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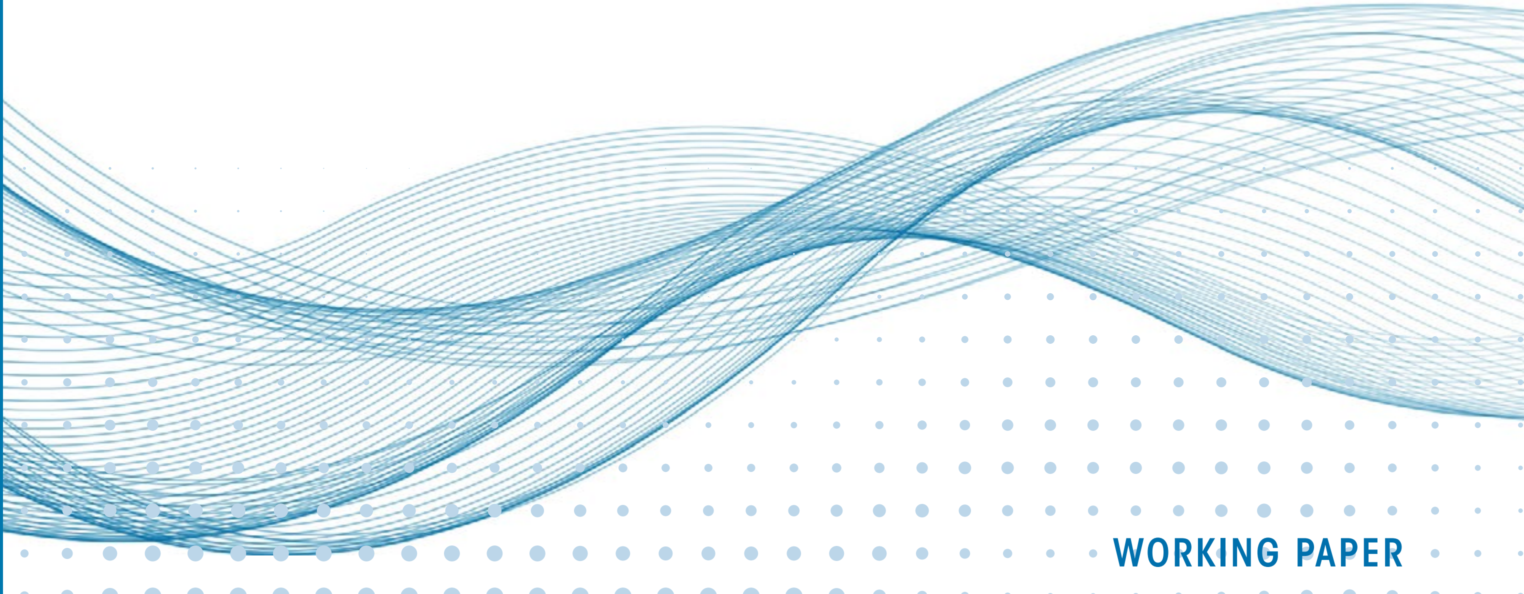
International Renewable Energy Agency

FROM BASELOAD TO PEAK: RENEWABLES PROVIDE A RELIABLE SOLUTION



WORKING PAPER

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SUMMARY

An oft-heard critique of renewable power generation is that renewable options are unsuitable for baseload supply, therefore fossil power and nuclear power are needed. This critique is misleading. Baseload is a demand characteristic, not a supply technology characteristic. Nuclear or coal power plants are operated in baseload mode simply because: i) they are not technically capable of operating in a more variable mode and ii) they must rely on high utilisation to recover their high investment costs.

In the future power system, the value of baseload will decrease. With higher shares of renewable power, particularly from variable sources such as wind and solar, supply and demand will be matched in a much more concerted and flexible way. Variable renewable power generation can ideally be combined with smart-grid technologies, demand response, energy storage and more flexible generation technologies, including gas power plants and dispatchable renewable power supply options. A flexible, renewables-based power system is not only reliable, but also economically efficient.

1 BASELOAD REFLECTS DEMAND, NOT SUPPLY

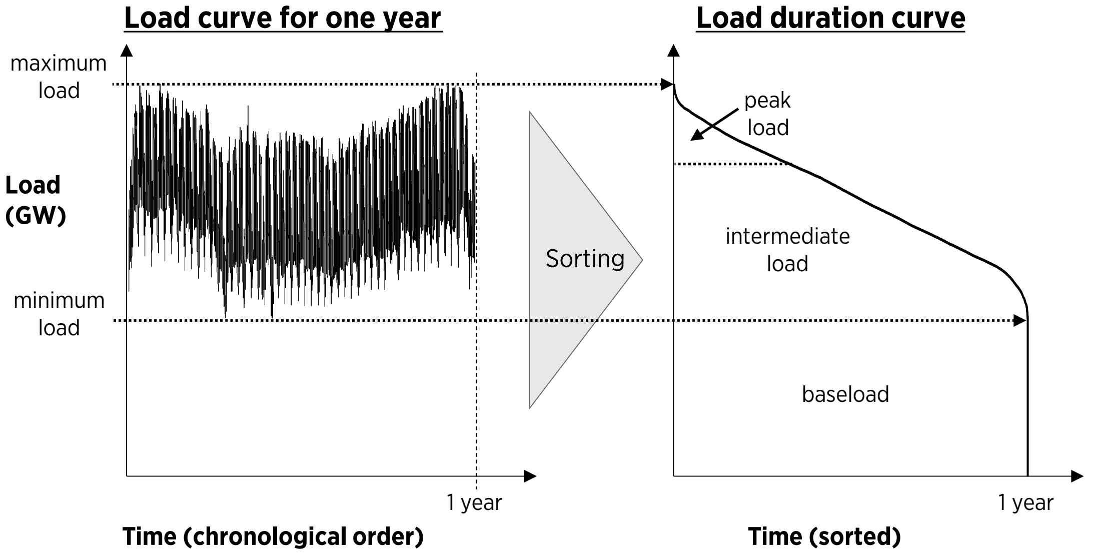
Baseload is a characteristic of electricity demand and not a necessity of the supply side

Electricity demand (also termed load) varies over the course of a year (*Figure 1*, left, shows an annual load curve for Germany). In most power systems it never drops to zero, *i.e.* there is a minimum load during the year, which is often termed baseload (*Figure 1*, right). This is true for grid-connected power systems of at least a medium size, for two reasons. Firstly, some processes continuously consume electricity. Examples include industrial processes, such as aluminium smelting, or residential applications such as refrigerators, freezers and electronics in stand-by mode. The second and more important reason is a result of statistics: at any moment in time, lights are switched on, mobile phones are charging and washing machines are running. Baseload is a concept that describes a characteristic of the power demand side, and not a necessity of the supply side.

In the example in *Figure 1*, baseload is about half peak load capacity. This illustrates that, for a typical power system, baseload constitutes more than half of total annual electricity demand. In addition, part of the load varies over a broad range of time (peak load and intermediate load). For example, the highest load hours are only recorded over a small portion of the year.

The time in which the minimum demand, which determines baseload, occurs varies by power system. In Northern latitudes without air conditioning (*e.g.* NW Europe, NE USA) it is typically a summer weekend night. In more Southern latitudes where peak demand depends on air conditioning (*e.g.* Japan, SW USA, Middle East and North Africa) it is typically a winter night. The gap between baseload and peak load capacity can vary, but in the example of Figure 1 for Germany, baseload accounts for more than half of total electricity demand. So the question of whether renewables-based power system can meet baseload is key to the viability of a renewable power supply.

Figure 1: Electricity demand (here for Germany in 2011) varies over different time frames, from hours to seasons (left). The load duration curve (right) is derived by sorting the load curve (left) in descending order. According to their duration, different parts of the load can be distinguished: baseload, intermediate load and peak load.



Source: adapted from Ueckerdt, Brecha and Luderer (2015).

2 TODAY'S BASELOAD PLANTS HINDER FUTURE GENERATION MIX

Today, baseload is often covered by "baseload power plants" such as nuclear or coal power plants. However, this could hinder the future power generation mix

Load is inherently variable. Therefore, a heterogeneous mix of different generation technologies, bringing flexibility in output and incurring different degrees of fixed and variable costs, is more cost-effective than a single technology. Traditionally, baseload is often covered by so-called "baseload power plants", like nuclear or coal power plants. These plants are characterised by high capital costs and low variable costs and, as such, prefer running at a constant output. Typically, gas-combined-cycle plants are deployed for intermediate load and gas turbines or oil-fired plants are used for peak load. The latter "peak load plants" have low capital costs, but high variable costs.

Opponents of renewable power generation argue that "renewables cannot supply baseload power, therefore we must rely on fossil or nuclear plants". This argument is both untrue and misleading. Providing baseload power with a single plant should not be seen as an end in itself. The objective should be to supply all parts of load, from baseload to peak load, in a reliable and cost-effective way.

In fact, having constant power output is not necessarily positive, but can have negative outcomes. "Baseload power plants" actually rely on running at almost constant output throughout the year for two reasons. Firstly, these plants tend to lack the flexibility to ramp at high rates and follow variable load. More importantly, even if baseload power plants were operated more flexible, they would still rely upon a high utilisation rate so that enough electricity can be sold for producers to recover their high specific investment costs.

Consequently, since future power systems incorporating a higher share of renewables will require a more flexible interplay of its components, it cannot be guaranteed that any technology will run at a high utilisation rate or even provide a constant output. Thus, the role of "baseload power plants" is likely to decrease. In fact, a large share of "baseload power plants" could even hamper the required transformation towards renewables and might cause 'lock-ins' for power systems dominated by reliance on conventional plants.

3 VARIABILITY CHALLENGES BASELOAD PLANT CONCEPT

A transformation towards variable renewables requires rethinking the concept of "baseload power plants"

There are two distinct categories of renewable power generators: dispatchable and variable. Dispatchable renewable power generators control their output within a specific range, just like conventional fossil power plants. These generators can provide baseload power if needed. Reservoir hydropower plants, biomass (including biogas) power plants, geothermal power plants, and concentrated solar power (CSP) plants with thermal storage (such as in molten salt) all generate dispatchable renewable power. Integrating these renewable sources into power systems does not pose additional challenges. In fact, many power systems already achieve high electricity shares from dispatchable renewables, particularly hydropower and geothermal power (*e.g.* in 2013: Austria 72%; Canada 61%; Colombia 79%; Iceland 100%; New Zealand 69%; and Norway 96%).

The output of variable renewable energy (VRE) sources, such as wind and solar photovoltaic (PV) is much less controllable. Power generation from VRE is growing rapidly. Worldwide, newly installed capacity from wind and solar PV reached around 54 GW and 39 GW, respectively, in 2014. This represented about 38% of global power generation capacity additions. By the end of 2014, there was around 370 GW of wind and 185 GW of solar PV power installed, together accounting for about 10% of global power generation capacity. But this capacity is not distributed evenly; shares are much higher in some countries than in others.

In 2013, Denmark, Germany and Spain had renewable electricity generation shares of 56%, 25% and 42%, respectively, with at least half of it coming from variable renewable sources. For Denmark and Germany, electricity trade with neighbouring countries helps to stabilise the grid. These examples show that it is feasible to operate power systems with high shares of variable renewable power.

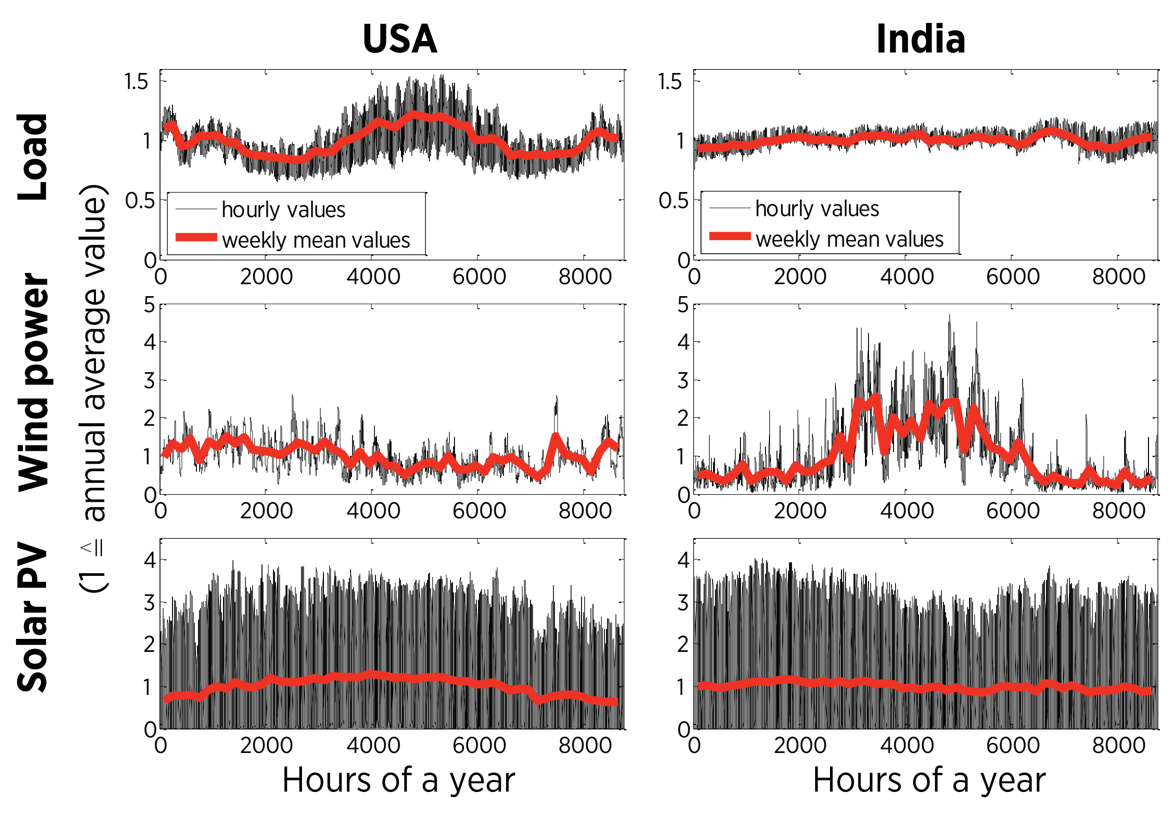
VRE cannot cover baseload power demand at all times. This does not need to be a disadvantage, since covering baseload power is not an end in itself. A combination of VRE and dispatchable renewable power, or of VRE and flexible fossil-fuelled power, can reliably meet total power demand (including baseload) at all times.

Figure 2 shows the temporal variations (hourly and weekly averages) of load, and wind and solar PV production over one year for the USA and India, indexed to the annual average. Hourly load varies for the USA, as a whole, by 50% above and below the annual average. The variation of load in India is even lower than in the USA. In contrast, for wind and solar PV power supply, the variations are much higher than those of load. The values range from close-to-zero values up to 3-4 times the average annual generation. Solar PV shows periodic diurnal and seasonal cycles, while wind power shows seasonal cycles and varies rather erratically on diurnal time scales. The time series are derived for a future power system under the assumption that all regions of the respective country are well-interconnected. Consequently, variability has already been smoothened somewhat.

Experiences with wind power in Spain and the UK confirm this range of variability. Spain had 20 GW of wind capacity installed in 2010, while the production of wind varied between 1% and 76% of installed capacity (Martin-Martinez, *et al,* 2012). The minimum and maximum for the UK, with 10 GW of installed capacity, were 0.05 GW and 6 GW, respectively, so production was 5%-60% of installed capacity (Best, 2014). Similar effects have applied to solar PV. In Germany, peak generation in summer 2013 was around 75% of installed PV capacity, while the lowest recorded daily peak generation in winter 2013 was around 6% of installed PV capacity (SMA, 2014). Of course the variability of solar PV is different from that of wind, in the sense that there is no solar generation at night.

It should be noted that variability is highest for an individual wind or solar plant. When different plants of the

Figure 2: Load, wind and solar PV temporal variations over one year for the United States and India.



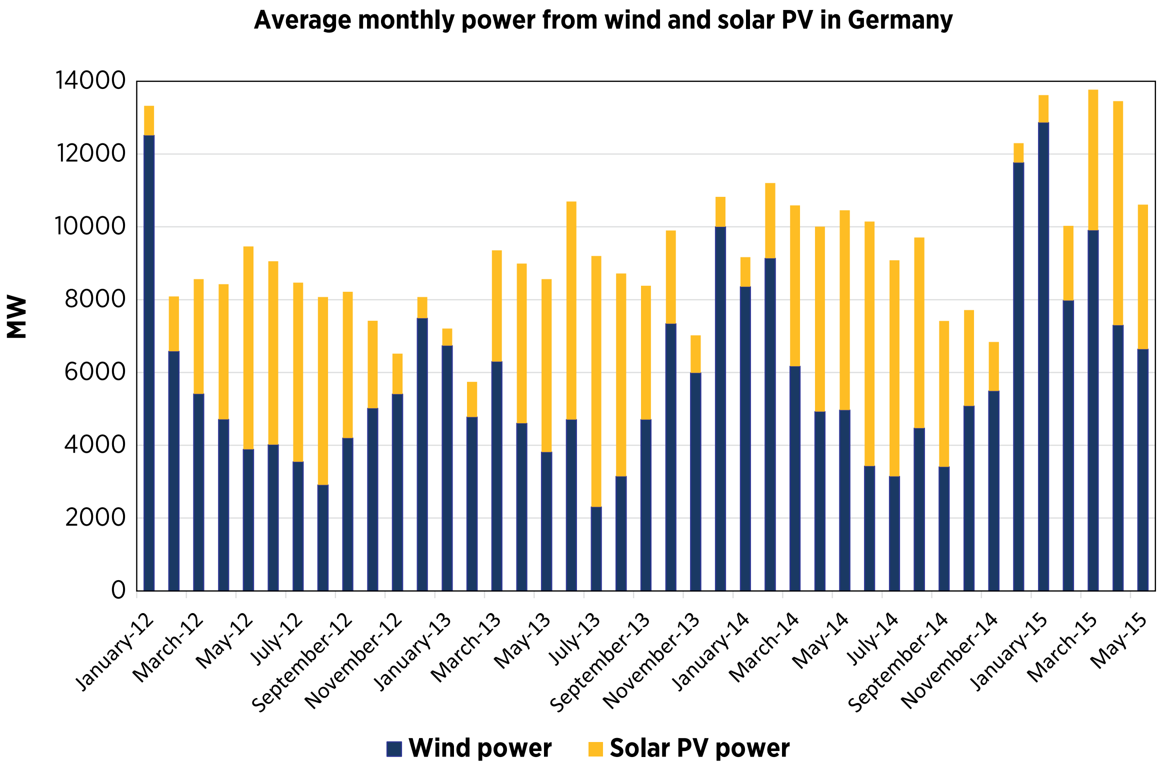
Source: adapted from Ueckerdt et al., 2014.

same type are combined across a country or continent, variability decreases. Variability also decreases when different types of VRE such as solar and wind are combined.

A number of countries have already shown that a mix of renewables can reduce variability. Hydro and wind complement each other in Brazil: in the rainy season hydropower plants produce at their maximum, while in the dry season wind generation is at its peak (IRENA and GWEC, 2012). Similarly, solar PV and wind power generation have shown to complement each other in Germany due to opposite seasonal variations. While there is a higher solar intensity and more sunny hours in summer, more wind is blowing during winter. Adding the monthly generation averages of wind and solar power results in less seasonal variation than for solar PV or wind alone (*Figure 3*). However, within each month the variability can still be high. For example, under the conditions of a high-pressure system in Northwestern Europe, neither wind nor a solar PV power plants can operate at night. But a broader technology mix containing (pumped) hydropower, biomass power generation or energy storage can ensure power generation under such conditions.

Furthermore, the examples of Denmark, Germany and Spain show that up to 20-30% VRE in total annual electricity supply poses no major challenge and can be accommodated easily in power systems that are well interconnected with neighbouring countries. Higher VRE shares pose challenges and require a rethinking of power system operation and planning. With the moderate average VRE shares we are seeing already, instantaneous penetration levels can become very high in some hours of the year, and VRE supply can sometimes even exceed electricity demand. Hence, the permanent minimum load that is covered by dispatchable power plants is reduced and even vanishes at a certain level of VRE deployment. In future power systems with higher shares of VRE, distinguishing between baseload and other load types, and attributing power generating technologies accordingly, is less meaningful.

Figure 3: Seasonal complementarity of solar PV and wind power generation in Germany based on monthly averages from January 2012 until January 2015.



Source: Wind Journal, based on data from German transmission system operators (Amprion, Tennet TSO, TransnetBW, 50Hertz), 'http://www.windjournal.de/erneuerbare-energie/entwicklung_windenergie_einspeisung', (accessed May 2015).

4 INTEGRATION COSTS DEPEND ON SYSTEM CONDITION

The costs for integrating variable renewables depend on the condition of the entire power system

There is a broad consensus that VRE creates no insurmountable technical barriers. However, VRE inflicts so-called integration costs at the system level (International Panel on Climate Change (IPCC), 2011; Holttinen, *et al.*, 2011; International Energy Agency (IEA), 2014; Hirth, Ueckerdt and Edenhofer, 2015).

Integration costs are not specific to VRE. In principle, every generation technology imposes additional costs on the power system. However, variable renewables have three characteristics that may require specific measures and additional costs to integrate these technologies into current power systems: temporal variability in VRE resource availability, uncertainty because resource availability is less predictable, and the location-specific nature of resources due to their geographical availability.

At low VRE shares, integration costs are low or even negative, which means that VRE deployment can save costs on a system level. High VRE shares do not pose insurmountable technical challenges, but integration costs will increase.

1. VRE provides electricity, but due to *temporal variability* VRE sources cannot be relied upon during peak demand times (VRE have a low so-called capacity credit). Thus, VRE requires some dispatchable 'back-up' capacity in case solar and wind resources are unavailable. Furthermore, the utilisation of dispatchable power capacity is reduced, which increases the specific costs in the non-VRE part of the system. These so-called profile costs, which comprise all costs of variability including back-up costs, can reach EUR 15-25 per MWh at wind and solar power shares of 30%-40% (IEA, 2014; Hirth, Ueckerdt and Edenhofer, 2015). A mix of wind and solar PV significantly decreases these costs. Electricity storage can reduce profile costs, but it is a relatively expensive option, starting at around EUR 5 per kWh for pumped hydro and reaching more than EUR 150 per kWh for battery storage. Reducing peak demand instances through demand side management can lower this cost component (IRENA, 2013).

2. *Uncertainty* is caused by deviations between forecasted VRE generation and actual production, which need to be balanced at short notice (from seconds to hours). Improved forecasting techniques have decreased associated costs, yet unpredictability remains. The impact of uncertainty receives much attention in literature and public debate, yet the required flexibility is technically feasible at less than EUR 6 per MWh of VRE, less than 10% of VRE generation costs, even at high wind shares (Holttinen, *et al.,* 2011; IEA, 2014; Hirth, Ueckerdt and Edenhofer, 2015).

3. *The location-specific nature of resources* has an impact on investment needs in transmission and distribution lines. In transmission networks of developed power systems, the resulting grid costs tend to be less than EUR 10 per MWh of VRE at wind shares of about 30%-40% (Holttinen, *et al.*, 2011; NREL, 2012; Hirth, Ueckerdt and Edenhofer, 2015) – small compared to VRE generation costs. In weak grids, these costs can become significant. In distribution networks, distributed VRE generation from sources such as solar PV can actually decrease grid enhancement costs, as VRE generators, such as rooftop solar PV stations, can be installed closer to load (estimates in Europe range from EUR 2.5-5 per MWh of savings). However, with higher VRE shares in the distribution network (typically around 10%) grid enhancement costs in the distribution network increase.

Note that integration costs should not be entirely attributed to VRE, because the level of grid integration costs necessary is highly dependent on the characteristics of the existing power system. Integration costs will be low in a VRE-friendly power system consisting of flexible generation plants, flexible demand (including demand side management), and strong grids. In addition, innovative grid operations and regulatory frameworks can significantly reduce grid integration costs by harnessing the potential for technical flexibility.

Integration costs are reduced if the power system adapts in response to increasing VRE shares. Importantly, baseload power plants are not a suitable complement to high VRE shares. A shift from capital-intensive baseload plants to peak and intermediate load plants, which are less capital-intensive and more flexible, can significantly reduce total costs in a system with high VRE shares.

5 FLEXIBILITY OPTIONS MATCH VARIABLE RENEWABLES

Variable renewables can be efficiently combined with a flexible generation mix, enhanced grid infrastructure, demand-side options and energy storage

Since covering baseload power is not an end in itself, it is not necessary to adjust and supplement VRE to cover baseload power, *i.e.* operate at constant output. For example, storage technologies and gas power plants should not be seen as an add-on to wind and solar PV plants to provide constant generation. Instead, smart grid technologies (IRENA 2013), demand response, energy storage (IRENA, 2015a) and more flexible generation technologies will be able to match supply and demand in a more concerted and flexible way (IRENA and IEA-ETSAP, 2015) while "baseload power plants" will become less and less relevant for future power systems with high VRE shares. A balanced mix of all renewable sources is likely to help build a major pillar of future power systems, and already does so in some parts of the world today.

An efficient system integration of VRE requires a transformation of the design and operation of power systems. System technologies, such as enhanced grid infrastructure, smart grid technologies, energy storage and demand-side options, play an important role (IRENA, 2013). Electricity demand will go from being variable and requiring flexibility to a source of flexibility in the future. Consequently, demand and supply will become more integrated, *i.e.* demand-side options will be able to shift demand in response to variations of renewable supply. In addition, pooling the supply from renewable sources distributed over large distances can significantly smoothen variability and decrease the need for backup capacity. Thus, further interconnecting national and regional power systems into continental power systems is likely to decrease overall energy system costs. By contrast, for island systems costs of accommodating VRE generators tend to be higher. A balanced mix of variable wind and solar PV power will further decrease costs and should be complemented with flexible generation from reservoir hydropower, geothermal, CSP, biomass or natural gas power plants.

All components of a power system with high VRE shares need to complement one another. The cost of a mismatch of components can be very high. Rapidly introducing VRE into a system that does not complement VRE well (*e.g.* with a large share of inflexible assets such as baseload plants or underdeveloped grid infrastructure) leads to fairly high total system costs. Since power plants and transmission infrastructure take years to be built and last for up to half a century, introducing VRE requires concerted energy planning today. An inadequate investment decision made today can hamper the transition towards renewable power generation and might even create a lock-in within a conventional-based power system. Proactive energy planning, with a long-term planning that accounts for short-term variability of VRE, enables a smooth transition towards power systems with high shares of renewable energy.

6 COSTS AND BENEFITS DETERMINE ECONOMIC VIABILITY OF RENEWABLES

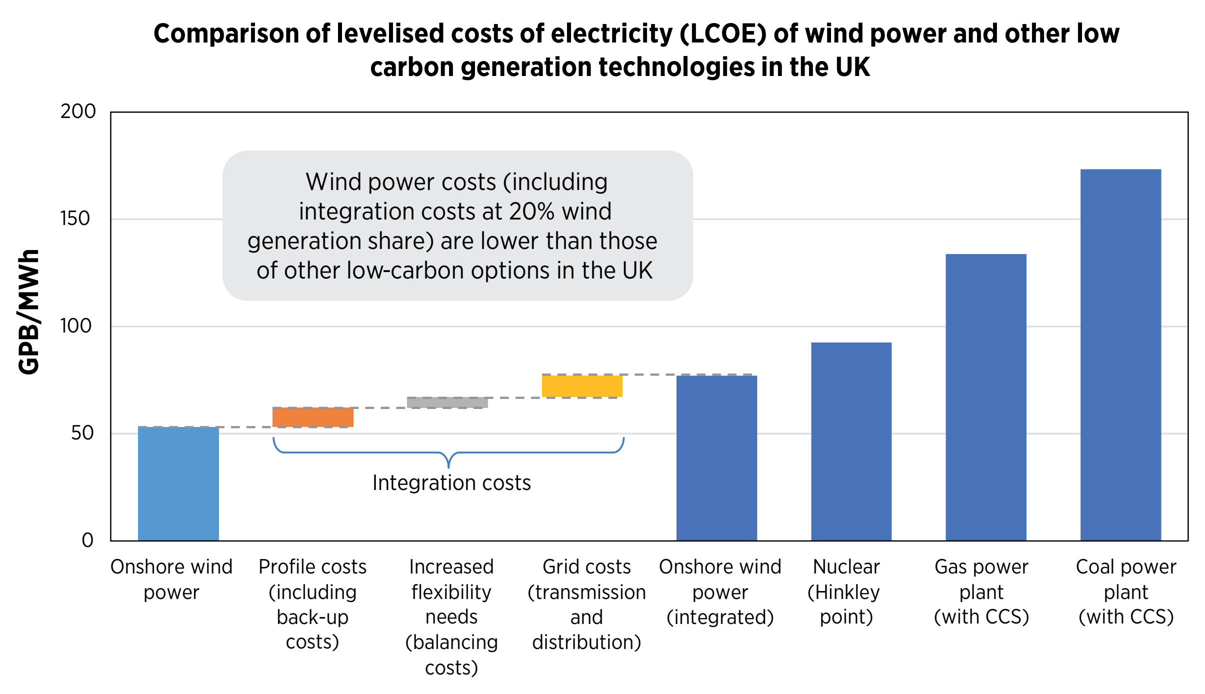
High shares of renewables are economically efficient in many power systems when both costs and benefits of all power sources are considered

While the generation costs of renewable power projects can be in the cost range of conventional generators (IRENA, 2015b), the impacts of variability might discourage renewable energy expansion. However, the economic viability and competitiveness of VRE increase if the full costs and benefits of all technologies are accounted for.

Most importantly, factoring in the appropriate costs of climate change caused by burning fossil fuels significantly enhances the competitiveness of renewable energy. Many climate change mitigation studies, which consider carbon costs, show that renewables are a crucial mitigation option (IPCC, 2011; GEA, 2012). The IPCC (2011) has shown in a comprehensive review that, in the majority of forecast scenarios, renewables become the dominant supply option by 2050.

IRENA's REmap analysis (IRENA, 2014a) confirms that high shares of power generation from renewables actually reduce total power generation costs if climate change and the health impacts of conventional plants are considered. Increasing the electricity share of renewables in the 26 REmap countries from 18% in 2010 to 44% in 2030 will lead to cost savings in the range of

Figure 4: Generation cost data for onshore wind power, nuclear, gas and coal power plants (with CCS).



Source: Data for onshore wind power, and gas and coal power plants with carbon capture and storage (CCS) are based on the UK Department of Energy and Climate (DECC) calculator for low carbon scenarios (assumed discount rate of 10%) and IRENA (2015c). For nuclear power, costs are estimated from the strike price guaranteed to the operators of the planned reactor Hinkley Point C (92.5 GBP per MWh for 35 years, fully indexed to inflation). Wind integration costs are estimated conservatively according to cost values in SKM (2008), Strbac, et al. (2007), Gross, et al. (2006) and Hirth, Ueckerdt and Edenhofer, (2015). We assume wind shares of 20%. For lower shares integration costs would be reduced. Also, additional measures such as smart grid technologies, demand response, energy storage and more flexible generation technologies would reduce integration costs.

EUR 5-60 per MWh (compared to a business-as-usual scenario of 26% renewable electricity in 2030). Hence, energy policy should account for all costs including environmental and health impacts when evaluating power supply options.

Among low-carbon technologies, renewable energy technologies take prominence for both economic and sustainability reasons. Comparing the levelised costs of electricity for onshore wind power in the UK with those of fossil plants combined with carbon capture and storage (CCS) and nuclear plants implies that renewables are economically favourable, even considering the cost impacts of variability (*Figure 4*).

In addition to the cost advantages, there are broader sustainability advantages of renewable energy sources compared with other low-carbon technologies. Fossil plants combined with carbon capture and storage (CCS) and nuclear plants face much more severe sustainability impacts than renewables plants. This reduces the social acceptance of nuclear and CCS plants. If a society considers sustainability concerns of paramount importance, renewable energy technologies are clearly the most important low-carbon technologies.

In the past, the main argument for ambitious renewables targets and policy support schemes was mitigating greenhouse-gas emissions. This argument has broadened in recent years. Other social objectives have gained importance, such as energy security, job creation, reducing local environmental damage, poverty reduction and energy access (IPCC, 2011; IRENA, 2014b; IRENA, 2014c). There is a broad consensus that reducing local environmental impact and greenhouse-gas emissions are convincing economic arguments for a positive cost-benefit balance of policies aimed at accelerating the deployment of renewable energy, including accounting for baseload provision.

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