Renewable Integration in Power Grids

HIGHLIGHTS

■ **PROCESS AND TECHNOLOGY STATUS –** The brief deals with the integration of variable renewable power technologies (primarily wind and solar power) into the power grids. Renewable energy technologies for electricity generation can be grouped into dispatchable renewables, which are basically ready for production on operator's demand (e.g. hydro, geothermal and biomass power), and non-dispatchable (or variable) renewables, which electricity production depends from meteorological conditions and/or daily time (e.g. wind and solar). The typical modular size of variable renewable technologies is well suited to so-called distributed power generation systems where a number of small power plants are connected to the distribution grid and produce electricity close to the demand site. However, the connection of variable renewables to the distribution grids requires several factors to be examined such as the impact on slow voltage variations, the power plants behavior under faulted condition, and their interaction with the protection systems. The integration of a significant amount of variable renewables into power grids requires significant transformations of the existing grids aimed to: **a)** allow electricity to flow not only from centralized power plants to users, but also from small users/producers to the grid; **c)** introduce a significant energy storage capacity to store electricity (energy) from variable renewables when the production exceeds the demand; **c)** establish intelligent grid and demand management in order to reduce peak-loads; and **d)** improve grid interconnection at regional and international level to increase flexibility, stability, and security of supply. All together these transformations lead to the concept of so-called *smart grids* which are intended to provide the power system with the necessary flexibility to balance supply and demand in the presence of a significant share of variable renewable power capacity. The available experience in the integration of a significant share of renewable power into large grids comes from European countries such Denmark, Germany, Italy, Spain, and the United kingdom, with significant wind and solar power installed capacity. In these countries, the associated issues are being solved in the light of further increase of the renewable electricity share. Experience with the integration of very high (>>50%) renewables share is available from applications for small islands.

■ **PERFORMANCE AND COSTS –** Small and fast (seconds to minutes) variations of variable renewable power output (e.g. wind power) rarely impact the power system. More important are slow (minutes to hour time-scale) variations that result in an increased need for reserve capacity and other interventions to ensure a stable operation of the power system. In general, the level of interventions depends on the share of the renewable electricity and capacity in the power system. For a 10% renewable electricity share the increase of reserve capacity is estimated to range between 1.5% and 4% of the installed variable (e.g. wind) capacity. However, variability issues may also solved through more interconnection of the grid to other grids to achieve more flexibility in supply-demand balance. The cost incurred in the integration of variable renewables in existing grids can be categorized in grid infrastructure costs and system operation costs. The grid infrastructure costs include grid connection and grid upgrading costs. For most renewable technologies the grid connection cost is estimated to be in the range 0-5% of the project investment cost; for onshore wind projects this cost is estimated at around 8%, for off-shore wind projects the cost ranges between 10% and 25%. Grid upgrading costs depend on grid characteristics and are estimated at between €0.5/MWh and €3.0/MWh for a 20-30% renewable (wind) electricity share. System operation costs refer to the extra cost incurred in the conventional part of the power system. Based on a variety of empirical studies on wind power, system operation costs are in the range of €2-4/MWh for low wind penetration (below 10% of capacity share) and about €5-6/MWh for high wind penetration (above 20% capacity share).

■ **POTENTIAL AND BARRIERS –** All major energy projection studies anticipate a very significant increase of renewable power in the electricity mix in all world regions. Key questions deal with the cost of renewables integration into power grids, policy and regulatory issues, and the availability of suited technologies (e.g. energy storage technologies). For example, it has been estimated that for the European distribution network the total investment need will amount to € 480 billion by 2035. In modern liberalised electricity markets, electricity generation and supply (retail) are market-based activities, governed by market competition rules, while transmission and distribution services are usually regulated. Grid investment would require a proper and stable regulatory and policy environment, with appropriate incentives and long-term horizon. Experts generally agree that no insurmountable technical constraint exists for the achievement of the projected renewable share in 2050, but the economic and regulatory frameworks are critical issues to be dealt with.

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PROCESS

The increased use of renewable energy sources is a key part of the international policies to reduce greenhouse gas emissions and mitigate climate change. For example, the European Union (EU) has set targets (so called '20-20-20 EU targets') to achieve a 20% renewables share in the overall energy use, a 20% reduction of CO_2 emissions, and a 20% energy saving by increased efficiency by the year 2020. According to EURELECTRIC [1], a 20% renewables share in the overall energy use by 2020 means approximately a 35% renewables share in the electricity mix.

Renewable energy technologies for electricity generation can be grouped into **dispatchable r**enewables such as hydro power (ETSAP E06, E18), geothermal power (ETSAP E07), biomass power (ETSAP P09, P11, E05, E21) and **non-dispatchable** renewables that are also referred to as variable or intermittent renewables, such as wind power (ETSAP E09), solar photo-voltaics (ETSAP E10), concentrating solar power (ETSAP E11), wave and tidal power (ETSAP 08). The dispatchability of an electricity generation source refers to the source's ability to produce electricity on demand, i.e. at request of the power grid operator. In general, dispatchable renewables are constantly available for production (apart from maintenance needs) and offer high capacity factors[1] (i.e. close to those obtained from fossil fuels or nuclear power plants, though with certain limitations). In contrast, electricity generation from non-dispatchable renewables depends on sunlight availability and meteorological conditions. As a consequence, capacity factors are modest, grid operators cannot fully plan the electricity generation from these sources, only a fraction of the installed capacity can be considered as *statistically* dispatchable, and an appropriate amount of back-up capacity[2] is needed in power grids with significant share of variable renewables.

The typical small size and capacity of variable renewable power technologies is particularly suited to so-called **distributed power generation** systems where many small power plants are connected to the distribution network and produce electricity close to the demand site. This may reduce the need for centralized power generation and high-voltage transmission lines, as well as transmission and distribution costs. However, appropriate adaptation and control of the electricity system (generation plants and transmission/distribution lines) is needed to ensure the reliable operation (i.e. supplying electricity on demand with required frequency and voltage, and balancing active and reactive[3] power) of grids with high share of variable renewables.

■ **Renewables Integration into Power Grids -** The integration of a significant share of variable renewables into power grids requires significant transformations of the existing networks aimed to:

a) Allow for a bi-directional flow of energy, either top-down (from generators to users) and bottom-up (with end-users contributing the electricity supply);
b) Establish an efficient electricity-demand and grid management in order to reduce peak loads, improve grid flexibility and security of supply;
c) Introduce a significant energy storage capacity to store electricity (energy) from variable renewable sources when they are available in excess of demand;
d) Improve interconnection of grids at regional, national and international level;
e) Introduce technologies and procedures to ensure proper grid operation stability and control (frequency, voltage, power balance) in the presence of significant share of variable renewables.

These transformations all together lead to the concept of so-called **smart grids,** which main components, systems and operation are discussed below.

■ **Smart Grids –** Smart grids are conceived to accommodate an increasing share of variable renewables and distributed generation. They involve a new integrated architecture of transmission and distribution, with smart metering of bidirectional flows of energy and communication technologies that provide central operators with the information needed for an efficient control of electricity supply (from both centralized and distributed power plants) and demand (smoothing demand peaks and/or meeting demand peak with variable renewable as well as possible). The new architecture may eventually include automated intelligent management of end-use appliances to shift electricity demand towards off-peak periods, e.g. overnight, or make use of energy when it is available from variable renewables. The concept of *smart grids* as well as the extent to which it applies (i.e. central operator, grids and/or final users/technologies) is still matter of discussion.

Of key importance is the involvement of variable renewables and distributed generation plants in a number of tasks aimed to ensure efficient and reliable operations such as voltage and frequency regulation, reactive power regulation, active power reservation, congestion management, optimization of grid losses, network restoration, etc..

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[1] The capacity factor is the ratio of the actual electricity produced by a power plant in a year to the electricity that the plant could produce in theory should it operate continuously at full power during the same period.

[2] In power grids with variable renewables, conventional back-up power operates at partial load in a less efficient mode.

[3] In alternating current (AC) circuits, elements such as inductance and capacitance result in a phase shift between the voltage and current waveform, meaning that there is a time difference in each cycle between the instances that they change polarity. As the instantaneous power is the product of voltage and current, it takes both positive and negative values during a cycle. In a typical cycle, only a portion of the total power is active power, i.e. 'useful power' which can be converted to other forms of energy, while another portion of the total power is reactive power, that is used to energize the magnetic and electric fields (inductive and capacitive elements). The reactive power does not produce 'useful' energy, but is needed to transfer the active power in a power system. The presence of reactive power in the grid involves higher current to transfer a certain amount of active power, and increased losses. As a consequence, an active balancing of both active and reactive power is needed.

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By reducing peak demand and enabling a more efficient energy management, smart grids can also reduce the need for new and back-up capacity,

Smart grids require the use of power-electronics components such as advanced inverters, which are crucial for the integration of variable renewables. Besides the main task of feeding renewable-based power to the grid, inverters provide additional functions such as the balance of active and reactive power. They can participate in frequency control through active power regulation (with proper control algorithms) and can provide voltage control, fault-ride-through capability, and the reduction of grid losses that mostly depend on the reactive power control.

In most countries, power grid regulations require power plants operators to contribute the grid management functions [2], such as

- Static voltage control to limit slow voltage variations;
- Dynamic support to operation in case of voltage dips
- Active power limitation in case of frequency rise or risks for safe operation
- Provision of reactive power for network re-phasing

Technical issues to be addressed for renewables integration into power grids also include the connection of renewable power plants to the distribution grids, the so-called Fault-Ride-Through (FRT) operation, and the impact on protection systems.

Connecting Renewable Capacity - The connection of renewable electricity generation plants to distribution grids requires the analysis of several factors which may impact the grid operation. A major criterion for plant connection is the impact on the grid voltage during normal operation, i.e. slow voltage variations.

In conventional distribution networks with radial configuration (i.e. centralized power generation), a node voltage decrease is observed as a result of a voltage drop on network elements. In networks with distributed generation either negative or positive deviations of node voltage may occur. The plant to be connected is required to keep the voltage rise in an acceptable range of typically 2-3%.

Voltage changes can be determined by complex load-flow calculations[4]. The voltage rise depends on the network short-circuit power and the impedance angle at the connected point. It also relates to equipment characteristics (i.e. transformers, distribution lines) and is affected by the phase angle (φ) of the plant, which can be adjusted by reactive power control.

A recent study has calculated for various cases that the operation of PV plants at a power factor of 0.9 could increase the maximum allowable PV power that can be connected to low-voltage radial distribution networks by a factor of 1.5 to more than 2 [3]. However, the thermal limits of transformers and cables have to be considered. In general, a high withdrawal of inductive reactive power can reduce the voltage rise. However, a trade-off has to be accepted as this also leads to increased losses and reduced transmission capacity.

A further criterion considered for connecting a renewable electricity generation plant to the distribution grid is the thermal limit of the grid components (mainly electric lines). At the Medium Voltage (MV) level, the loading limits of the lines are determined by their short-circuit capacity. The network short-circuit current is increased by the power plant short-circuit current capacity, particularly in the vicinity of the connection point. The following rules of thumb can be used to estimate the contribution of the power plant to the short-circuit current [2]:

- 8x rated current for synchronous generators
- 6x rated current for asynchronous generators and double-fed asynchronous generators;
- 1x rated current for generators with inverters (depends on time-scale: could be 3 to 5 times for events under 1 second).

A major requirement is that the total fault level, which is determined by the combined short-circuit contribution of the upstream grid and the distributed electricity source, should remain below the network rated value. This constraint is often the main inhibiting factor for connecting new distributed electricity source to existing grids. Distributed electricity sources coupled by inverter can relieve this constraint.

Fault-Ride-Through (FRT) Operation. In conventional power grids, inverter-based distributed generation plants are required to be disconnected timely when the grid voltage or the frequency exceed the allowable operating range. In grids with high share of distributed renewable units, the simultaneous loss of a large number of generation plants and capacity due to short-term voltage or frequency fluctuations (which may result from e.g. a fault in the transmission network) can threaten the overall stability of the grid. In this condition, an appropriate management of the generation plants can help react to the voltage and frequency deviations[5]

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[4] An approximate calculation of the expected relative voltage rise is given by the formula:

$$\Delta U_{aV} = [S_{Amax} \bullet \cos(\Psi_{kV} + \varphi)] / S_{kV}$$

Where:

S_{Amax}	=	Max. apparent power of the generating plant
S_{kV}	=	Short-circuit power at the connection point
Ψ_{kV}	=	Network impedance angle at connection point
φ	=	Angle between generating plant current & voltage

[5] Frequency in a power system depends on the balance between generated and consumed active power. Small load variations or intermittent generation may result in a power imbalance and frequency deviation. In conventional power plants, automatic mechanisms respond to deviations and restore the initial frequency value by adjusting the output power to meet the net load.

Voltage mostly depends on reactive power balance. In conventional power plants, electricity generators are the main sources of reactive power (further to active power), and voltage control is accomplished through automatic mechanisms that act on the excitation of synchronous generators. However, further reactive power compensation is needed at load locations. Local compensation helps reduce distribution losses and better use the other elements of the power system.

and avoid grid instability or even collapse. The ability of generation plants to remain connected to the network during such short-term fluctuations, also referred to as Fault-Ride-Through (FRT) capability, is crucial for large-scale renewable integration into the power grids. FRT requirements for the connection of generation plants to transmission and distribution networks have already been included in several national grid regulations to solve the problems associated with the connection of wind parks and a large number of PV systems. The dynamic support of the grid operation in the case of voltage dips (at medium and low voltage level) is mandatory in some countries. This means that generation plants must remain connected for a certain time period in the case of network faults and support the network voltage by injections of reactive power.

Impact on Protection Systems - The operation of a power grid requires protection systems to detect abnormal conditions and restore normal operation through corrective action. In general, distribution networks mostly use overcurrent protection, but other systems can also be usedl[6]. Protection systems are usually designed assuming a mono-directional power flow and a proper coordination of overcurrent devices based on the available fault current. The introduction distributed electricity sources in the distribution network may cause unwanted impacts on the protection systems, mainly due to load flow changes and increased fault current contribution. For example, the introduction of a distributed source and the associated current may cause erroneous operation of distance relays. Furthermore, in contrast with the basic rule of the protection systems that disconnect only the faulted parts, the overcurrent protection device of distributed sources may also be activated by faults in adjacent sections (sympathetic tripping). Therefore, to ensure safe and selective protection, the impact of distributed electricity sources on protection systems should be taken into account in planning grid operations by considering new relays, as well as the development of new directional protection algorithms.

Communication Technologies – The introduction of variable renewable power generation and distributed electricity generation in the power grids require significant advances in monitoring and control systems to obtain optimal performance. As a consequence, information and communication technologies (ICT) are key elements of smart grids. In order to allow local renewable, distributed generation units to interact each other and with the grid management systems, a harmonization of communication methods and/or physical media that are used by different vendors and users is needed. In this context, developers and manufactures all over the world propose harmonization through specific standards, with the IEC-61850 as the most representative. This standard permits the interoperability between different systems from different vendors, thus increasing the cost benefit to all owners, operators, and users of distributed generation systems. The IEC 61850 models cover all operational aspects of distributed generation systems. However, they do not address market operations [4].

■ **Electricity Storage -** Electricity (energy) storage is dealt with in more detail in ETSAP E18. In power grids with significant share of variable renewables, storage is needed to allow energy to be captured and stored when renewable sources are available for production and the production exceeds the demand. The storage energy can then be used on operator demand, even when renewable production is not available. The electricity storage plants can also help ensure the required grid voltage and frequency stability, at various timescales and operating conditions. Because electricity cannot be stored as it is, electricity storage involves the conversion of electricity in other forms of energy using. several technology options with different individual characteristics and performance, i.e. **pumped hydro** storage; **compressed air energy storage; electric batteries** (lead acid, lithium- and nickel- based, flow-batteries, etc.); **superconducting magnets**; **flywheels**; **super-capacitors**; **chemical storage** (e.g. electricity conversion into hydrogen by electrolysis); and **thermal storage** (e.g. heat storage in concentrating solar power plants, see ETSAP E10 and ETSAP E17). Electricity storage can also be obtained from end-use technologies such as plug-in electric vehicles (EV) which batteries could be charged overnight using electricity in excess, and used during the day. The technical feasibility of this approach is being carefully investigated as it could also contribute the grid demand-supply balance. Among electricity storage technologies, pumped hydro power plants are currently the only commercial option for large-scale electricity storage (in form of potential energy). Though electricity storage plays a key role for renewable integration in power grids, the global potential for pumped hydro is limited and largely exploited worldwide since these plants require specific siting, with natural or artificial water reservoirs located at different geodetic elevations. New, cost-effective storage technologies are still under development as storage is a crucial issue to be addressed for renewables integration in power grids.

■ **Grid Interconnection** – Increased grid interconnection at regional, national and international level would enable more flexibility in power transmission from regions with large availability of renewables to regions with high electricity demand. Another advantage is the integration of variable renewables with conventional power and the possibility for variable renewables to complement each-other at different time (e.g. solar power during the day, wind power overnight) and/or in different regions (South, North). Higher interconnection and transmission capacity also helps the optimal use surplus generation, alleviates the

[6] Other protection systems include e.g. differential protection and distance protection. Differential relays compare currents on both sides of a protected zone and operate when the difference exceeds a certain value, as a result of a fault inside the protected zone. Distance protection uses an impedance measured by the distance relay (through voltage and current measurements) to detect any faults on the network. Relays of this category also allow for directional protection.
In overhead line networks, automatic re-closure devices are also often used. Faults in overhead lines are mostly temporary and disappear after the re-closer is switched off for a short period (0.3-0.5 s) and then switched on again.

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problem of daily and seasonal demand peaks, and reduces the need for new (and backup) generation capacity. Modern, high-voltage direct-current transmission lines for long distance are highly efficient, though their implementation takes time and involves very significant investment. Grid interconnection also requires a full integration of the grid management systems.

TECHNOLOGY STATUS

The share of renewable energy sources in the electricity generation system is usually measured by:

- **Renewable share in the annual electricity generation**: ratio of renewable-based electricity to the total annual electricity generation;
- **Renewable share in the installed power capacity:** ratio of nominal installed (connected) renewable power capacity to the total power capacity;
- **Instantaneous renewable share in the current load:** ratio of the total output power of operating renewable units to the load, at a certain point in time.

According to the IEA energy statistics [5], the renewable share in the global 2010 annual electricity generation (i.e. 21,408TWh) was about 19.6%, including a 16% from hydro power and 3.6% from other renewables (about 1.6% wind, 1.5% biomass, 0.3% geothermal, 0.1% PV). In terms of capacity, renewables accounted for 26,1% (19.9% hydro, 3.8% wind, 1.4% biomass, 0.2% geothermal, 0.7%% PV) of a total 2010 global cumulative installed capacity of 5183 GW.

However, over the past years renewable-based electricity (particularly wind and solar PV power) has been growing very fast worldwide, driven by policy incentives and the increased economic competitiveness (wind) and cost reduction (PV). Wind and PV cumulative installed capacities in 2010 were about 198 GW and 40 GW, respectively, while corresponding values at the end of 2012 were 282 GW and 102 GW. [6,7]. Leading countries in terms of wind and PV annual installations in the period 2011-2012 were China, Germany, Italy and the United States.

In the European Union (EU), the renewable share in the annual 2010 electricity generation (i.e. 3310 TWh) was about 20.8%, including a 11.1% from hydro power and 9.7% from other renewables (about 4.5% wind, 4.3% biomass, 0.2% geothermal, 0.7% PV). In terms of capacity, renewables accounted for 31.9% (15.9% hydro, 9.3% wind, 3.1% biomass, 0.1% geothermal, 3.3% PV) of a total 2010 cumulative installed capacity of 910 GW [8].

While other world's regions have exploited so far only a small part of their large renewable potential, the EU is currently the world's leading region in terms of cumulative installed renewable capacity. At the end of 2012, about 70% (about 70 GW) of the global PV capacity and 39% (about 109 GW) of the global wind capacity were installed in the EU, with Germany and Italy as leading European countries for PV, and Germany and Spain for wind power.

In addition to 31 GW wind and 32.64 GWp of PV power, Germany also produces renewable electricity from biomass (7 GW in 2012), geothermal energy (0.012 GW), hydropower (4.8 GW) and waste (2 GW). On an annual basis, Germany currently (2012) produces about 22.9% of its electricity from renewables, with a total installed renewable capacity about 77 GW in 2012, that is higher than the level of the minimum load demand of the country's power system. This translates into power system operation at very high instantaneous renewable share, with very significant electricity generation based on variable renewables (wind and solar). For example in May 2012, during the midday hours of May 25 (Friday) and May 26 (Saturday), Germany's solar power plants[7] fed into the grid renewable electricity equivalent to 22 GW per hour (equal to the production of about 22 nuclear power plants), meeting about 30% of the country's electricity needs on May 25, and 50% on May 26.

Apart from Germany, energy projections suggest that in the coming years renewable power generation (particularly wind and PV power) will continue to grow in a number of countries reaching very significant (even dominant) shares in the country electricity mix. As the capacity factor of these plants is modest[8], the achievement of high renewable electricity shares involves very high renewable capacity shares, with power systems running for prolonged periods at very high instantaneous renewable share. This translates into very significant technical implications for grid adaptation and management, and economic investment, as discussed in the previous sections.

■ **Small islands and micro-grids –** Small islands provide valuable fields for testing new technologies and operation modes for renewables' integration in power grids. Islands have small, isolated power grids with often high share of renewable power. In principle, the electricity demand of a small island with a peak-load of a few hundreds kW could be fully met by renewables such as wind and PV power, with energy storage units to balance supply and demand. A proper design of the power system requires extensive simulation, and depends on load profile, wind and solar resources and the level of renewables penetration.

However, the achievement of a 100% renewable electricity penetration is usually difficult and costly as it involves oversized renewable power capacity and storage capacity. More affordable is to manage high shares of renewable electricity sources with appropriated energy storage and the use of back-up conventional power (e.g. diesel generators). The

[7] More than 70% of PV installations in Germany consist of small plants (< 100 kW) that are connected to the Low Voltage grid, while 25% of the PV installations are plants with more than 100kW capacity connected to the Medium Voltage grid.

[8] On annual basis, typical PV capacity factors range from 10% (Northern latitudes) to nearly 18% (tropical sites), while wind plants have capacity factors ranging from 20% to 40% for sites with a high wind potential.

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implementation of such systems requires bi-directional inverters as the interface between the energy storage units and the grid. Inverters are key components of the grid to ensure stable operation and provide dynamic balance of active and reactive power. The operation of such grids may also require renewable units to stop the production (if needed) on central operator's request, along with a proper management of non-critical loads.

However, a limited number of these small-scale field applications with high renewable share exist, and at present there are no ready standard solutions, technologies, and operating modes.

A lot of research focuses on **micro-grids** [9] that aim to facilitate the integration of variable renewables and distributed generation units into the grids. Micro-grids consist of a combination of generation sources, loads and storage units that are connected to the distribution network through a single coupling point, and work – from the network perspective - as a single unit. A major characteristic of micro-grids is that they can operate either in parallel with the grid and in "island" mode (i.e. isolated from the grid) whenever this is required. When the main network is not available, a local control system enables independent operation of the micro-grid. The required flexibility in energy management and control is ensured by the local control response of the distributed RES and storage grid-connected inverters, combined with that of controllable loads.

The operation of a micro-grid as a single unit aims to avoid the negative impacts of distributed generation units on a centralized grid and turn them into positive impacts such as improved energy efficiency and local reliability, reduction of energy losses and need for grid expansion. Key challenges for the success of micro-grids are the development of appropriate control algorithms as well as protection and communication issues.

Two examples of small island systems and micro-grids are given below.

El Hierro, Canary Islands, Spain [10] - El Hierro, is one of the Canary Islands (located in the Atlantic ocean) where a hybrid hydro-wind power system aims to meet a significant proportion (about 80%) of the local energy needs using renewable sources. The plant consists of a pumped-storage hydro power plant (i.e. 11.3 MW generation capacity and 6 MW pumping capacity) coupled with a 11.5 MW wind farm (5 turbines). The plant (currently under construction) is expected to start the operation in 2013 and to provide reliable power supply for the 10,960 residents of the island. It will provide about 80% of the island's energy needs, with the remaining 20% generated through solar thermal collectors and grid-connected photovoltaic systems. The island's pre-existing diesel generators will remain in place for emergency generation. The project is managed by a public-private partnership including the Island Council (60%), the Spanish energy company Endesa (30%) and the Canary Islands Technological Institute (10%). The project budget was about € 65 million. The project developer is "Gorona del Viento El Hierro S.A.

Gaidouromantra-Kythnos, Cyclades islands, Greece [11,12] - The Gaidouromantra system in the Kythnos island (Aegean See) is a 3-phase micro-grid for electrification of residential houses (with mono-phase electric services) in a certain region of the island. The system consists of main power lines and a communication cable running in parallel to serve monitoring and control needs. At present, this micro-grid is a permanently "islanded" with respect to the island's electric grid. The system was installed in 2001. Most important features are 1) Electricity generation from distributed PV systems; 2) No physical connection with the island public grid (permanently "islanded" system); 3) Voltage and frequency control by battery inverters; 4) Power system balanced by battery storage and load controllers.

From 2006 to 2010, the system was upgraded and used as a test field for different control strategies in the framework of the *More-Microgrids* project (EU 6th Framework Programme). Software/hardware systems for centralized and de-centralized load control were developed and installed. They consist of Intelligent Load Controllers (ILC) that are used to monitor the house power line and measure voltage, current and frequency. The main objective of this application is the management of non-critical loads (e.g. water pumps) that may be disconnected in the case of energy shortage.

OPERATION EXPERIENCE AND PERFORMANCE

Variability is not actually new for power systems as demand and supply are variable by definition and influenced by a number of planned and unplanned factors. Such variability is usually dealt with by established control methods and backup. Existing procedures and protocols have been adapted by operators to the new requirements associated with large-scale integration of variable renewables.

Experience in large-scale grid integration of variable renewables comes basically from European countries with a high wind and solar PV penetration [13,14,15] where the Fault-Ride-Through (FRT) is now mandatory and the problems associated with simultaneous loss of a large amount of generation capacity have almost been solved. The main concern in the operation of these power systems is to cope with the wind variations, the increased need for capacity reserve, and the accommodation of wind curtailment events.

While small and fast (seconds to minutes) variations of aggregated wind power output do not impact significantly the grid, longer-time (hourly) variations involve variation of the net load (load minus wind power), leading to a significant increase of reserve capacity needs. This increase depends basically on the wind penetration level. Taking into account that load variations are more predictable than wind variations [16] it is estimated that the increase in reserve capacity that is needed for a 10% wind energy penetration is in the order of 1.5-4% of installed wind capacity.

Wind forecasting also plays an important role in the operation of a power system with a high wind power

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penetration. Forecasts with 1 to 48h time horizon are used as a basis for scheduling the balancing power reserves through appropriate commitment of conventional power plants. The annual average error on day-ahead wind power forecasting currently impacts about 5% of the wind installed capacity. The largest errors are experienced during storms when high wind speeds exceeding cut-off limits may result in shut-down of wind turbines. However, the operating experience for large regions show that usually some hours are needed for the power to be reduced to its final value. Therefore, the threat for the stability of the power system is usually modest.

Curtailments of wind power may be needed because of network limitations or in the following cases: a) during low-demand periods, if a minimum conventional capacity must be kept connected to ensure grid stability and control; b) during rising demand periods, if a risk exists for wind power output reduction, and the operators must ensure that the load gradient to be met by remaining power plants is within the dynamic capacity of such plants; c) if non-dispatchable generation exceeds the demand plus the interconnection capacity, and the generation surplus is to be removed. It should be noted that with appropriate wind conditions, modern wind turbines are able to switch from partial load to full power within 10 s. This makes wind power a valuable asset for fast regulation.

Valuable experience with large-scale wind power integration has been gained in countries such as Denmark, Germany and Spain.

In Denmark (wind electricity share of about 22% and wind capacity share of 58%), most wind variability problems are solved through the strong interconnection with the Scandinavian and German grids. Curtailments of wind power have rarely occurred also due to the flexibility provided by the presence of a large amount of distributed combined heat and power plants (CHP).

Germany has an average wind electricity share of about 7% and a wind capacity share of 33%, with regional peaks (Northern Germany) of 30% and 80%, respectively. Because of the uneven geographical distribution, some wind power curtailments have occurred due to surplus production and grid limitations. The required regulation power is provided by the four national Transmission System Operators (TSO) and the interconnections to neighboring countries (Netherlands, Poland) are also occasionally used. However, a massive upgrading of the transmission system is in progress to further increase the penetration of renewable electricity.

Spain has a wind electricity share of 16% and a wind capacity share of 44%, with certain regions exceeding wind electricity share of 40%. Spain is weakly interconnected with the rest of the Europe and has to provide domestic balance capacity to compensate for the variable renewables. Wind forecasting based on real time information is a key tool for power system operation. The wind power plants provide real time information to a control center, which is able to adapt their production. The real time data allows the system operator to deal with generation and demand, control wind generation and achieve an optimal operation of the power system. On an annual basis, curtailments of wind production in 2010 were in the order of 0.5% of operating time [14].

A remarkable example of integration of variable renewable electricity is also available in the Greek island of Crete [17]. With an annual peak load of 650 MW, Crete is served by an isolated electric system with an average annual renewable electricity share of 20% (2012) and a maximum renewable capacity share of 38.5% (consisting of 180 MW wind power and 70 MW of PV power). During the early years of operation with mainly wind parks, the system has been faced by some problems due to: a) sensitivity of wind turbines to voltage dips; b) faults on grid connections of wind parks to the HV substations; and c) voltage setting of wind parks protective disconnection devices. All these problems have been solved over time by the distribution system operators and the wind park owners. Especially the FRT capability of wind turbines has dramatically improved the performance of the system.

At present, during normal operation, PV plants provide power output without any restrictions, while wind parks contribute taking into account the maximum allowable instantaneous renewable share, which is about 40%. If this value is reached, the power output of the wind parks is appropriately reduced. The Energy Control Center of Crete monitors continuously the wind parks and a set-point for maximum power output is given up to every 5-minutes, if needed. However, in some periods, the operators may decide to operate the system with higher instantaneous capacity share (up to 60%, see Figure 1). The Energy Control Center also monitors selected PV plants at various locations in order to assess the total PV production with a good accuracy. This helps the daily scheduling of conventional capacity. Distributed PV plants also support the grid voltage stability during daily hours.

The experience gained so far from the operation of high share of renewables in European grids, shows that no increase of reserve capacity is needed, but an increased use of operating capacity reserve.

CURRENT COSTS AND COST PROJECTIONS

The additional cost of renewable integration into the power grid can be categorized mainly in **grid infrastructure costs** and **system operation costs** [18]. The additional costs for smart grid technologies such as ICT, smart metering, etc. is roughly estimated to be comparable with the cost savings due to the reduced peak loads and increased energy efficiency.

■ **Grid infrastructure costs** include grid connection costs and grid upgrading costs:

- **Grid connection costs** include the cost of a new line from the plant to the existing grid. This cost depends basically on the distance between the plant and the grid, the voltage level of the connection line, and the possibility to use standard equipment. The grid connection cost is an important economic constraint for

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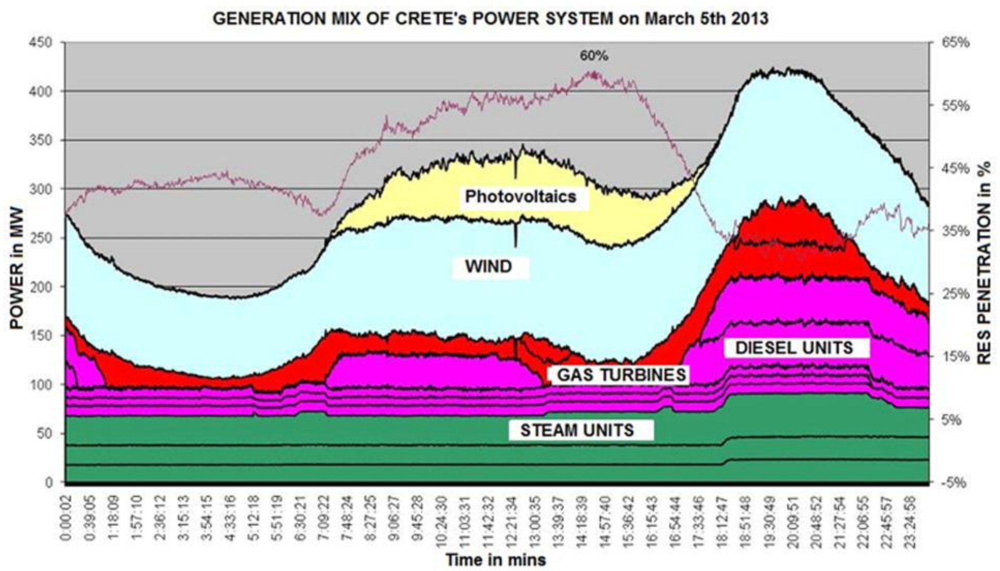

Figure 1 - Generation mix for Crete's power system on 5/3/2013 and Renewables penetration (violet line).

renewable development in remote locations. Based on various case studies and current practice, the grid connection costs for most renewable power projects in developed and populated regions are estimated to range between 0% and 5% of the total project investment cost. The connection cost may increase up to an average 8% for onshore wind power, and between 10% and 25% of the project investment cost for off-shore wind power [18]. In general, grid connection cost is the dominant component for wind power integration cost. In most countries grid connection costs are faced by the investor, as part of the initial investment cost.

- **Grid upgrading costs** include the cost of the additional network equipment that is needed to integrate the renewable power into the existing grids This depends mostly on the amount of renewable capacity, the location of the power plants, and the structure of the existing grid. Based on load flow analysis, various studies carried out in different countries for wind power integration suggest a significant impact of the level of renewable electricity share, i.e. costs in the range between €0.5/MWh and €3/MWh for 20-30% renewable share in annual electricity generation. [18]

■ **System operation costs** can be divided into system adequacy costs (capacity costs) and short-term system balancing costs. They account for the extra costs of the conventional part of the power system caused by the integration of variable renewable power. Studies dealing with these costs have been carried out primarily for wind power.

- **Capacity costs** – In a power system, the term *capacity credit* refers to the amount of conventional capacity that can be displaced by variable renewable capacity while maintaining the same level of system security, e.g. without affecting the probability of loss of load (LOLP). For example, wind power provides a contribution to meeting the peak demand in a power system, but this contribution is lower than the contribution that is provided by an equivalent conventional capacity. This means that wind power has a lower capacity credit. The capacity credit depends on the specific renewable resource, the season and the structure of the power system. It is higher in systems where peaks of generation and demand coincide. An overview of methods to calculate the capacity credit and a summary of results is given in [19]. The capacity credit as a percentage of the installed wind capacity is roughly equal to the average capacity factor of wind generation for low wind share, but decreases with increasing wind share in the electricity system. The low capacity credit of wind energy can be expressed as a cost. Based on the determination of the capacity credit of wind power, the extra cost for non-variable power that is needed in a particular power system to maintain system adequacy can be estimated. Methodology and results for various cases can be found in [20].

- **Short-term system balancing costs** - In order to maintain a secure and stable grid operation, demand and supply (generation) must be continuously balanced. Due to the variability of wind power, the reserve capacity that is needed for up- and down–regulation increases if compared to the situation where the same energy is delivered by conventional power. In particular, the impact of second- to minute-scale wind power variability is modest or negligible while minute- to hour-scale variability may affect the grid operation more significantly. The increased requirements for reserve power correspond to extra costs for the conventional part of the power system. These extra costs originate from the measures taken to ascertain increased reserve power, caused for example by the operation of conventional plants at partial load, the start-up and contribution of conventional power plants of higher operating cost in the power system, increased wear and maintenance costs of plants etc.

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Based on a variety of empirical studies, the total extra system operation cost is around €2-4/MWh for wind capacity share below 10%, and around €5-6/MWh for wind capacity share above 20% [18]. Short-term balancing costs are approximately 50% of the capacity cost.

POTENTIAL AND BARRIERS

Several scenarios have been proposed regarding the penetration of renewable power in the future electricity mix. The IEA Blue Map scenario [21] suggests that in 2050 the renewable share in the global electricity generation could reach about 47.9% (Table 1) including 14.3% from hydropower, 12.2% from wind and 12.3% from solar power. Tables 2 and 3 present the Eurelectric estimates [22] for the electricity share and installed capacity in Europe (EU 27). All sources project a very high share of renewable electricity in the coming decades. The question "who pays for the integration cost of renewable energy into power grids" is an important issue to be dealt with and involves either the cost of renewable technologies and the integration costs [23]. Potential payers are - of course – renewable producers, grid operators and consumers.

In a liberalised market, electricity generation and supply (retail) are market-based activities, governed by market competition rules, while transmission and distribution services, a natural monopoly, are usually regulated.

In the generation sector, markets have developed in which generators sell electricity within a structure with defined prices, time frames and other rules. In many countries a separate balancing market has also been established for maintaining short- and medium-term balance in the power system. In the case renewable producers do not participate in the power market, as is the case where a feed-in tariff scheme exists, the integration costs related to short-term balancing costs will usually be borne by the network operators and hence, ultimately, by consumers. If the renewable producers participate in the electricity market, then they have to bear the costs of any imbalance they are causing based on current balance power price. Hence in the light of an adequate treatment of the integration costs, an increased market integration of renewables offers clear advantages, but requires a proper design of the rules of the balancing market.

As for the integration costs for grid connection and upgrading, two distinct charging approaches can be considered: deep and shallow connection charges. In the deep connection charges approach, the renewable producer bears both grid connection and grid upgrading costs that are both included in the total project cost. In the shallow connection charges approach the renewable producer bears the grid connection cost, not the grid upgrading cost. Deep and shallow connection charges have both advantages and disadvantages, whereas mixed approaches may also be used. The main disadvantage in the deep connection approach is that the exact and fair allocation of grid extension requirements and costs to individual renewable producers is difficult. In the shallow connection approach, the grid upgrading costs are borne by the network operators, and will have to be socialised through the use of system charges approach. Network operators also have to bear the extra costs required for the transformation of existing grids into smart grids by ICT.

It has been estimated that for the European distribution network the total investment needs will amount to € 480 billion by 2035. Grid investment would require a proper and stable regulatory environment, with appropriate incentives and long-term horizon.

Experts generally agree that no serious technical constraints exist for the achievement of the projected renewable share in 2050, but the economic and regulatory frameworks are critical.

Table 1 – Estimated World Energy share in 2050 (IEA ETP 2010 - Blue Map scenario)

Nuclear	23.9%
Oil	0.6%
Solids	12.4%
Gas	15.2%
Renewables	47.9%

Table 2 – Europe Estimated Energy share in % (Power Choices, Eurelectric [22]

	2020	2030	2050
Nuclear	24.5	26.1	28.4
Oil	1.8	1.2	0.7
Solids	21.4	18.5	16.9
Gas	20.3	16.5	13.6
Renewables	32	37.7	40.4

Table 3 – Europe estimated installed capacity in GW (Power Choices, Eurelectric [22])

	2020	2030	2050
Nuclear	124	132	175
Solids	158	174	162
Gas-Oil	277	258	253
Hydro	114	117	118
Biomass	46	53	70
Wind on-shore	163	207	257
Wind off-shore	53	86	125
Solar	41	65	140
Other Renewables	2	7	17.6
TOTAL	978	1099	1317.6

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Table 4 – Summary Table – Estimated Current Costs for Renewable Power Integration into Existing Grids [18]

		Offshore wind plants	Onshore wind plants	Other Renewable Technologies
Grid infrastructure costs	Grid connection costs	10-25% of the project investment costs for off-shore wind plants (300-800 Euro/kW)	8% of the project investment costs for off-shore wind plants (100 Euro/kW)	0-5% of project investment costs for other Renewable Technologies (0 - 75 Euro/kW)
	Grid upgrading costs	Usually the upgrading cost is included in the grid connection cost	0.5 - 3 €/MWh for 20 to 30% energy penetration level	
System operation costs up to 20% variable renewable capacity share	Capacity costs	2 – 4 €/MWh for 25% capacity credit		
	Short term system balancing costs	1 - 2 €/MWh		

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