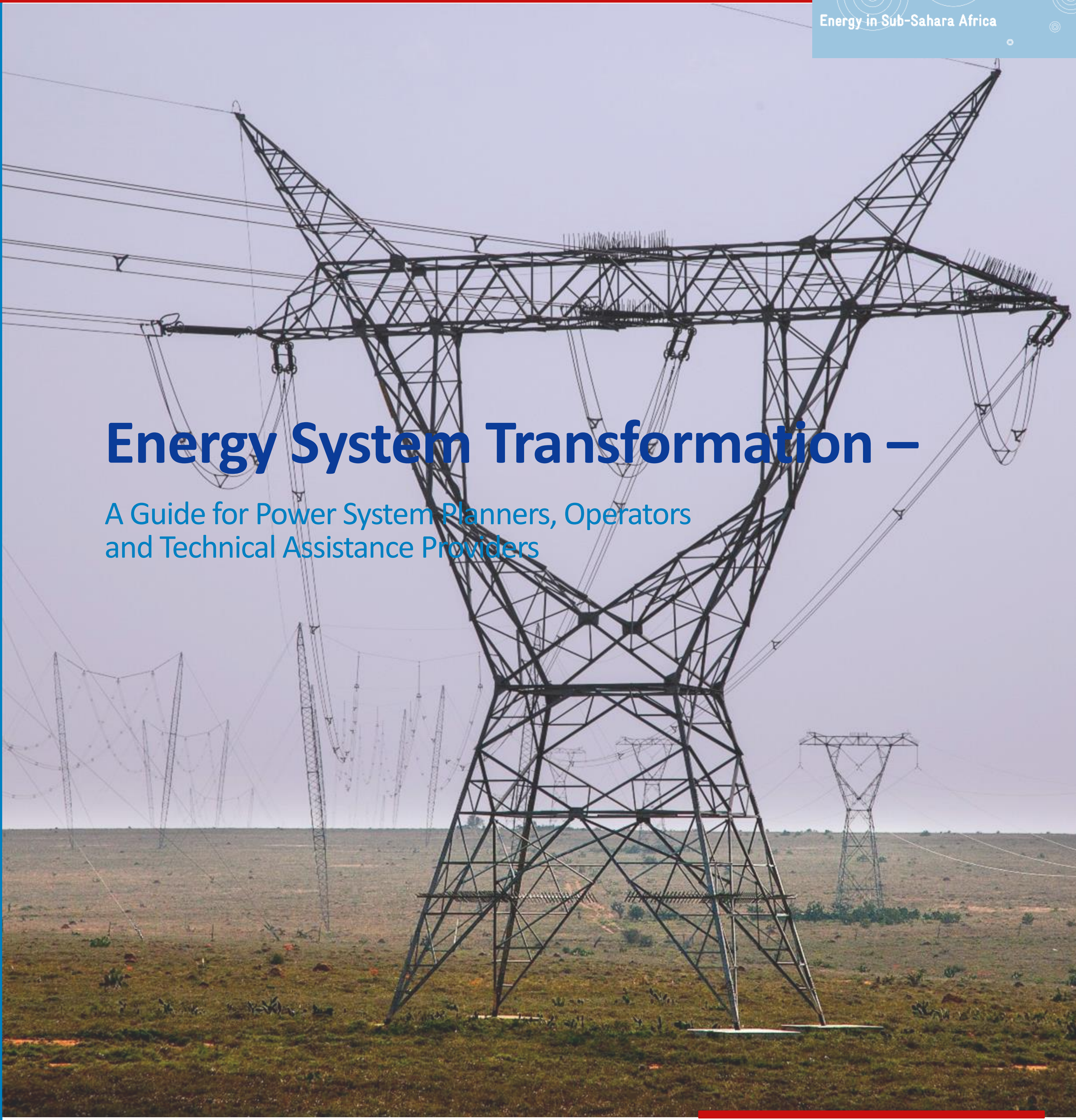
Sector Network Energy in Sub-Sahara Africa (SN Energy SSA)

SECTOR NETWORK
Energy SSA

Energy in Sub-Sahara Africa



Energy System Transformation –

A Guide for Power System Planners, Operators and Technical Assistance Providers

GET.transform
Transforming Energy Sectors Globally

SAGEN
SOUTH AFRICAN-GERMAN ENERGY PROGRAMME

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

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This report has been prepared for the Sector Network Energy in Sub-Sahara Africa (SN Energy SSA) under the guidance of the Working Group on Grid-Connected Renewable Energy, GET.transform, and with input from SAGEN.

About SN Energy SSA

The SN Energy SSA is a network of energy programmes of the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. The mandate of the sector network is to facilitate technical knowledge management and exchange amongst GIZ energy programmes in Sub-Sahara Africa.

About GET.transform

GET.transform is a European technical assistance programme which supports national and regional partners and institutions in advancing their energy transitions. The programme is supported by the European Union, Germany, Sweden, the Netherlands and Austria. For more information, please visit: www.get-transform.eu/services/renewable-energy-grid-integration

About SAGEN

The South African-German Energy Programme (SAGEN) is part of the bilateral collaboration between South Africa and Germany. SAGEN is funded by the German Federal Ministry for Economic Cooperation and Development (BMZ and collaborates with South African partners from government and the private sector to promote a diverse and inclusive energy transition for all. For more information, please visit: sagen.org.za/publications/power-system-planning-operation

About M.P.E. GmbH

M.P.E. GmbH offers a wide range of international consulting and engineering services in the electricity energy sector. The company specialises in the grid integration of renewable energies and covers the entire spectrum, from the electrical planning and grid connection of small wind or PV generators, to the integration of large onshore and offshore wind farms, and the system studies of entire power-systems.

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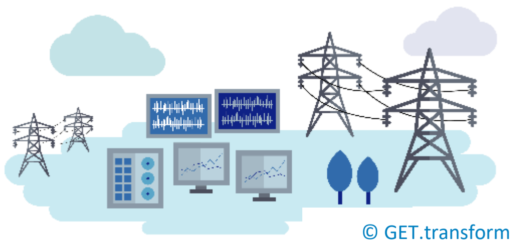
24/7	Operation during 24 hours at 7 days per week (operation without any interruption)
AC	Alternating current
BESS	Battery energy storage system
CAPEX	Capital expediture
CCGT	Combined cycle gas turbine
CCUS	Carbon capture utilization and storage
CH4 or CH_4	Methane (Chemical symbol)/Natural gas
H2 or H_2	Hydrogen (Chemical symbol)
CO2 or CO_2	Carbon dioxide (Chemical symbol)
DC	Direct current (here in the sense of HVDC transmission)
E-fuels	Electrofuels, fuels synthetized fuels, generated by electricity (typically on basis of hydrogen)
FACTS	Flexible AC-transmission device (based on static converters)
HVDC	High voltage direct current
IEA	International Energy Agency
LH2 or LH_2	Liquid hydrogen
NZE	Net zero emission
OCGT	Open cycle gas turbine
OPEX	Operational expediture
PV	Photovoltaic
STATCOM	Static Synchronous Compensator
vRE	Variable renewable energies (essentially wind and PV generation)

Foreword

The world faces two central challenges that need to be resolved by middle of this century: meeting the growing energy demand to power socio-economic development while at the same time phasing-out CO_2 emissions. Technically and economically, solutions to tackle these challenges are already available today. Yet more coordination and a systematic approach are needed to leverage their full mitigation potential and deliver on a global energy transition at the required speed.

This report aims to outline a systematic approach to developing a sustainable power sector. As electricity-generation represents the largest source of energy-related greenhouse gas emissions, the power sector is of vital significance to realising international climate goals. The transport, heat, and industrial sectors will need to be decarbonised, and require the transition of relevant industrial processes from fossil fuels to electricity, as well as green hydrogen. As the production of green hydrogen is based on electricity, decarbonised energy sectors will rely almost exclusively on green electricity, thus leading to a substantially increased demand for electric energy.



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The variable nature of renewable energy sources, such as solar photovoltaics (PV) or wind, calls for transformational changes in the technical planning and operation of power-systems. The need for change often goes hand-in-hand with a number of energy security-related concerns, particularly early on in renewable energy deployment. GIZ, by mean of its energy sector support programmes, such as the global GET.transform programme, the South African-German Energy Programme (SAGEN) or the Kenya Energy Programme, support power-system planners and operators to cost-efficiently and reliably integrate variable renewable energy into their networks.[1]

Energy System Transformation – A Guide for Power-System Planners, Operators and Technical Assistance Providers

In this report, GIZ presents an analytical framework to guide energy-system planners, operators, and technical assistance providers throughout their collaborative journey of energy-system transformation. The framework describes a path from a fossil-fuelled to a decarbonised energy-system in five phases, and suggests technical assistance approaches to discuss and prioritise different measures to support this transition.

Depending on the country context, short, medium, and long-term measures to update planning and operating procedures of the power-system are provided which can be discussed with project partners to derive recommendations for further technical assistance. Based on the recommendations, adequate support measures can be deployed which may range from developing grid codes and compliance procedures in Phase 1 to reviewing operational procedures and vRE short-term forecasts in Phase 2, to analysing and managing flexibility and stability requirements in Phases 3 and 4, to developing storage technologies and exploring sector coupling strategies in Phase 5.

The model presented in this report mainly applies to thermal power systems and the transition from a pre-dominantly thermal system to a hydrogen/wind/PV-system. For hydro-thermal systems, the model would require substantial adaptations, which are not part of this report.

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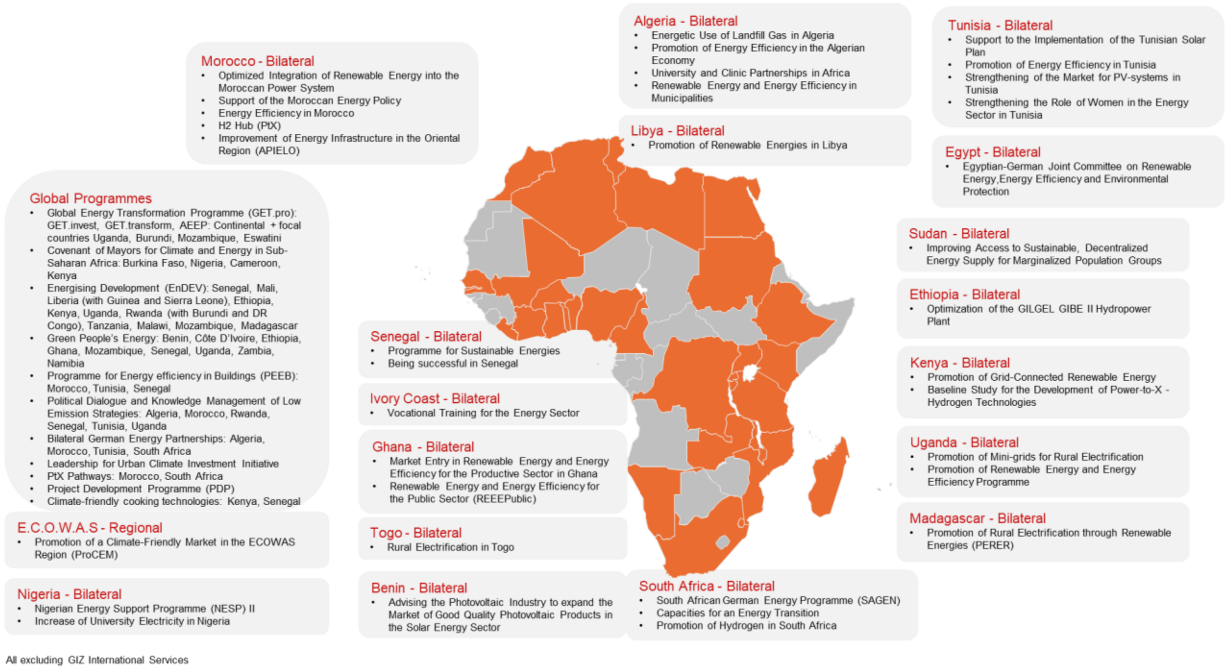
[1] Global (GET.transform): https://www.get-transform.eu/; South Africa: https://sagen.org.za/; Kenya: https://www.giz.de/en/worldwide/77899.html

The report is intended to assist and guide the scoping, planning and implementation of core priority, impact-orientated and partner-driven technical assistance, as promoted by GIZ projects organised under the Sector Network Energy in Sub-Sahara Africa (SN Energy SSA).

The report has been prepared for the SN Energy SSA under the guidance of the Working Group on Grid-Connected Renewable Energy, GET.transform, and with input from SAGEN. We would like to thank the lead author, Dr Markus Pöller (M.P.E. GmbH), for his tireless efforts and considerable achievements in advancing global sustainable energy transitions with GIZ. Appreciation should also be shown to the members and contributors of the network, namely Christopher Gross (GET.transform), Ayoub Chajadine (Nigeria Energy Support Programme), and Philipp Vanicek (SAGEN) for the conceptualisation of the report and technical proof-reading, as well as to Stefanie Bradtner (GET.transform) for the design and communication.

GIZ Energy Projects in Africa

A great number of technical assistance projects, under the roof of GIZ, advance analytical work to establish a sound base for updating energy-system planning and operational procedures, as well as to provide capacity-building for boosting confidence in the operation of renewable energy dominated power-systems across the African continent.



Global Programmes
- Global Energy Transformation Programme (GET.pro): GET.invest, GET.transform, AEEP: Continental + focal countries Uganda, Burundi, Mozambique, Eswatini
- Covenant of Mayors for Climate and Energy in Sub-Saharan Africa: Burkina Faso, Nigeria, Cameroon, Kenya
- Energising Development (EnDEV): Senegal, Mali, Liberia (with Guinea and Sierra Leone), Ethiopia, Kenya, Uganda, Rwanda (with Burundi and DR Congo), Tanzania, Malawi, Mozambique, Madagascar
- Green People's Energy: Benin, Côte D'Ivoire, Ethiopia, Ghana, Mozambique, Senegal, Uganda, Zambia, Namibia
- Programme for Energy efficiency in Buildings (PEEB): Morocco, Tunisia, Senegal
- Political Dialogue and Knowledge Management of Low Emission Strategies: Algeria, Morocco, Rwanda, Senegal, Tunisia, Uganda
- Bilateral German Energy Partnerships: Algeria, Morocco, Tunisia, South Africa
- Leadership for Urban Climate Investment Initiative
- PtX Pathways: Morocco, South Africa
- Project Development Programme (PDP)
- Climate-friendly cooking technologies: Kenya, Senegal

E.C.O.W.A.S - Regional
- Promotion of a Climate-Friendly Market in the ECOWAS Region (ProCEM)

Nigeria - Bilateral
- Nigerian Energy Support Programme (NESP) II
- Increase of University Electricity in Nigeria

Morocco - Bilateral
- Optimized Integration of Renewable Energy into the Moroccan Power System
- Support of the Moroccan Energy Policy
- Energy Efficiency in Morocco
- H2 Hub (PtX)
- Improvement of Energy Infrastructure in the Oriental Region (APIELO)

Senegal - Bilateral
- Programme for Sustainable Energies
- Being successful in Senegal

Ivory Coast - Bilateral
- Vocational Training for the Energy Sector

Ghana - Bilateral
- Market Entry in Renewable Energy and Energy Efficiency for the Productive Sector in Ghana
- Renewable Energy and Energy Efficiency for the Public Sector (REEEPublic)

Togo - Bilateral
- Rural Electrification in Togo

Benin - Bilateral
- Advising the Photovoltaic Industry to expand the Market of Good Quality Photovoltaic Products in the Solar Energy Sector

Algeria - Bilateral
- Energetic Use of Landfill Gas in Algeria
- Promotion of Energy Efficiency in the Algerian Economy
- University and Clinic Partnerships in Africa
- Renewable Energy and Energy Efficiency in Municipalities

Libya - Bilateral
- Promotion of Renewable Energies in Libya

South Africa - Bilateral
- South African German Energy Programme (SAGEN)
- Capacities for an Energy Transition
- Promotion of Hydrogen in South Africa

Tunisia - Bilateral
- Support to the Implementation of the Tunisian Solar Plan
- Promotion of Energy Efficiency in Tunisia
- Strengthening of the Market for PV-systems in Tunisia
- Strengthening the Role of Women in the Energy Sector in Tunisia

Egypt - Bilateral
- Egyptian-German Joint Committee on Renewable Energy,Energy Efficiency and Environmental Protection

Sudan - Bilateral
- Improving Access to Sustainable, Decentralized Energy Supply for Marginalized Population Groups

Ethiopia - Bilateral
- Optimization of the GILGEL GIBE II Hydropower Plant

Kenya - Bilateral
- Promotion of Grid-Connected Renewable Energy
- Baseline Study for the Development of Power-to-X - Hydrogen Technologies

Uganda - Bilateral
- Promotion of Mini-grids for Rural Electrification
- Promotion of Renewable Energy and Energy Efficiency Programme

Madagascar - Bilateral
- Promotion of Rural Electrification through Renewable Energies (PERER)

All excluding GIZ International Services

Overview of GIZ Energy Projects in Africa (as of Nov. 2021) **Source: GIZ**

1 Introduction

The urgent need to decarbonise our worldwide industries requires the electricity sector to move away from fossil-fuelled power plants and to replace them with renewable energies.

At the same time, the decarbonisation of transport, heat, and industrial sectors requires the transition of relevant industrial processes from fossil fuels (coal, gas, oil) to electricity (for example, electric vehicles, electric heating) resulting in an overall increase in electricity demand.

Additionally, green hydrogen will be required for many other carbon-reduction objectives, for example, steel production using direct-reduction of iron (H_2-DRI), E-fuels for aeroplanes, or green ammonia for fertiliser production. As the production of green hydrogen is also based on electricity, this will result in a further increase in the demand for green electricity.

Therefore, the main challenges of the energy transition of the electric power system are:

- Replacing fossil-fuelled power plants by renewable energies.
- Increased electricity demand from:
    - Normal increase due to economic growth
    - Transition of other sectors directly to electricity
    - Demand for green hydrogen

This report describes the path from a fossil-fuelled to a decarbonised power system in five phases and proposes capacity-building activities to support this worldwide energy transition. The main partners with whom these subjects are to be discussed, and who will implement the proposed activities, are typically system operators (or power utilities in the case of a vertically-integrated power sector). Other organisations in the electric power sector, such as regulators, ministries, private organisations, (e.g. planners and operators of renewable energy power plants) can also be involved, but because the operation of the power system is the key responsibility of system operators/power utilities, engineers who are tasked with power system operation and planning should be the key partners for the proposed activities.

2 The five phases of the Energy Transition

The energy transition is a continuous process and not a sequence of individual phases which can be completely separated. However, to better understand the priority of the measures and actions required, the definition of different phases, as well as the required activities per phase, can be very useful.

Such a model, like any model, represents a simplification, and it is always possible that the transition of a real system from fossil fuels to renewables does not precisely follow the sequence of phases outlined in this report. It is, therefore, always necessary to study and understand each system individually, and to make the right decisions based on that information.

For example, the models shown in Figure 1, Figure 3 and Figure 4 are without the import and export of electricity or hydrogen. In the case of electricity, import and export is usually only feasible with limited capacity and across limited distances. However, it makes a big impact if a power system has strong interconnectors allowing the exchange of electricity with neighbouring countries, compared to an isolated system.

Electricity export and import can greatly contribute to power balancing and significantly reduces storage requirements. When comparing grid integration challenges of vRE in European countries with developing or emerging countries, the large interconnector capacities in Europe represents a key difference.

Hydrogen can be transferred across substantially greater distances than electric energy (via ships or pipelines, in the form of liquid hydrogen/LH2, ammonia or any other synthetic fuel). Hydrogen can therefore be imported and exported in much larger volumes than electrical energy. It is therefore a likely scenario that countries with substantial vRE potential will produce excess green hydrogen and export it, whereas central European countries will tend to import hydrogen. However, these are very long-term visions and in the earlier phases of establishing hydrogen infrastructures. Generally, locally produced green hydrogen should play the dominant role.

There are numerous publications describing the different phases of an energy transition, but there is no generally accepted definition of those phases. The model presented in this report is based on the IEA publication entitled ‘Getting Wind and Sun onto the Grid – A Manual for Policy-Makers’ [1] from 2017, which was prepared as part of Task 25 ‘Design and operation of power systems with large amounts of wind power’ of the IEA Wind Technology Collaboration Programme (with contributions from Jonathan Horne and Markus Pöller of M.P.E.). The model presented in this IEA manual comprises four phases, whereby only the first three phases are described in detail. In the meantime, other IEA publications have been released describing the energy transition with more than four phases (for example, six phases in the IEA technology report [2] from 2020). As the real energy transition is a continuous process, more phases generally achieve a better approximation to it. On the other hand, an increasing number of phases also leads to a more complex mode. Therefore, this report uses a model with four phases, as per the IEA report [1] from 2017 and adds the ‘100% renewables’ state as a fifth phase to the model.

2.1 Phase 1: Fossil-fuelled energy system with initial vRE installations

The starting point of this model is a predominantly fossil-fuelled energy system as shown in Figure 1 below.

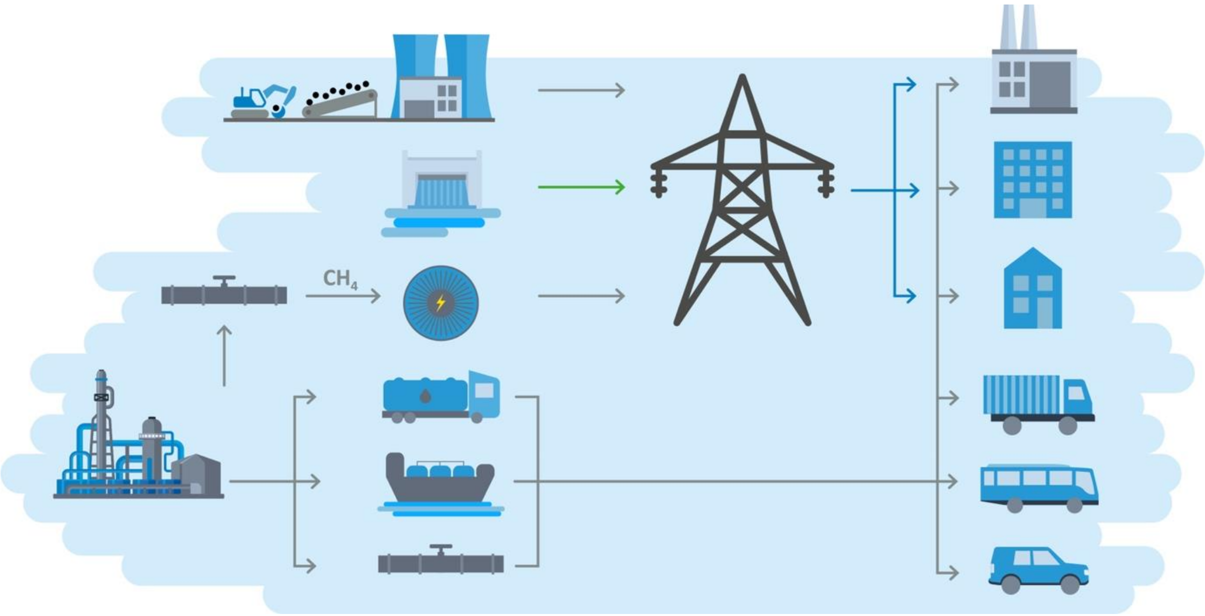


FIGURE 1: FOSSIL-FUELLED ENERGY SYSTEM (PHASE 1)

Except for some large hydro-power plants, primary energy is essentially fossil energy, namely coal, gas and oil. This includes:

- Power sector: Fuelled by coal-fired power plants, gas turbines (OCGT and CCGT), large hydro-power plants and possibly nuclear power.
- Transport sector: Mainly oil-fueled automobiles, ships and partly also trains (diesel trains).
- Heating sector: Oil and gas heating (in some countries even coal)
- Other industries, like steel manufacturing, cement production, production of fertilisers, etc.

Such a system possibly also integrates some small quantities of variable renewable energies (wind and PV), but at a very low level, so that it does not have any notable impact at the system level.

In a first step, and in most countries, only the electricity sector undergoes a transition towards renewables, whereas other sectors like transport, heating, or chemical industries remain unchanged. This is a development that we have been observing in many European countries and the USA since the late nineties, and in many other countries for the last 10-15 years. During these phases, installed capacities of wind and solar farms grow considerably and the characteristics of the power system undergoes substantial changes. This transition of the electric power sector from a predominantly baseload-driven power system to a flexible power system that relies predominantly on renewable energies, is described by phases 2, 3 and 4 of the IEA publication [1], which are summarised below.

2.2 Phase 2 and Phase 3: Growing use of vRE

Phase 2 and phase 3 are characterised by the increasing penetration of vRE and a subsequent reduction in electricity generation by fossil-fuelled power plants.

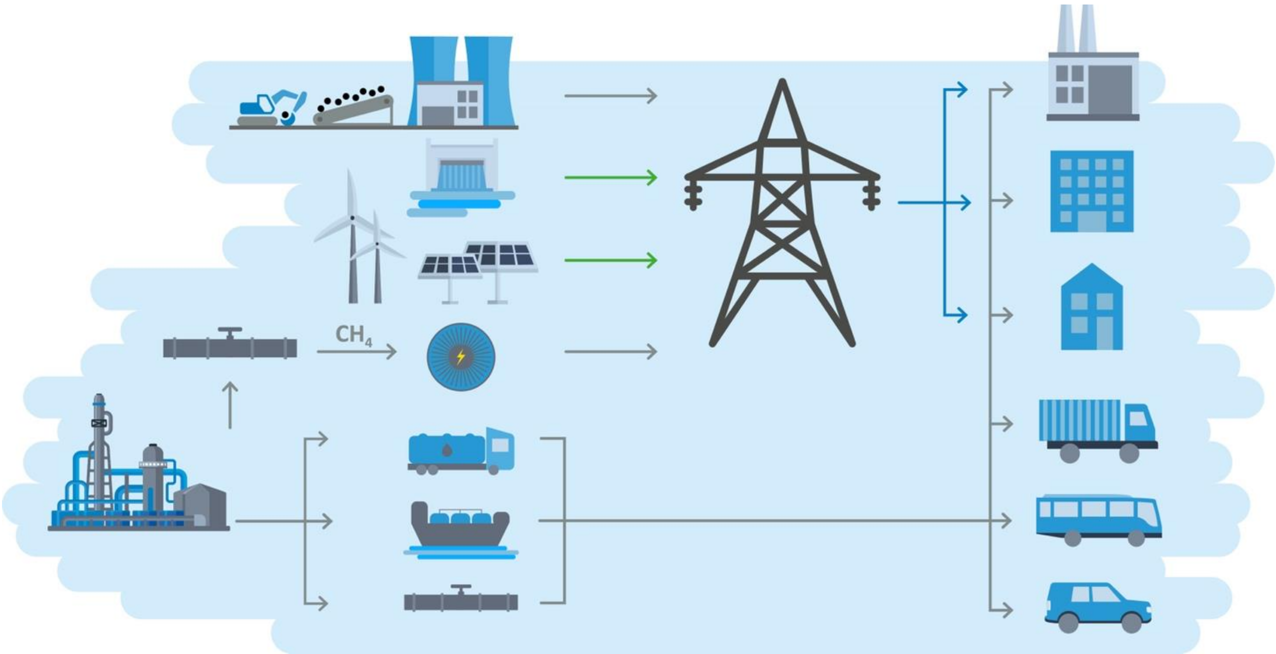


FIGURE 2: POWER SYSTEM WITH MEDIUM PENETRATION OF WIND AND SOLAR (PHASE 2 AND PHASE 3) AND FOSSIL-FUELLED HEAT AND TRANSPORT SECTORS

In most countries, installed capacities of fossil-fuelled power plants (coal and gas) remain unchanged during phases 2 and 3, but they generate less energy due to rising electricity generation from wind and solar (fuel-saving). In the longer term, increasing vRE capacities will also have an impact on the installed capacities of fossil-fuelled power plants, for example, less baseload power plants, (e.g. coal) will be required, but more flexible power plants, (e.g. gas) will be installed to reflect the requirements imposed by variable renewable energies.

In central European countries, in which there has not been any substantial growth in demand during the last 20-30 years, electricity generation from vRE has a faster impact on the replacement of energy from fossil-fuelled power plants during phase 2 and phase 3.

However, in developing and emerging countries, there is usually considerable growth in electricity demand, and it is therefore possible that additional vRE capacities will not necessarily just lead to reduced CO_2-emissions in the electricity sector but will also avoid even more fossil fuels being required to supply the increasing electricity demand. For this reason, an effective CO_2-reduction strategy requires the massive installation of vRE capacities in these countries.

2.3 Phase 4: vRE is the dominant source of electricity

Phase 4 is characterised by a power system with a very large penetration of wind and PV, with no fossil-fuelled baseload power plants and flexible gas turbines (OCGT and CCGT) to balance wind and PV variations. In order to smooth the fast variations, especially resulting from PV, storage installations (battery energy storage and pumped storage) may also be required in those systems. In addition, large interconnectors using the flexibilities of neighbouring systems can help the balancing of demand and generation.

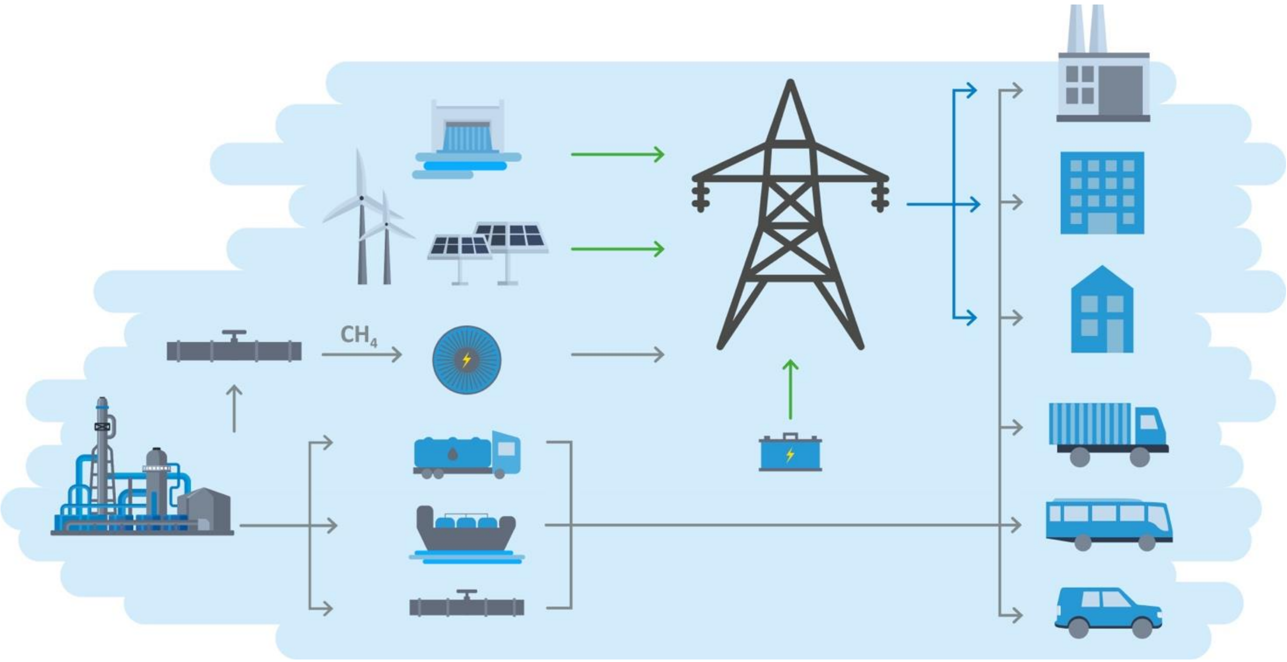


FIGURE 3: HIGH VRE POWER SYSTEM (WIND, PV AND GAS, PHASE 4)

In power systems with large hydro resources[2], a major part of the required balancing of tasks can be taken over by hydro-power stations which allow the balancing of diurnal, or even weekly, variations in wind and PV. Such systems require less, or even no other, peaking plants to balance demand and variable renewable generation.

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[2] *Run-the-river hydro-power plants cannot be used for balancing*

2.4 Phase 5: The carbon-free energy system

In a carbon-free power system (phase 5), hydrogen, instead of natural gas, is used to fuel gas generators. In order to be really carbon-free, hydrogen must be 'green hydrogen' which, in turn, needs renewables to generate the required quantities thereof.

Figure 4 shows such a phase 5 system, which is 100% carbon-free. As a carbon-free power system cannot exist without sector-coupling, the system depicted in Figure 4 not only shows a carbon-free power system, but also a complete energy system which is carbon-free. This includes all other industry sectors, such as the:

- Transport sector: conversion to electric vehicles (battery and, in the case of buses,long-distance trucks and trains, maybe also fuel-cell based). Potentially also other E-fuels, e.g. for aeroplanes
- Heating sector: conversion to electric heating (heat-pumps), solar-thermal or other non-electric renewable heating and hydrogen-based heating in the case of high-temperature heat
- Steel production: use of direct-reduction and electric heating (or other carbon-free steel routes, see e.g. [3])
- Production of fertilisers from green hydrogen
- And other sectors requiring energy but which are not shown here.

As shown in Figure 4, electricity will replace almost all the primary energies in a carbon-free energy system and, consequently, the demand for electrical energy will dramatically increase

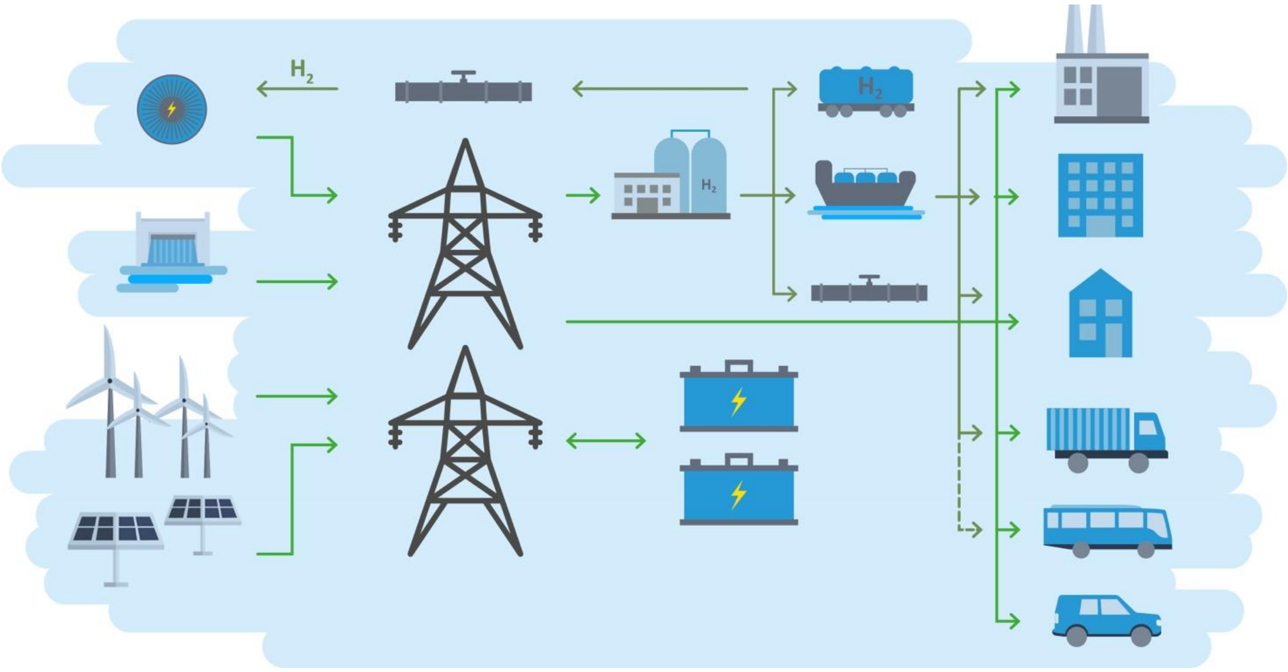

FIGURE 4: CARBON-FREE ENERGY SYSTEM (PHASE 5)

When comparing the electricity generating systems shown in Figure 3 (phase 4) and Figure 4 (phase 5), it becomes obvious that the structure of the electrical systems is comparable. Only the gas fuel changes from natural gas (which is predominantly Methane, CH_4) to hydrogen (H_2)[3] with the contribution of vRE (wind and solar) being substantially higher. Due to the large contribution of vRE, more short-term storage components (BESS and/or pumped-storage) and interconnections will be required to balance diurnal variations of vRE. Longer-term variations of vRE (weekly, seasonal variations) will be balanced using hydrogen.

Other scenarios, such as the IEA 'Net Zero Emissions by 2050' Scenario [4], assign a more important role to technologies like CCUS in combination with fossil-fuelled power plants, bioenergy and chemical processes, as well as nuclear power generation, than the scenario visualised in Figure 4. However, all the zero emission scenarios have in common that electric energy demand will increase significantly when moving towards a carbon-free society, and that electricity generation from wind and solar (vRE) will play a key-role in this.

The diagram in Figure 5 shows global electricity demand and the contribution of renewable energies (total and vRE) for the time-frame between 2020 and 2050, as predicted by the IEA NZE scenario [4].

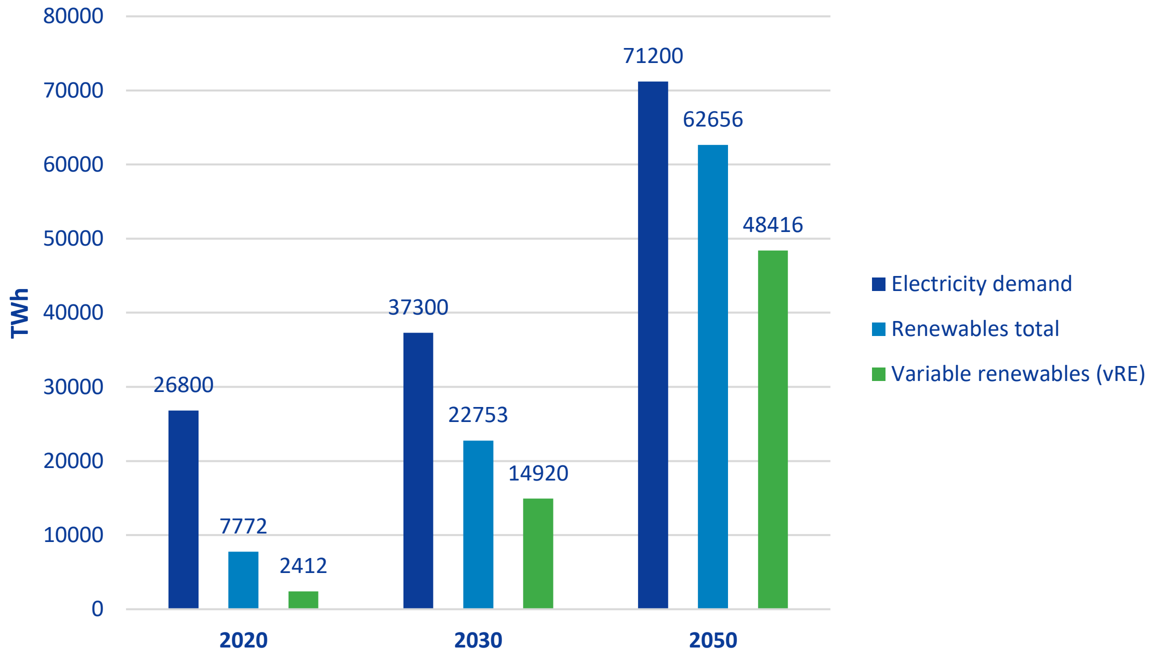

FIGURE 5: ELECTRICITY DEMAND, RENEWABLE GENERATION AND VRE GENERATION BETWEEN 2020 AND 2050, ACCORDING TO THE IEA NZE SCENARIO [4]

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[3] *Existing gas turbines cannot be simply changed from natural gas to hydrogen. Many commercially available gas turbines can run on different H_2-blends with a path towards 100% H_2*

3 System impact and activities to support the Energy Transition

The following sections describe the impact of different renewable energy integration phases on the electric power system and propose actions to cope with the challenges imposed by the transition from a fossil-fuelled to a carbon-free power system.

It is important to mention that each power system is individual and thus imposes individual challenges for system planners and operators when integrating large quantities of variable renewable energies. There are, therefore, several operational challenges in the various phases of the renewable energy integration in different systems and it is important to analyse each system individually before making recommendations. The examples and guidelines mentioned in this paper can only provide high-level ideas of the challenges that may arise in the different phases of renewable energy integration and provide only very general recommendations on mitigation options; it cannot replace a thorough analysis of the system's properties.

The operational characteristics of power systems mainly depend on their size and the type of power plants installed in the system. In terms of size, we can mainly distinguish:

- Small island networks (peak demand up to around 10-50MW, typically fuelled by diesel gensets or small gas turbine generators).
- Medium-size island networks with peak demand in the range of a few hundreds of MW and fuelled by diesel gensets, small gas turbines and a few (small) thermal power plants.
- Large power systems with peak demand in the range of several GW.

In the case of large power systems, we can further distinguish power systems with strong interconnector capacities, (e.g. national power systems in Central Europe) and systems with only weak or no interconnector capacities, (e.g. African countries).

Small island networks have very particular characteristics, and the operational challenges resulting from the integration of variable renewable energies differ substantially from large, national power systems. Medium-size island networks are more similar to large national power systems, but still very individual, so that only a few of the aspects described in the following sections apply. A publication describing the integration of large amounts of variable renewable energies into a small island system can, for example, be found in [5]. The particular challenges of small and medium island networks are beyond the scope of this paper, and therefore not further discussed in the following sections.

Apart from system-size, the operational characteristics of power systems depend on the type of power plant, or the combination of power plants, which are used to supply electricity demand:

- Baseload power plants
  Typically, baseload power plants are permanently synchronised to the power system and only started and stopped for maintenance work, but not for operational purposes. While being synchronised, they can adjust their active power level in a range which is typically between around 70% and 100% (load-following). Baseload power plants have high CAPEX and low OPEX (fuel cost) and require a large number of equivalent full-load hours to be economic.
- Mid-merit power plants
  Mid-merit power plants can be started and stopped for operational purposes, but start-ups and shut-downs should not be too frequent, (e.g. once-per-day). While being synchronised, they can adjust their power output in a range between typically 50% and 100%.

- Peaking plants
  They are only used during times of high load and are very flexible. They have short start-up times (in the range of a few minutes) and can be started frequently. While being synchronised, they can follow the load in a range between 30% - 50% to 100%. Peaking plants have low CAPEX, but high OPEX (fuel costs). Instead of peaking power plants, storage installations (pumped hydro storage or battery energy storage) can be used to cover peak demand.
- Variable power plants
  Variable power plants are power plants that are not dispatchable and generate as much electricity as possible based on the availability of primary energy. Typical variable power plants are wind and PV farms, but also 'run-the-river' hydro-power plants and even co-generation plants behave similar to variable power plants. In terms of cost structure, variable power plants are similar to baseload power plants (high CAPEX, very low OPEX).

The most economic combination of power plants mainly depends on the following two aspects:

- Demand characteristics.
- Availability and cost of fuels.

There are power systems with relatively constant demand, meaning that the difference between maximum and minimum demand (or average demand and maximum demand) is relatively low (high load factor, which is defined by the ratio between average and maximum demand). Countries with electric heating and lots of automated industries (where industrial production runs 24/7) usually have a demand with a high load factor. A typical example of such a country is South Africa (electric heating and mines).

Countries in which electricity demand is dominated by private and commercial consumers, and by industries that mainly operate during regular working hours, typically have a relatively low load factor (ratio between average and maximum demand is low). Typical examples are countries like Tunisia, Ghana and many other African countries.

Systems with low installed capacities of vRE, and an electricity demand with a high load factor, typically use power plants that can be much less flexible than power plants in systems with a low load factor (or large installed capacities of vRE).

The main power source of systems with a high load factor are therefore baseload power plants, which are complemented by some peaking plants. Systems with a low load factor (or high vRE capacities) require much more flexible power generation, which means that, in those systems, there are less baseload power plants and more peaking plants.

Apart from demand characteristics, the availability of fossil fuels (coal and/or gas) and other primary energies, (e.g. hydro, solar irradiation and wind) defines which combination of power plants is most economic. There are the following main power plant technologies:

- Large thermal power plants: steam turbines fuelled by coal, nuclear or gas[4]. Installed capacity is typically in the range of several GW, if several units are combined into one power plant. Large thermal power plants typically operate in baseload mode.
- Gas turbines, either in combination with a steam turbine (CCGT) or 'stand-alone' (OCGT).
  CCGTs typically operate in baseload (or mid-merit) mode, OCGTs are usually very flexible and operate as peaking plants. The installed capacity of CCGTs is in the range of several hundreds of MW (up to 500…600MW). The installed capacity of OCGTs is usually lower. CCGTs have a higher efficiency than

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[4] *only older gas power stations are of the gas-steam type*

OCGTs, but also cost more, and therefore require a larger number of equivalent full-load hours per year to be economic. CCGTs can either be of the single-shaft type, where there is one gas turbine, one steam turbine and one generator mounted onto the same shaft, or of the multi-shaft type, where gas turbines (typically two) and steam turbines are each on individual shafts with individual generators. Multi-shaft CCGTs can also be operated in open-cycle mode, and are therefore more flexible than single-shaft CCGTs.

- Large hydro-power plants with reservoir: large hydro-power plants are equipped with a dam to store river water in a reservoir which can store substantial volumes of water. Hydro-power plants with reservoir can be operated very flexibly to optimise the water usage within weeks, or even months, and they can be used to balance the variable power generation of vRE.
- ‘Run-the-river’ hydro-power plants: smaller hydro-power plants are often of the ‘run-the-river’ type, where only a part of a river is used to generate electricity. Run-the-river power plants do not have a reservoir (or only a very small one) and must use the water ‘just in time’ to generate electricity.
- Variable renewable energies: Wind farms and solar power plants are also named variable Renewable Energies (vRE). Typically, vRE power plants generate electricity depending on the momentary availability of their primary energy resource (wind or sun) and they are therefore ‘non-dispatchable’. Their power output can only be limited (in which case the excess primary energy is ‘wasted’), but not dispatched.

There are other types of power plants (co-generation plants, biogas, CSP, etc.) which may also become important in future, but which are of minor relevance to the operational characteristics of today’s power systems.

Depending on the combination of the above types of power plants, the operational characteristics can be very different. The examples in the following sections mainly apply to large power systems (installed capacity in the range of several GW) with no, or only limited, interconnector capacity. The examples are based on systems with predominantly thermal and gas-fired power plants (coal and gas).

Systems with large hydro-power plants (with reservoir) provide a high degree of additional flexibility because they can balance the variations of wind and PV very well by adjusting their diurnal and weekly generation profile to the availability of wind and solar power. The specific characteristics of those systems are not covered by the examples in the following sections.

3.1 Phase 1: Fossil-fuelled system with initial vRE installations

3.1.1 System impact

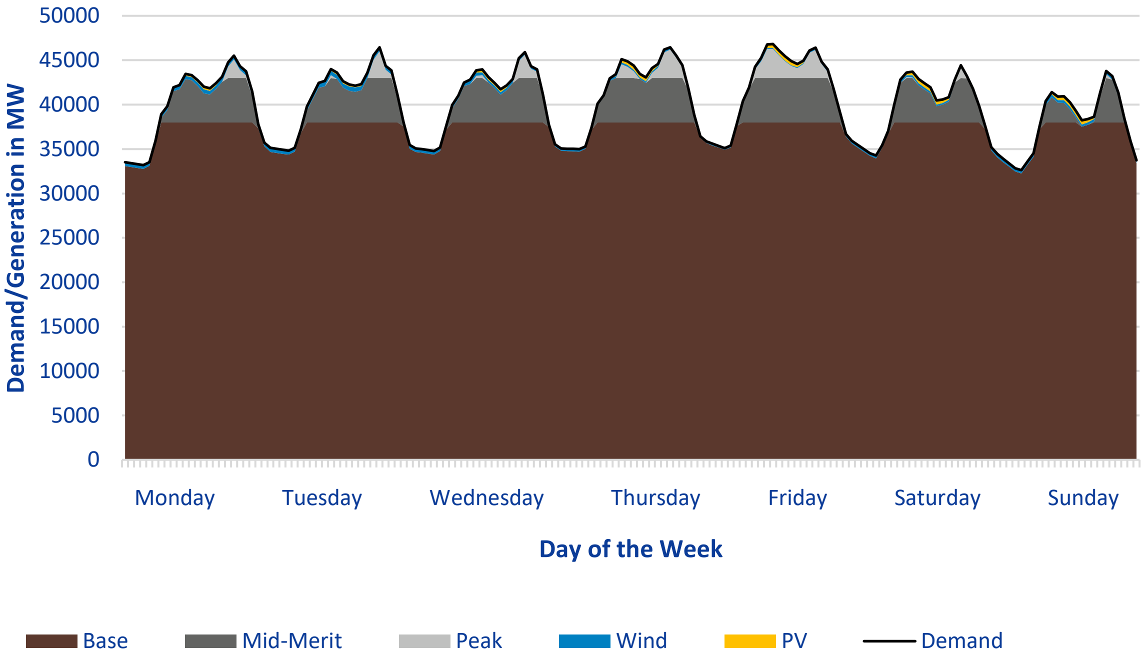

FIGURE 6: PHASE 1 – VERY LOW SHARE OF VRE: TYPICAL POWER PLANT DISPATCH FOR ONE WEEK

Phase 1 is characterised by a fossil-fuelled power system with very few vRE installations, which are almost not visible at a system level. Energy supply mainly relies on baseload power plants, which are permanently synchronised to the system and only stopped and started for maintenance work. Baseload power plants can do load-following (typically in a range between 70% and 100% of rated power). Mid-merit power plants typically start and stop once-per-day and can provide load-following in a range between 50% and 100% of rated power. In order to cover peak demand, peaking plants, (e.g. OCGTs, hydro[5], pumped-storage) are used, which can be quickly started and stopped.

Even if the contribution of vRE is very small in this initial phase of the energy transition, it is important that vRE operates reliably and does not disturb the electrical system at a local level, (e.g. adverse power-quality impact or negative impact on the voltage of the surrounding system).

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[5] *Only large hydro with water storage. Run-the-river hydro-power plants are inflexible and cannot be used for peaking*

3.1.2 Support activities

In this first phase of an energy transition, it must be ensured that initial vRE installations are seen as a success. Support activities should, therefore, mainly aim at ensuring that initial wind and PV farms operate reliably and that there is no adverse impact on the surrounding grid and the consumers connected to the surrounding grid. Thus, power-quality aspects, protection and electrical safety are the key technical topics relating to grid impact of the first wind and PV installations.

This can be achieved by supporting the development of grid codes for vRE (connection conditions) and the execution of local and regional grid studies.

In many developing and emerging countries, the power sector is vertically integrated, thus grid codes which define roles, and the responsibilities of different actors and the interfaces between these actors, do not exist. However, together with the first wind and PV projects, the first IPPs may enter the country which creates the need for the introduction of a grid code, or at least connection conditions, for renewable energy plants.

In some other cases, grid codes are already established, but do not address the specific characteristics of wind and PV power plants (non-synchronous vs. synchronous generation). As the time needed to modify or amend an existing grid code can be very long (especially, if a grid code represents a legal document requiring public consultation, etc.), the relevant authorities often define a separate grid code for renewable power plants.

However, in the longer term, managing two separate codes, one for conventional power plants and one for renewable power plants, is time-consuming and there is a high risk that the two codes will not be consistent. Therefore, in the longer term, we generally recommend preparing one integrated grid code for the entire power system, which addresses the specific aspects of all generator technologies (as is also European practice).

Before starting activities around grid code definitions, the responsibilities of the different stakeholders must be well understood. In most countries, it is the regulator who is responsible for the grid code. In some countries, the responsibility lies with a ministry, (e.g. ministry of energy) or directly with the system operators/utilities. However, even if the formal responsibility of grid code development lies with the regulator or a ministry, it is usually the system operators (transmission and distribution system operators or vertically integrated utilities) who are the key contributors because the technical knowledge about system operation and planning always lies with the system operators. Thus, the system operators must always be a key partner in all grid-code-related activities, even if the formal responsibility for grid code development is with other stakeholders.

List of possible support activities:

- Support regulators and system operators (and other involved stakeholders) in the preparation of grid code requirements for variable renewable energies, (e.g. technical input, preparation of draft documents, workshops on grid code requirements for variable renewable energies)
- Support regulators and system operators (and other relevant stakeholders) in the elaboration of grid code compliance processes (process definition, elaboration for grid code compliance studies and grid code compliance tests, etc.)
- Presentation of workshops and training on grid impact studies to system planners and system operators, as well as to other relevant stakeholders, (e.g. regulator) depending on their role in the grid planning process
- Support distribution network operators in the execution of grid impact studies at a local level (around the grid connection point)

- Provide training and workshops to all stakeholders in the power sector on relevant grid integration aspects of vRE in future phases

3.2 Phase 2: vRE is a niche market

3.2.1 System impact

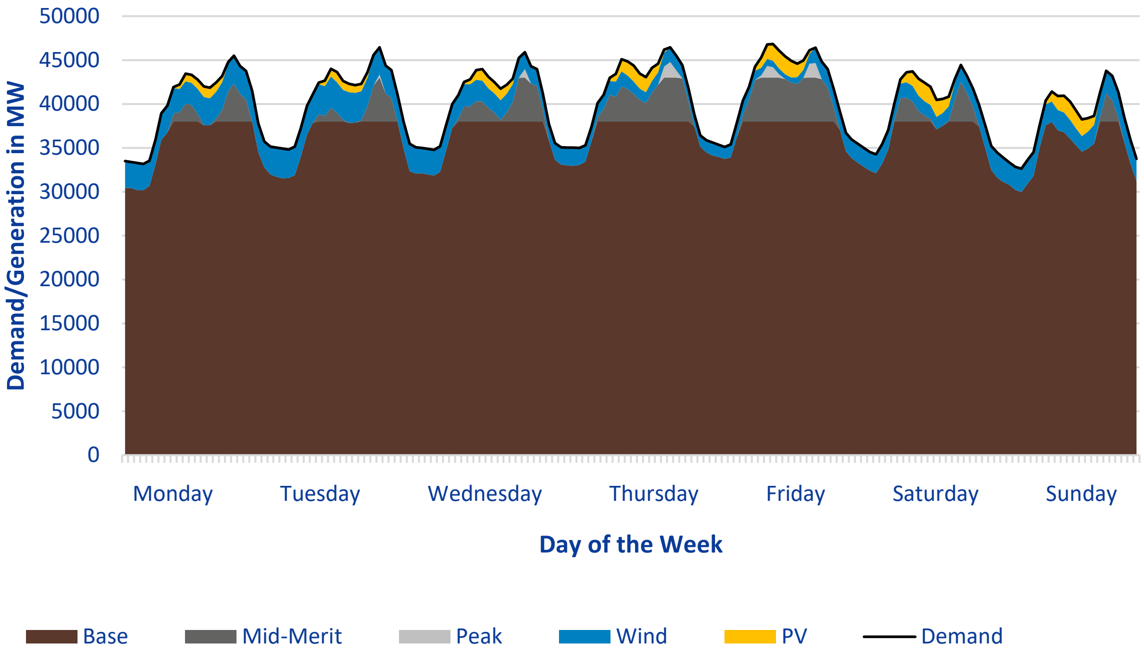

FIGURE 7: PHASE 2 – LOW SHARE OF VRE: TYPICAL POWER PLANT DISPATCH FOR ONE WEEK

Phase 2 is characterised by the increasing share of vRE. vRE is now visible at a system level, but its impact on the power plant dispatch is still very low. This phase applies to systems with a less than approximately 10% of energy contribution by vRE. In power systems with large interconnector capacities, the penetration level of vRE could also be higher for this phase.

When comparing the dispatch in Figure 6 with the curves shown on Figure 5 (same demand, but different share of vRE), it becomes obvious that, due to increasing levels of vRE, peaking and mid-merit power plants generate less energy. The impact of vRE on energy generated by baseload power plants is very low in this phase. This seems to be a contradiction, because higher levels of vRE generally require more flexible conventional power plants. However, in this phase of the transition, flexibility is not yet an issue. According to market principles, vRE replaces generation with the highest variable cost (highest fuel cost), which is usually gas.

In this phase of the energy transition, system operators start worrying about the short-term demand forecast, which becomes more and more inaccurate if no wind and PV forecast systems are used. It is therefore important to introduce state-of-the-wind and PV forecast systems and to integrate them into the operational planning processes, otherwise the required amounts of operating reserve (especially tertiary and secondary reserves) increase considerably, and system balancing becomes more and more challenging.

Even if the system-wide penetration level of vRE is still low in this phase, installed wind and PV capacities at a local level, (e.g. in very windy areas) can already be quite high, which would have an impact on local and regional power grids (distribution and sub-transmission networks, typically at voltage levels of 30kV, 60kV, 90kV, 110kV or 132kV). If variable renewables are installed without any prior analysis of the surrounding local and regional networks, grid congestions, or even local voltage stability issues, could occur. Therefore, grid reinforcements at local and regional levels may be necessary to ensure the secure operation of local and regional power networks and to avoid curtailments due to local grid congestion.

However, even if the system-wide penetration of renewable energies is still relatively low, vRE penetration in particularly windy or sunny regions is very high, so that wind and PV power plants can also have an impact on main transmission grids (with voltage levels of 220kV and above); this is something which must be evaluated on a case-by-case basis.

3.2.2 Support activities

The relevant support activities in this phase 2 of the energy transition should address the integration of variable renewable energies at system level.

In this phase, operational procedures should be reviewed and updated where necessary. Wind and PV forecast tools or services must be introduced to support day-ahead and intraday operational planning processes. In countries with many rooftop PV installations, real-time estimation of distributed PV-generation should be applied. If the requirements and needs for future systems (wind and PV forecast, operational planning tools, additional control centre functionality, etc.) has been identified, support with the preparation of specifications and tender documents for tendering the required systems can be offered.

These support activities must be executed with the engineers who are responsible for transmission system operation (real-time operations, operational planning). In cases in which there are many renewable energies at distribution levels, tools and procedures to manage the distribution system, especially grid congestion at a distribution level, should be analysed together with distribution network operators and updated, if required.

In phase 2, the grid impact of variable renewables will mainly be local and regional. In most countries, larger wind farms are connected onto sub-transmission grids (which are sometimes part of distribution, sometimes part of transmission) with voltage levels at a range between 60kV and 132kV.

Support activities for distribution network operators should focus on the analysis of procedures and tools for distribution network operations, (e.g. congestion management), and grid studies looking at the grid impact of variable renewable energies on subtransmission and distribution grids.

Even if the system-wide impact of renewable energies is still low in phase 2, longer-term planning studies looking into phase 3 or phase 4 should already start in phase 1 or phase 2, depending on the renewable energy expansion plans of each country. To ensure that related activities will have an effect, they must be carried out together with the right partners. Roles and responsibilities in long-term system planning must therefore be well understood prior to the implementation of any activity in this area. In many countries, there are several stakeholders involved in long-term system planning (master-planning): Ministries, (e.g. ministry of energy), the regulator, transmission system operators and local consultant and research institutes.

List of possible support activities:

- Support regulators and system operators (and other involved stakeholders) in reviewing and updating grid codes and related documentation, (e.g. grid code compliance procedures, manuals etc.)
- Presentation of workshops and training to distribution network operators on grid impact studies at a local and regional level
- Support distribution network operators in the execution of grid impact studies at a local and regional level
- Support transmission system operators in reviewing and updating operational processes and procedures, (e.g. day-ahead and intraday operational planning processes, real-time operating processes, etc.)
- Provide workshops and training on short-term wind and PV forecasting to system operators and support the preparation of tenders for wind and PV-forecasting services
- Support the relevant stakeholders (see above) in the preparation of long-term planning studies to prepare future phases of vRE integration

3.3 Phase 3: VRE is an important source of electricity

3.3.1 System impact

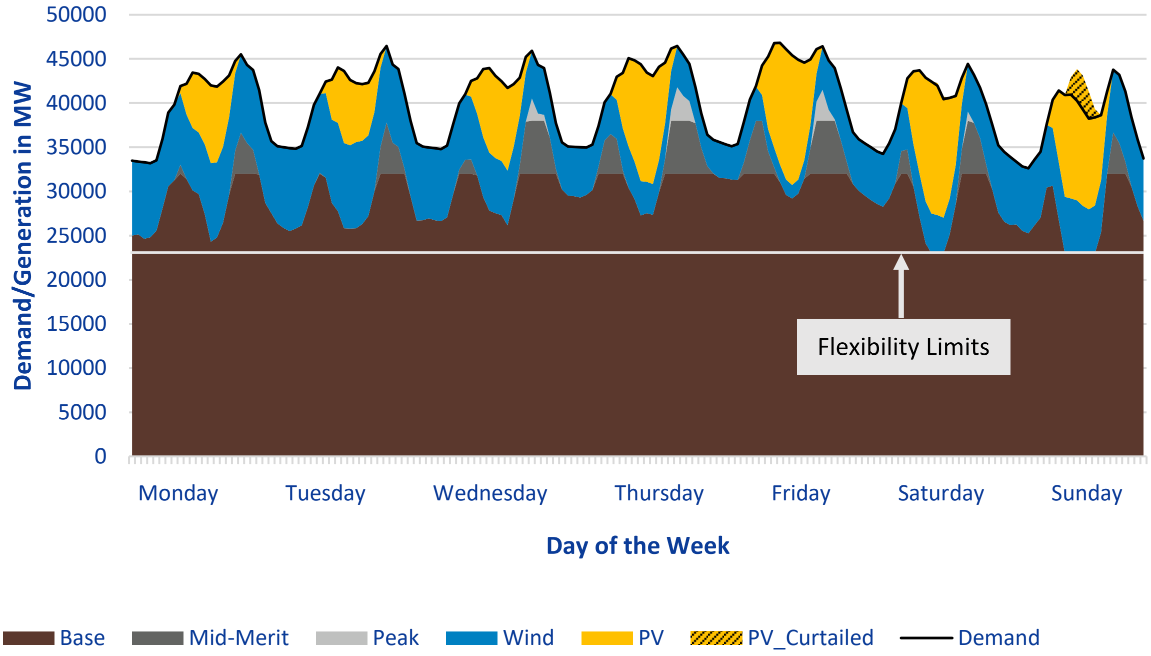

FIGURE 8: PHASE 3 – CONSIDERABLE SHARE OF VRE: TYPICAL POWER PLANT DISPATCH FOR ONE WEEK

In phase 3, the share of vRE is in the range of 10…30% of the generated electric energy. In this phase, vRE has a considerable impact on the power plant dispatch. However, the minimum level of residual demand (demand minus vRE generation) is still sufficiently high for baseload power plants to be operated economically, but at a lower level than in phase 1 and phase 2.

In systems with large interconnector capacities (large import and export capacities), the actual vRE penetration level can also be higher than 30%. The German power system, for example, has a vRE penetration of around 50% but, from an operational point of view, it can also be classified as a phase 3 system due to the large interconnector capacities, which allow baseload power plants to remain synchronised during times of high vRE generation because power excess can be exported to neighbouring countries.

In phase 3, the integration of professional wind and PV forecasting in market and operational planning processes is essential, as it is not possible to operate such a system securely and economically without this.

For system security reasons, it is important that the power of large wind and PV farms can be curtailed by the system operator. The required communication interfaces must be specified in the grid codes and system operators have to upgrade their control centres to be able to monitor and control large wind and PV farms.

In this phase of the energy transition, there is a considerable impact on the electricity grid at all levels, including main transmission levels, regional sub-transmission grids and local distribution networks. As wind and larger PV farms are usually located remote from load centres, the transmission grid must be significantly reinforced to allow the unrestricted transfer of electricity.

Due to the fact that, in some areas of the system, installed vRE capacities can be very high, and only few synchronous power plants are synchronised during times of high vRE generation, voltage stability can increasingly become an issue – additional voltage support by fixed reactive power compensation equipment, (e.g. MSCDNs or shunt reactors), or dynamic reactive power compensators, (e.g. STATCOMs or synchronous condensers), might therefore be required.

As shown by the example in Figure 8, the flexibility constraints of conventional power plants can cause vRE curtailments, especially during sunny and windy weekends when demand is low. In the example in Figure 8, synchronised baseload power plants cannot reduce their active power level below 70% of rated capacity and it would be neither economic, nor even technically feasible, to shut-down and re-start a baseload power plant just for three or four hours. In a free market, operators of baseload power plants would bid negative energy prices in such a situation in order to ensure that their power plants can remain synchronised and do not need to be shut down and restarted a few ours later.

As this example shows, in this phase 3 of the transition, baseload power plants struggle more and more with increasing flexibility requirements. In order to allow baseload power plants to operate economically, (e.g. to avoid situations with negative spot market prices), power plant operators invest money to make their power plants more flexible, e.g. to enable a lower minimum stable level of operation, (e.g. Pmin=50% instead of 70% of rated power, or even lower in the case of some CCGT plants), or to allow operation with reliable start-up and shut-down times and at reduced start-up costs. Whilst these investments are economically reasonable, they can mean increased CO_2 emissions, especially if they lead to older, coal-fired power plants delaying their retirement date, and when their replacement by more flexible power plants, e.g. gas turbines with lower CO_2 emissions (per generated MWh), is postponed.

Instead of making baseload power plants more flexible, storage could be installed to make the system more flexible, (e.g. pumped-storage or BESS). Figure 8 shows the dispatch of one week with the same installed capacities as in Figure 7, but with 3GW (12GWh) of storage.

As shown by the example in Figure 8, curtailments can be almost fully avoided in this example. However, during the majority of hours, storage is used to increase generation by baseload power plants and to reduce generation by mid-merit and peaking plants, and not to support vRE.

Generally, we can say that storage increases generation by power plants with low fuel costs and decreases generation by power plants with higher fuel costs. This is the economic benefit of storage. If ‘generation with low fuel costs’ means that generation by wind and PV power plants is increased (by reducing curtailments), CO_2 emissions are reduced and storage has a very positive climate impact. However, if storage increases the use of coal-fired baseload power plants, as shown by the example in Figure 8, then such storage increases CO_2 emissions.

Consequently, only in systems whereby storage predominantly avoids wind and PV curtailments, or in systems in which baseload is covered by hydro, gas-fired (CCGTs), or nuclear power plants, does load-shaping by storage reduce CO_2 emissions.

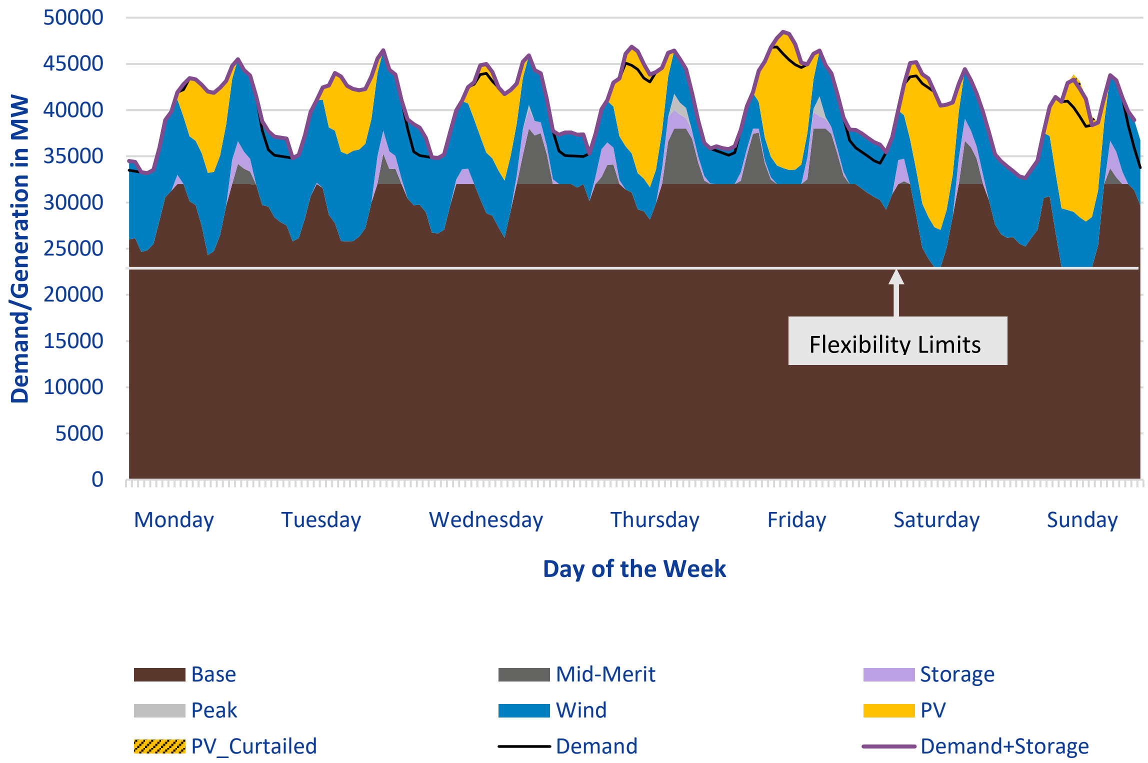

FIGURE 9: PHASE 3 – CONSIDERABLE SHARE OF VRE: TYPICAL POWER PLANT DISPATCH FOR ONE WEEK, WITH STORAGE

3.3.2 Support activities

As described above, phase 3 is characterised by an increasing system-wide impact of variable renewables, mainly impacting upon system flexibility and the transmission grid.

In order to cope with new challenges arising in phase 3, regulators and system operators should be further supported in reviewing their grid codes to verify that the connection conditions of variable renewable power plants (and conventional power plants) are still adequate.

In order to ensure that the grid will be able to transfer the energy generated by variable renewables without endangering system security, transmission and distribution network engineers must carry out network studies including all voltage levels (distribution, sub-transmission and main transmission levels).

In this phase 3 of the energy transition, the impact of vRE on system flexibility becomes more relevant. Therefore, assistance to transmission system engineers with the execution of flexibility studies should be provided. These studies should analyse the impact of vRE on flexibility requirements and verify that the balancing of demand and generation can be ensured in the future. Should these studies identify issues, transmission system engineers should be supported in identifying the necessary mitigation measures.

List of possible support activities:

- Support system operators and regulators in reviewing and updating grid codes and related documentation, (e.g. grid code compliance procedures, manuals, etc.)
- Support transmission and distribution network operators in executing grid studies at all levels, including main transmission levels. Support can be provided in the form of workshops, training or direct assistance with the preparation of studies
- Support transmission system operators and planners in executing flexibility studies looking at the impact of vRE on generator dispatch and operating reserve. These studies should also identify additionally required flexibility resources, (e.g. BESS, pumped-storage, demand-side-management, interconnection, etc.). Support can be provided in the form of workshops, training on the job activities, or the provision of direct assistance.

3.4 Phase 4: VRE is the dominant source of electricity

3.4.1 System impact

In phase 4, vRE is the dominant source of electricity. vRE penetration levels are in a range between 30% and 60% of the overall generated electric energy. In systems with large interconnector capacities, vRE penetration levels can be even higher.

In such a system, the residual demand can be as low as zero during some hours (see Figure 9) and practically all the system's conventional power plants must be flexible, meaning that they are able to start and stop within reasonable times when needed. As shown by Figure 9, the dispatch of power plants is therefore not based on the classical baseload – mid-merit – peaking scheme, but vRE is dispatched as much as possible and flexible, conventional power plants (like CCGT, OCGT or large hydro-power plants) are dispatched to balance load and generation. Baseload power plants cannot be operated economically in such a phase 4 system.

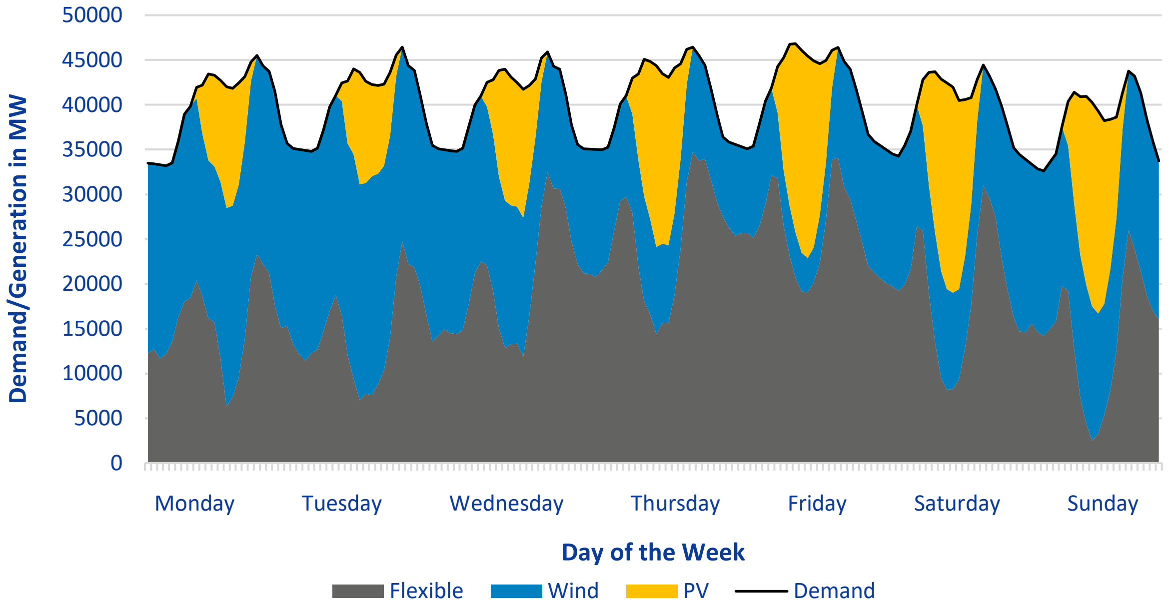

FIGURE 10: PHASE 4 – HIGH SHARE OF VRE: TYPICAL POWER PLANT DISPATCH FOR ONE WEEK, (WITHOUT STABILITY CONSTRAINTS)

Assuming that conventional power plants are fully flexible in this phase 4, which means that they can be quickly started and stopped and can support high load-following ramp rates, there are practically no flexibility constraints as long as wind and PV-generation is lower than demand (residual demand is positive).

However, in such a system, stability constraints become more of a concern. Stability issues can occur at a local, regional or global level. Stability issues at a local or regional level are usually related to voltage stability and must be resolved by providing fast voltage control, either at wind turbine or PV-inverter level, or by installing additional, dynamic reactive power compensation devices, (e.g. STATCOMs).

Global stability constraints are imposed by reduced inertia and the reduced primary frequency control capability of synchronised power plants, or by voltage stability problems at the main transmission level, (e.g. resulting from highly loaded transmission lines). Global stability constraints may cause 'must-run-constraints', meaning that a minimum number of synchronous machine power plants must always be synchronised to the system in certain areas of the network. As every synchronised power plant must generate a minimum level of active power (typically in the range of around 50% of rated capacity), these must-run units impose a constraint on the maximum vRE generation at any moment in time.

As shown by Figure 10, stability constraints lead to increased curtailments of wind and PV, which reduce the efficiency and increase the cost of electricity generation, especially if such situations occur regularly.

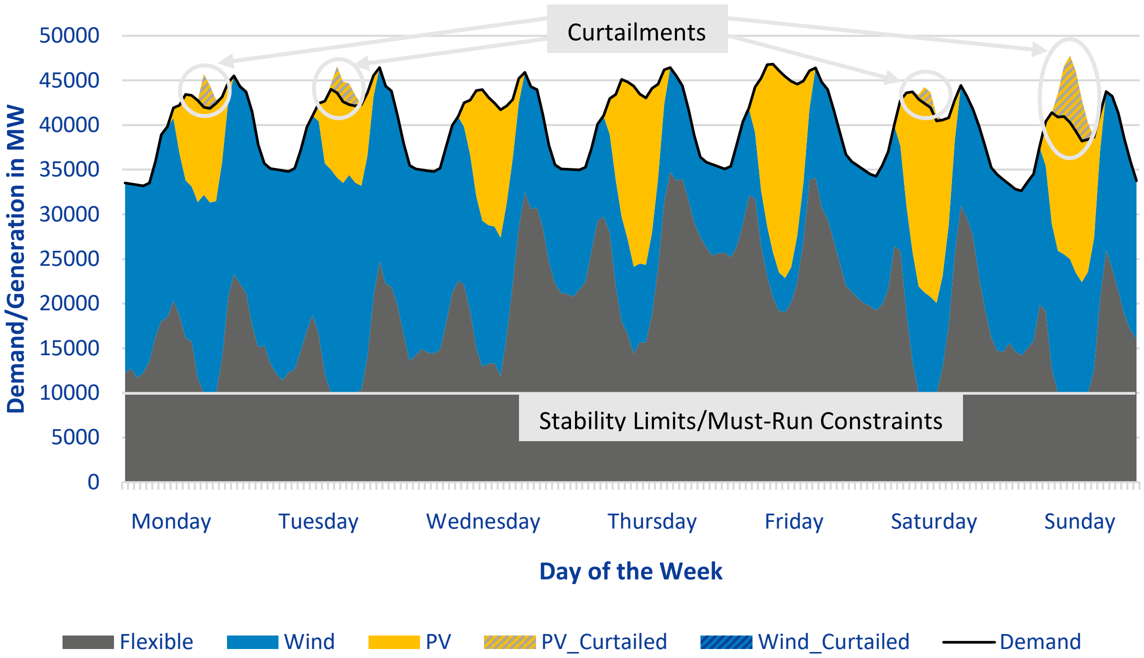

FIGURE 11: PHASE 4 – HIGH SHARE OF VRE: TYPICAL POWER PLANT DISPATCH FOR ONE WEEK, WITH STABILITY CONSTRAINTS

Curtailments caused by stability constraints can be avoided or reduced by various measures:

- Use of demand-side management and storage to increase demand if required
- Provision of stability-related ancillary services
- Installation of special power system components to reduce stability-constraints

Stability-related ancillary services can be:

- Fast voltage control
- Provision of ‘artificial inertia’
- Provision of fast frequency control
- Provision of synchronising torque and damping torque

Power system components, which can provide those services are:

- Wind and PV farms (fast voltage control, fast frequency response, artificial inertia)
- STATCOMs (fast voltage control)
- BESS (fast frequency control, artificial inertia, primary and secondary frequency control)
- STATCOMs with short-term storage and grid-forming converter control (new component, under development): can provide all the services (including synchronising torque)
- Synchronous condensers (synchronous machines without turbine)

This list includes the most common measures to support system stability in a power system with a very high level of vRE. Some components, (e.g. BESS) can provide more than one service, (e.g. fast frequency control and primary frequency control) but, in some countries, the regulatory framework does not allow for the combination of generator-type services, (e.g. primary frequency control) and services which are within the responsibility of the TSO, (e.g. voltage control and inertia). Thus, BESS, which combine voltage control, fast frequency control and primary frequency control, are not common in Europe but, technically, would be a very good option.

The example in Figure 11 shows the same system as Figure 10, but with additional services and components to reduce stability limits from 10000MW (Figure 10) to 5000MW (Figure 11).

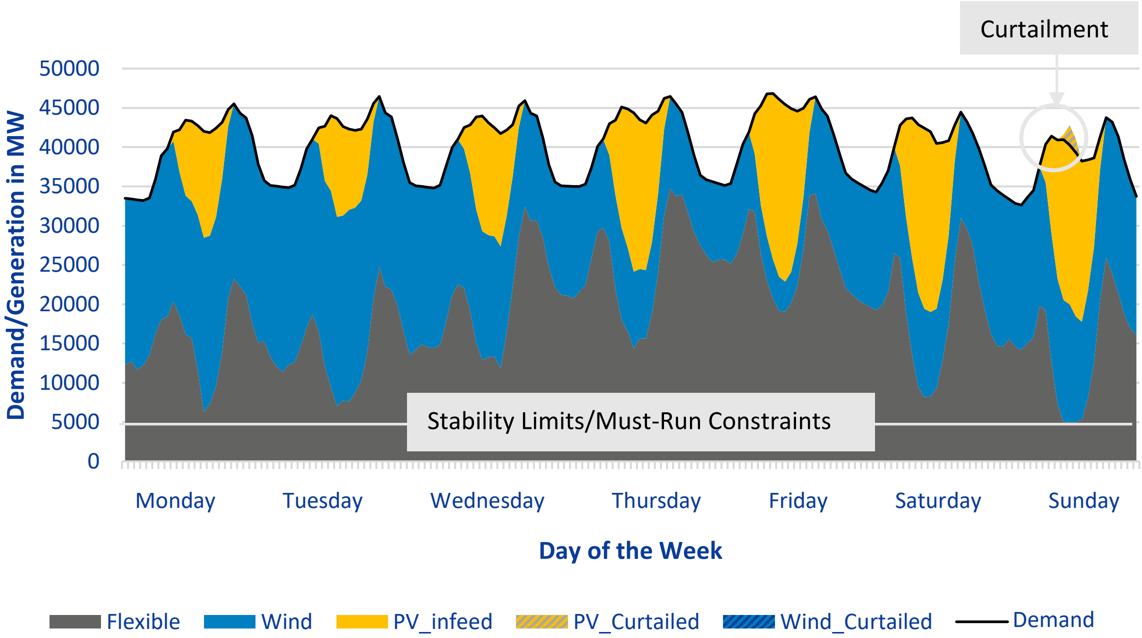

FIGURE 12: PHASE 4 – HIGH SHARE OF VRE: TYPICAL POWER PLANT DISPATCH FOR ONE WEEK, WITH REDUCED STABILITY LIMITS

When comparing the number and level of curtailments of the example in Figure 11 with Figure 10, it can be observed that reducing stability constraint allows the considerable reduction of wind and PV curtailments.

These measures do, of course, come at a cost, which is mainly CAPEX for the installation of additional components. Such costs must be justified by the benefit of reducing fuel consumption in conventional power plants (cost and CO_2-reduction).

Instead of reducing stability constraints, energy storage equipment, (e.g. pumped-storage power plants or BESS) can be used to increase the load during times of high vRE generation. In Figure 12, the stability limit is the same as in Figure 10 (10000 MW), but there is 5GW (E2P=4h) of energy storage connected to the system allowing the increase of the load (charging) whenever it is necessary to avoid curtailments of wind and PV. During times of high demand and low vRE generation (high residual load), the stored energy is made available to the system (discharging, light blue areas in Figure 12).

Comparing the results in Figure 11 and Figure 12 shows that, with both approaches, the same benefit (reduced curtailments and therefore reduced fuel consumption) can be achieved. It is therefore necessary to compare the cost of both options – measures to reduce stability constraints vs. power system storage.

In most cases, adding components to reduce stability limits is substantially less expensive than adding storage components for load-shaping. For example, in cases of minimum inertia constraints (which is a stability constraint), the addition of BESS with an E2P-ratio of around 15min…1h for fast frequency control is much less expensive than the addition of BESS with an E2P-ration of 2h…4h, which is required for load-shaping.

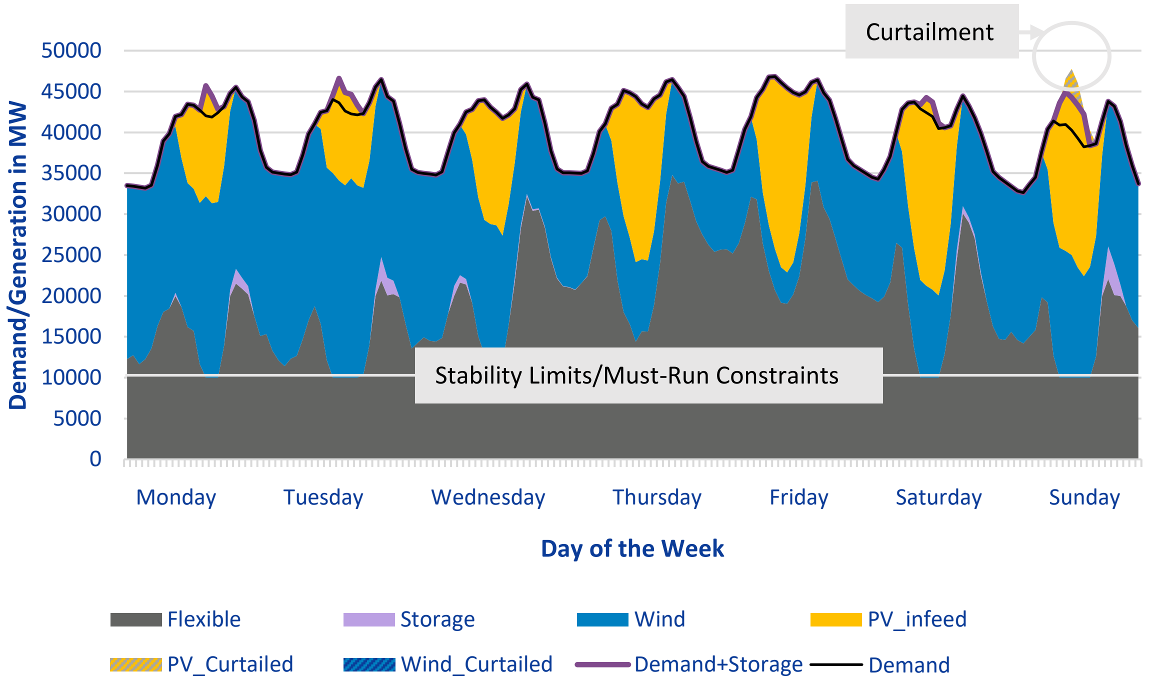

FIGURE 13: PHASE 4 – HIGH SHARE OF VRE: TYPICAL POWER PLANT DISPATCH FOR ONE WEEK, SUPPORTED BY STORAGE COMPONENTS USED FOR LOAD-SHAPING

When combining both strategies, i.e. reducing stability constraints and charging storage components during times of low residual load, curtailments can be completely avoided as shown in the example in Figure 13.

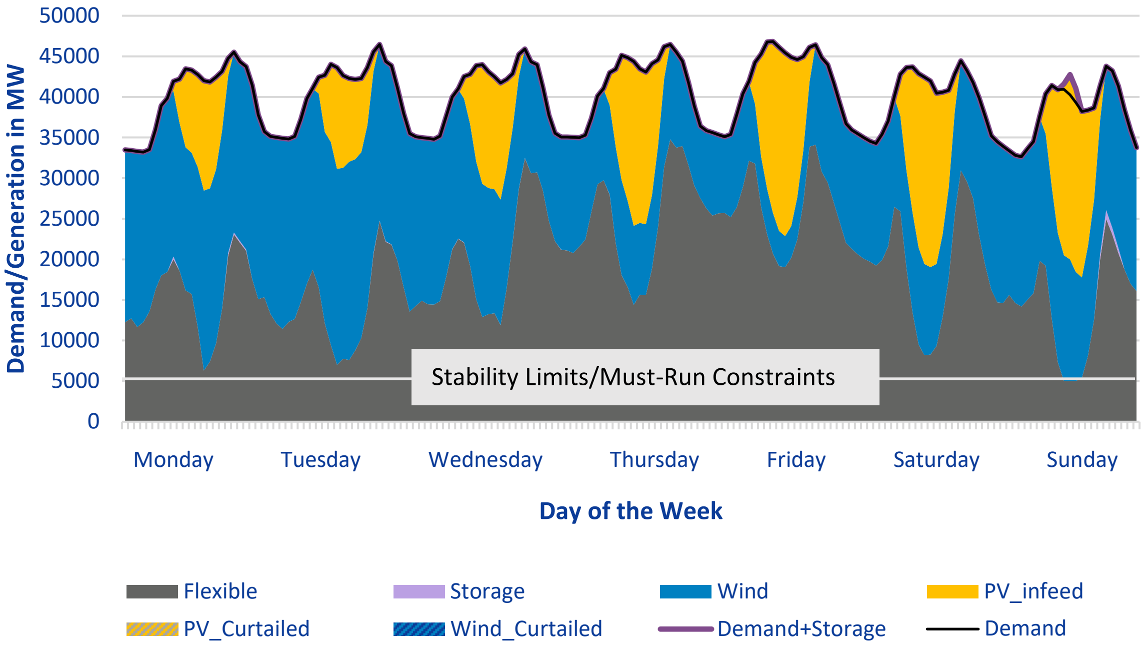

FIGURE 14: PHASE 4 – HIGH SHARE OF VRE: TYPICAL POWER PLANT DISPATCH FOR ONE WEEK, WITH REDUCED STABILITY LIMITS AND STORAGE COMPONENTS FOR LOAD-SHAPING

However, a cost-benefit analysis would have to identify whether the cost of additional components to reduce stability constraints, or the cost of storage for load-shaping would be recovered by reduced fuel costs (avoided curtailments). In systems in which curtailments only occur occasionally, this is usually not the case, and some curtailments should be accepted.

Only if curtailments occur very frequently, can the cost of storage components be recovered by avoided fuel costs.

3.4.2 Support activities

In this phase 4, the operation of power systems must be well-adapted to the characteristics of variable renewable energies. Operational procedures and appropriate market rules are therefore key to a successful and cost-effective operation of a system with very high vRE penetration. For example, shorter dispatch intervals can help with tracking the power plant dispatch to predicted variations of demand and (vRE-) generation. Intra-day markets can help operators of vRE power plants to balance day-ahead prediction errors ahead of real-time. In countries with liberalised power markets, market rules must be reviewed and updated to support an improved integration of variable renewables. In countries with vertically integrated power sectors, operational procedures need to be adapted accordingly.

Grid studies should focus on required transmission expansions (which can be AC or DC) and power system stability, especially voltage stability and frequency stability (weak inertia problems). To solve stability issues, STATCOMs, series compensation and grid-forming inverter technologies with storage capability should be considered. It is very important that system operators understand well the nature of stability problems and the technologies that can resolve it.

Increasing flexibility requirements resulting from increased variability will require new technologies, like ‘battery energy storage systems’ (BESS), demand-side response and the potential of vRE to provide frequency control services. System operators must be trained to better understand the technology and application of these new technologies. New ancillary service definitions and well-adapted ancillary markets (or procurement schemes) can help with integrating these technologies efficiently and at reasonable cost. In countries with well-developed electricity markets, it is therefore necessary to offer capacity-building activities not only to the technical staff of system operators, but also to market operators, energy economists, etc., who are tasked with the design and operation of power markets.

List of possible support activities:

- Support system operators and regulators in reviewing and updating grid codes and related documentation, (e.g. grid code compliance procedures, manuals, etc.)
- Support system operators and market operators in reviewing and updating market rules and operating procedures
- Support the technical staff of system operators and market operators in reviewing and updating ancillary service definitions and remuneration schemes
- Assist system planning and system operation engineers with the execution of grid studies (load flow, short circuit, and stability studies) at all voltage levels (including main transmission levels)
- Support transmission system operators and planners in executing flexibility studies to analyse the need for additional technologies to provide the required flexibility resources
- Offer workshops and training to all the technical staff in the electric power sector on the application of advanced and new technologies, such as STATCOMs, grid-forming converters, battery energy storage systems (BESS), HVDC and other FACTS devices to support stability and flexibility.

3.5 Phase 5: The carbon-free energy system

3.5.1 System impact

In principle, the operation of a carbon-free power system based on wind, PV and hydrogen, as explained in section 2.4, is not fundamentally different from the phase 4 system described in the previous section. Only the level of installed wind and PV capacities and installed (short-term) storage capacities are substantially higher. Additionally, in order to achieve 100% carbon-free electricity generation, gas turbines operate with hydrogen[6].

In addition to this, the following assumptions apply:

- There are numerous additional components installed to ensure system stability (e.g. STATCOMs with short-time storage and grid-forming converters)
- The system can operate with non-synchronous generation only (during times of high wind and PV-generation)
- Electricity generation with gas turbines (hydrogen-turbines) is fully flexible
- A considerable part of the load is flexible, (e.g. electrolysers used for the production of hydrogen) meaning that a substantial part of the load will be tracked with the availability of wind and PV

Figure 14 shows the weekly unit dispatch of a fully decarbonised power system. In this example, the ‘fix demand’ (dashed line in Figure 14) is the same as in the previous examples. On top of this ‘fix demand’, there is flexible demand, (e.g. electrolysers for the production of hydrogen) and additional demand, which is required to charge storage plants (BESS and pumped-storage). The solid black line is equivalent to the sum of all three load components.

Short-duration mismatch between supply and demand, as it happens at the beginning of the week shown in the example in Figure 14, can be compensated by storage, (e.g. BESS). However, if wind and PV-generation is low during longer periods (as at the middle of the week shown in Figure 14), gas turbines driven by hydrogen must fill the gap between demand and vRE generation.

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[6] *Existing gas turbines cannot be simply changed from natural gas to hydrogen, but many new commercially available gas turbines can run on different H_2-blends with a path towards 100% H_2*

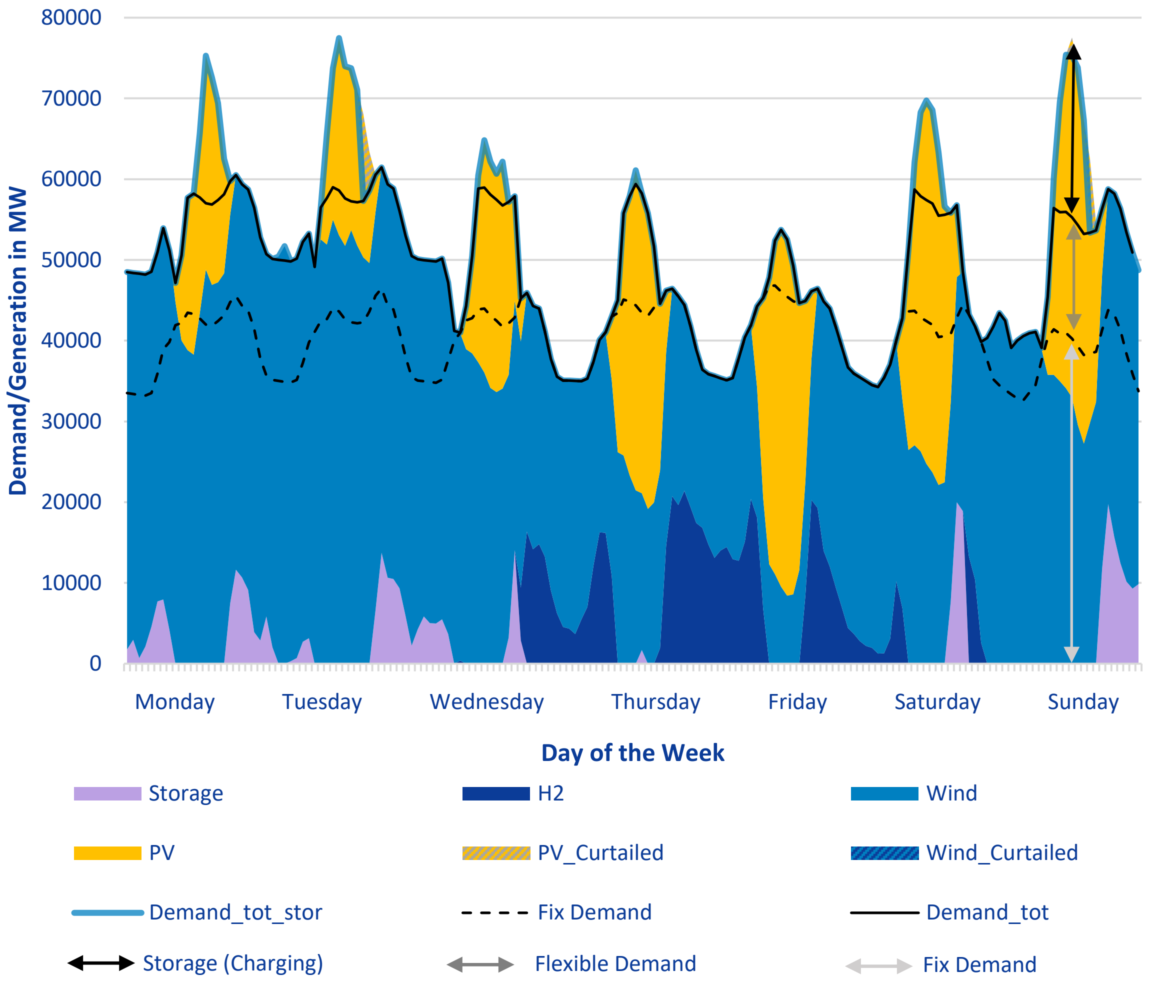

FIGURE 15: PHASE 5 – CARBON NEUTRAL POWER SYSTEM: TYPICAL POWER PLANT DISPATCH FOR ONE WEEK

Especially in systems with large wind contribution, the transmission system must be significantly expanded so that wind energy can be transferred to the load centres.

As the use of short-term storage, (e.g. BESS) highly correlates with PV-generation, BESS should be installed near to PV installations, so that the balancing of PV and BESS does not result in balancing power flowing across long transmission lines.

3.5.2 Support activities

Activities to support phase 5 are very similar to phase 4, but with a very strong focus on sector-coupling and the operation of power systems with (almost) 100% non-synchronous generation (during times of high wind and PV). Support activities should therefore mainly focus on hydrogen technologies, BESS, the operation of highly flexible power systems and the adaptation of market rules to a power system with 100% renewable generation.

List of possible support activities:

- Present training on H_2-generation technologies for all the relevant stakeholders (system operators, regulator, relevant staff of ministries, private sector organisations, universities and research institutes)
- Present training on sector-coupling technologies (system operators, regulator, relevant staff of ministries, private sector organisations, universities and research institutes)
- Assist the technical staff of system operators and market operators with reviewing and updating market rules and operating procedures which are adapted to markets with a zero variable generation cost during considerable periods
- Support system operators and regulators in reviewing and updating grid codes and related documentation, (e.g. grid code compliance procedures, manuals, etc.)
- Support the technical staff of system operators and market operators in reviewing and updating ancillary service definitions
- Assist planning and system operations engineers with the execution of grid studies (load flow, short circuit, and stability studies) at all voltage levels (including main transmission levels)
- Support transmission system operators and planners in executing flexibility studies to analyse the need for additional technologies to provide the required flexibility resources
- Provide training on the application of advanced and new technologies, such as STATCOMs, grid-forming converters, battery energy storage systems (BESS), HVDC and other FACTS devices to support the stability and flexibility for the technical staff of all the relevant stakeholders (system operators, regulator, relevant ministries, private sector organisations, universities and research institutes)

3.6 System impact and support activities – Summary

With the increasing penetration of variable renewable energies, their impact on system operations becomes more and more relevant. Figure 15 below shows a high-level overview of the main technical challenges that have to be managed in each phase of the energy transition:

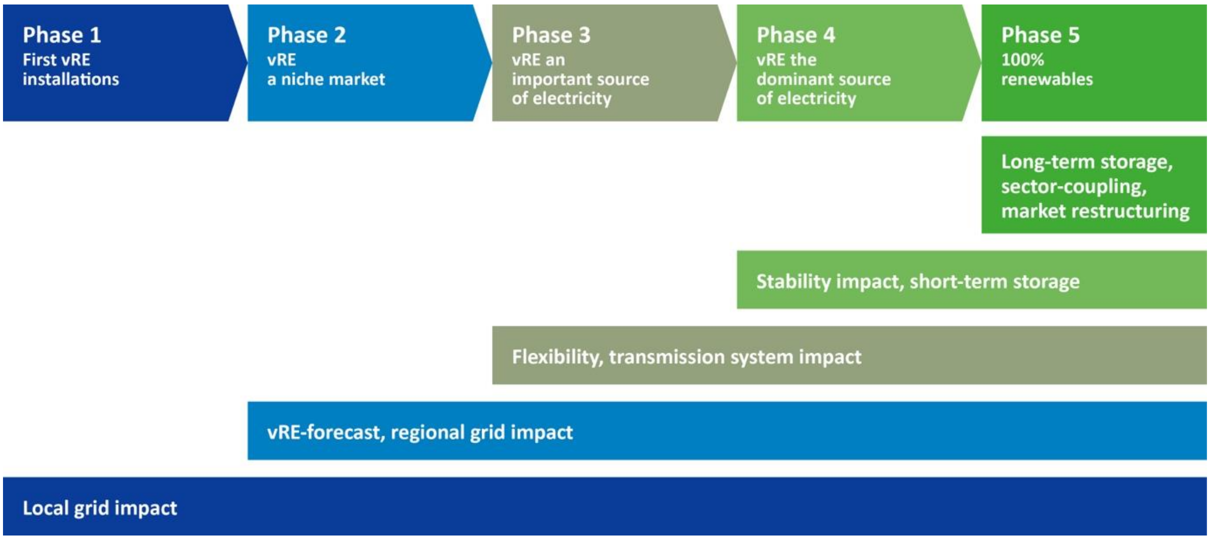

FIGURE 16: SYSTEM IMPACT OF VRE IN THE DIFFERENT PHASES OF THE ENERGY TRANSITION

During initial phases of the energy transition, it is mainly the local grid aspects which have to be analysed. At this stage, it is most important to ensure the definition of proper connection conditions and to avoid any adverse impact on the surrounding grids.

As soon as the contribution of vRE becomes more important, and the impact of vRE becomes visible at a system level (phase 2), operational processes must be adapted to reflect the specific characteristics of vRE. The introduction of short-term wind and PV forecast services, and their integration in all the relevant operational processes, is of most relevance in this phase.

With increasing vRE contributions, the main technical characteristics of a power system will be increasingly dominated by the technical characteristics of vRE. Instead of large, dispatchable power plants based on large synchronous generators, energy supply will rely more and more on variable, non-dispatchable power plants using non-synchronous (inverter-based) generator technologies.

In addition, vRE power plants will be installed in different areas to those of conventional power plants, i.e. near to areas with high wind or solar resources, and power flows will therefore substantially change, thus requiring substantial grid expansions.

To ensure stable operation of a power system with very high vRE penetration (phase 4), additional flexibility resources (such as BESS, demand response, and increased interconnection) must be applied. Market rules, ancillary service definitions and operational procedures need to be adjusted. The grid must be strengthened to accommodate the altered load flows and new devices, such as STATCOMs, grid-forming converters, synchronous compensators, and other FACTS devices, will have to be installed to ensure system stability.

To allow the transition from a power system with very high vRE penetration, to a carbon-free power system, electricity generation using hydrogen and sector-coupling technologies will need to be employed. In addition, electricity markets must be re-structured to reflect power generation at zero variable cost during most periods.

Most aspects of this document refer to power systems with predominantly thermal (steam), gas and vRE generation. In power systems with a major share of large hydro-power stations, carbon-free operation can be achieved more easily with substantially less contribution from vRE and, in many cases, even without any contribution from hydrogen-fuelled power plants.

Support activities must be well-aligned to the technical challenges of each phase of the energy transition, with a specific focus on the power system under study. Figure 16 summarises relevant support activities and relates them to the different phases of the energy transition. It is important to note that most activities required for each phase will have to be executed ahead of time. For example, flexibility studies to analyse the impact of vRE on system flexibility must be executed at least two years in advance, so that there is sufficient time to take the required measures.

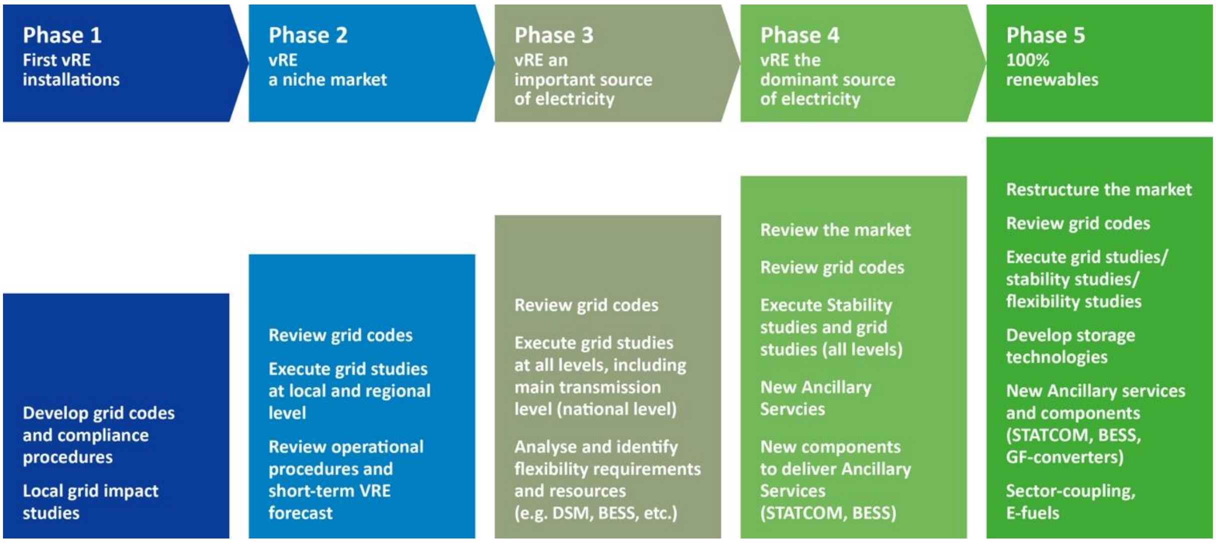

FIGURE 17: ACTIVITIES TO SUPPORT THE ENERGY TRANSITION

4 Summary and Conclusions

This report describes technical challenges of an energy transition starting with a conventional, fossil-fuelled power system, which is transformed into a carbon-free power system supplied by wind, solar, hydro and gas turbines operated with hydrogen or biogas. The model presented in this report approximates the continuous transition in five discrete phases, which are characterised by different levels of renewable generation.

To support the energy transition in developing and emerging countries, this report presents capacity-building activities which are tailored to each phase of the energy transition.

To ensure that the first renewable energy projects will operate successfully, it is important to ensure that these wind and PV-farms do not have an adverse impact on the surrounding grid. This can be achieved by grid code updates (connection conditions for generators) and grid studies analysing the surrounding distribution, as well as sub-transmission grids.

With the growing number of wind and PV-installations, their contribution to electrical energy generation becomes more and more visible at system level. As a result, wind and forecasts must be introduced to support day-ahead and operational planning activities. At the same time, relevant operational procedures must be reviewed and adapted. Moreover, the impact of vRE plants on regional distribution (or sub-transmission grids) must also be simultaneously studied and the grid reinforced, if necessary.

In further phases of the energy transition, the impact of vRE on system flexibility and stability become the relevant topics. Flexibility refers to the ability of a power system to balance demand and generation at any moment in time. Stability describes the ability of a power system to return to a secure state after a disturbance.

The variability of wind and PV-generation increases the flexibility requirements of a power system. Conventional power plants must therefore be increasingly flexible, which means that not only should their load-following range be as large as possible, but they should also be able to operate at high ramp rates; furthermore, they should be able to start and stop at reasonable cost and within a reasonable time. To support the flexibility of the system, additional components and strategies are required, such as demand response, increased interconnection, or battery energy storage systems. From phase 4 on, baseload power plants can no longer be operated economically, and will thus finally disappear from the system. To integrate typical baseload technologies into such a system, they must be equipped with thermal storage, (e.g. melted salt storage, as known from CSP plants) in order to be able to provide the required flexibility at a reasonable cost.

The stability impact of vRE is mainly a result of generator technology (converter-driven instead of synchronous machines) and altered power flows requiring grid reinforcements.

It is important to conduct related studies with a sufficient lead-time, so that new operational processes, control/monitoring concepts and components can be implemented in time to ensure system security at every level of vRE integration.

The carbon-free power system (labelled ‘phase 5’ in this report) represents a very big step because it includes the transitions of other sectors, (e.g. heat, transport, industries, etc.) towards carbon-free technologies. This phase 5 is therefore characterised by a large increase in electrical demand because decarbonising the heat and transport sectors requires the replacement of fossil fuels by electricity. The decarbonisation of other sectors, (e.g. steel manufacturing, high-temperature heat, fertilisers, etc.) will require green hydrogen generated by electricity. Therefore, the main challenge of this phase 5 is to install the required carbon-free generators, gas turbines which can be driven by hydrogen, and the required transmission lines and cables to supply the additional electricity demand.

5 References

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6 Annex: Structure of electrical grids

Similar to road systems, electrical grids can be subdivided into:

- Transmission grids ('highway')
- Regional grids ('country roads')
- Medium voltage distribution grids ('larger local roads')
- Low voltage distribution grids ('smaller local roads')

Transmission grids:

Transmission grids are used to transfer large volumes of electricity (high power) across long distances (several hundreds of km). Transmission grids interconnect the main generation centres (classically large power stations) with the main load centres. All the lines and substations which have a voltage level of v>=220kV are part of the transmission grids. In some countries, and some areas, the 132kV grid is also part of transmission (in most places, 132kV grids tend to be a part of regional distribution grids). Transmission grids are fully meshed. Depending on the voltage level, transmission lines can transfer power in the range of 500MW up to 2 or 3 GW.

Regional grids (subtransmission grids)

Regional grids are typically built by voltage levels in the range of 60kV, 90kV, 110kV or 132kV and interconnect regional load centres, (e.g. towns) with each other. In some countries, these networks form part of 'transmission', in most countries, however, they are nowadays part of the distribution network. Distances and power transfers are smaller than in a transmission grid (typically less than 100km). In some countries, the various regional grids are not directly interconnected and are only interconnected via the transmission grid. In other countries, regional subtransmission grids are fully interconnected and form a meshed layer below the transmission grid. Regional subtransmission grids have classically been pure distribution grids with a clearly defined power flow direction (from the main transmission substation to the distribution substations). With the increased integration of wind and PV, regional transmission grids also interconnect generators and export power to the next higher transmission level. As substations at subtransmission levels are considerably cheaper than substations with a voltage level of >=220kV, most utility-scale wind and PV farms are connected to subtransmission grids. In regional transmission grids, depending on their voltage level, typical power transfers are in a range up to 100MW.

Medium voltage distribution grids

Medium voltage distribution grids operate at voltage levels of 30kV, 20kV, 10kV, (or 6.6kV in industrial networks). They have one supply point from a regional subtransmission grid (substation) and, in more developed countries, a second, optional supply point that can be used as a back-up in case of a complete substation outage. Medium voltage distribution grids are organised in radial strings or rings, whereby each substation transformer supplies several strings or rings. Each string or ring interconnects several distribution substations supplying the different underlying low voltage networks. With a few exceptions, rings are operated radially, meaning that one switch along the ring is opened, so that the grid is effectively radial.

Overall string-lengths are in a range of up to 50km in rural areas, and substantially shorter in urban areas. Depending on the voltage level and cross-sections of the lines and cables, typical power transfers at MV are in the range of 5MW-40MW. Typical sizes of substation transformers are 20MVA, 40MVA, or maybe 63MVA. MW distribution networks are typically three-phase networks but, in some countries, especially in rural areas, single-phase or even single-phase-to-ground medium voltage networks can be found, too.

Low voltage distribution grids

Low voltage grids are supplied by distribution transformer stations having a capacity in the range of a few hundred kVA up to a maximum of 1MVA. Typical voltage levels are 400V (440V) in 50Hz systems, and 190V (207V) in 60Hz networks. LV networks supply individual households. In many European countries, (e.g. Germany), LV networks are three-phase networks and each house has a three-phase connection. In most other countries, houses usually only have a single-phase connection. This can be relevant in the context of rooftop PV or electric mobility. Just like MV distribution networks, LV networks are organised in strings or rings and operated radially (with very few exceptions). Power flows at LV are typically in the range of a few hundred kW, in some areas up to 1MW.