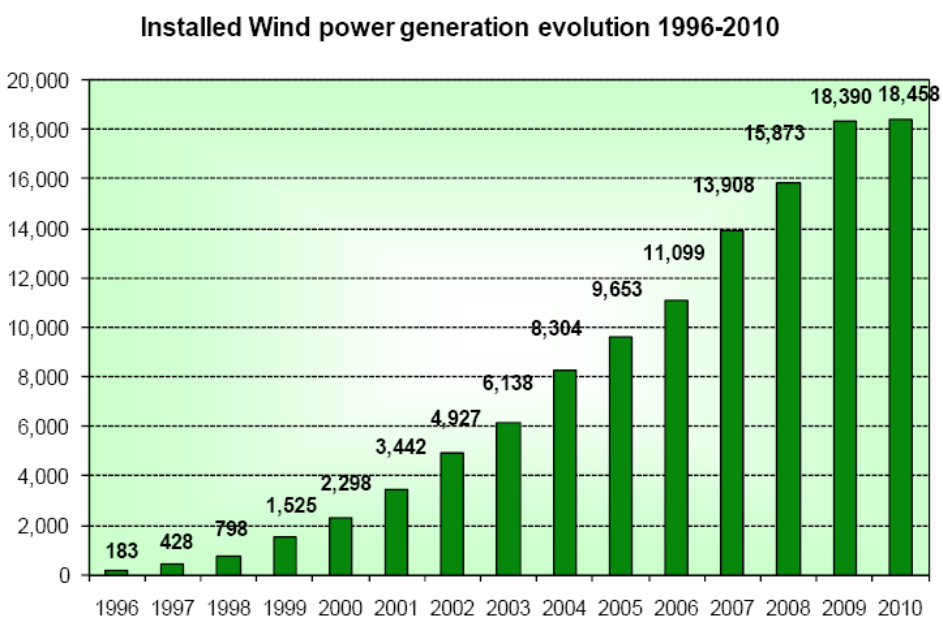
Pumping installations (MW) (mixed + pure)	
Today	2700 + 2700
2014	2700 + 3900
2016	3100 + 5700

Pumped hydro is considered a very important means of supporting high volumes of wind generation. There are incentives to try to encourage the development of pumped hydro, especially on the Canary Islands.

Presently ~18.5GW of wind generation capability is connected to the network, made up of 640 individual wind farms distributed fairly evenly across the country. About 90% of existing wind turbines are doubly fed induction generators (DFIGs, i.e. type C turbines with power converters that are rated for only part of the turbine's full output).



For the past few years, new wind generation has been installed at a rate of approximately 2GW/year, although this is now decreasing to around 1GW/year.



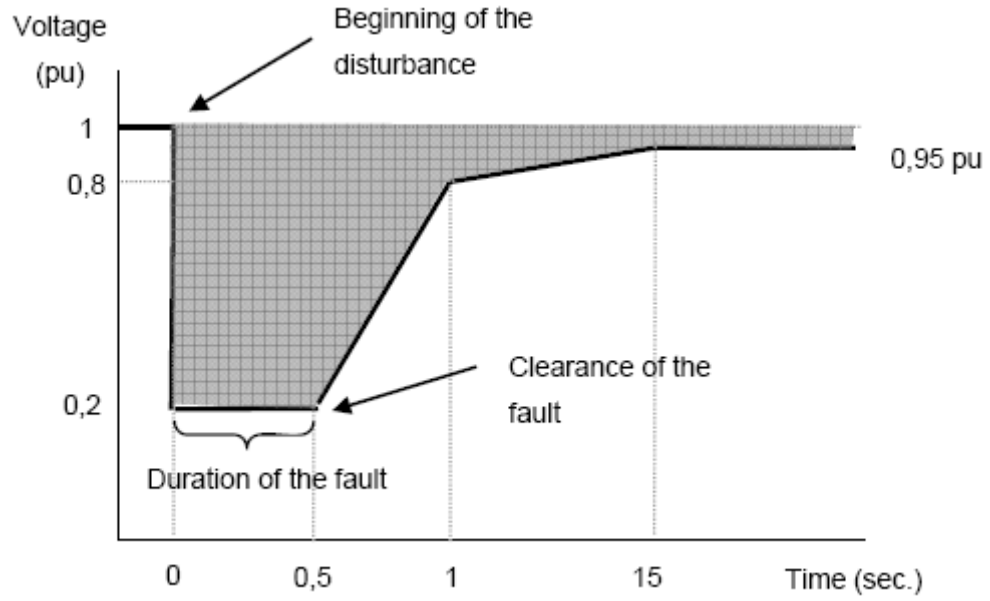
In the year 2005, the target for wind generation in the year 2010 was 20GW. REE expect that Spain will slightly exceed this target before the end of 2010. The target for 2016 is 30GW of wind generation.

Approximately 40% of existing wind generation is connected via distribution networks. About 20-30% of new connections are distribution connected, and this trend is decreasing with time (i.e. wind is increasingly transmission connected) as there are now high levels of congestion on distribution networks and competition with distribution-connected solar PV.

Requirements for Wind Turbines

Initially there were few requirements placed on wind turbines, including no prescribed fault-ride capability. During system faults, the wind generation in the region close to the fault (where the voltage is depressed) would commonly trip. As the volume of wind generation increased, the sudden loss of that generation following a fault increased to the point where managing system security was becoming a challenge. Additionally, REE needed to ensure that the maximum loss of generation remained under the 3GW maximum loss of infeed requirement applicable throughout the synchronous continental European power system.

In 2005, new requirements were introduced and required that turbines should be capable of riding through a voltage depression as depicted below:



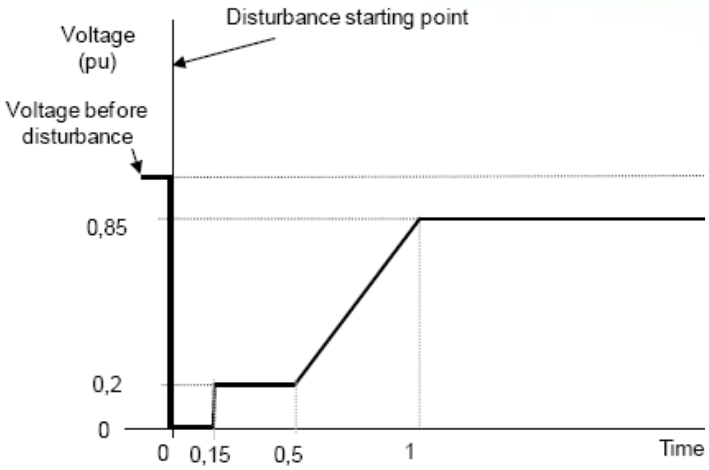
Because of the extent of the existing problem, the Spanish government applied the new fault ride through requirements retrospectively through a scheme that would constrain off non-compliant generation first (should there be a need to constrain off wind generation). Most wind turbines have subsequently been retrofitted to enable them to comply with the new

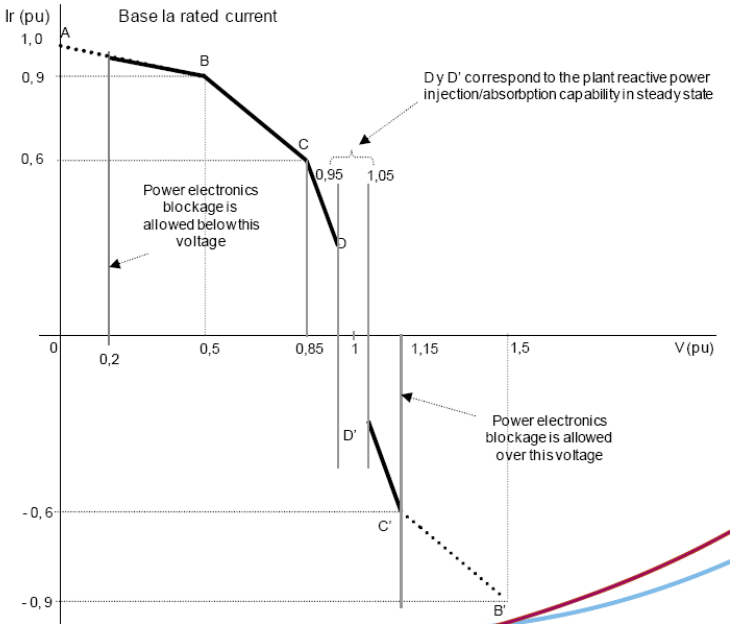
requirements, although this would not be economic or technically feasible for some wind turbines and these will continue as is, being constrained offline as required. Sufficient generation has now been retrofitted such that it is quite uncommon for generation to be constrained offline for this reason.

In REE's experience, wind turbine manufacturers were initially reluctant to comply with the new grid code requirements as they had previously been asked to trip at the first sign of trouble (a typical distribution requirement) and their R&D had tended to focus on developing larger and more efficient turbines. However, wind turbine manufacturers have now accepted the need to comply with increasingly onerous grid-code requirements as an essential requirement and have considerable R&D in this area. Indeed, the ability to comply with grid-code requirements without external STATCOMs etc is a key selling point of many modern wind turbines.

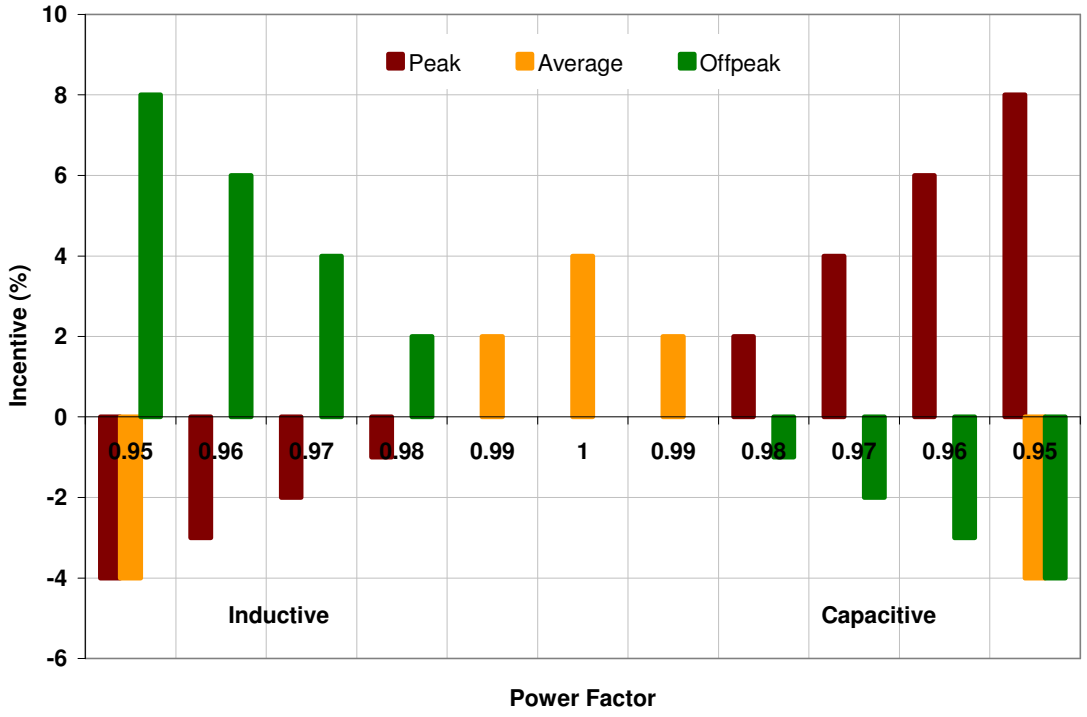
DFIG turbines remain the dominant technology used in Spain. Limited experience with full converter turbines have highlighted issues with maintaining synchronism in very weak island networks (i.e. not connected to the Spanish mainland).

Given the very high, and still increasing volume of wind generation, and the low fault contribution from intermittent generation, voltages during a fault can now be below 0.2pu. Therefore, new fault ride through requirements have recently been developed that require riding through 0pu for 150ms. The new requirements also specify the minimum fault contribution permitted at different voltage levels. These new requirements have yet to be formally incorporated into the grid code. Wind turbine developers have indicated to REE that they should be able to comply with the new requirement.

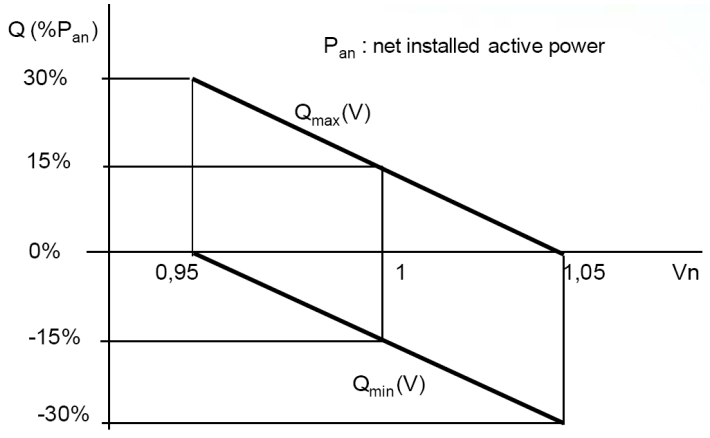


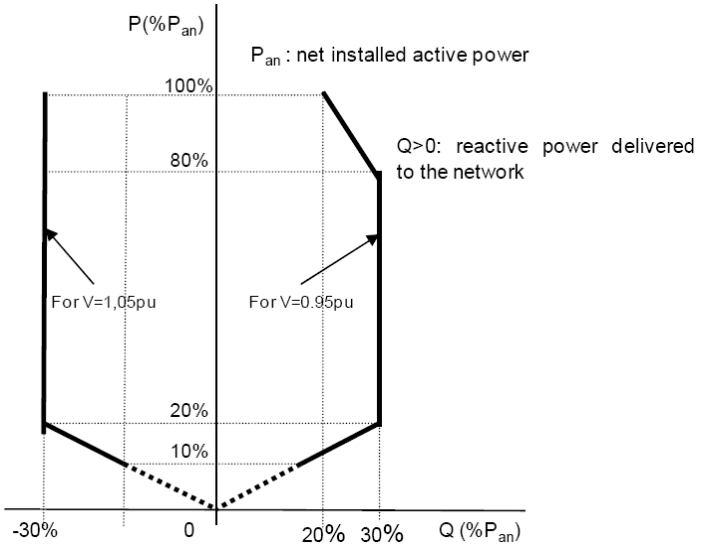


Presently, rather than enforcing a required reactive power output capability, wind turbines are incentivised to produce reactive power at appropriate levels by a scheme that rewards them for appropriate behaviour and penalises them for inappropriate behaviour. The power factor which is appropriate varies with the level of demand. This is depicted in the figure below.

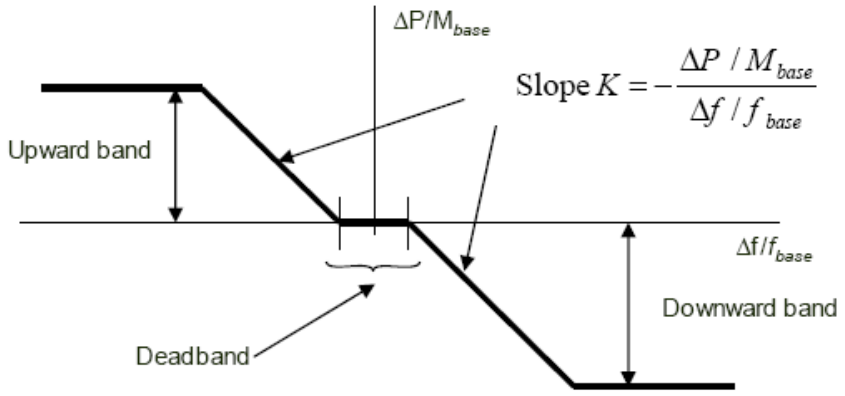


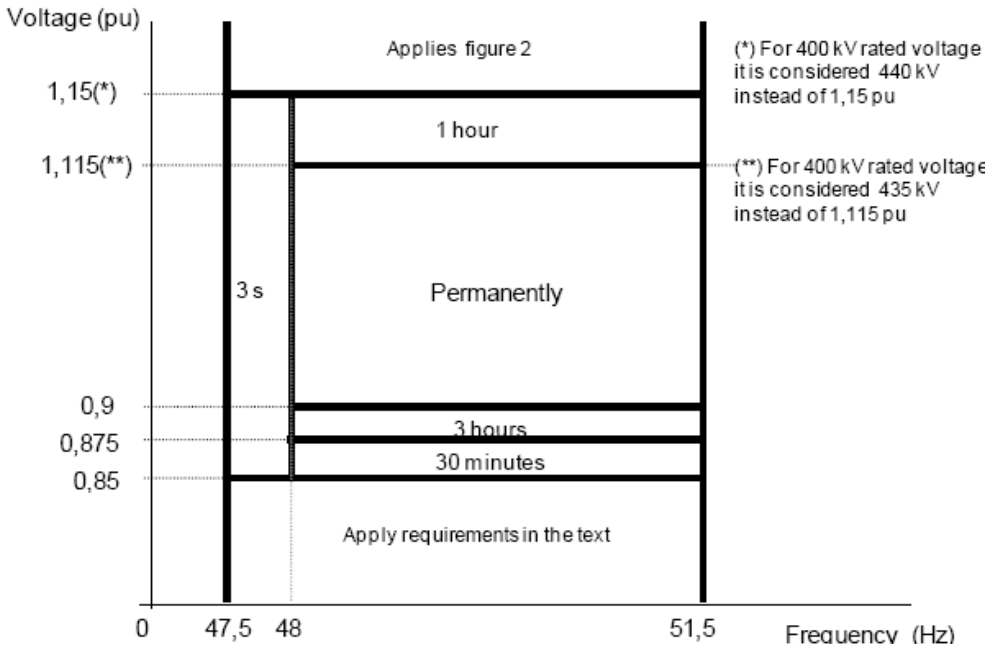
REE are able to change the targets for wind farms with several days notice, to support a network outage for example. However, almost all modern wind farms are able to be operate at defined power factors or regulate the voltage to a specific level and have the facility to modify the set point voltage remotely in real-time. REE are therefore looking to have the legislation changed to include required reactive power capabilities given different real power output levels and busbar voltages. Additionally, REE will require that wind farms are able to apply new voltage targets in real-time.





REE's draft new wind farm requirements also specify the required resilience to voltage and frequency conditions, and the response to frequency variations.



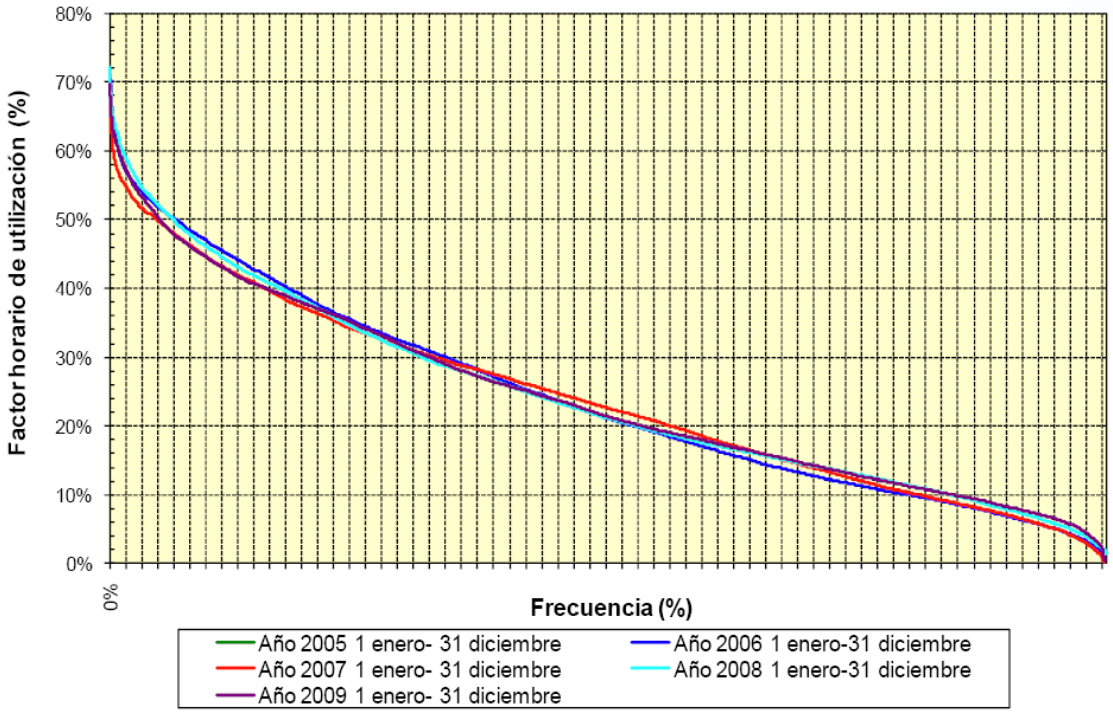


REE are also giving consideration to requiring that turbines support synthetic inertia.

In general, the requirements for wind turbines are becoming more and more similar to those for large conventional generators. This is necessary to maintain system security as the proportion of wind generation increases, and is becoming increasingly possible given wind turbine technology developments.

Operational Experience

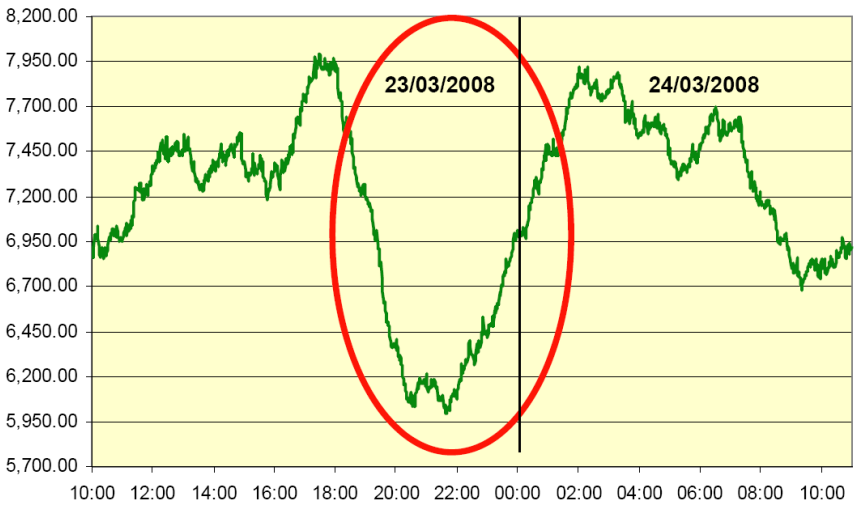
The availability factor of wind generation in Spain is quite low, with a national average of ~25% of installed capacity, as illustrated in the time-distribution plot below.



As of February, the maximum output of wind generation was 11759MW generation (64% of the installed capacity at the time). When wind generation is high, it tends to be well distributed across the country. To date, the maximum wind generation as a proportion of the demand at the time is 54%. The minimum level of production in 2009 was 164MW.

The biggest sudden loss of wind in Spain so far is 1100MW. Recently there was a sudden loss of 1500MW in Portugal (of 6000MW installed capacity). There are presently no fault-ride-through requirements on wind turbines in Portugal and the utility there has experienced difficulty with their government in getting such a requirement legislated.

The fastest ramp rate of wind generation observed so far is 1500MW/hour as a result of a storm front causing many wind turbines in a region to suddenly switch from full output to zero output (a safety mechanism to prevent overloading). An example instance of this is shown in the figure below.



Although the effect is sudden on each turbine, the effect is staggered when there are many turbines spread throughout a wide area. Although 1500MW/hour is significant, REE pointed out that this is still relatively slow compared to demand which can change at 4000-5000MW per hour.

The level of production from wind generation normally tends not to change very quickly. However, there is a trend for the wind to be stronger in the afternoon and evening, with a downward ramp in generation during the morning at the same time that the demand is starting to ramp upwards (i.e. further increasing the rate at which conventional generation needs to be ramped upwards).

Spain presently has 5000MW of hydro (4000MW of which is pumped hydro and can pump at -4000MW) which is well spread across the center of the country. This generation provides primary and secondary regulation and is the key to facilitating the wind generation that is presently connected to the system. When the wind is strong and demand is light, the seven nuclear power units in Spain remain at full capacity, but the pumped hydro will pump fully.

To date, wind generation has seldom needed to be constrained offline: one day in 2008, Dec 30 2009, Jan 1 2010 and Jan 20 2010. On these days, only 0.1% of generation needed to be constrained offline. However, the penetration of wind generation has now reached a stage where the present amount of pumped hydro can be insufficient in high wind situations. As more wind generation connects to the system, constraints will occur more frequently and involve a greater proportion of generation until more pumped hydro generation is brought online in 2014, and again in 2016. REE is supporting government incentives to encourage more pumped hydro development, as well as developing demand response services from electric vehicles. Wind is only constrained offline at last resort.

Congestion on the transmission network has increased somewhat due to wind generation, but most of the congestion affecting wind generation is on the distribution networks – especially when outages are being taken.

Because wind generation has a very low fault contribution, overall fault levels are decreasing. Therefore, REE now require that at least one protection scheme on each item of plant has to be differential/unit protection. REE are in discussions with the distribution networks they supply regarding the adequacy of their overcurrent relays.

REE have not yet constrained off wind generation due to concerns about system inertia and this is not envisaged as a concern on the peninsula/continental system. However, inertia is a potential problem in canary islands, which have a *peak* demand of 600MW and may soon have up to 400MW of wind. REE expects that the Canary Islands will be a proving ground for technologies to facilitate such a high penetration. The government has launched incentives to encourage pumped hydro development on the islands.

The location of some of the wind generation has in the past led to problems managing the steady-state voltage in some regions. However, this situation is now greatly improved following the development of a new 400kV circuit, and the construction of several new CCGTs in strategic areas.

Managing the loss of power generation following system faults is still the main difficulty associated with wind generation, and is a key function of the renewable generation control centre. In retrospect, it would have been much better to require fault ride through capability years earlier. Convincing the government of the need to apply the requirement retrospectively was very difficult.

Control of Wind

REE has established a renewable energy control centre to help manage the 640 wind farms (plus other intermittent renewable generators) in Spain. It is co-located with their main power system control centre. In the photograph below, the renewable control centre is visible to the left, and the power system and transmission control centre to the right.

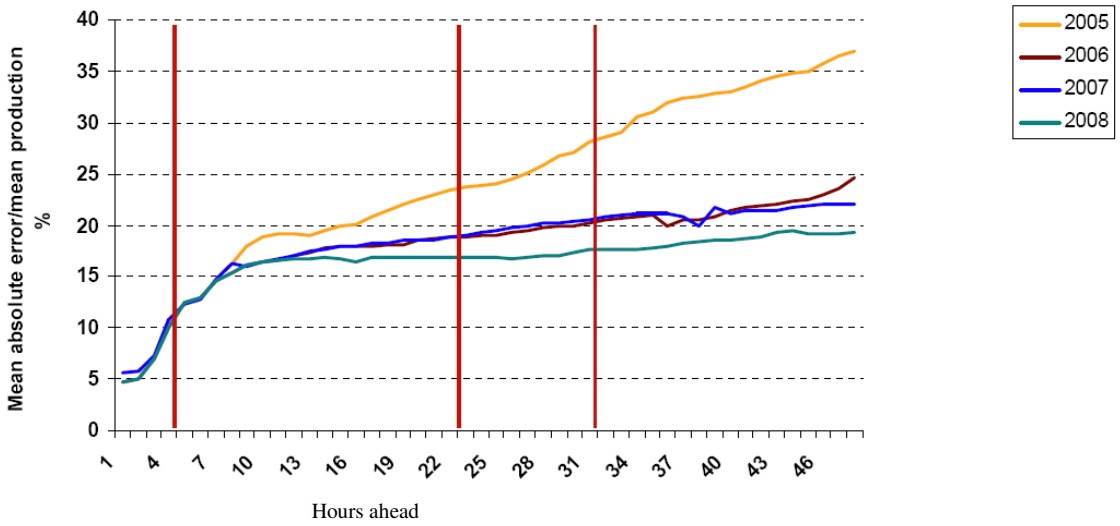
The main functions of the renewable control room are to:

- aggregate data from all of the individual wind farms
- forecast future generation
- assess the system's ability to cope with the generation
- if necessary, issue constraints to generators (sent automatically by SCADA)

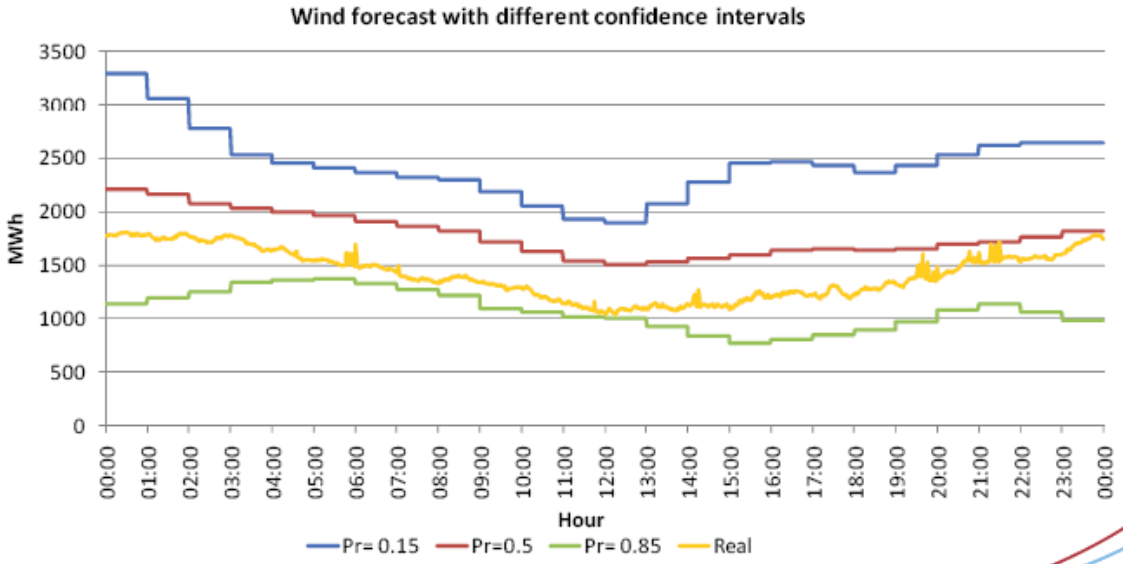
Photograph copied from REE's public website: http://www.ree.es/ingles/operacion/regimen_especial.asp

All renewable generation over 10MW in capacity is visible to the renewable control room. The control room does not liaise directly with each wind farm/generator. Instead, most wind farm developers have contracted out the monitoring, operation and bidding of their wind farm to one of 23 non-REE control centres. REE therefore liaises and interfaces with these control centres, on behalf of the individual generators. This is certainly easier for REE than liaising with 640 individual wind farms, but still presents a challenge to the operators.

Over the past few years, REE have been refining a wind forecasting application. The accuracy of the tool is continually benchmarked. Its typical accuracy from the past few years is shown below.



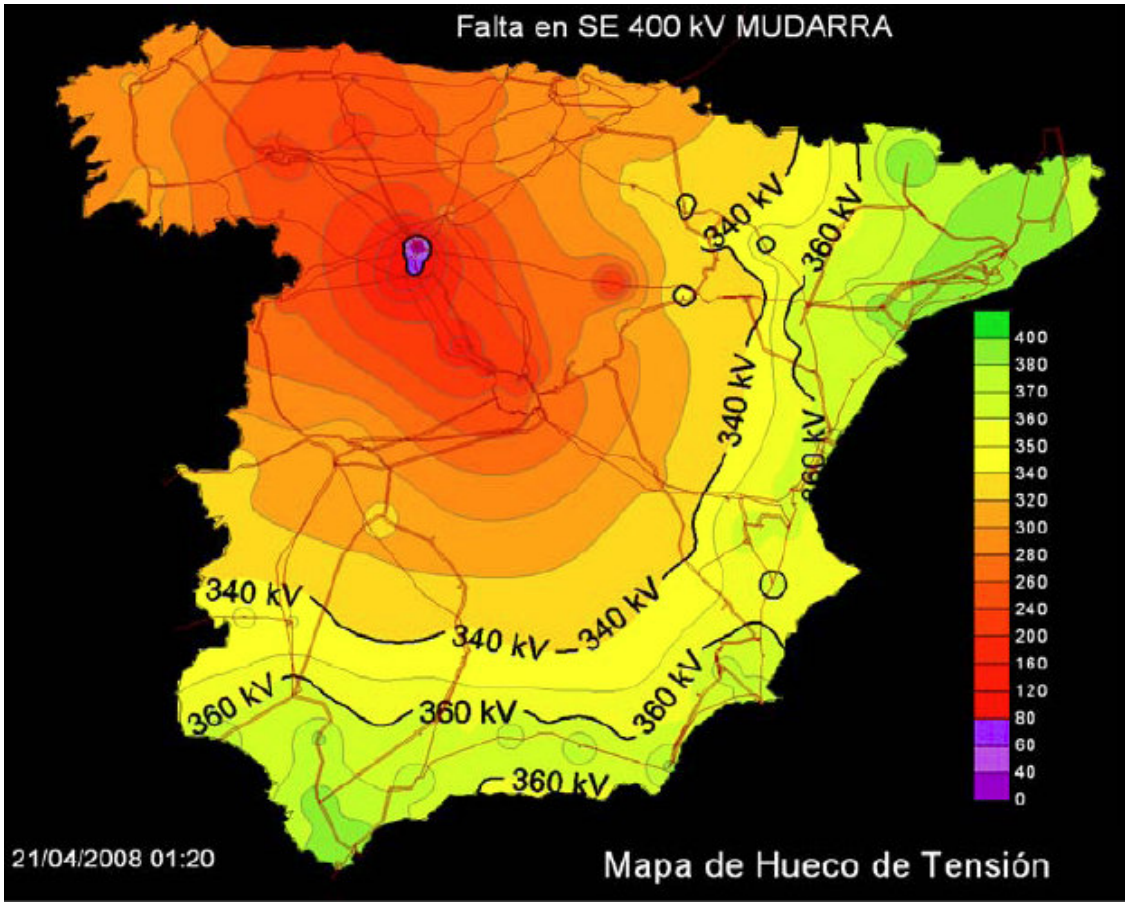
The forecasting tool is mainly used in the intermediate term (day ahead) to plan generation reserves. To take account of the uncertainty, upward reserve is planned based on the 85% confidence interval and downward reserve is planned based on the 15% interval.



REE categorise their outages into two groups:

- Outages related to the important maintenance of HV equipment and implementing the capital program are part of an annual outage plan. These outages take priority over wind conditions.
- Flexible outages relating to vegetation management or outages that have a fast return to service. These are programmed to try to coincide with times that minimise disruption to the market, including periods when the wind is forecast to be such that will minimise the impact of the outage.

The renewable control centre constantly performs studies to assess how much will disconnect were a three phase to earth fault occur at each of the main nodes in the system, to ensure that the European 3GW infeed loss limit is being respected. The margin between the worst fault and the 3GW (or the spare capability left on interconnectors to France if lower - which is usually the case) is then monitored. A screenshot from the application that performs the analysis is included below, and shows the voltage gradient resulting from a fault. The likely loss of generation can then be calculated using the known fault ride through capability of the different wind farms.



Market

In the Spanish electricity market, generation can be traded via bilateral contracts or through the spot market. The spot market similar to that in Australia, with all generation paid the marginal price. Additionally, there are markets for ancillary services.

There is presently no provision for negative spot prices. The spot market doesn't see the cost of green energy, and wind is often offered with a price of zero. However, the price being passed onto consumers has increased in recent years. €5b was paid to renewable generators last year via Spain's feed in tariff support scheme. However, only part of this bill is presently being passed onto consumers, with the balance contributing to government debt (a controversial issue).

REE have observed a reduction in the amount of conventional generation being planned, although this may also be attributable to general economic circumstances.

Planning

REE use a probabilistic approach to planning the capacity of the main transmission system, based on 700 scenarios that combine:

- high demand and low demand:
  - on the mainland: 60% of installed wind generation (20% probability), 10% of installed wind (10% probability)
  - on the islands: 100% and 30% of installed capability
- high and low demand (6 tiers of each)
- summer and winter
- high and low hydro

Practically, this is implemented using PSSE and an internally-developed package to manage the scenarios.

For regional studies, historical statistics are used to identify reasonable worst case situations to plan against.

The process takes quite a long time to work through. The first time REE used the probabilistic approach, they also ran their existing deterministic approach in parallel both to compare the results, and as a backup should problems be encountered. REE were initially concerned that the probabilistic approach could overlook certain important network conditions and result in a network that is not adequate for all situations. However, this hasn't been a problem to date and most planners are becoming more confident in the process.

The reliability criteria are generally based on N-1 with N-2 for double circuit overhead lines greater than 30km in length.

Network Development/Technology

REE has agreed a €9.2b investment plan with the government for the period 2008-2016, that includes:

	Whole planned infrastructure			Specific infrastructure planned to integrate RES		
Lines and cables	**Total**	**400kV**	**220kV**	**Total**	**400kV**	**220kV**
New ones [km]	12656	7488	5168	4465	3504	961
Refitting [km]	8308	3850	4458	1730		
Substations	**Total**	**400kV**	**220kV**	**Total**	**400kV**	**220kV**
New bays	3476	1163	2313			
New substations	399	106	293	39	20	19
Extension of substations	405	76	329	59	18	41
Transformers	**Total**	**400 / 220 kV**	**400 / 132 kV**	**Total**	**400 / 220 kV**	**400 / 132 kV**
Additional capacity [MVA]	68540	52450	16090	5305	3500	1805

Reactances and Capacitors	**Total**	**400kV**	**220kV**
[MVAR]	3900	2800	1100

Apart from renewable energy (RES), the major drivers for reinforcement are load growth and the development of high speed rail links.

REE have a fairly conservative approach to new transmission technologies. There is an existing phase-shift transformer on one of the interconnectors to France, and REE are presently installing two phase-shift transformers. The only use of FACTS is a research project studying the effectiveness of a FACTS flow controller on the 120kV network.

After serious public opposition to a new AC overhead interconnector to France, HVDC (line commutated, 2000MW) is going to be used for this link. A smaller HVDC scheme will also be used to connect to an island off the east coast.