Dynamic power markets enabling effective decarbonisation in the EU:

How to boost investment in the flexible balancing capacity?

2030 dynamic modelling study on roadmap scenarios
Table of Contents

Introduction .............................................................................................................. 3
Power system architecture ....................................................................................... 4
New challenges of decarbonised European Electricity System ............................... 5
Dynamic Balancing Solutions ............................................................................... 10
Smart Power Generation in the 2050 roadmap scenarios ..................................... 13
Necessary stops towards the optimum power system .......................................... 22
The enablers of dynamic balancing power ............................................................ 23
Conclusions ............................................................................................................ 27
Introduction

The European Commission released the Energy Roadmap 2050 on 15 December 2011. The purpose of the roadmap is to explore the challenges posed by the EU’s decarbonisation objective (80-95% cut in CO₂ emissions by 2050). The Roadmap seeks to develop a European framework for reducing greenhouse gas emissions from the energy sector and presents scenarios that explore possible pathways to show how our energy landscape might look like if certain routes towards decarbonisation are taken. All of the scenarios imply major changes in, for example, carbon prices, technology and networks.

The common aim of the Commission, Council and the European Parliament is to agree on concrete deliverables which would use the 2050 roadmap as the basis for developing a long-term stable EU policy framework. One key aim of the future policy is to reduce investor uncertainty in order to boost market-driven investments into low-carbon energy production.

The Council has already emphasized the urgent need for a major transformation of the EU energy system in a sustainable, cost-efficient and technology-neutral way. The challenge is that the characteristics of each Member State need to be taken into account without allowing major national policy deviations while at the same time securing competitiveness and security of energy supply.

This background paper outlines the key system level points that Wärtsilä wishes to emphasize in the 2050 Roadmap follow-up work. It also evaluates the role of dynamic balancing power which is needed for ensuring the maximum level utilisation of power generation based on renewables. Furthermore, it proposes some follow-up actions for the European Commission which are needed in order to ensure reliability of the system and to advance investments crucial for enhancing renewable energy generation in the EU.
Power system architecture

An optimum power system consists of the system components (e.g. generation plants and grid) and system operations. The system components include:

- Generation capacity mix
- Transmission and distribution grids
- System balancing solutions

System operation is about forecasting future demand and all the actions and decisions made to start and stop generation plants in merit order, to continuously maintain the power system frequency at 50/60 Hz, and to utilize the grid optimally. In some markets such decisions are made thru competitive markets which define how and when the plants are operated.

The desired state of an optimum power system is such where the system delivers affordable and reliable power without polluting the planet. These three cornerstones of a smart power system are carried through this document, when simulating the future power systems based on EU 2050 Roadmap scenarios.

![Affordable, Sustainable, Reliable power system](image)

*Fig. 1. A good power system delivers competitive and clean power, and offers good security of supply.*

Fortunately power system operation can be simulated using dispatch modelling softwares, which simulate the operation of the power system and are capable of optimizing the full system utilization with regard to costs, emissions and system function. Future system models always consider the necessary balance between demand and supply, but unless dynamic hour-to-hour and minute-to-minute modelling is done, they cannot answer the question would the system actually work and would it be capable of delivering the targeted cost and emissions. Such dynamic softwares enable the true seeking of the optimal power system, being simultaneously affordable, sustainable and reliable.

One major hurdle in designing a good power system is that the players (grid companies, utilities, distributors, regulators, markets...) have different targets and they can hardly take the system jointly towards the optimum cost, reliability and emissions. Sub-optimization is inevitable. Having a common view of the desired power system of the future would enable the parties to agree on goals and rules that would guide the whole power system towards the optimum.
New challenges of decarbonised European Electricity System

System balancing

Maintaining a real-time balance between electrical energy generated and consumed is essential for safeguarding power system security. Because of the non-storability of electricity, disturbances of equilibrium between generation and load cause the system frequency to deviate from its set value, which affects the behaviour of electrical equipment and - in the case of large deviations - may lead to protective disconnection of consumers and generation units and eventually even to a system black-out. For this reason, aberrations in demand, generation and transmission must be handled instantly and constantly.

As soon as electricity demand exceeds the output of the generators, the difference will result in energy being drawn from the rotating mass, the inertia, of the generators so that their rotational speed will decrease. If the speed of the generators drops, the frequency of the voltage and current waves decreases. As described, such frequency change has an immediate effect on sensitive equipment such as large electric motors driving production processes, electric clocks and special types of illumination equipment. At the same time the capacity of a generator decreases when its rotational speed goes down. Keeping the system frequency constant is the main goal in a power system. A constant frequency is by itself a perfect indicator for balance between electricity production and demand.

“Balancing” refers to the process through which Transmission System Operator (TSO) manages the physical equilibrium between injections (generation) and withdrawals (consumption) on the grid. The physical balance of the electricity system changes all the time due to demand or supply variations, which need to be managed by the TSO to ensure stable frequency and voltage levels second by second.

There are several common rules for balancing, but also variations from country to country. Regardless of the market or country, some universal principles to well-designed balancing can be found:

- The system level frequency and voltage should be steady, since variations in frequency can lead to disconnection of generation and in the worst case to black out
- Failure in supplying electricity for even one hour per year can result in high financial losses for sensitive applications. Annual loss of electricity supply of 0.01% of the time equals to 53 minutes per year
- The TSOs require a wide range of services to manage the power system securely in different timescales and during various situations. The procurement cost of these services should be minimized without jeopardizing the electricity quality in the system
- Balancing services should enable wide scale integration of renewable capacity and to ensure maximum utilization of this capacity. To secure this the balancing services should be able to react on fast changes, have high efficiency, avoid unnecessary operation, and start and stop when required. These characteristics are needed to secure successful integration of renewables.
What are the system balancing tasks and specific requirements in the current system?

A power system needs to balance the generation and consumption of energy over multiple timeframes from seconds to hours and days. Regardless of careful planning and forecasting, events when the demand and generation vary, occur. Traditionally, there are three main causes for the imbalances between supply and demand that requires actions from TSOs:

1. Load varies in a predictable pattern throughout the day. Demand for electric energy changes continuously, depending upon the time of day, day of the week and the season. After midnight, demand generally minimises because of reduced human activity. In the morning, when people wake up, they switch on appliances, railway systems intensify running, offices open up, shops will start business and factories increase their power demand. This requires active “load following” by the system operator.

2. There are unpredictable, constant small fluctuations in most loads.

3. There are generator and transmission & distribution line outages.

In all these cases the TSOs need to guarantee security of supply and maintain stable frequency and voltage levels. The TSOs require a wide range of services to manage the power system securely in the different timescales and during various situations. This is typically done via a series of contracts, signed by TSOs with different parties, for different services over different timescales. These services form part of what are commonly referred to as Ancillary Services. The definitions and treatment of the ancillary services vary quite a lot from country to country, but the objective of these services is same in each country: secure stable system operation.

Load following

The processes of meeting generation and load consist of day-ahead schedule, hour-ahead schedule, and real time dispatch planning. Forecasted load duration curves give ramp rates, indicating the speed of the resource that needs to be available to meet it. Over time statistical information has been collected and load patterns are largely well understood and can be forecasted with high accuracy. The morning and evening demand ramp rates are large. However, they are well predictable so the ramp response requirements can be met e.g. by starting thermal power plants well ahead of the actual load growth.

The system operator task is to forecast the daily load curve on hourly and sub-hourly basis, and to plan the operation order of various plants in optimal way (merit order). In the liberalized and open markets, the optimal dispatch order is defined usually in day-ahead markets, where the generation merit order is settled according to competitive marginal costs. The TSO gets information on the anticipated production mix and compares this information to the estimated demand, and plans actions to cover the difference between scheduled generation and actual load.

Even though the load curve is quite predictable and generation levels are known in advance, some changes in the production and consumption level occur all the time. Therefore, TSO may need to carry out some reserves to balance the demand and production close to real time to maintain the system balance. There are differences among European countries, but usually there is some kind of close to real time balancing mechanisms that provides a way to buy and sell additional energy before actual moment.
Unpredictable and constant small fluctuations

The frequency of the power system describes the balance between electricity production and consumption: The better the balance, the smaller the frequency variation in the grid and the better the electricity quality. In the current electricity systems, the load and generation can be quite well predicted which enables efficient and reliable system operation. However, there are constant small fast fluctuations in the electricity consumption and generation that can't be foreseen e.g. lights are lighted up at stadium or some industrial process is shut down rapidly etc. The TSO or DSO (Distribution System Operator) needs to be prepared to take care of these constant fluctuations to maintain the frequency level and electricity quality. This requires a sufficient volume of so-called spinning reserve in the power system. This is provided by so-called frequency controlled normal operation reserve, which is provided by operating plants that can decrease or increase the level of production in seconds and restore the generation levels in a few minutes. It is obvious that such reserve costs money to the provider as the spinning reserve power plants are operated at part load and typically with somewhat reduced efficiency, and higher CO₂ emissions.

If it is not possible to keep the frequency within in the allowed limits using the operation reserve alone, automatic frequency control reserves are activated. These reserves are typically also spinning reserve that react rapidly to changes in frequency levels. This is a tool for TSO to maintain system balance at least 30 minutes or even longer.

Generator or transmission line outages

As stated before, the system frequency needs to be maintained at a certain level second to second, even in the case of big generation or transmission line outage. This security of supply procedure is called as N-1 principle, which defines the contingency level as a trip of the biggest generation or transmission line that cannot be predicted in advance. Unpredictable loss of generation unit, for instance a nuclear power plant, causes immediate frequency drop, in which TSO can react with a series of actions. Partially these actions are the same ancillary services that are used for normal frequency control caused by constant small difference between generation and demand levels:

- **Primary reserve** (frequency controlled normal operation reserve) automatically reacts within seconds as a joint action of all parties involved. The primary reserve usually tries to minimize the frequency dip. These reserves are all in operation (spinning) as there has not been any thermal power plants that can provide primary reserve from stand-still within the required 30 seconds time frame (i.e. without emissions and fuel costs)
- **Secondary reserve** (automatic frequency control reserves) replaces primary reserve over minutes and is put into action by TSO only. The secondary reserve tries to get the frequency back to the nominal
- **Tertiary reserve** partially complements and finally replaces secondary reserves by re-scheduling generation and is put into action by TSO. When the primary and secondary reserves are commonly provided by operating plants (so-called spinning reserve), tertiary reserve is provided by so called non-spinning reserve.
How will intermittent renewables integration affect system balancing?

In the current systems, TSOs contract reserve and response capacity in day-ahead and longer-term markets with generators to provide flexibility that can be called upon on short notice to balance the system when earlier described forced power plant outages or load prediction errors occur. Balancing has been necessary for relatively small volumes (load or generation prediction errors) or fault events of small probabilities (power station failures) and relatively small size compared to the total system size (i.e. 0.5...3 %).

Load forecasting is quite predictable day-ahead, so currently TSO can estimate well in advance the system balancing requirements to meet the demand uncertainty and load volatility, and start and stop power plants well in time before they are needed. Increasing the amount of intermittent renewable generation (wind & solar) brings a new aspect to the system balancing. Such renewable energy generators cause unpredictable fluctuations in the generation fleet output. These have to be balanced – or mirrored - with other generation units or with some other means (storage, demand response etc.) to maintain system balance. In the future systems with high level of wind and solar power capacity, TSO need to be prepared to much greater uncertainty and fast variations of generation output.

The uncertainty of wind generation forecast increases rapidly when the lead time is prolonged. The forecast error for wind production in 24 hours ahead can be more than 25-30%, corresponding to ~100 GW on EU 2020 power system. The magnitude of this “error” is something totally different than the reserved capacity for managing system failures today. Wind forecast gets more accurate when the forecasting time period is reduced, but some forecasting error will remain also in very short lead times (minutes) , which needs to be taken in consideration by TSO when estimating adequate fast reserve levels for system balancing. TSOs can’t fully trust on today’s short term balancing markets to provide necessary balancing when the wind production decreases as such fast capacity does not exist in the quantity necessary in the system. They need to find a way to procure more balancing capacity, which are available fast enough to react on unpredictable changes in wind generation. Such reserves were not needed in the past so they do not exist in adequate quantity in the present power systems.

Over the course of minutes and hours, the output of a wind generator continuously varies, ranging from zero MW at 3 m/s wind to maximum output at around 12 m/s. While TSOs try to predict changes in wind generation, they also need other capacity, sufficiently flexible, to offset unexpected changes in its output. The need for this kind of flexible balancing capacity depends on wind characteristics, which are somewhat different e.g. on-shore and off-shore. In a recent study by Wärtsilä the maximum changes in wind generation output in EU in 2020 were estimated. The total wind generation output was estimated at 285 GW out of which 40 % off-shore.

<table>
<thead>
<tr>
<th></th>
<th>10 min</th>
<th>1 h</th>
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<tbody>
<tr>
<td>Max. wind production negative change rate GW</td>
<td>-17</td>
<td>-40</td>
</tr>
<tr>
<td>Max. wind production negative change rate %</td>
<td>-6</td>
<td>-14</td>
</tr>
<tr>
<td>Max. wind production positive change rate GW</td>
<td>37</td>
<td>63</td>
</tr>
<tr>
<td>Max. wind production positive change rate %</td>
<td>13</td>
<td>22</td>
</tr>
</tbody>
</table>

Table 1. Maximum wind generation changes in 10 minutes and 1 hour, EU 2020. Source: Wärtsilä
A large amount of wind data was analyzed, both in North Sea and on-shore. The numbers in table 1 represent magnitudes i.e. they describe the necessary quantity of fast reserves of wind balancing. Naturally the balancing reserve needs to ramp in the other direction than the wind power. To give a magnitude to the numbers, the 63 GW upswing in wind power production in 1 hour corresponds to the whole German power system load.

The amount of solar power in the EU power system will approach 100 GW by 2020. Adding the changes in solar output during sunrise and sunset to the wind changes expands the hours dynamic reserve need close to 100 GW. The capability to start and stop 100 GW within an hour must be built in the EU power system by 2020. Starting and stopping capability of such capacity may be needed and used several times per day, without any clear or predictable pattern between days, months or years.

TSO must schedule sufficient flexible resources to meet the flexibility requirements continuously. The most efficient operational resources are those, which maximize the amount of flexibility available while minimizing cost and emissions. Since the wind production levels in a region can vary significantly in 10-15 minutes for example when a low pressure frontier enters the region, this balancing capacity need to have true dynamic characteristics to maintain the frequency levels and to support set decarbonisation goals:

- Fast starting and stopping, without impacting on product reliability and operating costs
- Fast loading: from standstill, ramp up and ramp down (matching the speed of change of wind power output, the fastest reserves need to be on-line producing full power in 5 minutes and back at full stop in 1 minute
- Capability for continuous cyclic operation
- Wide load range, preferably as close as possible to 0-100% with maintained high efficiency
- Low carbon and other emissions (high efficiency and gas operation where reservoir hydro is not available)
- Optimal plant size and location from total power system (TSO!) point of view
- Fuel flexibility (natural gas and biofuels)

<table>
<thead>
<tr>
<th></th>
<th>Nuclear</th>
<th>Thermal Coal</th>
<th>GTCC</th>
<th>HDGT</th>
<th>Aero GT</th>
<th>Smart Power Generation</th>
<th>Hydro</th>
<th>Pump Hydro</th>
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<td>&gt;60</td>
<td>6-13</td>
<td>6-13</td>
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<td>60-90</td>
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<td>&lt;2</td>
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<tr>
<td>Stop from full load (min)</td>
<td>30-60</td>
<td>10</td>
<td>5</td>
<td>1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td></td>
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Table 2. Starting and stopping times of various power plants.
Dynamic Balancing Solutions

Various solutions are available for system balancing tasks. Some of these solutions are still untested, some already proven and available. Different balancing solutions have different characteristics with regard to the time they can be utilized and the amount available. Below is a short summary of available options.

Demand response and smart grids

Power system balancing and reduction of peak loads or load shifting, can to some extent be handled with demand response. The magnitude of the potential depends on the type of load. Demand response is most cost effective for larger loads, such as industrial processes, especially in cases where the process itself includes an intermediate storage or buffer. Naturally there is always cost involved in form of lost revenue, and the time of the plant shut down may be limited due to process etc reasons.

On a smaller scale, such as households, smart grids with smart meters are being promoted. There, however, the specific cost compared to load shifting potential is high. There are also limitations on how long continuous household loads can be shut off, e.g. a refrigerator 15 minutes and heating approximately 4 hours so it will function best as a short term load shifter.

The potential of demand response is though not insignificant. A recent study made for the ERCOT grid in Texas shows that 8% of the peak load would be shiftable with reasonable costs.

Spinning reserve

Spinning reserve is unused generation capacity that is synchronized and ready to ramp up and thereby serve additional demand on decision of the system operator. Such capacity can be called for relatively rapidly. Typically the system operator pays a generation company to provide spinning reserve, based on lost revenue. Spinning reserve requires that capacity is operated at lower than nominal output, which with most technologies results in lower efficiency and consequently higher carbon emissions.

Storage

Electric energy is difficult to store. Capacitors have limited capacity and are very expensive making them unattractive in large scale use. Conventional lead-acid batteries cost about 75 000 €/MWh and have the restriction that they prefer slow charging and rather fast discharging. Additionally, lead-acid batteries should not be discharged completely since it reduces their lifetime. Lithium based batteries on the other hand can accept fast charging and discharging but cost at least 800 000 €/MWh. Present batteries do not make much commercial sense in grid size storage applications while a lot of R&D is put in developing better batteries.

Pumped hydro has potential to play a role in storing energy from renewable generation. The principle is that surplus electric energy is used to pump water into an elevated reservoir, and later when power is needed the stored water is lead through a turbine generator system. In larger scale, around 500 MW, the cost of a pumped hydro system is approximately ¼ of a lead-acid battery based system.

There are some challenges related to pump hydro: the electricity needed to drive the pumps must be generated with some other power plants and about 25% of the electrical energy is lost in the process. Another aspect is the fact that depending on the original power source pumped hydro isn’t
necessarily renewable energy. If, for example, pump storage is used during the night to enable coal fired power stations to maintain minimum load (to avoid stopping them), the power produced later by the pump hydro is most carbon intensive as the pumping was done with high carbon minimum loaded coal plants, and some 25% of the power was lost on the way. At the same time, if the system contains enough wind power to stop all thermal generation, pumping excess wind power makes more sense. Locations with suitable water storage possibilities are not widely available.

**Compressed air energy storage (CAES)** is another storage technology. The principle is to compress air to a pressure of about 70 bar using an electrically driven air compressor. At this pressure the energy density of air is 29 MJ/m³, which is not much compared to natural gas that compressed to the same pressure contains 2.5 GJ/m³. It is hard to see how compressed air storages would ever make commercial sense.

**Hydrogen** is another potential electric energy storage medium that is being developed. It can be used as a non-polluting fuel both for transportation or stationary energy generation. Hydrogen would presumably be produced using electrical energy or heat, then compressed or liquefied, stored, and then converted back to electricity using a heat engine or fuel cells.

A significant problem with the “hydrogen economy” is it’s huge conversion losses. The total efficiency of a hydrogen storage system, electricity-hydrogen-electricity, can depending on how the electricity initially has been generated, fall below 20%. Obviously the cost of such electrical power would be extremely high.

**Reservoir hydro**

Reservoir hydro power utilises dams that are constructed in mountainous areas, in narrow sections of valleys, downstream of a natural basin. The flow of water drives hydro turbines that generate electricity. Reservoir hydro is dispatchable, it can be totally closed for a period, making it ideal for both base load, load following and system balancing. Depending on reservoir size, water can be stored for future needs, making it the perfect carbon-free balancing solution for wind power during low-wind conditions.

Dams with significantly large capacity take years to plan and construct, and involve remarkably high capital cost. Suitable locations for new plants are also difficult to find. Construction approval is another major challenge as construction could displace residents and dramatically affect the local environment. Reservoir hydro is only a solution for areas where suitable infrastructure with major height differences and valleys exits.

Reservoir hydro is currently the most widely integrated renewable energy source, yet most suitable locations that can tolerate the environmental impact have already been utilised. New sites tend to be remote, requiring significant investments in infrastructure, such as new roads and transmission lines, while gaining approval is often very difficult because of the environmental impact.

Reservoir hydro is part of the future balancing solution, but there is not and will not be adequate capacity in the EU system to handle the full balancing task with reservoir hydro. Norway has 30 GW producing mainly base load power to Norway and Nordpool area. It also requires a strong grid to be built to connect the remote hydro plants (e.g. in Norway) to the EU main grid.
“Super grid”

A “super grid” has been marketed as a solution for balancing renewables over large geographical areas, the assumption being that wind conditions over larger areas always differ from each other, which should allow excess wind power to be transferred to areas with no or low wind. However in Europe the wind conditions are largely determined by Atlantic low pressures, creating similar wind conditions all the way from North Sea to Spain (see figure below). Transferring excessive wind power from North Sea region to Spain or vice versa does not provide the desired balancing solution as everybody has excess wind power at the same time. Of course a “super grid” will be needed in the North Sea region to bring all the coming offshore wind power to land.

![Combined wind power output (GW)](image)

**Fig 2. European wind power generation in January 2010 at various regions.**

**Smart Power Generation**

Smart Power Generation offers high operational flexibility and high generation efficiency in the same product. These features have in the past been either or, not both at the same time. Such a combination benefits both power systems and power producers, enabling high integration of renewable sources in the power systems and thereby the transition to a sustainable, reliable and affordable power system. It is the missing piece of the low carbon power system puzzle.

Gas fired Smart Power Generation can operate in multiple operation modes from base load power generation to peaking, from load following to “wind chasing” and also something important for the TSO’s, ultra fast grid reserve. Such plants can go online instantly when the wind calms down and the sun sets, and stop in just one minute when the wind starts to blow again. This enables full utilization of valuable and green wind and solar energy.

High energy efficiency (about 50 %) enables competitive generation cost and high dispatch in power markets. The combustion engines used in Smart Power Generation have the highest simple cycle electrical efficiency of any prime mover. Multi-unit configuration enables high net plant efficiency over a wide load range.

Smart Power Generation offers the capabilities that are needed to balance the renewables: Unlimited, fast starts and stops, and fast load ramps with no maintenance impact. 5 minute plant start to full
load is normal start, and it can be repeated 10 times every day! Such situations have been witnesses in the USA where such plants are common.

Natural gas and biogases as well as liquid bio fuels can be used as fuel offering a true low carbon balancing solution for large grids.

**Smart Power Generation in the 2050 roadmap scenarios**

The role of Smart Power Technology in Energy 2050 Roadmap scenarios has been assessed and simulated through dynamic calculations with Plexos dispatch modeling software. The main findings of each scenario are presented below.

In this study we explore the 2030 situation, not 2050. This is because in 2050 the system should include “storage capabilities” which have not been clearly defined and cannot therefore be mathematically modelled. Also CCS plants are part of the 2050 situation while their performance and costs are largely unknown as the technology still requires major R&D. In 2030 such storage capabilities and CCS are not yet part of the system so it can be modelled much more accurately.

To keep the modelling in reasonable size and to make it as accurate as possible, it is based on the Spanish power system. The Spanish system is fairly isolated, with limited interconnectivity, and can therefore show impacts of large scale renewable integration as an “example of how such a system behaves” without modelling major grid constraints and the whole power system cost structure to get the price signals over the interconnections correct. The intention of the study is NOT to try to extrapolate the results to whole of Europe, instead this study may work as a thought source for the discussion about flexibility needs in Europe and the role of dynamic modelling.

Modelling is based on true Spanish load data (10 minute intervals) from 2010 and on true 10 minute wind generation data from the same year. These have been scaled to match the 2030 situation based on the different scenarios. The system capacity mix is specific for each scenario and the scenario data is based on EU information of Spain.

Modelling covers one full year (2030), in 1 hour intervals, and takes into consideration dynamic characteristics (for example starting and stopping times, costs and emissions) of various power plants. Such modelling reveals optimum operation model from cost and CO₂ emission point of view, and situations with major overproduction and lack of energy, which would lead to obvious system reliability problems. To reveal fast reliability challenges, 10 minute modelling is necessary. It requires however huge computing power and will be done for one week only. As soon as the results are available, they will be added later to this study.

In each scenario we present two graphs:

- A one month graph illustrating system operation over 4 weeks
- A one week graph, captured from the above graph (second week)

The week that was chosen is the week number 8 as it has fairly windy conditions and also substantial renewable generation variations.
Fig. 3 Spanish power system capacity mix 2030 in the different scenarios.

The EU Energy roadmap 2050 presents only the consolidated capacity mix of EU27 members states. The Spanish 2030 capacity mixes in the various scenarios have been calculated by using the Spanish power system capacity mix of “EU Energy Trends to 2030”, and by applying relative change rates of EU27 member states average production capacities from “EU Energy Trends to 2030” figures to “EU Energy Roadmap 2050” for year 2030.

The power systems contains about 30 GW of combined cycle gas turbine plants. Today the system contains 25 GW of such plants so their capacity is slightly increased. To illustrate the benefits of Smart Power Generation, the same amount of Smart Power Generation plants were “installed” in the system to operate in parallel with the CCGT’s. The software freely dispatches all the plants, allowing them to operate when their overall cost (including starting and stopping etc.) is the best for the national power system.

The scenarios state that biomass fired power generation is running first i.e. probably has some kind of feed-in tariff. This has been incorporated in the modelling and biomass fired plants run before everything else, including nuclear. However, from total system cost point of view this does not provide lowest cost and often not even the lowest total CO₂ (as biomass is replacing wind and nuclear). Running biomass generation like this, before the nuclear, possesses a clear challenge to the whole system as nuclear plants are often forced to go down to minimum load and their revenues are thereby greatly reduced.

One challenge with this type of dynamic modelling is that it always produces ONLY the best case scenario! This is because the software knows the coming wind conditions exactly for the full year ahead, and can plan the operation of inelastic older thermal plants without any forecasting errors in wind generation. In real life the system reserves need to be bigger as the wind error can be several % even over the next 10 minutes, and even more over an hour. Stochastic modelling errors can be introduced to the model, which will be done later.

Reference scenario

The Reference scenario includes current trends and long-term projections on economic development (gross domestic product (GDP) growth 1.7% pa). The scenario includes policies adopted by March 2010, including the 2020 targets for RES share and GHG reductions as well as the Emissions Trading Scheme (ETS) Directive. For the analysis, several sensitivities with lower and higher GDP growth rates and lower and higher energy import prices were analysed.
Fig. 4. Reference scenario system operation during February-March 2030.

**Note 1:** The lower picture is an enlarged view of the second week from the left in the upper graph!

**Note 2:** The black curve illustrates the actual load. If there is colour above the curve it is overproduction. If there is white colour under the curve, it is underproduction. Such situations are not easily visible in 1 hour modelling as all CCGT's can start in 1 hour but will emerge in 10 minute modelling graphs.

**Findings:** Smart Power Generation (orange) technology produces the fast peaks with lower costs and emissions than the Combined Cycle Gas Turbine plants. Combined cycle gas turbine plants are used as soon as they have adequate running time available (which the software knows “too well” as it knows the accurate wind production data of the days ahead). Coal plants are not running at all due to excessive costs. Nuclear produces on almost full power all through the period. Because of high costs, pump storage is very little utilised for balancing during high wind periods. No major overproduction or underproduction occurs in this scenario during this period i.e. system balance is maintained quite well.
EU 2050 Roadmap Scenarios

High Energy Efficiency

Political commitment to very high energy savings; it includes e.g. more stringent minimum requirements for appliances and new buildings; high renovation rates of existing buildings; establishment of energy savings obligations on energy utilities. This leads to a decrease in energy demand of 41% by 2050 as compared to the peaks in 2005-2006.

Findings: The load is lower in this scenario than in the others. Nuclear plants need to reduce their output to minimum during the high wind periods and still there is substantial overproduction of electricity (wind power must be curtailed or energy stored). Restarting nuclear plants takes several days and costs a lot so that is not an option. Pump storage does not provide a cost efficient method for balancing. On all scenarios solar causes a major balancing challenge every evening when the sun sets while the load remains high. The balancing peak varies strongly, from a few GW to over 20 GW on some days while it always lasts about 4...5 hours. Smart Power Generation technology takes away the abusive peaky generation pulses from Combined Cycle Gas Turbines (CCGT). CCGT plants do not run at all during high wind periods. Coal is not used either. This scenario offers quite a challenging environment for the system operator as over- and underproduction occurs frequently and in substantial quantities.
Diversified supply technologies

No technology is preferred; all energy sources can compete on a market basis with no specific support measures. Decarbonisation is driven by carbon pricing assuming public acceptance of both nuclear and Carbon Capture & Storage (CCS).

![Four week production and consumption (MW) starting from February week 7](image)

![Production and consumption (MW) of February week 8](image)

**Fig. 6. Diversified supply technologies scenario system operation during February-March 2030.**

**Findings:** Again nuclear power plants need to reduce their output to minimum during the high wind period and still there is overproduction of electricity, and hereby nuclear plants lose a big part of their revenues. Pump storage again does not provide a cost effective means for system balancing. Smart Power Generation technology takes care of the fast peaks and balancing. CCGT plants do not run at all during high wind periods. Substantial over- and underproduction occurs again over longer periods of time.
High Renewable energy sources (RES).

Strong support measures for RES leading to a very high share of RES in gross final energy consumption (75% in 2050) and a share of RES in electricity consumption reaching 97%.

Findings: Major overproduction of electricity takes place during the study week almost every day for extended periods. Nuclear power plants need to reduce their output to minimum most of the time. Pump storage does not help as overproduction is almost constant. Smart Power Generation technology takes care of system balancing and fast load peaks. CCGT plants do not run at all during high wind periods, and operate only a few hours during the whole week 8. It is obvious that there is a lot of excess energy for producing hydrogen or for some other “storage” during this week.
Delayed CCS

Similar to Diversified supply technologies scenario but assuming that CCS is delayed, leading to higher shares for nuclear energy with decarbonisation driven by carbon prices rather than technology push. In 2030 there is almost no CCS in the system so the actual performance and costs of CCS-coal are not relevant.

Fig. 8. Delayed CCS scenario system operation during February-March 2030.

Findings: During the study week nuclear power plants reduce their output to minimum load over several lengthy periods. Smart Power Generation again runs the peaks and effectively works as the system balancer. CCGT plants do not run at all during high wind periods. The system is out of balance on Tuesday and Wednesday for longer periods of time. Again the biomass fired generation is pushing all the other generation types up on the graph.
Low nuclear

Similar to Diversified Supply Technologies scenario but assuming that no new nuclear (besides reactors currently under construction) is built, resulting in a higher penetration of CCS (around 32% in power generation).

Findings: Nuclear plants are used but again they operate long periods on minimum load. The amount of nuclear plants is not really affecting their operating profile in the scenarios, they always need to reduce their output to minimum when the wind blows strongly. Pump storage does not provide an economical solution for balancing even in this fifth scenario. Smart Power Generation again handles the peaks and system balancing. CCGT plants run only when they can run on extended periods (due to long and expensive starts and stops). If wind forecasting errors were included, starting and stopping them would be more risky and Smart Power Generation would operate even more hours.

Fig. 9. Low nuclear scenario system operation during February-March 2030.
Conclusions

This dynamic power system study looked at the 2030 situation, in Spain, as part of the EU system, with the EU targets and actions in place. All 5+1 scenarios were modelled and studied. The results indicate that the high portion of renewables dramatically change the way the system is operated. Wind power pushes coal totally and gas plants partially out of the system, and forces even the nuclear plants to run on minimum load during long hours, thereby making their economy and payback look worse for the nuclear plant investors. Biomass fired plants do not have a clear role in the system as they produce high cost power and force lower cost nuclear to reduce output, and also cause substantial overproduction over longer periods especially in the high renewable scenarios.

The carbon emissions of the power system are in all scenarios between 20...45 % of the average level of 2007...2009, which was 337 kg/MWh. A distinctive step forward in decarbonising.

Gas fired power plants have a central role in balancing the system. This they can do with high efficiency and with low carbon emissions. The results clearly indicate that economically and environmentally Smart Power Generation is a better solution than CCGT’s in balancing. From system reliability point of view the results do not yet prove a clear difference between CCGT and Smart Power Generation as all plants can start within the given 1 hour time interval. When the period is shortened to 10 minutes, the differences in system balance will be more visible.

The optimum quantity (in GW) of Smart Power Generation varies depending on the capacity mix in question. To reach the optimum cost and system efficiency, CCGT plants are also needed, in parallel with Smart Power Generation. The optimum amount of each technology capacity can be modelled, when the desired energy mix is known.

Smart Power Generation reduces the average system level variable generation costs from 1 to 5,5 % depending on scenario. Also the CO2 emissions were reduced in all scenarios from 1 to 12 %. This is a remarkable result taking into account that in the Spanish energy system in question has a high penetration of highly efficient Combined Cycle Gas Turbine plants.

![Fig. 10. Average cost reduction with Smart Power Technology](image-url)
Fig. 11. CO2 emissions in different scenarios and CO2 emission reductions achieved with Smart Power technology.

**Necessary steps towards the optimum power system**

Europe needs concrete measures which can enable the development of optimal power system in controlled manner. These measures could include e.g.

1. Define the desired optimum power system for Europe thru dynamic power system simulation
   - Generation capacity mix & location
   - Grid
   - System balancing solutions
   - System operation thru competitive markets

2. Set concrete mid-term targets and framework (2030) towards the optimal power system for the whole system and for each main party participating in the system development

3. Develop EU wide dynamic power markets to construct adequate flexible capacity with private funding

4. Ensure dynamic availability of competitive gas all over Europe

It should be noted that accurate analysis of the future needs, which together with new power markets enable investments to the right solutions, will ultimately enable EU to reach the 2050 targets.
The enablers of dynamic balancing power

Technical norms

The role of the thermal power plants has long been to generate all or at least most of the electricity needed. It will dramatically change over the next years because these plants are only expected to generate the electricity which cannot be generated by renewable sources. The typical operational profile of the thermal plants will be 1000-3000 running hours per year, capacity factor maybe 15 %, hundreds of starts and stops, cyclic operation and unpredictable running patterns. Not really a dream environment for inelastic steam power plants.

In the future we need flexible thermal capacity with:
- Ability to start and stop quickly
- High efficiency and low emissions also in part loads and during starts and stops
- Optimal decentralisation of the plants from energy system point of view
- Reliability
- Cost-efficiency

Current electricity markets are based on trading of energy. The available income for balancing plants with 15 % capacity factor combiner with great uncertainty of volatility electricity market price is not adequate to justify investments on new capacity. There is a need for dynamic power markets that reward balancing plants also for the multitasking capabilities even when the plants are not running, but are on stand-by, waiting for the next balancing task.

In the future thermal plants do the best decarbonising job when they are standing still and able to balance the system when needed – the less the thermal plants are used, the more renewable electricity can be utilized, and the lower the total emissions are. Gone are the days of base load and continuous thermal generation.

If and when private funding is desirable, it is a fact that the present energy markets do not provide adequate returns for investments with reasonable market risk in such thermal plants. For example in Spain the increase of wind and solar power has already today lowered the capacity factor of combined cycle gas turbine plants to under 30% (80-100% being normally the expected and acceptable level for an investment decision) and the owners of the plants are not happy with their loss making investments.

In order to secure getting the right type of dynamic balancing capabilities, technical norms should be determined for balancing plants participating in the dynamic balancing power markets. Such technical norms shall translate the wind and solar balancing needs to technical language i.e. define what features are required from the balancing capacity in order to be able to successfully balance a low carbon power system with high wind and solar generation capacity. The technical norm should take into account that not all the balancing capacity need to be online in 5 minutes, also slower (e.g. 1 hour start) capacity may be utilized for some balancing tasks. Below is an example of such technical norm structure allowing market participation.
**Norm 1: Starting time from start signal to full load**

Plants need to start fast when wind calms down. There may be more than 1 start time categories depending on the need – The faster the reserve, the higher the value for the system, and the higher the reward. Demand response should be allowed to participate in the market if it can start within the given time limits.

Starting time to full load requirement for dynamic balancing plants:

- Category 1: <10 minutes – fast reserve, go online first
- Category 2: 30 minutes (medium reserve)
- Category 3: 60 minutes (slow reserve)

Longer than 60 minutes starting time does not allow the plant to participate in dynamic balancing markets.

**Norm 2: Stopping time from full load**

Plants need to stop fast when wind starts to blow to enable full utilization of all valuable renewable energy. There may be more than 1 stop time categories depending on the need - The faster the reserve, the higher the value for the system, and the higher the reward.

Stopping time requirement for dynamic balancing plants:

- Category 1: 2 minutes – fast reserve, go offline first
- Category 2: 15 minutes (medium reserve)
- Category 3: 30 minutes (slow reserve)

Longer than 30 minutes stopping time does not allow the plant to participate in dynamic balancing markets.

**Norm 3: Starting frequency**

Dynamic balancing plants should be capable of starting and stopping any amount of times per day and year without extensive costs. Typical operation will have 300...1000 starts per year. The plants should be capable of this without excessive costs in form of maintenance and wear.

Plants that cannot start > 5 times per day without excessive costs are not allowed to participate in the dynamic balancing markets.
Norm 4: Ramp-up & down rate

When running, the plants need to be able to change their load rapidly enough to balance the wind. Again, there may be 2...3 categories with different rewards.

Ramp up/down requirement for dynamic balancing plants:
- Category 1: 50 % per minute – fast reserve
- Category 2: 20 % per minute – medium reserve
- Category 3: 10 % per minute – slow reserve

Slower than 10 % per minute ramp rate does not allow the plant to participate in dynamic balancing markets.

Norm 5: Minimum down time

Thermal power plants may have a minimum down time between stop and next start. During this period the plant is cooling down and cannot be restarted. Such cool down breaks are not good for dynamic balancing as wind conditions continuously change and may require a restart almost immediately. Therefore, as short a possible minimum downtime is beneficial for the system. Again, the market should reward the faster restarting capability higher than the slower.

Technical requirement for dynamic balancing plants:
- Category 1: 5 minutes – fast reserve
- Category 2&3: 30 minutes – slow reserve

Longer than 30 minutes minimum down time does not allow the plant to participate in dynamic balancing markets.

Market mechanism

In addition to technical norms, which state which plants are allowed to participate in the dynamic power markets, commercial market mechanisms, which enable profitable investment to these plants, are needed.

Market mechanism
- 5 minute market
- Bilateral market, open access for all qualified market participants including TSOs procuring grid reserves
- Possibility for long term financial products
- Rewarding mechanisms:
  1. Reliability service fee
     - Plants are divided into categories 1...3 based on their agility. Category 1 plants get a higher reliability service fee than the slower category 3.
     - Transparent auction mechanism which takes into account all technical norms described above
     - The fixed payment should reduce investor uncertainty and mitigate market risk
2. Energy market fee

- Payment based on the generated energy
- The plants offer their energy cost to the dynamic balancing market - fast category 1 plants can offer to all markets, slower plants only to category 3 slow reserve markets
- Marginal pricing to reflect the system challenges at times of scarcity
- Market merit order based – rewarding high efficiency
- Capacity dispatch
  - Dynamic power markets clearing defines which plants are operated in 10 minutes intervals

The capacities traded in this market correspond to the wind and solar balancing challenge i.e. should approach 100 GW by 2020.

Note: In many countries today the TSOs is required to maintain in dedicated grid reserve for system contingency situations. Such plants are typically not allowed to participate in the energy markets, their main task is to keep the system balance in contingency (fault) situations. In the new market structure the new dynamic balancing plants can take care of the full grid reserve functions, i.e. the grid companies do not need to, and should not invest anymore separately for those plants - the dispatcher can utilise dynamic balancing plants for emergency situations as well.
Conclusions

In order to advance the work on concrete policy deliverables the European Commission and the Council, assisted by ACER, will need to ensure that enough dynamic capacity and flexibility are incentivized. Without incentives such capacity will not be built. And without such reserves the system will not be able to produce low carbon electricity i.e. the CO2 targets will not be met, and at the same time system reliability is at a high risk. The bottlenecks and rigidness of the present EU Gas and Electricity markets need to be addressed in this context.

In order to reach these general aims - as immediate follow up - the Commission needs to examine the effectiveness of different EU wide market models for remuneration of capacity and flexibility and how they interact with increasingly integrated wholesale and balancing markets. The need to strengthen system level robustness in the future should receive highest priority.

The need for this across-the-board examination in order to develop new market incentives is already recognized in the original Roadmap. The document highlights:

- "the need for flexible resources in the power system (e.g. flexible generation, storage, demand management) as the contribution of intermittent renewable generation increases"
- "Access to markets needs to be assured for flexible supplies of all types, demand management and storage as well as generation, and that flexibility needs to be rewarded in the market. All types of capacity (variable, baseload, flexible) must expect a reasonable return on investment."

In all scenarios renewables rise to at least 55% in gross final energy consumption in 2050. The fact that in the ‘High Renewable energy sources’ scenario 97% of the electricity is based on renewables requires strong performance on system level balancing. As summarized in this paper, Smart Power Generation technology has the potential to play a key role in new EU policy implementation and enable the targeted extremely low carbon levels because – regardless of the scenario -decentralization of the power system will dramatically increase due to more renewable generation and the back up system has to be efficient, low carbon and located at the right places in the grid. Wärtsilä believes that in the next phase the Commission needs to concentrate on concrete mid-term framework and targets (2030) in order to ensure that EU level policies will effectively guide the development and investment of EU energy system in line with the overall 2050 Roadmap targets.
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