Transition towards a decarbonised electricity sector – A framework of analysis for power system transformation
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## Abbreviations

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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
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<tr>
<td>AGC</td>
<td>Automatic Generation Control</td>
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<tr>
<td>BMU</td>
<td>The Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und Nukleare Sicherheit)</td>
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<tr>
<td>CAES</td>
<td>Compressed Air Energy Storage</td>
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<tr>
<td>CAMMES (CAMMESA)</td>
<td>Administrative Company of the Wholesale Electricity Market (Compañía Administradora Del Mercado Mayoralista Eléctrico Sociedad Anónima)</td>
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<tr>
<td>CCGT</td>
<td>Combined Cycle Gas Turbines</td>
</tr>
<tr>
<td>CECRE</td>
<td>The Special Regime Control Centre (Centro de Control del Régimen Especial)</td>
</tr>
<tr>
<td>CESI</td>
<td>European Confederation of Independent Trade Unions (Confédération Européene des Syndicats Indépendants)</td>
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<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>COP</td>
<td>Conference of the Parties</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
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<tr>
<td>DER</td>
<td>Distributed Energy Resources</td>
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<tr>
<td>DISCOMMs</td>
<td>Distribution Companies</td>
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<tr>
<td>dRES</td>
<td>Dispatchable Renewable Energy Sources</td>
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<tr>
<td>DS3</td>
<td>Delivering a Secure, Sustainable Electricity System Programme</td>
</tr>
<tr>
<td>DSO</td>
<td>Distribution System Operator</td>
</tr>
<tr>
<td>EAPP</td>
<td>Eastern Africa Power Pool</td>
</tr>
<tr>
<td>ENTSO-E</td>
<td>European Network of Transmission System Operators for Electricity</td>
</tr>
<tr>
<td>ESMAP</td>
<td>Energy Sector Management Assistance Programme</td>
</tr>
<tr>
<td>ETS</td>
<td>Emissions Trading System</td>
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<td>FIP</td>
<td>Feed-In Premium</td>
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<td>FIT</td>
<td>Feed-In Tariff</td>
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<td>FRT</td>
<td>Fault Ride Through</td>
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<td>GHG</td>
<td>Greenhouse Gas</td>
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<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>GIZ</td>
<td>German Corporation for International Cooperation (Gesellschaft für Internationale Zusammenarbeit)</td>
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<tr>
<td>GW</td>
<td>Gigawatt</td>
</tr>
<tr>
<td>GWh</td>
<td>Gigawatt hours</td>
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<tr>
<td>HVDC</td>
<td>High Voltage Direct Current</td>
</tr>
<tr>
<td>ICT</td>
<td>Information and Communication Technology</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
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<tr>
<td>IKI</td>
<td>International Climate Initiative (Internationale Klimainitiative)</td>
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<tr>
<td>IRENA</td>
<td>International Renewable Energy Agency</td>
</tr>
<tr>
<td>KETRACO</td>
<td>Kenya Electricity Transmission Company Limited</td>
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<tr>
<td>kV</td>
<td>Kilovolt</td>
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<tr>
<td>kW</td>
<td>Kilowatt</td>
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<tr>
<td>kWh</td>
<td>Kilowatt hours</td>
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<tr>
<td>LCPDP</td>
<td>Least Cost Power Development Plan</td>
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<tr>
<td>LDC</td>
<td>Load Duration Curve</td>
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<tr>
<td>MINEM</td>
<td>Ministry of Energy and Mining</td>
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<tr>
<td>MW</td>
<td>Megawatt</td>
</tr>
<tr>
<td>MWh</td>
<td>Megawatt hours</td>
</tr>
<tr>
<td>MtCO$_2^{eq}$</td>
<td>Metric tons of carbon dioxide equivalent</td>
</tr>
<tr>
<td>NDC</td>
<td>Nationally Determined Contribution</td>
</tr>
<tr>
<td>OECD</td>
<td>Organisation for Economic Co-Operation and Development</td>
</tr>
<tr>
<td>PHS</td>
<td>Pumped Hydro Storage</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>REE</td>
<td>Spanish TSO (Red Eléctrica de España)</td>
</tr>
<tr>
<td>REN21</td>
<td>Renewable Energy Policy Network for the 21st Century</td>
</tr>
<tr>
<td>RES</td>
<td>Renewable Energy Sources</td>
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<tr>
<td>RES-E</td>
<td>Electricity from Renewable Energy Sources</td>
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<tr>
<td>RO</td>
<td>Renewable Obligations</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>-------------</td>
<td>--------------------------------------------------</td>
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<tr>
<td>RPO</td>
<td>Renewable Energy Purchase Obligations</td>
</tr>
<tr>
<td>RPS</td>
<td>Renewable Portfolio Standards</td>
</tr>
<tr>
<td>SNSP</td>
<td>System Non-Synchronous Penetration</td>
</tr>
<tr>
<td>SONI</td>
<td>System Operator for Northern Ireland</td>
</tr>
<tr>
<td>TFC</td>
<td>Total Final Electricity Consumption</td>
</tr>
<tr>
<td>TW</td>
<td>Terawatt</td>
</tr>
<tr>
<td>TWh</td>
<td>Terawatt hours</td>
</tr>
<tr>
<td>REC</td>
<td>Renewable Energy Certificates</td>
</tr>
<tr>
<td>TSO</td>
<td>Transmission System Operator</td>
</tr>
<tr>
<td>UNDESA</td>
<td>United Nations Department of Economic and Social Affairs</td>
</tr>
<tr>
<td>UNFCCC</td>
<td>United Nations Framework Convention on Climate Change</td>
</tr>
<tr>
<td>vRES</td>
<td>Variable Renewable Energy Sources</td>
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Glossary

**Aggregators**
Aggregators are companies that aggregate a number of grid-connected units (such as end-users and distributed resources), provide services to the grid and participate in the market on behalf of the aggregated units as one single entity. From the system operation point of view, an aggregator acts as intermediary between end-users and other power system participants.

**Curtailment**
Curtailment describes an intended, temporary reduction of the power output of variable renewable energy plants compared to the actual potential offered by the resource. This may be motivated by network congestion, operational restrictions of the generation mix (e.g. minimum must run capacity from dispatchable plants) or other reasons.

**Dispatchable generators**
The electricity production of dispatchable generators does not depend on fluctuating resources like wind and solar. Generally speaking, dispatchable generators are controllable and their availability can be scheduled.

**Distributed Energy Resources (DER)**
Distributed energy resources (DER) are small- to medium-scale resources that are mainly connected to the lower voltage levels (distribution grids) of the system or near the end users. DER can consist of one or several of the following elements: distributed generation, energy storage and demand response.

**Dynamic line rating**
Dynamic line rating describes an approach of operating overhead lines allowing some overloading in case of favourable conditions instead of fixed maximum loading according to datasheets or standards. Overhead lines are heated by the current flowing through the wires. The maximum temperature is determined by the manufacturers’ component specifications and by the resulting sag of the line (minimum clearing distance to ground). However, in case of low ambient temperature or strong wind, the conductors of an overhead line are effectively cooled and, hence, with the same current their temperature is lower than under conditions assumed in standards and manufacturers’ specifications.

**Fault**
An electrical fault is an abnormal condition in a power system resulting in a parameter (e.g. current or voltage) exceeding specifications. Electrical faults can be caused by equipment failures, human errors or environmental conditions. Faults need to be managed and, hence, proper planning and design of electrical power systems needs to consider realistic fault scenarios (see also protection).
Flexibility parameters of dispatchable generators

In power systems, flexibility can be understood as the capability of the system to cope with sudden changes and uncertainty at different time scales in an efficient manner. Some parameters determining the flexibility that dispatchable generators can provide are **ramp rates, start-up times, minimum loads and cycling**. **Ramp rates** refer to the rate of change in a power plant’s output from maximum to minimum generation (i.e. ramp-down), or vice-versa (i.e. ramp-up). **Start-up time** is the period that a power plant takes from being offline to injecting power into the grid. **Minimum operating load** is the lowest output a power plant can generate in a reliable and efficient way. **Cycling** is referred to as the start-up and subsequent shut-down of a power plant. Factors influencing the cycling of power plants include their economic viability, equipment’s lifetime, maintenance, and the minimum time required to be operating once plants have started generating (or time required to be offline when they have shut-down).

**High Voltage Direct Current (HVDC) links**

If power is transmitted over very long distances, the costs of alternating current (AC) overhead lines and their resulting losses increase considerably. In these cases, high-voltage direct current (HVDC) lines are an efficient and economical alternative. With dedicated converter stations, AC power is converted to DC, transported for very long distances with HVDC links and converted back to AC. DC links allow the coupling of systems that do not operate in synchrony (i.e. at different nominal frequency levels). However, some benefits of synchronous connection (e.g. inertial response) are lost when using HVDC links.

**Imbalance**

From a system operation point of view, imbalance describes the difference between generation and load at a given point in time. From a market perspective, imbalance describes the difference between the energy committed ahead in the dispatch by a market participant and its actual energy delivered in real time. Such imbalances in the market are typically reflected in additional costs.

**Inertia**

Inertia refers to the kinetic energy stored in the rotating mass of synchronous generators and their drive trains. Synchronous generators are the standard technology in thermal and hydroelectric power plants. Immediately after a contingency event (e.g. sudden shortfall in power), system inertia supports system frequency before reserves pick up. As vRES displace generation from synchronous machinery with power electronic converters that do not provide inertia, overall system inertia will be reduced in the long term.

**Marginal costs**

Marginal cost is the incremental cost of generation when the output of electricity is being increased marginally. In the short-run, marginal cost is typically determined by variable costs (in particular fuel cost). Once installed, vRE generators can generate electricity with little additional costs, which makes their marginal costs equal to zero (or near zero). At the system level, the system marginal cost is determined by the variable cost of the marginal unit generating at a given moment in time.
Meshed vs radial networks

The spatial structure of networks, i.e. their topology, varies depending on geographical features, generation and load characteristics, reliability requirements, voltage levels, grid investment costs and environmental impact. In general, a distinction can be drawn between meshed and radial networks. Meshed networks are redundant and offer multiple paths (i.e. branches) to reach loads from nearby nodes. As a consequence, not every fault forces a supply interruption for the connected customers. A meshed topology is most common in transmission grids (i.e. high voltage). Radial networks resemble a tree shape where power flows in a unidirectional way. A single failure often results in supply interruptions for some customers connected to the affected branch. A radial topology is most common in distribution grids (i.e. low voltage).

Must-run capacity

In many power systems, the term must-run-capacity is used for power plants which generate power although the merit order does not require them to be operational for the energy-only market. Reasons for keeping them online may be their importance for providing ancillary services or their operational inflexibility/prohibitive costs for shut-down and restart. The definition of must-run capacity is driven by technical restrictions but determined by regulation and energy policy.

Nowcast

Nowcast refers to the shortest-term forecast of vRES availability and generation. A nowcast provides information on a very short time period in the future (for the coming 2 to 10 hours) and with high temporal granularity (i.e. forecasts for fractions of an hour). The information provided by nowcasts is valuable for variable renewable energy generators, system operators and market players.

Power electronic converters

Power electronic converters take the electrical energy from a power source, i.e. DC current in the case of solar PV and wind power, and convert it into a suitable form needed by the system, i.e. AC current. Power electronic converters use power semiconductors to regulate and shape the exported current in the required form. As the shape of the current solely depends on the control of the power electronic converter and not on the rotational speed of the generator (as opposed to synchronous generators), generation using power electronic converters is called non-synchronous.

Power electronic converters behave differently than synchronous generators in some respects:

- They represent a current source and are not able to energise a network without some existing voltage;
- They have a lower short circuit capacity than synchronous generators;
- They have no inertia so that system frequency changes more rapidly when responding to power imbalances.

Protection

In electrical power systems, all electrical circuits, assets and generation units are subject to faults. Protection is essential in order to maintain stability of the system and minimise the impact of faults, i.e. avoid damage, minimise supply interruptions and maintain or restore parameters to their tolerances. To this end, protection systems must:

- Detect fault conditions and respond to them within appropriate time frames (speed);
• Clearly distinguish between faultive and healthy situations, including transient values like inrush over-currents (sensitivity);
• Be selective in a sense that they isolate the fault but as little as possible of the healthy system (security);
• Be completely functional whenever a fault situation occurs (reliability).

**Regulation power and reserves**

The reliable operation of power systems requires to hold reserves readily available to restore system balance. Event related reserves can be distinguished from non-event related reserves. Event related reserves, for example, provide electricity supply in the case of unexpected contingencies such as component failures or power plant tripping. Non-event related reserves are essential for compensating forecast errors or the inevitable permanent noise in supply and demand patterns.

**Residual load**

Residual load is understood as the part of the total load that is not supplied with generation from variable renewable energy sources, i.e. wind and solar power, and needs to be covered through other technologies, i.e. dispatchable energy sources. In simple terms, residual load is the difference between total load and variable renewable energy generation in a given period or moment in time.

**Resource-adequacy mechanisms**

In liberalised power sectors, where investment decisions are not centralised, resource-adequacy mechanisms, also known as capacity mechanisms, are regulatory instruments that aim to overcome market failures and encourage investments that guarantee the availability of electricity supply in the long-run. As such, resource-adequacy mechanisms can reinforce the economic signal provided by other electricity markets (usually short-term markets) in order to attract enough investment and ensure system adequacy.

**Resource and generation adequacy**

Resource and generation adequacy define the required availability of resources in the system – i.e. generation assets and demand resources – either installed or expected to be installed, to match supply and demand in the long-term. As the availability of power plants can be described by statistical distributions, the commonly accepted level of shortage or generation deficit is a key input parameter for assessing adequacy.

**Synchronous generators**

The terminals of synchronous generators are directly connected to the network. The shape of the current ejected into the network is determined by physical laws and the rotational speed of the generator is the same as the system frequency. Because of this synchronism the mechanical energy stored in the rotating masses of the generators is coupled to the system (see inertia).
1. Introduction

The global energy sector is undergoing a rapid and radical transition of the way energy is produced, distributed and consumed. The shift is motivated by the urgency to ensure secure energy supply, achieve sustainable development and limit climate change. Technological innovation, the rapid decline in costs and rising investments in renewable energy and energy efficiency determine the pace and the direction of the transition. Increasing certainty about the destination of this process – while the best way to get there is still unclear – make a strong case for the development of adequate institutional and policy frameworks that can support countries on their way to a modern, low-carbon energy sector.

The energy sector is at the core of global efforts to combat climate change. Around two thirds of global greenhouse gases (GHG) and 90% of carbon dioxide (CO₂) emissions stem from energy production and use (OECD/IEA, 2018a). Hence, the transition to a cleaner and more efficient energy system is key for achieving the global goal of the Paris Agreement to limit global temperature rise to well below 2°C, aiming at 1.5°C. Studies have shown that in order to be consistent with a 1.5°C pathway, global total CO₂ emissions must become net zero at around 2045-2060. A rapid and full decarbonisation of the global energy system by mid-century is therefore essential (Rogelj et al., 2015).

Key for a comprehensive transformation of the energy system is the decarbonisation of the power sector (Rogelj et al., 2015). Unabated fossil-based electricity generation must be phased out, and the introduction of low-carbon technologies accelerated. Power systems around the world are already undergoing a transformation process, which is accompanied by rapid cost reductions in supply- and demand-side technologies, increasing digitalisation, the promotion of system resilience, and the expansion of energy access through innovative technology and market solutions (OECD/IEA, 2018b). Reflecting this development, the International Energy Agency (IEA) refers to “power system transformation”, describing the creation of a policy and market environment that encourages innovative and sustainable technology solutions for electricity production, distribution and consumption (OECD/IEA, 2018c).

A major concern in the context of power sector transformation is the smooth integration of large amounts of variable renewable energy capacities (i.e. wind and solar) into existing power systems. These variable sources have specific features that differ from those of dispatchable energy sources, posing new and fundamental challenges to the operation and governance of a power system. It is important that these challenges and their temporal sequence are recognised and understood in order to identify adequate and timely measures to address them. While at a technical level, proven measures exist for many of the technical challenges identified to date, adequate policy frameworks that support the implementation of these measures in a specific country context are often more difficult to determine and must be decided on a case-by-case basis.

The objective of this paper is to support policy makers and energy sector planners to better understand in which stage of the power system transformation process their country finds itself, with a focus on the technical configuration of this country’s power system and the resulting challenges posed by the integration of variable renewable energy sources. Technical measures are defined that can help to address and resolve these challenges. At a policy level, more general guidance is provided for policy makers and technical experts.
in the energy sector on how to facilitate the design and implementation of a smooth transition towards a Paris-compatible power sector.

Following the introduction, chapter 2 defines the term ‘power system transformation’ in the context of the Paris Agreement. In chapter 3, specific features of variable renewable energy sources are analysed that are often perceived to create new challenges for existing power systems. Chapter 4 focuses on the different phases of power sector transition and how challenges interact with the time dimension. In chapter 5, country specific geographical and socio-economic characteristics are revealed and their interaction with the challenges is analysed. Chapter 6 includes a set of technical measures to address the challenges. The results of the analysis are consolidated in chapter 7. Finally, the different steps of analysis are illustrated in chapter 8 at the example of eight country cases, offering a snapshot of the country’s situation with a view to the power system transformation process and including a set of recommendations for policy makers to reach the next stage.
2. Defining power system transformation in the context of the Paris Agreement

The Paris Agreement, which was negotiated during the 21st Conference of the Parties to the UNFCCC (COP21) in 2015 and entered into force in 2016, creates a new imperative for global efforts to limit climate change and foster sustainable development: Article 2a formulates the overall goal of the Agreement as “holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C” (UNFCCC, 2015). To achieve this objective, total global GHG emissions must be reduced to net-zero by the end of the century. This creates a need to reach full decarbonisation of the global energy system and net-zero CO₂ emissions by around 2050 (Rogelj et al., 2015).

A full decarbonisation of the energy system requires huge efforts in various sectors, including in the transport, industry and buildings sectors. However, a major part of the transition of the energy system is the decarbonisation of the power sector (Rogelj et al., 2015). In 2014, electricity generation was responsible for almost 42% of energy-related CO₂ emissions, making the power sector the largest single sector contributing to climate change (Sterl et al., 2017). It is expected that the power sector must decarbonise earlier than other sectors, given that it is the only sector where market ready emissions-free technology solutions exist already today. Moreover, the feasibility of deep emission cuts in other sectors, for example through increased electrification, heavily depends on a successfully decarbonised power sector.

Reflecting the great relevance of power sector decarbonisation, the IEA recently defined the term “power system transformation” as “the active process of creating the policy, market and regulatory environments, as well as establishing operational and planning practices, that accelerate investment, innovation and the use of smart, efficient, resilient and environmentally sound technology options” (OECD/IEA, 2018c).

Different interpretations exist regarding the final state of a full “power system transformation”. In this paper, the importance to fully decarbonise the power sector and achieve a 100% renewable energy-based electricity production in the long-term is stressed. Renewable energy sources (RES) thereby refer to wind, solar, hydro, geothermal, biomass and wave and tidal power. While natural gas may serve as a bridge technology to a low-carbon energy future, particularly in those countries that have natural gas infrastructure, nuclear power is not considered to be a renewable energy source.

In many countries around the world, the transformation of the power sector has taken up speed due to the rapid development and deployment of RES at decreasing costs. Yet, there is an intense debate on the feasibility and viability of a full power system transformation resulting in a 100% renewable-based power system (see e.g. Heard et al., 2017; Brown et al., 2018). Although many countries have embarked on the transition process, only one country has achieved a full power sector transformation to date: Iceland can claim to have a 100% renewable-based power system, thanks to its generous endowment of dispatchable renewable energy sources (dRES), i.e. geothermal and hydropower. Other countries that come very close to the 100% include Paraguay (99%), Norway (97%), Uruguay (95%), and Costa Rica (93%), all of which have sufficient

While nuclear power is a low-carbon technology, it is not considered a renewable energy source. The role that nuclear power can play in the power system transformation process in countries that have an existing fleet (e.g. France, Japan, South Korea) needs further consideration which however goes beyond the scope of this report.
synchronous generation from either hydropower, geothermal or biomass, or have an interconnection to a neighbouring country (Brown et al., 2018b).

Little practical experience exists on how countries without significant potential for dRES and/or interconnections to neighbouring countries can make the transition to a 100% renewable-based power sector.
3. Characteristics and challenges of variable renewable energy sources

In most regions of the world, substantive generation capacity from variable renewable energy sources (vRES) will be needed to decarbonise the power sector. The integration of vRES gives rise to specific technology challenges in power system planning and operation which have to be tackled adequately during the power system transformation process:

- The driving natural resources are fluctuating. To permanently maintain the required balance between generation and load, dispatchable and flexible generation is required. This affects system planning and operational concepts and impacts power markets.
- **Forecasting accuracy is limited**, meaning that system operation needs to deal with deviations between expected and actual generation.
- Often, large renewable capacities are installed in remote locations, such as coastal or offshore areas in case of wind, or deserts in case of large solar installations. This means that transmission networks must be built and expanded in order to bring the power to the load centres.
- Substantial vRES capacities are small scale, dispersed and connected to lower voltage levels. Examples are solar rooftop PV plants or solitaire wind turbines. This results in a need to adapt distribution networks. From a system operator’s point of view, small scale generation plants are invisibly embedded and difficult to monitor or control. This is different from the past, where most of the generation was connected to transmission networks and closely monitored in real time by the system operator. With high vRES shares, technical facilities and operational procedures need to be implemented allowing reasonable access to these capacities as well.
- Wind and solar technologies use (static) electronic power converters instead of synchronous generators (rotating machinery). The behaviour of these technologies differs, for example in case of disturbances, but is largely a matter of design and programming.
- In contrast to larger power plants, small scale and dispersed generation like rooftop PV is not permanently operated and maintained by professionally trained staff. Once installed, plants run without close supervision. After some time, the plant’s behaviour may not meet the requirements anymore, either because requirements have changed but plant characteristics have not been adjusted or because settings of the facility have been modified without giving notice to the network or system operator. To keep an informed overview of the status of the system it is important to maintain a register of all generation facilities regardless of their size.
- Once installed and operational, vRES technologies can generate electricity at very little (near zero) marginal cost, depending on the availability of the variable renewable source (i.e. wind or sun). This has implications for system operation and electricity markets where these exist: under an economic dispatch, vRES technologies are always among the first plants to be dispatched to meet the demand, displacing technologies with higher variable generating costs (i.e. conventional generators). Hence, market shares of conventional generators are reduced, which also affects the cost structure of the system.\(^2\)

\(^2\) A thorough analysis of the cost structure of vRES and its implications is beyond the scope of this report.
In the following, several key technical challenges that are typically encountered during the integration of vRES in existing power systems are listed.

- **Load balancing and reserves**: This challenge refers to the limitations of the system, mainly the supply side, to cope with the additional variability and uncertainty introduced by an increasing penetration of vRES. From the technical point of view, stricter balancing requirements include, among others, adjustments of reserves, steeper generation gradients, and shorter start-up times for generators. Traditionally, dispatchable generators have been the main source of flexibility to respond to imbalances in the system, serving as an enabler for the integration of renewable energy sources. The sizing and procurement of reserves is closely associated with the capability of the system to keep the balance between supply and demand. The increasing penetration of vRES into the system demands a re-evaluation of the current practices around balancing requirements and reserves management. For instance, definition of the necessary amounts of reserves and their allocation should account for load and vRES forecasts and the impact of their accuracy on the system’s reliability. A system that is not able to cope with load balancing challenges may face the emergence of other challenges such as non-served demand or excessive vRES curtailments.

- **Monitoring and control**: The reliable operation of a power system requires a minimum level of visibility and control of its generation resources to be able to respond to all contingencies. Conventional power systems were designed and built to operate with a top-down unidirectional power flow, from centralised, controllable power plants to decentralised consumers. The increased participation of decentralised vRE generation is changing this paradigm. Concepts for monitoring, control and protection of power systems need to be adjusted accordingly. Control and monitoring challenges grow with the share of renewables connected to lower voltage levels (i.e. at the distribution level). In order to facilitate the identification of measures to address the challenges, control and monitoring challenges can be divided in two broad categories:
  - Monitoring, communication and control challenges in **system operations**: This refers to challenges associated with the operation of the system in the short- to real-time (e.g. between a couple of days ahead to real-time operation).
  - Monitoring and communication challenges in **planning and development**: This refers to challenges in the long-run. The planning and development of power systems rely on monitoring and communication tools that enable the safe and reliable deployment of different technologies. The small-scale and distributed character of vRE technologies require a revision and coordination of these planning and development tools.

- **System Non-Synchronous Penetration (SNSP)-related challenges**: VRES technologies, mainly wind and solar PV, rely on power electronic converters, so called non-synchronous generation. In contrast to traditional generators, these converters do not directly contribute to providing inertia to the power system, challenging how traditional systems maintain a safe and reliable operation. This also applies to High Voltage Direct Current (HVDC) links in transmission networks. In many aspects, these converters behave differently than the synchronous generators found in thermal or hydro power plants\(^3\). Massive replacement of synchronous generation from thermal or hydro power plants by

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\(^3\) For more details on power electronic converters see Glossary.
wind and solar plants changes the behaviour of the entire power system. The difference in technology is independent from and additional to the fluctuating character of the resource. This challenge is particularly relevant for non-interconnected systems with little inertia (e.g. small isolated systems with little inertia) that cannot rely on their links with synchronised systems to provide the required inertia.

- **Network congestion and restrictions from network operation:** The grid is the backbone of the power system, being the physical link between supply and demand. The capacity of the network and its operation play a key role in keeping the system in balance. In fact, other challenges – e.g. non-served energy or excessive vRES curtailments – can be linked to network-related limitations. Together with supply-side flexibility, network congestions are among the first challenges encountered by countries when embarking on the power system transformation process. The strong influence of geographical and demographic characteristics of a country on the design and planning of power networks implies that some countries face more pronounced network-related challenges than others.

- **Reduced utilisation of dispatchable plants needed to balance fluctuations:** The effect of increasing shares of vRES to the operation of conventional generators is twofold. On the one hand, dispatchable generators are needed to provide operational flexibility (steeper gradients, shorter start-up time, etc.) to cope with the increased variability and uncertainty in the system and peaking dispatchable units are also desirable to cover peak residual load. On the other hand, an increasing share of vRES in the system, with low to zero marginal costs, reduces the average wholesale electricity prices and displaces generation from thermal generators, impacting their profitability and inducing a change in the cost structure of the system. In consequence, conventional generators are forced to reduce their electricity output while increasing the provision of flexibility needed by the system. The adoption of technical and policy measures to ensure the availability of flexible capacity on the supply-side must take this conflicting interplay into account. Such measures must consider the change of system cost structures due to a greater penetration of vRES.

- **System balance and negative residual load:** In advanced stages of the power system transformation, i.e. in systems with very high shares of vRES penetration, the instantaneous generation potential – driven by renewable energy sources – will regularly exceed the load in the area. Negative residual load means that the system is not able to absorb all the power generated. If no structural changes occur in the system (e.g. no change in demand pattern, no further interconnections), a substantial growth of vRES capacity will lead to significant variable renewable energy generation curtailments that are not economically viable. In the first place, the assessment of curtailment as a solution or as a challenge requires a cost-benefit analysis that evaluates a) different investment options to reduce curtailments, and b) the economic and environmental losses due to curtailment. While in early phases of the transition process, temporary and moderate curtailment of vRES can be a source of flexibility or even as a reliability measure for the safe operation of the system\(^4\), later phases of the transition process may witness curtailment as a result of oversupply of renewable energy (currently, this is an issue in very few countries). Prolonged and large curtailments are typically indicators of non-flexible systems. vRES curtailment constitutes a challenge in the decarbonisation of power systems, because, if unsolved, it implies that further penetration of vRES will not translate into higher renewable shares but into greater curtailment levels. The challenge of curtailment is exacerbated

\(^4\) vRES curtailments are a structural part of planning and operation of power systems with enhanced shares of renewables. In early phases of vRES system integration, curtailments are typically a response to limited supply side flexibility and network congestions.
when more expensive and polluting technologies continue generating instead. To overcome this challenge, vRES generation inevitably has to be combined with seasonal storage, interconnections and/or sector coupling.

Table 1 captures the relationship between vRES characteristics and challenges, which in a later instance facilitates the identification of key technical measures to overcome them.

Table 1: Simplified presentation of interactions between specific features of vRES and challenges

<table>
<thead>
<tr>
<th>Feature</th>
<th>Fluctuating resources and generation</th>
<th>Limited forecast and scheduling accuracy</th>
<th>Electrically remote</th>
<th>Small-scale, dispersed and connected to lower voltage levels</th>
<th>Electronic power converters instead of synchronous generators</th>
<th>Not permanently operated and maintained by professional staff</th>
<th>Very little marginal cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load balancing and reserves</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Monitoring, communication and control (planning and development/system operations)</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td></td>
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<tr>
<td>SNSP-related challenges</td>
<td></td>
<td>X</td>
<td>X</td>
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<tr>
<td>Network congestion and restrictions from network operation</td>
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<tr>
<td>Reduced utilisation of dispatchable plants needed to balance fluctuations</td>
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<td>X</td>
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<td>X</td>
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<tr>
<td>System balance and negative residual load</td>
<td>X</td>
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</tr>
</tbody>
</table>
4. Phases of power system transformation

Countries undergo different phases in the power system transformation process that mark the steps of increasing shares of vRES in a country’s power mix and the specific configuration of the power system along with this transformation process. Six phases can be distinguished, from phase 0 (pre-development – negligible amount of vRES shares) to phase E (stabilisation – over 80% vRES shares). Each phase of the power system transformation process gives rise to a set of technical challenges linked to the proceeding integration of vRES.

Box: Phases of power system transformation

The approach taken here is very similar to the six phases of vRES integration identified by the IEA (IEA, 2019; OECD/IEA, 2018d). Yet the phased approach described below places a focus on the necessary changes in the configuration of the power system, looking at specific parameters and how they change from one phase to the other, and outlines concrete challenges per phase. The role of the country context and how certain characteristics can shape the challenges and either accentuate or alleviate them is also analysed in detail.

4.1. Conceptual background

The progress from one phase to the next and the respective changes in the configuration of the power system can be described along the following parameters:

- **Installed vRES capacity in relation to system’s minimum and peak load**: from zero vRES capacity (in % of peak load) in the first phase to a saturation level at the end of the transformation process;
- **Coverage of the annual load**: from zero load coverage through vRES in the first phase to 100% of load supply at the end of the transformation process;
- **Carbon intensity**: from x tons of CO2 emissions per kWh of electricity generation in the first phase to zero CO2 from electricity generation at the end of the transformation process.

The following four graphs illustrate these three parameters and their interdependence. They allow to identify milestones which characterise particular phases of power system transformation.
**Installed capacity of vRES and range of instantaneous generation**

The **installed capacity** of vRES plants measured in GW will grow over time. The installed capacity determines the maximum instantaneous generation from vRES, i.e. the peak generation which has to be managed by the system operator. In very few geographical areas the maximum infeed will be close to the installed capacity. In extended regions (e.g. Europe) with a lot of distributed generation, the correlation between the wind and the solar resource will be limited and the maximum instantaneous generation lower than the total installed capacity.

With the growth of installed capacity, the range of instantaneous generation passes two symbolic milestones: in a certain year, installed vRES capacity equals the **minimum system load** and the **peak load**. These characteristic values are indicated by the lower and upper edges of the filled area in the bar on the right.

**RES-share in annual load coverage**

With an increase in the installed vRES capacity, the **share** of wind and solar electricity in the total electricity supply, i.e. the **load coverage** by vRES, increases as well.

It is important to note that the increase in installed capacity does not necessarily translate into an increase in the share of vRES in electricity generation (instantaneous penetration and yearly shares), as the later may be limited by technical system restrictions.

**Load duration curve**

The **load duration curve** (LDC)\(^5\) is traditionally used to illustrate the variation of a certain load over one year (8,760 hours) in a descending order. The load is represented by the total coloured area below the curve. With increasing vRES capacities, a growing share of the load is covered by vRES (area in light blue) while the area below the LDC not covered by vRES (dark blue) decreases. The latter part of the load needs to be supplied by other sources than vRES and is called the residual load.

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\(^5\) For a brief introduction into the concept of LDCs see for example [https://greycellsenergy.com/articles-analysis/load-duration-curves-and-peak-demand/](https://greycellsenergy.com/articles-analysis/load-duration-curves-and-peak-demand/)
Carbon intensity of electricity generation

The share of vRES in annual load coverage influences the total carbon emissions of the power sector and, hence, the carbon intensity of electricity generation. The basic assumption of policies supporting renewable energy is: the higher the annual vRES share in generation, the lower the carbon intensity of the power sector.6 (At first glance, the growing slope of the graph may look counterintuitive. This is due to the arrangement of the axes where the share of vRES in load coverage is shown on the y axis.)

Conceptual limitations

Data availability: It is important to note that while the graphs are meant as an illustration of important dependencies, it is generally impossible to derive general quantitative relationships from them. The data required to generate for example the LDC (hourly time series of load and generation preferably covering several years) is not available from any public database that covers a representative number of countries and power systems in a consistent way. For an individual country, however, the data may be obtained from the responsible system operator.

Simplification of the approach: The LDC represents a simplified ‘copper plate view’ of a system with a high degree of abstraction of electrical networks, geography and chronology. It ignores the impact of network congestion, technical parameters like voltage profiles and reactive power balance and all kinds of dynamic phenomena which may put restrictions on system operations. The chronological break of the load profile to build the LDC also limits the possibility to capture temporal aspects of the operation of the system and the valuation of flexibility. Hence, the LDC approach presents an optimistic – and not always realistic – view of system capabilities.

Comparability of the results: A comparison of countries along the four graphs in Figure 4 must take into account that although two countries may find themselves in the same phase, the graphs and the relationship between them may differ. For example, the same ratio of vRES capacity to peak load may translate into different shares of renewables to cover the load on an annual basis, due to different characteristics of power systems. Similarly, the same share of vRES may translate into different CO2 intensities. To account for these disparities, the analysis must be carried out at the country level.

4.2. Definition of phases

With the use of the introduced parameters, six phases of power system transformation can be distinguished with different implications for power system planning and operation. A careful analysis of each phase allows

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6 This basic statement accounts only for generation shares and assumes that the rest of the system stays the same e.g. no growing demand, export and imports remain constant, flexibility needs are neglected.
to understand, structure and address the technical challenges resulting from increased vRES integration into a power system better.\textsuperscript{7}

**Phase 0 – negligible amounts of vRES and no systemic effects**

At the starting point of the power system transformation the Installed vRES capacities are so limited that they do not have any noticeable impact on system load and power system operation. The LDC remains unchanged. The impact of variable renewables is insignificant at the system level but can be a local challenge.

![Figure 1: Development of vRES - Phase 0 with negligible vRES capacity.](image)

*General challenges to be tackled in phase 0 and all later phases:*

Some local network extensions and reinforcements may be required when connecting new vRES generation facilities in order to avoid any negative impact on the operation of the existing network and quality of supply.

\textsuperscript{7} Please note that the focus is placed on the integration of vRES into a power system, momentarily ignoring the possible availability of dRES in a country. How the availability of dRES as well as other country characteristics can facilitate or complicate the integration of vRES into a power system is being discussed in chapter 5.
Phase A – first systemic effects of vRES can be observed

As installed vRES capacity slightly increases and vRES start to contribute to the load, the residual load slightly decreases. The regular concepts of power system operation are still sufficient for day to day business. However, new incentives and adjustments in regulation may help to drive the transformation and increase efficiency along the process. Power system planning already needs to anticipate the upcoming phase.

**Figure 2: Development of vRES - Phase A with limited vRES capacity.**

**General challenges to be tackled in phase A and all later phases:**

In this phase some changes in system operation may be required, without affecting regular concepts. Most general challenges relate to load balancing and provision of reserves. Examples include:

- Existing tools for load-generation balancing may insufficiently reflect variability of wind and solar generation and respective forecasts need to be integrated;
- Control and system wide coordination of generation may not be sufficiently fast and correct when done manually by the dispatcher;
- Dispatch mechanisms, definition of schedules and operating system rules (e.g. power market design, when applicable) may need to reflect forecasted vRES generation and move closer to real time (e.g. day ahead or shorter);
- Operational processes, for example definition of the necessary amounts of reserves, their allocation and contracting may require review and adaptation.

Depending on the geographical location of the vRES capacities with respect to the existing network, also some transmission extension may be required in order to reduce network congestion or other restrictions from network operation.
Phase B – temporarily substantial shares of load are covered by vRES

As installed vRES capacity further increases (upper left in Figure 3) also the annual contribution to load grows (lower left in Figure 3). Because of the fluctuating character of vRES, the share in load coverage at particular times differs. There are periods where the vRES contribution is still very low and others where significant vRES penetration is achieved. Furthermore, hourly generation gradients become more extreme.

Figure 3: Development of vRES - Phase B with still limited but growing vRES capacity.

General challenges to be tackled in phase B and all later phases:

Power system planning and operation needs to be adapted to guarantee reliable and safe power supply. General challenges include:

Load balancing and reserves

- The system operator may need nowcasts for ‘invisible’ distributed generation connected to lower network levels;

Monitoring, communication and control

- Operating the system without real time data from and access to distributed generation may compromise system efficiency and security;
- Operating the system without established communication and coordination processes between system operator, transmission network operator and distribution network operators may compromise system efficiency and security;
- Connecting new generation capacity without established processes for monitoring and verification of conformity with technical codes and standards implies the risk of unexpected system behaviour in case of disturbances;
- Having no consistent, easily accessible and high-quality track record of the complete population of installed generation facilities, their specifications, characteristics and connection, is an obstacle in the long
run when it comes to assessing system behaviour and developing the system further. It is important to start collecting these records at an early stage of development already.

**SNSP-related challenges**

- Existing technical codes for network users may insufficiently reflect changing system needs. This may be particularly relevant for distributed generation at lower voltage levels;
- Protection schemes may require review and adjustment reflecting reverse power flows and changes in short circuit capacity;

**Network congestion and restrictions from network operation**

- Networks and their assets may require extension and reinforcement due to substantial power flows between regions at transmission level and across network levels;
- Uncoordinated operations of transmission system operators (TSOs) and distribution system operators (DSOs) in day to day operations introduce inefficiencies and may compromise system security;
- Reactive power becomes key for system stability due to intense transits and changed reactive power balances across network levels.

**Phase C – system operation with temporarily high system non-synchronous penetration (SNSP), technology restrictions**

VRES technologies, mainly wind and solar PV, rely on power electronic converters, so called non-synchronous generation. This also applies to High Voltage Direct Current (HVDC) links in transmission networks. In many aspects, these converters behave differently than the synchronous generators found in thermal or hydro power plants.

In phase C, situations where system behaviour is dominated by large portions of non-synchronous generation occur regularly (Figure 4).

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8 For more details on power electronic converters see Glossary.
Figure 4: Development of vRES – Phase C with vRES capacity similar to average load.

With existing technologies, there are limitations regarding the highest acceptable instantaneous penetration of non-synchronous generation in the total power balance. Quantifying the maximum allowable System Non-Synchronous Penetration (SNSP) is a key aspect of phase C.⁹

Accepting SNSP restrictions implies curtailment of vRES whenever the vRES share in instantaneous generation comes close to the maximum SNSP level or, in turn, the residual load is lower than the technologically required must-run capacity. Because of the small amounts of electricity being curtailed in this phase, curtailment often is the most economical way to restore system balance. From a policy perspective, it is important to understand which annual vRES shares can be achieved under a given SNSP restriction.

As long as technical restrictions limit the maximum instantaneous SNSP, the basic idea of further reducing the annual residual load by steadily increasing vRES capacity will not work. Assuming no fundamental changes of the load characteristics, a growing share of the potential vRES yield cannot be used. In the longer run, curtailment of vRES generation is not an economically viable option anymore and the annual share of vRES in covering the annual load tends to stagnate (Figure 5).

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⁹ As an example, Ireland has an SNSP limit of 65% today, with the objective to increase this limit to 75% over the coming years (see http://www.eirgridgroup.com/how-the-grid-works/ds3-programme/).
General challenges to be tackled in phase C and all later phases

A first step in this phase is to understand the interaction of power electronics with the system, quantifying the maximum SNSP in day to day operation which may reveal certain SNSP-related challenges. The following questions may be raised in this context:

- How much synchronous must-run capacity is required? What are the underlying reasons for allocating must-run capacity? Inflexibility of plants, lack of reserves or restrictions related to frequency or voltage response in systems with large contributions from power electronic converters?
- What are suitable concepts of voltage and reactive power management if more and more synchronous generators are replaced by vRES or generation is moving from the transmission to the distribution level?
- What are suitable concepts for frequency control if more and more dispatchable power plants are replaced by vRES?
- How does short circuit capacity in the network change? What does this mean for protection concepts and settings?
- Which of those aspects is most limiting for system stability and security of supply?

Technical restrictions related to high SNSP must be effectively addressed and overcome. Otherwise, despite further growth of vRES capacity, the RES share in total load coverage may stagnate. New concepts of power electronic converters are key, allowing them to completely replace synchronous machines. Once appropriate concepts have proven successful in several regions and commercial solutions are available, they may be replicated in other countries, facilitating the progress from phase C to phase D.

Additionally, new concepts for secure system operation for periods without any (thermal) must-run capacity are a precondition for further increase of vRES. This also affects provision of reserves.
Phase D – high load coverage by vRES over many hours to entire days and reduction of the periods with positive residual load below 5000 to 6000 hours per year

With a further increase in installed vRES capacities, the periods with zero or negative residual load increase (see green triangle below the x axis of the LDC in Figure 6). A negative residual load means that the system is not able to absorb the generated power. This may already happen in phase C from time to time. However, since in phase D the occurrences and associated volumes of affected electricity are significantly higher, curtailment is not economically viable anymore.

Figure 6: Development of vRES – Phase D with vRES capacity exceeding peak load.

General challenges to be tackled in phase D

The key challenges in phase D are related to excessive curtailments due to restrictions from network operation and to the reduced utilisation of dispatchable plants needed to balance fluctuations. Both aspects are essential for maintaining the system balance.

Fundamentally, there are three options for maintaining system balance in case of negative residual load:

- **Curtailment** of excess generation (limitation: not economically feasible);
- **Interconnection** allowing to export excess electricity to regions with a positive residual load, i.e. transfer in space (limitation: only possible for countries embedded in interconnected power systems);
- **Storage** allowing to transfer excess electricity from the moment of generation to the moment of demand, i.e. transfer along the time axis (limitation: implementation of seasonal storage is technically and economically challenging in itself).

Given that in phase D, the use of conventional dispatchable plants is reduced, another challenge lies in balancing intense fluctuations of the residual load. Now, more than before, the design and regulation of power markets may require a fundamental review. Note that these changes are potentially already desirable in
phases B and C, to send appropriate long-term signals in a system that anticipates to advance quickly in the power system transformation and reach phase D in the near to mid future.

Finally, the safeguarding of long-term generation and transmission adequacy can present a challenge that may require the implementation of dedicated policies. Strong signals and attractive conditions for investments in new generation capacity have to be implemented.

**Phase E – high shares of RES-E in load coverage (80+% RES-E scenarios)**

In phase E, the transformation process approaches the target system: a power system which is economically viable, technically reliable and secure, and sustainable in the long-term, operating at carbon levels close to zero.

The key technical challenges in phase C to D are related to decreasing or even negative residual load at the right end of the LDC. The left side of the LDC, however, only changes gradually. Even with extremely high vRES capacities, there are periods where variable renewable resources cannot cover significant amounts of the instantaneous load. Further extension of vRES capacity will not translate into a significant reduction of the annual residual load.

In order to achieve RES shares of 80% or higher on an annual basis with relevant contributions from vRES, RES generation inevitably has to be combined with several or all of the following options:

- Extended (Seasonal) storage;
- Extended interconnection allowing for exports and imports of power with geographic neighbours;
- **Sector coupling** allowing for export and import of power between economic sectors in the same country;
- **Import of renewable-based energy chemical carriers**, e.g. hydrogen production from renewable energy sources.

Depending on the country context, a focus on the development of these options may be more cost effective than increasing indigenous vRES capacities excessively, which might not even resolve the issue. However, the integration of these new processes into the power system will increase the load and change its patterns. This means that the shape and level of the LDC may substantially differ.

It is important to realise that while phases 0 to D follow in sequence, the efforts to reach phase E must be deployed in parallel to phases C and D in order to deliver results once these phases have been passed.
Ambition to Action

Figure 7: Development of vRES – Phase E with nearly complete load coverage by vRES.

**General challenges:**

Phase E involves many and very diverse challenges. The necessary changes do not only concern the power sector and one single country. Some examples:

- Charging infrastructure for electric mobility as well as large scale application of heat pumps affect infrastructure planning. Distribution networks must be reinforced in order to accommodate these new loads, also in areas where no vRES capacity will be installed. Network planners are faced with high uncertainty about how much of these new loads will finally penetrate the distribution networks. The target system is highly uncertain, due to unknown variables. In the past, planning and investment cycles for network infrastructure covered decades. Adjustments were possible along the way. Given the speed and the impact of the power system transformation this is changing.

- The uncertainty becomes even more relevant as the target system relies on technology advances in the other sectors. The success of electric mobility depends on progress of car manufacturers and their component suppliers (e.g. storage batteries). Large-scale application of heat pumps assumes an ambitious insulation level of buildings, i.e. an increase of the efficiency of the existing building stock. Changes like these must be initiated and pushed completely outside of the power system.

- Power-to-fuel technologies are capital intensive and associated with substantial financing costs, even when they are not operational. Revenues, in turn, can only be expected when the plants are running. In phases C and D excess generation occurs only during limited periods of the year and, hence, plant utilisation in these phases may be low. This represents an investment barrier for the technologies which may hinder the transition into phase E.

The complexity resulting from the diversity of uncertainties and challenges, the need for long term planning and coordination as well as the variety of affected stakeholders and economic sectors involved make it
difficult to describe a blueprint for this phase. On the one hand, solutions will be country specific while on the other hand, many technological solutions can be applied globally, and countries will learn from each other using similar technology approaches.

<table>
<thead>
<tr>
<th>Most countries with implemented policies stimulating vRES find themselves in phase A or B. A few countries already moved into phase C, and some are clearly faced with SNSP restrictions. Examples are the Irish All Island and the Great Britain power systems.</th>
</tr>
</thead>
<tbody>
<tr>
<td>If considering the integration of vRES exclusively, phase D has only been achieved in island systems and microgrids at a small scale, using technologies that are prohibitively expensive for large-scale application. Elements of phase E are investigated and demonstrated in various countries[^10], but large-scale deployment is still pending.</td>
</tr>
</tbody>
</table>

4.3. Overview of interaction with challenges

Table 2 provides an overview of how the specific challenges related to an increased share of vRES in a power system interact with the different phases of the power system transition. While most challenges are likely to be marginal or only show first signs in phase A, they become more central in phase B. Other challenges, such as reduced utilisation of dispatchable plants and negative residual loads, are especially pronounced once a country has entered phase D.

Table 2: Interaction of challenges with the time dimension

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Phase 0</th>
<th>Phase A</th>
<th>Phase B</th>
<th>Phase C</th>
<th>Phase D</th>
<th>Phase X</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Load balancing and reserves</strong></td>
<td></td>
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</tbody>
</table>
5. Country characteristics impacting power system transition

Country specific geographical and socio-economic characteristics may determine the starting point, speed and scale of power system transformation process in a country. The individual country characteristics discussed here are relatively constant over time but differ from country to country.

A set of six relevant characteristics and their indicators are defined and analysed with respect to their effect on power systems and the transformation process. For each characteristic, the impact on the integration of vRES and related challenges are outlined.11

The country specific characteristics and their indicators can be grouped into three dimensions:

1) Geography, natural resources and climate;
2) Population and economy;
3) Flexibility.

5.1. Geography, natural resources and climate

Availability and potential of dispatchable renewable energy sources (dRES)

Dispatchable renewable energy sources (dRES) include hydro, geothermal, biomass and waste. The respective technologies offer similar operational flexibility as thermal power plants relying on fossil fuels. In most cases they rely on synchronous generators and, hence, do not contribute to SNSP restriction.

Impact on RES-E integration and related challenges

The more dRES a country has in its system, the less vRES are needed to decarbonise the power sector. Allocation of reserves depends on dispatchable generation. System inertia depends on synchronous generators and, hence, dispatchable plants as well. For countries with little or no dRES capacity, it is more challenging to replace dispatchable fossil-fuel based thermal capacity.

Systems with high shares of dRES facilitate the integration of vRES by enabling the system to cope with their short-term variability and exploiting potential seasonal complementarities between dRES and vRES to ensure greater power system reliability. For example, several power systems in Latin America (hydro-dominated systems) have evidenced complementarities between hydropower and vRES.

Challenges identified

- Load balancing and reserves challenges
- SNSP-related challenges

11 A detailed description of the indicators and data used for the quantitative analysis of each characteristic can be found in Annex I.
Patterns of renewable resources in time (seasonal ratio of solar)

Given that both vRES resources and load profiles are largely inflexible, their correlation can be interpreted as a country-specific characteristic. On the one hand, vRES generation profiles follow site-specific weather patterns, while on the other hand, load profiles respond to regional climate patterns and socio-economic factors of the country.

Unfortunately, hourly load or generation profiles are rarely publicly available. Time series of wind or solar can be extracted from public sources only with significant effort. For that reason, the correlation between load and renewable resources cannot be addressed in this analysis here. It should however be part of any in-depth country analysis.

As a proxy, on a per country basis we assess the seasonal ratio of the solar resource. It describes the annual variation of the solar resource. This variation is limited in areas close to the equator but can be significant for regions at higher latitudes. Generally, the load as well is likely to be subject to minor seasonal variation in regions close to the equator.

Impact on RES-E integration and related challenges

For scenarios with high vRES contributions, the matching of seasonal fluctuations of vRES with typical load patterns becomes a key challenge. Low load-vRES correlation limits the direct contribution to cover the load. Therefore, effectiveness of vRES capacity extension to meet the demand decreases over time.

A low load-generation correlation may imply additional measures in order to manage the security of supply in those periods in which high levels of demand coincide with low vRES availability (e.g. winter at night for some countries with large penetration of solar power). Simultaneously, a low correlation may lead to significant curtailments for those periods when the demand is low but the vRES availability is high (e.g. in summer for some countries with large penetration of solar power).

The challenge applies to the daily cycle as well. The daily correlation between vRES generation and load profiles raises flexibility challenges regarding the system’s responsiveness to abrupt variations in the residual load. For instance, countries with high generation from solar power and with a load peak shifted towards the night perceive more pronounced variations in the residual load (i.e. the peak electricity generation from solar resources at midday, when demand is moderate, is followed by a reduced generation after sunset that coincides with increasing demand at night; this is known as the ‘duck curve’). These conditions demand more resources able to cope with steeper variations in the residual load.

<table>
<thead>
<tr>
<th>Challenges identified</th>
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<tbody>
<tr>
<td>- Load balancing and reserves challenges</td>
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<tr>
<td>- Reduced utilisation of dispatchable plants needed to balance fluctuations</td>
</tr>
<tr>
<td>- Significant curtailments may be necessary</td>
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</tbody>
</table>
5.2. Population and economy

Trend of load growth

Many regions in the world experience significant growth of electricity consumption. Considering electrification of key sectors (e.g. transport) further significant increases can be expected in future.

Impact on RES-E integration and related challenges

Countries with significant load growth may favour the extension of vRES capacity in order to meet the demand boost. In relative terms, countries with increasing consumption require high growth rates for RES to keep the share of renewables in total electricity generation constant over time. This intense growth means that tackling technical challenges and planning risks as well as managing investment security are different from those in countries with stable consumption. In a country with stagnating demand, on the other hand, an increase in vRES capacity may lead to reduced utilisation of existing assets and consequently to the risk of stranded assets.

A significant growth in the load with no important changes in the system structure (e.g. increase in distributed generation) will ultimately lead to increased energy flows in the network. In response, countries with growing load eventually need to reinforce networks to cope with congestion. This is a win-win situation for decentralised RES integration, which can reduce grid reinforcement needs.

<table>
<thead>
<tr>
<th>Challenges identified</th>
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<tbody>
<tr>
<td>- Network congestion and restrictions from network operation</td>
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</table>

Density and distribution of population

From a demographic point of view, the density and distribution of population across a country affects the planning and operation of its power system. This affects generation, transmission and distribution as well as operational procedures.

Impact on RES-E integration and related challenges

In densely populated areas it may be difficult to find the space to install large solar, wind, hydro, geothermal or biomass plants. Limited public acceptance for extension of the transmission infrastructure regularly causes delays and uncertainties in network planning and implementation. The potential consequence of lacking network extension is network congestion which, in turn, triggers curtailment and power plant redispach.

On the other hand, distances between new generation and load centres may be smaller and the existing infrastructure may already support the integration of substantial RES capacities.
More sparsely populated areas may have the space to easily install large-scale renewable energy generation plants; however, the distance between the new generation and load centres is likely to be larger, indicating challenges for the planning, expansion and operation of transmission networks.

### Challenges identified

- Network congestion and restrictions from network operation

### 5.3. Flexibility

**Interconnection to directly neighbouring countries**

Interconnections allow to exchange power with neighbouring systems, helping a country to balance the system in case of oversupply (through power export) or a supply deficit (through power import). Synchronous connections rely on three-phase alternating current (AC) lines. They tie systems mechanically together. High Voltage Direct Current (HVDC) lines also allow to export or import power but decouple the connected systems mechanically. They contribute to SNSP and, in that sense, together with wind and solar generation add up to the SNSP limit. Hence, HVDC interconnectors – while offering operational flexibility – may compete with vRES in case of SNSP restrictions.

**Impact on RES-E integration and related challenges**

The interconnection capacity with neighbouring countries is an important source of flexibility that enables the integration of vRES. A country with high interconnection capacity can more easily and cost effectively cope with the variability and uncertainty of renewables while demanding less flexibility from its dispatchable generation assets. A country with limited interconnection capacity, in contrast, faces greater challenges to balance power generation from vRES.

Although the technical interconnection capacity is the decisive factor, other factors such as synergies between policies or commercial agreements between interconnected countries have an impact on the actual use of the interconnections.

### Challenges identified

- Load balancing and reserves challenges
- Network congestion and restrictions from network operation
- SNSP-related challenges
5.4. Impact of country characteristics on the integration of vRES

Individual country characteristics can shape the way in which the challenges related to an increased share of vRES in a power system influence the further integration of vRES. Certain characteristics may be very favourable for the integration of vRES, while others may be only moderately favourable or even unfavourable for the integration of vRES. In other words, certain country characteristics may accentuate or alleviate the respective challenges related to the share of vRES in the system. For instance, low availability of dRES may increase load balancing and reserve challenges, while the presence of interconnectors may ease this challenge.12

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12 The interaction between country characteristics and challenges is country specific and is reflected in the country factsheets in Chapter B.
6. Policies and measures guiding power system transformation

The power sector transformation process must be accompanied and stimulated by country-specific policy frameworks and implemented through targeted technical measures. At early stages of the power sector transformation process, supportive policies are required to create an enabling environment that guide investments to support the development and uptake of vRES in a country. Throughout the system transformation process, different sets of policies are needed to guide the implementation of necessary technical measures to support the technical integration of vRES into the existing grid. While various enabling policies exist that have proven successful in supporting the development and uptake of vRES, there is less clarity on universally applicable policy frameworks to accompany the technical integration of vRES. Yet, many of the technical challenges encountered during the integration process may be comparable across countries, depending on their characteristics, and may call for similar technical measures to ensure a smooth power sector transition.

Against this background, the following chapter starts with a brief overview of policies supporting the creation of an enabling environment for vRES (6.1) before it delves into technical measures that can help to overcome the challenges arising from the integration of vRES into an existing power system (6.2). Implications for policy makers will be highlighted where appropriate; however, the decision on the design of an effective policy framework to guide the technical integration of vRES in the long-term must be made under consideration of the specific country context.

6.1. Policies supporting the uptake of variable renewable energy sources

A first step towards power system transformation lies in levelling the playing field between renewable energy sources (RES) and non-renewable energy sources. While significant cost reductions for RES technologies have already led to grid parity of these sources in many parts of the world, there are still countries that have not yet embarked on the transition towards RES or where the system or market are not yet fully set for the uptake of RES technologies. In those countries, enabling policies and support schemes are essential to drive the development and encourage the deployment of RES technologies.

Today, nearly all countries have renewable energy targets and corresponding support policies in place. The number of countries directly supporting RES through policy incentives has tripled over the last decade, from 48 in 2004 to around 147 in 2017 (IRENA, IEA, & REN21, 2018a). Renewable energy targets provide a high-level signal to encourage investments in RES technologies and a foundation for many of the support policies encouraging their deployment.

Many studies have analysed enabling policies for the uptake of RES in general and of vRES in particular at early stages of power system transformation (GIZ, 2018; IRENA, IEA, & REN21, 2018b). While this is not the focus of this study, Table 4 synthesises the information from the existing studies, breaking policies down into enabling policies, direct support mechanisms and indirect support mechanisms. **Enabling policies** contribute to the creation of a favourable environment for the development of vRES and set the scene for initial power
sector transformation. Typical instruments include RES targets, specific grants for research and development of new technologies, and the definition of quality and technical standards for these technologies. **Direct support mechanisms** (i.e. *push policies*) support the development and deployment of vRES through mandating certain actions (e.g. electricity quotas to mandate the use of certain technologies) or providing financial incentives, while **indirect support mechanisms** (or *pull policies*) are implicit payments or actions that favour and incentivise the development of vRES (e.g. positive discriminatory rules). The decision to adopt one or several of the policies or instruments, as well as their level of success, largely depend on the country context, the maturity of the technology and the design of a policy package accompanying the implementation of a specific policy or instrument.

Table 3: Overview of policies and instruments supporting the development and uptake of vRES

<table>
<thead>
<tr>
<th>Classification</th>
<th>Policy instruments</th>
<th>Options</th>
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<tr>
<td><strong>Enabling policies</strong></td>
<td>RE targets</td>
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<td><strong>RD&amp;D and innovation policies</strong></td>
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<td><strong>Standards</strong></td>
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<td><strong>Direct RE support mechanisms</strong></td>
<td>Price instruments</td>
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<td></td>
<td>- Feed-in Tariff (FIT)</td>
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<td>- Feed-in Premium (FIP)</td>
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<td>- Capital subsidies and</td>
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<td>grants to RE projects</td>
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<td>- Fiscal incentives</td>
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<td>(e.g. tax exemptions,</td>
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<td>soft loans, production</td>
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<td>tax credits)</td>
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<td><strong>Quantity instruments</strong></td>
<td>- Quotas and obligations</td>
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<td>- renewable portfolio</td>
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<td>standards (RPS)</td>
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<td></td>
<td>- RE purchase obligations (RPO)</td>
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<td>- Renewable obligations (RO)</td>
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<td>- Tradable renewable</td>
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<td></td>
<td>energy certificates (REC)</td>
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<td><strong>Hybrid</strong></td>
<td>RE Auctions backed by</td>
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<td>long term contracts</td>
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<td><strong>Indirect RE support mechanisms</strong></td>
<td>Carbon pricing policies</td>
<td>ETS</td>
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<td>Carbon tax</td>
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<td><strong>Fossil fuel subsidy reforms</strong></td>
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<td><strong>System costs to renewables</strong></td>
<td>- RE exempt connection</td>
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<td></td>
<td>costs (Shallow connection costs for RE projects)</td>
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<td>- Advantageous grid</td>
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<td>tariffs for RE</td>
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<td><strong>Renewables in system operation</strong></td>
<td>- RE do not face</td>
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<td>- Priority of dispatch</td>
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<td>and guaranteed purchase</td>
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<td></td>
<td>- Favourable grid codes</td>
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Considering the evolution of vRES in the system, the policies and instruments adopted to encourage their uptake at early stages of the power system transformation should be continuously adjusted, as the share of vRES increases and the technologies become more mature. Most support schemes, regardless of the technology supported, cause disruptions to the operation of the system and markets, for instance by providing out-of-market compensation or favouring the market access of vRES through targeted support schemes. However, as vRES technologies become more competitive and their shares increase, such disruptions must be mitigated and support mechanisms should be adjusted to the actual conditions and needs of the system. An example is the shift from flat feed-in tariffs to feed-in premiums that incentive vRES not to generate when demand is low, partially exposing vRES generators to dynamic market prices. Beyond such time signals, adjustments of support mechanisms include the gradual exposure of vRES generators to costs of imbalances or the introduction of spatial signals that capture network limitations.

6.2. Measures supporting the integration of variable renewable energy sources

This section describes measures that guide the power system transformation, with a focus on the integration of vRES into an existing power system. Measures need to target different components of a system including a system’s technical capabilities, system operation, regulatory design, market design (if applicable), and the institutional framework.

Whereas measures implemented at early phases of power system transformation involve few of these components in a superficial way (e.g., adopting technological improvements or adjusting system operation practices) the implementation of measures at later phases is often more difficult, because it typically requires deeper involvement of several components. Measures that require structural changes in the regulatory or market design and/or address institutional frameworks face significant implementation challenges that need to be considered when planning the transition process. The challenges grow with increasing involvement of and coordination between sectors and cooperation across systems and countries (IRENA, 2019a).

Existing studies have addressed measures to support the integration of vRES in more detail from a technical perspective (Agora Energiewende, 2017; Eurelectric, 2011; OECD/IEA, 2018c), policy perspective (IRENA et al., 2018a), or market design perspective (IRENA, 2017a) and regarding innovative solutions to increase system flexibility13 (IRENA, 2019b). While the present study builds on these findings, it aims to put them into perspective of the framework developed here.

A set of potential measures is presented for each of the challenges identified in Chapter 3, outlining the relevance of the measure to address a specific challenge and the direct policy implications that arise from the preparation for and the transition towards a renewable-based power system (see Table 5).

It must be emphasised that these measures do not provide a one-size-fits-all recipe for vRES integration. Rather, the applicability and effectiveness of the measures must be assessed on an individual country and system basis, considering technical requirements, resource options, and the institutional framework in place. Furthermore, the identification of a measure must be followed by its successful implementation.

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13 This report present an easily navigable structure to categorise and analyse the complex interplay of a wide range of innovative measures to provide specific solutions for vRES integration.
Table 4: Summary of challenges and respective measures that guide the power system transformation process

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Measures</th>
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</table>
| **Load balancing and reserves challenges**    | • Advanced forecast systems and their integration into system operation  
• Adjustment of operation practices and scheduling programs closer to real-time  
• Incentivise conventional flexible generators  
• Revision of ancillary services and providers  
• Distributed energy resources supporting system balance |
| **Monitoring, communication and control challenges in system operations** | • Advanced forecast systems  
• Real time monitoring of distributed generation  
• Control of the power plant portfolio  
• Stakeholder coordination |
| **Monitoring, communication and control challenges in system planning and development** | • Cyber security  
• Verification of conformity  
• Registry of generation facilities and plants |
| **SNSP-related challenges**                   | • Assessment of system capabilities  
• Development of technical codes and standards  
• Revision of protection schemes |
| **Network congestion and restrictions from network operation** | • Ensure network access  
• Optimised operation of networks and network reinforcement  
• Network expansion  
• Interconnection  
• Manage curtailment |
| **Reduced utilisation of dispatchable plants and must-run capacity** | • Short-term signals – Remuneration of ancillary services and providers  
• Short-term signals – Price formation  
• Long-term signals – Resource adequacy mechanisms |
| **System balance and negative residual load** | • Manage curtailment  
• Seasonal storage  
• Interconnection  
• Sector coupling |

**Load balancing and reserves challenges**

The increasing share of vRES in power generation leads to additional variability and uncertainty in the system, which challenges existing practices to keep the balance between supply and demand. This demands a rethinking of existing tools to maintain the balance, a new definition of flexibility in the context of high vRES penetration, as well as a new allocation of reserves and the design of advanced forecasting practices.
**Advanced forecast systems and their integration into system operation**

**Why is this important?**
From the system operation perspective, enhanced vRES forecasting is key for the effective integration of intermittent energy sources into the system. All meteorological models are subject to simplification and uncertainty and, hence, the forecasted generation inevitably deviates from the actual realisation.

More accurate forecasts minimise uncertainty in the operation of the system, resulting in more efficient dispatch of the generating resources, optimised allocation of reserves and lower average prices of electricity. At the same time, advanced forecast systems provide a powerful tool for system operators to quickly counteract the predicted variability in the system.

**What are potential measures?**
Forecast techniques can be improved by:

- **Increasing the time and spatial resolution of vRES measurements:** Forecasts are more accurate the closer they are to real time. Already available tools such as vRES generation models based on meteorological forecasts with high spatial and temporal resolution, improved mathematical models, big data and machine learning are extremely valuable to improve the accuracy and level of detail of forecasts.

- **Ensuring that vRES plants continuously provide real-time data on power and resource availability (‘nowcasts’):** Forecasting systems nowadays use more accurate spatial and temporal estimates of parameters that affect renewable generation in real time, e.g., wind speed, solar radiation, cloud patterns, or air temperature. These estimates are known as nowcasts. The timescale of nowcasting varies from a few minutes to several hours.

**Implications for policymakers**
The system and/ or market operator has a vital interest in advanced forecast systems to minimise the forecast errors. Beyond that, also network companies, operators of vRES plants as well as dispatchable generators benefit from advanced forecasts. The use of multiple forecast providers can, in general, be beneficial for system operations.

Although the implementation of advanced forecast systems is largely driven by technological measures, regulation and market design (or remuneration schemes) need to be modified to incentivise the adoption of forecast systems. Regulation can impose the implementation of forecast systems. Market design and remuneration schemes allow to capture the economic benefits of improved forecasting, by moving market rules closer to real-time and designing shorter trading products. The economic value associated with forecast errors and their allocation depends strongly on the regulation of wholesale power markets as well as markets for reserves and other ancillary services.
Adjustment of operation practices and scheduling programs closer to real-time

**Why is this important?**

Technical and operational modifications of practices that already exist to decide the scheduling of plants in the short-term can create or remove obstacles to accommodate higher shares of vRES in the system. The scheduling of plants in the short-term, which is typically done one day ahead of actual dispatch, allows system operators to keep the balance between supply and demand.

Ensuring that operation practices become faster and cover more system components is crucial to increase system flexibility. This also allows to better reflect the real-time value of energy and balancing resources (Hogan, Weston, & Redl, 2014).

**What are potential measures?**

The scheduling of power plants and operating practices to improve the capability of the system to react faster can be enhanced through:

- **Modification of operating practices**: In most power systems, flexibility of existing plants is not fully exploited due to specific operating practices or market rules that drive them to operate less flexibly than they technically could. Measures that lead to a more flexible operation of power plants include changes in generation scheduling and dispatch, removing generation quotas for given technologies determined by regulation, reducing must-run constraints or reassessing contractual arrangements. The modification of these practices not only encourages a more flexible operation of existing power plants (without technical modification) but also incentivises operators of technically inflexible dispatchable generators to undertake retrofits.

- **Adjusting the scheduling programmes** based on more up-to-date information, moving decision making closer to real time (i.e., gate closure\(^\text{14}\)). In a market context, examples that allow for scheduling adjustments include intraday markets (Europe) and continuous trading until gate closure (US). More frequent adjustments of dispatch programmes and a gate closure closer to real time allow for more accurate forecasts and encourage a more flexible system operation. Allowing vRES generators to adjust their bidding position closer to real time based on more accurate weather forecasts allows them to avoid costly imbalance penalties, which directly affect the profitability and risk levels of these projects.

- **Increasing the time granularity of the dispatch intervals**\(^\text{15}\). Since dispatched units are generally not allowed to alter their generation within a dispatch interval, long intervals (e.g. more than an hour) limit the flexibility of the system to meet the balancing requirements in shorter time frames due to the increased variability of vRES. Shortening the dispatch intervals allows to

\(^{14}\) In a market context, gate closure is the last moment until market agents can modify their programmes before the actual delivery of electricity.

\(^{15}\) Depending on the system, dispatch intervals can be calculated on a weekly to sub-hourly basis.
reduce the conventional generation required to balance the system, leading to more cost-efficient and flexible power system operations.

- **Capturing technical characteristics of generation assets** in the scheduling of the plants. The large deployment of vRES requires that the scheduling programmes effectively incorporate technical constraints of existing and upcoming resources. This can be done by adjusting the parameters communicated by generators to the system (or market) operator, such as minimum and maximum output, ramp rates, etc.

**Implications for policy makers**
The system operator requires tools to respond to sudden imbalances in the system. These tools can be facilitated by adequate parameters of system operation, such as scheduling time frames according to system characteristics and representation of technical constraints in system operation. The regulator, provided with information from the system operator, is responsible to identify the needs of the system and rules that facilitate a reliable and cost-effective operation of the system. Regulators can also encourage a more flexible operation by implementing policy measures or market designs that mandate or incentivise a more flexible operation of the system according to its needs.

**Incentivise conventional flexible generators**

**Why is this important?**
Enhancing power system’s flexibility is key in the power system transformation. Historically, dispatchable power plants were the main flexibility source to meet variations in the system. With increasing shares of vRES, new flexibility requirements urge the adaptation and redesign of conventional power plants changing their cost structures and technical characteristics.

**What are potential measures?**
The flexibility of conventional dispatchable generators can be increased through:

- **Retrofitting existing conventional dispatchable generators**: Flexibility can also be increased through retrofitting components of existing plants, e.g. to achieve higher ramp rates, shorter start-up times, lower minimum loads and more frequent cycling. Whereas the decision to retrofit an existing generator is typically done based on a profitability analysis, its impact on climate targets should be taken into account. Although retrofitting measures may lead to increased flexibility in the system, they also often result in a greater use and extended operation of emissions-intensive conventional generation units. If available, generation potential from dispatchable renewable energy sources (dRES) such as hydro, geothermal and biomass should be prioritised.

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16 This might be partly offset by a reduction of a plant’s lifetime due to a more flexible operation of the unit, e.g., lower minimum loads and increased cycling.
• **Investment in new and more flexible dispatchable generators**: The identification of flexibility needs in the system can guide the investment in new generators that increase flexibility, such as gas (if considered a transition technology) or, ideally, dRES alternatives. Through the compensation of additional costs and the rewarding of flexibility services, either through markets or mandated by regulation, power plants receive an additional revenue stream that is integrated in their business models and can send adequate long-term signals to invest in flexible supply.

• **Inclusion of flexibility requirements in long-term energy plans**: Regardless of the structure of the power system (i.e. liberalised or regulated), the expansion and evolution of the system must be conducted following long-term energy plans. Power systems envisioning substantial participation of vRES in the future should consider flexibility requirements in their long-term planning, which must be translated into policies and/or system operation signals that guide the evolution of a system and its ability to accommodate vRES.

**Implications for policy makers**

Mechanisms that value flexibility may improve the economic attractiveness of retrofit programmes for conventional power plants. Regulators can encourage a retrofit of generators and investment in new and more flexible dispatchable generators by providing policy and system operation signals to foster investment in flexible dispatchable generators that account for changing cost structures (e.g. capacity markets valuing flexibility).

**Revision of ancillary services and providers**

**Why is this important?**

Ancillary services are essential to ensure reliable and secure power supply. This includes scheduling and dispatch services, provision of operating or spinning reserves, reactive power and voltage regulation, amongst others, which is generally provided by network users, primarily power generators. Balancing reserves is probably the most important service at early stages of the system transformation. The other services (inertia, reactive power, voltage regulation) are only relevant at later phases of vRES integration. Since every system faces different challenges to balance supply and demand, it is crucial that the definition, design and deployment of ancillary services suits the system characteristics.

With increasing shares of vRES in the system, ancillary services need to be updated or redesigned in order to maintain grid stability and security. The provision of ancillary services needs to be open to other system components such as demand response management systems, storage, or new flexible generation units. New technologies enter the system that can be used to provide ancillary services.

**What are potential measures?**

The **upgrade and redesign of ancillary services** must be based on the identification of needs in a system with higher shares of vRES. Common needs in systems with high shares of vRES include: faster response times during contingencies...
(critical in systems with reduced inertia), steep ramping regulation (to cope sudden fluctuations of residual load), operating reserves and load-following regulation. The definition of new and the redesign of existing ancillary services ideally acknowledge and address these needs.

**Implications for policy makers**

System and network operators are responsible to identify the needs of the system and reflect this in the definition and operation of ancillary services. The regulatory framework as well as system operations and market design should also be consistent with such definition of ancillary services.

**Distributed energy resources supporting system balance**

**Why is this important?**

Power system transformation processes across the world indicate that distributed energy resources (DER) will be part of future power systems. They introduce various new technologies to the system that may be located at low- to medium-voltage levels, including rooftop solar PV, behind-the-meter batteries, electric vehicles, residential heat pumps and demand response mechanisms, among others. While the non-coordinated\(^{17}\) uptake of new DER technologies may lead to significant challenges for the operation and planning of the system, especially at low voltage levels, their system-friendly integration carries substantial flexibility potential that can be used to balance the system.

**What are potential measures?**

The coordinated integration of DER can be facilitated by enabling their participation in the power markets (provision of energy and ancillary services). When power markets are designed to capture relevant system characteristics, the participation of DER in the market may encourage them to respond to system needs. As such, DER can provide balancing services to the grid if allowed to participate in day-head or intraday markets and ancillary services. Furthermore, by exposing DER to price signals, they are encouraged to adopt a more active role in their interaction with the system, catering to system needs and facilitating the integration of vRES.

The benefits confined in DER are easier to unlock the more aggregated they are. **Aggregation** allows for the coordination of a large number of these resources as one single entity, making them better manageable from a system perspective.

**Implications for policy makers**

The system operator is responsible to provide guidelines for the technical interaction of DER with the system and for their participation in power markets. Regulators can establish adequate frameworks that encourage distribution companies to act as market facilitators for DER. Regulation and market design can also promote the aggregation of these resources, creating new business models that support their coordination as aggregated units.

\(^{17}\) Most of the times, DER are operated in a “plug-and-forget” approach, which can potentially harm the system with increased deployment of DER.
Monitoring, communication and control challenges in system operations

Increased participation of decentralised vRES in power generation challenges the conventional top-down system characterised by a unidirectional power flow from centralised, controllable power plants to decentralised consumers. Concepts for monitoring, control and protection of power systems that are related to the short- and real-time operation of the system must be adjusted accordingly.

Advanced forecast systems and their integration into system operation

Monitoring and control challenges can be addressed with improved forecasting techniques and their incorporation into system operations, as discussed in load balancing and reserves challenges.

Real time monitoring of distributed generation

**Why is this important?**

The system operator must always be aware of the state of the system and, in case needed, able to adjust the settings for particular plants (manually or via automatic schemes). With increasing shares of vRES, distributed generation continuously replaces larger power plants but is not easily visible to the system operator due to limited monitoring and control infrastructure.

**What are potential measures?**

Tools such as appropriate communication technologies, protocols, or new data formats need to be implemented that provide real time information on embedded generation in distribution networks to both the system operator and the distribution network operator. Different aspects must be considered:

- Larger distributed generators need a communication link with their network operator, with an aggregator or with a national control centre.
- For small generators, e.g. rooftop PV plants, a direct communication link creates unreasonable costs. The cumulated instantaneous output of all these plants can be estimated in real time by making use of nowcasts.
- Apart from the communication between a plant and the distribution network operator, also the communication between the distribution network operator and the system operator is a vital part of the overall monitoring concept. Respective data needs must be identified, protocols developed, and communication interfaces specified in a coordinated manner.

Implementing adequate schemes for monitoring and communication does not only involve technological aspects. Access to data and managing data quality are equally important, as are institutional aspects.

**Implications for policy makers**

Defining appropriate communication technologies, protocols and underlying data formats is a common task for system operators, transmission and distribution network operators and generating plant operators. Some of the solutions may be regulated by technical standards and codes, some via contractual
agreements or industry covenants. A supportive regulatory environment is important for fair and non-discriminatory rules and reasonable allocation of costs.

**Control of the power plant portfolio**

**Why is this important?**

The system and network operators must be able to control the output of dispatchable as well as non-dispatchable plants. The supply of the dispatchable plants must be matched with the residual load in real time. Additionally, the power output needs to be controlled in order to manage network congestion, support related redispatch of power plants and maintain system balance in case of disturbances.

The more vRES capacity is installed, the stronger the residual load fluctuates and optimum load distribution among the dispatchable plants becomes too complex for manual coordination. Generally, the system and network operators do not have direct access to the control of distributed generation, and there is usually little monitoring and control infrastructure in place in distribution systems.

**What are potential measures?**

Measures to improve the control of the power plant portfolio include:

- **Infrastructure for automatic generation control**: The system operator needs to implement the infrastructure for automatic generation control (AGC) for a sufficiently large share of the dispatchable plants.

- **Infrastructure for control of distributed generation**: Control of distributed generation may rely on the same infrastructure as real time monitoring of distributed generation (see above). The choice for the communication technologies, again, depends on system size. Options are broadcasting via radio-frequency, audio frequencies superimposed on the network's frequency, mobile phone networks, the internet or proprietary networks with isolated physical connections. Small-scale solar rooftop PV projects may be completely excluded while for a multi-MW wind farm a real time communication interface from the network or system operator may be justified.

Implementing adequate schemes for control does not only involve technological aspects. Responsibilities and verification of conformity are equally important, as are institutional aspects.

**Implications for policy makers**

The implications are similar to those related to real time monitoring of distributed generation (see above).
Stakeholder coordination

Why is this important? 
Renewable generation capacity is often connected to distribution networks. Hence, the responsibility of distribution companies for system operation increases. They actively support the system operator in steady state operation as well as contingency management. Furthermore, plant operators and their market representatives take over new responsibilities and communicate with the system and network operators.

What are potential measures? 
New responsibilities lead to a change in the positions, interaction and communication between distribution companies, plant operators, aggregators and the system operator. Their actions must be coordinated, and they need to adapt to the changing conditions in a joint effort. This concerns planning and processing of curtailment due to network congestions or power plant redispatch, as well as outages of lines or substations due to maintenance. The evolution of responsibilities and roles must be translated into adequate institutional structures.

Implications for policymakers
Most of these changes are a matter of coordination across the entire power industry, i.e. system operators, transmission and distribution network operators and generating plant operators. The regulator needs to create an appropriate legal framework and provide incentives for all actors to grow into their new roles.

Monitoring and communication challenges in system planning and development

Beyond the adjustment of monitoring, control and protection schemes for the short- and real-time operation of the system (see above), an increased participation of decentralised vRES in power generation also requires the modification of monitoring and communication tools that are used for the long-term planning and development of the system. The establishment of such tools facilitates the reliable operation of the system while deploying new technologies and adopting new operational practices.

Cyber security

Why is this important? 
Power system components are increasingly interconnected and integrated in information and communication technology (ICT) infrastructure. Unauthorised or erroneous access to and manipulation of the behaviour of generation capacities via these interfaces can jeopardise system stability.

What are potential measures? 
For reliable system operation, consistent and stringent cyber security policies must be implemented by all actors of the power industry. Security and
robustness standards for all data interfaces must be high and need to be updated regularly.

Implications for policy makers

Cyber security issues must be addressed by technical standards defined and supported by the entire power industry. Because of the system relevance, legally binding regulations may be appropriate.

Verification of conformity

Why is this important?

For secure and reliable operation of power systems, it is essential that the generators behave as expected, i.e. as specified in the technical codes and standards. Verifying conformity of plants is an important quality control process.

Distributed generation has specific features that can affect the verification of conformity, such as varying levels of capacity (ranging from a few kW to dozens of MW), connection to several voltage networks, diversity of technical characteristics and the fact that distribution networks are often managed and operated by small companies with limited technical and human resources, making the performance of conformity tests and quality control more difficult.

What are potential measures?

A consistent process for verification of conformity is an essential component of a plant’s commissioning process. In many countries, verification of conformity is delegated to authorised certifiers who issue a certificate to the plant owner. Certification requirements should be balanced with the size and economic potential of a project.

Most countries implement procedures and obligations for verification of conformity during project commissioning. Less procedures exist for verification of conformity during project implementation. Repetitive verification of conformity with regard to selected aspects and in reasonable intervals may be beneficial for maintaining system security. This applies to all generators, not just distributed generation or vRES.

Implications for policy makers

Policy and regulation must guide the process in order to guarantee reasonable requirements and costs related to the verification process. Ideally, technical codes and standards as well as procedures for verification of conformity are agreed upon power sector wide in a multi-stakeholder process. A level playing field and reasonable requirements are important for the viability of projects. In case the system operator or network companies define requirements and verification procedures, it is recommended that regulating authorities check and approve these requirements.
**Registry of generation facilities and plants**

**Why is this important?**
For robust system planning, it is of vital importance to have a comprehensive understanding of the composition of the power plant portfolio and of the capabilities and technical features of the individual plants.

The growth of distributed generation changes the composition of the power plant portfolio, with more generators being connected at different voltage levels and in diverse locations. The technical characteristics of distributed generators evolve and change periodically. Only if this diversity is documented, it is possible to assess power system robustness and to update technical requirements.

**What are potential measures?**
A database covering all generation facilities and including important technical parameters is a precondition for managing the adequacy of the generation portfolio. For each plant, the database should record: i) information on geographical location, ii) time of connection, iii) connected network level, iv) technology, and v) date of commissioning. It is important to track the changes related to the installation of new plants as well as those related to the decommissioning of generators at the end of their life.

**Implications for policy makers**
Depending on institutional arrangements, registries may be set up and maintained by different stakeholders: regulators, system operators, or independent service providers. Ideally, appropriate and manageable data structures are defined in a multi-stakeholder process involving all affected actors in a country. An adequate policy framework is central to create a transparent and legally binding structure for data collection and management.

In most countries, registries related to vRES generation already exist. Where a feed-in tariff is in place, all plants benefitting from the support scheme must be registered and metered. Existing registries may be incomplete or fragmented but nevertheless provide a good starting point for comprehensive tracking of the power plant portfolio.

**SNSP-related challenges**
The fact that vRES technologies rely on power electronic converters and contribute to non-synchronous generation compromises the stability of the system under very high shares of vRES penetration. These challenges are more pronounced in non-interconnected systems and must be addressed to ensure a safe and reliable operation of the system in advanced stages of the power sector transformation process.
Assessment of system capabilities

Why is this important? The technical characteristics of power electronic converters have implications for power systems planning and operation. These implications must be analysed and understood in order to quantify SNSP restrictions that are adequate for secure system operation.

What are potential measures? Dedicated technical studies are the basis for a comprehensive understanding of system limitations. These studies allow to distinguish between restrictions which can be relaxed through changes implemented by the system and/or network operator and those which can only be overcome by changing the technical characteristics of power electronic converters.

As the system changes over time, a series of studies or updates may be required. However, since these technical studies are usually extremely complex and resource intensive, an iterative approach addressing a limited number of aspects at a time and building on previous results promises steady progress.

Implications for policy makers Generally, the required technical studies are performed by the system operator in cooperation with scientific institutions. The conclusions and policy implications, however, need to be reviewed by and discussed with policy makers, regulators and affected stakeholders.

Development of technical codes and standards

Why is this important? The technical capabilities of power generators are decisive for the secure and reliable operation of a power system under normal conditions as well as in the case of contingencies. The required capabilities are specified in technical codes and standards.

With increasing shares of vRES in the system, the composition of the generation portfolio changes and with it the behaviour of the system. These structural changes require the modification and further development of existing technical codes and standards.

What are potential measures? Adequate technical requirements for generators need to be specified in technical codes and standards that reflect the specific situation of the power system. These codes and standards need to be adjusted regularly, and, if necessary, new requirements must be applied to both new and existing generators.

Implications for policy makers Technical codes and standards are typically developed by power industry committees. A respective policy framework needs to ensure that there is a non-discriminatory, level playing field for the different stakeholder groups (i.e. system and network operators, component manufacturers, developers and operators of plants) and that the requirements are evidence-based and reasonable from a cost-benefit point of view.
Revision of protection schemes

**Why is this important?**

When designing power systems, planners consider various fault scenarios like lightning strikes and short circuits. The task of protection systems is to isolate faults and manage their treatment. Adequate protection schemes are a precondition for safe, reliable and efficient operation of power systems.

Distributed generation changes the technical parameters in networks and the design of adequate protection schemes. Distributed generators drive reverse power flows from end users back into the network or from lower to higher voltage levels, which are generally not considered by the traditional design of the protection schemes. Furthermore, short circuit capacity at a certain network node may increase, or, in some cases, also decrease.

**What are potential measures?**

Protection schemes potentially need to be adjusted. The settings for individual protection devices and concepts have to be reviewed.

**Implications for policymakers**

Assessments of required changes to and specification of new rules for protection schemes is the task of technical committees of the power industry that define technical guidelines and standards. The work of these committees can be organised at the international or country level. At the level of individual connections, adequate protection is the responsibility of the network and plant operator.

Network congestion and restrictions from network operation

Electricity from generation facilities can only be exported if a network exists to transmit the power. Transforming the generation portfolio changes load flows in the networks which can lead to a number of challenges, including network congestion, non-served energy and vRES curtailments. Therefore, these changes need to be reflected in network planning and operation.

Network access

**Why is this important?**

Connection to the network is a precondition for electricity generation. In most cases, the direct connection between a generation site and the existing network must be established first. Clarity regarding rights and procedures, planning processes and cost allocation are important for successful project implementation. Since distributed generation is often small-scale, the complexity of application procedures and connection costs can be decisive for project viability.

**What are potential measures?**

Ideally, the legal and regulative framework removes all potential barriers related to network access and establishes an enabling environment. This includes the right to connect, easy and uniform application procedures and distribution or socialisation of connection costs.
Implications for policy makers

Technically, solving issues related to network restrictions are the task of network planners and operators. However, their decisions are highly dependent on existing regulation. Important aspects to be considered include:

- Are connection investments socialised or charged to project developers?
- What are the time frames for planning and permitting new power lines?
- Can asset owners in the network industry make investments based on expected developments, accepting a certain risk of stranded assets?
- Are there incentives to opt for the most economical solution from a societal point of view?
- Which rules guide these decisions?

The harmonisation of policy frameworks in the interconnected area is decisive for the growth of vRES capacities. However, there are several challenges associated with this harmonisation, including differences in incentive schemes for renewables, dissonant preferences for a given technology, non-harmonised expansion planning and the fear of transfer of rents across countries.

Optimised operation of networks and network reinforcement

**Why is this important?**

Distributed generation needs to be connected to existing networks. Depending on the locally installed capacity, network loading near the connection point may be higher than in the past and may exceed the rated capacity of the existing network assets. In these cases, network reinforcements are a precondition for expanding distributed generation capacity. In rural areas with weak networks, even individual generation sites may exceed the design ratings of the existing network assets.

**What are potential measures?**

The options for dealing with network restrictions depend on the specific situation. Some of the options sorted from the least to the highest impact are:

- In meshed networks, it may be possible to optimise power flows across different branches and integrate additional generation capacity without major investments. In radial networks, this option does not exist.
- Because of the impact of weather conditions on the capacity of overhead lines, dynamic line rating may be an attractive solution, especially the case of wind power. Thermal ratings of conductors are higher if they are cooled by strong winds, which is a precondition for the high output of wind farms. By adding some monitoring equipment, an existing line can be dynamically uprated during suitable weather conditions, while avoiding massive investments.
- If optimisation of the existing assets is insufficient to carry the new load, the network needs to be reinforced. This may be done by adding more conductors to an existing overhead line. In selected cases, it may be feasible to use
existing towers and to exchange existing conductors by new ones with higher rating. Where higher cross-sections are not an option due to additional weight, high temperature conductors may offer supplemental capacity at minimum costs.

- The option causing the highest investment is **network reinforcement by adding extra lines**. The difficulty for network planners is that the final generation capacity in a region is often unknown. Adding transmission capacity for an individual project may be inefficient if more projects are planned in the near future. On the other hand, there is a certain risk of stranded investments if networks are built based on announced but unsecured project capacities.

**Implications for policy makers**
The implications for policy makers are similar to those for **Network access** (see above).

### Network expansion

**Why is this important?**
Large vRES capacities may be planned and constructed in remote areas with low population density and no transmission infrastructure. Examples are large PV plants in deserts or wind farms in coastal areas or offshore. In these cases, new networks need to be built to deploy the resources.

**What are potential measures?**
Remote generation requires dedicated transmission networks. Network planning is a strategic process that often takes several decades. Therefore, the development of renewable energy generation and network assets must be coordinated. An important instrument is **scenario-based planning**, involving representatives from the affected stakeholders (see for example ENTSO-E 10 Year Network Development Plan)

The **coordination of generation and transmission planning** is straightforward in vertically integrated systems, where the expansion of both is coordinated by one body. In liberalised systems, on the other hand, where grid expansion still relies on a centralised body while generation expansion decisions are dispersed across independent investors, the coordination effort can be more challenging.

**Implications for policy makers**
The implications for policy makers are similar to those for **Network access** (see above).

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18 Available at: [https://tyndp.entsoe.eu/](https://tyndp.entsoe.eu/).
### Interconnection

**Why is this important?**
Interconnection of extended geographical areas offers various benefits, such as an increased security of supply, while allowing to reduce reserve margins in each of the connected areas. Simultaneously, interconnection may lead to lower wholesale electricity prices by giving access to cheaper generation sources.

Interconnection helps to reduce variability of vRES generation. The larger the total geographical area with vRES generation, the easier it is to smooth out the variability from local vRES.

**What are potential measures?**
Network planning is a strategic process that often takes several decades. Therefore, the development of interconnectors must be coordinated across the affected areas. An important instrument is scenario-based planning, involving representatives from the affected stakeholders (see for example ENTSO-E 10 Year Network Development Plan).

**Who is the problem owner?**
The implications for policy makers are similar to those for Network access (see above).

### Curtailment

**Why is this important?**
It is important to acknowledge that some curtailment of vRES is a structural part of planning and operating power systems with enhanced shares of renewable energy sources. It is not economically reasonable to implement massive transmission capacities or storage batteries for peak generation occurring only a few hours per year.

**What are potential measures?**
The issue of curtailment can be addressed through the following considerations:

- **Techno-economic optimisation**: The choice between investments in new network assets (or other alternatives to reduce curtailments) or economic losses due to curtailment must be made based on a careful cost-benefit analysis. However, there is no single optimum since many parameters in the cost-benefit analysis express perceived values and underlying political choices rather than pure economic costs. These parameters include the societal value of one kWh of renewable electricity, the value given to carbon emissions, the depreciation of network assets and respective cost recovery, or the handling of spatially uneven investments in network infrastructure.

- **Allocation of economic losses**: Economic losses due to curtailment can be socialised or allocated to individual stakeholders, i.e. project owners or network operators. In the second case, the details of cost allocation are

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19 Available at: [https://tyndp.entsoe.eu/](https://tyndp.entsoe.eu/)
are decisive for the (perceived) risks of the affected party. Hence, these
details can be crucial for the growth or stagnation of renewable capacity.
A reliable and supportive legal framework must be created in order to
address these risks.

Implications for policy
makers

The power industry, in collaboration with scientific institutions, can contribute
to the cost-benefit analysis. However, major choices related to dealing with cur-
tailment must be made at the political level. Because of the strong impact on
investment risks and, hence, renewables development, policy makers must ad-
dress curtailment questions already at an early stage and with adequate policy
frameworks.

Note: Beyond phase C, the dominating reason for curtailment will be excess supply exceeding the instanta-
eous system load, rather than network restrictions. This aspect is addressed more in detail below under
system balance and negative residual load.

Reduced utilisation of dispatchable plants and must-run capacity

Increasing vRES shares in the system lead to reduced utilisation of dispatchable plants, a decline in electricity
prices in the short-term, and to a reduced remuneration for dispatchable plants. This is especially challenging
for existing plants, whose investment decisions were taken long time ago and that face financial difficulties
because they were planned as baseload plants but their operation regime and remuneration was substan-
tially altered. This also creates a challenge with a view to the flexibility required from dispatchable plants to
ensure system stability.

Short-term signals – Remuneration of ancillary services and providers

Why is this im-
portant?

In a high-vRES system, dispatchable generators are not only required to provide
electricity but also flexibility to the system. The remuneration of ancillary ser-
vices not only encourages a more flexible operation of the system to meet
stricter flexibility requirements (see Revision of ancillary services and providers)
but also covers part of their costs.

With increasing vRES shares in the system, the definition of ancillary services and
their economic value change due to greater uncertainties in the system. These
changes should be reflected in the remuneration of ancillary services.

What are potential
measures?

Ancillary services must be designed, provided and remunerated based on the
reliability and flexibility requirements of the system. The remuneration of an-
cillary services constitutes an additional revenue stream for conventional dis-
patchable generators that are forced to reduce their operating hours but are still
needed to keep the system in balance.
By allowing to recover the extra costs of a more flexible operation, the remuneration of ancillary services provides short-term signals to operate generating units in response to system needs and incentivises investments in new and more flexible resources.

The remuneration of ancillary services can rely on market mechanisms where participants can bid or on regulated remuneration schemes that account for additional operating and opportunity costs.

### Implications for policymakers

System operators must provide definitions of different ancillary services based on reliability and flexibility requirements of the system. These definitions ideally account for the impact of increased vRES shares in the system. Based on these definitions, regulators can frame the remuneration of ancillary services through market mechanisms and/or regulated schemes that consider additional operating and opportunity costs.

### Short-term signals – Price formation

#### Why is this important?

More complex power systems require modifications to clearing and pricing models. If the complexity of a power system is not sufficiently captured, system efficiency can be undermined, and the effects of reduced plant utilisation aggravated. Thus, with increasing shares of vRES, the price formation model in place must adapt to the increasing complexity of a power system.

#### What are potential measures?

As variability increases in the system, the definition of clearing and pricing rules that consider the effects of vRES in short-term markets provide incentives to generators to operate in a more flexible way. By increasing the time granularity in the formation of prices in electricity markets, electricity prices send finer short-term signals to respond to system needs. Additionally, the more detailed representation of technical parameters (e.g. start-up costs, minimum up- and down-times, etc.) and the capability of the market to mirror them through prices allows dispatchable generators to operate in a more flexible way and recover most of the costs through the market (or through a regulated remuneration scheme in case no market is in place).

#### Implications for policy makers

Based on policy priorities that go beyond market efficiency, the regulator must define the guidelines for the formation of electricity prices. These guidelines determine the allocation of responsibilities between the market and the system operator. Once defined, the guidelines need to evolve to capture the increasing complexity of vRES-based systems.
Long-term signals – Resource adequacy mechanisms

Why is this important?

Short-term signals must be complemented with long-term signals that guide investment decisions to guarantee that the system counts with sufficient firm capacity and electricity in the long-term. Resource adequacy mechanisms, or capacity mechanisms, are financial vehicles that can provide an additional revenue stream to generators to ensure the availability of their capacity and electricity in the future. Resource adequacy mechanisms gain importance as increasing vRES generation with zero marginal costs, combined with reduced utilisation of conventional generators, removes incentives to invest in new capacity and challenges the profitability of the exiting capacity.

What are potential measures?

The design of resource adequacy mechanisms must capture the effects of increasing participation of vRES in electricity markets and system operation. Central to the resource adequacy mechanism is an adequacy assessment system that considers future concerns related to security of supply. The design of any new capacity mechanism should incorporate future adequacy needs to guide the flexible evolution of the system. Some features to consider in the design include changes in the net load duration curve, new players participating in the system and stricter flexibility requirements. By introducing flexibility requirements in the capacity mechanism, financial incentives are provided to build future capacity that is flexible enough to accommodate higher shares of vRES.

The economic value of the products defined in the capacity mechanism can be determined by market or regulated means. In either case, the value should account for the foreseen reduced utilisation of dispatchable plants and allow cost recovery of their investments. Additionally, the design of a capacity mechanism should be technology neutral, allowing the participation of emerging technologies in areas such as demand response, interconnections and storage.

Implications for policy makers

Policy makers must ensure that an assessment system for long-term adequacy is in place and linked to the expansion planning of the power system. However, the design of capacity mechanisms is complex and subject to policy priorities that go beyond the efficiency of the market. The long-term nature of guiding the evolution of the technology mix and ensuring security of supply makes the design of capacity mechanisms incomplete when exclusively assessed in terms of market and system operation.

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20 Market or regulated means refer to the approach adopted to determine the economic value of the products procured in the capacity mechanisms (e.g. firm capacity in $/MW or firm energy in $/MWh). Market means indicate that the remuneration is determined in a price-based approach that results from the competitive interaction of supply and demand (e.g. auctions). Regulated means refer to the determination of the remuneration as a centrally defined administrative payment. Note that both means can exist in vertically integrated and liberalised systems.
**System balance and negative residual load**

As the share of vRES in power generation increases to a point at which vRES generation exceeds the load in an area at certain times, the system requires structural changes to address new challenges related to the capability of the system to absorb the power generated. Such challenges include dealing with significant vRES curtailments and finding solutions to excess electricity.

**Curtailment**

Curtailment, as far as economically justified, can be an alternative to balance the system and counteract the negative residual load. However, with significant shares of vRES, reflected in frequent and ample negative residual load, curtailment becomes a non-economically viable alternative. Certain key parameters must be considered when assessing the viability of vRES curtailment in power systems (see *Network congestion and restrictions from network operation*).

**Seasonal storage**

<table>
<thead>
<tr>
<th>Why is this important?</th>
<th>With very high shares of vRES, long-term energy storage becomes crucial to smooth out supply fluctuations over days, weeks or months. Seasonal storage systems allow to address the seasonal mismatch between demand and supply of renewable sources, reducing vRES curtailments and adapting the load duration curve. The ability of storage to offset demand and absorb excess generation makes them a key player in the integration of large shares of vRES.</th>
</tr>
</thead>
<tbody>
<tr>
<td>What are potential measures?</td>
<td>Storage options offer a wide range of services to the power system depending on their technology. Different storage options come along with different cost and performance characteristics. Some technologies providing seasonal storage capabilities are pumped hydro storage (PHS) with very large reservoirs and compressed air energy storage (CAES). The scale and cost of these technologies nonetheless depends on geographical characteristics, which make them non-deployable in many systems. The development of storage systems requires a comprehensive valuation and remuneration of the services they provide. From the economic point of view, price arbitrage from load shifting is not enough to guarantee economic viability of seasonal storage technologies. Other revenue streams can complement the business models for storage systems in order to incentivise their participation in the power system. For instance, storage can contribute to ancillary services, reliability and capacity mechanisms.</td>
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</tbody>
</table>

**Implications for policy makers**

Policy makers must establish a regulatory framework that clearly defines the role that storage plays in the power system. The revenue streams accessible to storage owners determine their economic viability and subsequent development.

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21 A detailed description of storage capabilities, uses and costs can be found in (IRENA, 2017b).
Policy makers are responsible to develop clear regulation and market designs that recognise the value of storage in a high vRES system.

**Interconnections**

**Interconnection with neighbouring systems** allows to transport excess electricity over long distances from areas with temporary oversupply to demand centres, reducing the occurrences of negative residual load in the exporting system. From the grid perspective, negative residual load (i.e. non-economic curtailment) can be addressed by strengthening the interconnections, as discussed in *Network congestion and restrictions from network operation*.

**Sector coupling**

**Why is this important?**

The electrification of other economic sectors is desirable to reach higher vRES penetration shares in systems that already count with high vRES levels – starting from phase C. The electrification of end-use sectors is a precondition to achieve a comprehensive energy transformation that is compatible with the Paris Agreement.

The key challenge regarding sector coupling is to ensure that it happens in a system-friendly way. If managed well, sector coupling can add significant flexibility to the system by absorbing the temporary excess generation from vRES and reducing non-economic curtailments.

**What are potential measures?**

Some of the key aspects that must be addressed to enable a favourable electrification of other sectors include: the revision of cross-sectoral institutional frameworks, integral planning across sectors, reinforced and advanced operation of distribution networks and shaping of new loads through active demand response. Together, these elements can feed into an *electrification roadmap* that fits the specific system and country characteristics.

**Implications for the policy maker**

At a technical level, the system operator must implement the required measures in the power sector. However, the changes affect the infrastructure more broadly and developments often take several decades. For that reason, long-term national strategies are needed to provide guidance and create investment security for a large group of stakeholders. Topics to be addressed include the rights of a project developer to connect to the network, the securities to be provided for the infrastructure investments, the charges for using the network and the right to export electricity.
7. Conclusions

The Paris Agreement delivers a strong message to all countries that elevated efforts are necessary to limit the global temperature increase to 1.5°C. Given the centrality of the energy sector for total global greenhouse gas emissions, the transformation of the energy system is key to achieving the Paris goal.

Power systems around the world have initiated the transformation process as they phase out fossil-fuel based electricity generation and accelerate the introduction of renewable energy technologies. The introduction of variable renewable energy sources (vRES) such as wind and solar at a large scale poses new challenges that need to be acknowledged, understood and overcome in order to facilitate the full decarbonisation of the power sector by mid-century.

This paper develops an assessment framework that allows policy makers to analyse their country’s phase in the power sector transformation process, including the challenges arising in the current and in future phases as well as potential measures to address them.

The measures identified must always be embedded in a regulatory framework that incentivises and supports their implementation. However, given that each country’s regulatory and policy framework is unique and subject to complex political negotiation processes, recommendations may not be universally applicable.

Taking this into account, the analysis undertaken in this paper conveys seven central messages for policy makers:

- Power sector transformation is a process that cannot be implemented overnight but progresses through phases.
- Specific challenges are likely to appear at certain points, i.e. in each phase, independent of a country’s geographic and/or socio-economic characteristics.
- A country’s geographic and/or socio-economic characteristics can shape the way in which these challenges influence the integration of variable renewable energy sources. Some characteristics may be favourable, while others may be unfavourable for vRES integration.
- Based on the analysis carried out in this paper, it is possible to anticipate the time of occurrence, plausibility of occurrence and the magnitude of the challenge in different country contexts.
- Measures to address the challenges in different country contexts already exist, and are readily available, requiring different levels of action in different areas of intervention, i.e. the technical, policy, and system operation or market design area.
- Measures must be embedded in an effective regulatory framework that supports their implementation. The regulatory framework is country-specific and ideally arises from a careful consideration of several political and socio-economic factors.
- Key to a successful power sector transformation process is the careful and timely planning of each phase, anticipating the main challenges and identifying appropriate measures and policies for their solution. This ensures the rapid progress from one phase to the next until ultimately achieving full decarbonisation of the power sector.
Although several countries may encounter similar challenges when passing through a certain phase of the power sector transformation process, or when assessing their geographical and socio-economic features, it is difficult to compare countries along these parameters and to derive generally applicable recommendations to guide the power sector transition process. However, the assessment of different countries - and how they have approached certain challenges arising in their country context - can offer inspiration and orientation for policy makers on selective aspects, which they see applies to them. Thus, policy makers can make a choice on the elements of the power sector transformation process where they see room for peer-learning from others’ experiences and those elements where they prefer to go their own way.
8. Country factsheets

Below are eight country factsheets that illustrate the steps of the analysis explained previously. They offer a snapshot of the situation each country currently finds itself in regarding its power system transformation process. Each factsheet examines country-specific characteristics and the development status of the country in the power system transformation process, which translate into country and system-based challenges. Policy options to address these challenges and advance from one phase to the next are enclosed. While the power system transformation is a highly complex process that does not offer simple solutions for replication, the country factsheets provide a higher-level overview that may encourage peer-learning between countries that show similarities in their respective situation.

8.1. Argentina

Argentina - Characteristics

Geography, population and flexibility\textsuperscript{22}

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Argentina has 17 cities with more than 300,000 inhabitants, but more than 30% of the country’s population lives in the Greater Buenos Aires area. The population density outside the 17 cities is extremely low, with about 7 inhabitants per km\textsuperscript{2}.

\textsuperscript{22} Map based on figure published at OnTheWorldMap.com combined with a network map as published by Cammesa.
Between 2005 and 2016, per capita electricity consumption grew in line with the economy and reached about 3000 kWh/person/year in 2016. The total population grew slightly and, simultaneously, electricity access achieved 100%.

These three factors together resulted in a significant growth of total final electricity consumption (from 100% to 145% between 2005 and 2016). Until 2030, the Ministry of Energy expects a further increase to more than 230% compared to 2005 levels for the ‘Trend Scenario’ and to about 200% for the ‘Efficient scenario’ (MINEM, 2017).

Argentina is a net importer of electricity.

Argentina and Uruguay together form a synchronous electrical island. Interconnections to Brazil are based on non-synchronous, HVDC technology.

The large extension of the country leads to diverse RES potentials.
| Wind resources are extremely favourable in the South and in particular at the coast line\(^{23}\). | Solar resources very favourable in the North\(^{24}\). The average solar ratio as indicated in the bar graph at the top is about 0.3 for the complete country. However, the value in the North-West is close to 1. |

### Impact of country characteristics

Due to the concentration of the population in the larger cities and the large distances to the existing hydro capacities, the existing transmission network is sparse. The degree of meshing is low, especially in the rural parts of the country.

Large-scale deployment of the remote solar and wind resources will inevitably trigger network reinforcements.

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\(^{23}\) Map obtained from the “Global Wind Atlas 2.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU) in partnership with the World Bank Group, utilizing data provided by Vortex, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info”

\(^{24}\) “Solar resource data obtained from the Global Solar Atlas, owned by the World Bank Group and provided by Solargis.”
Argentina – Status of power system transformation

Installed RES capacity, contribution in covering annual load and specific CO2 emissions - past trend and 2016 status

By 2016, RES supply has been exclusively hydro and, hence, dispatchable. Favourable resources allowed for significant capacity of 11 to 12 GW. Since 2000, the hydro capacity has been relatively constant. However, due to growing load, the share of hydro in generation decreased from more than 30% in 2005 to about 26% in 2016. Until 2030, the scenarios of the Ministry of Energy foresee an additional expansion of Argentina’s hydro capacity of about 3 GW (MINEM, 2017).

Expansion of vRES capacities is just starting to take off and has seen significant growth rates. At the end of 2018, about 1000 MW of vRES was operational. For 2019, another 3000 MW of new capacity
is expected. Until 2030, the scenarios assume a further capacity expansion of 14,000 to 18,000 MW compared to 2018 levels.

As with an increasing participation of gas in the generation mix the renewables share slightly decreased, specific CO₂ emissions per kWh slightly increased. Absolute emissions grew by 60% from 50 MtCO₂eq in 2000 to 80 MtCO₂eq in 2016.

Recent and ongoing developments and related challenges

Looking at vRES development only, Argentina is rapidly moving from phase A to phase B in the power sector transformation process. Currently, wind power is impacting system operations noticeably. Tools for forecasting are necessary and currently being introduced in system operations by CAMMESA²⁵.

In the coming years, automatic generation control (AGC) coordinating the real time output of dispatchable plants will replace the current, manual dispatch. This is a precondition for maintaining efficient and reliable system operations with increasing shares of variable renewables.

Tasks and policy options for progressing in the near future

If vRES capacities in the GW range are deployed in the North-West and South, new transmission corridors will be required. Experience shows that planning and implementation is often faster than construction of new transmission lines. From that perspective, it is important to start planning and permitting processes soon.

The growth plans for vRES capacity are ambitious. The move from phase B through to phase C and even to phase D may be fast and may just cover a couple of years. This requires a stable regulative framework and anticipating policies. Otherwise, inherent risks for new projects may unexpectedly block developments. Examples for relevant policy areas are:

- Redispatch of hydro and thermal capacity as a means of congestion management;
- Regulations for vRES projects experiencing congestions in their export networks or SNSP restrictions;
- Planning and tendering of new transmission capacity in times of decreasing utilisation.

²⁵CAMMESA (Compania Administradora del Mercado Mayorista Eléctrico) is the administrator of the wholesale electricity market in Argentina. Its main functions include the real-time operation of the electricity system, the dispatch of generation and the administration of the commercial transactions in the electricity market.
8.2. Germany

Germany – Characteristics

Geography, population and flexibility

A sixth of the country’s population lives in larger cities with more than 300,000 inhabitants. Many smaller municipalities and exist resulting in a high average population across the country.

In the recent past (since 2005), per capita electricity consumption changed only slightly. The same holds for the total population. Hence, total final electricity consumption did not change substantially and is expected to remain stable in the near future.

Germany’s power system is part of the synchronous interconnected Central and Western European power systems. The existing transmission networks cover all regions and are highly meshed. They are also strongly interconnected with the neighbouring countries.

Germany has been a net exporter of electricity. This is due to the abundant capacities in thermal generation and the high share of lignite in electricity supply resulting in wholesale prices which are low compared to the neighbouring countries.

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The potential for sustainable expansion of dRES capacities like hydropower, geothermal but also biomass is limited.

Wind resources are better in the Northern and coastal part of the country.

In the North Sea wind resources are favourable. The relatively shallow North Sea allows large scale implementation of offshore wind. The specific shape of the German territorial waters however results in higher water depth than in the neighbouring countries like Denmark or The Netherlands.

Impact of country characteristics

For nearly three decades, the policy framework has been actively supporting vRES. Compared to more sparsely populated countries, the size of most solar as well as wind generation facilities is moderate. For instance, the entire onshore wind capacity is connected to distribution networks (110 kV and below). A large portion of the PV capacity is represented by solar rooftop systems below 30 kW.

Due to the favourable wind resource but spatial restrictions onshore, Germany’s renewable energy policies strongly supported offshore wind. Starting in 2015, connected offshore capacity increased significantly. Compared to other countries bordering the North Sea, German offshore capacity is located far from the coast and, unlike in many neighbouring countries (e.g. the Netherlands or Denmark) offshore wind farms are connected to the onshore transmission networks by HVDC links.

Renewables and in particular wind power contribute to regular and strong North to South power flows.
Germany – Status of power system transformation

Installed RES capacity, contribution in covering annual load and specific CO₂ emissions - past trend and 2016 status

The share of vRES grew dynamically during the last decades. Total RES supply currently covers more than 30% of annual generation.

Power system transformation is in phase C. However, the figures must be interpreted carefully, since the country is part of the synchronous interconnected Central and Western European power systems. The Total Final Electricity Consumption (TFC) of Germany is about 23% of the total synchronous system. Given the strong interconnections with its neighbours, SNSP is not a directly limiting factor for vRES growth at the country level. The total share of dRES in generation in the interconnected system is about 18%. The solar ratio at a European scale is between 0.1 and 0.3.
Generation of the large coal capacities is hardly affected by the growth of renewables. Excess generation is exported to neighbouring countries via the liberalised European electricity markets. This leads to a stagnation of absolute levels of CO₂ emissions, regardless the growing contribution of RES to the supply.

**Recent and ongoing developments and related challenges**

Germany will not meet its target to reduce carbon emissions by 40% in 2020 compared to 1990, as laid down for the first time in the Government’s Integrated Programme for Energy and Climate in 2007 (BMU, 2007).

By 2022, nuclear capacity in Germany will be phased out completely. Between 2019 and 2022, this will result in a 10 GW decrease of capacity. A large share of this capacity is located in the South of the country. North-South power transits across the country will further increase. This trend will be intensified by the further growth of offshore capacities in the North Sea.

The Coal Commission appointed by the German government in 2018 recommended a complete phase-out of electricity generation from coal by 2038 (BMWi, 2019). This recommendation is not legally binding. Given that it will be impossible to meet the 2030 targets (which are not legally binding) and highly unlikely that the German obligations from the Paris Agreement can be met, the recommendation is criticised by NGO’s and environmentalists.

In the recent past, the incentive scheme for renewables was changed from fixed feed-in tariffs to an auction scheme. In that period, growth rates of vRES started to fluctuate considerably and are are still fluctuating a lot.

Simultaneously, the first significant shares of the existing RES capacities achieve an age of 20-years. At this age, they are no longer subject to any incentive scheme. Thus, it is likely that substantial RES capacities will be decommissioned in the near future. For maintaining a net growth, the rates for newly installed capacity must increase to a higher level than in the recent past, before stabilising again.

Because of existing bottlenecks in the transmission networks within the country, the North to South power flows result in network congestion. Curtailment of renewables generation and redispatch of thermal power plants are used to manage congestion.

In 2017, about 2.9% of RES generation had to be curtailed because of network congestion²⁷. Most of this curtailment affected wind generation, in particular in the North of the country. Connection of substantial offshore capacities contributed to an increase in curtailments and redispatch compared to previous years.

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Network reinforcements are planned regularly by the Transmission System Operators (TSOs). An important part of the reinforcements is the implementation of three DC interconnectors in the country increasing the transport capacity from North to South.

In many cases, planning and construction of new distribution and transmission capacity is substantially delayed due to resistance among local population.

As a consequence of the existing bottlenecks within the German transmission networks, generation including vRES regularly drives transits into and through the neighbouring countries. These power flows are a matter of discussion between the affected TSOs. In the recent past, neighbouring TSOs installed phase shift transformers at their interconnectors with Germany in order to reduce power flows into their system.

### Tasks and policy options for progressing in the near future

Safeguarding stable net growth rates for renewables and achieving net reductions in CO₂ emissions requires a stable policy framework based on clear policy targets. Potential elements are:

- Legally binding decisions regarding phase out of coal generation;
- Legally binding decisions or targets regarding renewable shares in load coverage or CO₂ reduction;
- Accelerated network reinforcement (transmission and distribution) in order to reduce network congestion;
- Increase efficiency of the system by integrating redispatch and congestion management, both in a planned process.

Coordination of the German renewables and climate policies with those of the neighbouring countries would increase efficiency.

In the near future, trends driven by the power system transformation may lead to an increase of electricity consumption. E-mobility, conversion of heating systems to be supplied by electricity (heat pumps) and other forms of sector coupling (power to gas) represent significant new loads.

The regulative framework has to be adjusted in order to make these sector coupling options economically viable and allow the required growth rates.
8.3. India

India – Characteristics

Geography, population and flexibility\(^{28}\)

India has nearly 200 cities with more than 300,000 inhabitants. About 2% of the population of the sub-continent live in the largest city, Delhi. The majority of the total population, however, lives in rural areas. Even outside the major cities, the population density is high with about 360 inhabitants per km\(^2\).

Between 2005 and 2016, per capita consumption nearly doubled from 430 kWh/person/year to 840 kWh/person/year. Simultaneously, the population grew to 115% and the population with access to electricity even to 150%. As a consequence, the total final electricity consumption grew to nearly 230% compared to 2005, amounting 1100 TWh in 2016.

India has five transmission regions (Northern, Western, Eastern, North-Eastern and Southern, see map above). In the past, these regions represented separate networks. As the last one, the Southern region was synchronised to the others at the end of 2013. With this step, a single integrated synchronous system was created, covering the complete sub-continent. However, load and generation are unevenly distributed across the regions. The North and the South regions rely on imports and, despite massive extension of the transmission network, capacity between the regions is still insufficient to completely cover the deficits.

\(^{28}\) Map derived from POWERGRID_Network_As_on_May_2019_0.pdf downloaded from https://www.powergridindia.com/sites/default/files/POWERGRID_Network_As_on_May_2019_0.pdf (last reviewed at June 13\(^{th}\), 2019)
Interconnections with neighbours exist. Compared to the size of the system, however, they are rather insignificant for the behaviour and the flexibility of the system.

Due to the huge extension of the country, meteo characteristics in general and the solar resource in particular are diverse.

The wind potential realistically is restricted to the coastline and is estimated at about 100 GW. The potential for solar PV is vast and is estimated at about 750 GW. In large parts of the subcontinent, the solar winter-summer ratio is close to 1.

Impact of country characteristics

The dominating factor for the development of the Indian power system is the surging demand. Generation capacity grew from about 115 GW in 2005 to 275 GW in 2015 and interregional transmission capacity was expanded from about 30 GW at the end of the 11th plan (2012) to about 70 GW at the end of the 12th plan (2017). The large extension of the country requires long distance transmission. Both, high AC voltages up to 675 kV and DC interconnectors are used.

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29 Map obtained from the “Global Wind Atlas 2.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU) in partnership with the World Bank Group, utilizing data provided by Vortex, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info”

30 “Solar resource data obtained from the Global Solar Atlas, owned by the World Bank Group and provided by Solargis.”

31 Report (Part – A) on Advance National Transmission Plan for 2021-22 Ministry of Power, Central Electricity Authority, January 2016
A large part of the population lives in rural areas. Still, more than 10% of the total population does not have access to electricity.

The additional dRES potential is considerable. For the period 2017 to 2027 an extension of the existing large hydro capacity with about 20 GW is foreseen plus an additional 20 GW of imports from hydro resources. The additional indigenous potentials of small hydro (up to 25 MW per unit) and biomass are estimated at 20 GW and 25 GW, respectively. 32

32 National Electricity Plan (Volume 1) Generation, Ministry of Power, Central Electricity Authority, 2018
India – Status of power system transformation

Installed RES capacity, contribution in covering annual load and specific CO2 emissions - past trend and 2016 status

During the last years, vRES grew much faster than dRES capacity. Existing dRES consists of nearly 50 GW of hydro plus nearly 10 GW of biomass.  

Load as well as thermal generation are growing faster than renewables generation, hence, the share of renewables in the total annual balance decreased slightly over the past 10 year.

The transformation process for India as a whole can be qualified as phase A. This country wide assessment, however, is misleading. Given the uneven distribution of generation and load across the

33 National Electricity Plan (Volume 1) Generation, Ministry of Power, Central Electricity Authority, 2018
country in combination with the existing transmission constraints, some regions are faced to challenges typical for phase B or even approaching C.

The regional mismatch together with the lack of transmission capacity between the regions causes regular power cuts in parts of the country. This has been a stimulus for projects being implemented by autoproducers and independent power producers.

Specific CO₂ emissions per kWh generated are at a constant, high level.

**Recent and ongoing developments and related challenges**

In the National Electricity Plan, the government set targets for installed renewable capacities. For 2022, a total installed capacity of 100 GW PV is anticipated, of which 40 GW is supposed to be rooftop PV. For the current 13th plan, this means a capacity addition of nearly 90 GW. Similarly, a total wind capacity of 60 GW is foreseen requiring an addition of nearly 28 GW in the same period. Connecting these new capacities to load centres requires network reinforcements and extensions. Dedicated ‘Green energy transmission corridors’ are going to be developed in parallel with the generation capacity.

These activities are supported by several national and state programmes. However, measures are not always sufficiently coordinated, and programmes are subject to delays. This has been affecting RES integration in the current planning period.

The share of losses in the supplied load has been high (see graphs above). A significant share represents non-technical losses (unpaid services and theft). This is a serious problem for the distribution companies (DISCOMMs) because they are unable to cover their costs. By now, efforts to reduce these losses show limited success. Much of the losses occur in rural areas. (Energy) poverty is a high priority issue. Not all potential measures addressing loss reduction are applicable due to political choices. In some states, dedicated PV programmes focusing on the agricultural sector (water pumping) try to tackle this problem and simultaneously stimulate RE development. In urban areas DISCOMMs managed to effectively reduce non-technical losses by aggressively rolling-out smart meters.

For DISCOMMs RE targets are also difficult because the remuneration for renewables is higher than for electricity from fossil fuels. As end user prices are politically set, effective mechanisms to recover the extra costs do not exist. Similarly, DISCOMMs are responsible for balancing the system and, hence, have to deal with the risk of vRES forecast errors in their supply area.

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34 National Electricity Plan (Volume 1) Generation, Ministry of Power, Central Electricity Authority, 2018
Tasks and policy options for progressing in the near future

Targets set for RE and transmission expansion (Green Energy Corridors) certainly are challenging. All efforts to achieve these targets are relevant. However, in the perspective of the anticipated load growth, the existing targets have been qualified just as a no regret scenario. They do not promise a deep decarbonisation of the power sector.\(^{37}\)

The National Electricity Plan assumes nearly 50 GW of lignite and coal plants to be retired in the decade 2017 to 2027. Part of the retirement until 2022 is forced by new environmental standards, in particular control of SOx emissions, which cannot be met by large numbers of coal plants (about 100 units with a cumulated capacity of nearly 17 GW).

However, 45 GW of new coal capacity are projected for the same period. These new plants have an operational life reaching to 2050 and beyond. Together with an expected nuclear capacity of 10 GW in 2022 or 16 GW in 2027, respectively, the amount of thermal capacity in 2027 is nearly 230 GW. An additional 50 GW of hydro is also qualified as must run capacity. Thus, even on the long run, a dominant share of the generation portfolio has to be considered as being inflexible. This potentially conflicts with the need to integrate additional amounts of vRES – which is a precondition for replacing fossil-based generation.

This is even more relevant because the targets put much emphasis on PV. Inevitably, this technology choice introduces a strong daily cycle of the residual load, asking for high ramp rates of the load following, dispatchable generation. (The annual cycle is less challenging than in other regions of the world.)

Ambitious policies and targets with respect to RE deployment will need further and even growing attention in the near future.

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8.4. Ireland

Ireland (All Island) - Characteristics

Geography, population and flexibility

Ireland and Northern Ireland operate as one interconnected synchronous system and a single power market. Most figures presented here are for the complete island.

There are two cities with more than 300,000 inhabitants, Dublin and Belfast. Nearly 20% of the island’s population lives in the largest city, Dublin. The population density excluding these two cities is moderate. The existing transmission networks are not very dense.

As the population is stable, total final energy consumption in the electricity sector did not change significantly during the last decade. Per capita consumption is just above 5500 kWh/person/year.

The Irish All-Island power system is an electrical island. It is connected with the Great Britain power system by two non-synchronous HVDC links. A third interconnector with France (Celtic Link) is under development and possibly available after 2025.

A large share of primary energy is imported.

The wind resource is very favourable. The solar resource is less promising. The seasonal solar ratio between winter and summer is about 0.1.

The share of dRES in generation covers about 6% of annual consumption. There is little additional potential. Hence, vRES, especially wind, inevitably play a key role in renewables deployment.

**Impact of country characteristics**

Because of the outstanding wind resource, renewables generation is dominated by (onshore) wind power. The island nature of the power system already early lead to high instantaneous penetrations of wind / vRES. Offshore wind has been proposed for the more shallowish Eastern coast.

Wind farms are dispersed across the country. Transmission extension projects like the North-South interconnector (400 kV AC, under planning) are important in order to smoothly integrate vRES generation.

However, the population is very scattered across the country. Planning and permitting of large infrastructure projects easily affects large numbers of land owners and residents. Local resistance against transmission projects is significant and lead times tend to be long (more than a decade).

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39 Map obtained from the “Global Wind Atlas 2.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU) in partnership with the World Bank Group, utilizing data provided by Vortex, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info”

40 “Solar resource data obtained from the Global Solar Atlas, owned by the World Bank Group and provided by Solargis.”
Ireland (All Island) – Status of power system transformation

Installed RES capacity, contribution in covering annual load and specific CO2 emissions - past trend and 2016 status

The island character in combination with the large share of vRES introduces particular challenges. Thermal generation in Ireland is carbon intensive and, hence, progress in renewables generation does not evenly translate in emission reductions. Structural changes in the power sector are still necessary in order to successfully decarbonise the power sector.
Recent and ongoing developments and related challenges

The Irish government set a target for a 40% renewables share in electricity generation in 2020. The country will get close to this value. However, the 40% target has been derived from a 16% target in overall primary energy supply and, because of delays in other sectors, it seems to be unlikely that this target will be met. For that reason, some stakeholders used this as an argument to increase the contribution from the power sector, for example, by pushing offshore wind development.

The All Island system is in phase C of the power system transformation. Overcoming SNSP restrictions is a major challenge enabling further progress.

The two system operators Eirgrid and SONI have been dealing with studies related to feasible SNSP levels already since 2000. They defined maximum SNSP values affecting system operation and network access of new vRES projects. Simultaneously, they actively contributed to technical development and promoted measures allowing a gradual increase of the maximum allowable SNSP, e.g. by updating grid codes for vRES as well as for thermal and hydro generation.

In addition to SNSP restrictions inter-area constraints influence the power plant dispatch. These constraints are related to a variety of technical aspects, like dynamic stability, voltage control and reserve provision.

As a consequence of the technical limitations wind generation regularly has to be curtailed. In 2018, the total wind energy generated in Ireland and Northern Ireland was about 11 TWh, while about 0.7 GWh of wind energy was dispatched-down. This represents 6% of the total available wind energy in 2018.

Tasks and policy options for progressing in the near future

In this stage the technical challenges are the most relevant to tackle. In order to progress power system transformation, Eirgrid and SONI – in close collaboration with manufacturers and system integrators – started the so called DS3 programme (“Delivering a Secure, Sustainable Electricity System”). The aim of the DS3 Programme is to increase allowable levels of instantaneous renewable generation on the system gradually to 75% over the coming years. Starting with a 50% limit and based on past progress, currently, 65% penetration levels are technically feasible.

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8.5. Kenya

**Kenya - Characteristics**

**Geography, population and flexibility**

The majority of Kenya's population lives in rural areas (73%) and the country is relatively sparsely populated (87 persons per km²).

Kenya has high insolation rates, and the potential for photovoltaic generation is estimated at 23 TWh/year (CESI, 2017a). As indicated by the graph above, the country has an average solar ratio of close to 1.

The existing transmission network is concentrated in the South-West of the country, where the few big cities are located, and is characterised by radial configuration and poor meshing (CESI, 2017b). Plans exist to establish a better meshed grid with connection to the North and East of the country as well as three major regional interconnectors to Ethiopia, Uganda and Tanzania (Power Africa, 2016a).

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44 See: https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS?locations=KE
Kenya’s population grows at a rate of 2.5%. The current electricity access rate is 64.5%. Compared to 2005, the number of people with electricity access more than tripled. The Government aims at universal electricity access by 2022 (Power Africa, 2018a).

In 2015, final electricity consumption per capita was 167 kWh. However, as still only two thirds of the population have access to electricity, the consumption of this fraction is about 300 kWh per person and year. Total demand is predicted to grow considerably, doubling from approx. 1,500 MW in 2015 to 2,500-3,600 MW by 2020, due to anticipated growth in population and economic activity, conversion of latent demand through increased electricity access, and the implementation of large industrial projects foreseen in Kenya’s Vision 2030 (Power Africa, 2016b).

The Kenyan Government pursues plans to significantly expand the electricity sector. Around 2,700 MW of new generation capacity could come online by 2020 and the transmission network could more than double in length. Between 20 and 30% of Kenya’s population may receive off-grid access to electricity by 2020, primarily through solar power (Power Africa, 2016b).

Kenya is part of the Eastern Africa Power Pool (EAPP) in which eleven countries in Eastern Africa seek to interconnect their electricity grids. Today, Kenya is a net importer of electricity through an interconnector with Uganda (132 kV power line). Further interconnectors are planned with Ethiopia (500 kV, advanced stage) and Tanzania (400 kV, currently on hold) (KETRACO, 2019).

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45 See: https://data.worldbank.org/indicator/SP.POP.GROW?locations=KE
The wind resource is attractive only in some parts of the country. Solar potential is high across the whole country.

Kenya is extremely rich in dispatchable renewable resources, i.e. geothermal and hydropower.

**Impact of country characteristics**

The main challenge for further expansion of these resources as well as variable renewable sources is the poor transmission grid infrastructure and the lack of interconnectors to export excess electricity.

Kenya has also proven oil and coal resources that may compete with the further expansion of renewables. Commercial reserves of coal were discovered in the Mui Basin of Kitui County and have raised hopes for cheap coal-based electricity generation in the future (Gitonga, 2017).

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47 Map obtained from the “Global Wind Atlas 2.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU) in partnership with the World Bank Group, utilizing data provided by Vortex, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info”

48 “Solar resource data obtained from the Global Solar Atlas, owned by the World Bank Group and provided by Solargis.”
Kenya – Status of power system transformation

Installed RES capacity, contribution in covering annual load and specific CO2 emissions - past trend and 2016 status

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Kenya’s installed electricity generation capacity consists of approx. 80% renewable energy sources, with enormous potential to be expanded. The current mix includes mostly hydro (36%), followed by thermal (33%) and geothermal (29%). Other renewables (in particular wind power and bagasse-based co-generation) account for 2% (Power Africa, 2018b).

The significant potential of dispatchable renewable energy sources (i.e. hydro and geothermal) allows for high overall shares in renewable energy supply. The expansion of variable renewable energy sources is just taking off, with the first 310 MW wind farm in Lake Turkana having been connected to...
the grid in late 2018. Despite the very favourable solar irradiation, solar is not yet deployed on a large scale.

The most recent Least Cost Power Development Plan (2017-2037) foresees an expansion of renewable energies by almost 4,000 MW by 2030, with an additional 760 MW wind, 646 MW solar and 1,388 MW geothermal generation 2030 (Republic of Kenya, 2018).

Due to the phase-out of medium speed diesel plants and the delayed uptake of coal, CO₂ emissions per kWh are decreasing and already close to zero in 2019. If developments proceed along the lines of the 2017-2037 LCPDP, with delayed and very limited use of coal-based electricity generation and no use of natural gas, CO₂ emissions will remain near zero until 2024 and rise slightly thereafter due to the introduction of a down-scaled coal plant, to around 0.3 MtCO₂e in 2030 (Republic of Kenya, 2018).

Recent and ongoing developments and related challenges

Power system transformation is in phase 0. Due to the very low share of variable renewable energy sources that are currently fed in to the grid (around 1%), their impact on power system operation is still negligible.

The most important challenges can be expected to come from the limited flexibility of the existing generation fleet and, related to that, the risk of excess generation and the need for non-economic curtailment. High shares of geothermal (and potentially coal) increase the inflexibility of the generation fleet and augment excess generation. This issue might become more critical in the long-term, due to must-run capacity of geothermal, take-or-pay power import through the HVDC link to Ethiopia, and priority dispatch of vRES. The integration of more vRES might increase the situations of excess generation (CESI, 2017a).

Another challenge is the timely expansion of the transmission grid and the improvement of meshing, to avoid future network congestion and to allow for efficient and reliable power transport across the country and even beyond its borders (CESI, 2017a).

Tasks and policy options for progressing in the near future

Electricity generation in Kenya is projected to increase significantly by 2030. If developing as planned, Kenya’s power sector will be close to 100% renewable around 2020. However, the foreseen introduction of coal power in 2024 would bring about significant changes to the power mix and would considerably increase the emissions of the country’s power system, delaying the power sector transformation process.

In order to meet the fast-growing demand while further increasing the shares or vRES in power generation – advancing from phase 0 to phase A in the transformation process – a well thought-out electrification strategy is key, taking into account the potential of geothermal power as an alternative to coal power as well as the potential of solar-based mini-grids to electrify in particular more remote areas of the country.
To facilitate higher shares of vRES in the electricity grids, targeted policy making in the following areas is crucial:

- Definition of a realistic mid- and long-term renewable energy target for Kenya’s power sector to provide a policy signal for future planning;
- Reconsideration of the coal plans at highest political level, taking into account scientific findings on the economic viability and environmental compatibility of a coal plant, with a focus on operational flexibility and resulting energy costs;
- Careful planning and coordination of supply and demand in the future, for example through combination of new geothermal projects with development of industrial zones;
- Clear regulation for the further expansion of renewable-based off-grid electrification of rural and isolated areas, facilitating private sector involvement;
- Prioritisation of transmission expansion to ensure timely evacuation of power from new projects;
- Facilitation of regional cooperation and power trade through fast-tracking interconnection plans with neighbouring countries (in the framework of the EAPP);
- Modernisation of the dispatch regime to allow for a reliable and efficient operation of the power system with substantial presence of intermittent resources.

8.6. Spain

Spain – Characteristics

Geography, population and flexibility

The largest city in Spain is Madrid. The agglomeration accounts for almost 14% of the total population. There are other large urban centres that concentrate large shares of population. However, the population
density excluding the largest cities is moderate. Consequently, the existing network is not very dense and links the main load centres.

After many years of sustained growth, electricity demand plummed in 2008 as result of a strong economic crisis and has not fully recovered since then. In fact, total electricity consumption has slightly decreased and stagnated at levels below those of 2008. Since total population has remained constant, electricity consumption per capita decreased slightly in the same period.

Spain exchanges slightly more than 5% of its electricity generation and load with its neighbours. Exports and imports are balanced.

Together with Portugal, the Iberic system is considered an isolated system. The interconnection with the rest of Europe (through France) is limited compared to its peak demand and balancing needs.

Wind resources are very attractive at the coasts and in the North. But also in the centre of the country there are extended regions with a reasonable wind potential.

However, in most parts of the country the solar resource is attractive. Ignoring the extreme North, irradiation is just slightly increasing from North to South.
Impact of country characteristics

The actual vRES installations are evenly distributed across the country. Due to the geographical distribution of generation resources and main load centres across the country, the existing network is highly meshed and dense around largest load centres.

Up to the crisis, the steady demand growth was accompanied by a similar growth in total installed capacity. After 2008, a decreasing and eventually stagnating demand led to considerable oversupply of electricity in the system. Together with the priority of dispatch of renewable-based electricity, this led to a reduced (or null) utilisation of Combined Cycle Gas Turbine (CCGT) plants that were originally intended to operate as baseload units.

The Spanish load profile changes substantially from winter to summer, shifting peak hours from night-hours to noon-hours. This makes the load-solar ratio favourable in the summer but challenging in the winter, when the annual peak demand usually occurs.

Despite efforts to increase the interconnection capacity and reinforce lines linking the Iberic system with France, the relative interconnection with the rest of Europe is still very limited and the system is virtually operated as an isolated system.
Spain – Status of power system transformation

Installed RES capacity, contribution in covering annual load and specific CO2 emissions - past trend and 2016 status

RES supply currently covers around 40% of total annual power generation. Despite the significant participation of hydropower generation, its annual generation fluctuates responding to hydrological conditions. Hydropower generation is used as a load-following technology in Spain.

The share of renewables has increased in the last decades led by a significant growth of vRES capacity in the first decade of 2000, when capacity – mainly wind power – increased more than tenfold. This development has turned wind power generation into the main renewable power source since 2008 – 18% of total electricity generation in 2017 – and the second source of power generation after nuclear – 21 % in 2017 (REE, 2018). Although the total installed capacity of variable and dispatchable
renewables has remained relatively constant in the last years, demand stagnation has allowed to maintain high shares of renewables with the same capacity.

In the mainland system, hourly generation from renewable sources has reached record levels greater than 80% in load coverage and wind power generation alone has reached levels close to 70%.

As both demand and generation mix have remained to a great extent constant since the uptake of vRES in the system (coincidentally, the economic crisis that led to demand stagnation and the deployment of wind power occurred at the same time), the CO₂ emission intensity per kWh has remained relatively constant over the last decade with fluctuations responding to the annual availability of water resources.

Power system transformation is in phase C.
Recent and ongoing developments and related challenges

Looking at vRES growth, Spain made the transition from phase A to phase B in the first years of 2000. The adoption of new system operation practices, improved forecasting systems and a shift of the operating mode of dispatchable thermal generation since 2006 allowed Spain to smoothly integrate the increasing vRES capacities. This is reflected in higher shares of vRES, moving the country from phase B to phase C.

![Figure 8: Share of wind power in total generation in Spain, 2001-2017 [%]](image)

Given the limited interconnection with the rest of Europe, Spain has exploited other flexibility sources and adopted advanced operational practices to cope with the increasing variability of wind generation in covering the demand: in 2017, the wind generation share oscillated between 1%-69% values. Some of the most relevant developments implemented in Spain to integrate higher shares of vRES include:

- Continuous increase and reinforcement of the interconnection capacity with neighbouring countries (although it remains limited and continues to be a challenge).
- Increase in capacity and meshed topology of the national grid. Digitalisation and modernisation of the existing grid to optimise its use. These measures have reduced vRES curtailments associated with grid limitations.
- In 2006, the Spanish TSO launched the Renewable Energy Control Centre (CECRE) with the aim to maximise and integrate the generation from vRES while maintaining reliability and security standards in the system. CECRE increases the response capability in the operation of the system by overseeing and controlling the generation of renewable installations bigger than 5 MW (receiving information every 12 seconds from the installations).
- Benefitting from near real-time information from renewable installations, the system operator has developed and improved forecasting tools that are incorporated into the operation of the system.
- The need for additional flexibility in the system led to a shift in the operating regime of CCGT units in Spain. CCGT units that were initially installed to operate as baseloads carry out retrofits to increase their flexibility (e.g., reduce minimum loads to avoid shut-downs) that allow them to respond to vRES variability and participate in ancillary services.
- The Spanish regulator has developed a regulatory and market framework regarding ancillary services that respond to the increasing participation of vRES. Since 2016, vRE generators can
participate in ancillary services markets. The design and liquidity of this market also attracted the participation of dispatchable conventional generators that had reduced their utilisation rates.

Tasks and policy options for progressing in the near future

A substantial increase in vRES shares from current levels requires ample and deeper restructuration of the regulatory framework and market design. The limited interconnection with Europe will remain one of the most significant challenges for Spain in the future. Potential elements for further progress in the power sector transition are:

- Legally binding decisions regarding the phase-out of coal generation. Power generation from coal fuel has benefited from state support (in the form of subsidies and generation quotas). Coal phase-out is a precondition for a carbon-free power system.
- Legally binding decision on the future role of nuclear power (phase-out or extension of their operating lifes). This will determine the need for flexibility in the system and affect long-term planning.
- Development of remuneration schemes for dispatchable generators that are needed despite their reduced utilisation. Remuneration should not be based solely on generation but on its availability and flexibility it provides to the system. The limited interconnection capacity with the rest of Europe undermines the full phase-out of gas-fired power generation in Spain, which can provide the minimum inertia requirements and the needed flexibility to cope with greater variability.
- Active demand management to facilitate the integration of higher shares of vRES. Spain already counts with demand management programmes that provide flexibility to the system (e.g., interruptible loads).
- The Spanish TSO (REE) is taking active steps to incorporate the large deployment of electric vehicles. In 2017, REE launched an electric vehicle control centre (Cecovel) to facilitate the integration of electric vehicles in the system and benefit from its positive impact in vRES integration.
- Design of additional hedging alternatives to ensure the cost recovery of new generation technologies. This is needed to absorb the emergence of new technologies and the effect of high vRES shares on market prices (e.g., short-time volatility and long periods with near-zero prices).
- Ample revision of electricity markets (from long-term to short-term markets). The effects of a high-vRES system should be reflected in the design of capacity markets, ancillary services and other remuneration instruments. These markets need economic signals that reflect the additional costs that result from keeping a high-vRES system in balance.
8.7. Turkey

Turkey – Characteristics

Geography, population and flexibility

Almost 20% of the total population of Turkey lives in Istanbul, Turkey’s largest city. Half of the total population is concentrated in the eight largest cities, most of them located in the north-west of the country. The population density outside the main cities is very moderate. As a consequence, the grid is heavily meshed and concentrated in the north-west of the country. The Turkish system is interconnected to the rest of Europe through Bulgaria and Greece. There are additional interconnections with isolated systems (i.e., asynchronous to the main system).

Electricity consumption per capita increased from about 2000 kWh per year in 2005 to about 3000 kWh per year in 2016. Additionally, the population with access to electricity increased by nearly 15% compared to 2005. The combination of these two factors explains the steady demand growth between 2005 and 2016 (at average annual rates of about 5%). A further growth of electricity demand can be expected in the future due to continuous population growth, an increase in connections, and the rapid urbanization rates.

Turkey has – compared to the extension of its system – limited connections with its neighbours. This is reflected in the export/import balance: the volumes exchanged are small compared to the annual load or generation. Turkey is a net importer. The Turkish main system has synchronous interconnections with the European
The wind resources are moderate in most parts of the country\(^{49}\). Coastal and mountain areas show a higher potential. The solar potential is attractive and evenly distributed across the country with a slight increase from North to South\(^{50}\).

### Impact of country characteristics

The good availability of hydro resources in Turkey contributed to the smooth and steady growth of wind power generation in the last decade.

Most existing vRE installations are concentrated in the north-west due to the concentration of load centres and a highly meshed grid in this region.

Load is highest during summer days, when the availability and intensity of the solar resource is higher for power generation, presenting a favourable vRES-load ratio in the country.

The degree of meshing in Turkey’s main grid is relatively low in the rural areas. The interconnection with Europe in the west (ENTSO-E system) allows the Turkish system to improve its frequency stability and share spinning reserves among ENTSO-E countries. However, the interconnection with the rest of Europe is still very limited and the system is virtually operated as an isolated system. Moreover, the interconnections with other neighbouring countries are either through isolated systems, which does not contribute in the interconnection flexibility to increase vRES shares, or through non-synchronous links that compete with vRES in the SNSP limitations of the system.

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\(^{49}\) Map obtained from the “Global Wind Atlas 2.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU) in partnership with the World Bank Group, utilizing data provided by Vortex, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info”

\(^{50}\) “Solar resource data obtained from the Global Solar Atlas, owned by the World Bank Group and provided by Solargis.”
Turkey – Status of power system transformation

Installed RES capacity, contribution in covering annual load and specific CO2 emissions - past trend and 2016 status

RES supply currently covers around 30% of annual load. Hydropower is the main source of renewable generation, providing 20% of total RES supply, followed by wind with 8%. Despite the decreasing participation of hydropower in covering the demand, its generation in absolute terms has increased over the last decade. A substantial growth in installed hydropower capacity has not only contributed to meet the increasing demand but also to facilitate the integration of emerging vRES.

The increased penetration of vRES is reflected in the displacement of oil-fired technologies. Consequently, the CO2 emission intensity per kWh has remain relatively constant despite the steady and remarkable demand growth (between 5-10% load growth per year in the last decade).
## Recent and ongoing developments and related challenges

Turkey is currently in phase A of the power system transformation process. While solar power generation is starting to develop (currently representing 1% of total generation), the vRES development is led by the substantial growth of wind power in the last decade. The significant annual growth in electricity demand and the availability of flexible generation sources such as hydropower plants have contributed to the installation of more than 7.5 GW of wind capacity without significant implications for system operations. First measures taken to facilitate the initial incorporation of vRES into the system included the definition of grid codes for wind power generators, such as:

- Fault Ride Through (FRT) capability
- Active Power control
- Frequency contribution
- Reactive power capacity and support
- Monitoring of wind power plants

However, the biggest obstacle to scaling-up vRES shares in the system remains the physical installation of vRES plants. In 2007, a support programme by the government resulted in an abrupt increase in applications to connect vRES installations to the grid. Hundreds of projects expressed their interest to install power plants in the west and south, where grid capacity is still limited. Some regulatory measures were taken to enable the connection of wind power plants while guaranteeing the security of the system, including the following:

- The transmission system operator (TSO) determines and publishes the maximum connection capacity on a regional/substation basis;
- In case of overlapping connection requests that exceed the capacity of a substation, the respective applications are subjected to a competitive process (i.e. a bidding process);
- Based on grid studies, new substations are planned to increase the connectable capacity of vRES in the region.

Given that several load base plants are displaced to generate less hours, but they are still needed to guarantee security of supply in the system, the Turkish regulator put in place capacity remuneration mechanisms to secure enough capacity, including reserve capacity required for security of supply.

In addition to the hourly day-ahead, ancillary services and balancing markets, in 2015, Turkey launched an intraday market to provide participants the opportunity to trade almost real-time and balance their portfolios. These markets contribute to the balancing and security of the system in the presence of fluctuating vRES generation.
**Tasks and policy options for progressing in the near future**

To keep up with the strong annual demand growth, Turkey must continue to encourage the installation of new vRE plants to increase or maintain the share of vRES in total generation in the near future.

To substantially increase vRES shares, major challenges related to network limitations must be overcome. On the one hand, a significant number of vRE projects are held back by limited grid access capacity. Moreover, the national grid is not strong enough especially in the sites rich in renewable resources. The limited interconnection with Europe will also remain in the near future. Some options to make progress in the power system transformation process are:

- Reinforcement and connection capacity in renewable-rich regions.
- Turkey plans to install nuclear power plants in the near future. The role and operation of higher vRES shares must be assessed in the context of reduced flexibility from nuclear power plants. Given Turkey’s limited interconnection, must-run requirements from nuclear power plants could accentuate flexibility challenges in the future.
- Although aggregators are already participating in the system, better regulation is needed to specify the role that aggregators can play in providing flexibility.
- Energy storage systems and demand side management are planned to be included within ancillary services in the future, which widens the portfolio of flexibility providers.
- Turkey is expecting to significantly increase the participation of distributed generation, mainly through PV rooftop panels. In order to mitigate the impact of non-coordinated generation at low level, the association of DSOs are developing a smart grid and metering roadmap.
8.8. Uruguay

Montevideo is the largest city in Uruguay, holding almost half of the national population. The population density outside the capital is very low.

The per capita electricity consumption is about 3200 kWh per person and year. During the last decade the demand has been constantly growing.

Due to the concentration of the population in the capital, the grid is sparse and concentrated around the main load centre in the south.

In the North of the country interconnections exist with Argentina (AC/ synchronous) and Brazil (HVDC/ non-synchronous). The interconnection capacity with Argentina alone is greater than Uruguay’s peak demand. However, the electricity exports are significantly higher to Brazil.

Because of the character of the interconnections, the power systems of Uruguay and Argentina together form one joint but isolated synchronous system. The total final electricity consumption of Uruguay is about 8% of the total interconnected system.
Wind resources are most favourable in the coastal areas in the South, where the main load centre is located (near Montevideo)\(^5\).

Solar resources are favourable in the whole country with a slight increase from South to North\(^2\).

Uruguay counts with remarkable hydro resources that allows it to cover around 60% of the total generation.

### Impact of country characteristics

The availability of hydro resources contributed to the significant uptake of vRES in 2014.

Load is expected to continue to grow in the future, lessening the risks of curtailments associated to high shares of vRE generation.

Due to the concentration of the population in the South and the large distances to the existing hydro capacities and interconnection links in the North, the existing transmission network is sparse. Despite the large interconnection capacity with Argentina (2000 MW) and Brazil (570 MW), there is not an active cross-border market. Hence, interconnections are not fully exploited and the system experiences high vRES curtailments due to oversupply.

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\(^1\) Map obtained from the “Global Wind Atlas 2.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU) in partnership with the World Bank Group, utilizing data provided by Vortex, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info”

\(^2\) “Solar resource data obtained from the Global Solar Atlas, owned by the World Bank Group and provided by Solargis.”
Uruguay – Status of power system transformation

Installed RES capacity, contribution in covering annual load and specific CO2 emissions - past trend and 2016 status

Uruguay’s generation mix is nearly 100% renewable, with a significant 33% from vRES (the majority from wind) and 67% from dRES (mainly hydro). Before the uptake of vRES in 2014, the Uruguayan system was highly dependent on hydro resources. Thermal participation in the generation mix varied from year to year to cope for occasional lack of water. This is reflected in the fluctuating emission intensity until 2015. Furthermore, fossil fuel resources for thermal generation were imported. The strong reliance on hydropower and energy security concerns were the main challenge that triggered the development of vRES technologies. With an increased share of vRES and the opportunity to export excess generation, thermal generation is mainly used to balance the system in case of...
contingencies. Since the development of vRES in 2014, Uruguay has turned the historical trend and became a net electricity exporter.

### Recent and ongoing developments and related challenges

Uruguay is currently in phase C. However, because of the strong link with Argentina the power system cannot be considered as isolated. Due to the large hydro capacities, the contribution from vRES is still limited and SNSP restrictions do not apply.

The significant participation of hydro resources and the high interconnection capacities equipped Uruguay with valuable flexibility resources to accommodate an important share of vRES: scaling from a symbolic 5% in 2013 to a remarkable 33% in 2017, less than a decade after they started the transition towards vRES.

In addition to the flexibility provided by dRES and interconnections, Uruguay adopted additional measures to facilitate the integration of higher shares of vRES, including advanced forecasting systems, monitoring and control measures, all of them with relatively limited technical effort.

### Tasks and policy options for progressing in the near future

The major challenge that Uruguay faces in the near future is the curtailment of renewable power. Uruguay currently experiences high vRES curtailment levels, mostly at night when wind generation exceeds demand. Despite the large interconnection capacity with Argentina, this is not used at its maximum capacity to export the excess of generation due to the lack of commercial agreement between the two countries.

Uruguay is considering the following options to efficiently integrate higher shares of vRES in the future:

- Establish an active cross-border market with Argentina and Brazil that increases the export of renewable energy surplus and reduces vRES curtailment levels;
- Install and use Automated Generation Control (AGC) systems for economic dispatch;
- Promote long-term planning for the grid that accounts for higher shares of vRES and their implications for grid congestion and voltage stability;
- Incorporate battery and pumped systems to cope with the variability of vRES;
- Develop demand side management programmes;
- Develop hybrid (wind-solar) power plants to benefit from their complementarity, increase the capacity factor and reduce net-variability.

Uruguay already foresees the key role of sector coupling alternatives to address the electricity surplus in a high vRES-system. In this context, Uruguay is exploring the development of heat-pumps, electric vehicles and hydrogen production.
References


Annex I – Quantitative analysis of country characteristics

For the quantitative analysis of the country characteristics that have been defined in chapter 5, the focus is placed on indicators for which consistent data is publicly available. A comprehensive overview of characteristics, indicators, metrics and data sources is provided in Table 6.

Availability and potential of dispatchable renewable energy sources

Although the decisive factor is the technical dRES potential in a country, two proxies are used in this study, since information on the dRES potential is often limited.

The first indicator is the installed dRES capacity (upper graph in Figure 10). For the countries where the figures are available installed dRES capacity is mirrored with the system’s minimum and peak load. The second, complementary indicator is the share of dRES generation in net electricity generation of a country (lower graph in Figure 10). Interpretation of the first indicator must be done carefully, since the availability of dRES throughout the year may be limited. An illustrative example is Spain with installed hydro capacity of more than 18 GW which have a capacity factor of just 20% (representing slightly more than 1700 full load hours per year).

Figure 10: Installed dRES capacity (most recent value highlighted) and share of dRES in net electricity generation. Example Iceland.
Patterns of renewable resources in time (seasonal ratio of solar)

The most insightful indicator would be the combined seasonal ratio of vRES and dRES availability which translates into the residual load. However, because of the lack of input data and the complexity of this combined parameter a simplified parameter is used. The solar ratio is calculated as the ratio between the average daily solar energy yield of the darkest three months (winter) and the sunniest three months (summer).

![Figure 9: Solar ratio being the monthly solar yield of three winter months divided by solar yield of three summer months. Example Denmark.](image)

In this study, a focus is placed on the solar resource\(^{53,54}\) for two reasons: first, solar data for almost all countries in the world is publicly available and can be used to characterise geographical regions with reasonable accuracy. Secondly, depending on the location, the solar resource shows a strong seasonal pattern which has obvious consequences for power system planning and operation.\(^{55,56}\)

Trend of load growth

Drivers of load growth are growth of population, economic growth and/or the unlocking of suppressed demand\(^{57}\).

In this study, simplified indicators are used for the expected load growth: the past normalised trend of the absolute population is presented against the annual final electricity consumption per capita for the period from 2000 to 2016 (see Figure 12, example of Kenya). The population of 2000 is set to 100%. The second plot in the same graph shows the per capita consumption only for the share of the population with access to electricity. When electricity access rates approach 100%, the per capita values of both lines are equal.

If one of the lines shows a trend to the right (increasing population – with access to electricity) or up (increasing per capita consumption) the absolute load will grow.

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\(^{53}\) Wind power is equally important. However, the wind resource depends heavily on local site conditions. Even small differences in wind speed have significant consequences for wind power output. For that reason, the average wind speed in extended geographical areas is of little value for a realistic assessment of potentials. The quality of more generic data simply is insufficient to draw robust conclusions for a whole country. More detailed, national or regional studies are an essential extension of the analysis provided here.

\(^{54}\) The seasonal ratio of dRES capability deserves attention as well. In case of hydro, summer-winter variations may be substantial and the ratio may be significantly lower than 1.

\(^{55}\) The daily pattern of the solar resource is important as well.

\(^{56}\) The correlation of the monthly averages of load with the seasonal ratio of the solar (or wind) resources or, more directly, the correlation between RES generation and load would be an ideal indicator. Again, for many countries time series of load data are not publicly available.

\(^{57}\) Suppressed demand may be related to limited access of the population to electricity but also to regular load shedding of existing customers due to temporary shortages in generation.
The per capita final electricity consumption may be benchmarked against international levels like OECD averages. However, much care is required with international comparisons because country specific climatic conditions and power system structures may influence the per capita consumption significantly.

**Density and distribution of population**

Two indicators for population density and distribution can be used. The first indicates the shares of population in the largest city, in cities with more than 300,000 inhabitants and in rural areas, respectively (pie chart at the top of Figure 8 – example of Ireland). Additionally, the population density (i.e., inhabitants per square kilometre) in rural areas, i.e., outside cities of more than 300,000 inhabitants, can be estimated (bar graph at the bottom of Figure 8).

**Interconnection to directly neighbouring countries**
Information on the interconnection capacity is difficult to find. As a proxy for the indicator, the share of export or import volumes in the total annual generation can be used. It must be noted that the exchanges are strongly driven by market conditions. Moreover, the consulted data source does not distinguish between synchronous interconnection and HVDC links. For that reason, a very simplified, semi-quantitative scale is used relating the annual export or import shares to annual load and consumption. To limit the effect of year to year fluctuations data are averaged over the 5-year period 2012 to 2016:

- Export / import less than 6% of annual load / generation: no relevant interconnection,
- Export / import less than 12% of annual load / generation: little interconnection and
- Export / import more than 12% of annual load / generation: reasonable or high interconnection capacity.

In this report, the higher absolute value is used (either for export or import), assuming that capacity is symmetrical. If imports are high, export capability should be in a similar range, even if absolute export volumes are much lower due to market conditions.

Two potentially more meaningful indicators for flexibility are a) the percentage of dispatchable generation capacity connected to transmission and distribution networks, and b) the existing fleet’s ability to operate flexibly. However, these indicators are not feasible due to a lack of data.

Table 5: Overview of geographical and socio-economic characteristics, indicators and sources

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Characteristic</th>
<th>Indicator</th>
<th>Metric/ range</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geography, natural resources and climate</td>
<td>Availability and potential of dRES (based on current situation)</td>
<td>Installed dRES capacity</td>
<td>MW</td>
<td>S&amp;P Global Platts, 2017</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Share of dRES generation in total final electricity consumption, used data cover the period from 2005 to 2016</td>
<td>%</td>
<td>IEA/OECD, 2018</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Correlation of monthly averages of load with the seasonal ratio of the solar resource</td>
<td>MJ/m2, %</td>
<td>IRENA, 2018a</td>
</tr>
<tr>
<td>Population and economy</td>
<td>Trend of load growth: development of per capita electricity consumption</td>
<td>Total final electricity consumption per capita, taking changes in access to electricity into account, used data cover the period from 2005 to 2016</td>
<td>kWh/capita/a</td>
<td>IEA/OECD, 2018</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>World Bank, 2019a</td>
</tr>
</tbody>
</table>

58 Data in the period from 2009 to 2012 are influenced by the economic decline resulting from the financial crisis. They are purposely not included here.
59 As an example: a country that regularly exports 10 GW but imports maximal 1 GW needs transmission capacity for 10 GW. Another country that exports only 1 GW but imports 10 GW equally needs transmission capacity for 10 GW.
60 The existing fleet’s ability to operate flexibly provides insights into the capability of the system to cope with greater vRES (IEA, 2018b). Conventional thermal power plants – similar to hydropower plants – provide short-term flexibility to cope with the variability introduced by vRES. Some of the parameters to measure fleet’s flexibility include, the rate of change in output (i.e. ramping rate), minimum output, and minimum run time. The technology mix of the thermal power plant fleet in the system provides an indication of the flexibility of existing plants. However, plant characteristics vary greatly, even within the same technology. Additionally, the behaviour of existing plants can be changed by moderate adaptations. Any indication has to be based on a detailed assessment.
61 See, for example, [http://www.opensolardb.org/downloadcsv](http://www.opensolardb.org/downloadcsv), or RETScreen Expert (only accessible with commercial license).
| **Density and distribution of population** | Number of inhabitants in largest city, cities >300,000 inhabitants and rural / cities < 300,000 inhabitants. Inhabitants per square kilometre outside larger cities (>300,000 inhabitants) | Inhabitants | IEA/OECD, 2018  
UNDESA, 2018  
World Bank, 2019b |
|------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|--------------------------------------------------|
| **Flexibility**                          | Power exchange per year, used data cover the period from 2012 to 2016                                                                                                                                                                                                  | Ratio of export and import to load and generation in %, Qualified whether connection is synchronous (AC) or non-synchronous (HVDC) | IEA/OECD, 2018  
Various country specific sources |