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# WIND POWER GRID INTEGRATION: THE EUROPEAN EXPERIENCE

W.L. Kling, L. Söder, I. Erlich, P. Sørensen, M. Power, H. Holttinen, J. Hidalgo, B.G. Rawn

**Abstract** – Europe currently holds the largest installed capacity of wind power plants of all continents. Over decades of development, significant adaptations have been implemented to integrate wind turbines into the electrical power system. Wind power research has been accelerated by the need to maintain grid performance and reliability in the face of the exponential deployment of wind turbines. This paper explains the basic requirements and principles in grid codes, modeling, reserves, forecasting, system planning, and operation, and relates how experience especially in Europe has led to new practices and new research.

**Keywords:** *wind power, wind power forecasting, grid codes, wind turbine generic models, power system planning, power system reserves, power system operation*

## 1 INTRODUCTION: TRENDS AND DEVELOPMENTS IN EUROPE

Wind power implementation has increased significantly during the last decade and there are currently many power systems, or subsystems, with comparatively large amounts of wind power. In 2010 Denmark covered 21.8% [1],[2] of their electric energy demand with wind power. The corresponding figures were for Portugal 17% [3], Spain 16% [4], and Ireland 11% [5]. This means that the experience from areas with large amounts of wind power has increased and in addition to this a large amount of integration studies have been performed the last years [6],[7],[8],[9],[10],[11]. In this paper the challenges concerning wind power integration as encountered will be summarized.

From the consumer's point of view there are three basic requirements on the power system:

1. The voltage level at the connection point has to stay within an acceptable range as most customer appliances (e.g. lighting equipment, motors, computers, etc.) require a specific voltage range (e.g.  $230\text{ V} \pm 10\%$ ) for reliable operation.
2. The power should be available at exactly the time the consumers need it in order to use their various appliances (i.e. when a customer switches on a certain device the electrical power starts to flow).
3. The consumed energy should be available at a reasonable cost (this should also include low external costs to reflect the environmental impact of electricity production).

From the producer's point of view, requirements are similar; they require a certain voltage for secure operation of their plant and access to the network to deliver their power, all at a cost-efficient access fee.

The likelihood that requirements 1-2 are met underlies power system reliability. Greater reliability leads to higher costs and hence a conflict arises between the first

two requirements and the third, namely the demand for reasonable costs. 100 percent reliability and perfect voltage quality are technically impossible and the closer one comes to this level the more expensive the supply will be.

The voltage requirement means that the voltage should not change too much for different situations with, e.g., different loading levels and different wind production levels. This is mainly a reactive power management issue, but is also related to the dimensioning of the system including the amount of controllable devices and the strength of the system. In addition to this there is a challenging issue concerning handling the consequences of short interruptions caused by, e.g. lightning and other faults. The basic requirements remain the same in a power system with smaller or larger amounts of wind power. But wind power can change power system behaviour, and network operators have to take this into account.

Grid codes help to ensure that the needs of all connected parties to the grid can be met in the most efficient and optimum way. To form grid codes wisely and also conduct planning and operation studies, a wide array of wind power models are needed. Section 2 of this paper addresses grid codes and Section 3 gives an overview about the modeling of wind power including standardization of models.

On a fundamental basis, three special cases can be distinguished that affect dimensioning of both generation and transmission most. These issues are further treated in Section IV, which addresses planning:

- A. *Low wind power production and high power consumption.* Such situations are the basis for dimensioning the conventional generation capacity that has to be installed. This issue is often called the "capacity adequacy issue". This challenging situation occurs in most power systems comparatively seldom; but the power consumption may be high in the neighboring areas and countries too, which reduces the possibilities of importing power.
- B. *High wind power production and high power consumption.* Looking at past situations of high power consumption in many countries, there are situations both with low wind power production and with high amounts of wind power. When dimensioning the power system, in order to handle such situations in a rational way, wind power production both in a certain area and in its neighboring areas as well as the transmission capability have to be taken into account.
- C. *High wind power production and low power consumption.* Such situations can be handled in many different ways, but it has a very large impact on the

system. If one adds large amounts of wind power to a certain area without changing anything else, this may result in very low prices and/or that not all wind power can be used. If such situations often occur, it becomes economically beneficial to increase transmission capacity from the area, or encourage flexible power consumption by deploying storage devices (district heating, charging of electric vehicles) or accepting curtailed or deferred demand. The key point here is that appropriate dimensioning is an economic issue as low prices promote investment in transmission or flexible power consumption; on the other hand, large investments will increase electricity prices.

Another serious issue is maintaining the power balance in case of large amounts of fluctuating and hardly predictable wind power, and this is dealt with in Sections 5 and 6 on reserves and forecasting respectively. The challenge is that controllable production and consumption have to secure the balance on all time scales. With larger amounts of wind power, there is a larger uncertainty because wind power forecasts are not as exact as the corresponding power consumption forecasts.

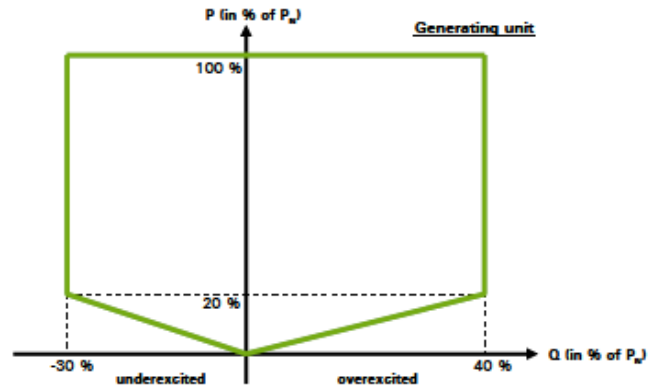
The continuous balancing process applies to both the technical capacity available for increasing other generation when wind power decreases and for decreasing other generation when wind power increases, but also to do it in an economically feasible way.

The impact of the challenges mentioned is related to how much wind power there is in a certain area, but also to the available transmission capacity to neighboring systems and the way electrical energy can be exchanged with the neighbors planned as well on a short notice. Experiences with operation of power systems that have a truly high penetration of wind are discussed in Section 7. This overview paper then ends with the main conclusions in Section 8.

## 2 GRID CODES

With the increasing penetration of wind power the need to consider the special technical characteristics of wind turbines in grid codes becomes obvious. Disconnection, e.g., and thus loss of a considerable amount of wind generation following voltage dips of down to 20%-30% of the nominal voltage, as was the case in the past, is not acceptable from the power system point of view. Today wind power plants have to contribute to system services and guarantee a certain level of contribution to system security. Also, some technical standards for operation and design of grid connections need to be defined.

Many European countries developed grid codes at utility or national level [12],[13]. With increasing experience most of them necessitated several revisions and adaptations and have, in the process, attained some degree of convergence, but they still differ from country to country in many aspects. To coordinate national grid codes ENTSO-E established a working group on "Requirements for Grid Connection Applicable to all Gen-



**Figure 1:** Minimum requirement for the P/Q operation of an offshore wind power unit within the voltage range of +5% of  $U_n$  at the unit.

erators" [14] where special focus is directed to wind power generators. Manufacturers will benefit from such standardization even though the implementation requires usually more expensive technical solutions. On the other hand, frequent changes in grid codes and differences between requirements, sometimes within the same country, are affecting negatively the development process.

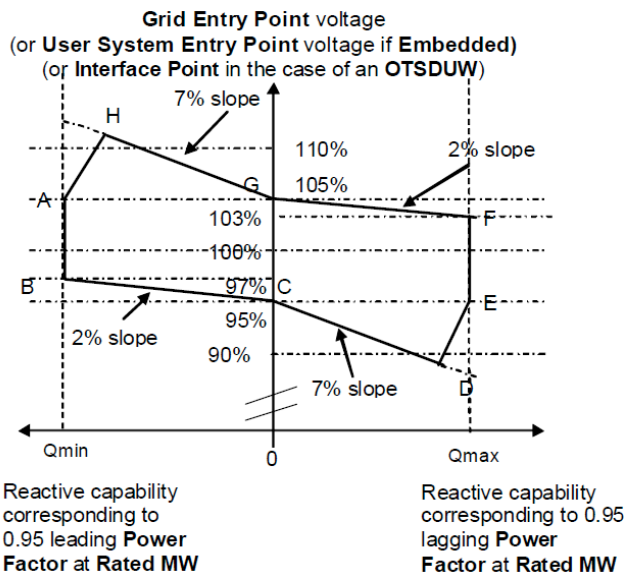
The grid codes define steady state and also dynamic requirements. To prove that wind turbines and wind power plants meet these requirements, validation and certification procedures are established.

### 2.1 Steady state requirements

One of the most important issues addressed in grid codes is the reactive power capability of wind turbines and wind power plants under (quasi) steady state operating conditions. In the past wind turbines did not contribute to maintaining voltage level at the connection point by contributing to reactive power management and supplied only active power to the grid, except in special cases where capacitor banks were required. However, without the contribution of wind turbines often the grid voltage cannot be kept within the desired band in all situations and at all points. Additional devices like Statcom, SVC or capacitor banks may help voltage-Var control but wind turbines must provide built-in capability in terms of reactive power provision. To design wind power plants taking their Var generating and consuming capabilities into consideration, the required P-Q-diagram at the point of connection is essential. A German requirement for offshore wind power installations is given in Figure 1 [15]. The proper allocation of Var exchange of wind turbines and external devices is a tradeoff taking into account costs, effect on the grid, static and dynamic grid requirements and the characteristic of the devices.

In grid codes the reactive power capability is defined usually at the grid connection point but sometimes even at the wind turbines themselves.

Changes in the load flow demands for adaptation of Var exchange of wind power plants. Since these



**Figure 2:** Generator reactive power requirements for inductive and capacitive operation for offshore transmission system development (OTSD) [16]

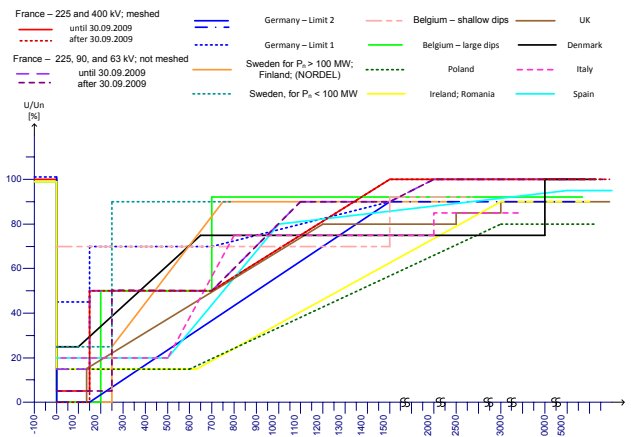
changes are slow, the time response requirements are not challenging; usually several seconds are acceptable [17], and some jurisdictions change requirements for Var support a few times a day [18]. The reactive power generation can be defined as a function of active power by specifying power factor (fixed P/Q relationship means constant power factor) or by a voltage-Var droop (Figure 2) that guarantees capacitive power supply at low voltage levels and inductive power when the voltage increases above the desired nominal value. For large wind power plants specification by the transmission utility of the reactive power set point is reasonable. The current practice of European utilities is non-uniform motivated by different grid design and operational experiences. Therefore, wind turbine manufacturers usually implement all alternative options and allow utilities to choose the most appropriate setting. Some grid codes still do not clearly distinguish between slow voltage-Var control requirements and the fast acting voltage controller that is essential for proper dynamic response following sudden and large voltage changes. The missing clarity makes proper design and coordination of voltage-Var controllers at wind power plant and wind turbine levels difficult.

## 2.2 Requirements during abnormal and grid fault conditions

Fault Ride-Through (FRT) requirements are introduced in most European countries. The most important stipulations are twofold, namely that:

- 1) Wind turbines have to stay connected to the grid during voltage dips and
- 2) They have to initiate forced (mandatory) reactive current injection for supporting the grid voltage

The second requirement implies that wind turbines have to implement a fast voltage controller which, according to several grid codes [19],[20], is activated only outside a certain dead band (e.g.  $\pm 10\%$  around the oper



**Figure 3:** FRT characteristics in Europe [13]

ating point). However, by including an outer control loop that ensures that steady state requirements are met at the point of coupling (e.g. constant power factor or voltage-Var droop) the dead band can be eliminated. The injection of reactive current in proportion to the deviation of the terminal voltage by wind turbines may help to keep the voltage at acceptable level during the fault and avoid subsequent disturbances. Recent amendments to grid codes require this “reactive current boosting” during a fault [17],[21]. Most of the manufacturers limit the reactive current injection to 1 p.u., although wind turbines would be capable of more on a short term. Concerning the dynamic response time, challenging requirements are defined in [17] which, however, can be fulfilled by modern wind turbines. A rise time of 30 ms and a settling time of 60 ms are required to acknowledge the time frame of the grid protection.

FRT does not necessarily presuppose voltage control. In grid codes voltage-time diagrams are used to define a dip profile area where disconnection is not allowed. Depending on specific requirements and experiences, the European countries have defined different characteristics up till now (Figure 3).

The voltages refer to the voltage level at the point of connection and the diagrams describe border lines, and tripping is not allowed above the lines. According to the common interpretation of the expected wind turbine behavior below the border line, a wind turbine can be tripped by the circuit breaker. However, in [17] only short-term interruption, such as converter blocking, is permitted and definitive tripping is done only by a wind power plant safeguard, and that not before 1.5 s following a fault. Further specification in grid codes is necessary based on discussion between wind turbine and converter manufacturers on the one side and network operators on the other. In general converter blocking, which may be required due to overcurrent and/or loss of synchronism with the grid, is still not discussed in any of the grid codes. Although several wind turbine control schemes include separate positive and negative sequence control, the specification in the grid codes is still insufficient to account for unsymmetrical faults. Most of the FRT requirements address only symmetrical

three-phase grid faults which are very rare in transmission networks.

### 2.3 WT validation and certification procedure

The validation and certification of grid code compliance includes tests and measurements on real wind turbines. Certification means that the required characteristics are attested by independent institutions. However, type tests are only done on single wind turbine units. The behavior of large wind power plants is assessed based on simulations that presuppose reliable validated wind turbine models. For harmonization of grid codes and standardization of validation and certification procedures, standard wind turbine models would mean a considerable progress in wind energy utilization.

## 3 MODELING AND STANDARDIZATION

Modeling of wind power serves several purposes. Right from the early commercial development of wind power, it has been essential to model the wind flow on potential sites to be able to assess the wind power resources and thus the feasibility of a specific wind power project. Later on, modeling of wind turbine aerodynamics and mechanical structures has been a key enabler towards development of larger and more cost effective wind turbines. Today, as a result of the significant role wind power plays in many power systems, it has also become essential to develop wind power models for power system studies.

### 3.1 Users of models

Models for wind power behavior in power system studies are used by many different stake holders involved in wind power development, for different purposes. The main users are:

- Transmission system operators (TSOs), who use models for power system security assessment and for planning and development of the transmission system.
- Distribution system operators (DSOs), who use models to ensure compliance with TSO requirements and to ensure the voltage quality in the distribution network.
- Wind power developers, who use models to design and validate grid compliant wind power plants.
- Power producers (often identical to the developers) and investors, who use models to assess the feasibility of investment in wind power as well as in other units of the power system.
- Wind turbine and wind power plant manufacturers, who use models to design the electrical system of the plant, and to provide the developer with technical documentation.
- Manufacturers of main electrical components of wind power plants, who use models for determining design ratings.
- Consultants, who use models to advise manufacturers, power producers and grid operators.

- Developers of software for power system studies, who implement models with typical parameters to provide turbine and plant equivalents
- Universities and other research institutions, who use wind power models in power system integration studies and wind power plant design studies.

### 3.2 Types of wind power models for integration studies

There are several types of power system studies, which require specialized models of wind power. Different approaches have been suggested to classify these models, which differ in how they represent the wind and in the detail of their mechanical and electrical models. This paper identifies and discusses in turn the following main types of wind power models:

- Grid codes mainly refer to *dynamic stability models* which are needed by the grid operator for dynamic power system stability simulations.
- Wind power plant developers use static *electromagnetic transient models* and *short-circuit models* for technical specification of grid components, protection and grounding systems.
- Grid operators, mainly of the distribution grid, use *power quality models* to assess the emission of harmonics and flicker from wind power plants.
- Wind plant owners and grid operators use *reliability models* and *market models* which require wind power time series.

#### *Dynamic stability models*

The purpose of dynamic wind power models is to represent wind power plants in power system stability studies. IEEE/CIGRE Joint Task Force on Stability Terms and Definitions [22] has classified power system stability in 3 categories: rotor angle stability, frequency stability and voltage stability. Furthermore, these classes are divided into short-term and long-term phenomena. The dynamic stability models are mainly developed to support short-term simulation of power system response to phenomena such as short-circuits, tripping of large production units or loads and isolation of areas in large interconnected systems.

Wind turbine technology is quite different in terms of generator types, power electronics and blade angle control. Wind turbines can be categorized by their generating system [23], and the IEEE has adopted 4 types of wind turbines [24], which have become a general standard for power system studies: Type 1 (directly connected induction generators), Type 2 (variable rotor resistance), Type 3 (doubly-fed generators) and Type 4 (full scale converters).

The bandwidth of dynamic stability models is limited because these models are typically simulating fundamental frequency phasors of voltages and currents. In order to maintain an acceptable simulation time, the wind power plant models for this purpose also need to be aggregated [25]. The wind power plant models can be divided into physical models and performance mod-

els. In some cases, the performance models can be more accurate than physical models with the same complexity (e.g. in terms of number of state variables), but most engineers prefer physically justified models.

Wind turbine manufacturers in some cases provide black-box models, which gives the grid companies a problem with the confidence in the models because they do not have any idea how the model will respond to different disturbances. However, black box models are a way to protect intellectual property rights.

#### *Electromagnetic transient models*

As a consequence of the limited bandwidth and the need for aggregation, the wind power models for dynamic stability are not sufficient for studies of transients e.g. due to lightning strikes and switching of breakers. Assessment of transient overvoltages and overcurrents must be based on detailed electromagnetic transient (EMT) models for the electrical components in the grid.

The EMT models of wind power plants are in principle not different from EMT models of other parts of the grid. But the application of large-scale offshore cable networks in offshore wind power plants is causing an increased focus on these models.

#### *Short-circuit models*

Models for short-circuit currents are needed to support the technical specification of grid components, protection and grounding systems. In [25] a model for representation of a Type 3 wind turbine is developed with chopper protection by an equivalent synchronous generator, valid for such short-circuit current calculations. This approach was selected because the industry standard in power system simulation software is to represent generators by their equivalent synchronous generator impedances. However, there are no generally accepted models for Type 3 and Type 4 turbines, and most short-circuit calculations are therefore carried out using asynchronous generators with short-circuit rotors.

#### *Power quality models*

Assessment of emission of flicker and harmonics from wind power plants is normally done based on single wind turbine tests and simple rules for summation of contributions from multiple wind turbines as specified in the standard wind turbine power quality test procedure IEC 61400-21 [26].

Instead of testing the wind turbine, wind models have been developed [27] and applied to simulate the dynamics of active and reactive currents from a wind power plant, and use these simulations to calculate the expected flicker emission from a wind power plant [28].

Harmonic emission is another area where models could replace or supplement the standard wind turbine power quality test and assessment procedure. Models are particularly relevant for harmonic calculations, because it has been reported that the standard procedure often leads to overestimation of the actual harmonic emission from wind power plants.

#### *Reliability models*

Reliability studies provide a number of reliability indices as outputs. Most reliability indices reflect either the interest of the power system operator (TSO) or the plant owner. Examples of this is Loss Of Load Probability (LOLP) which is a system index of interest to the system operator, while the Capacity Factor (CF) of a power plant, e.g. a wind power plant, is more of interest to the plant owner.

Negra [30] has identified and considered the following relevant aspects in modeling of reliability of offshore wind power:

- 1) wind speed simulation;
- 2) wake effects;
- 3) correlation of output power for different WTs;
- 4) wind turbine technology;
- 5) offshore environment;
- 6) power collection grid in the wind park;
- 7) grid connection configuration;
- 8) hub height variations.

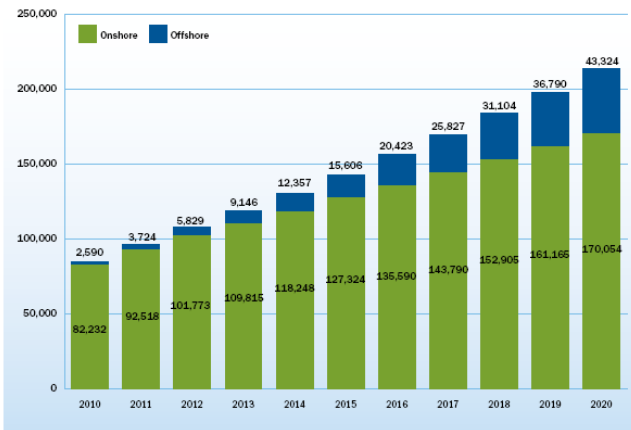
#### *Market models*

Market models are widely used for planning of investment in generation capacity as well as grid development. Market models typically use wind power time series and in some cases also wind power forecast errors as input. The wind power fluctuations and prediction errors are important for these market simulations, because this wind behavior has significant influence on the commitment and dispatch decisions taken on other power plants.

In order to represent wind power in future power systems, historical wind power time series are often scaled. Appropriate statistical methods can be used to interpolate wind speed or power measurements and aggregate them to reflect inter and intra farm smoothing [31]. When such historical time series are not available, modeling of the wind power time series is needed. This is particularly relevant for the North Sea, where a very large-scale wind power development is planned, or on island power systems. Models capable of simulating wind power fluctuations from many wind turbines simultaneously have also been developed [28],[32] taking into account the impact of geographical spreading of the wind turbines.

### 3.3 *Standardization*

As a result of the specific focus in grid codes on dynamic stability models for wind power plants, IEC has started a working group with the purpose of developing an international standard IEC 61400-27 on electrical simulation models for wind power generation. The plan is to divide this standard into two parts: part 1 for wind turbines and part 2 for wind power plants. Presently, the work on part 1 is progressing. This part will specify standard generic models for the 4 types of wind turbines, and a procedure for model validation. The validation procedure will be based on power quality tests according to IEC 61400-21 [26]. The working group has several wind power plant manufacturer members, which



**Figure 4:** Cumulative wind power installations in the EU (MW). Source: EWEA.

is necessary to ensure that the specified models will be representative for the wind turbines on the market today. There are also several grid company members (TSOs and DSOs) and software developers, which helps to specify models that can be applied in power system stability studies.

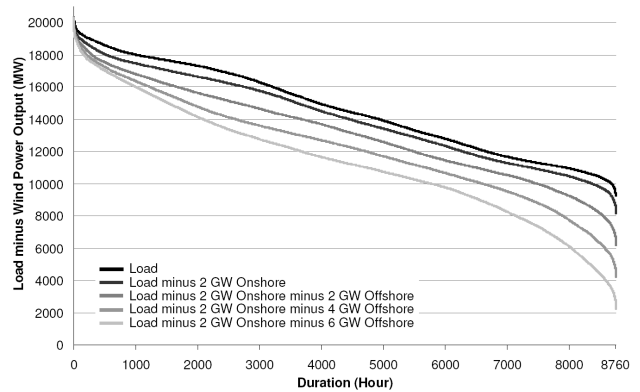
#### 4 PLANNING

According to the renewable energy plans of the EU-27 states, wind energy production will increase seven-fold from just over 70 TWh in 2005 to 495 TWh in 2020, meeting 14% of EU consumption. This will continue to affect power system planning throughout Europe. In 2010 the amount of wind energy production was 165 TWh covering 5.3% of the power consumption; Irish plans predict the highest regional level meeting over 36% of the country's electricity consumption in 2020. Denmark, currently the country with the largest wind energy penetration, is expecting to cover 31% of its electricity consumption with wind power. This will be compensated by EU countries such as Slovenia, where only 1.3% of electricity consumption is expected to be met by wind energy [33].

Adding up the EU-27 plans, the total wind power capacity will increase from 84.3 GW in 2010 to 213.4 GW in 2020. The share of offshore wind will increase from 2.9 GW in 2010 to 43.3 GW forecasted for 2020 (Figure 4). Wind turbines will continue to be the most commonly built new generation capacity.

##### 4.1 Impact of wind power on generation schedules

Load-less-wind power duration curves can be developed for a given year by aggregation of load and wind power output data (i.e. wind power is regarded as negative load) using 15min. time intervals and sorting this data in order of decreasing magnitude. It should be noted that wind speeds and energy yields may vary between years as may also wind turbine availability, leading to different curves. Figure 5 gives the example of the Netherlands [34]. There is little correlation between load and wind power and the probability of wind



**Figure 5:** Load-less-wind power duration curves for a future year in the Netherlands.

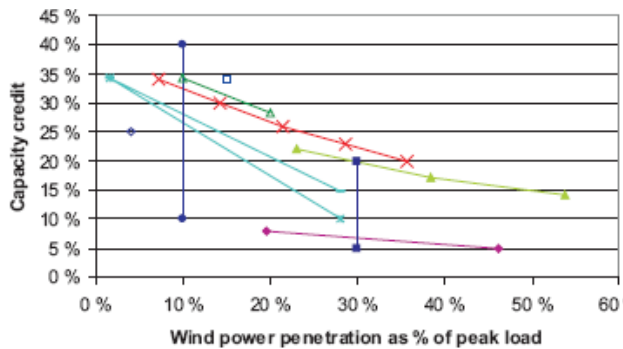
generating high output at moments of maximum load is low. Thus from the figure it follows that wind power is an energy source rather than a capacity source.

From the data in Figure 5 it also follows that for an assumed installed wind power capacity of 10GW (of which 6GW offshore) load-less-wind hours of 10GW or less increase from 50h to 3500h in a year and the minimum load-less-wind value decreases from about 9.5GW to 0.5GW, in particular affecting the full load hours of base-load units. Since it may not be technically feasible to take these units out of operation during low load-high wind power moments, additional solutions such as exports or wind power curtailments may be necessary in order to prevent minimum load problems. These operational issues are discussed in Section 7.

##### 4.2 Capacity credit of wind power

Integrating wind power in the system should not lead to less reliability. Power system reliability can be distinguished by system security and system adequacy. A power system is adequate if there are sufficient installed power plants to meet customer needs. A system is secure if it can operationally withstand a loss (or potentially multiple losses) of key power system components such as generators or transmission links. Planning activities assess mostly the impact that wind generation has on generation adequacy. The estimation of the required production facilities includes the system demand and the availability data of generating units.

The capacity credit (sometimes called capacity value) is the contribution that a given generator makes to overall system adequacy. The availability of wind power is mainly affected by natural phenomena, but the availability of conventional generation is also not assured at all times because there is always a risk of mechanical or electrical failure. The capacity value of any generator is the amount of additional load that can be served at the target reliability level with the addition of the generator in question. Numerous studies have been performed to quantify the capacity credit of wind power [35], [36]. The IEA annex Task 25 group made an overview report on the outcome of those studies, and produced Figure 6 [37]. A more in depth comparison of multiple methods



**Figure 6:** Capacity credit of wind power, as calculated in several studies [37].

and results has recently become available from the IEEE Task Force on the Capacity Value of Wind Power [38].

It is clear that the capacity credit decreases as the installed wind capacity is increased. Furthermore the capacity credit increases as demand uncertainty (and hence risk) increases, as additional generation should be more valuable when risk is higher.

#### 4.3 Transmission impacts

The location of wind power plants may have a large impact on the flows in the network. Normally the Transmission System Operators will be responsible for connecting the wind power plants and to ensure that transmission occurs without network congestion. New sites (especially concentrated offshore sites) might need huge reinforcements in the network. The EWIS study has shown the impact of wind power on the network for the next decade [39].

#### 4.4 Connection of offshore wind power plants

Normally the following options exist for connecting offshore wind power to the main grid:

- 110 or 150 kV AC cables;
- 220 kV AC cables;
- HVDC VSC cables connection.

400 kV AC cables are mostly not taken into account due to their excessive reactive power generation and consequent need for additional compensation.

HVDC LCC connection is mostly also not taken into account due to expected difficulties in conduction to the establishment and maintenance of a HVDC LCC converter station in an offshore environment. The actual choice depends on the distance to shore and the amount of power to be transported [40].

## 5 OPERATIONAL RESERVES

Increasing levels of wind power in power systems always sparks the debate about the impact on reserves. The amount of generation capacity that is operationally kept in reserve in the event of unforeseen circumstances is called operational reserve as opposed to planning reserves, the additional capacity required in the event of known circumstances. For example forecast errors in wind power will drive the need for operating reserves while wind power availability will drive the need plan-

ning reserves. Planning reserves and the capacity credit issue have been dealt with in Section 4. Operating reserves is dealt with here. If wind power were perfectly predictable then there would be no need for additional operational reserves (unless wind varies too steeply for manageable plants to follow) so it is not the variability of wind power that drives the need for operating reserves but the predictability. Hence this section has a strong link with the following section on forecasting.

Operating reserves are for convenience (both descriptively and from an operational perspective) sub-divided into different types. For example, speed of response (e.g. primary, secondary, tertiary, etc.), nature of source (spinning on the system, non-spinning, etc.), event catered for (load following, contingency, etc.). There is unfortunately no common globally accepted set of definitions and there is overlap in the terminology e.g. different speeds of response can come from many different types of sources and cater to the needs of many different types of events [41]. As a consequence of this lack of a consistent set of clear unambiguous definitions the operating reserves area is potentially burdened with confusion, misleading concepts and inefficiencies. The advent of increasing levels of wind power being integrated into electricity grids is highlighting this issue and the need for the development of a robust set of definitions and a proper framework within which to advance our understanding of how operating reserves will need to evolve as more wind power is integrated into electricity grids.

Some general observations are given here. Wind power over short periods of time is very predictable, and by its distributed nature is unlikely to cause a large sudden contingency. Over longer time frames wind power is difficult to predict and does have particular dynamic characteristics that can impact on the needs for additional and new types of reserve. Hence any changes in operating reserves detailed below will be confined to certain types and may require the development of new definitions.

#### 5.1 Experiences: reserves in Ireland, Denmark, Portugal and Spain

Ireland is a single synchronous power system with 11 % of its electricity derived from wind power and at times the instantaneous penetration level hits 50%. The island has one HVDC interconnection to Britain. There has to date been no changes to existing operating reserve policies except for the introduction of a new reserve type, negative reserve, which is used to plan and monitor for unexpected increases in non-dispatchable generation. It is used during unit commitment and is the difference in the running output of the synchronized generators and their minimum output. Ireland's current reserve requirements are defined in [42].

Denmark is synchronously and asynchronously connected to its neighbors in Norway, Sweden and German, with 21% of its electricity derived from wind power.



Eastern Denmark is part of the Nordic synchronous system. Most of the wind generating capacity is in Western Denmark, which is part of the Continental Europe synchronous system. Thus, although there is significant wind electricity generation in Denmark, this amount of generation does not represent a significant proportion of the total electricity generated in either of the synchronous systems that include portions of Denmark. As a result, the frequency control and frequency response requirements associated with integration of Danish wind generation into these two very large and distinct systems is virtually nonexistent because these issues are addressed by the respective interconnections as a whole, and the contribution of Danish wind generation is comparatively small. Current reserve practice in Denmark is outlined in [43].

The Portuguese system is approximately twice the size of the Irish system and wind provides about 17% of its annual electricity requirements from an installed wind capacity of 3.9GW [3]. It shares the Iberian Peninsula with its larger neighbor, Spain, to whom it is synchronously connected. Reserves levels in Portugal have not changed with the advent of wind.

Spain is synchronously interconnected to Morocco, Portugal and France with 16 % of its electricity derived from wind power. At times the instantaneous penetration level is already higher than 50 %. Currently, reserves are calculated using a deterministic methodology. A probabilistic methodology is now being analyzed as outlined in [44]. The effect of short-term wind fluctuations on primary, secondary and tertiary reserve is still only minor but slower running reserve levels have been increased to deal with the uncertainty associated with wind forecast errors.

## 5.2 Studies

The All Island Grid Study (AIGS) [45] studied penetration levels of up to 60 % of electricity from renewables which was mainly wind power. With respect to operating reserves it did find that there were needed changes to the policies and procedures. In particular, it was found that the pumped hydro storage facility, coal fired units and the new CCGTs are the main sources of positive spinning reserves while almost the entire demand for replacement reserves is provided by off-line OCGTs in all portfolios studied. This study also found that the curtailment of wind power is a relatively expensive way of providing spinning reserve.

The goal of the EWIS 2015 [7] analysis was to develop common pan European recommendations on how best to integrate wind power into the European grid. To facilitate this, European-wide scenarios were derived to analyze the impact of wind generation on the future grid. These scenarios and associated market simulations enabled the assessment of wind power production, conventional power plant production and exchange schedules. One of the main recommendations related to coordinated operation which recommended that TSOs should further develop improved operational tools and

procedures which will permit reserve monitoring and management across the European network.

## 5.3 Conclusions and recommendations

None of the reserves which existed prior to the advent of wind generation have been changed in any of the countries considered above. In Ireland a new reserve type, negative reserve, has been introduced.

Countries such as Ireland and Portugal face significant operational challenges during periods of rapid change of wind generation, demand and interconnector flow. These challenges may prompt the need for the provision of ramping reserve, the purpose of which is to respond to failures and events that occur over longer time frames. It is also known as variable generation event reserve, forecast error reserve and balancing reserve [41].

The EWIS recommendation to improve operational tools which will allow reserve monitoring and management, which presumably includes reserve sharing, will be critical in wind integration.

## 6 FORECASTING

The uncertainty of wind power that drives the need for operational reserves can be greatly reduced by using forecasting. For wind power it is also relevant to update the forecasts, as the accuracy will improve compared to day-ahead forecasts as the operating hour is closer.

### 6.1 How forecasts are made

Forecast tools for wind power plants have been developed since the 1990s and there is still work on-going [46],[47]. Basically the predictions rely on the measured on-line production and the forecasts from numerical weather prediction (wind speed and direction, also temperature and air pressure can be useful). Tools using a statistical approach use methodology like time series or neural networks to make a direct transformation from the input variables to wind power plant output. Tools using a physical approach need also the terrain description as input and will include steps like downscaling the wind to turbine hub height and conversion to power.

For system operators and utilities with numerous wind power plants in their portfolio, the forecasted output of several wind power plants is then upscaled for the wind power production of the whole area.

Predictions eight hours ahead or more rely almost entirely on meteorological forecasts for local wind speeds. The predictions of the power production 3-4 hours ahead also benefit from meteorological forecasts. On-line production data can be used for very short-term prediction (less than 3 hours).

### 6.2 Accuracy of the forecasts

There are several ways of presenting the forecast error. The most commonly used metrics for the average

error are the mean absolute error (MAE) and the root-mean-square error (RMSE), that are presented relative to installed wind power capacity (see formulas 1 and 2). As power producers and system operators are also interested in how much of the total production will need to be corrected, the error can be calculated relative to the average power (or as a total absolute error relative to total production), (MAPE, formula 3).

$$MAE = \frac{1}{N} \sum_N \frac{|error(h)|}{P_{installed}} \quad (1)$$

$$RMSE = \frac{1}{N} \sum_N \frac{\sqrt{error(h)^2}}{P_{installed}} \quad (2)$$

$$MAPE = \frac{\sum_N |error(h)|}{\sum_N production(h)} \quad (3)$$

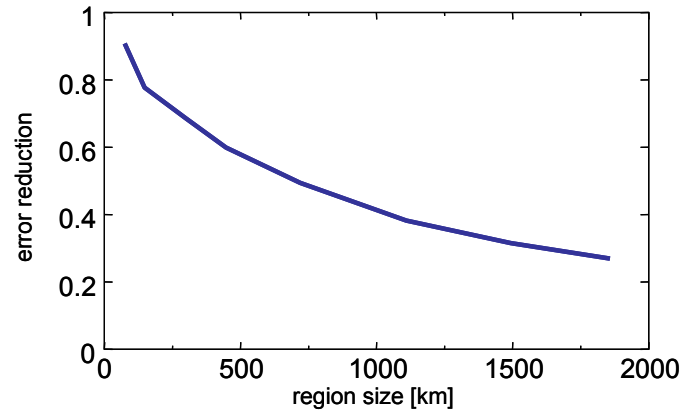
The level of accuracy improves when combining predictions for larger areas (Figure 7). For a single wind power plant the mean error for day-ahead forecasts is between 10 % to 20 % (as RMSE % of nominal capacity) or 40 to 50 % of produced energy (3). For a single control area this error will be below 10 % as RMSE, or less than 30 % of yearly energy. Besides improving with spatial smoothing, the forecast accuracy also improves as the forecast horizon decreases [46], as shown in Figure 8.

The latest results from Western Denmark day-ahead forecasts show an average prediction error MAE of 6.0 % of installed capacity (1), as the RMSE is 8.9 % (2). In these numbers the forecast errors are relative to nominal capacity of wind power. When looking at the errors relative to average power (which give errors in terms of energy) the 6.0 % error for Western Denmark corresponds to an error of 24 % in yearly energy (3). The forecasts refer to day ahead, that is,  $t + 13 \dots t + 37$  hours [47].

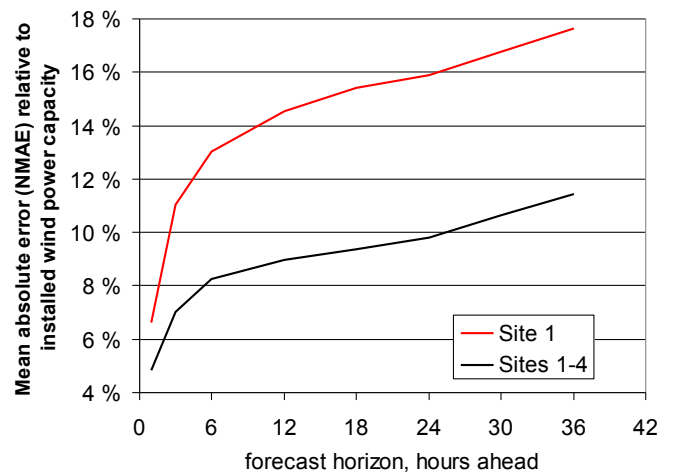
### 6.3 Improvements for forecast accuracy in future

The errors in forecasts have reduced in recent years through combining different forecasts. The results from Germany show the best model performing at 5.1 % RMSE, a ‘simple’ combination 4.2 % and an ‘intelligent’ combination 3.9 % [49]. The main error for the predictions comes from wind speed forecast errors. Improving the wind forecasting is thus crucial for further improvements. The model calculations can improve by using a better network of wind speed and other meteorological parameter measurements from wind power plants. This work is currently ongoing both in US and Europe.

Wind power predictions are increasingly moving to probabilistic forecasts, showing also the uncertainty of the predicted power production. There are also special cases like ramp forecasts, especially useful during the rare but critical storm events. Very short-term forecasts (hour ahead) are also being developed.



**Figure 7:** Decrease of forecast error of prediction for aggregated wind power production due to spatial smoothing effects. Source: Energy & meteo systems



**Figure 8:** Increasing forecast error as forecast time horizon increases. Results from Finland [46]

### 6.4 System operation and forecasts

Predictability is most important both at times of high wind power production and for a time horizon of up to 6 hours ahead, which gives enough time to react to varying production. For unit commitment, and producers operating in day-ahead markets, the day-ahead time scale is important. An estimate of the uncertainty, especially the worst-case error, is also important information for system operation. This can be used for reserve allocation. For system operation, updates of forecasts are important.

## 7 OPERATION

The scenario that the system operator faces has changed notoriously in the last 10 years, mainly due to the interest of the whole society in moving to a low carbon economy, demanding higher levels of renewable energy penetration.

Reaching these objectives implies operating a system with an increasing proportion of non-manageable generation, maintaining the security of the electrical system and seeking a compromise between the quality of service, the costs of the system and the ecological footprint. That is an ambitious goal that becomes complicat-

ed due to the inherent limitations in each system, but that has also led each country to boost their available capacities to the maximum.

The best strategy to face renewable energy variability in weakly interconnected systems, whose main back up generation is the thermal units (with its start-up time and the minimum technical capacity limitation), along with the hydraulic generation (with the drawback of the fluctuations between wet and dry cycles) is having observability and controllability over the renewable and non-manageable generation.

Furthermore distributed resources belonging to different companies, with different policies of operation, switching and maintenance lead to very loose contact in case of an emergency. That is the reason why progresses in the fields of the system operation and the coordination between generation and transmission are required to achieve observability and controllability.

Telecommunication deployment carried out among generation, transmission and operation activities allows the complex integration of distributed sources by reducing the time response. In Spain that has been achieved [49] as a result of the aggregation of all the distributed resources of more than 10 MW in Renewable Energy Source Control Centres and the connection between them with the Central Control Centre for Renewable Energies of Spain (Figure 9).

This hierarchical structure, together with the applications used to analyze the maximum wind generation supported by the system, allows the system operator to instruct set-points to limit their output or even shut down (in a process called curtailment) when current or expected wind generation causes the system to reach a technical limit. Supervision and control of the wind generation in real-time allows a decrease in the number and quantity of curtailments. This maintains scrupulously the international power exchanges and ensure the quality and security of the electricity supply at the same time as maximizing renewable energy integration.

### 7.1 Wind production variability

The variability of the renewable generation implies a new uncertainty when the sizing of the generation reserves is performed, making the wind forecast tools one of the basic tools for system operation. There are two critical horizons: 24-36 hours in advance to check the available running reserve after the day-ahead market and 4-5 hours in advance for the real-time operation (that is the time required to switch on non scheduled thermal units, with real time re-dispatch, due to their start-up time). Forecast errors reduction results in fewer needs for reserves.

Combining wind forecast tools with real-time production data and the generation location allows the study of present and future scenarios taking into account the wind forecast.



**Figure 9:** Control Centre for Renewable Energies of Spain (CECRE).

### 7.2 Existing assets improvement

The predictability of new distributed resources coming from the wind has fostered the development of the transmission network and the evolution of its operation in order to cope with power flows extraordinarily dependent on the weather conditions. This fact, as a direct consequence of the renewable energy integration maximization, as well as the social and environmental barriers to the deployment of the grid has fostered the network intelligence. This is currently accomplished by progress in new technology through R&D projects, such as the development and in-field installation of new (FACTS) devices to direct and control the power flows and the improvement of the existing assets capacity through the use of dynamic line rating (RTTR) in the Redes 2025 [50] and the E.U TWENTIES [51],[52] projects.

### 7.3 Wind Turbine Technology

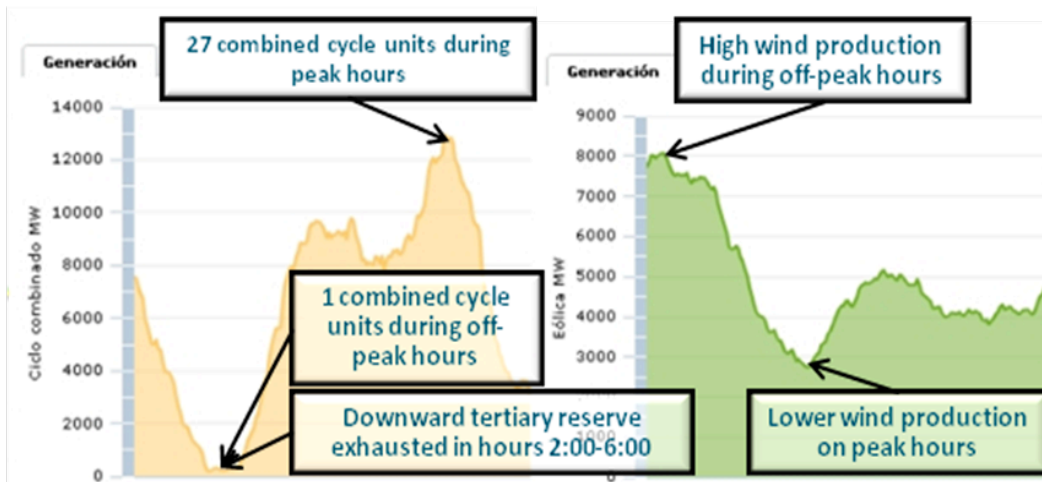
The technical adaptation of the wind facilities in response to voltage transients as required by grid codes and explained in Section II can solve the problem of significant wind generation tripping. Thank to this (currently in Spain, 97.5 % of the wind farms have installed fault ride-through capabilities) no wind production curtailment has been done due to this reason since 2008.

Fault ride-through capability requirements allow better RES integration, especially when requirements are sufficiently coordinated within the adjoining countries of the whole synchronous system.

### 7.4 Voltage Control

Dynamic voltage control needs to be addressed due the increasing penetration of renewable and non-manageable generation as it is mentioned in section II. Using a reactive power bonus table, for which a financial bonus or a penalty is applied depending on the power factor provided could be a temporary measure while real-time voltage control is developed.

The experience with an hourly dependent reactive power bonus table shows that sometimes producers behaved against system requirements because periods did not distinguish between labor days and holidays.



**Figure 10:** Wind integration increasing the requirement over conventional generation

During period changes there were sudden changes in the network voltage profile due to simultaneous connection / disconnection of wind farms capacitors. In Spain, in order to avoid these situations, and as a short-term measure, in April 2009 it was established that the wind facilities of more than 10 MW must maintain an inductive power factor between 0.98 and 0.99, except in certain nodes of the system where particular instructions were sent due to specific requirements. However a new operational procedure has already been proposed and is pending approval [53]. This proposal contains the requirement for continuous voltage control provided by the RES. Real continuous voltage control tests (based on real-time voltage set-points sent by the operating centre) have been carried out with wind farms accomplishing remarkable results.

For future performance improvements, the performance of continuous voltage control by aggregated wind farms that also takes into account the interaction among clusters to optimize the reactive power management is being tested within the framework of the EU TWENTIES project [51],[52].

### 7.5 Power balancing

The real time capacity of a system to integrate non manageable generation depends on the amount and flexibility of the manageable generation as well as the behavior of the load (Figure 10).

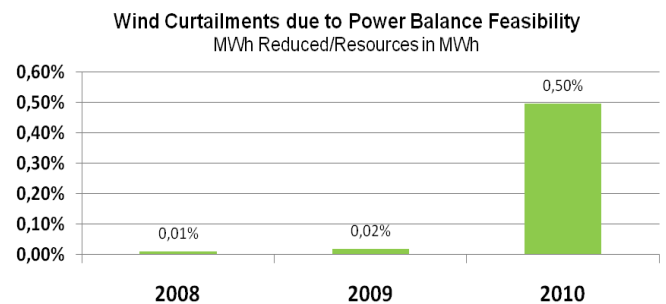
Curtailments due to power balance feasibility have occurred since 2008 and they will probably occur again in the future (Figure 11).

To increase the capacity of the system to integrate more renewable and non-manageable generation implies:

- Increasing the international exchange capacity between neighboring countries. This is one of the priorities of the EU.
- Turning the demand into a flexible resource. This will impact the demand load shape through: interruptible service, time of use tariffs, the promotion

of an efficient integration of the electric vehicles and the implementation of smart metering. Demand participation in the system operation is facilitated with these actions and their integration in the Smart Grid.

- Reducing the minimum manageable generation required by increasing the flexibility of the manageable generation and reducing their time response.
- The installation of centralized managed storage with the objective of maximizing renewable integration. Various projects have started in order to evaluate the capabilities of these technologies to increase network flexibility, participate in demand side management, and provide ancillary services.



**Figure 11:** Wind curtailments due to power balance feasibility in Spain (GWh).

## 8 CONCLUSIONS

Wind integration has entered a phase in which cooperation and coordination becomes important. While at first similar problems were discovered and dealt with independently by adding new practices to grid codes, there is an increased collaboration and convergence regarding issues such as low-voltage ride-through and its associated operational risks. The need for generic, accurate wind turbine models for power system studies has also resulted in cooperation and the development of

common tools, with the benefit of improved integration and the replacement of some turbine field tests by model studies.

The interaction of transmission network planning in neighbouring countries has become more important to allow the fair and profitable export of wind power instead of requiring production curtailment in the case of system constraints. The issue of calculating an appropriate capacity credit for wind farms is an issue that has received joint attention from utilities and researchers. Updates on how overall capacity credit for a wind farm fleet declines as more turbines are installed will remain of interest. Less developed are the methodologies for determining the level of reserves needed to counteract prediction uncertainty, which usually exceed load uncertainty. Some jurisdictions have finally encountered situations where some reserve types will need to be altered, and new types of reserve may be required. The need for operating reserves can be reduced with improved forecasts. By combining forecasts, a root-mean square error as low as 5% to 4% in power forecasts can be achieved. Moving to probabilistic forecasts and paying special attention to potential ramp events are both helping the crucial aspects of dealing with periods of high wind production, and planning for variability six hours ahead.

In addition to improved forecasts, control centers reducing curtailment and maintaining security with the use of centralized information collection from and dispatch of wind farms that comes with the ability to issue active power ramping commands and reactive power set points. However, challenges are imminent for the control of flows throughout the network, which experience extraordinary new patterns. Exploration now occurs of flexible demand, reduction of “must-take” generation, FACTS devices and RTTR, and increased international exchange capacity in order to meet these challenges.

This paper has offered explanations and details about how experiences have changed the practice of grid integration in six important areas: grid codes, wind power plant models, system planning, reserves, forecasting, and operations. Although the experiences described are European ones, similar issues are emerging in many power systems around the world, though in new ways which require examination of the root principles. New challenges can be expected in these places and in others in the years to come, as offshore wind farms and super-grids come on-line.

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