Executive summary

Wind power and solar photovoltaic (PV) are expected to make a substantial contribution to a more secure and sustainable energy system. However, electricity generation from both technologies is constrained by the varying availability of wind and sunshine. This can make it challenging to maintain the necessary balance of electricity supply and consumption at all times. Consequently, the cost-effective integration of variable renewable energy (VRE) has become a pressing challenge for the energy sector.

Based on a thorough assessment of flexibility options currently available for VRE integration, a major finding of this publication is that large shares of VRE (up to 45% in annual generation) can be integrated without significantly increasing power system costs in the long run. However, cost-effective integration calls for a system-wide transformation. Moreover, each country may need to deal with different circumstances in achieving such a transformation.

This study

This publication deepens the technical analysis of previous International Energy Agency (IEA) work while also analysing economic aspects of VRE integration. It is based on a set of seven case studies comprising 15 countries.[1] A revised version of the IEA Flexibility Assessment Tool (FAST2) is used for a technical analysis of system flexibility in case study regions. Economic modelling of system operation on an hourly basis is used to study the effect of high shares of VRE on total system costs (see Box ES.1). In addition, the four flexible resources that enable VRE integration – flexible power plants, grid infrastructure, electricity storage and demand-side integration (DSI) – are assessed for their technical and economic performance.

The project has been carried out in close co-operation with work in the framework of the IEA Electricity Security Action Plan (ESAP).

Main findings

The interaction of VRE and other system components determine opportunities and challenges of integration

The difficulty (or ease) of increasing the share of variable generation in a power system depends on 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 can be costly to connect them to the grid. On the other hand, where sunny periods coincide with high electricity demand, solar PV generation can be integrated more easily.

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.

1. Brazil, Electric Reliability Council of Texas (Texas, United States), Iberia (Portugal and Spain), India, Italy, Japan East (Hokkaido, Tohoku and Tokyo) and North West Europe (Denmark, Finland, France, Germany, Ireland, Norway, Sweden and the United Kingdom).

System integration is not a relevant barrier at low shares of VRE

It is not a big technical challenge to operate a power system at low shares of VRE. Depending on the system, a low share means 5% to 10% of annual generation. Experience in countries that have reached or exceeded such shares (including Denmark, Ireland, Germany, Portugal, Spain, Sweden and the United Kingdom) suggests that system integration is not a significant challenge at these shares – but only if some basic principles are adhered to:

- to avoid uncontrolled local concentrations of VRE power plants ("hot spots")
- ensure that VRE power plants can contribute to stabilising the grid when needed
- forecast the production from VRE and use forecasts when planning the operation of other power plants and electricity flows on the grid.

The properties of VRE that are relevant for system integration are not new to power systems. This is the main reason why integrating low shares of VRE is usually not a challenge. Electricity demand itself is variable and all power plants may experience unexpected outages. When VRE contributes only a few percent to electricity generation, its variability and uncertainty is much smaller than that coming from electricity demand and other power plants. The influence of VRE usually becomes noticeable beyond annual shares of 2% to 3%. In order to reach higher shares, those resources that have been used to deal with variability and uncertainty from other sources can also be used to integrate VRE.

An assessment of case study regions with the revised IEA Flexibility Assessment Tool (FAST2) showed that annual VRE shares of 25% to 40% can be achieved from a technical perspective, assuming current levels of system flexibility. The analysis assumes that sufficient grid capacity is available inside the power system. According to the same analysis, this share can be increased further (reaching levels above 50% in very flexible systems), if a small amount of VRE curtailment is accepted to limit extreme variability events. However, mobilising system flexibility to its technical maximum can be considerably more expensive than least-cost system operation.

Integrating large shares of VRE cost-effectively calls for a system-wide transformation

The classic view sees VRE integration as adding wind and PV generation without considering all available options for system adaptation. This 'traditional' view may miss the point. Integration effects are determined by both VRE and other system components. Consequently, they can be reduced by interventions on either side. In short, integration of VRE is not simply about adding VRE to "business as usual," but transforming the system as a whole.

The cost of reaching high shares of VRE differs from system to system. Most importantly, costs depend on how well different components of the system fit together. Minimising total system costs at high shares of VRE requires a strategic approach to adapting and transforming the energy system as a whole.

Supposing that high shares of VRE are added overnight significantly increases total system costs. Using a test system, an extreme and purely hypothetical case was investigated. A share of 45% VRE in annual generation was added to the system overnight and only the operation of the remaining system was allowed to change (Legacy case, see Box ES.1). In this case, total system costs increase by as much as USD 33 per megawatt hour (/MWh) or about 40% (rising from USD 86/MWh to USD 119/MWh, Figure ES.1). This increase is the result of three principal drivers:

- additional cost of VRE deployment itself (which in this modelling exercise is assumed to remain similar to today's levels)
- additional grid costs associated with connecting distant VRE generation and grid reinforcements
- limited avoided costs in the residual system, because VRE can only bring operational savings in the form of fuel and emission cost reductions in the Legacy scenario.

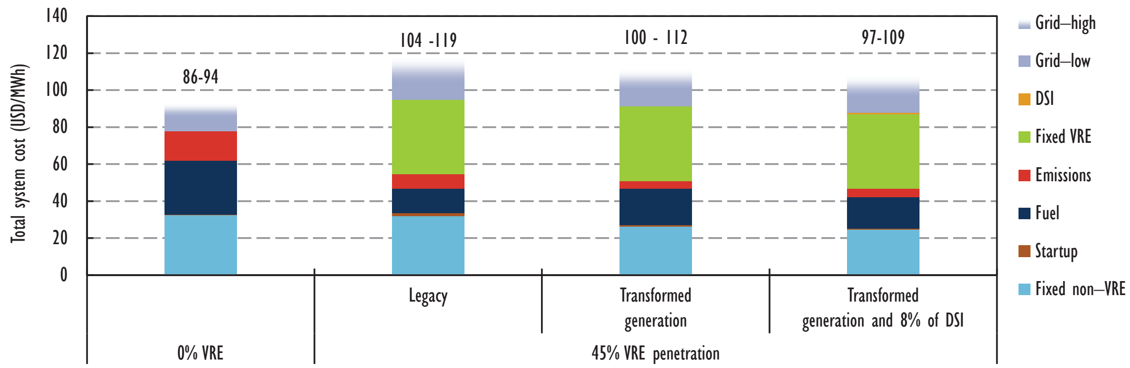
The additional costs of more flexible operation of existing power plants (more frequent start/stop, more dynamic changes in output) are not an important element in the increased costs.

A co-ordinated transformation of the entire system reduces additional costs. A different scenario of the test system considers a more transformative approach. The installed power plant mix is re-optimised in the presence of 45% VRE and additional flexibility options are deployed (Transformed case). Compared to the Legacy case, the power plant mix shows a structural shift:

- a strong decrease in the number of power plants that are designed to operate around the clock and that cannot change their output dynamically (referred to as baseload technologies)
- an increase in the number of flexible power plants that are designed for part-time operation (referred to as mid-merit and peaking generation).

In addition, a better strategy for managing grid infrastructure is assumed. In this case, total system costs increase only by USD 11/MWh. This is two-thirds less than in the Legacy scenario. At a share of 30% of VRE in power generation, the increase in total system costs stands at USD 6/MWh.

Figure ES.1 • Total system cost of a test system at different degrees of system transformation



Note: DSI = demand side integration

Key point • System transformation reduces total system cost at high shares of VRE.

In the long term, high shares of VRE may come at zero additional costs. In the modelling analysis, all cost assumptions are kept constant. However, future VRE generation costs are likely to be lower and the cost of CO_2 emissions higher.[2] This means that high shares of VRE may be achieved without increased total system costs compared to a system with 0% VRE. Costs may even be lower than in the absence of VRE deployment. However, achieving this requires a successful transformation of the system as a whole.

System transformation has three main pillars

Successful system transformation requires tackling three different areas:

- first, system-friendly VRE deployment
- second, improved system and market operation
- third, investment in additional flexible resources.

2. A cost decrease in the VRE mix between 30% and 40% would put total system costs in the Transformed case (including DSI) on a par with total system costs in the absence of VRE. In addition, according to IEA projections, CO_2 emission prices are likely to exceed the assumed level of USD 30 per tonne (/t). In the 450 Scenario (implying a 50% chance of meeting the 2°C target) of the *World Energy Outlook 2013*, CO_2 prices reach USD 70/t to USD 97/t in 2030 and USD 100 to USD 125/t in 2035 (year 2012 purchasing power parity).

1) Letting wind and sun play their part: system-friendly VRE deployment

The first pillar of system transformation is system friendly VRE deployment. The main intent behind system-friendly VRE deployment is minimising overall system costs, in contrast to minimising VRE generation costs alone.

VRE power plants can contribute to their own system integration. But they need to be asked and allowed to do so. The common view of integration sees wind power and solar PV generators as the "problem". The solution has to come from somewhere else. However, wind and solar PV power plants can facilitate their own system integration; they will need to do so to achieve system transformation cost-effectively. Five elements are relevant in this regard:

- **Timing.** VRE additions need to be aligned with the long-term development of the system as a whole. Experience shows that deployment of VRE capacity can outstrip development of suitable infrastructure, for example where wind power plants are completed before full grid connection is available. This calls for adopting an integrated approach to infrastructure planning.
- **Location and technology mix**. From a system perspective, cost-effectiveness is not just about choosing the cheapest technology or building VRE power plants where resources are best. In contrast, optimising the mix of VRE (and dispatchable renewable generation) can bring valuable synergies – for example, where sunny and windy periods are complementary (e.g. in Europe). In such a case, a mix of wind power and solar PV will tend to minimise total system costs, even if one option is more costly in terms of direct generation costs. Furthermore, by locating VRE power plants strategically, aggregate variability and costs for grid connection can be reduced. For example, roof-top PV systems deployed in a city can be more valuable from a system perspective than a distant large-scale PV plant, even if the direct generation costs of the roof-top systems are higher.
- **Technical capabilities**. Modern wind turbines and PV systems can provide a wide range of technical services needed to maintain short-term grid stability. Historically, such services have been provided by other power plants. While providing such services tends to increase VRE generation costs, it can be cost-effective from a system perspective, for example by reducing the need to curtail VRE generation.
- **System friendly power plant design**. VRE power plant design can be optimised from a system perspective, rather than simply aiming to maximise output at all times. For example, modern wind turbines can facilitate integration by harvesting relatively more energy at times of low wind speed (by using a larger rotor size). Design of PV systems can be similarly optimised by considering PV panel orientation and the ratio of module capacity to inverter capacity. This reduces variability and makes VRE generation more valuable.
- **Curtailment**. Occasionally reducing VRE generation below its maximum (ideally based on market prices) can provide a cost-competitive route to optimising overall system costs by avoiding situations of extreme variability or moments of very high VRE generation, which can be costly to accommodate.

2) Make better use of what you already have: improved system and market operations

The second pillar of system transformation is making better use of what you have. Best-practice system operations are a well-established, low-cost and no-regret option. Poor operation strategies – such as failure to use state of the art forecasts – become increasingly expensive at growing shares of VRE. Improving system operations has proven to be a major success factor in countries that have pioneered VRE integration (for example Spain, Denmark and Germany). 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. However, changing operational practices may face institutional resistance and thus delay despite their cost-effectiveness (such as system operators' reluctance to adopt innovative approaches for calculating reserve requirements).

Improving short-term power markets is a critical element for better operations. Market operations determine how demand and supply of electricity is matched. In order to deal efficiently with short-term variability and uncertainty, market operations need to facilitate trading as close as possible to real-time. In addition, power prices should be allowed to differ depending on location, in order to make the best use of available grid capacities. Analysis of case study market design shows recent improvements, such as the adoption of location specific (nodal) pricing by the Electric Reliability Council of Texas (ERCOT) in 2010, or the introduction of power delivery contracts in Germany that allow trading electricity in 15-minute blocks (rather than one full hour) and up to 45 minutes before real-time (rather than one day before real time).

System service markets need to price flexibility at its value. System services are required to maintain reliability. Analysis has found that system service markets, including those for short-term balancing of supply and demand (balancing markets), remain underdeveloped. In all reviewed markets, some system services are either not remunerated (for example in Italy, Iberia and ERCOT) or not priced efficiently (Germany and France). In addition, market functioning could be improved by moving trading on system service markets closer to real-time. Aligning the trade in system services and wholesale power markets helps to ensure efficient price signals on both markets and the pricing of flexibility at its true value.

Adopting improved operations is possible also in the absence of liberalised markets. Even where short-term power markets are not fully established (e.g. Japan), shifting operational decisions closer to real-time, making use of VRE production forecasts and better co-operation with neighbouring service areas can all improve system operations.

3) Long-term strategy: investment in additional flexible resources

Investments in additional system flexibility are required to integrate large VRE shares cost-effectively and in the long term. The point at which investment in additional flexible resources becomes necessary depends on the system context. Two different contexts can be distinguished:

- "stable" power systems are characterised by stagnating electricity demand and little or no short-term need to replace generation and grid infrastructure
- "dynamic" power systems have high growth rates in electricity demand and/or face significant investment requirements in the short term.

Many OECD power systems belong to the stable category, while emerging economies are typically dynamic systems.

Stable systems face different challenges and opportunities compared to dynamic systems. The opportunity is that stable systems can use what they have already (existing asset base) to a larger extent. Integration of higher VRE shares is possible by increasing flexibility via improved operations. The challenge is that the rapid addition of new VRE generation and a more flexible operating pattern can put existing generators under economic stress. While this does not pose any short-term threat to generation adequacy in stable systems, it can lead to stranded assets and raise concerns regarding the investment climate for future investments in flexible resources.

The rapid introduction of VRE into a stable power system (e.g. via support payments) tends to create a surplus of generation capacity. Such an oversupply (pre-existing capacity plus VRE additions) will tend to depress wholesale market prices, in particular if existing capacity is already underutilised. This can be observed in a number of European markets, such as Spain, Italy and Germany. Such low prices can, at some point, trigger the retirement of generation capacity, which can raise concerns about security of supply. However, in such situations depressed market prices correctly signal an oversupplied market. Market prices can be expected to revert to more sustainable levels by addressing a possible surplus and ensuring appropriate market design.

It is important to note that not all types of generation capacity are in-line with stringent decarbonisation targets. In particular, CO_2-intensive, technically and economically inflexible baseload power plants are inconsistent with such targets. A decarbonisation-conform response to deal with surplus supply under such circumstances would be to free the system of surplus capacity by ensuring corresponding market signals or by introducing appropriate regulation. If security of supply is a concern, power plants could be kept out of the market rather than being fully decommissioned.

The cost of rapid system-transformation in stable systems thus consists of two components:

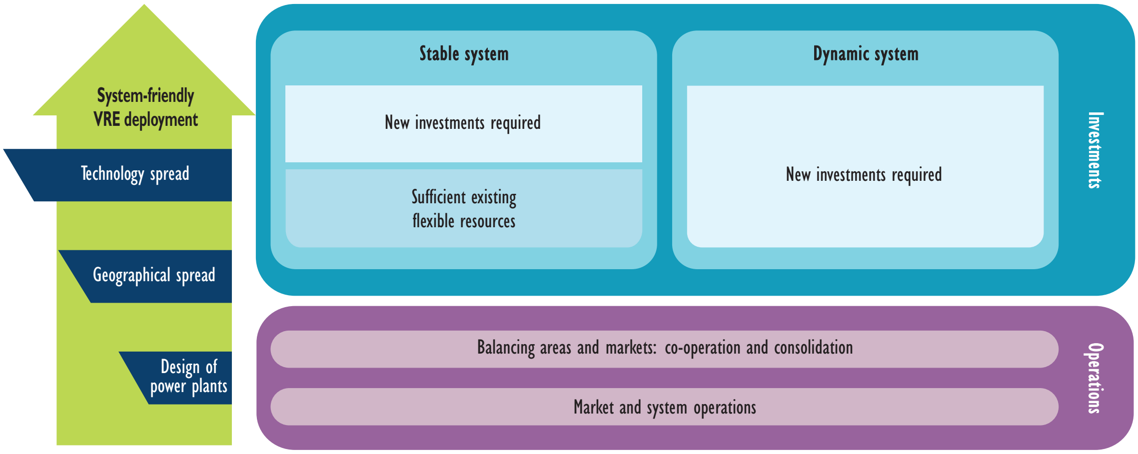
- the cost of new investments
- the cost associated with the reduced value of existing assets.

It is important to distinguish both sources of costs. Only the cost of new investments can be directly controlled by increased cost-effectiveness of VRE-build out. The second group of costs is determined by the overall speed of the transformation. In addition to the impact on total costs, there may be strong distributional effects under such circumstances, which tend to disfavour in particular incumbents.

Dynamic systems can leap-frog their stable counterparts, but only if investment strategies prioritise flexibility. In dynamic power systems, adding VRE does not put incumbents under the same level of economic stress, which can facilitate system transformation. In addition, the system can be built out taking into account VRE. For example, new grids can be planned and deployed in line with VRE targets, avoiding the need for later retrofits. However, these systems are unlikely to enjoy the flexibility contribution of existing assets (e.g. power plants, existing grids) to the same degree as stable systems. As a result, long-term investment strategies for additional system flexibility are likely to be relevant at earlier stages of VRE deployment. This raises the importance of planning tools that take into account VRE in longer-term system planning.

Despite the differences in timing, investment in additional flexibility is required at some point in both system contexts, if high shares of VRE are to be achieved (Figure ES.2).

Figure ES.2 • The three pillars of system transformation



Key point • System transformation has three main pillars: system friendly VRE deployment, improved operations and investments in additional flexibility.

A suite of flexibility options is needed to reach high shares of VRE

Flexibility comes in different forms. Using two different economic modelling tools, the **cost-benefit** of the different flexible resources was investigated. Costs are the additional costs for building and operating the flexible resources, while benefits are the saved investment and operating costs in other parts of the power system compared to a baseline case.

- **DSI** (in particular distributed thermal storage) showed significant promise, as suggested by its superior cost-benefit performance compared to other flexibility options. However, a degree of uncertainty exists regarding its full potential in real-life applications.
- Cost-benefit profiles of **storage** are less favourable, reflecting higher costs. Adding pump-back functionality to existing reservoir hydro plants showed the most favourable cost-benefit ratio. However, the potential use and storage technology cost reductions should remain important areas for investigation.
- **Interconnection** allows a more efficient use of distributed flexibility options and generates synergies with storage and DSI. Modelling for the North West Europe case study showed favourable cost-benefit of significantly increased interconnection.
- Cost-benefit analysis of retrofitting existing **power plants** to increase flexibility shows a wide range of outcomes, driven by project-specific costs.

The cost-effectiveness of distributed thermal storage points to the importance of coupling the electricity sector with other sectors of the energy system to achieve cost-effective VRE integration. In addition to coupling the heat and electricity sectors, a more widespread adoption of electro-mobility can open an additional avenue for energy sector coupling.

Neither opting for the cheapest option nor pursuing only the option with the best cost-benefit performance will suffice. While the different resources can substitute for each other under many circumstances, certain integration issues may only be addressed by some of them. For example:

- transmission infrastructure is the only option able to connect distant VRE resources
- only distributed options such as customer-side demand response or small scale storage can deal with some of the impacts related to high shares of distributed generation
- flexible hydro plants can step in when VRE generation is not available, but flexible generation cannot avoid VRE curtailment once net load becomes negative while storage can
- VRE curtailment can help to reduce situations of VRE surplus, but it does not help resolving situations of very low wind power and solar PV output.

While the above list provides only a few examples, they make clear that a suite of flexibility options is needed to meet flexibility requirements for successful VRE integration.

Conclusions and recommendations

Detailed recommendations relating to the above findings can be found at the end of this book in Chapter 9. On a high level, the recommendations can be grouped according to the context of VRE integration:

Countries beginning to deploy VRE power plants should implement well-established best practices to avoid integration challenges, at shares of up to 5% to 10% of annual generation. This means avoiding uncontrolled local "hot spots", ensuring that VRE power plants have sufficient technical capabilities and make effective use of short-term VRE forecasts.

All countries where VRE is becoming a mainstream part of the electricity mix should make better use of existing flexibility by optimising system and market operations. Moreover, VRE power plants need to be allowed to actively participate in their system integration by implementing system friendly VRE deployment strategies.

Countries with stable power systems should seek to maximise the contribution from existing flexible assets for system transformation. They may consider accelerating system transformation by decommissioning or mothballing inflexible capacities that are surplus to system needs. Policy makers and industry will need to carefully manage the impacts of related effects, including stranded assets. However, they need to maintain a clear focus on delivering the investments needed to address long-term climate change and energy security imperatives.

Countries with dynamic power systems should approach system transformation as a question of holistic, long-term system development from the onset. This requires the use of planning tools and strategies that appropriately represent VRE's potential for a cost-effective, low-carbon energy system.

Future work

A number of questions have arisen during the course of this project that merit further analysis. First, the specific circumstances of dynamic power systems warrant further investigation, specifically regarding appropriate strategies for achieving ambitious VRE targets cost-effectively in these systems.

Second, further investigation into options for system-friendly VRE deployment and the concrete design of system-friendly VRE support policies are ready for further analysis.

Third, while analysis has shown significant room to improve short-term markets, there remains the more fundamental issue of how to achieve a market design consistent with long-term decarbonisation, in particular in the context of stable power systems. On the one hand, VRE generators need to be exposed to price signals that reflect the different value of electricity (depending on the time and location of generation), so as to facilitate system integration. On the other hand, VRE requires capital-intensive technology and, as such, is highly sensitive to investment risk, a risk that is increased by short-term price exposure. An appropriate market design will need to strike a delicate balance between these two objectives.

Box ES.1 • Modelling tools used for this publication

The IEA has refined its Flexibility Assessment Tool (FAST). The revised tool (FAST2) provides a snapshot of what shares of VRE generation can be integrated into power systems from a purely technical perspective and given existing flexible resources by assessing system flexibility on a timescale of 1 to 24 hours.

In addition to technical analysis, two economic modelling tools were used for this publication.

The Investment Model for Renewable Energy Systems (IMRES) was used to analyse a generic island test system of a size equivalent to Germany at 30% to 45% of annual VRE generation. IMRES optimises the investment in non-VRE power plants and the hourly operation of the power system. Scenarios were designed to capture different degrees of system adaptation. In the Legacy scenario, VRE is added to an existing power plant mix "overnight". Consequently, system adaptation can only be operational. In the Transformed scenario, the power plant mix is optimised in a comprehensive way, taking into account generation from VRE and the contribution from flexible resources. In both cases the model calculates the least-cost electricity generation mix.

As part of a co-operation with Pöyry Management Consulting (UK) Ltd (Pöyry), a cost-benefit analysis for different flexibility options for one of the case study regions (North West Europe) was performed using Pöyry's hourly BID3 power system investment and operation model. The analysis is based on a high-VRE adaptation of the Pöyry central scenario for 2030, assuming an increased level of wind power and solar PV generation, leading to a total share of 27% VRE in power generation.