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Accelerating the Global Clean Energy Transition

Next Generation Wind and Solar Power

From cost to value

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Summary for policy makers

Highlights

- Wind and solar photovoltaics (PV) are currently the fastest-growing sources of electricity globally. A "next generation" phase of deployment is emerging, in which wind and solar PV are technologically mature and economically affordable.
- The success of variable renewable energy (VRE) is also bringing new challenges to the fore. Electricity generation from both technologies is constrained by the varying availability of wind and sunshine. This can make it difficult to maintain the necessary balance between electricity supply and consumption at all times.
- As long as the contribution of wind and solar PV to the annual electricity mix does not exceed a few percentage points, their integration poses few challenges. However, as VRE enters its next generation of deployment, the issue of system and market integration becomes a critical priority for renewables policy and energy policy more broadly.
- A comprehensive and systemic approach is the appropriate answer to system integration, best captured by the notion of transformation of the overall power system. This requires strategic action in three areas:
    - System-friendly deployment, which aims to maximise the net benefit of wind and solar power for the entire system.
    - Improved operating strategies, such as advanced renewable energy forecasting and enhanced scheduling of power plants.
    - Investment in additional flexible resources, comprising demand-side resources, electricity storage, grid infrastructure and flexible generation.
- Wind and solar power can facilitate their own integration by means of system-friendly deployment strategies. Six areas are most important:
    - System service capabilities. Technological advances have greatly improved the degree to which VRE output can be forecasted and controlled in real time. With the right framework conditions in place, VRE can help to balance supply and demand despite its dependence on the availability of wind and sunlight.
    - Location of deployment. With the cost of solar PV and (onshore) wind power falling rapidly, deployment is becoming economical even in lower resource conditions. This gives a wider choice for developing power plants, allowing electricity to be produced closer to demand.
    - Technology mix. The output of wind and solar power is complementary in many regions of the world. VRE can be complementary to other renewable resources, such as hydropower. Deploying a mix of technologies can thus bring valuable synergies.
    - Local integration with other resources. Distributed deployment of VRE can open the opportunity to integrate generation resource directly with other flexibility options to form an integrated package. For example, solar PV systems can be combined with demand-side response or storage resources to achieve a better match with local demand and thus reduce the need for investments in distribution network infrastructure.
    - Economic design criteria. The design of wind and solar plants can be optimised to facilitate integration. For example, a detailed modelling study that was carried out as part of this project highlighted that wind turbines with larger blades compared to generator capacity produce electricity in a less variable fashion, which reduces integration challenges.

  - Integrated planning, monitoring and revision. The relative costs of VRE and other generation technologies, as well as the cost of various flexible resources, are changing dynamically. Consequently, the optimal mix of flexible resources as well as system-friendly deployment strategies will change over time, prompting the need to adjust strategies.

- Unlocking the contribution of system-friendly deployment calls for a paradigm shift in the economic assessment of wind and solar power. The traditional focus on the levelised cost of electricity (LCOE) is no longer sufficient. Next-generation approaches need to factor in the system value of electricity from wind and solar power.
- System value (SV) is defined as the overall benefit arising from the addition of a wind or solar power generation source to the power system; it is determined by the interplay of positives and negatives. Positive effects can include reduced fuel costs, reduced carbon dioxide (CO_2) and other pollutant emissions costs, reduced need for other generation capacity and possibly grid infrastructure, and reduced losses. On the negative side are increases in some costs, such as higher costs of cycling conventional power plant and for additional grid infrastructure, as well as curtailment of VRE output due to system constraints.
- SV provides crucial information above and beyond generation costs; in cases where SV is higher than the generation cost, additional VRE capacity will help to reduce the total cost of the power system. As the share of VRE generation increases, the variability of VRE generation and other adverse effects can lead to a drop in SV.
- It is important to distinguish the short-term and long-term SV of VRE. In the short term, SV is strongly influenced by existing infrastructure and the current needs of the power system. For example, if new generation is needed to meet growing demand or retirements – as in South Africa – SV will tend to be higher. By contrast, the presence of large amounts of relatively inflexible generation capacity – as is the case in Germany – can lead to a more rapid SV decline in the short term. For long-term energy strategies, the long-term system value is most relevant. This accounts for both fuel savings and capital investments.
- In order to attract investments in VRE at least cost, policy mechanisms that provide sufficient long-term revenue certainty to VRE investors are needed. In turn, such mechanisms need to be designed in a way that accounts for the difference in SV of different generation technologies. Existing policy practice already provides a number of ways in which the value of VRE can be boosted by facilitating system-friendly deployment strategies (Table 1).

Table 1 • Overview of system-friendly policy tools and impacts on System Value (SV)

System-friendly strategy	Policy tool	Country example	Impact on SV
System service capabilities	Grid codes that require advanced capabilities Advanced design of system services markets	Participation of wind in balancing the grid in Denmark and Spain	By providing system services from VRE, more thermal generation can be turned off during times of abundance, which "makes room" for VRE and increases SV
Location of deployment	Integrated planning of grid infrastructure and generation	Integrated planning in Brazil	Siting VRE generation in locations where electricity is needed and infrastructure available boosts SV
	Locational signals in remuneration schemes	Mexican auction system; differentiation of FIT levels in China	
Technology mix	Technology-specific auctions that reflect the value of each technology as determined in long-term planning	South Africa	Deploying a mix of technologies can lead to a more stable VRE profile and reduce periods of VRE excess, hence boosting SV
	SV reflected in multi-technology auctions	Mexico	

Economic design criteria	Partial exposure to market prices via premium systems	German and Danish market premium systems, US Tax Credits	Investors are encouraged to choose a technology that generates during times of high electricity prices
Integrated planning, monitoring and revision	An integrated long-term plan for VRE and flexible resources, updated regularly	Integrated system planning in Denmark	Aligned deployment of VRE and flexible resources enhances SV; regular update of the long-term path allows reaping the full benefit of technology innovation

Note: FIT = feed-in tariff.

This document

This document summarises the study *Next-Generation Wind and Solar Power,* which was carried out by the International Energy Agency (IEA) as part of its Grid Integration of Variable Renewables (GIVAR) programme. It contributes to the work of the Multilateral Wind and Solar Working Group as part of the Clean Energy Ministerial. Its main focus is the contribution that next-generation wind and solar power technology can make to transforming power systems around the globe when combined with advanced, system-friendly deployment strategies. The main purpose of system-friendly deployment is to maximise overall value to the power and wider energy system – in contrast to minimising the generation cost of wind and solar power in isolation. This summary places such strategies in the context of integrating renewables in a wider system, and presents policy makers with concrete recommendations for unlocking this contribution. This document also features brief summaries of country case studies, which were carried out as part of *Next-Generation Wind and Solar Power.* The main project report is scheduled for release in July 2016.

Next-generation wind and solar power

Wind and solar PV are currently the fastest-growing sources of electricity globally. In 2015, their additional annual generation met more than 90% of incremental demand for electricity. Between 2008 and 2015, the average cost of land-based wind decreased by 35% and that of solar PV by almost 80% (Figure 1).

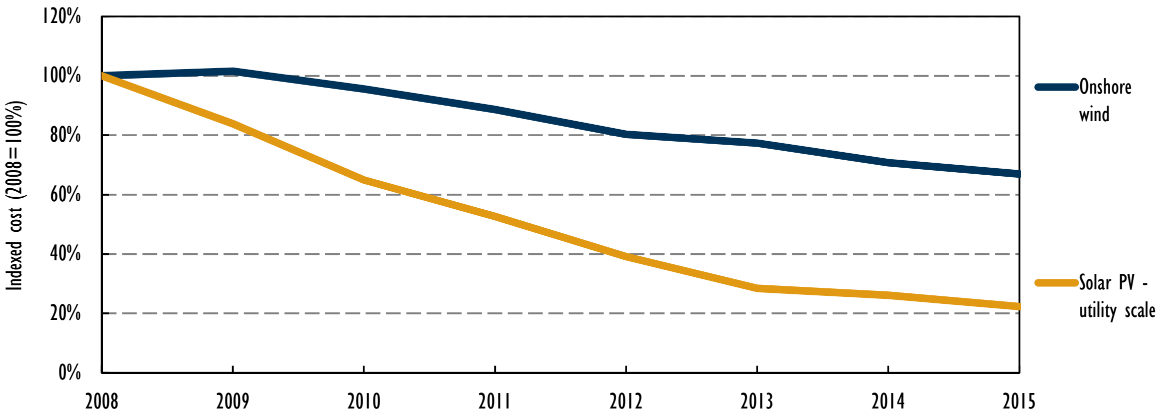
Their deployment is moving on from a phase where the main priorities were technology learning and cost reduction. Today, increasing evidence of a new phase of deployment can be encapsulated by the notion of next-generation wind and solar power; in this phase, wind and solar PV are technologically mature and economically affordable.

Technological maturity and lower costs make wind and solar power an increasingly attractive option for policy makers seeking to meet energy policy objectives, such as improving energy security by diversifying supply, reducing local pollution and reducing CO_2 emissions. Wind and solar power are expected to make a critical contribution to meeting the ambition of the Paris Agreement. Their contribution to power systems around the globe is rapidly moving from marginal to mainstream, including in emerging and developing countries.

The success of these sources of VRE is also bringing new challenges to the fore. Electricity generation from both technologies is constrained by the varying availability of wind and sunshine. This can make it challenging to maintain the balance between electricity supply and consumption at all times, a requirement of all power supply networks.

As long as the contribution of wind and solar PV to the electricity mix does not exceed a few percentage points, significant evidence from across several countries demonstrates that their integration poses few challenges (IEA, 2014; IEA, 2015b). However, as sources of VRE enter their next phase of deployment, the issue of system and market integration becomes a critical priority for renewables policy, and energy policy more broadly. Consequently, next-generation wind and solar power – and the policy, market and regulatory frameworks that accompany them – must deliver cost-effective system and market integration.

Figure 1 • Indexed cost of onshore wind and utility-scale PV



Note: Costs refer to global average of levelised cost of electricity (LCOE) with country specific assumptions on investment costs (declining over time) and cost of financing (fixed over time). Different costs per country are averaged weighted by annual capacity additions.

Key message • The falling cost of wind and solar PV is opening up new opportunities for cost-effective deployment.

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; these include the constraints that weather and daylight patterns have on where and when they can generate. It is also relevant that VRE power plants are often smaller in scale than conventional generation and deployed in a more dispersed fashion. Finally, VRE connects to the grid using power converter technologies, which are different from conventional generators and lead to important integration effects.
- Second, the flexibility of the power system into which VRE is integrated, the characteristics of the system's electricity demand and climatic conditions. For example it is easier to integrate large shares of VRE where there is a good match with demand, and solar PV show less seasonal fluctuation in countries that have constant daylight hours during the entire year. Flexibility is defined as the ability of a power system to respond to rapid swings in the supply-demand balance, expected or otherwise. It can be provided by four fundamental resources: demand-side resources, electricity storage, grid infrastructure and flexible generation.

Policy, market and regulatory frameworks have a critical impact on the way in which these two factors interact. The frameworks determine how the power system is actually operated and hence whether what is technically possible is both practically achievable and economically attractive for stakeholders in the electricity system (Figure 2).

Figure 2 • The integration challenge

Key message • The integration challenge is shaped by the interaction of VRE properties, the flexibility of the overall power system and the policy, market and regulatory frameworks that govern this interaction.

The interaction between the two factors differs from system to system as a result of technical variation as well as the influence of policy and market frameworks. However, a growing body of experience across a diverse range of power systems shows a common pattern of challenges. This allows for the development of best practice principles for policy and market frameworks – principles that can be applied in a wide range of circumstances.

In this context, advanced VRE technologies and deployment strategies can make a valuable contribution. Indeed, a VRE power plant is not simply a wind turbine or a collection of solar panels. Modern VRE plants connect to the grid using electronic power converters, so-called inverters. Simply put, these can be programmed like a computer to allow the way in which VRE power plants behave on the power grid to be controlled.

From integration to transformation

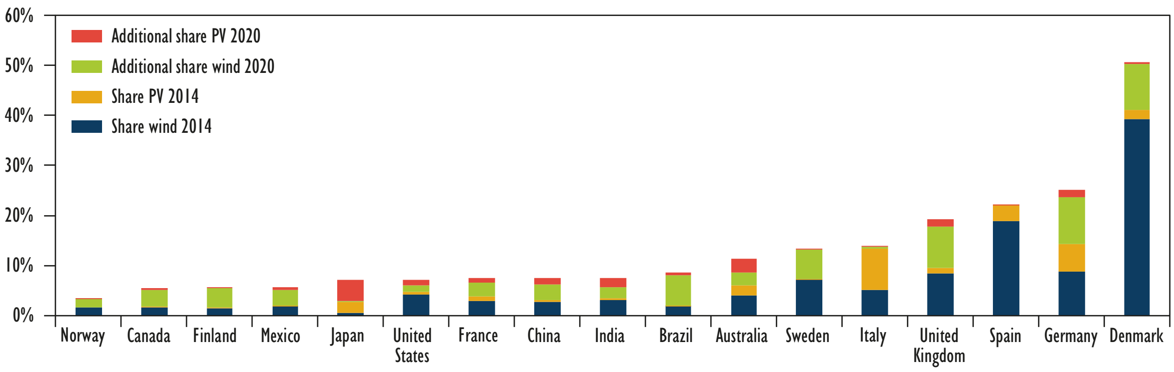
Any increase in the share of VRE beyond a few percentage points can affect the power system at all timescales, ranging from several years (system planning) to days, hours and minutes (system operations) and even seconds (system stability). The effects of high shares of VRE can also be seen at all geographic scales, from system-wide impacts (affecting entire continental power grids) all the way down to individual lines of the distribution grid. High shares of VRE, where these challenges typically become apparent, are increasingly common in a growing number of countries (Figure 3). During certain periods, VRE can account for a much larger share in power generation than annual averages suggest. For example, the share of Spanish wind power in the country's electricity generation exceeded 70% at one point on 21 November 2015 (REE, 2016). During 2015, wind power production in Western Denmark exceeded demand for more than 1 450 hours of the year. In September 2015 the Danish power system was operated without any large-scale plants operating in the country (Energinet.dk, 2016). Finally, Germany registered a recent record in wind and solar PV penetration, when the output of these sources exceeded 90% of the country's electricity demand at one point on 8 May 2016 (Agora Energiewende, 2016).

Given the broad impacts that high VRE shares can have, a comprehensive and systemic approach is the appropriate answer to system integration challenges. As identified by IEA analysis, a co-ordinated approach can significantly reduce integration costs and ensure electricity security (IEA, 2014; IEA, 2016a). Achieving such a transformation requires strategic action in three main areas:

- System-friendly deployment to maximise the net benefit of wind and solar power for the entire power system. Such an approach leads to different deployment priorities as compared to a focus on generation costs alone. This component is explored in more detail in this summary.

- Improved operating strategies as a powerful tool to maximise the contribution of existing assets and ensure security of supply. These include advanced renewable energy forecasting and enhanced scheduling of power plants. Where liberalised wholesale markets are in place, this may require an upgrade of market rules and products. In heavily regulated systems, action will need to target operational protocols and key performance indicators (KPIs) for system and power plant operators.
- Investment in additional flexible resources. Even in concert, improved operations and system-friendly VRE deployment practices will be insufficient to manage high shares of VRE in the long term. The point at which investment in additional flexible resources becomes necessary depends on the system context. In all systems, however, an increase in flexible resources will become a cost-effective integration strategy at some point, requiring additional investment.

Figure 3 • Share of VRE generation in 2014 and 2020 for selected countries



Key message • Growing shares of wind and solar PV make grid integration issues a priority.

Mobilising the contribution of each of the three areas requires putting in place appropriate market, policy and regulatory frameworks. It frequently also requires changing the roles of institutions in the power system, which can require time and resources to achieve. In a nutshell, actions from the last two areas aim to make the overall power system more suitable for VRE generation, while the first area encompasses all those measures that make VRE more suitable for the existing power system.

To implement this strategy, actions across the entire power system are likely to be needed. For example, increasing the flexibility of the demand side (beyond large industrial consumers) is likely to require changes in the regulation of distribution networks, analysis of the acceptability of different business models to consumers, adaptation of wholesale market design, etc. By contrast, a common approach to integrating VRE views its place in the power system in isolation. This leads to an emphasis on solutions that first make VRE "more like traditional generation", for example by adding storage or dedicated power plants to balance VRE. As previous IEA analysis has demonstrated (IEA, 2014), such an isolated approach leads to significantly higher costs than a more system-wide strategy. Such an improved strategy will reveal that those power plants that are currently used to balance the variability of power demand can be put to work to balance the combined variability of VRE supply and electricity demand.

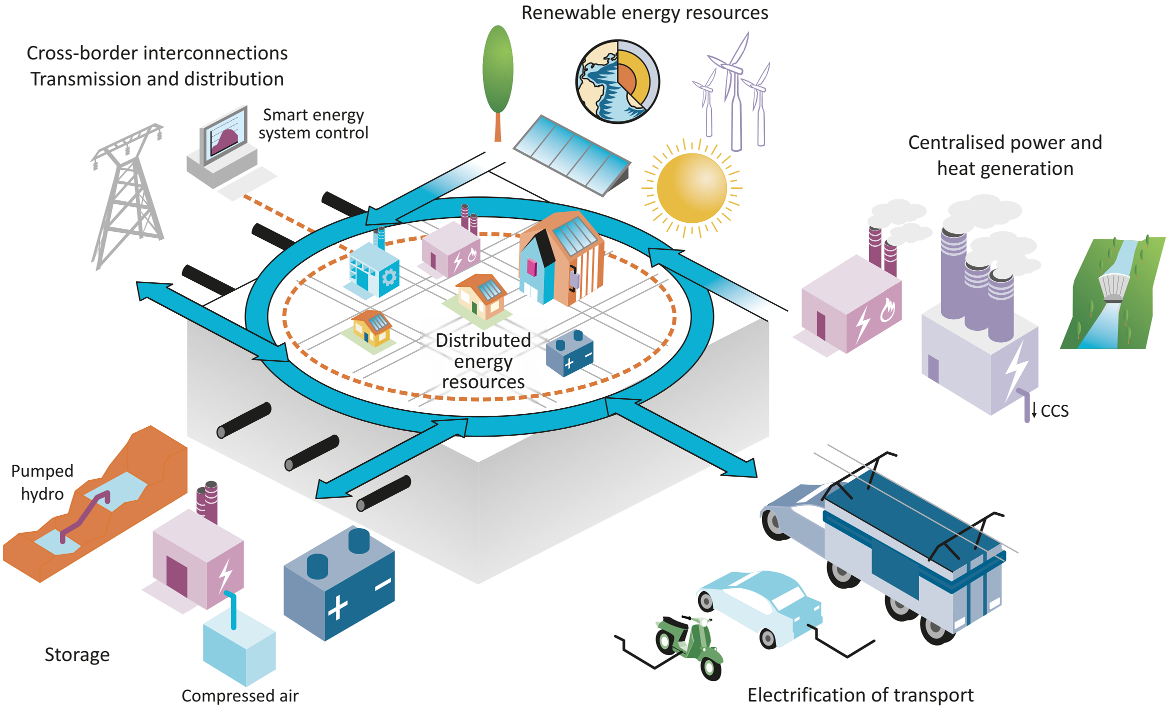
Given the need for a system-wide strategy, the traditional notion of integrating renewable energy into an otherwise unchanged power system can fall short of what is needed; it is not VRE that needs to adapt to what is already there for historical reasons. Successful integration of a high share of VRE requires finding a new optimum across all power system assets. In many cases, such an approach will lead beyond the confines of the current power system, calling for the electrification of end-use sectors such as heating and transport.

The need for a comprehensive approach is better captured by the notion of transformation of the overall power system: *Successful integration means system transformation*.

A paradigm shift for low- and medium-voltage grids

The greater uptake of distributed VRE shifts the historic balance of supply and demand in the electricity network, and calls for a revision of the institutional arrangements guiding low- and medium-voltage grids. The rise of distributed generation assets[1] – dominated by the rapid uptake of solar PV – translates into growing complexity of power flows within the distribution grid (Figure 4). This provokes the need for innovative approaches to the planning and operation of low- and medium-voltage grids, with technical, economic and institutional implications.

Figure 4 • Smart distribution grids at the heart of a transformed power system



Key point • Power system transformation implies a paradigm shift for low- and medium-voltage grids – away from passive distribution of electricity and towards becoming a critical hub for electricity and data.

On the technical side, more dynamic and bi-directional flows of electricity (from lower to higher voltage levels and vice versa) require reinforced monitoring and control capabilities as well as upgrades to infrastructure. Moreover, planning standards need upgrading to manage the uptake of large shares of distributed resources. In this context, next-generation VRE technology – such as advanced inverters – can offer technical capabilities to support and sustain safe and reliable

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[1] Distributed electricity resources are typically modular and/or small scale, connected to a local network, providing energy-related services with the capability of supplying energy or system services.

operations in local power grids, while also reducing energy losses in the overall power system. For example, under a business-as-usual approach, a high local penetration of distributed solar PV can create challenges related to maintaining voltage at appropriate levels. These challenges can be mitigated by using solar PV inverters themselves to control voltage – a next-generation approach to deployment. To unlock this contribution, however, the technical requirements for VRE (grid codes) need to ensure that inverters are technically capable and correctly programmed.

On the economic side, there is a need to reform electricity pricing. Where citizens install their own solar PV systems behind the electricity meter, the design of retail tariffs becomes a critical lever to guide investment in and operation of distributed resources.

In the past, consumers did not have a strong incentive to substitute grid-based electricity by generating their own power. The rise of distributed solar PV, combined with cost reductions in smart-home and battery technology, has begun to change this. However, the design of electricity tariffs is often based on the assumption that consumers have no alternative to the grid for obtaining their electricity. For example, the cost of the electricity network itself is frequently recovered via per-unit charges on electricity. In a situation where customers use their own solar PV generation to displace electricity from the grid, such pricing arrangements may be rendered dysfunctional.

Tariff design will need to evolve, reflecting the fact that consumers of electricity can now also become producers, and consequently requiring a fair allocation of grid costs across all consumers. This may entail a departure from the current model of recovering the cost of distribution grid infrastructure. For example, the state of New York is currently comprehensively reviewing the design of electricity tariffs (State of New York, 2016). As part of the reform, it is proposed to introduce a new pricing element, a so-called demand charge. Customers who use electricity when the grid is most strained will need to pay more, while those customers that avoid consumption during peak times will pay less.

Reform will need to take electricity tariffs beyond simply pricing consumption. Distributed solar PV systems, combined with smart-home systems and electric batteries, are valuable resources for the entire power system. However, a way is needed to allow these resources to offer their services and receive appropriate compensation. For example, distributed resources can contribute to the provision of system services (Box 1). But unlocking this contribution requires commercial arrangements to appropriately remunerate resources.

Box 1 • What are system services?

Reliable operation of the power system critically depends on a number of system services, which contribute to maintaining system frequency and voltage levels. Special capabilities may also be required when restarting the system after a large-scale blackout (so-called black-start capabilities). Some of these services are procured by system operators or traded on dedicated markets. Others are mandated via grid codes (known in North America as interconnection standards), which set out technical requirements for any entity that connects to the grid. Different systems may obtain the same service in different ways, e.g. some will mandate it in the grid code, while others use a procurement or market mechanism.

Traditionally, system services markets have been controlled by transmission system operators (TSOs) and only a small minority of these allow for the participation of distributed VRE assets. Looking ahead, making optimal use of the grid support services offered by distributed VRE may require that these services are procured and co-ordinated in a more localised fashion.

Finally, participation in distribution grids is bound to change. For example, electricity suppliers will increasingly compete with aggregators of system services for access to customers. Similarly, a strong case can be made for establishing transparent power markets, known as market platforms, governed by independent institutions that have the responsibility to operate them fairly.

System value, or the need to go beyond costs

Achieving successful system transformation requires the co-ordination of numerous stakeholders in the electricity system. It requires a vast number of decisions about investment in generation infrastructure and flexible resources. Consequently, the conceptual framework for assessing the economics of the various options is of critical importance.

The generation cost of various technology options is most commonly expressed in energy terms and labelled the levelised cost of electricity (LCOE). LCOE, as it is commonly defined, is a measure of cost for a particular generating technology at the level of a power plant. It is calculated by summing all plant-level costs (investment, fuel, emissions, operation and maintenance etc.) and dividing them by the amount of electricity the plant will produce. Costs that are incurred at different points in time (costs of building the plant, operational costs) are made comparable by "levelising" them over the economic lifetime of the plant – hence the name.

The LCOE of wind power and solar PV has seen significant reductions over the past two decades (IEA, 2015a; IEA, 2015b). In a growing number of cases, the LCOE of wind power and solar PV is close to, or even below, the LCOE of fossil or nuclear options. For example, the lowest currently reported costs for land-based wind are USD 30-35 per megawatt hour (MWh) (Morocco) and for solar PV are USD 49/MWh (Peru).

However, LCOE as a measure is blind to the when, where and how of power generation. The when refers to the temporal profile of power generation that can be achieved, the where refers to the location of power plant, and the how refers to the system implications that the type of generation technology may have. Whenever technologies differ in the when, where and how of their generation, a comparison based on LCOE is no longer sufficient and can be misleading. A comparison based only on LCOE implicitly assumes that the electricity generated from different sources has the same value.

The value of electricity depends on when and where it is generated, particularly in a power system with a high share of VRE. During certain times, an abundance of generation can coincide with relatively low demand – in such cases the value of electricity will be low. Conversely, when little generation is available and demand is high, the value of electricity will be high. Considering the value of electricity for the overall system opens a new perspective on the challenge of VRE integration and power system transformation.

System value (SV) is defined as the net benefit arising from the addition of a wind or solar power plant; it is determined by the interplay of positive and negative effects arising from the addition.

On the positive side are cost reductions: these include reduced fuel costs, reduced CO_2 and other pollutant emission costs, reduced need for other generation capacity, and possibly reduced need for grid usage and associated losses. On the negative side are increases in certain costs, such as higher costs of cycling conventional power plant and for additional grid infrastructure.

SV complements the information provided by classical metrics of generation costs, such as the LCOE. It captures the effects that additional generation has on the remaining power system. Simply put: LCOE informs how much one has to pay for a certain technology, while the SV of that technology captures the net effects on the system (Figure 5).

A high SV indicates a good match between what a technology provides and what the power system needs. For example, when a new VRE power plant generates during times of high electricity prices, this favourable situation will be reflected in a high SV of this power plant.

The SV perspective provides crucial information above and beyond generation costs. Indeed, a comparison between the LCOE and the SV yields critical information for policy makers and other power system stakeholders: where the SV of VRE is higher than its generation cost, additional VRE capacity will help to reduce the total cost of the power system.

Figure 5 • Illustration of LCOE and SV

LCOE

- Installation costs
- Operation and maintenance costs (fuel, emissions if applicable)
- Financing costs
- …

SV

Positive

- Reduced fuel and emission costs
- Reduced costs/need for other generation capacity
- Possibly reduced grid costs and losses

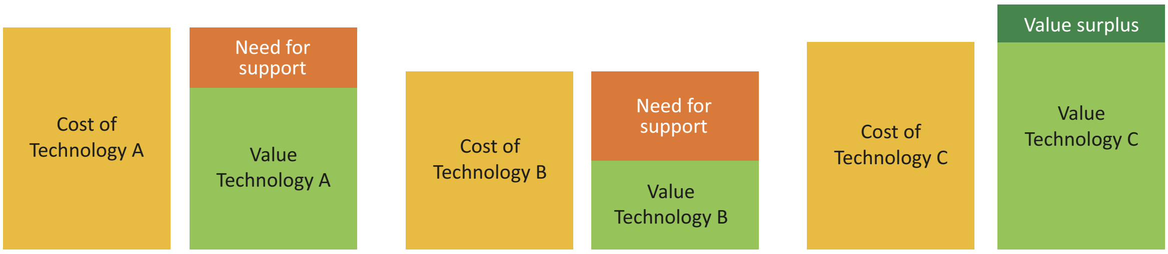
Negative

- Increased wear and tear for other power plants
- Additional costs for grid infrastructure
- Reduced utilisation rates of non-VRE assets
- Curtailment

Key point • Levelised cost of electricity (LCOE) and System Value (SV) provide complementary information. LCOE focuses on the level of the individual power plant, SV captures system level effects.

Comparing the SV of different technologies – and not just their LCOE – provides a more complete picture and a sound basis for policy design (Figure 6). In the example below, Technology B has the lowest cost, but also a very low value – hence it would require the most support to trigger deployment. By comparison, Technology C has an intermediate cost but a very high SV – its deployment would not require any support on the basis that an appropriate market design was in place.

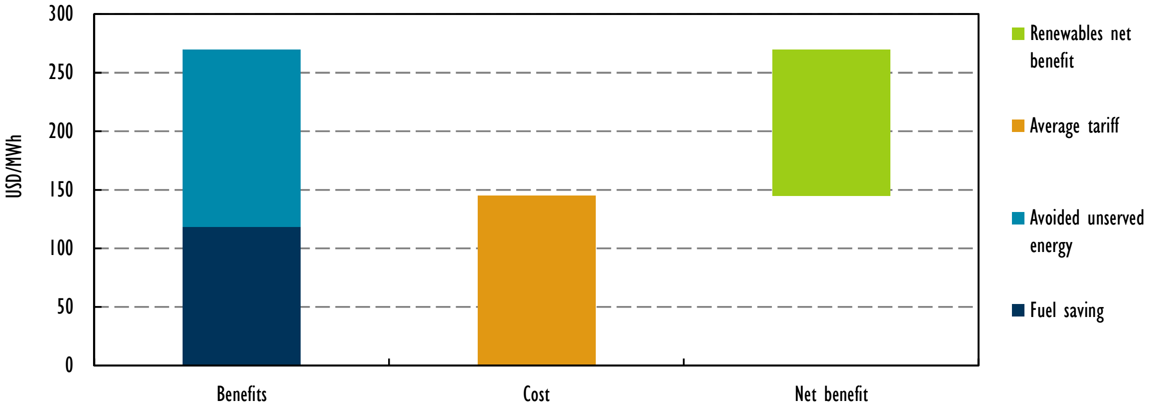
Figure 6 • The link between VRE cost, SV and competitiveness



Key point • Given well-designed markets, the relationship between cost and SV determines the need for financial support or the degree of competitiveness of a technology.

The power system of South Africa provides an effective example of a situation where VRE has a high SV. South Africa combines a tight supply situation and a good match of wind and solar PV generation with load. Generation costs have also been falling thanks to a well-designed auctioning mechanism. This suggests that the SV of VRE exceeds its LCOE. Indeed, a recent analysis carried out by the Council for Scientific and Industrial Research (CSIR 2015) has found that for currently operating VRE assets, the savings from avoided fuel and lost load more than compensate for the cost of wind and solar power (Figure 7).

Figure 7 • Illustration of SV and cost for wind and solar power in South Africa, H1 2015



Source: CSIR (2015), "Financial benefits of renewables in South Africa in 2015", CSIR Energy Centre.

Key point • The system value of the current mix of wind and solar power in South Africa is higher than its generation cost. This means VRE deployment reduces the overall cost of the power system.

Conversely, when additional VRE generates power at times and locations when it is not optimal for the overall system, this will yield a lower SV. A low SV can signal a misalignment between VRE generation and the rest of the power system. It is important to note that this is the result of an interaction between the system and VRE rather than a property of VRE per se.

As the share of VRE generation increases in power systems, the variability of VRE generation and other adverse effects can lead to a drop in the overall SV of VRE.

The example of Germany illustrates how rising shares can challenge the value of VRE generation. It is possible to analyse part of the SV of a generation resource by looking at its value on the electricity market. While such an analysis may not reflect all benefits of VRE, the overall trend of market revenues can inform about the evolution of SV at growing shares.

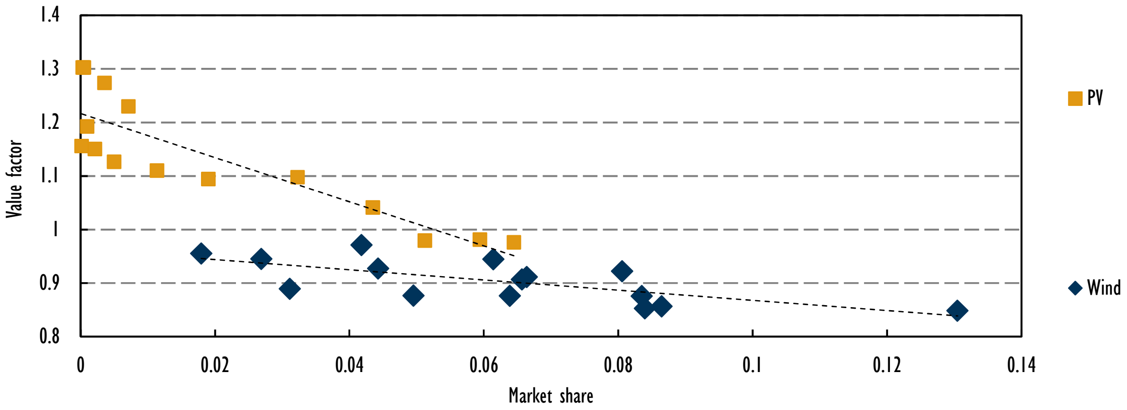
Liberalised short-term electricity markets have a different wholesale price for each hour of the day. The price in each hour is determined by the short-run (fuel) costs of the most expensive generator. When VRE generation is present during times of high demand, it will thus have a high value on the electricity market. It is convenient to express the wholesale market value as a so-called value factor. In short, a value factor below one means that electricity from a certain technology makes lower-than-average revenues selling electricity to the market, while a factor above one signals a high value.

At the onset of deployment, solar PV often generates at times of fairly high demand. This translates into a high market value as long as its share is low. However, as more PV capacity is added to the system, all PV systems will tend to generate at the same time. This means that when PV capacity is generating, increasingly there is an abundance of electricity. This is also known as the merit-order effect (Box 2). The merit-order effect leads to lower prices and, in turn, a lower market value. This effect is similar for wind, though not as pronounced (Figure 8). The exact magnitude of this decline is highly system specific. The principle itself, however, is universal: the economic challenge of system integration is reflected in the declining value of wind and solar power.

Box 2 • The merit-order effect and VRE

Once built, wind power and solar PV provide electricity practically for free. The low short-run costs imply that once VRE generation is built, it is likely to be among the first technologies to be called upon to generate. This is expressed by stating that VRE comes first in the merit order. The merit order ranks the power plants according to their short-run costs. It is often used to determine which units will be used to supply expected demand, with the cheapest units being used first. The availability of additional low-cost VRE power production pushes the offer curve to the right (pushes plants with higher marginal costs out of the market), thus displacing the (most expensive) generators and reducing the resulting market price for electricity. This will happen when a sufficient amount of VRE generation capacity is installed in the system, and when it is windy and/or sunny. This effect tends to be more pronounced the steeper the merit-order curve.

Figure 8 • Market value factor of wind and solar PV as a function of their market share in Germany, 2001-15



Notes: Each point corresponds to one year; the value factor is defined as the ratio between the electricity market revenue of the average wind/solar generator and the average electricity price; a value factor above one signals above-average market revenues; a factor below 1 signals below-average market revenues.

Source: Updated from Hirth (2013), "The market value of variable renewables: The effect of solar wind power variability on their relative price", *Energy Economics*, Vol. 538, Elsevier, Amsterdam, pp. 218–236.

Key point • As the share of VRE generation increases in power systems, its SV may decline. This decline is system specific.

The reason for the drop in value is a lack of flexibility in the power and wider energy system, combined with the variability of wind and solar power. The aim of power system transformation is to deploy a comprehensive package of measures that make the overall system more flexible. In a flexible power system, the SV of VRE remains high even at high penetration levels.[2]

It is important to distinguish between the short-term and long-term SV of VRE. In the short term, SV is strongly influenced by existing infrastructure and the current needs of the power system. For example, if new generation is needed to meet growing demand or retirements – as in South Africa – SV will tend to be higher. By contrast, the presence of large amounts of inflexible generation capacity – as is the case in Germany – can lead to a more rapid SV decline in the short term.

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[2] An increase in flexible resources not only boosts the SV of VRE. More generally, it can increase the value of all inflexible technologies. Historically, the uptake of flexible resources, such as pumped hydro storage or programmable electric heaters, was used to integrate inflexible generation, in particular nuclear energy.

When putting in place a strategy for VRE deployment, it is critical to keep in mind the difference between short- and long-term SV. In formulating long-term strategies, the long-term value of VRE is most relevant. It needs to be evaluated with due consideration of all available options to increase system flexibility and thus secure the value of wind and solar power at high penetration levels.

For example, a more responsive demand side boosts SV, because it can help to create demand when there is abundant supply. More generally, all options that increase the flexibility of the power system will have a positive impact on the SV of VRE.[3] Conversely, variable generation increases the SV of flexibility. The more variability there is in the system, the greater the need for flexibility and the higher its value. Economically speaking, high shares of VRE and flexibility are complementary goods; the presence of one increases the value of the other.

Most importantly, it is not only greater flexibility that can help to address the value challenge. VRE sources themselves can make a critical contribution to increasing their own SV by implementing system-friendly deployment techniques.

System-friendly VRE deployment

Power system transformation and the instruments to achieve it are receiving an increasing amount of attention. However, this attention is not distributed evenly. Options such as "back-up" capacity or electricity storage often feature prominently in the policy discussion, while potentially much more cost-effective options, such as demand-side response, are all too often forgotten. The same is true for the contribution that VRE itself can make to its cost-effective integration.

The fact that VRE is not seen as a tool for its own system integration has historic reasons. Policy priorities during the early days of VRE deployment were simply not focused on system integration. Rather, past priorities can be summarised as maximising deployment as quickly as possible and reducing the LCOE as rapidly as possible.

These objectives were sensible during the early phases of global VRE deployment (see IEA [2011] and IEA [2015c] for discussion of different deployment phases). Ignoring integration issues reduces policy complexity and avoids the potential need for trade-offs between different objectives. However, this approach is not sufficient at higher shares. Innovative approaches are needed to trigger advanced deployment and unlock the contribution of VRE technology to facilitating its own integration.

Combining advanced wind and solar power technology with system-friendly deployment practices provides a powerful tool to meet the integration challenge. Five areas are of particular relevance:

- **System service capabilities.** Technological advances have greatly improved the degree to which VRE output can be forecasted and controlled in real time. This means that system operators can know very accurately several hours in advance how much wind and sun they can count on reliably, which also allows the use of VRE to provide system services such as operating reserves. For example, wind power plants in Denmark are expected to participate in system services markets. This boosts SV in two ways: first, system services are often high-value services with a high remuneration; and second, obtaining system services from VRE allows thermal power plants, which historically provided such services, to be switched off. This can avoid the need to curtail VRE, which in turn boosts its SV.

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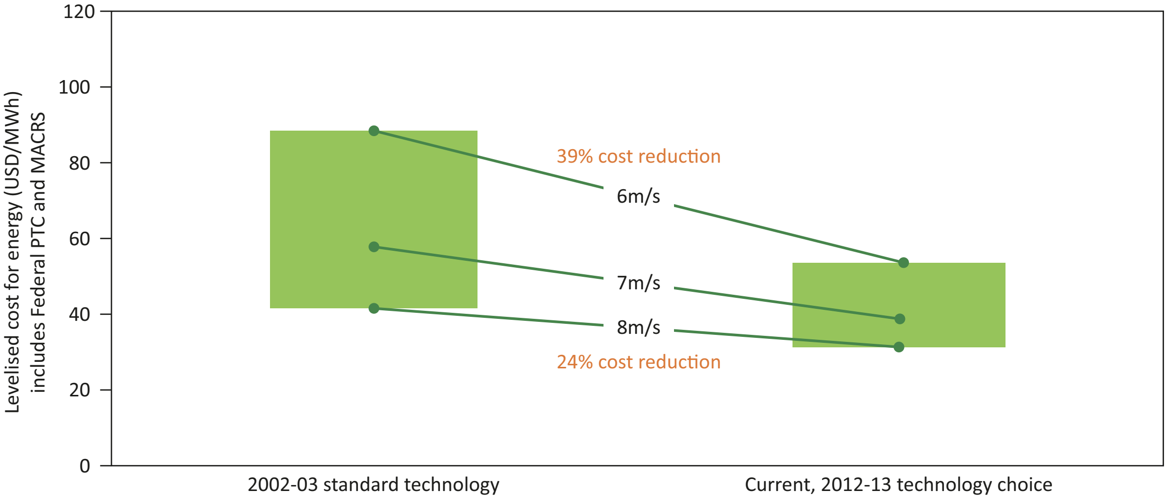
[3] Increasing interconnections between power systems will generally boost the overall value of VRE for the combined system. However, there may be distributive effects: one VRE system may experience a drop in value, while the other will then experience an increase.

- **Location of deployment.** With the cost of solar PV falling rapidly, deployment is becoming economical even in lower resource conditions. In the case of wind, improvements in turbine blades and other components have drastically reduced the cost of generating in medium-quality wind sites (Figure 9). This means that next-generation wind and solar power offers more flexibility in choosing the location of deployment. This can significantly increase SV by producing electricity closer to demand or in regions where alternative generation options are very expensive. For example, the recent auction in Mexico, which reflects the value of electricity depending on location, led to projects being selected in areas that have comparably less favourable resources, but where additional generation has a high value.

Figure 9 • Evolution of wind power costs according to wind resource in the United States



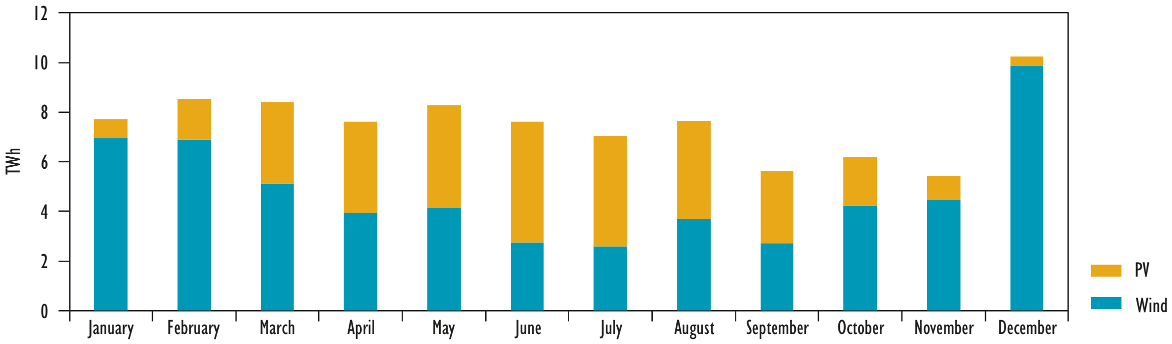
Notes: m/s = metre per second; MACRS = Modified Accelerated Cost-Recovery System; PTC = Production Tax Credit.

Source: Wiser, R. et al.(2012), "Recent developments in the levelized Costs of Energy from U.S. Wind power projects", presentation to IEA wind task 26, Paris.

Key point • Reductions in the cost of wind power production have been greater for low wind-speed technology in recent years. This opens up new deployment opportunities closer to power demand, which can boost the SV of wind.

- **Technology mix.** The output of wind and solar power is complementary in many regions of the world. In addition, the availability of VRE can be complementary to other renewable resources, such as hydropower. Deploying a mix of technologies can thus bring valuable synergies. For example, the current mix of wind and solar power in Germany leads to an overall more stable generation profile than each technology by itself (Figure 10), which raises the combined SV.
- **Local integration with other resources.** Distributed deployment of VRE can open the opportunity to integrate generation resource directly with other flexibility options to form an integrated package. For example, solar PV systems can be combined with demand-side response or storage resources to achieve a better match with local demand and hence increase the value of the generated electricity. However, it is critical to update distribution grid electricity tariffs and remuneration schemes to ensure that such resources are used in a way that is optimal for the system as a whole, including a fair allocation of fixed network costs. For example, the Reforming the Energy Vision (REV) process in the state of New York aims to establish retail electricity tariffs that incentivise grid-friendly consumption and create a market platform that remunerates the system services provided by VRE. Such an integrated approach ensures the collaborative operation of distributed resources, maximising overall SV.

Figure 10 • Monthly generation of wind and solar power in Germany, 2014



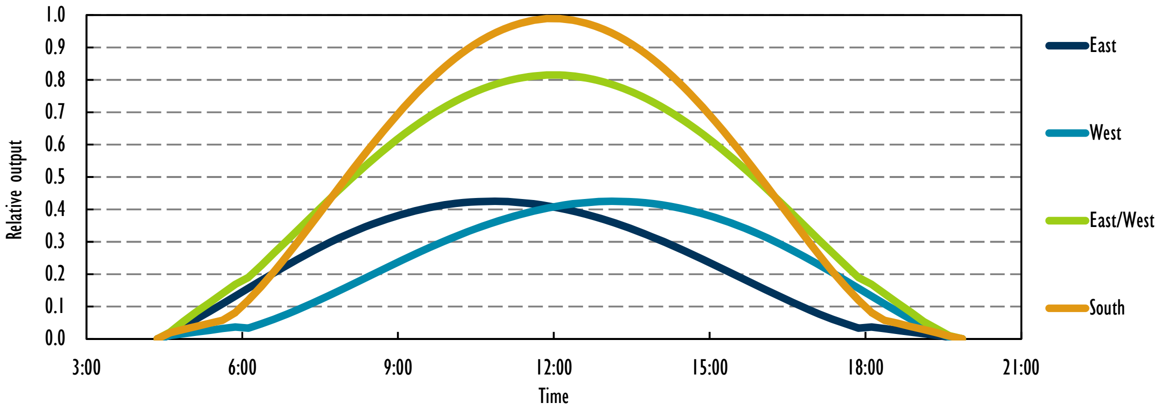
Note: TWh = terawatt hour.

Source: Adapted from Fraunhofer ISE (2016), "Monthly electricity generation in Germany in 2016", energy chart, www.energy-charts.de/energy.htm.

Key point • Combining wind and solar power in appropriate shares facilitates integration.

- **Economic design criteria.** The design of wind and solar plants can be optimised to facilitate integration even at plant level. For example, positioning solar panels to be east- and/or west- facing or actively tracking the sun rather than facing the equator can bring overall system benefits, thanks to generating relatively more electricity earlier and/or later in the day, when electricity is more valuable (Figure 11). This option is already used widely in California. A detailed modelling study that was carried out as part of the Next-Generation Wind and Solar Power project also highlighted that the design of wind turbines can increase the SV of their output (see Box 3 for details).

Figure 11 • Impact of panel orientation on solar PV production profile, month of May in Germany



Note: Identical profile results have been produced at the same latitude in other parts of the world.

Source: Adapted from Troester E. and Schmidt J. D. (2012), "Evaluating the impact of PV module orientation on grid operation", Energynautics GmbH, Darmstadt.

Key point • In Germany, the combined generation of panels oriented east and west leads to lower ramp gradients and slightly higher generation levels during morning and evening hours.

Box 3 • The link between wind turbine design and the value of electricity from wind power

System-friendly deployment may be achieved by spreading generators across large geographic areas or deploying a well-chosen mix of technologies. Another possibility lies in the technical design of VRE generators themselves. Wind turbine technology has evolved significantly during the past decade. The “low wind-speed turbines” that have entered the market are taller and have a larger rotor-to-generator ratio (a lower specific rating per area swept by the rotor). These turbines capture more energy at low wind speeds. This technology evolution also has implications for the value of the generated electricity. Simply put, a turbine with a larger tower and a relatively larger rotor (compared to its maximum power output) will produce more energy per installed unit of capacity. This means that less overall capacity will be required to generate the same amount of electricity. Ultimately, this means that the output from the overall fleet of wind power plants will become more constant, generating more electricity during times of moderate wind speed and having less pronounced peaks during high wind conditions. A further benefit is that less transmission capacity needs to be built, thanks to lower overall installed capacities.

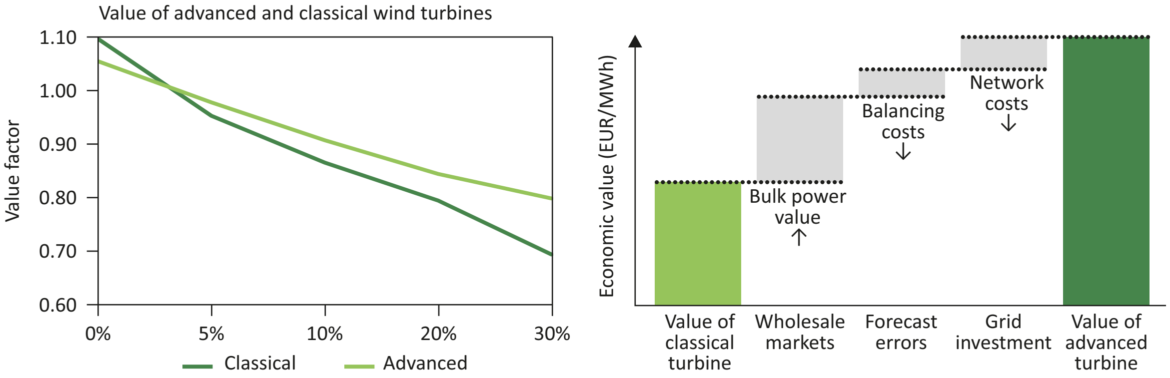
A detailed techno-economic modelling study of northwest Europe carried out as part of the GIVAR programme at the IEA (Hirth and Mueller, 2016) assessed the impact of advanced turbine technology on the value of the generated electricity.

The main finding of the study is that advanced wind turbine technology can significantly increase the SV of wind power. In the study, using a fleet of turbines with relatively larger blades and higher towers increased the market value of the generated electricity by 15% (Figure 12, left). The main reason for the increase in value is a more stable output of these turbines, reflected in a higher capacity factor.

The modelling assessment quantified in detail part of the overall benefits of this technology: the increase in spot market value. Additional benefits include a possible reduction in forecast errors and reduced need for grid capacity (Figure 12, right).

Source: Hirth and Mueller (2016), “System-friendly wind power: How advanced wind turbine design can increase the economic value of electricity generated through wind power”, Energy Economics, May.

Figure 12 • Comparison of the economic value of advanced and classical wind turbine designs for northwest Europe



Source: Adapted from Hirth L. and Mueller S. (2016), “System-friendly wind power: How advanced wind turbine design can increase the economic value of electricity generated through wind power”, *Energy Economics*, Vol. 56, Elsevier, Amsterdam, pp. 51–63.

Key message • Advanced wind turbine design increases the SV of wind power.

Policy priorities: Shifting from generation cost to system value

As wind and solar power enter their next generation of deployment, policy objectives need to be revised. Comprehensive policy, market and regulatory frameworks are needed to catalyse the transition of the power and wider energy system. This has broad implications beyond renewable energy policy and includes areas such as electricity market design, energy taxation and roll-out of infrastructure to enable demand-side response, as well as coupling to other energy sectors (heating and cooling, transport).

Previous IEA and Organisation for Economic Co-operation and Development (OECD) analysis has looked at various aspects of such frameworks, including the comparative assessment of different flexible resources (IEA, 2014), the design of renewable energy policies (IEA, 2015c), electricity market design (IEA, 2016b) and aspects beyond the electricity system (OECD, 2015). The following discussion addresses the implications of a focus on SV for renewable energy polices, in particular mechanisms to unlock the contribution of system-friendly VRE deployment.

Strategies to unlock system-friendly deployment

The previous section has highlighted a number of different avenues for achieving system-friendly deployment. Policy, market and regulatory frameworks need to be designed appropriately in order to unlock this potential to its full extent, considering the follow elements:

- **System service capabilities.** Enabling the provision of system services from VRE requires two principal ingredients. First, installed power plant hardware must be technically capable of delivering the service. This can be ensured by adopting forward-looking technical standards that specify what capabilities each plant must have in order to be allowed to connect to the grid (these interconnection standards are often referred to as grid codes). Second, system operation practices, including the design of system service markets (as far as they are in place), need to be upgraded to better accommodate VRE. The most relevant change is to allow 1) units to declare their availability to provide the service as close as possible to real time, 2) power plants that have the size of typical VRE projects to participate, and 3) aggregators to bundle the contribution from a portfolio of resources, including demand-side response and/or storage options. With its recent reform, Energy Market 2.0, Germany is taking steps in this direction. Spain has already implemented changes allowing wind power to contribute to balancing the grid in practice.
- **Location of deployment.** A variety of policy options exists to optimise the location of deployment. This can be achieved by reflecting SV in market premium payments (partial pass-through of wholesale market prices) or in advanced selection mechanisms in auctions (see next section), or by introducing location-dependent prices on wholesale markets. At a more basic level, it is possible to designate specific development areas for VRE and to differentiate support payments according to location. For example, the FIT system in China differentiates according to wind resource classes, providing higher remuneration per unit of energy for areas with lower wind speeds. In addition, beginning with the 12th Five-Year Plan in 2011, the allocation of new wind and solar power projects is co-ordinated at the national level.
- **Technology mix.** Based on long-term modelling studies, it is possible to determine the cost-optimal mix of VRE technologies. This information can then be used when putting in place and adjusting remuneration schemes for VRE capacity. Where technology-

specific auctions are used to contract VRE capacity, auctioned capacity can be set to achieve an optimal balance for the system as a whole.

- **Local integration with other resources.** The distributed nature of VRE, and solar PV in particular, allows generation to be located alongside other resources, including small-scale battery electricity storage or demand-side response resources. Co-location of resources can help avoid grid congestion and enable the provision of system services from a package of resources. Because such resources are often installed on the customer side of the electricity meter, policy interventions need to be applied thorough the design of appropriate retail electricity and grid tariffs (Box 4).[4] For example, the state of New York is currently implementing a systematic re-design of retail tariffs. The aim is to charge for consumption according to its cost and then pay the energy and system services provided by distributed resources according to their value, while ensuring a fair allocation of fixed network costs. For large-scale projects, co-locating wind and solar PV or solar PV with solar thermal electricity (STE) can increase the value of the generated electricity. For example, the Atacama-1 project in the Atacama Desert in Chile provides round-the-clock electricity via a mix of solar PV and STE with thermal energy storage.

- **Economic design criteria.** Influencing the design of VRE power plants to make them more system friendly is a dynamically evolving field. Simply put, all those measures that encourage an increase in the capacity factor of VRE resources will tend to make them more system friendly. For solar PV this can include tracking systems, or installing east/west-facing panels with a relatively smaller inverter capacity. For wind power, the relative size of the blades compared to the generation capacity is a critical parameter.

  Putting in place mechanisms that signal SV to developers (see next section) will, in principle, incentivise such options: power plants that generate electricity with a higher value receive a higher remuneration. However, existing policy frameworks may actually *hinder* the adoption of system-friendly design. For example, where the eligible amount of revenues under a support mechanism is capped at a certain level of full-load hours, project developers may choose to deliberately oversize the generation capacity to increase profit.[5] This leads to an incentive to reduce capacity factors. The example of Denmark shows how policies can be adjusted to prevent this. Under the new feed-in premium system, the size of the rotor is considered when calculating eligible full load hours.

- **Integrated planning, monitoring and revision.** The relative costs of VRE and other generation technologies, as well as the cost of various flexible resources, are changing dynamically. In addition, continuing innovations in technology are opening new deployment opportunities and technical capabilities of VRE. Most importantly, changes in electricity demand structures via energy efficiency can evolve more quickly than expected. Consequently, the optimal mix of flexible resources, as well as system-friendly deployment strategies, will change over time, prompting the need to adjust strategies.

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[4] More generally, the rise of distributed resources calls for a revision of regulation more generally (for details, see IEA, 2016b).

[5] For example, when a generator is eligible to receive payments for the first 10 000 full-load hours of operation, one way to increase the amount of payments is to simply install a larger generator, say from 2 megawatts (MW) to 2.5 MW. This increases the eligible amount of energy from 20 gigawatt hours (GWh) to 25 GWh. However, oversizing reduces the capacity factor and hence is less system friendly.

Box 4 • The role of retail electricity pricing for guiding investments in distributed solar PV

Retail pricing is increasingly gaining significance in directing VRE investments due to the fact that the cost of electricity from solar PV is close to or below electricity rates in a growing number of cases. In this context, pricing electricity consumption and remunerating distributed electricity production in a time- and location-specific manner is a crucial step in pushing for system-friendly VRE deployment.

Retail prices should give the right incentives to both network users and distributed energy resources, in a time- and location-specific manner. In particular, network tariffs need to cover the costs of infrastructure and should send a signal for efficient use of the network, as well as minimise the cost of future investments. Of course, this needs to be balanced with other policy objectives, such as economic development in rural communities. In the context of rising self-consumption, this is likely to require tariff reform.

For example, the introduction of demand charges that accurately reflect a customer's contribution to peak demand in a local distribution grid can be an appropriate way of ensuring fair charges for all users of the network. In addition, the gradual introduction of time-based pricing to reflect local power production should be encouraged.

Electricity taxation may also have to evolve. With distributed resources, electricity consumption is becoming more responsive to electricity prices, and high levels of taxation and levies can create a strong economic incentive for customers to offset grid-based electricity via their own solar PV system. Where used as a targeted strategy, this can help increasing solar PV deployment. But where left unattended, it can lead to inefficient investment decisions. For example, it may block the uptake of options such as efficient electric heat pumps to displace gas heating; a high electricity tariff will make a switch from gas to electricity uneconomic, even if the electricity-based solution is more efficient.

Reflecting SV in renewable energy policy frameworks

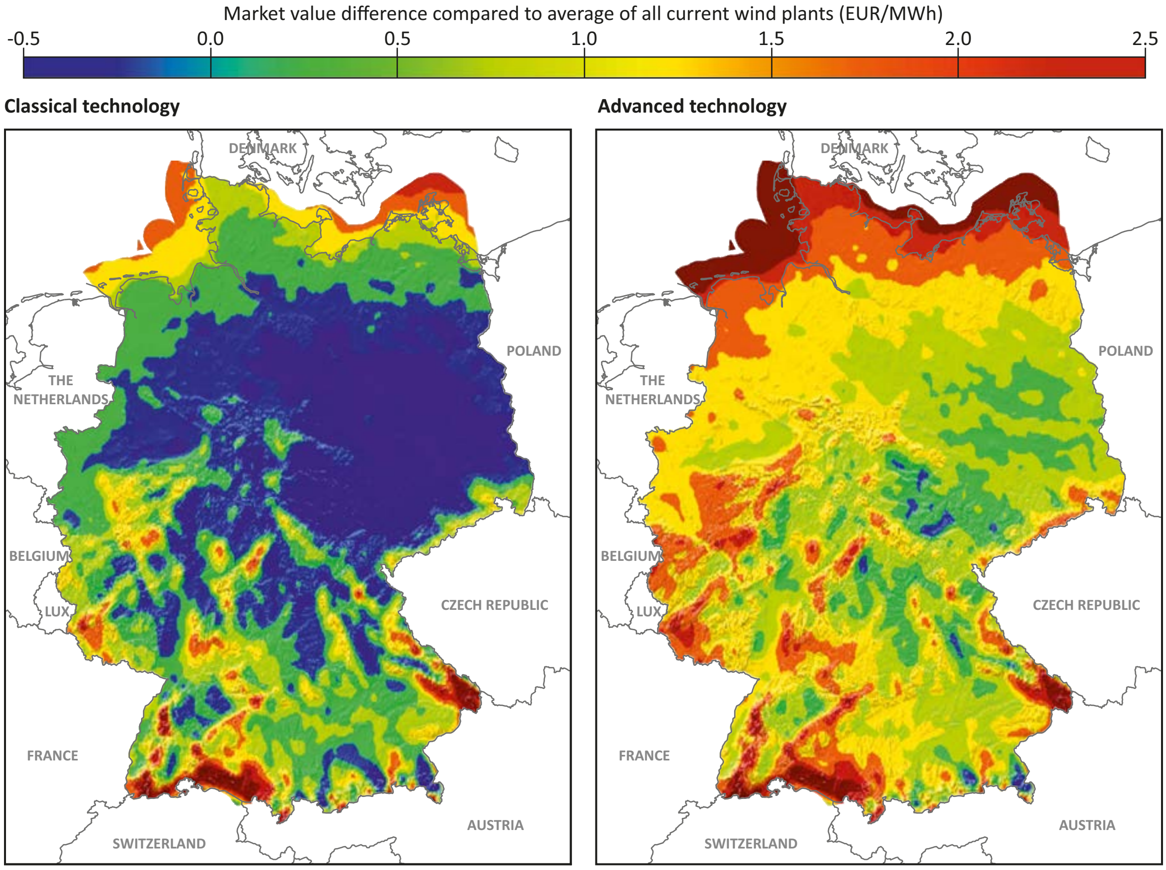
Reflecting SV in policy frameworks requires striking a delicate balance. On the one hand, policy makers should seek to guide investment towards the technology with the highest SV compared to its generation costs. On the other hand, calculating the precise SV can be challenging and, most importantly, current and future SV will differ.

In practice, the exposure to short-term market prices can be an effective way to signal the SV of different technologies to investors. However, the current SV of a technology can be a poor reflection of its long-term value. This is due to transition effects that can be observed in a number of countries where VRE has reached high shares. For example, in European electricity markets the combined effect of renewable energy deployment, low CO_2 prices, low coal prices and negative/sluggish demand growth (slow economic growth, energy efficiency) are leading to very low wholesale market prices. In turn, these low prices mean that any new type of generation will only bring limited cost savings and will thus have a very low short-term SV. Even where electricity demand is growing more rapidly, investments based purely on expected short-term wholesale power prices face multiple challenges (see Chapter 2 in IEA [2016] for a detailed discussion). Because wind and solar power are very capital intensive, such challenges will directly drive up the cost of their deployment, widening the gap between SV and generation costs.

Consequently, mechanisms that provide sufficient long-term revenue certainty to investors are needed. At the same time, such mechanisms need to be designed in a way that accounts for the difference in SV of different generation technologies. A number of strategies have emerged to achieve this. The first is to foster competition between investors in the same technology to make deployment more system friendly. The second is to conduct comprehensive modelling of the power system in order to determine the SV of different technologies and to take this into account when providing long-term contracts to investors.

The German market premium system provides incentives for investors to choose more system-friendly deployment options. The mechanism is designed such that an average wind power plant will generate revenues that match the FIT level. The mechanism to encourage a more system-friendly deployment is this: if a power plant has a higher-than-average market value, the generator can make an additional profit. Investors are now increasingly aware of the difference in value depending on when wind turbines generate. Specialised consultancies provide data on locations where the wind blows during times when the value of electricity is particularly high (Figure 13).

Figure 13 • Market value of wind power projects depending on location, Germany



2011
E66 1.5 MW

2011
N117 2.4 MW

Note: Blue areas indicate below-average market value; red areas show above-average market value.

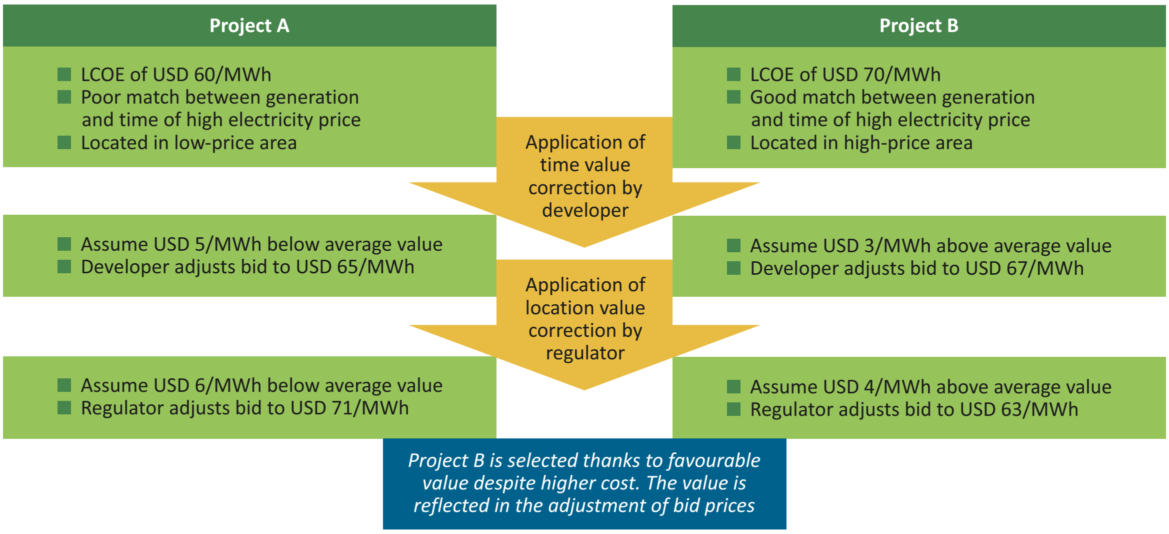
Source: Adapted from enervis/anemos (2016), *Market Value Atlas*, www.marketvalueatlas.com.

Key point • Depending on power plant location, wind power has a different value for the power system.

As part of its recent comprehensive electricity market reform, Mexico has taken an alternative approach to reflecting SV in investment decisions. It is based on comprehensive modelling of the future power system, including expected electricity market prices for the coming 15 years, calculated for each hour of a typical day for each month, differentiated for 50 regions of the country (price zones). In order to implement such an approach, it is critical to have available sophisticated modelling tools for power system planning. It also requires making a set of assumptions about the future evolution of fuel prices as well as expansions of the grid and additional investments in system flexibility. The large dataset of prices is publicly available (CENACE, 2016).

Combining electricity prices with the feed-in profile of a generation resource, it is possible to calculate its market revenue; this is a proxy for the SV. The exact calculation is somewhat technical and involves the combined revenue from electricity and the sale of green certificates. This does not change the main point, however. In essence, those producers that offer electricity with a higher-than-average value can reduce their bids in two steps (Figure 14). In the first step, a correction for the timing of generation is applied, as calculated by project developers. In the second step, a correction factor for location is applied. In summary, these factors are reflected in the order in which projects are selected. The Mexican system has recently been introduced and the first auction results were obtained in April 2016. While its design is excellent from the perspective of SV in principle, it remains to be seen if further modifications may become necessary in practice.

Figure 14 • Conceptual illustration of the Mexican auction system for variable renewables



Key point • The design of the Mexican auction system reflects the SV of different projects depending on when and where they generate electricity.

It is important to note that this auction design puts high demands on the accuracy of the modelling that underpins the auction. Procurement results will only be as good as the underlying simulation, which are updated for each new auction cycle. This means that they would also be required to factor in the possible contribution of demand-side options, grid expansion etc. Sensitivity analysis can reveal how the SV of wind and solar power can be improved by the adoption of certain flexibility measures. Such integrated long-term planning models are becoming increasingly adopted for the guidance of policy making. Their further development needs to be a priority wherever similar approaches are to be adopted.

The measures discussed in this section are summarised in the following table (Table 1).

Table 2 • Overview of system-friendly policy tools and impact on SV

System-friendly strategy	Policy tool	Country example	Impact on SV
System service capabilities	Grid codes that require advanced capabilities Advanced design of system services markets	Participation of wind in balancing the grid in Denmark and Spain	By providing system services from VRE, more thermal generation can be turned off during times of abundance, which “makes room” for VRE and increases SV
Location of deployment	Integrated planning of grid infrastructure and generation	Integrated planning in Brazil	Siting VRE generation in locations where electricity is needed and infrastructure available boosts SV
	Locational signals in remuneration schemes	Mexican auction system; differentiation of FIT levels in China	
Technology mix	Technology-specific auctions that reflect the value of each technology as determined in long-term planning	South Africa	Deploying a mix of technologies can lead to a more stable VRE profile and reduce periods of VRE excess, hence boosting SV
	SV reflected in multi-technology auctions	Mexico	
Economic design criteria	Partial exposure to market prices via premium systems	German and Danish market premium systems, US Tax Credits	Investors are encouraged to choose a technology that generates during times of high electricity prices
Integrated planning, monitoring and revision	An integrated long-term plan for VRE and flexible resources, updated regularly	Integrated system planning in Denmark	Aligned deployment of VRE and flexible resources enhances SV; regular update of the long-term path allows reaping the full benefit of technology innovation

Conclusions and recommendations

- Wind and solar power have reached a new stage of deployment characterised by economic affordability and technological maturity.
  - **Develop or update long-term energy strategies to accurately reflect the potential contribution of next-generation wind and solar power to meeting energy policy objectives.**
- Successfully integrating variable generation into power systems calls for making the power system more flexible. This requires a comprehensive transformation of the power and wider energy system. There are four principal sources of flexibility: generation, demand-side resources, storage and grid infrastructure.
  - **Upgrade system and market operations to unlock the contribution of all flexible resources to dealing with more frequent and pronounced swings in the supply-demand balance of electricity.**
  - **Make the overall system more accommodating to variable generation by investing in an appropriate mix of flexible resources.**
  - **Deploy wind and solar power in a system-friendly fashion by fostering the use of best technologies, and by optimising the timing, location and technology mix of deployment.**
- As next-generation wind and solar power grows in the energy mix, a focus on their generation costs alone falls short of what is needed. Policy and market frameworks must seek to

maximise the net benefit of wind and solar power to the overall power system. A more expensive project may be preferable, if it provides a very high value to the system. This calls for a shift in policy focus: from generation costs to SV.

  - **Upgrade existing policy and market frameworks to encourage projects that bring the highest SV compared to their LCOE, factoring in the impacts on other power system assets such as the need for grid expansion or a more volatile operating pattern for dispatchable generation.**

- Modern wind and solar power plants can actively support their own integration by providing valuable system services.
  - **Establish forward-looking technical standards that ensure new power plants are capable of providing state-of-the-art support for a stable and secure operation of the power system.**
  - **Reform electricity markets and operating protocols to allow for the provision of system services by wind and solar power plants.**
- The distributed deployment of wind and solar power is changing the role of low- and medium-voltage power grids, away from a passive distribution system and towards an important hub for exchanging electricity and data. By generating their own power, consumers can increasingly take control over their electricity supply.
  - **Review and revise planning standards as well as the institutional and regulatory structure of low- and medium-voltage grids, reflecting their new role in a smarter, more decentralised electricity system, and ensure a fair allocation of network costs.**
  - **Reform electricity tariffs to accurately reflect the cost of electricity depending on time and location. Establish mechanisms to remunerate distributed resources according to the value they provide to the overall power system.**

Summary of case studies

To support the analysis undertaken as part of the *Next-Generation Wind and Solar Power* project, a number of country case studies have been conducted, including Brazil, North-East China, Denmark, Germany, India, Indonesia, Mexico and South Africa. A summary of three case studies is included in this document, namely China, Denmark and South Africa.

The main objective of the summaries is to provide a succinct overview of the main aspects of wind and solar power deployment, highlighting in particular the impact that current policy, market and regulatory frameworks have on increasing the value of wind and solar power. To this end, five categories have been selected:

- system-friendly VRE deployment
- investments in power generation, grid infrastructure, demand-side response and storage
- system and market operations
- consumer engagement and uptake of distributed resources
- overall planning and co-ordination.

In each of these five categories, the most relevant items are briefly presented and their impact on the value of wind and solar power highlighted.

Focus on South Africa

South Africa has a dynamic power market, with strong growth in demand for the foreseeable future and a need for investment in additional generation capacity. Extended periods of load shedding and the impact of these on the economy have served to emphasise the importance of sufficient power supply for sustained economic growth.

Eskom, the vertically integrated state-owned utility, provides over 90% of generation and has a transmission monopoly. The company sells 60% of distribution volumes, while the remaining 40% are sold by municipalities.

Analysis shows that wind and solar resources naturally fit the country's load profile (CSIR, 2016). This is an important advantage given the limited flexibility that is available to South Africa today. The coal-driven generation fleet provides only modest levels of supply flexibility. Interconnection with neighbouring countries is limited and although South Africa is a member of the Southern African Power Pool (SAPP), this market has yet to reach the liquidity needed to become a reliable source of flexibility to South Africa. Finally, demand-side integration is mostly limited to a suite of bilateral curtailment contracts that Eskom maintains with large industrial clients.

The 2010 Integrated Resource Plan (IRP) sets a clear pathway towards a more diverse and robust supply mix, while providing appropriate signals for the phase-out of some older generation plants. Among other elements, the IRP dictates the procurement of 17 800 MW of solar PV and wind before 2030 (DOE, 2011). The government has implemented a competitive tender system to serve as the implementation vehicle for the IRP. This is known as the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP).

Since 2011, the REIPPPP has led to the procurement of 6 327 MW of various renewable technologies, unlocking USD 15 billion in private investment (DOE, 2015). To date, 2 400 MW of wind and solar PV have been successfully commissioned (BNEF, 2016).

Despite this success, the effectiveness of the REIPPPP could be improved by providing an incentive for independent power producers (IPPs) to develop in zones where incremental capacity is of higher SV. Providing locational incentives to IPPs can avoid the need for costly transmission upgrades that diminish the SV of VRE capacity additions. Locational signals can also increase the geographic diversity of deployment, which reduces variability. By approving the designation of development priority zones, the government has made an important first step in this direction (DEA, 2016). In addition, more cohesive planning co-ordination between the Department of Energy (DOE), Eskom and the National Treasury can help to mitigate increasing delays experienced in recent rounds of the REIPPPP.

Distributed generation, solar PV in particular, is becoming an important driver of change in the South African power system. Municipalities are slowly embracing distributed technologies as an opportunity, rather than a threat, and some have introduced net billing schemes. By incentivising home and business owners to register their PV system, these financial support schemes represent an important first step in the system-friendly development of distributed assets. Increased technical support from Eskom and legal clarity at a national level will support municipalities in successfully absorbing rising levels of distributed VRE.

As a dynamic power system, South Africa faces the opportunity of strengthening the various flexibility options in a comprehensive, forward-looking manner. With VRE destined to become a key contributor to overall electricity supply, more attention must be paid to the system-friendliness of future deployment.

Table 3 • Key issues for maximising VRE system value in South Africa

System-friendly VRE deployment
The effectiveness of the REIPPPP could be improved by incentivising IPP development towards zones/nodes where incremental capacity is of higher SV.
The government has approved the designation of Renewable Energy Development Zones and Power Corridors where grid reinforcement will be prioritised.
South Africa's wind and solar resource shows little seasonal variation and a high quality in many different locations. Combined with an already well developed grid infrastructure, this is a favourable situation for VRE uptake.
Investments
The IRP sets out a clear pathway to a more diverse energy mix, and reduces reliance on inflexible coal capacity by allowing for phase-out and gradual replacement of the existing coal fleet.
The time-of-delivery structure of the power purchase agreements under the REIPPPP could be extended to other renewable technologies.
Grid investments currently follow IPP development. A more comprehensive co-ordination between Eskom and the DOE may allow for a more cost-effective expansion of the transmission grid, and reduce connection delays.
Operations
Eskom takes a conservative approach to calculating available transmission capacity. There is room to increase available connection capacity by considering the different temporal production profiles of wind and solar PV.
Power plant performance indicators provide an incentive for thermal power plant operators to continue operating, which may reduce overall system flexibility.
SAPP allows for more efficient utilisation of energy and system services. However the power pool suffers from underinvestment in transmission and generation capacity and the limiting impact of long-term bilateral supply agreements.
Consumer engagement
Uptake of distributed solar PV has increased significantly in recent years, but important legislative documents (e.g. low-voltage grid codes) must be finalised to allow for a better utilisation of these assets in local grids.
Certain municipalities have pioneered remuneration of grid injection by distributed resources in order to increase registration rates and value embedded generation.
Visibility and controllability of distributed resources remains limited.
Planning and co-ordination
More comprehensive planning co-ordination between the DOE, Eskom and the National Treasury can help to mitigate increasing delays in the REIPPPP.
Increased technical support from Eskom and legal clarity at a national level will support municipalities in successfully absorbing rising levels of distributed VRE.

Focus on Denmark

Denmark is a member of the Nordpool spot (NPS) power market (which includes a day-ahead, intraday and a regulating power market), providing a unified market design across the Nordic and Baltic countries. Denmark has a stable power system, with consolidated electricity demand. Annual electricity consumption peaked in 2008 and has subsequently dropped by 7% to 32.5 TWh in 2015.

The Danish generation landscape has seen drastic changes over the last 30 years. Starting as a system with few centralised power plants, it evolved into a highly distributed system. Installed generation capacity is roughly 13 700 MW, with high shares coming from wind turbines (35.8%) and distributed thermal generation units (20%). Generation from wind power met approximately 42% of Danish electricity demand in 2015.

Denmark is a world leader in wind power deployment and system integration. It routinely utilises advanced system operation techniques, including dynamic use of abundant interconnection capacities with neighbouring countries as well as very flexible operation of thermal generation. Interconnection is particularly valuable in the Nordic region because it links diverse power systems with different characteristics, e.g. wind in Denmark and hydro power in Norway.

The Danish electricity system operated without any participation of its central generation units for the first time in September 2015. Newly installed, advanced grid support technology (synchronised condensers) was used to maintain grid stability under these conditions.

Denmark has reached a stage of VRE integration where periods of abundant VRE generation – often exceeding domestic power demand – are becoming increasingly common. Consequently, measures to boost the SV of VRE are quite advanced in Denmark compared to other regions of the world. For example, Denmark has seen an uptake of electricity boilers in co-generation plants.[6] These play an important role in making economically attractive use of abundant VRE generation.

More generally, measures to enhance electrification are being targeted for the medium term. Future electricity consumption is expected to rise by an additional 3.7 TWh from 2015 until 2024. This is due to the increased electrification of the Danish heating and transport sector through further uptake of electric boilers, heat pumps and electric vehicles.

The current support scheme for wind power plants has been designed to promote the use of larger rotors, which can help to increase the SV of the produced electricity. For onshore wind plants commissioned from January 2014, a guaranteed fixed feed-in premium (FIP) of USD 36/MWh (DKK 250/MWh) is provided. The maximum revenue (premium plus market price) is capped at USD 84/MWh (DKK 580/MWh). The support is paid for up to 6 600 full-load hours, plus an additional 5.6 MWh per square metre of rotor area. An additional premium of USD 3.3/MWh (DKK 23/MWh) is paid for covering the balancing costs. Offshore wind farms installed following a tender process are subject to separate incentives, set as variable FIPs.

Denmark is already one of the countries with the highest shares of renewables as a proportion of electricity consumption, but the goal of the Danish government is independence from coal, oil and gas by 2050.

To reach this goal, *Energy Strategy 2050* has been developed. The strategy sets out the actions needed for a full transition. It details the long-term energy infrastructure necessary for the

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[6] Co-generation refers to the combined production of heat and power.

integration of more variable electricity production and electrification of end uses and emphasises the need to plan and prepare for the roll-out of this infrastructure.

At the distribution level, the government will endeavour to strengthen its energy infrastructure to incorporate still larger amounts of renewable energy. At the distribution level, the government wishes to enter agreements with distribution companies for the installation of smart meters at the same time that consumers install heat pumps and recharging stations for electric cars (Efkm, 2011).

Table 4 • Key issues for maximising VRE system value in Denmark

System-friendly VRE deployment
Current support scheme for wind power plants has been designed to promote the use of larger rotors that can provide system-friendly wind power production.
Investments
Further upgrades of interconnection capacities with Germany and the Netherlands are planned, which will help smooth wind power fluctuations via geographical aggregation and thanks to linking diverse resources (hydro, wind). The Danish government aims to reach an agreement with distribution system operators to install smart meters when power consumers install heat pumps or recharging stations for electric cars.
Operations
System operation and wholesale power market design in Denmark have been systematically adapted to deal with high levels of VRE. Operating practices for thermal power are among the most flexible globally. As part of the Nordpool market, interconnection capacities are used via implicit auctions, enhancing system flexibility. Measures have been taken to create a common market with Nordic and other European countries for operating reserves. In the intraday market, demand-side response can be used to counteract any imbalance in the market.
Consumer engagement – distributed resources
Consumers may opt for variable tariffs that are linked to wholesale price levels. Danish energy prices are among the most heavily taxed in the European Union. The effect is a reduction in the effectiveness of real-time price signals and a possible misalignment of economic incentives. A review of taxation could help reflect SV, in particular of distributed resources.
Planning and co-ordination
Energy Strategy 2050 aims for independence from fossil fuels, using wind as a main power source. The plan covers all aspects of the energy system (transmission grid, distribution grid, non-variable renewables, etc.). The growing presence of wind capacity is reflected in transmission grid expansion plans, new interconnection management and redefinition of ancillary services.

Focus on China

China has experienced a marked increase in electricity demand over the past decade, requiring rapid and large investments in the power sector. This has provided an opportunity for streamlining system integration with the expansion of overall electricity infrastructure. However, this opportunity has not been fully realised and investments have predominantly been in coal-fired capacity. The dominance of coal in the power sector has translated into growing concerns over local air pollution and CO_2 emissions. To address these issues, China is ramping up deployment of renewable energy resources and putting in place measures to effectively limit increases in coal-fired capacity.

In recent years, wind and solar PV deployment have gathered significant momentum. In 2015, renewables represented over 50% of net additions to power capacity. Grid-connected onshore wind capacity increased by over 32 gigawatts (GW) in 2015, the highest rate of installation to date. China installed 15 GW of solar PV in 2015 according to government estimates. Overall cumulative capacity reached over 43 GW, with over 80% from utility-scale projects. China proposed more ambitious renewable energy targets under the 13th Five-Year Plan: nearly doubling land-based wind capacities from 128 GW in 2015 to 250 GW by 2020, and tripling solar PV capacity from 43 GW in 2015 to 150 GW by 2020.

The ramp-up of renewables capacity is complemented by measures to limit construction of new coal-fired capacity. The National Development and Reform Commission (NDRC) and National Energy Administration (NEA) issued special emergency guidance, requiring local governments and companies to suspend or cancel the permitting and construction of coal-fired power plants.

Against the background of slowing economic growth and restructuring of the Chinese economy away from heavy manufacturing, growth in power demand has been slowing dramatically. In 2015, China's power demand grew by only 0.5%, the lowest since 1998. In a growing number of regions of the country, the issue is no longer how to rapidly meet growing power demand. Rather, the question has become how to scale down coal generation in line with the expansion of renewable energy. This raises issues both within the power sector but also for the Chinese economy more widely, in particular how to deal with the possible negative impacts on employment and economic growth in coal-mining regions.

China is moving quickly from a dynamic power system context to a stable one – this is reflected in the growing issue of wind curtailment. The highest curtailment rates are observed in provinces where large coal-fired generation capacity is located or where a lack of transmission capacity prevents the dispatch of surplus wind power to demand centres. Gansu Province led the curtailment with 39% followed by Jilin (32%) and Xinjiang (32%).

In this context, the most central challenges relate to operating the power system in a more flexible manner, while deploying new wind and solar PV capacity in a system-friendly manner. The three provinces of Liaoning, Jilin and Heilongjiang (collectively referred to as North-East China is this publication) have been selected for a closer analysis of current operating practices. They are part of the same synchronous system, but each province is balanced separately.

With regard to system operations, the greatest barriers to an increased use of wind are the contractual arrangements for the purchase of electricity and the resulting constraints on full-load hours for thermal power plants. This leads to monthly, weekly and day-ahead scheduling for thermal generation, leaving little room for adjustment. In addition, once a power plant has been switched off, it is required to remain shut down for one week and unit start-up has a lead time of approximately 12 hours. These issues are further exacerbated by the presence of heat-driven co-generation power plants, which are particularly constrained by the nature of their operation. This creates challenges to the effective use of increasingly mature renewable energy forecast data. In addition, generators' KPIs include overall electricity generation above and beyond generated revenue. This can create perverse incentives to generate power even when it is not needed.

A further operational challenge is the use of interconnection capacity. Currently, flows over interconnectors linking different provinces are fixed for 12-hour periods, a lost opportunity for using this flexible resource. The improved use of interconnections would by itself already make a substantial contribution to reducing curtailment of VRE in North-East China.

Both of these challenges have been recognised by system operators and policy makers in China. In North-East China a pilot project has been put in place to remunerate thermal generation for also providing flexibility (ramping) in order to incentivise a more flexible operation. In addition, making co-generation more flexible has been identified as an important priority.

Considering system-friendly deployment, there still appears to be a tendency to focus on large-scale projects in resource-rich areas, far away from load centres. However, next-generation wind and solar PV technology allows for more flexible deployment, which could alleviate some of the current grid integration issues.

China already has tools available to diversify deployment. For example, FIT levels are differentiated according to resource endowment. In addition, beginning with the 12th Five-Year Plan, deployment of new wind and solar power is co-ordinated at the national level.

Table 5 • Key issues for maximising VRE system value in China

System-friendly VRE deployment
VRE deployment is focused in priority areas that are often distant from load centres. Advanced wind turbine technology and rapidly falling costs of solar PV provide an opportunity to diversify deployment locations with a view to boosting the overall value of the electricity to the power system. The regional differentiation of FIT tariffs could be further elaborated to actively promote a more diversified, system-friendly deployment pattern. Co-locating wind and solar capacities could make enhanced use of scarce grid capacities and minimise variability. This could be considered when developing national deployment plans for both technologies.
Investments
Continued expansion of transmission grid capacity is required to match the ambitious targets for scaling up wind and solar PV. Deploying a balanced mix of flexible resources – also including demand-side response and possibly energy storage options – could facilitate the transformation of the Chinese power system at least cost.
Operations
Flexibility of thermal capacity is constrained by contractual arrangements (guaranteed full-load hours) and generators' KPIs (incentive to maximise electricity generation irrespective of system need). Introduction of system service markets and revision of KPIs could enhance flexibility. Current power exchanges between provinces are undertaken on very coarse schedules (12-hourly), locking out flexibility and benefits of aggregating VRE and power demand across larger regions. More granular schedules, allowing for short-term exchange of power, would enhance the value of VRE.
Consumer engagement – distributed resources
The planned introduction of competition among different suppliers of electricity could stimulate the emergence of small-scale solar PV deployment and close-to-power demand, which could be favourable from a system perspective. The introduction of time-dependent electricity prices could provide incentives for end-users to increase demand-side flexibility.
Planning and co-ordination
The special emergency guidance, requiring local governments and companies to suspend or cancel the permitting and construction of coal-fired power plants, facilitates a co-ordinated expansion of VRE in the context of reduced reliance on coal. In areas with high shares of co-generation, increasing the flexibility of the combined electricity and heat production system can reduce the challenges of high wind curtailment, in particular in Northeast China. Depending on local circumstances, viable options may include increased flexibility of co-generation plants, installation of electric boilers and upgrades to the existing head network.

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