G7 GERMANY 2015

System Integration of Renewables: Implications for Electricity Security

Report to the G7

29 February 2016

Mandate

This note was drafted by the IEA in close cooperation with IRENA. It responds to the G7 Energy Ministerial Communiqué that was adopted by G7 energy ministers at their meeting in Hamburg, Germany, on 11 and 12 May 2015. Based on the principles agreed in Rome, G7 ministers agreed to take additional concrete joint actions in order to further strengthen sustainable energy security in the G7 countries and beyond. The communique included the following item:

> *"We will continue to exchange and to work on energy vulnerability assessments, in particular regarding the security of supply in the electricity sector and its interdependencies. This will include cross-border flows, acceptable risk levels for supply interruptions, demand response and infrastructure. We also* ***request IEA in close cooperation with IRENA to evaluate the most effective options to ensure electricity security, including through increasing system flexibility in order to integrate variable generation."***

This report elaborates on these points and identifies no-regret options for G7 countries to ensure that the large scale integration of variable renewable generation contributes to enhanced electricity security.

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1 Executive summary

This note responds to the G7 Energy Ministerial Communiqué that was adopted by G7 energy ministers at their meeting in Hamburg, Germany, on 11 and 12 May 2015. It provides a high-level summary of the implications of renewable energy on energy security in the power sector. The note focuses on the role of variable renewable energy (VRE), most notably solar photovoltaics (PV) and wind power.

Renewable energy and electricity security

Renewable energy (RE) is currently the only power sector decarbonisation option deployed at a rate that is close to what is required under long-term IEA scenarios to attain the 2°C target (IEA, 2015a). Wind and solar PV account for a large proportion of recent increases in RE generation (IRENA, 2015a), and are projected to contribute the vast majority of non-hydro RE generation over both the short and long term (IEA, 2015b, 2015c, IRENA, 2016a).

With the increasing maturity of renewable energy technologies and their growth in deployment, energy security concepts increasingly encompass the benefits and challenges stemming from renewable energy sources. The benefits of renewables for energy security more generally and electricity security in particular are clear: they can diversify the energy mix and the sources of supply, they often localise energy production and reduce import requirements and costs. However, dependence on large shares of renewable energy also brings challenges for energy security.

In summary large shares of renewable energy in the energy mix imply a paradigm shift for energy security. The classical risks associated with fossil fuels (geopolitical risks, upstream investments and infrastructure) are replaced by risks relating to the availability of natural resources such as biomass, water, wind and sunlight. The short-term variability of wind and solar PV adds another layer of complexity.

The integration challenge

The difficulty (or ease) of increasing the share of variable generation in a power system depends on the interaction of two main factors. First, the properties of wind and solar PV generation, in particular the constraints that weather and daylight patterns have on where and when they can generate. Second, the flexibility of the power system into which VRE is integrated and the characteristics of the system's electricity demand.

For example, where good wind and solar resources are far away from demand centres, it is necessary to build grid infrastructure to access the resource (this can also the case for other renewable energy sources). Where sunny periods coincide with high electricity demand, solar PV generation can be integrated more easily. However, as VRE generation provides a larger portion of supply, more pronounced swings in the supply demand balance of electricity can occur.

The interaction between both factors differs from system to system. As a result, the economic impacts of VRE also depend on the specific context. However, on both sides only a limited number of properties determine the positive and negative aspects of integration. This allows identifying best practice principles that apply in a wider range of circumstances.

Experience in the majority of G7 countries suggests that it is not a significant challenge to operate a power system at low shares of VRE, if some basic principles are followed which are detailed in this note. Depending on the system, a low share approximately means below 5% and possibly up to 10% of annual generation.

The need for a system approach

Given the broad impacts that high VRE shares can have, a comprehensive and systemic approach is the appropriate answer to system integration challenges at higher shares. This is best encapsulated by the notion of system transformation (IEA, 2014a). As identified by IEA analysis, a coordinated transformation of the system can significantly reduce integration costs. Such transformation can be implemented step-by-step and has technical, economic, political and social implications. Policy makers need to anticipate the far-reaching aspects of a power system transformation and act pro-actively to translate their ambitions into palpable actions on the ground (IRENA, 2015b). Ultimately, by combining the structural advantages of renewable energy with appropriate strategies to increase power system flexibility, the overall outcome can be a more secure and resilient power system.

As detailed in this note, G7 countries are at the forefront of developing and applying regulatory and technical measures that facilitate the transformation of power systems.

No-regret options for integrating VRE in G7 countries and future priorities

The note concludes with a list of no-regret recommendations for G7 countries to maintain and accelerate progress in a secure and cost-effective integration of high shares of VRE.

It distinguishes three set of no-regret options:

1. Must-have options for immediate implementation in G7 countries:
   - Adequate real-time monitoring and control of VRE plants
   - State of the art VRE production forecasts
   - Robust technical standards for VRE plants and their grid connection
2. Short-term improvements to existing policies for secure system operations:
   - Co-operation and consolidation of balancing areas
   - Improved operations and wholesale and retail power market design reform
   - System-friendly VRE deployment policies
   - Transmission and distribution system operators interface improvement and reform of distribution grid regulatory frameworks
   - Clear rules for handling the curtailment of VRE generation facilities
   - Development of the market for most cost-effective flexible resources
3. Future-proofing planning processes for long-term energy security:
   - Holistic assessment of the energy security implications of high RE scenarios
   - Systematic assessment of technical issues at high shares of VRE
   - Systematic review and upgrade of planning standards for distribution grids
   - Planning processes that include advanced technology solutions for system flexibility

Possible concerted action – the G7 is invited to:

- Endorse the no-regret options detailed in this note and continue to exchange best practice on integration of renewable energy and develop robust indicators to assess electricity security;
- Increase the focus on the changing role of distribution grids, including economically viable business models and modernization to allow higher shares of VRE
- Develop regulatory frameworks that address the technical, economic and institutional challenges associated with an increased uptake of distributed VRE and flexibility options such as demand side response and electric battery storage

1.1 The broader energy security context

Historically, energy security was primarily associated with oil supply. While oil supply remains a key issue, the increasing complexity of energy systems requires systematic and rigorous understanding of a wider range of vulnerabilities. Disruptions can affect other fuel sources (e.g. droughts causing a drop in hydroelectricity availability), infrastructure (e.g. technical failures affecting pipelines or power plants), or end-use sectors (e.g. sudden surges in demand for heat or electricity during extreme weather events). Thus, analysis of a country's oil import dependency, suppliers and emergency stocks is no longer sufficient for understanding its energy security situation (IEA, 2011a; IEA, 2014a).

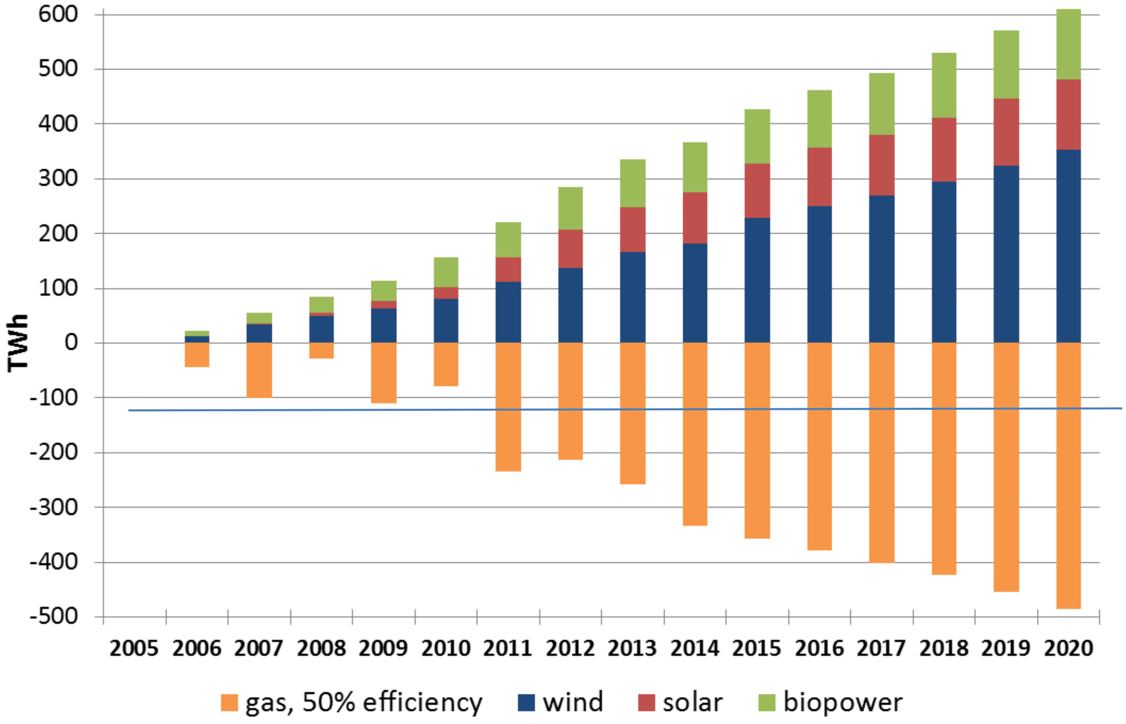
Security of natural gas supplies and electricity supplies has become part of national and regional energy security considerations. For example, the European Union (EU) is dependent on imports for around two-thirds of its natural gas, which is compounded by many EU member countries being heavily reliant on a single supplier, particularly Russia.

Fossil fuel supply chains can span long distances, transit sea lane choke-points, cross national borders, and include many steps, such as extraction, transport, conversion, and distribution Security needs to be ensured at each step in the supply chain. Reducing the steps, diversifying routes and suppliers, and sourcing supply domestically can serve to reduce the risk of supply disruptions and to increase the resilience of energy systems.

Renewable energy (RE) is currently the only power sector decarbonisation option deployed at a rate that is close to what is required under long-term IEA scenarios to attain the 2°C target (IEA, 2015a). Wind and solar PV account for a large proportion of recent increases in RE generation (IRENA, 2015a), and are projected to contribute the vast majority of additional non-hydro RE generation over both the short and long term (IEA, 2013a, 2014, 2015b, 2015c, 2015d, IRENA, 2016). With the increasing maturity of renewable energy technologies and their growth in deployment, energy security concepts increasingly encompass the benefits and challenges stemming from the paradigm shift coming from renewable energy sources and their technologies.

The benefits of renewables for energy security are clear: they can diversify the energy mix and the sources of supply, they often localise energy production and reduce import requirements and costs, they have less complex supply chains in many cases and fuel free technologies such as wind and solar power reduce long-term price volatility. Taking the example of the European continent, the growth in renewable energy since 2005 has compensated the reduction of domestic gas production and is expected to continue to do so in the coming years (Figure 1). This trend helps to limit the import dependency of Europe and provides a more diversified energy supply.

Figure 1: Incremental production of renewable energy and natural gas in OECD Europe, 2005-20



Note: all incremental domestic gas production converted to TWh assuming a power plant conversion efficiency of 50%.

Source: IEA Medium-Term Renewable Energy Market Report 2015 and IEA Medium Term Gas Market Report 2015

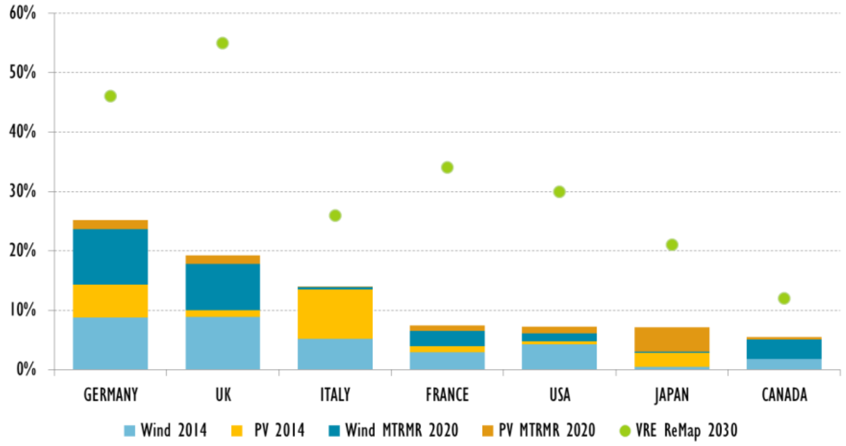
Key point: Growth in RE production more than compensates forecasted decline of natural gas production in OECD Europe.

However, dependence on large shares of renewable energy implies a paradigm shift for energy security in general and electricity security more specifically. The classical risks associated with fossil fuels (geopolitical risks, upstream investments and infrastructure) are replaced by risks relating to the availability of natural resources such as water, biomass, wind and sunlight. A well known example is hydro power with annual variations in precipitations and its exposure to the risk of droughts. Countries or regions that depend heavily in hydro power, such as the province of Quebec in Canada, have developed sophisticated tools to quantify and mitigate this well-known risk.

The rapid rise of wind and solar power are adding new challenges for maintaining system reliability. This includes dealing with the fluctuating availability of wind and sunlight, which can lead to more rapid and pronounced swings in the supply and demand balance of electricity.

A number of G7 countries have pioneered the operation of power systems with high shares of variable generation. In other G7 countries VRE have recently experienced rapid growth and/or is expected to do so in the coming years (Figure 2). Against this backdrop, the reliable integration of these resources has become a critical component of ensuring electricity security.

Figure 2: Shares of wind and solar power in annual electricity generation in G7 countries



Note: MTRMR=IEA Medium Term Renewable Energy Market Report forecast, ReMAP=IRENA ReMap analysis for technology options to double RE penetration globally by 2030.

Source: IEA estimates derived from *IEA Medium-Term Renewable Energy Market Report* and IRENA ReMap analysis.

Key point: Wind and solar power account for increasing shares of power generation in G7 countries.

The remainder of this note will focus on this aspect of energy security: integrating variable renewable energy in the power sector. It is structured as follows:

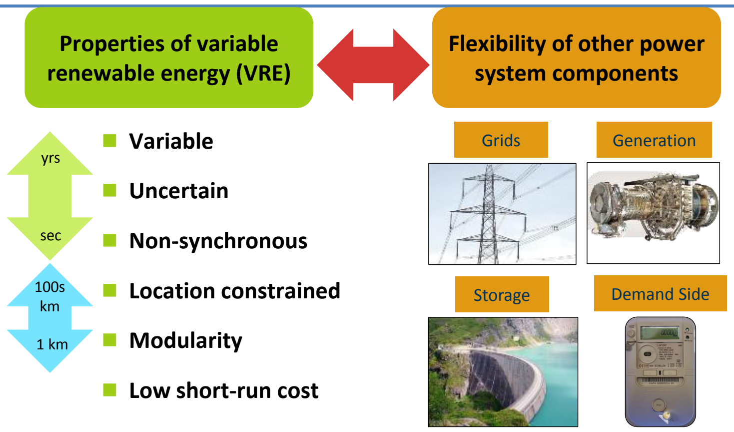
- The present chapter describes the challenge of integration and the concerns it raises. It introduces the notion of power system transformation
- Chapter 3 reviews best practice, highlighting how G7 countries are transforming their systems in addressing common concerns.
- A fourth chapter identifies no-regret options for VRE integration in G7 countries and future priorities.
- Chapter 5 reviews the tools and resources that the International Energy Agency (IEA) and International Renewable Energy Agency (IRENA) can provide to assist G7 governments.

1.2 The integration challenge

The integration challenge is determined by the interaction of two principal factors:

- First, the properties of wind and solar PV generation. Relevant in particular are the constraints that weather and daylight patterns have on where and when they can generate. This makes their output variable, not fully predictable and can constrain where plants can be located. In addition, VRE generators can be deployed at smaller scales and connect to the power grid using power converters (non-synchronous technology, see below).
- Second, the flexibility of the power system into which VRE is integrated and the characteristics of the system's electricity demand. This includes the flexibility of existing power plants (how well they can adjust their output), the short-term responsiveness of demand, the availability of electricity storage and the quality and smartness of the transmission and distribution grid. The size and degree of interconnection are also relevant (a larger and more interconnected system generally implies easier integration).

Figure 2: Interaction of VRE properties and power system flexibility



Key point: **The integration challenge is determined by the balance between properties of VRE and system flexibility.**

For example, where good wind and solar resources are far away from demand centres, it is necessary to build grid infrastructure to access the resource (this is also the case for other renewable energy sources). Where sunny periods coincide with high electricity demand, solar PV generation can be integrated more easily. However, as VRE generation provides a larger portion of supply, more pronounced swings in the supply demand balance of electricity can occur.

While the range of relevant attributes related to each factor is limited, the way they interact is system-specific and highly complex. Integrating VRE in the power system can be challenging, because supply and demand of electricity in an interconnected power system need to be balanced at any moment, respecting the operating limits of all equipment.

1.3 Initial deployment of wind and solar PV

Reaching the first few percent in annual electricity generation poses few technical and economic challenges. The reason behind the ease of integration of low shares is that the properties of VRE that are relevant for system integration are not new to power systems.

Since the early days of electrification, variability and uncertainty have been well-known issues for security of electricity supply. Electricity demand varies strongly depending on time of day and season. Fossil power plants experience unexpected failures and power systems hold reserves available that can quickly respond to such a disruption without compromising quality of service.

Consequently, power systems have sufficient resources to cater for the variability and uncertainty coming from the initial addition of VRE and deployment does not present a relevant challenge to electricity security at this stage. However, this is true only if some basic principles are adhered to. Current state-of-the-art practices can be summarised as follows:

- ensure that the technical standards (known as grid codes or connection standards) for VRE power plants are up-to-date and already contain appropriate provisions for technical capabilities that can become critical once VRE make up a larger portion of the generation fleet;

- forecast the production from VRE using centralised forecasts and effectively use forecasts when planning the operation of other power plants and electricity flows on the grid;
- ensure that system operators have access to real-time production data and that a sufficient share of VRE generators can be controlled remotely by them (priority should be given to large scale VRE plants);
- avoid unintended local concentrations of VRE power plants ("hot spots"), both in one region of a country as well as in certain parts of the grid within a given region to avoid technical challenges in these regions.

1.4 Impacts at high shares and common concerns

Growing VRE shares beyond a few percentage points can affect the power system at all timescales, ranging from several years (system planning) to days, hours and minutes (system operations) to seconds (system stability). Effects of high shares of VRE can also be seen at all geographic scales, from system-wide impacts (affecting entire continental power grids) all the way down to individual lines of the distribution grid.

The main effects that VRE have on the power system can be categorised according to the properties that give rise to them. Some of the most frequently voiced concerns are listed below. Typically, for a given power system and VRE penetration level, more detailed studies find that many concerns are not substantiated, others can be addressed easily and yet others may require dedicated action. The degree to which concerns are warranted or not depends on a number of system specific factors, and thus a detailed technical analysis is required to obtain clarity about their relevance in a given context:

- Variability
  - Low contribution to covering peak demand, increased need for peaking generation

    Concern: "VRE generation capacity may not be available during peak demand (dark-calm periods) and thus increase the need for peaking capacity to meet peak demand."
  - Reduced utilization of other generation capacity

    Concern: "VRE generation displaces other generators during times of high VRE infeed and thus reduces their capacity factor, this may cause the exit of generators that are needed for system security."
  - Increased need for ramping thermal generation up and down, increased wear and tear and possible technical infeasibility

    Concern: "VRE increase impose a more volatile operational pattern on other generators, which will increase costs related to wear and tear and may also lead to periods of 'over-generation'."
- Uncertainty
  - Forecast errors and increased need for holding reserve capacities

    Concern: "In order to balance the forecast error of VRE, an increase in reserve capacities is required."
- Location constraints
  - Increased need for grid capacities to connect distant resources

    Concern: "Good wind and solar PV sites tend to be far away from load centres, their connection will lead to increased costs; they will also tend to be connected in weak parts of the grid, which is prone to cause additional technical issues (voltage stability)."

  - Congestion of transmission grids in regions with high concentration of VRE

    Concern: "VRE deployment often occurs in a regionally concentrated fashion, which can lead to local hot-spots that are challenging to manage."

- Modularity
  - Local saturation of distribution grids

    Concern: "Distribution grids were not designed to host large amounts of distributed generation. The large scale uptake can challenge power quality, lead to overvoltage and overloading of equipment."

  - Power flows from the distribution to the transmission level

    Concern: "If very large shares of distributed generation are achieved, electricity may flow from the distribution to the transmission level. This is a threat for energy security."

- Non-synchronous technology
  - Reduced levels of system inertia and other stability issues

    Concern: "VRE have little (wind) or no (PV) rotating mass. Moreover, they are connected to the grid using power converter technology, which offset the inertia effect of rotating wind turbines. This can threat system stability, i.e. the power system's ability to limit adverse impacts in the first seconds following a disturbance."

G7 countries are at the forefront of developing and applying regulatory and technical measures that address the above concerns. Before investigating these solutions in detail, it is worthwhile to consider a framework for approaching the above issues in the most effective way: power system transformation.

1.5 Power system transformation for a secure integration of VRE

Given the broad impacts that high VRE shares can have, a comprehensive and systemic approach is the appropriate answer to system integration challenges. This is best encapsulated by the notion of system transformation (IEA, 2014b). As identified by IEA analysis, a coordinated transformation of the entire system can reduce integration costs. Such a cost-effective transformation can be implemented step-by-step and has technical, economic, political and social aspects. Policy makers need to anticipate the far-reaching implications of a power system transformation and act pro-actively to translate their ambitions into palpable actions on the ground.

From a technical perspective, changes are needed in the way that VRE is deployed ("system-friendly VRE deployment) as well as the need for additional flexibility in the power system. Furthermore, system operations may need to be revisited to ensure that best-practices are implemented.

From an economic perspective, the markets or remuneration schemes governing the economic returns will have to be revisited to strike a balance between two objectives. On the one hand, due to their capital intensive nature, the cost of capital is key for shaping the overall cost of wind and solar power generation. Consequently, market arrangements need to provide sufficient long-term certainty to keep financing costs low. On the other hand, investors in wind and solar power need to be exposed to price signals that reflect the value of their generation for the overall system, to optimise the location and and design of power plants. In addition, new schemes may have to be developed to ensure that investments into the additional flexibility measures required for power system transformation.

From a political perspective, VRE is changing the role of existing stakeholders and simultaneously allowing new stakeholders to enter the power sector. This requires measures to deal with institutional resistance as well as new regulatory frameworks to govern these new stakeholders. For example, controlling distributed power generation capacity remotely will require regulatory frameworks to address data ownership rights, and interconnectors will have to be accompanied by internationally-agreed frameworks to ensure that they are used in the most effective manner. For example, this changes the required information flows and responsibilities between operators of the transmission and distribution level of the power system.

Finally, this transformation will require engagement with civil society. Both new power generation as well as grid infrastructure will have an impact on the landscape and civil works, and a lack of acceptance can delay or complicate power system transformation significantly. On the other hand, a positive attitude will provide more options, especially in the end-use sectors such as facilitated adoption of demand side response technologies.

Ultimately, by combining the structural advantages of renewable energy with appropriate strategies to increase power system flexibility, the overall outcome can be a more secure and resilient power system.

2 Review of best practice in G7 countries

G7 countries are actively applying regulatory and technical measures that facilitate the transformation of their power systems. These instruments help dealing with the concerns listed in section 2.4, as the following examples highlights:

- Variability
    - *Low contribution to covering peak demand, increased need for backup generation*

      VRE by themselves do not need backup; the power system as a whole requires sufficient resources to meet load at all times, including peak demand. Deploying a well-chosen mix of wind and solar, spread across a large geographic area can increase the amount of capacity that is available to generate at any given time. Strengthening demand side response rather than focussing on supply side options can also help meeting peak demand cost effectively. For example, in the largest liberalised power market globally, PJM, a regional transmission organization in the United States, demand side response resources provide a capacity contribution of 13 GW (corresponding to approx. 10% of peak demand; PJM, 2016). The European TradeWind project has calculated that linking wind power plants across Europe can double the amount of wind power capacity that can be relied upon to meet peak demand (TradeWind, 2009).
    - *Reduced utilization of other generation capacity*

      G7 countries are currently characterised by slow or negative demand growth. Under these conditions adding any additional generation will come at the detriment of existing assets. Ensuring that appropriate exit signals are in place for generation capacity that is surplus to need is an important element of power system transformation. Conversely, an appropriate market design can ensure that system critical plants are remunerated according to their value to the system (see accompanying note on electricity security for details). For example, the recent re-design of the German power market, including the introduction of a strategic reserve, effectively addresses this issue (BMWi, 2015).

    - *Increased need for ramping thermal generation up and down, increased wear and tear and possible technical infeasibility*

      Thermal plants frequently dispose of a significant amount of output flexibility that can be used without inducing large costs. For example, the Western Wind Integration Study Phase II, carried out for the Western Interconnect of the United States, highlighted that costs associated with starting and stopping thermal plants more often in response to increased wind and solar generation are very small (NREL, 2013a). In North-America, certain coal power plants have been successfully converted from baseload plants to mid-merit generation in order to integrate nuclear power (NREL, 2013b). French nuclear power plants frequently ramp up and down to follow power demand (NEA, 2012). Systematic analysis in Japan has revealed that despite the fragmented structure of the power system and a relatively inflexible generation capacities, the current ramping capability is sufficient to integrate over 30 GW of VRE capacity in seven of the ten utility areas (METI, 2014) and a significantly larger amount when also considering the Tokyo, Chubu and Kansai areas.

- Uncertainty
    - *Forecast errors and increased need for holding reserve capacities*

      Reserves are needed to deal with errors in forecasting VRE production. Forecasting techniques for wind and solar have seen rapid improvement over past years. The quality of forecasts is also much higher a few hours ahead than one or two days ahead. By moving decisions for system operations closer to real time, required reserves can be minimised. For example, following a comprehensive market reform in the Electricity Reliability Council of Texas (ERCOT) in 2010, required regulation reserves could be reduced, by introducing more rapid market operation until close to real time. Sharing reserves across larger areas can also be used to minimise VRE impacts. Through improved collaboration between the four Transmission System Operators in Germany, the requirement for certain reserves has been *reduced* despite a rapid increase in VRE capacities (IEA, 2014b). Finally, new ways to provide reserves can be valuable as well: VRE plants are also capable to provide system services, including automatic reserves, themselves (REServices, 2013a,b) and industrial plants, such as Aluminium smelters, can be used for provision of fast-acting reserves (TRIMET, 2015).

- Location constraints
    - *Increased need for grid capacities to connect distant resources*

      Taking a systems perspective when deploying wind and solar power can help to reduce connection costs. Recent advances in wind turbine technology allow cost-effective generation in medium wind resource locations, closer to power demand (LBNL, 2015). Planning standards can also help to reduce costs for grid connection. For example, Germany is considering allowing for limited curtailment (BMWi, 2015) when planning grid connection and reinforcement standards to cut down on connection costs. Where large investments are inevitable to tap into favourable resource locations, a co-ordinated approach to building large transmission corridors for multiple wind projects can help ensure efficient outcomes (ERCOT, 2012).

    - *Local congestion of grid capacities in regions with high concentration of VRE*

      Probably one of the most frequent issues for transmission system operators in G7 countries for VRE integration today is the local congestion of grids in locations with high

VRE density, in particular during times of high VRE in-feed and low demand. G7 countries have applied a wide variety of strategies to deal with these issues. For example, the German TSOs Tennet and 50Hertz have introduced real time monitoring of transmission lines to boost the available capacity (dynamic line rating) and the Italian TSO Terna has systematically carried out reinforcement upgrades in areas with very high wind and solar PV concentrations. Japan is reforming its power market with a view to better utilise and increase the available capacities between different utility areas. The restructuring of power markets in the United States – in particular the introduction of location dependent pricing – have been effective tools for minimising congestion issues at least cost. If other options are exhausted, curtailment of VRE facilities is an effective tool to mitigate congestion issues and ensure security of supply.

- Modularity
  - *Local saturation of distribution grids*

    The rapid uptake of large amounts of solar PV on low voltage grids has been a particular challenge for distribution grids, including in regions of Germany, the United States and Italy. Originally designed as passive elements of the power system that deliver power to the final consumer, distribution grids are not necessarily well prepared for hosting large amounts of generation capacity. However, given that appropriate regulation is in place, solar PV systems themselves can help to keep local grids within normal operating ranges. In Germany, new PV systems are required to provide system services depending on their size and connection voltage in order to facilitate their own integration. Italy provides a very good example, how the large-scale roll-out of smart grid technologies can help to bring the capabilities of distribution grids up to its new role (ENEL, 2014).
  - *Power flows from the distribution to the transmission level*

    Despite not originally being designed to do so, all distribution grids are in principle technically capable to feed electricity back to the transmission level. Required technical upgrades mainly relate to protection equipment. Power flows from the lower to higher voltage levels are business as usual in G7 countries. For example, in Italy 32% of substations linking the distribution and transmission level experience upward flows during more than 1% of the hours of the year (seven hours per month; ENEL, 2015). There are a number of relevant energy security implications for such altered power flow patterns. The two most important ones are: 1) protocols for dealing with major system disturbances include automatic load shedding to stabilise the system during periods of generation shortage. However, if a distribution grid is feeding power up to the transmission level, it is effectively acting as a generator rather than a load. Its disconnection would thus exacerbate system stress. Protocols thus need to be upgraded to account for this effect. 2) Information flows from the distribution to the transmission level become critical for system operation. G7 countries are actively reforming this interface, the Reforming the Energy Vision in the state of New York in the US is a relevant example of a comprehensive upgrade of distribution grid governance.
- Non-synchronous technology
  - *Reduced levels of system inertia and other stability issues*

    Inertia is a fairly recent issue for renewable energy integration (see IEA, 2014b for details on the issue). It is currently relevant only for smaller power systems that feature periods of very high VRE penetration. For example, the Irish system operators EirGrid is currently limiting the combined contribution of wind power and HDVC interconnectors (which also do not contribute to system inertia) to 50% of power demand (Eirgrid, 2010). While not an immediate concern in G7 countries, the issue has been recognised by system operators. For example, NationalGrid in the UK has recently developed an integrated analytical framework for assessing the challenges of reaching high shares of VRE: the system operability framework (NationalGrid, 2015).

3 No-regret options for integrating VRE in G7 countries and future priorities

The previous sections have provided an overview of the possible challenges that grid integration of variable renewables bring, have discussed strategies to address these, and highlighted current practices in G7 countries. The concluding section of this note derives three sets of no-regret actions for G7 countries to ensure energy security with renewables in a timely fashion. Relevant conclusions are based on the analytical tools that IEA and IRENA have developed for assisting governments to succeed in integrating high shares of VRE, which are reported more in detail in chapter 5.

3.1 Must-have options for immediate implementation in G7 countries

The following items constitute a minimum package to ensure system security at growing shares of VRE. If not already implemented, these options should be enabled as an absolute priority.

Real-time monitoring and control of VRE plants

All currently experienced energy security challenges related to power system operations in G7 countries can be addressed, if the output of VRE generation can be reduced when needed. It is currently not the absence of VRE generation that is the main challenge during operations but rather times of high VRE output combined with low demand.

A precondition for system operators to respond to such situations appropriately is to a) be aware of the current generation level of VRE and b) be in a position to reduce the output of VRE plants during critical situations, if other options such as activating reserves are exhausted. Regulation needs to grant system operators the right to perform such interventions on the basis of transparent technical criteria. Technical solutions need to be in place to control a sufficient share of VRE output. Priority should be given to larger facilities, given the relatively higher cost of making small-scale systems controllable remotely. Transmission and distribution level operators also need to have clearly defined communication and operational protocols in place.

VRE production forecasts

Accurate VRE production forecasts are an indispensable tool for system operators to anticipate possible risks to system security and to take counter-measures in a timely manner. Experience in G7 countries has highlighted that a centralised forecast for the entire power system is a strict requirement and should not be substituted by forecasts based on the aggregation of individual VRE generators. These forecasts benefit from real-time monitoring of VRE generation and need to consider information on VRE plant status (such as forced outages, maintenance). VRE forecasts are commercially available, mature products. Ideally, system operators should use forecasts from several different providers. Frequent sharing of forecast information between neighbouring power systems including on the day of operation is also a critical element to enable co-ordination between different systems.

Technical standards for VRE plants

VRE generators use power converter technology to connect to the grid. Such converters can be programmed to behave in a pre-defined way. The regulations that set out the required performance characteristics are known as grid codes or connection standards. Historically, imperfect grid codes have caused risks to security of supply. If this issue has not already been addressed, a systematic review of existing grid codes / connection standards and a benchmark with best practices is imperative to ensure reliable operations at high shares of VRE.

3.2 Short-term priority improvements to existing policies for secure system operations

The previous options represent the bare minimum to ensure the 'lights stay on' when operating a power system at high shares of VRE. However, a number of additional, low-cost steps are available to minimize the overall system cost through VRE deployment. In addition, a number of these measures contribute to a more secure and efficient functioning of power systems irrespective of VRE integration. The most relevant options include:

Co-operation and consolidation of balancing areas

The geographic region over which demand and supply are balanced in real-time (balancing area) should be increased and co-operation between neighbouring balancing areas maximised. This allows reaping synergies through linking diverse resources in different power systems. As a result overall capacity requirements are reduced, because peaks do not occur at the same time in distant regions. At high shares of VRE there are important additional benefits: the smoothing of VRE output by aggregation across larger geographic areas, and a better utilisation of the various flexible resources, from flexible generating plants to demand response and pumped-hydro or other storage technologies. In Germany, the improved co-ordination of the four "parts" (balancing areas) of the grid has *reduced* the need for holding certain reserves despite a dynamic *increase* of VRE capacity.

Improved operations

Improving system operations has proven to be a major success factor in countries that have pioneered VRE integration (for example Germany, Italy and part of the United States). More specifically, this means enuring that operational decisions can be updated as close as possible to real-time and that operational schedules have a high temporal granularity (including power plant and transmission grid schedules and the calculation and deployment of operational reserves).

However, changing operational practices may face institutional resistance and delay despite their cost-effectiveness (such as system operators' reluctance to adopt innovative approaches for calculating reserve requirements).

Wholesale and retail power market design reform

Power market design has a critical role to play to ensure efficient system operations, kick-start the market for new technologies such as demand side response and ensure that power system resources are remunerated according to their value for the power system; including new resources such as distributed generation and storage. The accompanying note on Electricity

Security provides an in-depth discussion of this topic (IEA, 2016a), the most critical points are summarised in the following paragraph.

A flexible power market, with strong integration across borders, is critical to accommodating higher shares of VRE while maintaining reliability. Effective short-term markets – that facilitate making changes to the economic dispatch of power plants closer to real-time – are also critical. Electricity security can be further enhanced by adopting appropriate power market rules and planning, including setting high reliability standards that consider system resiliency and employing scarcity prices and possibly capacity mechanisms.

System-friendly VRE deployment policies

VRE can contribute to its own system integration – and it will need to do so to achieve system transformation cost-effectively. The main intent of system-friendly deployment is minimising overall system costs, in contrast to minimising VRE generation costs alone. These new priorities may challenge existing support policies for VRE. For example, it may be necessary to provide locational and timing signals to generators, and to expose generators to market prices to encourage deployment in places and at times when it is most highly valued. A particularly important aspect in this regard is to encourage VRE generators to maximise full load hours of their plants, by deploying appropriately designed technology. Existing policies may not encourage such a deployment or may even discourage it. A review of the policy framework for VRE with a view to maximise system friendly deployment is a key priority for short term action.

Transmission and distribution system operators interface improvement and reform of distribution grid regulatory frameworks

One of the most significant changes for power systems on the way to high shares of VRE has been the changing role of the distribution grid: away from a passive structure that supplies final consumers towards a much more complex system that locally integrates an increasing number of diverse resources (generation, demand side response, storage). Existing institutional and regulatory frameworks are inadequate for this new role. If not already the case, the systematic re-design of these arrangements should feature among the most important short-term priorities for policy makers.

Clear rules for handling the curtailment of VRE generation facilities

A limited amount of curtailment can be a cost-effective way for integrating wind and solar power. In scenarios with low available flexibility from demand side resources and storage, the cost-optimal share of curtailment will be relatively higher. The allocation of curtailment (which plant is asked to reduce its output, who pays for foregone revenues etc.) is a critical part of the equation when investors assess the risk of renewable energy projects. As such, defining curtailment rules consistent with a high VRE future are also a short-term priority.

Development of the market for most cost-effective flexible resources

Flexibility comes in four main different forms, including grid and interconnections, dispatchable supply (from both renewable and thermal power plants), storage, and demand-side response, plus VRE curtailment. Each flexibility option is suitable to address certain integration issues, so a well-balanced set of flexibility options is recommended. Consequently, a policy framework to add flexibility should neither opt for the cheapest option nor pursue only the option with the best cost-benefit performance. However, numerous analyses (e.g. IEA, 2014b) have pointed to demand side response as a particularly cost-effective option that brings benefits for power system operation and investment even in the absence of high shares of VRE. As such, kick-starting the market for demand side response may be considered a no-regret option in developing the mix of additional flexible resources.

3.3 Future-proofing planning processes

Looking ahead is key for successful and cost-effective power system transformation and ensure security of electricity supply. As such, planning processes for generation, grid infrastructure and other resources (e.g. storage) have a critical role in creating and improving energy security a proactive manner. The most relevant aspects identified in this regard are:

Holistic assessment of the energy security implications of high renewable energy scenarios

Energy security considerations are critical for identifying optimal long-term scenarios. However, it can be challenging to include such aspects in long-term planning models. For example, high shares of domestic renewable energy production reduce exposure to fossil fuel price volatility and contribute to mitigating climate change impacts. Conversely, understanding the weather and climate related impacts of high shares of renewable generation are equally important to develop a full understanding of energy security implications or reaching high shares of renewable energy.

Systematic assessment of technical issues at high shares of VRE.

Energy planners and system operators should work more closely together to develop and apply a framework for a systematic assessment of technical issues at high shares of VRE. This assessment should help ensure that technical specifications for all new assets entering the power system (including conventional generation, end-use devices and storage) are consistent with the specific characteristics of a power system with a high share of converter based generation technologies.

Systematic review and upgrade of planning standards for distribution grids

Such review and upgrade must be in line with its changing role towards a critical link between a large number of diverse resources. Planning processes for upgrades of the electricity grid should be coordinated with other infrastructure upgrades (*e.g.* water, road/rail infrastructure) to identify synergies and minimise costs.

Inclusion of advanced technology solutions in planning processes

Introducing advanced technology solutions for integrating VRE when planning transmission grid expansion and setting conventional power plant requirements should be considered. This includes the use of smart grids, assuming ambitious energy efficiency improvements, uptake of sophisticated demand side response technologies, coupling the electricity sector with heat and transport sectors, integration with neighbouring electricity systems with increased interconnection, and emerging technologies such as battery electricity storage.

4 Mapping of recent and most important work on this subject of IEA and IRENA

4.1 IEA

The IEA has had a dedicated work stream on the Grid Integration of Variable Renewables (GIVAR) since 2005, when the G8 requested the IEA to assess the implications of increased shares of variable renewable energies on power systems. Since then, the IEA has published three main reports as part of the GIVAR programme: *Empowering Variable Renewable*s (IEA, 2008); *Harnessing Variable Renewables – A Guide to the Balancing Challenge* (IEA, 2011b); and *The Power of Transformation – Wind, Sun and the Economics of Flexible Power Systems* (IEA, 2014b).

The most recent major GIVAR output – *The Power of Transformation* - deepens the technical analysis of previous IEA work and lays out an analytical framework for understanding the economics of VRE integration impacts. Based on detailed modelling, the impact of high shares of VRE on total system costs is analysed. In addition, the four flexible resources which are available to facilitate VRE integration – generation, grid infrastructure, storage and demand side integration – are assessed in terms of their technical performance and cost-effectiveness. The publication addresses the following questions:

- What are the relevant properties of wind power and solar photovoltaic (PV) power plants that need to be taken into account to understand their impact on power systems? What power system attributes influence the ease with which wind power and solar PV energy sources can be added to a power system?
- What challenges arise as variable renewable energy (VRE) sources are added to power systems? Are these transitory or likely to persist? Which are economically most significant?
- Which flexibility options are available to cost-effectively overcome these challenges and how can these be combined to form an effective strategy for VRE integration?

The GIVAR III project integrates analysis from a range of case studies. Case study analysis was supplemented by an extensive literature review of different options for VRE integration. Analysis was further informed by a suite of custom-tailored technical and economic modelling tools. *The Power of Transformation* has been presented in a number of G7 countries, including France, Germany, Italy and Japan; a full Japanese translation is available.

As part of GIVAR, the IEA has developed and constantly refined an analytical tool to assess the technical flexibility of power systems: the flexibility assessment tool (FAST2). The objectives of the FAST2 approach are: 1) provide an initial, high-level assessment of power system flexibility; 2) raise awareness among policy makers of flexibility issues and motivate more detailed analysis; and 3) inform scoping of more detailed analysis. The tool has modest data requirements and can be applied to a wide range of country circumstances (G7 countries that have been [partially] assessed are France, Germany, Italy, Japan, the United Kingdom, and the United States).

The GIVAR programme has most recently assessed the contribution that the design of wind turbines can make to facilitate integration with a detailed techno-economic modelling study. The results of this study will be integrated into a report to the 2016 Clean Energy Ministerial on

Securing the Value of Wind and Solar Power. GIVAR analysis has also informed other IEA publications, including the Projected Cost of Electricity Study (with a chapter on system costs) and the IEA Energy Technology Perspectives 2015 (looking at policy and market frameworks to facilitate integration of large VRE shares).

Finally, as part of the GIVAR programme the IEA is currently developing an assessment framework for tracking progress in power system transformation. It provides a comprehensive overview of all relevant components of system transformation, including technical and economic aspects. The framework will be part of a major publication on grid integration in 2017.

Since 2011, in parallel to GIVAR analysis, the IEA has been working on an *Electricity Security Action Plan* (ESAP). ESAP has a broader scope including a focusing on investment and assessing best practice principles for wholesale and retail power market design for the transition to decarbonised electricity systems (Baritaud, 2012; Baritaud and Volk, 2014; Cooke, 2011; IEA, 2013b; IEA, 2016b).

Through its Technology Collaboration Programmes the IEA also provides a framework for exchanging international research and best practice on integrating VRE. In this context the work of IEA Wind Task 25 Design and Operation of Power Systems with Large Amounts of Wind Power and the Photovoltaic Power System Task 14 High Penetration of PV Systems in Electricity Grids are particularly relevant. The IEA also has Technology Collaboration Programmes in the areas of demand side response and storage.

4.2 IRENA

The aim of IRENA's activities is to support policy makers and utilities in identifying the appropriate measures to accelerate a transformation of the electricity sector towards renewable power technologies. The studies range from technology roadmaps identifying opportunities for international cooperation to grid stability studies for islands to technology reports on the latest battery storage systems to introductory guides on the role of smart grids in supporting the integration of renewable power generation.

IRENA's activities can be categorized in three main categories, which correspond to the different electricity security aspects discussed in this paper.

Supporting a long-term security of electricity supply

On a global level, IRENA has developed guidelines for renewable energy targets (IRENA, 2015,c) and country-by-country assessment of renewable power options up to 2030 (IRENA, 2016a). The results of these analyses are subsequently used to identify priority areas for action on topics like electricity storage (IRENA, 2015d) and the electrification of the transport sector.

At a regional level, IRENA supports the accelerated deployment of renewable power through the development of clean energy corridors (IRENA, 2013a). The clean energy corridors allow neighbouring countries to take advantage of the cheapest renewable energy resources within the region by connecting their grid infrastructures to each other. The development of clean energy corridors is supported by modelling of the least cost power generation mix and grid infrastructure development (including interconnectors) (IRENA, 2015e), renewable energy resource assessments (IRENA and KTH, 2014), and the development of methodologies to identify renewable energy zones (IRENA and LBNL, 2015).

At a national level, IRENA has provided a framework that allows Member states to design their own national roadmaps, tailored to their own needs while using a consistent methodology (IRENA, 2015b).

Facilitating the deployment and integration of renewable power

IRENA has developed a number of tools that can be adjusted to suit the country conditions. Policy and regulation are supported through guidelines for renewable energy auctions (IRENA, 2015f) and the Regulatory Empowerment Project, guidelines for the development of grid connection codes (IRENA, 2016b), assessments of the need for baseload power (IRENA, 2015g), and guidelines for design and adaptation of renewable energy policies to changing market conditions (IRENA, 2014). Infrastructure design is supported by tools providing guidelines for adequate renewable power generation project development, including mini-grids applications (IRENA, 2016c), assessing grid investment needs to achieve specific renewable energy targets (IRENA, 2016d), and performing cost-benefit analyses of smart grids for renewables deployment (IRENA, 2015h), as well as practitioner's guide for VRE grid integration. Technology status and outlook reports provide the latest cost and performance data on smart grids (IRENA, 2013b), energy storage (IRENA, 2015i), off-grid renewable energy systems (IRENA, 2015j) and mini-grids (IRENA, 2016e).

Supporting operation and management

For electricity systems that are rapidly moving to high shares of VRE, it is important to understand the technical constraints associated with grid stability and system security on a daily basis. This requires dynamic models to test the stability of the system under a range of conditions. IRENA supports Members in conducting and reviewing grid stability studies and using their results appropriately. Subsequently, IRENA assist Members in identifying appropriate solutions to continue to increase the renewable energy share.

Islands and mini-grids

Within each of these three categories, IRENA has paid special attention to the power sector transformation in islands and remote areas. Due to their size, their dependence on expensive diesel power generators, and their abundance of renewable energy resources, islands, in particular, are in a position to transform towards renewable power based systems.

In this context, IRENA has developed or is developing national roadmaps for various islands (IRENA, 2015k;IRENA, 2015l), including power sector analysis for Cyprus, Maledives, and Naur and grid stability studies in Palau, Samoa, and the Cook Islands (Aitutaki) and is supporting a further five islands with reviews and grid stability studies. Furthermore, IRENA is examining policy and regulatory mechanisms, business models, the latest technology costs and performance data and capacity building in the Philippines and the ECOWAS countries to support the implementation of renewables-based minigrids. These efforts benefit from IRENA's continued engagement with stakeholders in the off-grid sector through platforms such as the International Off-grid Renewable Energy Conference and Exhibition (IRENA, 2015m).

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