renac
renewables academy

GRID INTEGRATION OF RENEWABLES

Exhibition brochure

Grid Integration of Renewables

renac
renewables academy

Dear readers,

Dear visitors to the exhibition,

Renewable energies have experienced significant development in recent years and in many countries have become an economically viable alternative to fossil fuels for the production of electricity. Today, photovoltaic (PV) and wind power stations are producing electricity in large quantities and feeding it safely into power grids. However, the fluctuating character of PV and wind energy changes the flexibility requirements of power systems and their components.

Grid extension, energy storage systems, flexible generation using conventional power systems and demand side integration are required. Furthermore, forecasting of renewable power generation and voltage control through distributed renewable power stations have to be implemented. With an increasing proportion of PV and wind energy in the electricity grid, a thorough understanding of the peculiarities of such an energy system is needed to ensure continuous and safe operation of the electricity grid.

The “Grid Integration of Renewables” exhibition, developed under the CapREG “Capacity Development on Renewable Energy and Grid Integration” programme, shall contribute to a better understanding of such power systems, based to a large extent on fluctuating renewable energy sources such as wind and PV. The highly complex topic is hereby formulated in a way that is intelligible to a broad audience with little or no technical background.

In addition to all of those involved in and supporting the exhibition, RENAC would particularly like to thank its local partners, who are overseeing the exhibition in CapREG partner countries, as well as the German “International Climate Initiative” (ICI), which is financing the exhibition.

Should you have any questions or comments regarding the exhibition please contact our CapREG team at

capreg@renac.de.

Enjoy the exhibition!

About CapREG

CapREG “Capacity Development on Renewable Energy and Grid Integration” is a three-year capacity building programme within the German “International Climate Initiative” (ICI). The Renewables Academy AG (RENAC) has been commissioned by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) to facilitate the capacity building programme from 2014 to 2016 in seven partner countries.

The objective is to provide professionals from both the public and private sectors with comprehensive know-how on renewable energy technologies and to assist in increasing their use. The programme offers various kinds of training, networking and exchange of experiences for professionals from Indonesia, the Philippines, Thailand, Vietnam, Mexico, Peru and Ecuador.

Supported by:

Federal Ministry for the
Environment, Nature Conservation,
Building and Nuclear Safety

based on a decision of the German Bundestag

By creating suitable framework conditions for the development of renewable energy and by overcoming obstacles for the grid integration of renewable energy, it will be possible to reduce greenhouse gas emissions, encourage the financing of renewables and contribute to energy security.

Content

Introduction

Section 1: Principles of the Power System

Section 2: Flexibility Options & Operational Measures

Section 3: Evaluation

Summary and Outlook

1

CapREG
Capacity Development
on Renewable Energy
and Grid Integration

INTRODUCTION

Future Energy

Aim

Reliable, sustainable and economically viable electricity supply from renewable energy sources

Challenges

Spatially dispersed and temporally fluctuating character of electricity generation from renewable energy sources in combination with irregular consumption of electricity

Solutions

Make use of flexibility options and operational measures:

- grid extension and enforcement
- energy storage
- flexible generation from conventional power plants
- demand side integration
- forecasting of variable renewable energies
- voltage regulation with variable renewable energies

Characteristics of renewables

Natural resources such as the sun or the wind are available free of charge for an infinite amount of time. Renewable energy technologies such as photovoltaic (PV) systems and wind turbines make use of these energy sources to generate electricity. Compared to conventional electricity generation based on fossil fuels (coal, oil or natural gas), renewable energy sources have the following advantages:

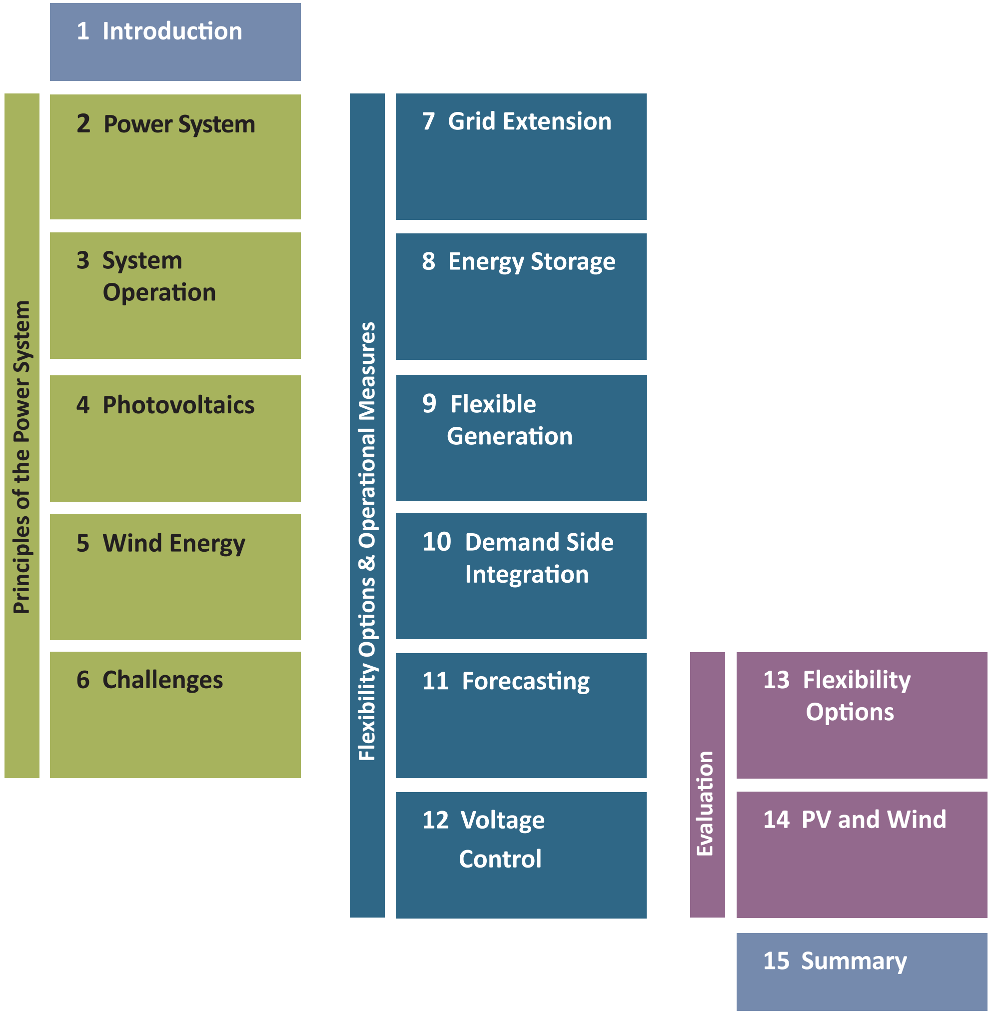
- independence from fossil fuel imports
- using locally available energy sources
- ability to empower the local economy
- reduction of CO_2 emissions and climate change mitigation
- free of other harmful emissions into the air

Content of the exhibition

This exhibition will inform you about the challenges and solutions relating to grid integration of renewables.

Grid integration refers to methods of feeding large volumes of electricity from renewable energy sources into transmission and distribution grids while ensuring a reliable and efficient electricity supply. The exhibition focuses on wind and solar energy. They are called variable renewable energy sources, because their fluctuating power generation is determined by weather or time of day.

Electricity systems can be supplied entirely by renewable energy sources. Nevertheless, if modern power systems want to maintain a good quality of electricity supply, they must be able to react to fluctuations in electricity generation. The aim of this exhibition is to create a better understanding of how to use flexibility options and operational measures in order to ensure a reliable and sustainable electricity supply with variable renewable energy sources.



1 Introduction

Principles of the Power System

2 Power System

3 System Operation

4 Photovoltaics

5 Wind Energy

6 Challenges

Flexibility Options & Operational Measures

7 Grid Extension

8 Energy Storage

9 Flexible Generation

10 Demand Side Integration

11 Forecasting

12 Voltage Control

Evaluation

13 Flexibility Options

14 PV and Wind

15 Summary

Power System

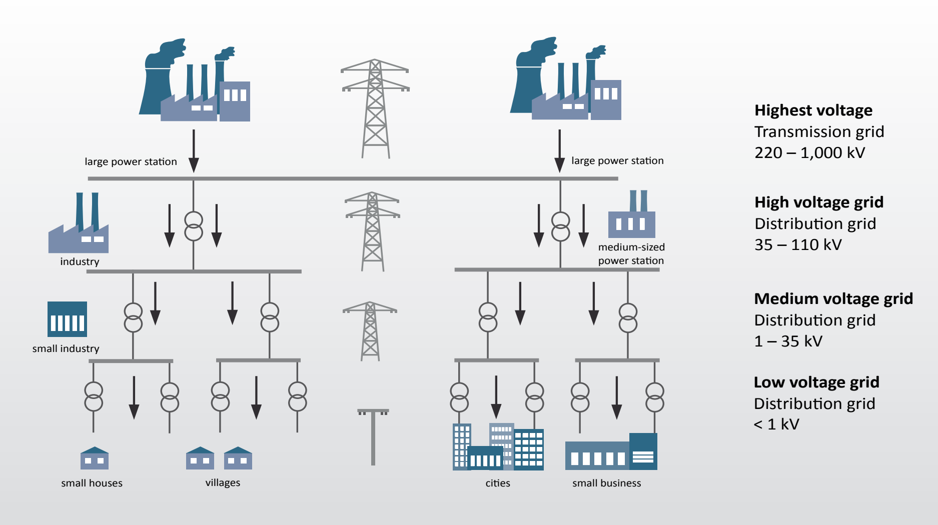


Fig. 1: Schematic diagramme of an electrical network

Structure of a power system

A power system includes electricity generation units, the electricity grid and the consumers. In order to reduce losses in the transmission and distribution grid, the power grid is divided into different voltage levels (see Fig. 1). Typically, the bulk power stations like nuclear, coal or gas power plants inject power into the highest voltage levels. The consumers are connected to medium and low voltage levels, depending on the amount of electricity consumption. Therefore the power flow in conventional power systems is unidirectional, i.e. from the highest to the lowest voltage level.

Consumption of electricity

The consumers' electricity demand, the so-called load, varies over time. Fig. 2 shows a typical load profile of a European country for a sample day. At night, energy consumption is lower than during the day. The shape of the load profile is different in each power system depending on climate conditions, economic activity etc. Fig. 3 depicts an electricity load profile for six days. It shows that demand fluctuations vary from day to day (e.g. energy consumption is lower at the weekend).

Operations planning for power stations

Planning the power system operation is necessary, as different types of stations can be used in different ways because of technical and economic characteristics. The schedule for operation of the different power stations, the so-called dispatch, is determined a few days in advance according to the load forecast. The aim is to find the most economical power generation mix in consideration of grid capacities and constraints.

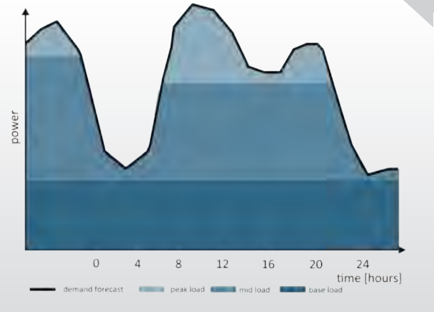


Fig. 2: Load profile for one day

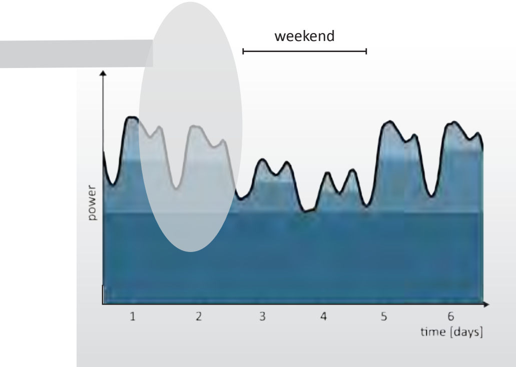


Fig. 3: Load profile for six days

Peak-load station

- High electricity generation price
- High flexibility
- In service only a few hours a day
- Examples: hydroelectric power stations with pumped storage, gas turbines

Middle-load station

- Average electricity generation price
- Medium flexibility
- Power output can vary according to demand
- Examples: coal-fired power stations, combined-cycle gas turbines

Base-load station

- Low electricity generation price
- Limited flexibility
- In service all day at maximum efficiency
- Examples: lignite, nuclear and run-of-river hydro power stations

Peak-, middle- and base-load

The maximum amount of power consumed at a certain point of time is called peak-load. The base-load is the minimum amount of power consumed irrespective of time. Power stations are divided into three types, depending on which share of the load they cover: Base-load stations operate with a constant output and generally cover the majority of the annual consumption. Middle-load stations operate mainly during the day when demand is higher. Peak-load stations are particularly flexible and cover the momentary demand peaks.

3 System Operation

Grid Codes define the rules

Many different types of equipment must work together in the power system. In order to ensure safe grid operation and high-quality electricity supply, all installations must comply with certain technical rules. These so-called Grid Codes regulate electricity generation, transportation, measurement and power plant maintenance. There can be a separate Grid Code for renewable power generation or one that covers all types of power plants.

Monitoring the status of the electricity grid

The consumption and production of electricity must be balanced to ensure the stability of the grid. Grid frequency and voltage are indicators to measure the quality of electricity supply and the stability of grid operation. While grid frequency has the same value throughout the entire grid (e.g. a nominal value of 50 Hz), the voltage differs at each point in the grid. Both parameters may not exceed certain limits which are specified in the Grid Codes.

Balance and imbalance in the grid

When generation and demand are in equilibrium, the grid frequency remains constant; otherwise it increases or decreases (Fig. 1). There can be various reasons for disequilibrium, for example a technical breakdown occurring on the generation side or unexpected demand changes on the demand side (either upward or downward). However, the actual load deviates from the predicted load even during normal operation, which makes constant provision of 'balancing power' necessary (Fig. 2).

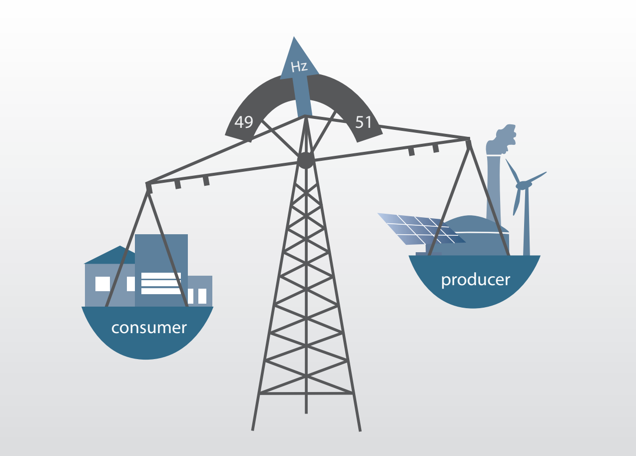


Fig. 1: Disequilibrium between production and consumption

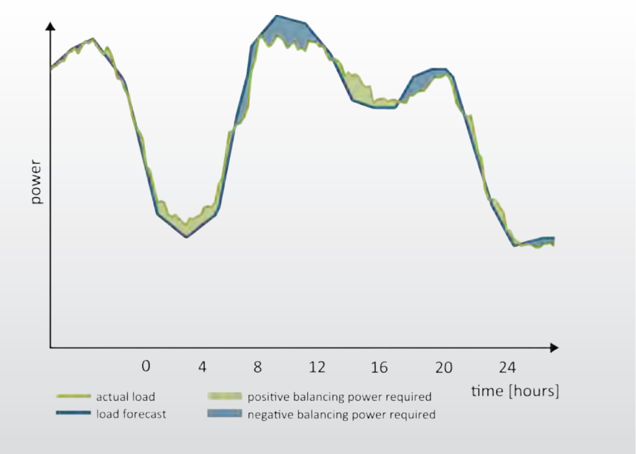


Fig. 2: Demand forecast and actual demand

Balancing the grid

Balancing power capacities are used to solve the disequilibrium between generation and load. This is done by increasing or reducing power generation or load. Positive balancing power refers to increased generation or load reduction; with negative balancing power it is the other way around. Without sufficient balancing power capacity, the power system might experience frequent brownouts (intentional voltage reductions) or blackouts (disconnection of load in certain grid areas).

Balancing power schemes

Different sources of balancing power have different reaction times. Therefore, balancing power schemes often have multiple steps. The primary balancing power reserve must be available within seconds, followed by the secondary and tertiary reserves (Fig. 3). The latter reserves usually replace the first one – this frees up the faster balancing reserves, making them available to react to new contingencies. It also reduces costs, as balancing power from the most flexible power stations is often the most expensive option.

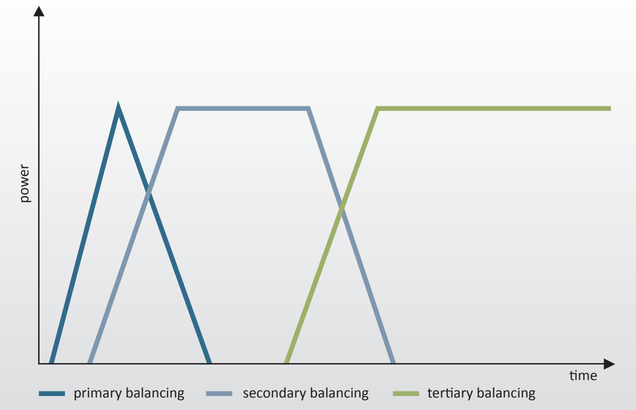


Fig. 3: Balancing power scheme

Frequency fluctuations

Each power system defines its own rules and regulations. If the frequency does not stay within a certain tolerated range (Fig. 4, red line), balancing power is activated in order to stabilise the frequency. The frequency fluctuations of the green line are well balanced, whereas those of the blue line are in the critical range. Heavy frequency fluctuations can affect electric appliances in a negative way, which should be avoided.

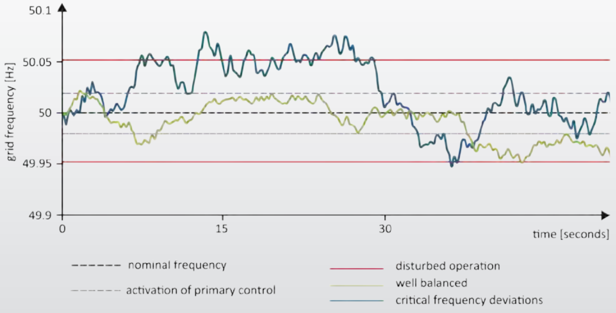


Fig. 4: Time series of two grid frequencies

4 Photovoltaics

Photovoltaic applications

Photovoltaics (PV) is a technology which makes use of the photoelectric effect to produce electricity directly from sunlight. The electricity generated using PV systems can be fed into the electricity grid, stored in batteries for later use or used directly on-site. The modular character of a PV system allows for a wide variety of system sizes and designs. The figure below shows some of the essential components in both off-grid and grid-connected systems.

Off-grid PV systems

Off-grid PV systems are used...

- as a back-up electricity supply in the case of weak power grids,
- for on-site consumption in domestic or commercial areas and
- as a direct power supply for solar water pumps.

Grid-connected PV systems

Grid-connected PV systems can...

- fully feed into the electricity grid (small-scale or large-scale systems, from kW to several MW),
- deliver electricity for on-site consumption and feed-in excess electricity only (small-scale systems, W to kW) and
- be used to stabilise the grid (see panel 12, Fig. 4).

Components of off-grid and grid-connected PV systems

Charge controller and battery

Most off-grid PV installations require a battery in order to store the electricity until it is used. Charge controllers monitor and protect the battery from overcharge and deep discharge. Batteries are also used in grid-connected PV systems in order to increase self-consumption.

PV cell

The PV cell is the smallest building block for a PV installation; it transforms the sun's rays into electricity. Nowadays, the most widely used material for the PV cell is silicon. Several PV cells are connected in series and/or in parallel inside a PV module.

PV module

PV modules are composed of many PV cells that are embedded between two glass sheets protected by an aluminium frame, for example. Modules produce direct current. Several modules are connected in series and/or in parallel forming a PV array.

Inverter

An inverter converts direct current into alternating current with a frequency and voltage matching that of the grid. Inverters also optimise the electricity feed-in and the system control. ‘String inverters’ are designed for PV systems in the kW range and ‘central inverters’ are designed for larger systems in the MW range.

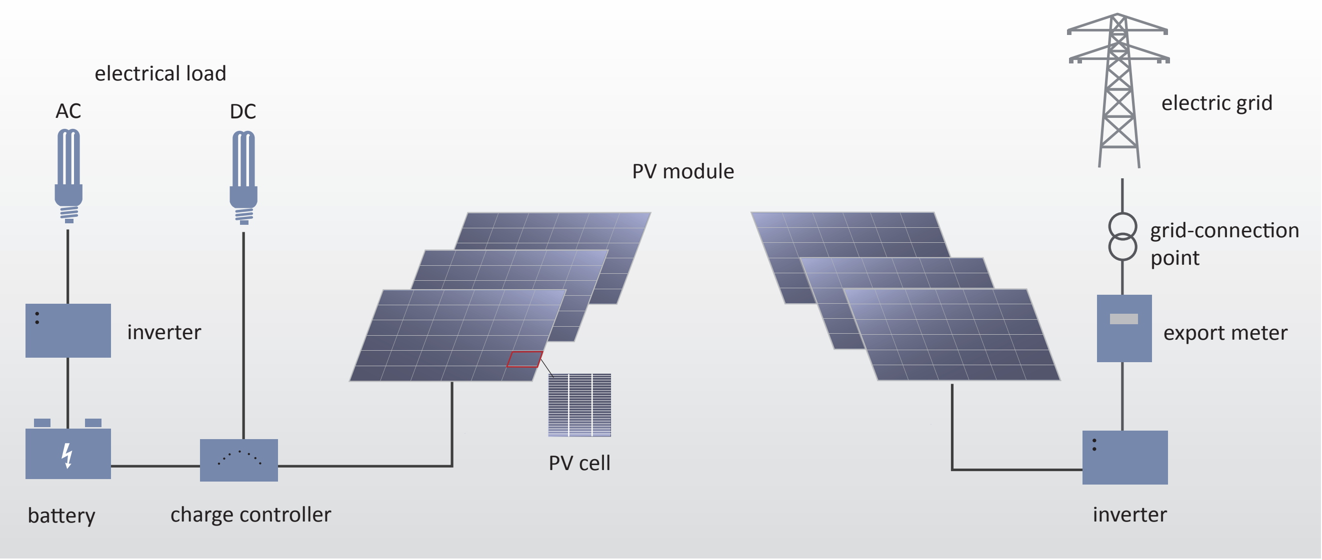


Fig.1: Components of off-grid and grid connected PV system

Variable power output

There are two main factors which affect the instantaneous output of a PV cell: the solar irradiance incident on the cell surface and the temperature of the PV cells. An increase in solar irradiance causes an almost linear increase in current output and therefore an almost linear increase in power output. An increase in cell or module temperature causes a significant decrease in voltage and therefore a significant decrease in power output (Fig. 2). As a consequence, the PV system usually does not generate electricity at its rated power ('peak power'). Instead the power output varies significantly during the day.

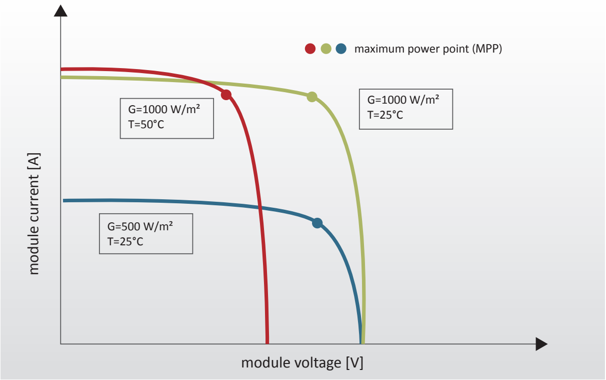
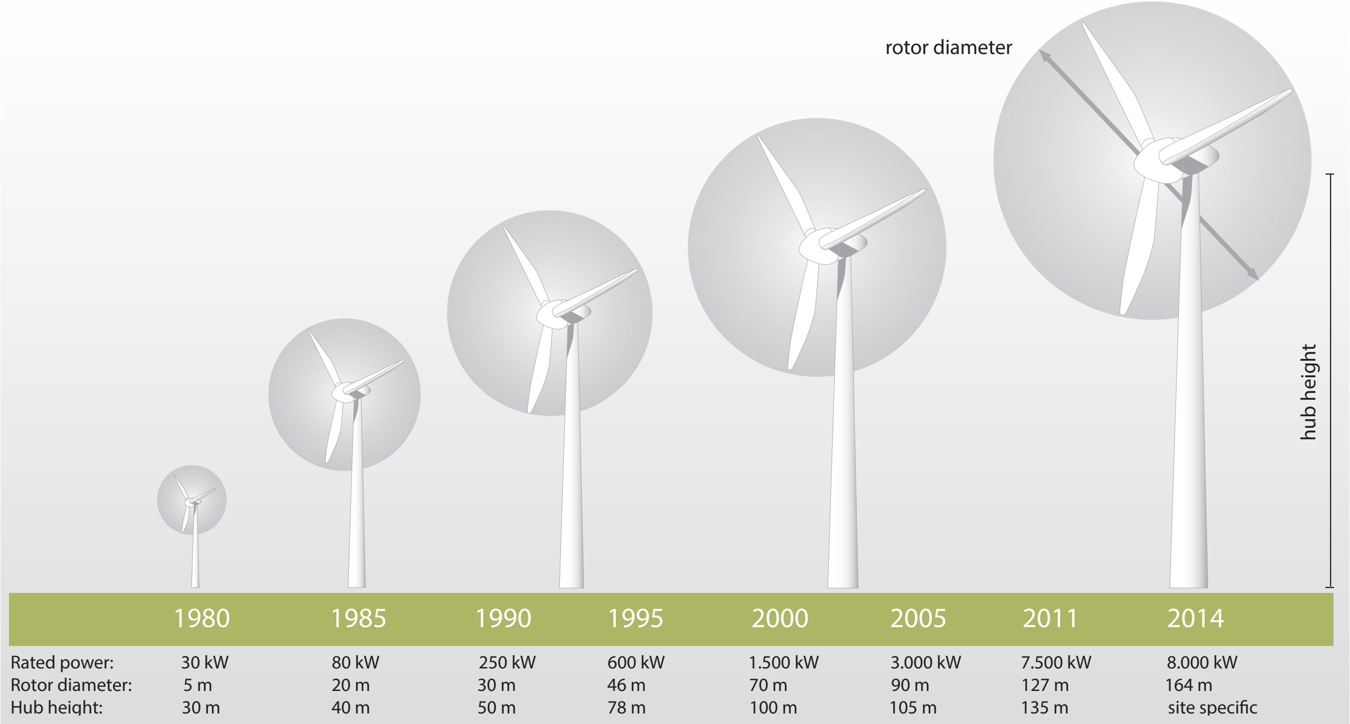


Fig. 2: I-V curve depending on irradiance (G) and module temperature (T)

5 Wind Energy



	1980	1985	1990	1995	2000	2005	2011	2014
Rated power:	30 kW	80 kW	250 kW	600 kW	1.500 kW	3.000 kW	7.500 kW	8.000 kW
Rotor diameter:	5 m	20 m	30 m	46 m	70 m	90 m	127 m	164 m
Hub height:	30 m	40 m	50 m	78 m	100 m	105 m	135 m	site specific

Fig. 1: Development of wind turbine size

Wind energy applications

The utilisation of wind energy is very old. Nowadays, instead of using it to pump water or mill flour, it is mostly used to generate electricity. Wind turbines use the kinetic energy of wind, converting it into a rotational movement and then into electric power. The generation capacity of a single wind turbine has grown over the last few decades, from below 100 kW to several megawatts (Fig. 1).

Wind turbine types

Wind turbines can be constructed to withstand heavy storms, operate under arctic or tropical weather conditions, off coasts in the sea or in deserts. Wind turbines rotate either on a horizontal or a vertical axis. The number of blades can range from one single rotor blade up to about 20 rotor blades (Fig. 2). The most common type is the horizontal axis turbine with three rotor blades.

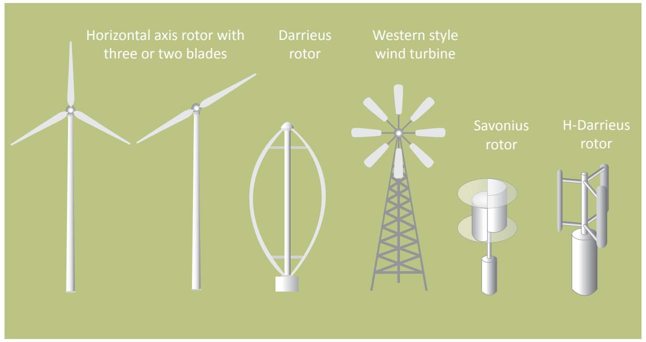


Fig. 2: Types of wind turbines

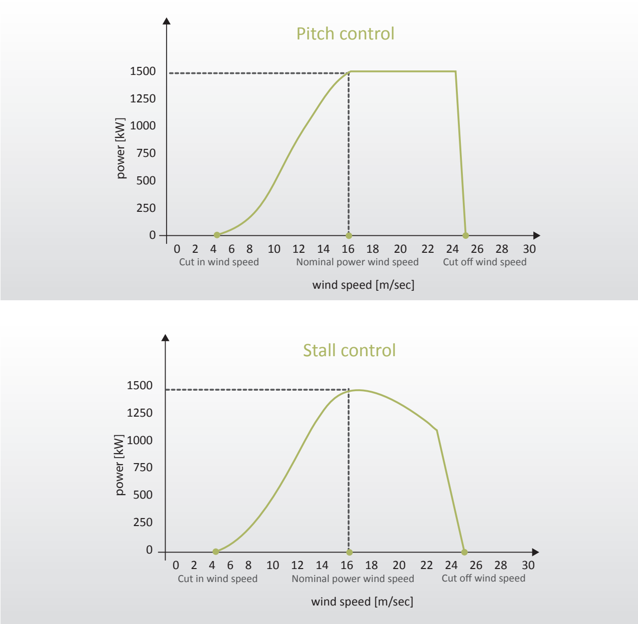


Fig. 4: Power curves of pitch and stall control

Principle of wind energy

The air flowing past the wind turbine creates a force at the rotor blades which makes the rotor spin. This drives the generator, which is located in the nacelle, and produces electricity. Frequency, voltage and electricity feed-in are controlled by power electronics. In order to maximise energy yield, the rotor has to face the wind. Moreover, the angle of the rotor blades and the rotational speed of the rotor have to be adjusted to the prevalent wind speed. For this optimisation, some turbine types use gearboxes while others use power electronics.

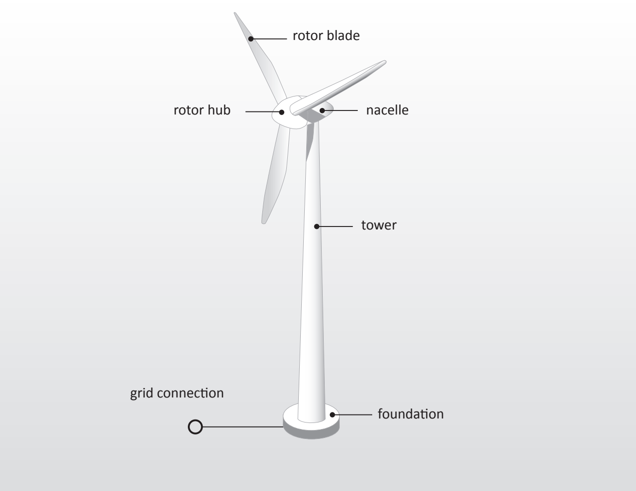


Fig. 3: Components of a wind turbine

Variable power output

The power output of wind turbines varies with wind speed. There are two ways to control the power output of a wind turbine: pitch control and stall control (Fig. 4).

With stall-controlled wind turbines, the rotor blades are fixed and they cannot rotate around their own axis. The air stream at the rotor blades will often lead to turbulences at the back of the blade, which reduces power output at high wind speeds.

With pitch-controlled wind turbines, the blades can be turned to an optimal position. Thus, at high wind speeds the nominal power output can be maintained. Beyond the cut-out wind speed, the wind turbine has to stop operating to avoid any damage. Most wind turbines on the world market use pitch control.

6 Challenges

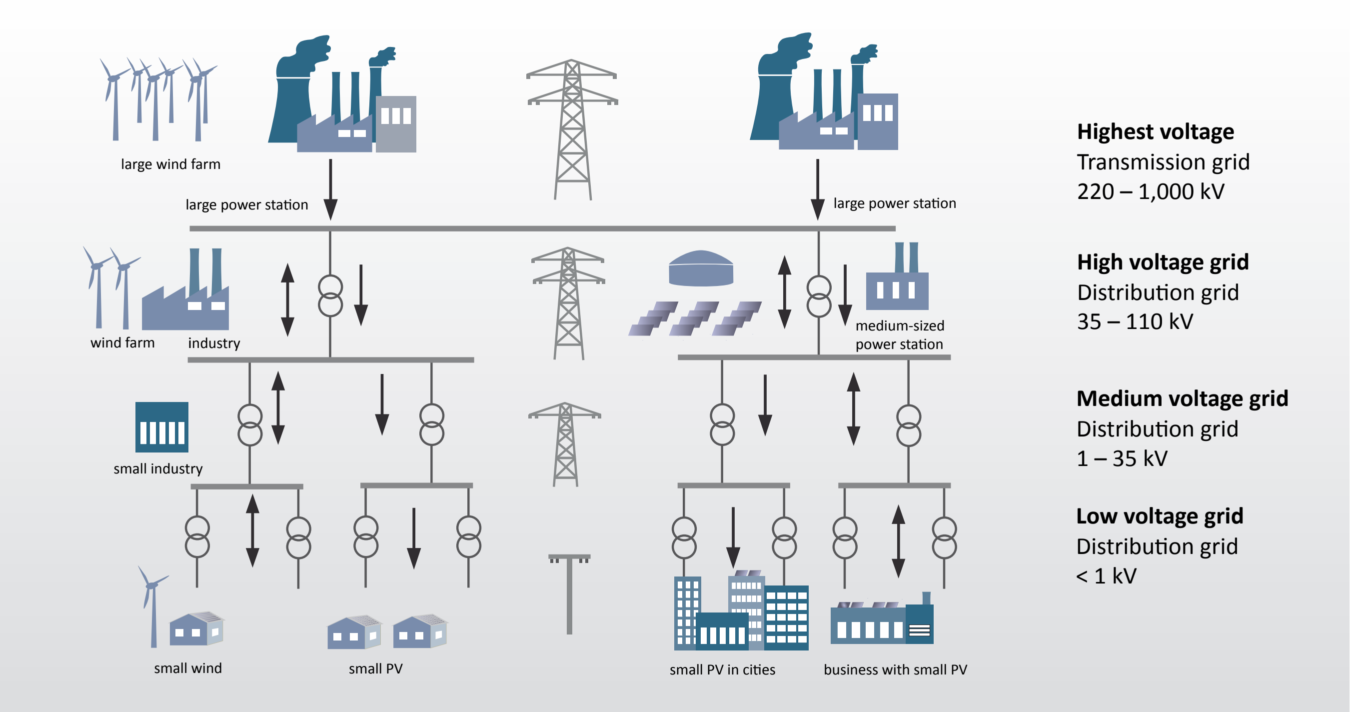


Fig. 1: Structure of electric grid with renewable energy power stations

Changes in the power system

PV systems and wind turbines (among other renewable energy systems) can be connected to all the different voltage levels of the grid, depending on system size (Fig. 1). If large numbers of such power systems are installed, power could flow from low voltage to high voltage levels. As a consequence, the conventional power system requires changes in infrastructure, operation and management.

Fluctuating power generation from PV and wind

The wind and the sun are not always available. Calm days or cloudy weather lead to breaks in the power output of wind and solar energy stations (see Fig. 2). These resources must be utilised when available. In many power systems, electricity feed-in from renewables is prioritised over feed-in from conventional power stations. However, PV and wind power stations only feed-in their maximum power capacity during optimal weather conditions.

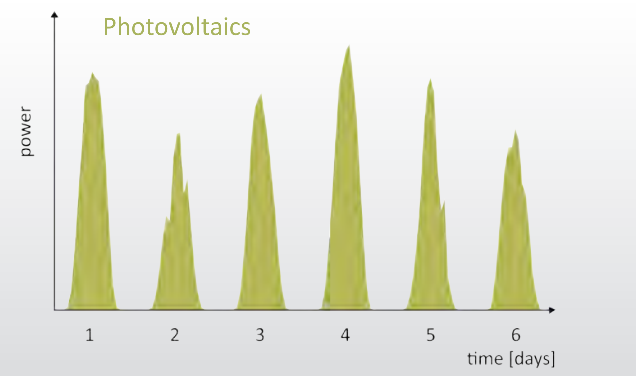


Fig. 2a: Generation profile of photovoltaics

Residual load

In power systems with a large share of renewable energy, the residual load becomes an important parameter to consider in operational and planning procedures. The residual load equals the total load minus the renewable energy generation. Options to supply the residual load will be presented on the following panels.

Fig.3: Residual load formula

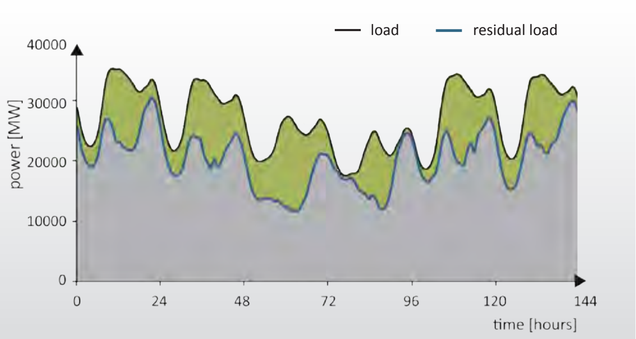


Fig. 4: Residual load over 6 days with a low renewable energy share

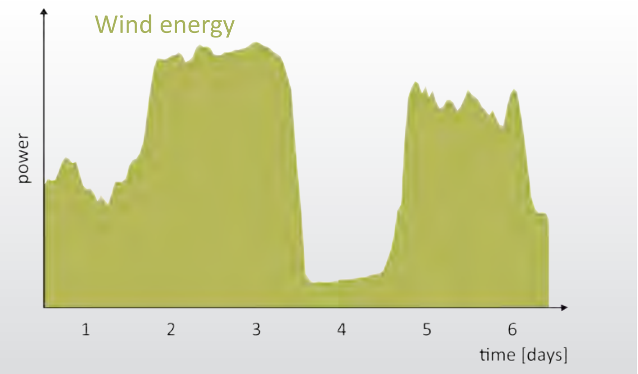


Fig. 2b: Generation profile of wind energy

Electricity supply with varying renewable energy volume

When PV and wind power stations cover just a relatively small share of electricity demand, the impact on the residual load is comparatively low (see Fig. 4).

In power systems with a large generation capacity from renewable energy, the residual load varies significantly over time. Residual load can even become negative when renewable energy generation is greater than demand (see third day on Fig. 5). The excess power at that moment can be exported via the grid, stored for later use or used by additional loads. Alternatively, some generation has to be curtailed.

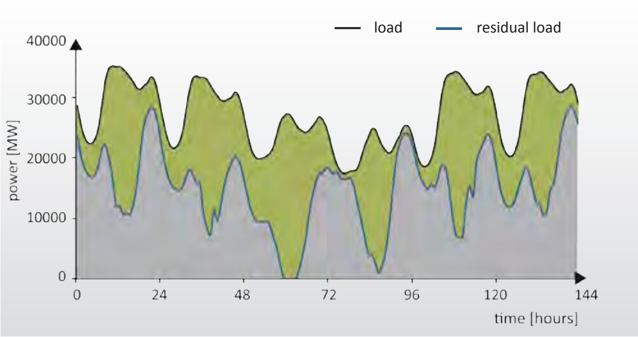


Fig. 5: Residual load over 6 days with a high renewable energy share

Grid Extension

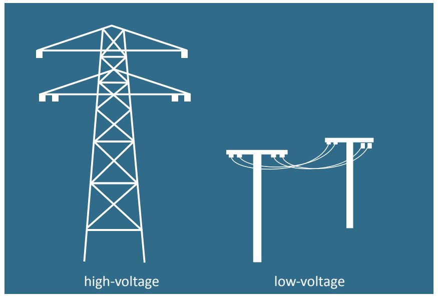


Fig. 1: Different power lines and masts

Components and function of the grid

In addition to cables and lines, the transmission and distribution grid also consists of substations with transformers, switchgear and monitoring equipment. The main function of the grid is the spatial transport of electricity from generators to loads. Some equipment at substations can be used to control the direction or amount of power flow.

Costs and benefits of grid extension

Grid extension and enforcement is a long-term measure concerning planning and actual construction. The planning of new transmission lines has to take the supply and demand situation into account several decades in advance, which is difficult to predict. But once installed, additional grid infrastructure can respond immediately to changing conditions. Switchgear can change the power flow within seconds and transformers react to voltage fluctuations without delay.

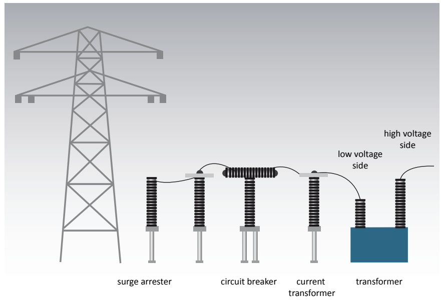


Fig. 2: Components of a substation

Congestion

In electrical power systems, transmission congestion is an important topic. Congestion is defined as the condition where the reliability limits of a particular element of the network are exceeded by planned or actual transmission line flows. Consequently, congestion management means avoiding congestion prior to its occurrence as well as relieving any element from its congested state. In the case of frequent grid congestion, grid extension should be considered.

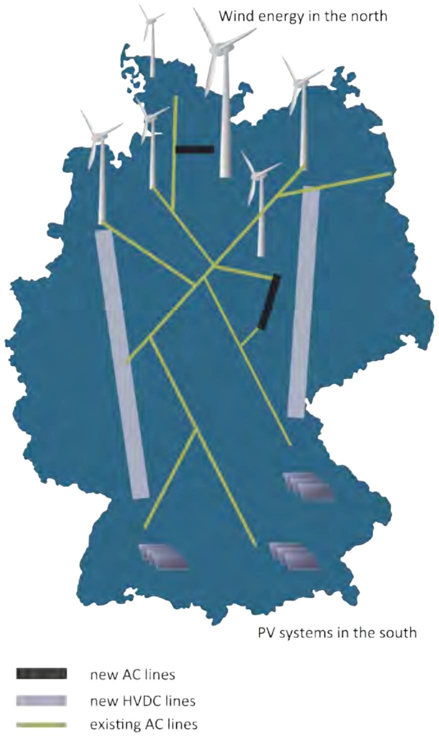


Fig. 3: Map of grid extension and enforcement plans

Expanding the capacity

In order to increase the transmission capacity, one can add new lines or increase the voltage level of existing lines. Another option is to install high temperature conductors, which allow higher electric current without reaching dangerous technical limits. High voltage direct current (HVDC) lines can also be installed to transfer large amounts of power over long distances. Fig. 3 shows plans to connect different sources of power, e.g. large wind power capacities with PV plants, using HVDC lines.

Managing grid congestion without grid extension

Dynamic line rating equipment can manage grid congestion without grid extension to a certain degree. This is based on the fact that weather conditions have an impact on the capacity of overhead transmission lines. The hotter the line, the smaller the transmission capacity. Dynamic line rating equipment measures ambient temperature and solar irradiation as well as wind speed and direction, and calculates the actual transmission capacity accordingly (see Fig. 4).

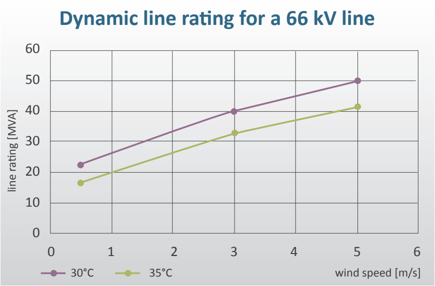


Fig. 4: Dynamic line rating diagramme

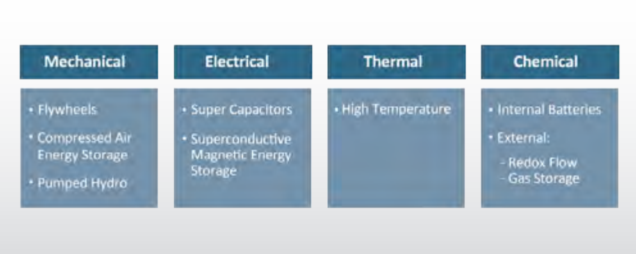
8 Energy Storage

Categories

Energy storage devices can offset temporary fluctuations in electricity generation or consumption occurring in the power system or can be utilised for mobile applications. Fig. 1 presents different categories of energy storage systems. Other categorisation methods are possible, e.g. according to storage duration (short- or long-term). A selection of storage systems is explained in greater detail below.

Components

Most energy storage systems consist of three main components: a charging converter, a storage unit and a discharging converter (Fig. 2). The sizes of these components are often independent of each other. For example, in a pumped hydro station, the size of the lake is independent of the size of the turbine or pump. For primary batteries, however, power output and storage capacity are interrelated.



Mechanical	Electrical	Thermal	Chemical
• Flywheels • Compressed Air Energy Storage • Pumped Hydro	• Super Capacitors • Superconductive Magnetic Energy Storage	• High Temperature	• Internal Batteries • External: - Redox Flow - Gas Storage

Fig. 1: Categorisation of electricity storage systems

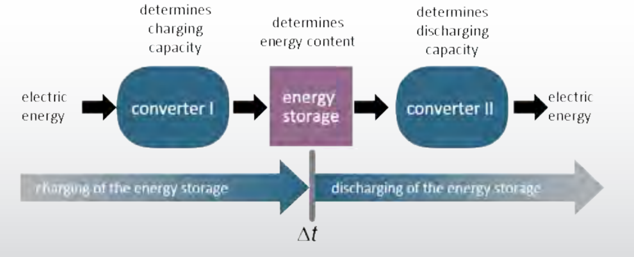


Fig. 2: Elements of an energy storage system

Battery storage

Secondary batteries (rechargeable), in contrast to primary batteries (single use only), are electrochemical accumulators. While charging, electric energy is converted into chemical energy. Lead-acid and lithium-ion batteries allow frequent transformations of this chemical energy into electricity and vice versa. Both battery types are often used for PV or hybrid systems. For large-scale applications, sodium-sulphur (NaS) and vanadium-redox technologies are more suitable.

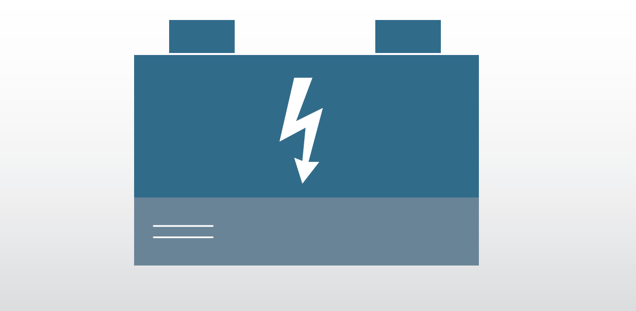


Fig. 3: Lead-acid battery

Pumped hydro storage

Pumped hydro storage systems transform electric energy into potential energy. While charging, pumps take water from a low water reservoir and transfer it to a reservoir at a higher altitude. The pumps operate whenever electricity prices are low or whenever there is an excess of electricity generation. During discharge, the water falls back down to the lower basin, passing through turbines and thereby generating electricity (see Fig. 4).

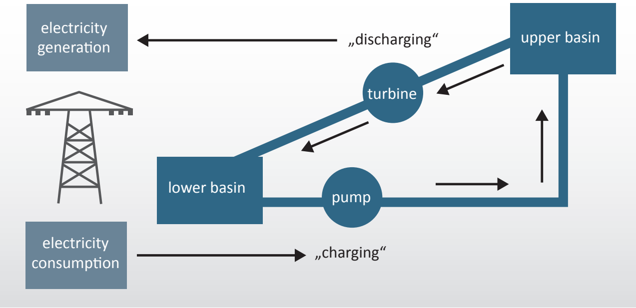


Fig. 4: Principle process of a pumped hydro storage system

Gas storage

The chemical process called electrolysis can produce hydrogen (H_2) using only electricity (e-) and water (H_2O). Hydrogen can be stored under high pressure. A fuel cell can then convert hydrogen back into electricity (see Fig. 5). Alternatively, hydrogen can be directly injected into the gas pipeline system or converted into methane (equivalent to natural gas). It can then be used in gas-fired power stations to generate electricity, so the existing gas and electricity infrastructure can be used.

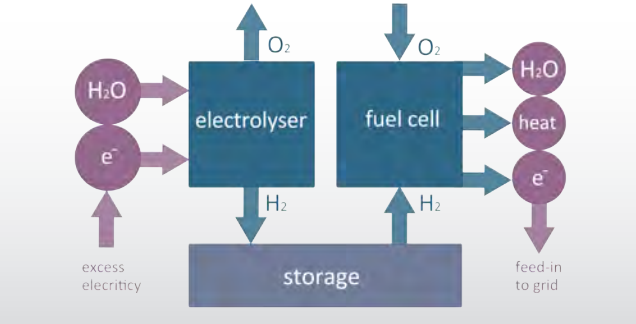


Fig. 5: Principal process of hydrogen production, storage and use

Technology selection

Due to different characteristics of energy storage technologies, each type is suitable for specific applications. Fig. 6 provides an overview of the different technologies depicting the ideal range of operation. The power capacity (measured in MW) refers to charging and discharging units, the energy storage capacity (measured in MWh) describes the volume, and the storage duration shows how long the energy can be stored without substantial losses.

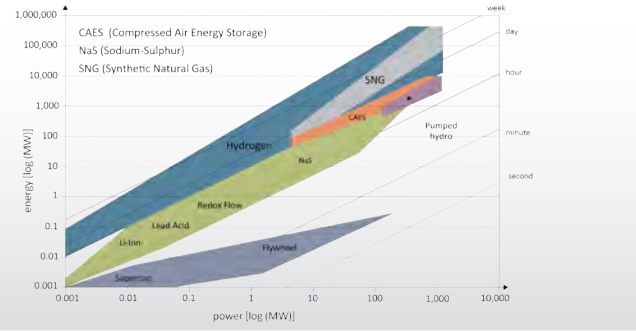
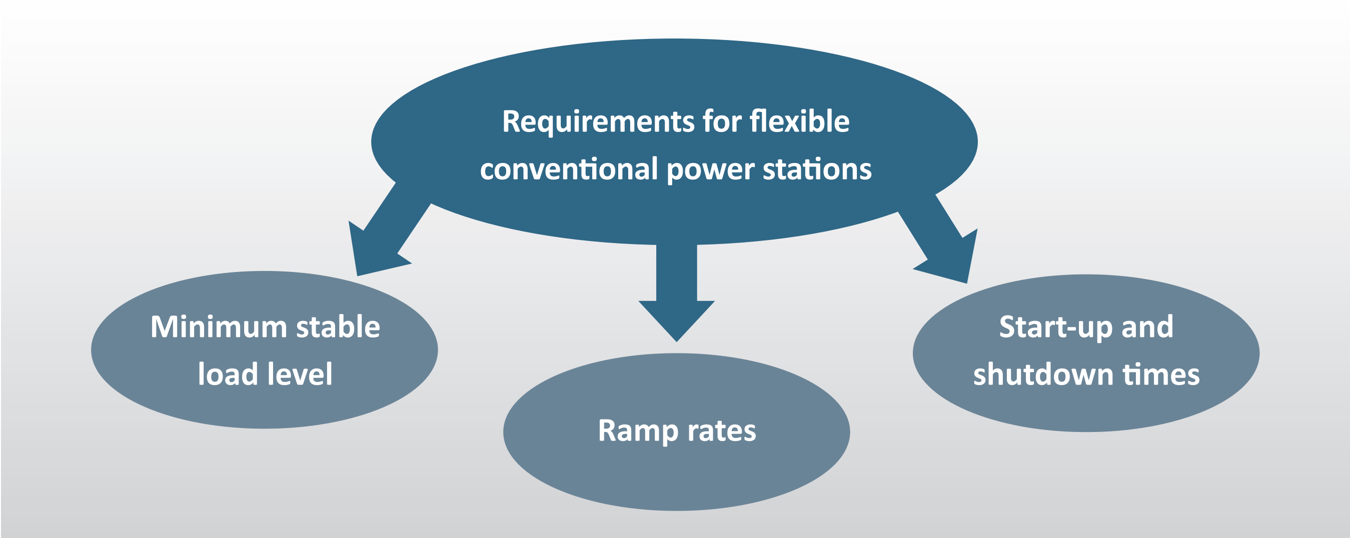


Fig. 6: Storage technologies matching different needs

9 Flexible Generation



Generation capacity requirements

With an increasing share of variable renewable energy sources, increasing capacity from highly flexible thermal power stations is necessary. Flexibility, in this case, refers to quick responses of the level of power output. Possible scenarios are that residual load patterns are shifted on the time axis and ramps are steeper and longer. In addition, the peak of the residual load can appear at different times to the peak of the total load. Investments into new thermal power stations must take the flexibility aspect into consideration. Flexible stations should take priority over non-flexible stations.

Minimum stable load level

When the full power output of a power station is not needed, it is operated in partial load mode. The back-up generation capacity that is ready for use is called 'spinning reserve'. However, the power output cannot be lower than the 'minimum load', typically provided as a percentage of nominal capacity (see Fig. 1). This minimum load is a technical limit, below which the power generation processes become unstable. Lower minimum load levels mean higher operational flexibility.

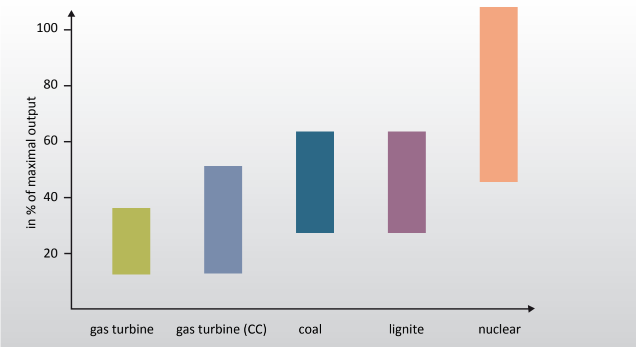


Fig. 1: Minimum stable load level

Ramp rates

Peak-load and middle-load power stations must be able to rapidly adapt their power output for balancing purposes. The 'ramp rate' describes the ratio of change in power output per minute to nominal power (see Fig. 2). For example, if a 1,000 MW gas-fired power station can increase its power output from 600 to 800 MW within one minute, the ramp rate is 20% per minute. Reducing the power output can be realised much faster, e.g. by using emergency mechanisms. This would, however, cause more wear and tear.

Start-up and shutdown times

Flexibility refers also to the ability to quickly start-up and shutdown a power station. Fig. 3 shows the amount of time necessary to start-up different conventional power plants from cold status. Another aspect is that there is a minimum period of time for which the power station must operate after start-up. It cannot be shut down immediately. Similarly, there is a minimum period of time for which it must be kept out of service after disconnection from the grid ('downtime'). These limits are due to thermal stress on the components of the power stations.

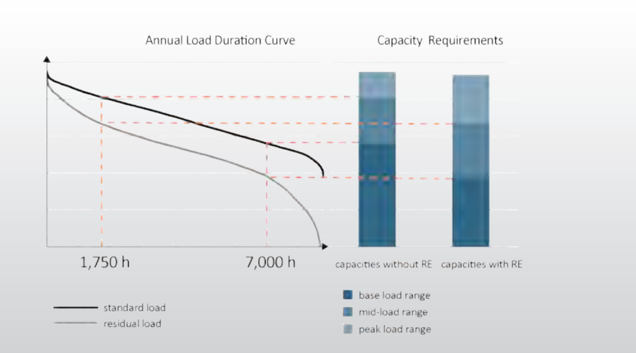


Fig. 4: Load duration curve and capacity requirements

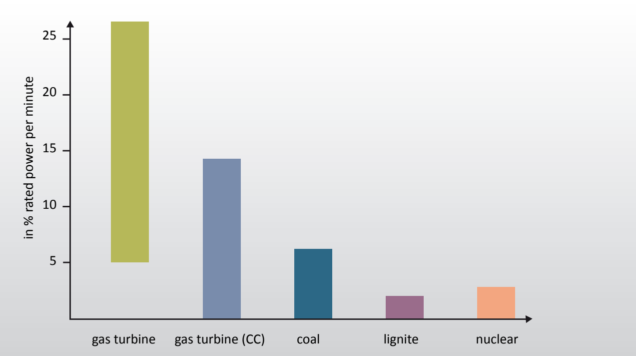


Fig. 2: Ramp rates

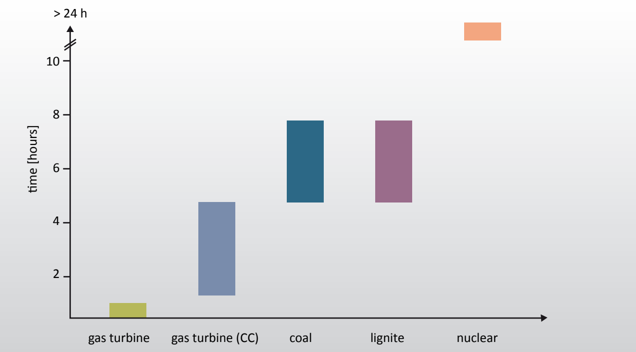


Fig. 3: Start-up times

Determining flexible generation capacity

Fig. 4 (left part) shows the annual load duration curve, which is the ordered list of all load values in one year. The curve represents the minimum load for a certain number of hours per year. The required generation capacity is derived from these curves. With high renewable energy shares, the required generation capacity for peak-load increases while the required generation capacity for base-load decreases in comparison to a system without renewables.

10 Demand Side Integration

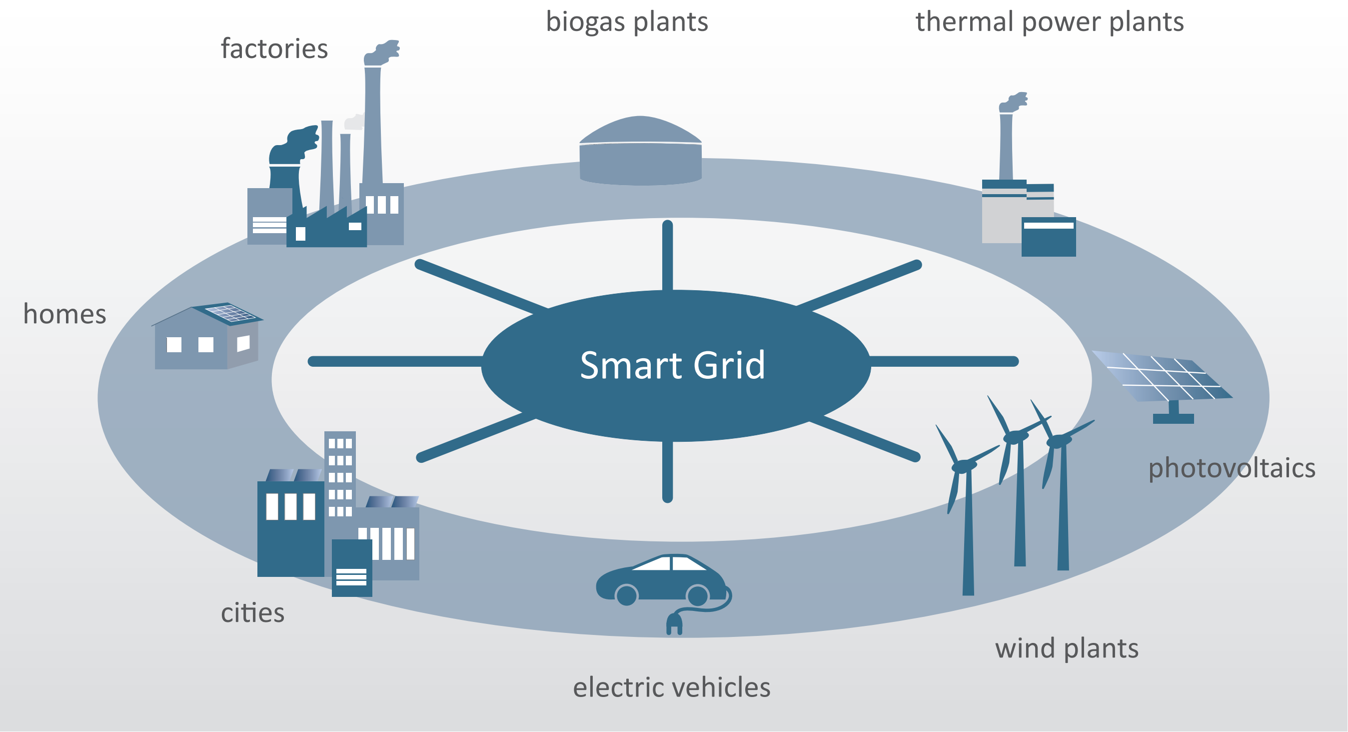


Fig. 1: Schematic of a smart grid

Categories of DSI

Demand side integration (DSI) includes all activities which increase the flexibility of the demand side. The fundamental goal is to control demand and to shift it on the time axis according to the availability of power from fluctuating renewable energy sources. Two subcategories of DSI are demand side management (DSM) and demand side response (DSR) (Fig. 2). DSM includes central control activities that directly influence electricity consumption. DSR, in contrast, describes a decentralised concept in which the electricity consumers decide about changes in power consumption themselves as a reaction to market signals.

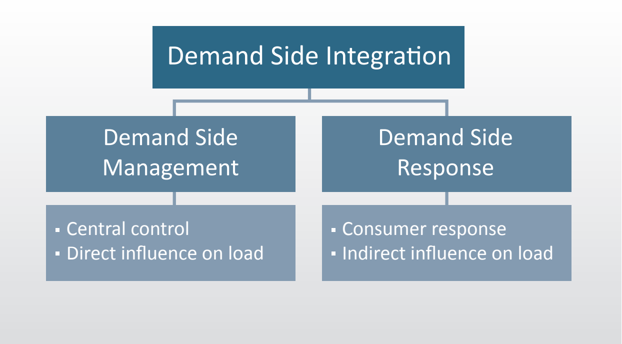


Fig. 2: Principles of DSI

Smart metering

Traditionally, electricity consumption is measured cumulatively, i.e. after a period of time the total consumption for that period can be read from the meter. Regardless of the consumption pattern, each unit of electricity is the same price. Smart meters, however, measure and record power consumption at each and every moment. This enables a time-variable tariff, which, for example, can be changed for hourly time slots according to the availability of renewable energy feed-in.

Benefits of DSI and smart grids

- Reduced need to increase generation and transmission capacity
- Only digital infrastructure is required for data transmission
- Reduced line losses and improved voltage profiles and stability
- Improved utilisation of generation and transmission capacities
- Increased flexibility of grid operation

Smart grids

Making an electricity grid 'smart' means that equipment is added to collect, process and distribute information about various parameters of the grid in real time as well as equipment to control these parameters instantly (e.g. power flow, voltage etc.). Furthermore, it refers to automatic responses by the participants in the power system (generators, consumers and grid operators) in order to utilise the existing capacities in the most economic and efficient manner.

Contribution from different sectors

- Residential & commercial buildings: appliances such as fridges/ freezers, washing machines, dishwashers, heat pumps, air conditioning, e-mobility
- Industry: heating, cooling, air pressure systems, IT, production processes for aluminium / steel / chlorine / pulp & paper / concrete
- Public facilities (swimming pools, waste water treatment plants, hospitals etc.): heating, cooling, electric appliances

Changing the load curve

There are basically three options to smooth the load curve, which is called 'peak power shaving' (see Fig. 3). One option is to simply increase demand during times of low demand (off-peak times). The second option is to shift demand from peak hours to off-peak without increasing total electricity consumption. The third option is to reduce peak demand in total without shifting anything on the time axis. To achieve these options, consumption behaviour has to be changed and energy efficiency has to be increased.

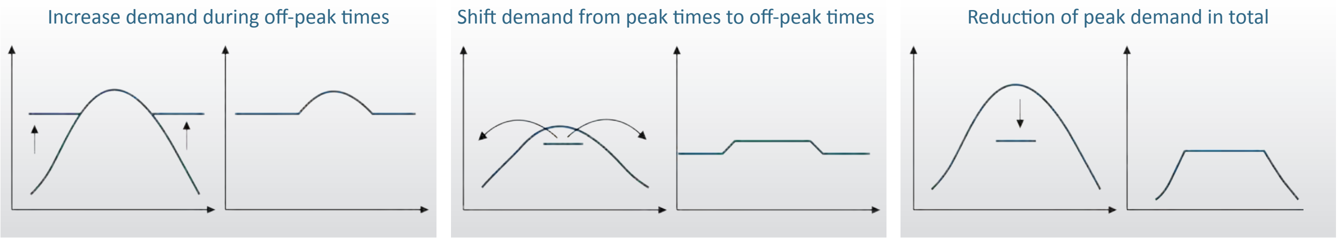


Fig. 3: Peak power shaving options

11 Forecasting

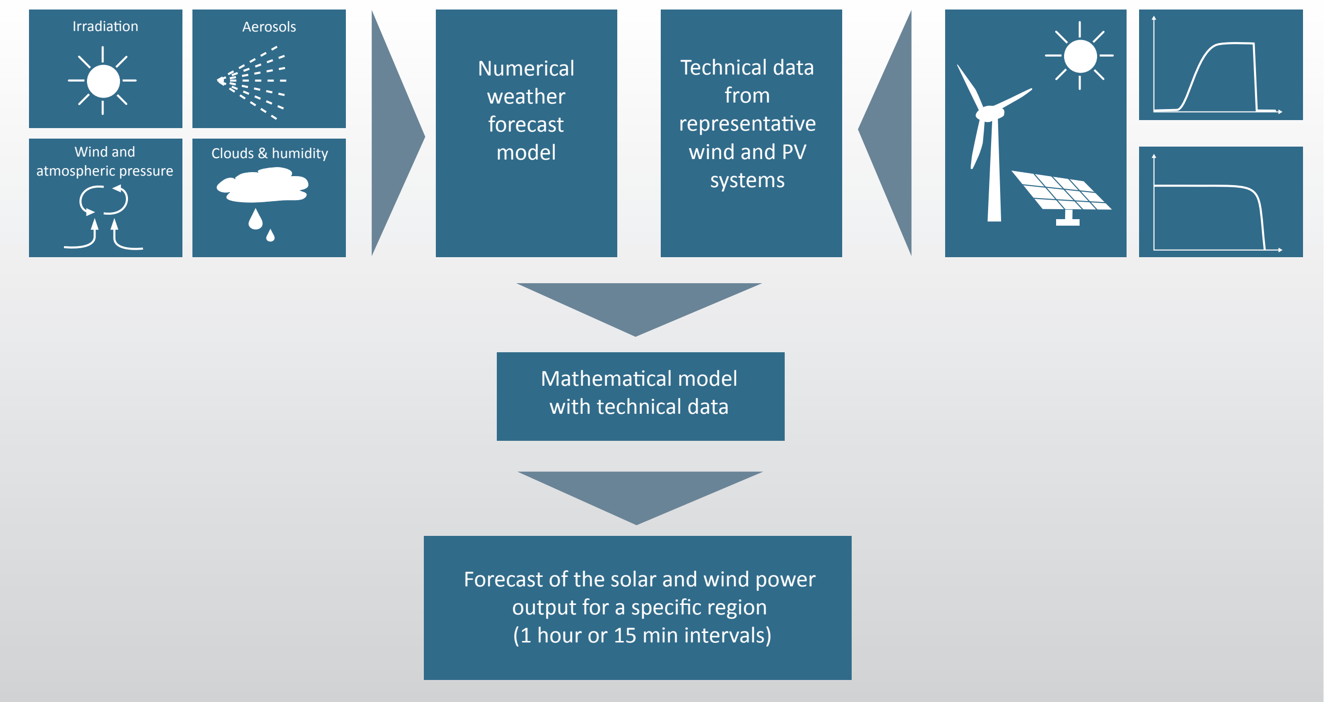


Fig. 1: Forecasting of PV and wind power

Purpose of forecasting

Power system operators depend on reliable meteorological forecasts in order to predict the output from PV plants and wind turbines. Following such predictions, operation of the controllable power stations (e.g. coal, gas and hydro) can be planned accordingly. In liberalised electricity markets, the operator of a PV plant or wind turbine also needs very precise forecasts for selling the power output on the power exchange or wholesale market.

Meteorological forecasts

Many different models, so-called numerical weather prediction models, are used to produce wind speed and irradiation forecasts around the world. Important parameters for these models are the current weather data and the geographical conditions of a region. The meteorological data is then combined with technical data from representative solar and wind plants in a mathematical model. Finally, a power forecast is calculated on the basis of hours or 15-minute intervals (see Fig. 1).

Forecast errors

In the case of any deviation between forecast and actual power output, the difference must be compensated using balancing power. Fig. 2 shows different examples of errors in wind forecasts. The measurement error shows a negative power output which cannot be true. The calculation error means that the actual power output of the turbines is computed incorrectly. The phase error refers to a shift on the time axis between the forecast profile and the actual generation profile.

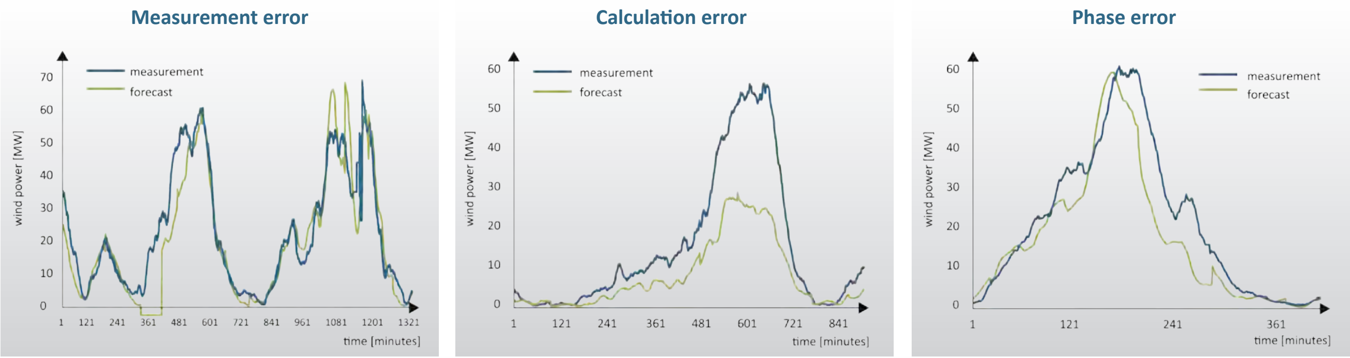


Fig. 2: Examples of forecasting errors

Wind power forecasting errors

Wind power forecasts for the next few days can have an accuracy of up to 93% and for forecasts made 2 to 4 hours in advance the accuracy can even be as high as 96%. For 10,000 MW of installed wind power, this means that the error is at least 700 MW in a day-ahead forecast and 400 MW for the next few hours.

PV power forecasting errors

PV power forecasts use a combination of meteorological forecasts (movement of clouds on satellite images), weather prediction models and PV plant simulations. A regional forecast over 1 to 5 hours can have an error of about 4%. For 10,000 MW of installed PV power, this means that the error is at least 400 MW.

Minimizing the forecasting errors

Costs for balancing power are usually higher than expenditure for a good power output forecast. However, the reliability of forecasts decreases for projections for two or more days ahead. Short-term forecasts and smaller time intervals should be given preference and different forecasts from different providers should be combined.

12 Voltage Control

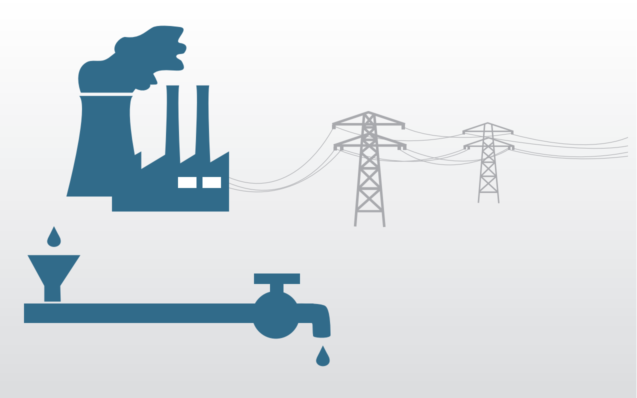


Fig. 1: Water system analogy

Voltage fluctuations

Voltage fluctuates over time because of variable power flow (power injection minus consumption) at the grid node. In a low voltage grid branch with PV generation and loads connected, the direction of power flow can even change between day and night (see Fig. 2a/b). A household connected at the end of this line faces severe voltage fluctuations. At night, voltage is low and at noon, when PV generation is at its peak, voltage is high.

Water system analogy

Using the analogy of water pipe systems, it is easier to understand the meaning of voltage. If electric current was the same as water running through a pipe, voltage would be equivalent to the pressure inside the pipe. Water only flows from high to low pressure ends. Similarly, the power flow direction is always from higher to lower voltage levels. Voltage is location-specific, i.e. it is different at each node in the grid.

Voltage control

Voltage needs to be controlled to ensure secure operation of the power system. Electronic devices require a specific voltage, which may only vary within a limited range, e.g. ±10%. In addition, electric losses in transmission and distribution grids can be reduced by applying voltage control. The provision of voltage control can be distinguished according to the status of the power system (static vs. dynamic voltage control) or according to different equipment, which provides either direct or indirect voltage control (see Fig. 3).

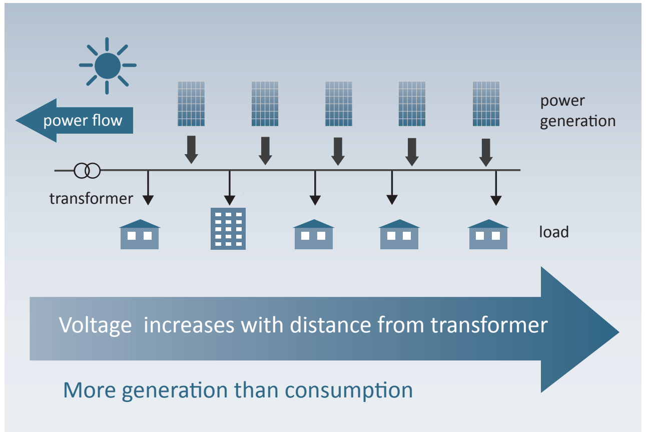


Fig. 2a: Voltage deviation in low voltage grids - day

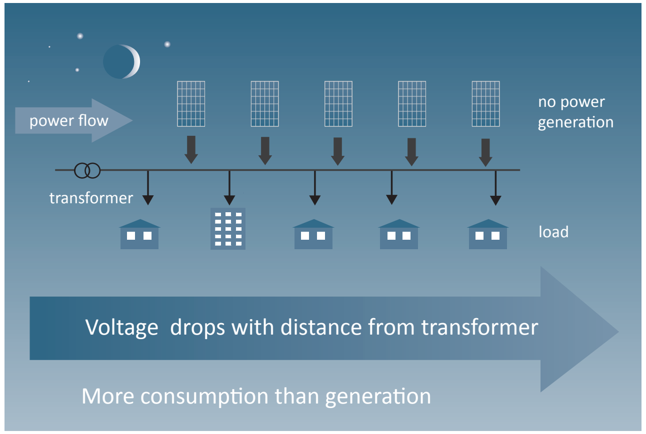


Fig. 2b: Voltage deviation in low voltage grids - night

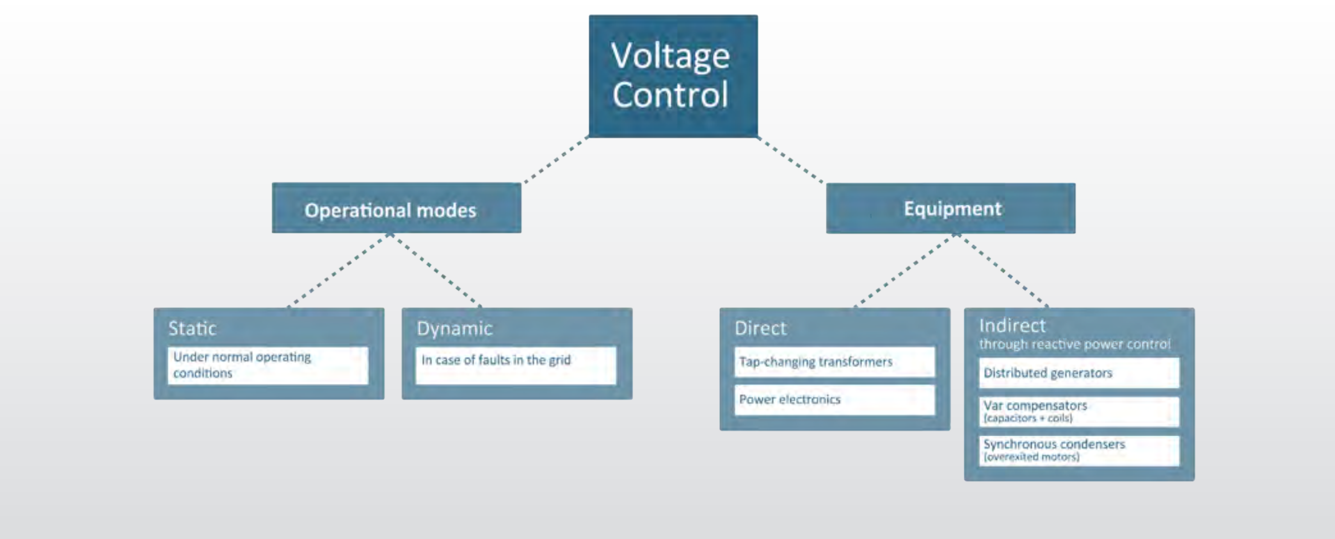


Fig. 3: Overview of voltage control options

Renewable sources stabilise the grid

PV systems and wind turbines are able to improve secure and stable grid operation. Fig. 4 shows data measured at a real multi-MW PV system connected to a medium voltage grid. Voltage fluctuations are reduced during PV power generation. This works even on days with fluctuating PV power generation. Nowadays, PV systems and wind turbines have the equipment to provide voltage control in different operating modes. As these power stations are usually connected at different locations throughout the distribution grid, they can minimise voltage fluctuations locally.

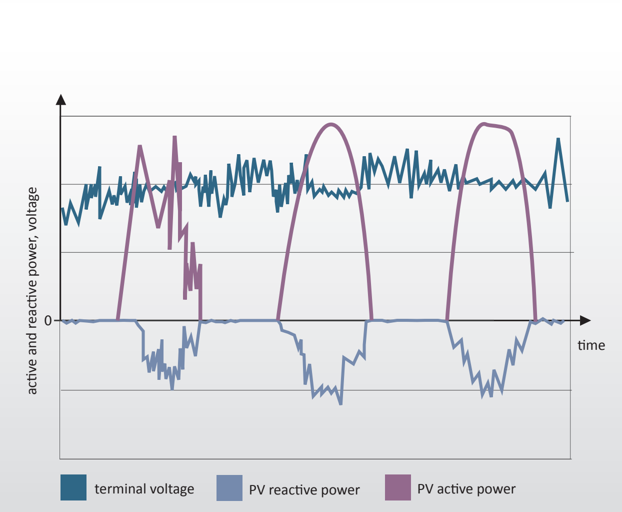
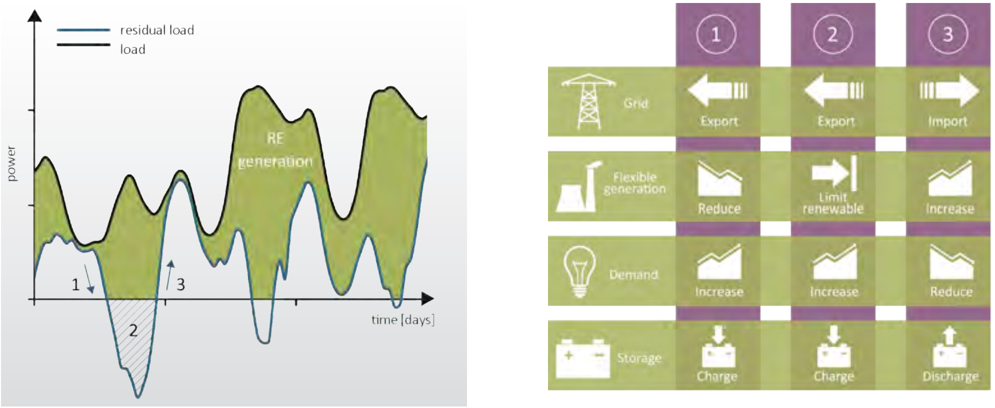


Fig. 4: Time series – active/reactive power and voltage stability

Flexibility Options

Applying the flexibility options

Depending on the actual value of residual load and its change over time, different strategies for power systems operation apply. Fig. 1 provides three scenarios: (1) the residual load is positive but drops; (2) the residual load is negative; (3) the residual load is positive and increases. The table depicts how to operate the four flexibility options in order to follow the residual load curve. These options can be used individually or in combination.



	①	②	③
Grid	Export	Export	Import
Flexible generation	Reduce	Limit renewable	Increase
Demand	Increase	Increase	Reduce
Storage	Charge	Charge	Discharge

Fig. 1: Residual load and operational strategies for flexibility options (Data source: [1])

Levelized Cost of Flexibility

One way to evaluate the flexibility options is to use the Levelized Cost of Flexibility (LCOF). The parameter provides an estimate of the additional cost of increasing the flexibility of generation, transmission or consumption by one megawatt-hour (MWh) of electricity. The LCOF depends on many factors such as the technology chosen, the method of operation or the extent of implementation. [2]

Working with the LCOF

Directly comparing the LCOF of the different flexibility options is not always appropriate. When comparing costs for storing with costs for transmission, one has to consider the actual value that storage and transmission provide for the power system in total. A comparison of total system costs can give a better picture of the cost-effectiveness of these options. Different scenarios for renewable energy integration should be derived and evaluated.

Grid extension

+Provides spatial and temporal flexibility; enables smoothing effects

- Has limited modularity; implementation takes a long time

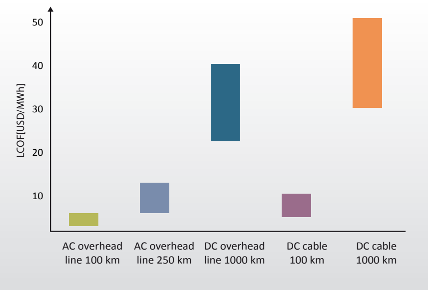


Fig 2: LCOF of grid extension (Data source: [2])

Energy storage

+Provides temporal flexibility; facilitates grid stability

- Is more expensive; some types have location constraints

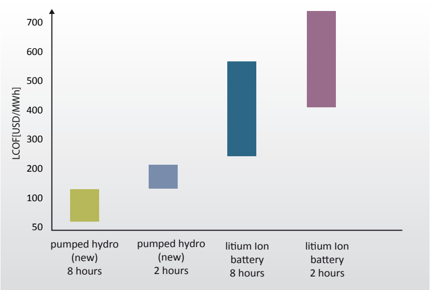


Fig 3: LCOF of energy storage options (Data source: [2])

Flexible generation

+Uses installed capacities; provides reserves to cover uncertainties

- Flexible operation leads to higher total generation costs per unit

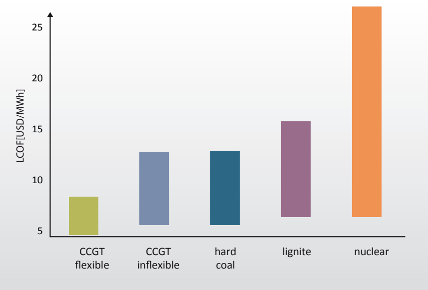


Fig. 4: LCOF of flexible generation (Data source: [2])

Demand side integration

+Is the lowest-cost flexibility option; allows gradual implementation

- Demand response management has only limited control

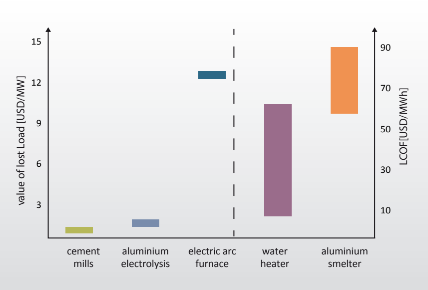
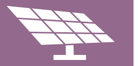


Fig. 5: LCOF of demand side integration (Data source: [2])

Sources:
[1] Müller, T.; Brunner, Ch.: Kostenvergleich von unterschiedlichen Optionen zur Flexibilisierung des Energiesystems; Energiewirtschaftliche Tagesfragen (et), 65. Jg. (2015) issue 6.
[2] International Energy Agency (IEA): The Power of Transformation – Wind, Sun and the Economics of Flexible Power Systems (2014), p. 115ff.

14 PV & Wind

Characteristics of Photovoltaics



- Smoothing effect: in a large grid, the fast output fluctuations of single PV systems cancel each other out forming a smooth generation curve
- Generation pattern: correlates with consumption patterns in countries with peak loads at midday
- Locations: PV can be installed almost anywhere (roof-tops, open field, any climate zone)
- Forecast accuracy: at plant level, forecast errors can be large due to local phenomena (fog, snow)
- Technology: no moving parts, just electronic [2]

PV		Wind (on and offshore)
1000 – 2500 h	**Full Load Hours** (depending on natural resources)	2000 – 4800 h
W – multi-MW	**range of rated power** (per system)	kW – multi-MW
1000 – 1800 € / kW	**specific costs** [1]	1000 – 1800 € / kW
6 – 14 €-ct/kWh (@ 1000 - 2000 kWh/m^2a)	**LCOE** [1]	4.5 – 11 €-ct/kWh (@ 1300 - 2700 Full Load Hours)

Characteristics of wind energy

- Smoothing effect: wind speed profiles are different at each site
- Generation pattern: mostly independent, but at some locations day-night relationships may occur
- Location: installation often not allowed in certain areas (residential, touristic etc.) due to noise and visual impact, good wind sites are often difficult to access (e.g. off-shore, on mountain tops)
- Forecast accuracy: errors can relate to timing or profile of wind speed
- Technology: mechanics and electronics, bulky components [2]

Combining PV and wind energy

Electricity generation from PV plants and wind turbines share some fundamental properties, but at the same time they also show significant differences. To some extent, the two technologies can be used complementarily when high wind speeds and high solar irradiance have a specific correlation. This means that, if power generation from wind turbines is high, PV power generation is low and vice versa. Often, PV and wind energy systems working together can reduce generation variability but cannot eliminate it completely (see Fig. 3).

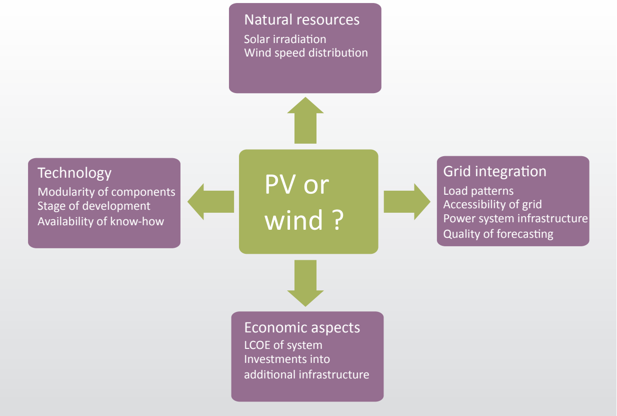


Fig. 1: Assessment of renewable energy systems

Assessment methodology

There are several aspects to the assessment of PV and wind energy technology for large-scale grid integration. The natural resources (wind and solar irradiance) determine the generation potential in principle. Technological aspects include the modularity of the system units, the stage of development and locally available know-how. Grid integration aspects cover the correlation of generation and load patterns, accessibility of grid infrastructure and forecasting methodologies, for example. Finally, economic aspects need to be taken into account, not only at plant level but also at overall system level.

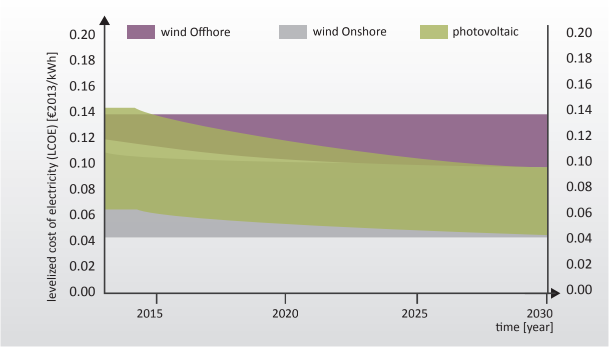


Fig. 2: LCOE for PV and wind energy technology [1]

Levelized Cost of Electricity

A methodology commonly used to compare the economics of electricity generation technologies is to calculate the Levelized Cost of Electricity (LCOE). The LCOE looks at the overall costs of electricity generation. It refers to the total costs of building and operating a power plant in relation to total electricity generation throughout its lifetime. Fig. 2 shows current and expected LCOE for PV and wind power plants.

Sources:

[1] Fraunhofer Institut für Solare Energiesysteme (ISE): Stromgestehungskosten Erneuerbare Energien (November 2013).

[2] International Energy Agency (IEA): The Power of Transformation – Wind, Sun and the Economics of Flexible Power Systems (2014).

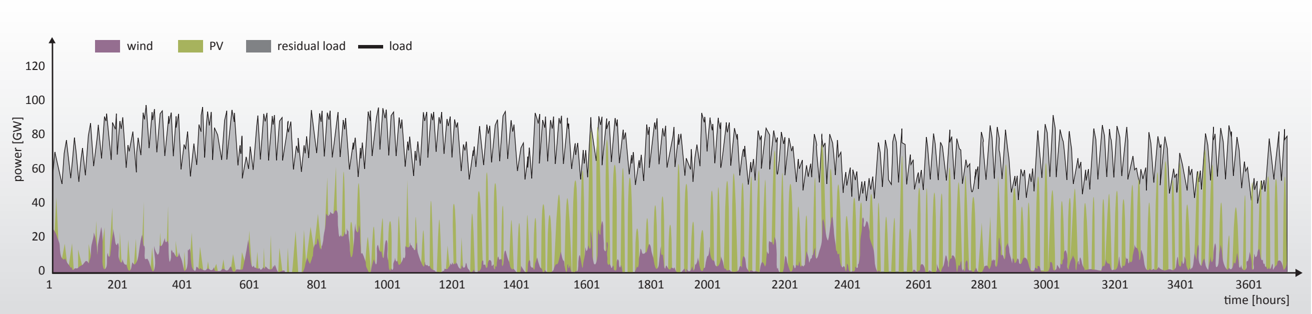
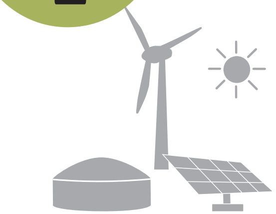


Fig. 3: Load, PV and wind profiles for three months

Summary

A power system can be fed from renewable energy at a rate of 60-80% or more. Generally, variable renewable energy generation can become noticeable in the power grid beyond an annual share of 3%. In order to realise the commonly agreed policy goal of having a power supply that is reliable and secure, economically viable and environmentally friendly, the entire power system has to adapt to the fluctuating character of renewable energy generation. This exhibition contributes to a better understanding of the implementation of flexibility options and operational measures in order to achieve a sustainable electricity supply with high shares of renewable energy.

Section
1



- 2 Power System
- 3 System Operation
- 4 Photovoltaics
- 5 Wind Energy
- 6 Challenges

Principles of the Power System

- Power systems comprise a wide range of different power stations, consumers and the interconnecting electricity grid, which has different voltage levels.
- For a reliable power supply, the grid frequency and voltage need to be stable, which requires balancing power and voltage control mechanisms at all times.
- PV systems and wind turbines are fluctuating, weather dependent power generators.
- The residual load (total load minus variable renewable energy generation) is a parameter with increasing importance for grid operation.

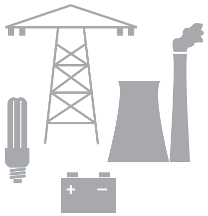
SUMMARY &

Section
2

Flexibility Options & Operational Measures

- With high shares of PV and wind power generation, the flexibility requirements of the power system in total increase significantly.
- Flexibility in the power system can be provided through grid extension, energy storage, flexible generation and demand side integration (DSI).
- Good forecasts for renewable power generation are vital for system operation; they usually cost much less than balancing power.
- Voltage control in medium and high voltage grids can be carried out by renewable energy power systems.

- 7 Grid Extension
- 8 Energy Storage
- 9 Flexible Generation
- 10 Demand Side Integration
- 11 Forecasting
- 12 Voltage Control



Section
3

- 13 Flexibility Options
- 14 PV and Wind

Evaluation

- The concept of Levelized Cost of Flexibility (LCOF) may help to assess the flexibility options.
- In general, grid extension, flexible thermal power generation and DSI are comparatively cheap options while battery storage is still relatively expensive. However, a direct comparison of the different flexibility options makes no sense.
- Only a comparison of different scenarios for renewable energy grid integration covering the entire power system provides a valid evaluation.
- A combination of PV and wind energy is, in many cases, a very good technical and economic solution for increasing renewable energy shares and security of supply.

Care and handling of the display banners

Banners may only be cleaned using a soft, dry cloth. The use of water, detergents or abrasive cloths is to be avoided. The surface of the banners must be dry when they are rolled up. Avoid exposing the displays to rain, which could harm the banner and might also damage the roll-up mechanism. The banners must be rolled up or unrolled slowly and carefully. When rolling them up, use both hands to prevent the banner from being retracted too quickly.

Positioning the displays

It is possible to arrange the displays in sequence. The banners have also been colour-coded into three main topic areas, in addition to an opening and closing banner, allowing the displays to be arranged more freely. It is important to position the opening banner in such a way that it is seen first. The opening banner presents an outline of each of the subsequent banners' content, enabling the visitor to decide whether he or she wants to follow the sequence or to focus on a single topic.

About RENAC

The Renewables Academy AG (RENAC), based in Berlin, Germany, is one of the leading international providers of education and training in the fields of renewable energy and energy efficiency. Since our founding in January 2008, over 6,000 participants from over 141 countries worldwide have benefited from our expertise in the technology, financing, management and market development of renewable energy and energy efficiency.

Our workshops and courses cover the whole value chain of renewable energy technologies and energy efficiency measures. We cover topics and required skills in the areas of financing, managing, engineering, assessing, implementing, designing and maintaining renewable energy systems and energy efficiency measures. We provide our clients with an understanding of the issues and challenges, as well as the skills to implement renewable energy projects on and off the electricity grid.

RENAC training is tailored to our customer's needs. Thus, the analysis of training needs is a standard element of our work. In our training, we use a wide variety of training techniques and methodologies and train our participants to be able to deal with and optimize context-specific issues.

Our goal is to equip our course participants for the challenges of real projects through an intensive and absorbing training experience.

Contact

Please contact the local project partner or us at RENAC, if you are interested in hosting the exhibition or have any questions regarding the exhibition: Albrecht Tiedemann, Matthis Brinkhaus, Cecilia Strandberg

Renewables Academy AG (RENAC)
Schönhauser Allee 10-11
10119 Berlin, Germany
Phone: +49 (0) 30-526 895 870
Fax: +49 (0) 30-526 895 899
E-mail: capreg@renac.de
Internet: www.renac.de

Disclaimer

Copyrights

renac
renewables academy

Renewables Academy (RENAC) AG

Schönhauser Allee 10-11

10119 Berlin (Germany)

Phone: +49 (0) 30-52 689 58 70

Fax: +49 (0) 30-52 689 58 99

E-Mail: info@renac.de, December 2015

www.renac.de

CapREG

Supported by:

Federal Ministry for the
Environment, Nature Conservation,
Building and Nuclear Safety

based on a decision of the German Bundestag