Executive summary

Great efforts are being made to boost the share of renewable energy sources in the global energy mix, driven by the need for enhanced energy security and environmental protection and by accelerating climate change.

The focus of this book is on the integration of renewables into power systems, which is to say the ensemble of power production, supply and consumption.[1] Some renewable energy technologies (*e.g.* biomass, geothermal and reservoir hydropower) present no greater challenge than conventional power technologies in integration terms. In contrast, another group of renewables – including wind, solar, wave and tidal energy – are based on resources that fluctuate over the course of the day and from season to season. Collectively known as variable renewable energy (VRE) technologies, these represent additional effort in terms of their integration into existing power systems.

The extent of the challenge is one of the most disputed aspects of sustainable energy supply: detractors claim that VRE technologies, at high levels of deployment, introduce a level of uncertainty into the system that makes it just too difficult to meet the moment-by-moment challenge of balancing supply and demand for electricity across a power system.

The Grid Integration of Variable Renewables (GIVAR) project was undertaken by the International Energy Agency (IEA) to address the critical question of how to balance power systems featuring large shares of VRE. *Harnessing Variable Renewables* gives a detailed description of all the main elements of the balancing challenge, as well as the tools presently used to manage it. It outlines step by step a new method developed by the IEA to assess the resources and requirements for balancing in a given system, and highlights resulting potentials in eight case-study areas, underlining the point that no two cases are quite alike.

Variability and uncertainty are familiar aspects of all power systems: the need for flexible resources to balance them has been long understood. Those who assert that large shares of variable supply represent an insurmountable, additional challenge to power-system operation may be looking with too narrow a gaze. Variability and uncertainty are not new challenges; power systems have long taken them into account. Fluctuating demand – from hour to hour, day to day, season to season – has been a fundamental characteristic of all power systems since the first consumer was connected to the first power plant. All power systems include a range of flexible resources to manage this fluctuation: dispatchable power plants for the most part, but some systems may also incorporate electricity storage, demand-side management, and/or interconnections to neighbouring power markets.[2] The question is: can the use of these resources be enhanced efficiently to balance increasing variability resulting from VRE deployment?

System operators have vast experience of responding to variability (in demand) by ramping flexible resources up or down. When a fast response is required to an unexpected or extreme spike in demand or the outage of a plant, the operator will call upon the most flexible resources. In most cases, these will be power plants designed for peaking (*e.g.* open-cycle gas plants, hydro plants) or storage facilities (*e.g.* pumped hydro).[3] To address largely predictable changes in demand – such as the morning rise and the evening fall – operators will dispatch mid-merit power plants (*e.g.* combined-cycle gas). Lastly, baseload plants (*e.g.* nuclear, some coal, geothermal) are designed to provide for that proportion of demand that is more or less constant around the clock. Most of these plants are designed to operate at full power all the time; their output can be changed less quickly and to a lesser extent.

Existing flexible resources may be able to manage additional variability resulting from VRE deployment although variability and uncertainty of VRE are greater than on the demand-side. It is

---

1. The principal elements of power systems include power plants, consumers and the transmission grid connecting them.
2. The importance and potential of response by electricity consumers (demand-side response) is beginning to be understood.
3. In some cases, this will also include interconnections and contracted demand-side management (load shedding).

© OECD/IEA - 2011

generally easier to predict fluctuations in demand than in VRE supply. In part, this reflects decades of experience and data in relation to demand drivers. It is also true that supply-side variability depends on the VRE resource: tidal power output, for example, is highly predictable. Solar (PV) plants can produce electricity even under cloud cover, so output is never less than around 20% of rated capacity (during daylight)[4], providing a measure of certainty. But it is unlikely that meteorological science will deliver fully accurate predictions of the outputs of wind and wave plants, which are highly irregular.

What share of VRE is possible with more effective use of *existing* flexible resources? A principal finding of this book is that there is no one-size-fits-all answer to this very common question. Power systems differ tremendously in design, operation and consumption patterns, in the natural resources that underpin them, the markets they contain, and the transmission grids that bind them together. Furthermore, and as this analysis shows, there is likely to be a wide gap between what is technically possible and what is possible at present. In other words, some systems are better able than others to manage large VRE shares of electricity production, and direct comparison among them of VRE deployment potential from the integration perspective is inappropriate.

Harnessing Variable Renewables describes how to take a snapshot of any power system, to derive an estimate of how much VRE it can manage in its present configuration. These estimates do not in any way represent a technical ceiling on deployment potential however: additional flexible resources can still be deployed as and when required.

The Flexibility Assessment Method: to identify a power system's balancing capability

Much of the uncertainty about the potential of variable renewables to contribute to power portfolios stems from limited understanding of the balancing capability of existing flexible resources. To address this, the GIVAR Project has developed the Flexibility Assessment (FAST) Method. Part 1 of this book guides decision makers and potential users of the FAST method along four steps to identify the present potential for VRE share in electricity demand (Figure ES.1).

- Step 1 assesses the maximum technical ability of the four flexible resources to ramp up and down over the balancing time frame.[5] This is the **Technical Flexible Resource**.

- Step 2 captures the extent to which certain attributes of the power area in question will constrain the availability of the technical resource, to yield the **Available Flexible Resource**.

- Step 3 is to calculate the maximum **Flexibility Requirement** of the system, which is a combination of fluctuations in demand and VRE output (the net load)[6], and contingencies.

- Step 4 brings together the requirement for flexibility and the available flexible resource to establish the **Present VRE Penetration Potential** (PVP) of the system in question.

---

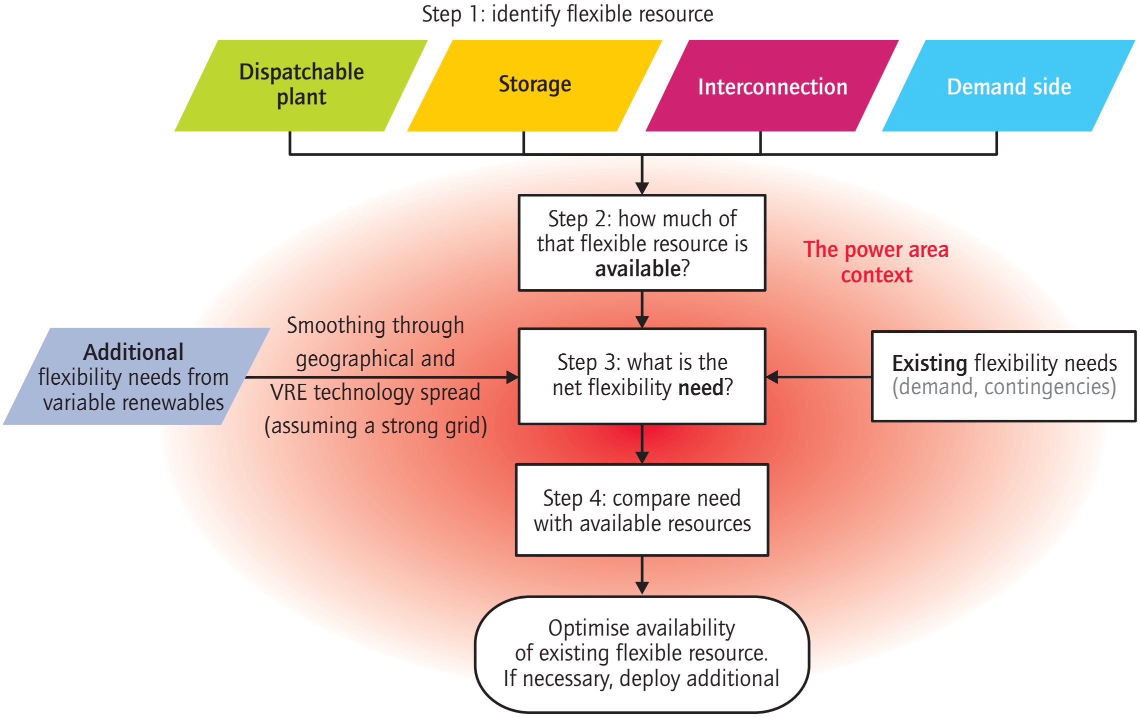
[4] Solar PV does not require direct sunlight to operate, though it is of course preferable.

[5] The timeframe for balancing is considered to be 36 hours; this period will see the maximum extent of variability in most cases. Within this period, three further timeframes are assessed: 6 hours, 1 hour and 15 minutes.

[6] "Net load" refers to the load (demand) curve after production from wind, PV, etc. have been taken into account. It is a very important concept, which can reveal significant complementarities between demand and VRE output, and is dealt with in detail in Parts 1 and 2.

© OECD/IEA - 2011

Figure ES.1 • *The FAST Method*



The GIVAR case studies revealed that considerable technical flexible resources (TR) exist already in all areas assessed. Applying the FAST Method to analysis of eight diverse power areas showed that from a purely hardware point of view (*i.e.* before constraints are taken into account), all areas have the technical capability to balance large shares of VRE. Potentials range from 19% in the least flexible area assessed (Japan) to 63% in the most flexible area (Denmark) (Figure ES.2). Using FAST, the IEA also assessed the resources of the British Isles (Great Britain and Ireland together), 31%; the Iberian Peninsula (Spain and Portugal together), 27%; Mexico, 29%; the Nordic Power Market (Denmark, Finland, Norway and Sweden), 48%; the Western Interconnection of the United States, 45%;[7] and the area operated by the New Brunswick System Operator (NBSO) in Eastern Canada, 37%.

The values shown in Figure ES.2 are indicative only, and reflect three conservative assumptions. Firstly, complementarity of fluctuating demand with VRE output (net load) was not quantified due to data limitations. Secondly, and for the same reason, the analysis does not fully account for the smoothing effect on variability of geographical and VRE technology spread. Thirdly, the opportunity to curtail the output of VRE power plants was not addressed. All three assumptions are likely to exaggerate the flexibility requirements of the areas assessed and therefore reduce PVP values.

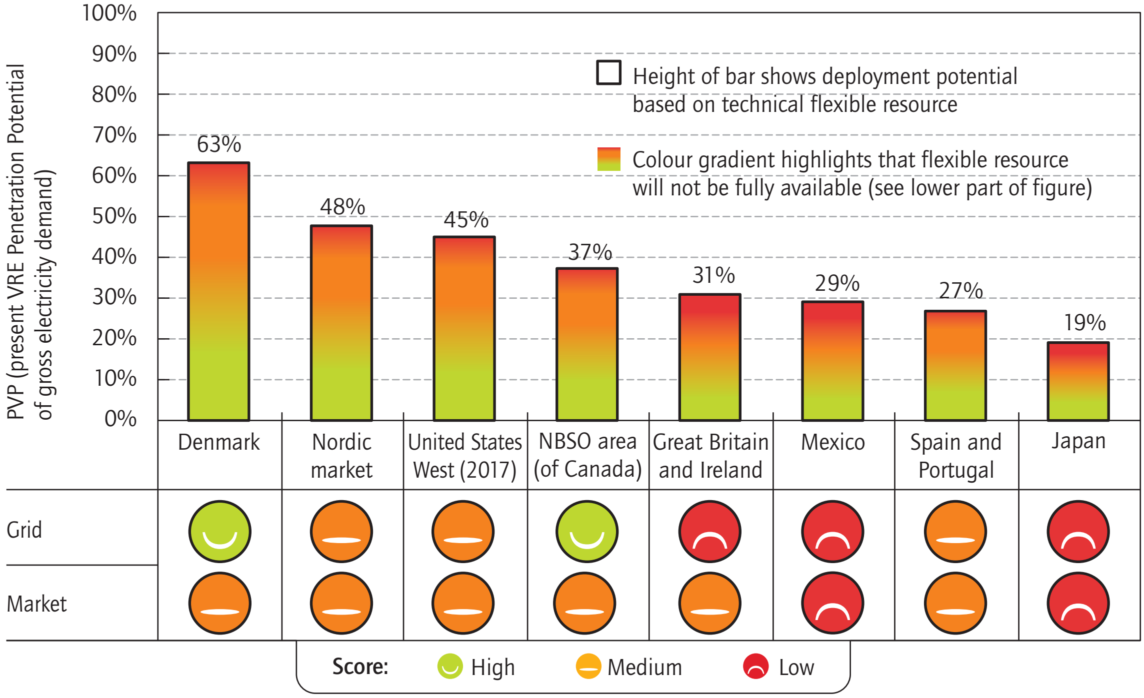
Furthermore, the analysis looks only at transmission level VRE power plants, setting aside for a later date the analysis of the potential for distributed VRE plants (*e.g.* building-integrated PV). It also assumes a portfolio of VRE technologies in each case that does not necessarily reflect existing policy targets. These portfolios reflect the resources of the area to a certain extent and highlight differences among VRE technologies.

---

[7] The assessment of the US Western Interconnection was carried out for 2017, to take advantage of the recent Western Wind and Solar Integration Study performed (in 2010) by GE Energy for the National Renewable Energy Laboratory of the United States.

© OECD/IEA - 2011

Figure ES.2 • *VRE deployment potentials today from the balancing perspective*



The availability of flexible resources for the balancing task is constrained by a range of power system attributes

The analysis has identified a range of characteristics, present to a greater or lesser extent in all cases examined, which will constrain the availability of flexible resources to take part in balancing electrical supply and demand. In some cases this will result in reduction of PVP to well below the values shown in Figure ES.2. Sub-optimal grid strength and market design are the most important of these (although system operation techniques and many other resource-specific factors can represent serious barriers also). The impacts of these two key characteristics in the case study areas are represented in the lower part of Figure ES.2, with a simple "traffic lights" approach. For practical reasons of data availability, it was not possible in this phase of the analysis to quantify these constraints. More refined assessment using the FAST Method, with sufficient data availability, should attempt to quantify the impact of these constraints.

Weaknesses in parts of the existing transmission grid can cause the temporary separation of flexible resources from both demand-side and VRE requirements for flexibility. Such weaknesses may exist for a number of reasons, but are particularly likely to be found at the borders of distinct balancing areas within large power systems. Additionally, VRE power plants, particularly onshore wind, may be located at a considerable distance from demand centres, where the wind resource is strong but where the grid in contrast is relatively weak. Reflecting strategic policy to deploy VRE capacity, in-depth studies to identify such grid weaknesses should be undertaken without delay. Remedial lead times may be lengthy particularly if new transmission corridors are required and their rollout is likely to encounter opposition from local communities. Measures should be examined whereby carrying capacity in weaker areas can be augmented through advanced grid technology and operation techniques with negligible disruption to the local environment.

Markets should be (re)configured so that the full flexible resource is able to respond in time to assist in balancing. Power markets should incorporate mechanisms that enable sufficient response from supply-side and demand-side flexibility assets. Electricity is usually traded through a combination of long-term bilateral contracts and daily power exchanges. Markets that rely heavily on the former will

© OECD/IEA - 2011

find it harder to balance variability and uncertainty as such contracts effectively "lock up" (sometimes months in advance) the potential of assets to respond to needs for flexibility that change dynamically. In contrast, trading closer to the time of operation (the moment in which electricity is produced and consumed), as occurs through power exchanges or mandatory pools, leaves more of the flexible resource free to respond to shifting needs.

The extent of economic incentive in the market place will determine the proportion of the flexible resource that will actually respond. Owners of flexible resources, particularly of slower power plants built for mid-merit or base-load operation, will need incentive additional to that of a fluctuating electricity price to prompt them to offer the full extent of their flexibility to the market. Although a CCGT plant may be *technically* able to ramp its production downwards by 50 MW, for example, it does not follow that it necessarily *will*: more frequent start-ups, shut-downs and ramping increase wear and tear on the plant, posing additional costs, and may have a negative impact on revenues. Similarly, response from demand-side assets is unlikely to occur if the effort required to change behaviour is greater than the compensation provided.

Some power markets today offer a measure of incentive for flexibility. Balancing market mechanisms, as in the Nordic and Iberian power markets for example, provide opportunity for more flexible power plants to benefit from higher than spot-market prices in response to a shortfall in supply. System operators may also contract with power plants to provide (usually hour or intra-hour) reserves against uncertain balancing needs. But new mechanisms will be needed to prompt slower assets to respond to flexibility needs forecasted 36 hours ahead, for example. The form such mechanisms should take will be pursued in the next phase of GIVAR project.

Accurate forecasting of VRE plant output combined with more dynamic power-trading and planning of system operation, can make more efficient use of the flexible resource. Regularly updated forecasts — particularly of VRE output — are a strong signal of evolving flexibility needs in the market place. At "gate closure" (when bids and offers to the power market close) electricity producers are committed to deliver a fixed amount of electricity. After this point, it is up to the system operator to balance any gap between what is committed and what is actually delivered, using flexible resources set aside (as reserve) for this purpose. In many markets, gate closure occurs one day before delivery (which in practice may mean 36 hours ahead or more). However, error in VRE output forecasts reduces as the time of operation approaches. Thus, if gate closure occurs only an hour ahead of this time, instead of thirty-six hours, or even within the hour ahead, producers have the opportunity to update their day-ahead offers on the basis of the latest forecast update, with the result that fewer "reserves" must be contracted in advance by the system operator. System operators should use the best available forecast tools for predicting VRE output, and should take these predictions into consideration when planning system operation.

Policy makers should take action to remove (unnecessary) barriers that constrain the availability of flexible resources. Regulations that pre-date VRE deployment may restrict the use of a particular flexible asset for balancing. A nuclear plant, for example, though it may be technically able to ramp to some extent, may be considered unavailable to cycle for historical and institutional reasons (as well as economic ones). Reservoir hydro plants may be unavailable due to seasonal constraints relating to fisheries or provision of potable water. Policy makers should assess whether such regulations can be reformed to facilitate balancing without undue negative impact on their original objectives.

Larger power markets with VRE resources widely distributed over a strong grid will see a lesser requirement for flexibility. It is important to understand that electricity production from a portfolio of VRE plants does not stop and start in a moment. It ramps up and down over periods of hours, the exact extent of which will depend on the size of the area over which plants are installed, as well as other factors outlined below. Nevertheless, extreme events like storms do occur, and having the right flexible resources to meet such events is critical.

Several opportunities exist to reduce the need for flexibility — and so increase PVP. Dispersing VRE plants over a large area increases their complementarity, *i.e.* their outputs will fluctuate at different

© OECD/IEA - 2011

times with the result that the aggregated output is smoother than if plants were clustered closely together. This smoothing effect is further enhanced if different VRE types (*e.g.* solar and wind) with complementary output profiles are included in the portfolio. Forecast uncertainty is also reduced with wider geographical spread of plants. An aggregated output that ramps more slowly and less extensively increases the value of base-load power plants, whose slower technical ability to ramp is no longer such a hindrance to provision of the flexibility service. Decision makers should plan for the widest possible dispersal of VRE plants within the bounds of grid and resource considerations.

Merging balancing areas enables smoothing through geographical spread and sharing of flexible resources. Discrete operation of individual balancing areas within a power system — and indeed of neighbouring power systems — misses the opportunity to optimise the use of flexible assets. If neighbouring areas are balanced separately, one may be facing an up-ramp in VRE output while its neighbour is facing a down-ramp. If areas collaborate in the balancing time frame, opposing or time-lagged ramps would complement one another to some extent, smoothing overall VRE output.[8] If the combined flexible resources of the merged area are now surplus to present requirements, PVP will increase.

Expensive new capacity measures should be considered a last resort, taken only after optimising the availability of *existing* flexible resources. System planners should first ascertain the level of PVP possible on the basis of existing flexible resources. If this is lower than targeted VRE deployment, it will also be necessary to plan the deployment of new flexible resources. The relative and system-specific costs of increasing the four flexible resources should be assessed carefully: it may be more cost-effective to increase demand response, for example, than to build new power plants. Or it may be that new dispatchable power plants built against demand growth, or to replace retiring plants, may be better able to offer flexibility services than their predecessors (assuming flexibility becomes a design driver), in effect increasing the proportion of installed capacity that is flexible, rather than the level of installed capacity itself.

Principal conclusions and further work in the GIVAR project

The VRE balancing challenge is far from insurmountable. Indeed, all power areas assessed show that greater technical potential for balancing VRE output exists than is commonly supposed. But availability of flexible resources will depend two key factors: strong and early investment in grid infrastructure and intelligence; and market mechanisms that adequately reflect the value of the flexibility service and that clearly signal the need for it well in advance.

Operation of existing mid-merit plants (in particular) must remain economic, or their contribution to the flexible resource may be lost. Areas with large existing shares of VRE capacity today (*e.g.* the Nordic Power Market) see heavily depressed electricity prices when wind power output is high because this low-cost electricity displaces generation from (higher-cost) fossil-fuel powered plants.[9] Unless compensated in some way, this will mean reduced revenues to those conventional plants that are called upon to operate for less time than intended when they were built. Coupled with increased cycling (and increased wear and tear) caused by responding to a more variable net load, this may make such plants uneconomic and result in their early retirement. Market design will need to reflect the system's continuing need to use such plants for balancing. The next phase of the GIVAR project will address possible market mechanisms to prevent a potential shortfall in flexible resources as VRE shares rise.

Sufficient economic incentive must also exist for investment in *new* dispatchable power plants (and other flexible assets), against demand growth and asset retirement, to maintain system adequacy. An adequate system is one that can meet peak demand in the long term (months/years), an aspect beyond the focus of this phase of the GIVAR project, which focuses on the ability of power

---

[8] There will also be times when ramps are not complementary.

[9] Short-run marginal costs.

© OECD/IEA - 2011

systems to manage *changes* in production and demand. The adequacy crunch would come during prolonged lulls in VRE output — does the system have the ability still to meet peak demand? Adding VRE plants into a system that is already adequate has only a beneficial impact on adequacy,[10] yet reduced revenue to dispatchable plants resulting from that deployment (as described previously) may nonetheless undermine it. Maintenance of system adequacy will be a key focus of the next phase of the GIVAR project.

Recent estimates in the literature suggest that at a 20% share of average electricity demand, wind energy balancing costs range from USD 1/MWh to USD 7/MWh. This phase of the project has undertaken a review of wind power integration cost studies, which distinguishes balancing costs from other integration cost categories (those resulting from transmission and support to system adequacy). The upper end of the identified balancing cost comes from estimates for the United Kingdom, wherein the availability of flexible resources is likely to be low due to grid and market constraints. In contrast, recent projections for the Eastern Interconnection in the United States in 2024, which assume optimisation measures such as balancing area consolidation and optimal forecasting, suggest a mid-range cost of USD 3.5/MWh at 20% wind energy share — rising to USD 5/MWh at a 30% share.

These are modelled costs and do not account for all of the flexible resources assessed by the FAST Method. The next phase of the GIVAR project will aim to develop a methodology for identifying cost curves of flexibility measures specific to an individual power system. These are expected to look very different from case to case, as they will depend on widely differing system design, operation and resources. The new phase will also examine the relative costs of dispatchable plants, storage facilities, interconnections and demand-side flexible resources.

---

[10] Although VRE power plants do not provide as high a contribution to system adequacy as do dispatchable plants.

© OECD/IEA - 2011