ENERGY TECHNOLOGY SYSTEMS ANALYSIS PROGRAMME

International Renewable Energy Agency

Renewable Energy Integration in Power Grids

Technology Brief

IEA-ETSAP and IRENA© Technology Brief E15 – April 2015

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international cooperation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

About IEA-ETSAP

The Energy Technology Systems Analysis Programme (ETSAP) is an Implementing Agreement of the International Energy Agency (IEA), first established in 1976. It functions as a consortium of member country teams and invited teams that actively cooperate to establish, maintain, and expand a consistent multi-country energy/economy/environment/engineering (4E) analytical capability.

Its backbone consists of individual national teams in nearly 70 countries, and a common, comparable and combinable methodology, mainly based on the MARKAL / TIMES family of models, permitting the compilation of long term energy scenarios and in-depth national, multi-country, and global energy and environmental analyses.

ETSAP promotes and supports the application of technical economic tools at the global, regional, national and local levels. It aims at preparing sustainable strategies for economic development, energy security, climate change mitigation and environment.

ETSAP holds open workshops twice a year, to discuss methodologies, disseminate results, and provide opportunities for new users to get acquainted with advanced energy-technologies, systems and modeling developments.

Insights for Policy Makers

The share of renewables in overall power generation is rapidly increasing, both in developed and developing countries. Furthermore, many countries have ambitious targets to transform their power sector towards renewables. To achieve these objectives, the structure and operation of existing power grid infrastructures will need to be revisited as the share of renewable power generation increases. Renewable energy technologies can be divided into two categories: dispatchable (*i.e.* biomass, concentrated solar power with storage, geothermal power and hydro) and non-dispatchable, also known as Variable Renewable Energy or VRE (*i.e.* ocean power, solar photovoltaics and wind). VRE has four characteristics that require specific measures to integrate these technologies into current power systems: 1) *variability* due to the temporal availability of resources*;* 2) *uncertainty* due to unexpected changes in resource availability; 3) *location-specific properties* due to the geographical availability of resources; and 4) *low marginal costs* since the resources are freely available.

A transition towards high shares of VRE requires a re-thinking of the design, operation and planning of future power systems from a technical and economic point of view. In such a system, supply and demand will be matched in a much more concerted and flexible way. From a *technical* perspective, VRE generation can be ideally combined with smart grid technologies, energy storage and more flexible generation technologies. From an *economic* perspective, the regulatory framework will need to be adjusted to account for the cost structure of VRE integration, to allow for new services and revenue channels, and to support new business models.

There are several technological options that can help to integrate VRE into the power system grid: system-friendly VREs, flexible generation, grid extension, smart grid technologies, and storage technologies. New advances in wind and solar PV technologies allow them to be used over a wider range of conditions and provide ancillary services like frequency and voltage control. Flexible generation requires changes in the energy mix to optimise production from both dispatchable and non-dispatchable resources. Smart grid technologies can act as an enabler for VRE integration, given their ability to reduce the variability in the system by allowing the integration of renewables into diverse electricity resources, including load control (*e.g.* Demand Side Management (DSM), Advanced Metering Infrastructure (AMI), and enhancing the grid operation and therefore helping to efficiently manage the system's variability by implementing advanced technologies (*e.g.* smart inverters, Phasor Measurement Unit (PMU) and Fault Ride Through (FRT) capabilities). Energy storage technologies can alleviate short-term variability (up to several hours), or longer-term variability through pumped-storage hydroelectricity, thermal energy storage or the conversion of electricity into hydrogen or gas. Two immediate applications for deploying innovative technologies and operation modes for VRE integration are mini-grids and island systems. The high costs for power generation in these markets make VREs and grid integration technologies economically attractive since they can simultaneously improve the reliability, efficiency and performance of these power systems. This is, for example, the case of the Smart Grid demonstration project in Jeju Island, South Korea.

Furthermore, the right assessment and understanding of VRE integration costs are relevant for policy making and system planning. Any economic analysis of the transition towards renewables-based power systems should, therefore, consider all different cost components for VRE grid integration, such as grid costs (*e.g.* expansion and upgrading), capacity costs and balancing costs. Integration costs are due not only to the specific characteristics of VRE technologies but also to the power system and its adaptability to greater variability. Therefore, these costs should be carefully interpreted and not entirely attributed to VRE, especially when the system is not flexible enough to deal with variability (*i.e.* in the short-term). Moreover, RE integration delivers broader benefits beyond purely economic ones, such as social and environmental benefits. Even though not straightforward, these externalities should be considered and quantified in order to integrate them into the decision-making process and maximise socio-economic benefits.

Due to the rapid technological progress and multiple grid integration options available, policy makers should build a framework for RE grid integration based on the current characteristic of the system, developing technological opportunities and long-term impacts and targets. In particular, policy makers should adopt a long-term vision for their transition towards renewables and set regulatory frameworks and market designs to foster both RE development and management of greater system variability. Such regulatory frameworks could include new markets for ancillary services and price signals for RE power generators that incentivise the reduction of integration costs.

HIGHLIGHTS

- **Process and Technology Status –** Since 2011, renewables have accounted for more than half of all capacity additions in the power sector. Renewable energy (RE) technologies for electricity generation can be grouped into *dispatchable* renewables (*e.g.* hydro, geothermal and biomass power), which are basically ready for production upon demand, and *non-dispatchable* or *variable* renewables (*e.g.* wind and solar), whose electricity production depends upon meteorological conditions and/or the time of the day. This brief deals with the integration of *non-dispatchable* renewable power technologies – primarily wind and solar power – into the power grids. The typical modular size of variable renewable technologies is well suited to distributed power generation systems in which 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 that several factors be considered, such as the impact on slow voltage variations, the power plants' behavior under faulted[1] conditions and their interaction with protection systems. The integration of a significant amount of variable renewables into power grids requires substantial transformations to increase the flexibility of the existing grids: **a)** to allow electricity flow, not only from centralised power plants to users, but also from small users/producers to the grid, which is aimed to ensure grid stability when installing distributed generation; **b)** to establish intelligent grid and demand management mechanisms aimed at increasing flexibility and responsiveness and reducing peak-loads in order to deal with increased variability; **c)** to improve grid interconnection at the regional and international level aimed at increasing balancing capabilities, flexibility, stability and security of supply; and **d)** to introduce energy storage capacity to store electricity (energy) from variable renewables generation when production exceeds demand. An "enabler" for these transformations is the implementation of smart grid technologies, which incorporate grid elements with "smart" functionality to balance supply and demand, together with information and communication technologies to increase flexibility, improve reliability and support the integration of renewables. The experience gathered to date comes mainly from European countries with significant wind and solar installed capacity, such Denmark, Germany, Italy, and Spain. In these countries, associated issues are being solved in the light of further increases in the renewable electricity share. Experience with the integration of a very high (50%) share of variable renewables is available from applications on small islands.

1 A fault is an event occurring on an electric system such as a short circuit, a broken wire, or an intermittent connection (NERC, 2014).

- **Performance and Costs –** Small, swift (*i.e.* seconds to minutes) fluctuations in variable renewable power output rarely impact the overall power system. More important are the slow (*i.e.* minutes to hours time-scale) variations that result in an increased need for reserve capacity and other interventions to ensure the power system's stable operation. In general, the level of interventions depends on the share of renewable electricity and capacity in the power system. For a ten percent renewable electricity share, the increase of reserve capacity is estimated to range between 1.5% and 4% of the installed variable capacity. However, variability issues may also be solved through more interconnection to achieve more flexibility in the supply-demand balance. The costs incurred in the integration of variable renewables into existing grids can be categorised as 1) grid infrastructure and 2) 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 up to 5% of the project investment cost; for onshore wind farms, it ranges between 11% and 14% of the total capital cost and between 15%–30% for offshore wind farms (IRENA, 2012). Grid upgrading costs depend on grid characteristics and are estimated at EUR 0.5–3.0/MWh for a 20%–30% renewable (wind) electricity share. *System operation costs* refer to extra costs incurred in the conventional part of the power system. As part of the system operation costs, the profile costs (*i.e.* costs incurred from reduced plant utilisation due to higher VRE penetration) is the single most important integration cost component and accounts for more than half of the integration costs at 30%–40% VRE penetration rates: that is, in the range of EUR 15–25/MWh.

- **Potential and Barriers –** All major energy projection studies anticipate a significant renewable power increase in the electricity mix in all the world's regions. Key questions deal with the cost of renewables integration into power grids, policy and regulatory issues and the availability of suitable technologies (*e.g.* energy storage technologies). For example, it has been estimated that for the European distribution network, the total investment needed will amount to EUR 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 tend to be regulated. Grid investment would require a proper and stable regulatory and policy environment with appropriate incentives and long-term horizons. Experts generally agree that no insurmountable technical constraints exist for the achievement of the projected high share of renewables by 2050, but the economic and regulatory frameworks are critical to this achievement.

Technology Options

The increased use of renewable energy sources is a key component of national energy policies. In fact, more than 140 countries currently have renewable energy targets in place. For example, the European Union (EU) has set targets to achieve a 37% renewables share in overall energy use, which could lead to renewable power generation shares in the range of 51%-68% (DNV GL, 2014). Many small island countries have renewable power generation targets of 50% or more.

Renewable energy technologies for electricity generation can be grouped into *dispatchable* renewables, such as hydro power (ETSAP E06, E18), geothermal power (ETSAP E07) and 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 photovoltaics (ETSAP E10), concentrating solar power (ETSAP E11) and wave and tidal power (ETSAP 08). The dispatchability of an electricity generation source refers to the source's ability to be controlled in response to system requirements, such as variation in demand (*i.e.* at request of the power grid operator). In general, dispatchable renewables are constantly available (apart from maintenance needs) for production and offer high capacity factors[2] (*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 meteorological conditions. As a consequence, capacity factors are modest and 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[3] is needed in power grids with a significant share of variable renewables.

The typically small size and capacity of variable renewable power generation technologies is particularly suited to **distributed power generation** systems where many small power plants are connected to the distribution network and produce electricity close to demand sites. This may reduce the need for centralised power generation and high-voltage transmission lines, as well as transmission and distribution costs. However, appropriate adaptation and control of the electricity

2 The capacity factor is the ratio of actual electricity produced by a power plant in a year to the electricity that the plant could *theoretically* produce if operated continuously at full power during the same period.

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

system (*i.e.* generation plants and transmission / distribution lines) are needed to ensure reliable operation (*i.e.* supplying electricity upon demand with required frequency and voltage, and balancing active and reactive[4] power) of grids with a high share of variable renewables.

- **Renewables Integration into Power Grids –** The integration of a significant share of variable renewables into power grids requires a substantial transformation of the existing networks in order to:

a) allow for a bi-directional flow of energy; that is top-down (from generators to users) and bottom-up (with end-users contributing the electricity supply) aimed at ensuring grid stability when installing distributed generation;

b) establish an efficient electricity-demand and grid management mechanisms aimed at reducing peak loads, improving grid flexibility, responsiveness and security of supply in order to deal with increased systemic variability;

c) improve the interconnection of grids at the regional, national and international level, aimed at increasing grid balancing capabilities, reliability and stability;

d) introduce technologies and procedures to ensure proper grid operation stability and control (*e.g.* frequency, voltage, power balance) in the presence of a significant share of variable renewables; and

e) introduce energy storage capacity to store electricity from variable renewable sources when power supply exceeds demand and aimed at increasing system flexibility and security of supply.

4 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 when they change polarity. As the instantaneous power is the product of voltage and current, it requires both positive and negative values during a cycle. In a typical cycle, only a portion of the total power is *active* (*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 energise the magnetic and electric fields (*i.e.* 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 a 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.

The implementation of smart grid technologies can act as an "*enabler*" for these transformations by incorporating grid elements of smart functionality to balance supply and demand, together with information and communication technologies to increase flexibility, improve reliability and efficiency and support the integration of renewables, among other benefits. The main components and system operation of smart grids are discussed below.

- **Smart Grids –** Smart grids are meant to improve reliability and service, enhance markets, reduce costs and improve the efficiency of power systems. Consequently, smart grids can play a crucial role in facilitating the smooth integration of high shares of variable renewables and supporting distributed generation [SG&RE]. They involve a new integrated architecture for transmission and distribution with smart metering of bi-directional flows of energy and communication technologies that provide central operators with the information needed for the efficient operation and monitoring of the grid (*e.g.* fault detection, isolation and system restoration), efficient control of electricity supply (from both centralised and distributed power plants) and demand (*i.e.* smoothing demand peaks and/or meeting peak demand with variable renewables as well as possible). This 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 as and when 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 users/technologies) is still a matter under discussion.

Of key importance is the involvement of variable renewables and distributed generation plants in a number of tasks aimed at ensuring efficient and reliable operations (*e.g.* voltage and frequency regulation, reactive power regulation, active power reservation, congestion management, optimisation of grid losses, network restoration).

By reducing peak demand and enabling 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, especially when higher penetrations (around 15%) are reached (IRENA, 2013). Besides the main task of feeding renewable-based power into 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 a reduction of grid losses that depend mainly on reactive power control.

In most countries, power grid regulations require power plant operators to contribute to grid management functions (BDEW, 2008). Some of the functions commonly implemented are:

- static voltage control to limit slow voltage variations;
- dynamic operational support in case of voltage dips;
- active power limitation in case of rising frequency or operational safety risks; and
- 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 distribution grids, Fault Ride-Through (FRT) operations and their 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's operation. A major criterion for plant connection is the impact on the grid voltage during normal operations (*i.e.* slow voltage variations).

In conventional distribution networks with radial configuration (*i.e.* centralised power generation), a node voltage decrease occurs, as a result of a voltage drop in 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 increase in an acceptable range of typically 2%–3%.

Voltage changes can be determined by complex load-flow calculations[5]. The voltage increase depends on the network short-circuit power and the impedance angle at the connection 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.

5 An approximate calculation of the expected relative voltage increase is given by the formula:

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

Where:

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

A 2011 study 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 could be connected to low-voltage radial distribution networks by a factor of 1.5 to more than 2 (Degner, 2011). 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 increase. However, a trade-off has to be accepted as this also leads to increased losses and reduced transmission capacity.

A further criterion 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 (BDEW, 2008):

- eight times the rated current for synchronous generators;
- six times the rated current for asynchronous generators and double-fed asynchronous generators; and
- one times the rated current for generators with inverters; this depends on the time-scale and could be 3–5 times for events under one 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, remain below the network rated value. This constraint is often the main inhibiting factor for connecting new distributed electricity sources to existing grids. Distributed electricity sources coupled with inverters can relieve this constraint.

Fault Ride-Through (FRT) Operation. In conventional power grids, inverter-based distributed generation plants must be quickly disconnected when the grid voltage or frequency exceeds the allowable operating range. In grids with a 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, for example, result from a fault in the transmission network) can threaten the grid's overall stability. Under such circumstances, appropriate management of the generation plants can help react to the voltage and frequency deviations[6] 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 renewables 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 (*i.e.* grid codes) to solve the problems associated with the connection of wind parks and a large number of PV systems. Dynamic operational support of the grid in the case of voltage dips (at medium and low voltage levels) is mandatory in some countries. This means that generation plants must remain connected for a certain length of time 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 operations through corrective action. In general, distribution networks use overcurrent protection, but other systems can also be used[7]. Protection systems are usually designed assuming a mono-directional power flow and proper coordination of overcurrent devices based on the available fault current. The introduction of distributed electricity sources into the distribution network may cause unwanted impacts on the protection systems, mainly due to load flow changes and increased fault current

6 Frequency in a power system depends on the balance between generated and consumed active power. Small load variations or intermittent generation may result in 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 depends largely on the reactive power balance. In conventional power plants, electricity generators are the main source 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 uses the other elements of the power system.

7 Other protection systems include, for example, 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 in 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 seconds) and then switched on again.

contribution. For example, the introduction of a distributed source and its associated current may cause an erroneous operation of distance relays. Furthermore, in contrast to 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 power grids requires 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. To allow local renewable and distributed generation units to interact with each other and with the grid management systems, a harmonisation of communication methods and/or physical media employed by different vendors and users is needed. In this context, developers and manufacturers all over the world propose harmonisation through specific standards, with the IEC 61850 as the most representative. This standard permits inter-operation between different systems from different vendors, thus increasing benefits 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 (IEC, 2006).

- **Electricity Storage –** Electricity (energy) storage is dealt with in more detail in ETSAP E18. In power grids with a significant share of variable renewables, storage is needed to allow energy to be captured and retained when renewable sources are available for production and this production exceeds the current demand. The stored energy can then be supplied upon demand, even when renewable production is not available. The electricity storage plants can also help to ensure the required grid voltage and frequency stability, at various timescales and operating conditions. Because electricity cannot be stored as is, electricity storage involves the conversion of electricity into other forms of energy using several technological options with different characteristics and performance, *i.e.* **pumped-storage hydro; compressed air energy storage; electric batteries** (*e.g.* 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) batteries that could be charged overnight using excess electricity, and used during the day. The technical feasibility of this approach is being carefully investigated as it could also contribute to the grid demand-supply balance. Among electricity storage technologies, pumped-storage hydro plants are currently the only commercial option for large-scale electricity storage (in the form of potential energy). Although electricity storage plays a key role for renewable integration in power grids, the global potential for pumped-storage hydro is limited and largely exploited worldwide since these plants require specific sites, with natural or artificial water reservoirs located at different geodetic elevations. New, cost-effective storage technologies are still under development. Near-term applications for advanced battery storage systems can be found in islands and off-grid systems and have started to penetrate the residential market coupled to rooftop solar PV systems (IRENA, 2015a).

- **Grid Interconnection –** Increased grid interconnection at regional, national and international level would enable more flexibility in power transmission from regions with an ample availability of renewables to other 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 times (*e.g.* solar power during the day, wind power overnight) and/or in different regions (South, North). Higher interconnection and transmission capacity also enables the optimal use of surplus generation, alleviates the problem of daily and seasonal demand peaks, reduces the requirements for regulation reserves, enhances congestion management and reduces the need for new (and back-up) generation capacity. Modern, high-voltage, direct-current (HVDC) transmission lines for long distances are highly efficient though their implementation takes time and involves significant upfront investment. Grid interconnection also requires full integration of the grid management systems.

Grid interconnection of several operating areas requires high levels of synergy among the system operators in order to achieve a single virtual control area. The technology implemented to achieve grid interconnection allows grid operators to optimise their control energy use through intelligent communication between the grid operators' load-frequency controllers. Moreover, there are some market-based mechanisms that facilitate the efficient operation of grid interconnection, such as market coupling, market splitting and market balancing between neighbouring operating areas.

Global Renewable Energy Shares

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

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

According to IEA energy statistics (IEA, 2014a; IEA 2014b), for the year 2012, renewables' share in the global annual electricity generation (*i.e.* 22 721 TWh) was about 21%; 16% from hydropower and 5% from other renewables (*i.e.* about 2.3% wind, 1.9% biomass, 0.3% geothermal, 0.4% PV). In terms of capacity, renewables accounted for 27.8% (*i.e.* 19% hydro, 4.9% wind, 1.7% biomass, 0.2% geothermal, 1.7% PV) of a total 2012 global cumulative installed capacity of 5 683 GW.

However, over the past years renewable-based electricity (particularly wind and solar PV power) has been growing rapidly worldwide, driven by policy incentives and increased economic competitiveness (wind) and cost reductions (PV). For example, solar PV, CSP and wind power capacity grew at an average annual rate of 55%, 48% and 21%, respectively, during the years 2009-2013 (REN21, 2014). Wind and PV cumulative installed capacities in 2011 were about 236 GW and 70 GW, respectively, while corresponding values at the end of 2013 were 318 GW and 138 GW (EPIA, 2014; GWEC, 2014; WWEA, 2014). Initial results for 2014 suggest a total installed capacity of 369 GW of wind and around 200 GW of solar PV (GWEC, 2015; Clover, 2014). Leading countries in terms of wind and PV annual installations in the period 2012-2013 (*i.e.* total GW installed) were China, Japan, Germany, the United States and the United Kingdom; Japan and the US with predominant growth in PV installations (Table 1).

Table 1: VRE installed capacity growth rate in the period 2012-2013 (IRENA, 2015b)

Country	Wind growth (%)	PV growth (%)	VRE growth (%)
China	21	168	33
Japan	2	106	76
Germany	11	11	11
US	2	65	9
UK	26	59	31
India	9	78	14

Tables 2a and 2b show this information disaggregated by regions, for generation and installed capacity, respectively.

Table 2a: Generation breakdown by region, 2012 (GlobalData, 2014; WWEA, 2014)

Technology	Global	European Union	OECD Americas	Latin America	Africa	Middle East	OECD Asia Oceania	Non-OECD Asia
Total generation (TWh)	22 721	3 260	5 268	1 152	741	905	1 850	7 402
Hydro (%)	16.2	10.3	13.5	60.9	15.1	2.4	6.3	15.7
Bioenergy (%)	1.9	5.2	1.8	3.9	0.3	0	2.5	1.0
Wind (%)	2.3	6.3	3.0	0.6	0.3	0	0.8	1.7
Geothermal (%)	0.3	0.2	0.5	0.3	0.3	0	0.5	0.3
Solar PV (%)	0.4	2.1	0.2	0.0	0.0	0	0.5	0.1
Total RE (% of total)	21.2	24.2	18.9	65.8	16	2.4	10.5	18.9
Total VRE (% of Total)	2.7	8.5	3.2	0.6	0.3	0	1.3	1.8

Table 2b: Installed capacity breakdown by region, 2012 (GlobalData, 2014; IRENA, 2015b)

Technology	Global	European Union	OECD Americas	Latin America	Africa	Middle East	OECD Asia Oceania	Non-OECD Asia
Total Capacity (GW)	5683	960	1356	258	165	256	454	1728
Hydro (%)	19.1	15.5	1.5	55.4	15.2	5.5	15.2	19.8
Bioenergy (%)	1.8	3.9	4.9	5.0	0	0	1.8	1.2
Wind (%)	5	11.0	0.3	1.2	0.6	0	1.3	5.5
Geothermal (%)	0.2	0.1	0.7	0.4	0	0	0.2	0.2
Solar PV (%)	1.7	7.2	0.1	0.0	0.0	0	2.2	0.5
Total RE (% of total)	27.8	37.9	14.3	62.0	15.8	5.5	20.7	27.3
Total VRE (% of Total)	6.7	18.4	0.4	1.2	0.6	0	3.5	6.0

Until 2013, Europe was the world's leading region in terms of cumulative installed renewable capacity of solar PV and wind. However, in 2014 Asia became the largest market for wind power (142 GW compared to 134 GW in Europe), with China adding almost half of the global added capacity (23 GW) in 2014 (GWEC, 2015). Global installed capacity is expected to have reached around 200 GW by the end of 2014 with the largest growth markets in China, Japan, and the USA.

Germany is one of the countries that has considerable experience in integrating variable renewables. In addition to 39 GW wind and 38 GWp of PV power, Germany also produced renewable electricity from biomass (8.1 GW), geothermal energy (0.012 GW), hydropower (5.6 GW) and waste (2 GW) in 2014. On an annual basis, Germany produced about 29.7% of its electricity from renewables in 2014, with a total installed renewable capacity about 87.5 GW in 2014 (Burger, 2014). As the total RE installed capacity is higher than the level of the minimum load demand of the country's power system, it can be interpreted as a power system operation with very high instantaneous renewable share with significant electricity generation based on variable renewables (wind and solar). For example; in 2012, during the midday hours of May 25 (Friday) and May 26 (Saturday), Germany's solar power plants[8] fed renewable electricity equivalent to 22 GW per hour — equal to the production of about 22 nuclear power plants — into the grid, 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 significant — in certain cases even dominant — shares in the national electricity mix. For instance, India is revising its targets upwards: from an initial target of 20 GW of solar PV installed capacity for 2022 to 100 GW by 2019; and from a target of 3 GW installations of wind power per year to around 10 GW per year. As the capacity factor of these plants is modest[9], the achievement of high renewable electricity shares involves very high renewable capacity shares, with power systems running for prolonged periods at high instantaneous renewable share. This translates into significant technical implications for grid adaptation, management, and economic investment, as discussed in the previous sections.

- **Small-island grids and micro-grids –** Small islands provide valuable opportunity areas for testing new technologies and operation modes for renewables integration into existing power grids. Islands have small, isolated power grids, often with high shares of renewable power. In principle, the electricity demand of a small island with a peak load of a few hundred kilowatts could be fully met by renewables, such as wind and PV power, with energy storage units to balance supply and demand (IRENA, 2012b). Proper power system design requires extensive simulation and depends on the load profile, wind and solar resources and the level of renewables penetration.

However, the achievement of a 100% variable renewable electricity penetration is usually difficult and costly as it involves oversized renewable power capacity and storage capacity. It is more affordable to manage high shares of renewable electricity sources with appropriate energy storage and the use of back-up con-

8 More than 70% of PV installations in Germany are small plants (< 100 kW) 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.

9 On an annual basis, typical PV capacity factors range from 10% (in northern latitudes) to nearly 18% (in tropical sites), while wind plants have capacity factors ranging from 20%–40% for sites with high wind potential.

ventional power (*e.g.* diesel generators). The implementation of such systems requires bi-directional inverters as an 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 production (if needed) upon the central operator's request, along with proper management of non-critical loads.

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

Much current research focuses on micro-grids (Hatziargyriou, 2007), which aim to facilitate the integration of variable renewables and distributed generation units into the grids. Micro-grids typically consist of a combination of generation sources, loads and possibly storage units that can be operated (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 or in "island" mode (*i.e.* isolated from the grid) when 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 renewable energy sources (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 centralised grid and turn them into positive impacts, such as improved energy efficiency and local reliability, reduction of energy losses and the 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. 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 local energy needs using renewable sources. The plant consists of a pumped-storage hydropower plant (*i.e.* 11.3 MW generation capacity and 6 MW pumping capacity), coupled with a 11.5 MW wind farm with five turbines. The plant officially started operation in June 2014 (Gorona del Viento, n.d.) in order to provide reliable power supply for the island's 10 960 residents. It will provide about 80% of the island's energy needs, with the remaining 20% to be 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 EUR 82 million and the developer is "Gorona del Viento El Hierro S.A.

Gaidouromantra-Kythnos, Cyclades islands, Greece (Tselepis, 2003; PPC, NTUA and CRES, 2088)**.** The Gaidouromantra system on Kythnos island in the Aegean is a three-phase micro-grid for electrification of residential houses (with monophase electric services) in one region of the island. The system consists of main power lines and a communication cable running in parallel to serve monitoring and control needs. The system was installed in 2001. Its most important features are: 1) electricity generation from distributed PV systems; 2) no physical connection with the island's public grid (permanently "islanded" system); 3) voltage and frequency control by battery inverters; and 4) a 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-Micro-grids* project (*i.e.* the EU's Sixth Framework Programme). Software/hardware systems for centralised and de-centralised load control were developed and installed. They consist of Intelligent Load Controllers (ILCs) 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 case of energy shortage.

Operational Experience and Performance

Variability is not actually new for power systems since 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 back-up. Existing procedures and protocols have been adapted by operators to match the new requirements associated with the large-scale integration of variable renewables.

Most of the experience to date in large-scale grid integration of variable renewables comes from European countries with high wind and solar PV penetration (Eriksen, 2005; Holttinen, 2009; Holttinen, 2011) where the Fault Ride-Through (FRT) is now mandatory and the problems associated with simultaneous loss of a large amount of generation capacity have been virtually solved. The main concern in the operation of these power systems is coping with wind variations, increased need for capacity reserves and accommodation of wind curtailment events.

While small and rapid (*i.e.* seconds to minutes) variations of aggregated wind power output do not impact the grid significantly, variations involving longer (*e.g.* hourly) periods of time involve variation of the net load (load minus wind power), leading to a significant increase in reserve capacity needs. This increase depends basically on the wind penetration level. Considering that load variations are more predictable than wind variations (Holttinen, 2005), it is estimated that the increase need for reserves for a 10% wind energy penetration is about 1.5%–4% of installed wind capacity.

Wind forecasting also plays an important role in the operation of a power system with high wind power penetration. Forecasts with a time horizon from minutes to 48 hours are used as a basis for scheduling balancing power reserves through the appropriate commitment of conventional power plants. The annual average error on day-ahead wind power forecasting currently impacts about five percent of the installed wind capacity. The largest errors are experienced during storms when high wind speeds exceeding cut-off limits may result in shut-down of the wind turbines. However, operating experience for large regions shows that it usually takes several hours for the power to be reduced to its final value. Therefore, the threat to the stability of the power system is usually modest.

Curtailment of wind power may be needed because of network limitations or in the following cases: 1) during low-demand periods, if a minimum of conventional capacity must remain connected to ensure grid stability and control; 2) 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; and 3) if non-dispatchable generation exceeds 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 ten seconds. This makes wind power a valuable asset for rapid regulation.

Valuable experience with large-scale wind power integration has been gained in such countries as Denmark, Germany and Spain. Table 3 displays the shares of wind power generation and installed capacity for those countries with higher wind penetration.

Table 3: Wind generation and capacity shares, 2013 (GlobalData, 2014; IRENA, 2015b)

Country	Capacity Share (%)	Generation Share (%)
Denmark	34.5	34.8
Portugal	23.8	24.4
Ireland	23.6	18.9
Spain	21.4	19.7
Germany	18.9	9.3

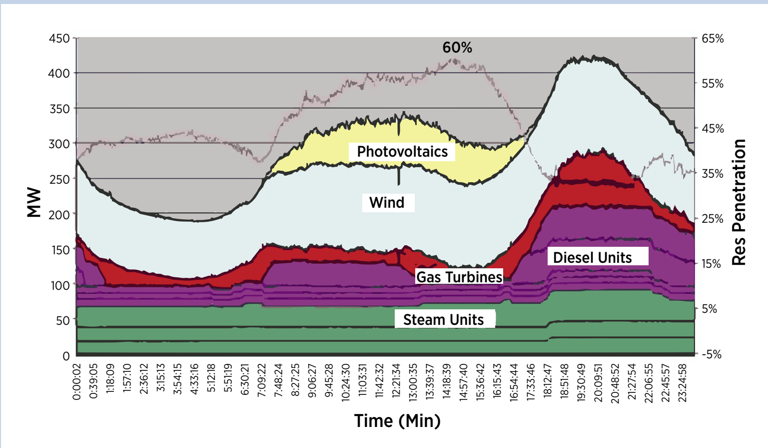
In Germany, because of uneven geographical distribution, some wind power curtailments have occurred due to surplus production and grid limitations. The required regulation power is provided by the four national Transmission System Operators (TSOs) and interconnections to neighbouring countries (*i.e.* Netherlands and Poland) are also occasionally used. However, in 2011 a comprehensive transmission system upgrading plan has been established in the Grid Expansion Acceleration Act (NABEG) to further increase the penetration of renewable electricity.

Spain is insufficiently interconnected with the rest of the Europe and has to provide domestic balance capacity to compensate for variable renewables. As wind forecasting represents a key tool for power system operation, wind power plants provide real time information to a control center, which is able to adapt to their production. Real time data allow the system operator to deal with generation and demand, control wind generation and achieve an optimal operation of the power system. Curtailments of wind production in 2010 were on the order of 0.5% of operating time (Holttinen, 2011).

A remarkable example of integration of variable renewable electricity is also available on the Greek island of Crete (Gigantidou, 2012). 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 (mainly with wind parks), the system has been faced with some problems due to: 1) sensitivity of wind turbines to voltage dips; 2) faults on grid connections of wind parks to the HV sub-stations; and 3) voltage setting of wind parks' protective disconnection devices. All of these problems have been solved over time by the distribution system operators and wind park owners. Especially the FRT capability of wind turbines has dramatically improved system performance in Crete.

At present, during normal operation, PV plants on Crete 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 wind parks' power output is appropriately reduced. The Energy Control Center of Crete continuously monitors the wind parks and a set-point for maximum power output is given up to every five minutes, if needed. However, in some periods, the operators may decide to operate the system with higher in-

Figure 1 - Generation mix for Crete's power system on 5 March 2013 and renewables' penetration (violet line).(Gigantidou, 2012)



stantaneous capacity share (up to 60%, see Figure 1). The Energy Control Center also monitors selected PV plants at various locations in order to accurately assess the total PV production. This helps the daily scheduling of conventional capacity. Distributed PV plants also support 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, but an increased use of operating capacity reserve, is needed.

Current Costs and Cost Projections

The additional cost of renewable integration into the power grid can be categorised mainly into **grid infrastructure** and **system operation costs** (Auer, 2007). The additional costs for smart grid technologies such as ICT, smart metering, etc. are roughly estimated to be comparable with the cost savings due to reduced peak loads and increased energy efficiency.

- **Grid infrastructure costs** include grid connection 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 availability of standard equipment. The grid connection cost is an important economic constraint for renewables development in remote locations. Based on various case studies and current practice, 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 (Auer, 2007). The connection costs, including electrical work, electricity lines and the connection point, are typically 11%–14% of the total capital cost of onshore wind farms and 15%–30% for offshore wind farms (IRENA, 2012a). In general, the grid connection cost is the dominant financial component in wind power infrastructure costs. In most countries, grid connection costs are borne by the investor as part of the initial investment cost.

Grid upgrading costs include the cost of additional network equipment needed to integrate renewable power into the existing grids. They depend mostly on the amount of renewable capacity, the location of the power plants and the structure of the existing grid. Based on load flow analyses, 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 EUR 0.5–3/MWh for 20%–30% renewable share in annual electricity generation (Auer, 2007).

- **System operation costs** can be divided into system *profile* 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.

Profile costs is a broad concept that captures all three impacts of the temporal mismatch between VRE generation and load profile: 1) capacity costs (adequacy costs) due to a low VRE capacity credit; 2) reduced average utilisation of thermal power plants; and 3) curtailed VRE generation when power supply exceeds demand (Ueckerdt *et al.*, 2013; Hirth *et al.*, 2015). According to Ueckerdt *et al.* (2013) and Hirth *et al.* (2015), the capital cost due to the utilisation effect is the single most important integration cost component and can amount to more than half of the integration costs at 30%-40% penetration share (EUR 15–25/MWh). At low penetration rates, the profile costs are estimated to be zero or can result in savings.

Adequacy costs are caused by the need for firm capacity to ensure generation adequacy; in other words, these costs address VREs' low capacity credit. 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; that is, without affecting the loss of load probability (LOLP). For example, wind power provides a contribution to meeting the peak demand in a power system, but this contribution is lower than the one 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 generation peaks and demand coincide. An overview of methods used to calculate the capacity credit and a summary of results is given in Ensslin, 2008. The capacity credit as a percentage of the installed wind capacity is roughly equal to the aver-

Table 4: Scenarios of RE generation share in the future according to different studies

Technology	REmap 2030[1]	New Policies 2030[2]	Blue Map 2050[3]
Nuclear	11%	11.9%	23.9%
Natural Gas	17%	23.2%	15.2%
Oil	1%	1.7%	0.6%
Coal	27%	33.0%	12.4%
Hydro	17.6%	16.1%	14.3%
Bioenergy	7%	3.4%	6.1%
Wind	12%	7%	12.3%
Solar	6%	2.9%	12.4%
Other renewables	1.4%	0.7%	2.8%
Total RE	**44%**	**30%**	**48%**

1 IRENA, 2014
2 IEA, 2014a
3 IEA, 2010

age capacity factor of wind generation for low wind share, but it 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 needed in a particular power system to maintain system adequacy can be estimated. Methodology and results for various cases can be found in Auer, 2004. Reduced average utilisation of thermal power plants is driven by higher VRE penetration, especially during base-load hours, and consequently increases thermal capital costs. Similarly, if VRE generation is curtailed when generation exceeds load, VRE capacity utilisation is reduced and therefore VRE generation capital costs are also increased.

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 and uncertainty properties of VRE generators, the reserve capacity needed for up-and down–regulation increases if compared to the case where the same energy is delivered by conventional power. In particular, the impact of second-to-minute scale wind and solar PV power variability is modest or negligible while minute-to-hour scale variability may affect grid operation more significantly. The increased requirements for reserve power correspond to the 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

Table 5: RE capacity share in 2012 vs. potential RE capacity share in 2030, by region (IRENA, 2015b)

Region	% RE (2012)	% RE (REmap 2030)
OECD Americas (excl. USA)	49	66
USA	17	49
Latin America (non-OECD)	62	80
European Union	38	55
Eastern Europe (excl. EU, incl. Russia/Turkey)	25	41
OECD Asia	21	53
China	28	42
India	28	57
Non-OECD Asia (excl. China/India)	22	43
Middle East	5	41
Africa	16	36

and contribution of conventional power plants of higher operating costs in the power system, increased wear-and-tear and maintenance costs of plants, etc. Balancing costs are relatively small (< EUR 6/MWh) and, at low VRE penetration (<10%), these cost can be zero or even negative; however, these costs, as with other integration costs, increase with the level of penetration (Hirth *et al*., 2015).

Potential and Barriers

Several reports contain scenarios regarding the penetration of renewable power in the future electricity mix; some suggest high potential for VRE penetration. Table 4 shows the projected renewable share in 2030 and 2050, according to three reports: 1) *REmap 2030* (IRENA, 2014); 2) *New Policies* (IEA, 2014a); and 3) *Blue Map 2050* (IEA, 2010). Table 5 presents the share of renewables in installed capacity by region in 2012 and compares it with the potential installed capacity share of renewables in 2030 (IRENA, 2014). All sources project a very high share of renewable electricity in the coming decades. However, the question of "who pays for the integration cost of renewable energy into power grids" is an important issue to be dealt with and involves both the cost of renewable technologies themselves, as well as their integration costs (Barth, 2008). Potential paying stakeholders are, of course, the 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, as natural monopolies, are usually regulated.

In the generation sector, markets have developed in which generators sell electricity within a structure with defined prices, timeframes and other rules. In many countries, a separate balancing market has also been established to maintain short- and medium-term balance in the power system. In the event that renewable producers do not participate in the power market (*e.g.* when 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 do participate in the electricity market, then they must bear the costs of any imbalance they may cause based on the current balance power price. Hence, in the light of an adequate acknowledgment and treatment of the integration costs, an increased market integration of renewables offers clear advantages but requires a proper and efficient regulatory structure of the balancing market.

As for the integration costs for grid connection and upgrading, two distinct charging approaches may be considered: *deep* and *shallow* connection charges. In the *deep connection charges approach*, the renewable producer bears both grid connection and upgrading costs and these are included in the total project cost. In the *shallow connection charges approach* the renewable producer bears only the grid connection cost, not the grid upgrading cost. Both deep and shallow charging approaches have advantages and disadvantages; moreover, 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 to assess. In the shallow connection approach, the grid upgrading costs are borne by the network operators and must be "socialised" through the use of a system charges approach. Network operators must also bear the extra costs required for the transformation of existing grids into smart grids by ICT.

For the European distribution network, it has been estimated that the total investment needs will amount to some EUR 480 billion by 2035. Grid investment will require a proper and stable regulatory environment with appropriate incentives and long-term horizons.

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

Table 6 – Summary of: Estimated Costs for Renewable Power Integration into Existing Grids (Auer, 2007; IRENA, 2012; Hirth et al., 2015)

		Offshore wind plants	**Onshore wind plants**	**Other RE Technologies**
Grid infra-structure costs	Grid connection costs	15%–30% of the total capital cost of offshore wind farms	11%–14% of the total capital cost of onshore wind farms	0%–5% of project investment costs for other renewable technologies (EUR 0–75/kW)
	Grid upgrading costs	Usually the upgrading cost is included in the grid connection cost	EUR 05-3/MWh for 20%-30% energy penetration level	
System operation costs	Profile costs	Costs due to reduced utilisation of plants constitute **more than half** of the integration cost at 30%–40% penetration rates (EUR 15–25/MWh). Costs are zero or negative at low penetration rates.		
	Short term system balancing costs	< EUR 6/MWh for thermal systems < EUR 2/MWh for hydro systems		

Table 7: Smart grid technology costs (IRENA, 2013)

Technology	Capital and O&M costs
Advanced metering infrastructure (AMI)	USD 50-250/meter; up to USD 500/meter, including communications and IT; O&M USD 1/meter/month
Advanced electricity pricing	Depends on programme; generally low if AMI already exists
Demand response (DR)	USD 240/kW capacity (vs. USD 400/kW for gas peaking plant); O&M costs low
Distribution automation (DA)	Depends on specific tech; IVVC/FLISR demo ~ USD 150 000/feeder
Renewable resource forecasting	Wind forecasting service USD 2 500/month/plant; PV expected to be similar
Smart Inverters	<5% more than conventional inverter; O&M same as conventional inverter
Distributed storage	Tech-dependent; typically higher than other energy/power production methods
Virtual Power plants (VPPs)	Low
Micro-grids	Technology-dependent; USD 5/Watt capacity

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