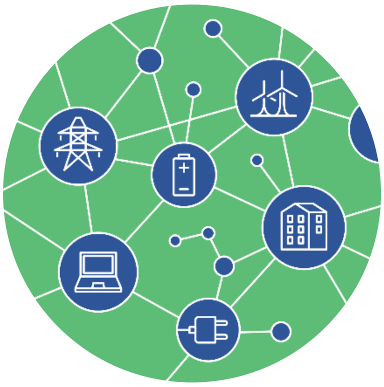
OSMOSE

OPTIMAL SYSTEM-MIX OF FLEXIBILITY
SOLUTIONS FOR EUROPEAN ELECTRICITY

Synergies between flexibility services

Internal Deliverable T1.5



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0 Executive summary

The identification of synergies between flexibility services becomes more important with increasing non-dispatchable energy provision by renewable energy sources. Decarbonization requires high utilization of variable renewable energy sources and hence market design needs to be suitable for all technologies to participate. As a result, the European Commission enforces trade processes for energy and ancillary services to be more standardized, such that competition is enhanced. This enables new business cases for stakeholders, yet it requires them to revise when and where to participate. In the greater perspective – assuming fair competition – this yield into the optimal mix of technologies to provide energy and ancillary services.

In this context, the various technologies have different technical restrictions and may provide energy or certain ancillary services. Ancillary services include the provision and release of power for frequency control, grid forming, voltage control, congestion management, fault current contribution, fault ride through and black start capability. Whereas conventional power plants technically can provide various ancillary services, variable generation can only provide certain services with limited foresight and thus in the short- and medium-term range, exclusively. Furthermore, load-shifting could support frequency control, but not non-frequency ancillary services[1]. Finally, transmission network assets can affect the voltages and currents, hence the power flows in the network.

There is no common consensus on a certain definition of flexibility in the energy system. Various frameworks have been established to assess and compare different dimensions of flexibility, e.g. usage time, response time, uncertainty, cost. Such measures can be employed to identify efficient technology-to-usage allocations. However, the scope of the state-of-the-art scientific energy models varies. Depending on the study, only certain aspects of the broad definition of flexibility are tackled.

Energy system models that depict optimal future technology-to-usage allocations model endogenous power plant capacities to derive implications for policy makers. These models include energy balancing and partially a simplified representation of reserve capacities for frequency control. Market models pick one calculation year and may also model strategic behavior of the market participants in some detail. Both markets – for energy and frequency control – are considered to derive bidding strategies of the participants. Research for optimal technology allocation for non-frequency ancillary services, as well as global efficient allocation among energy balancing, frequency and non-frequency ancillary services is still rare. Only technical

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[1] non-frequency ancillary service means a service used by a transmission system operator or distribution system operator for steady state voltage control, fast reactive current injections, inertia for local grid stability, short-circuit current, black start capability and island operation capability (Directive 2019/944 of the European Parliament and of the Council, 2019)

optimizations, e.g., regarding system security and system resilience, could be identified. Likewise, no studies treat synergies in flexibility provision between normal and abnormal energy system states[2] regarding the corresponding economic aspects.

State-of-the-art energy models cover today's market structures and include energy balancing and reserve markets for frequency-control. Approaches are available that reflect the European framework of sequential market clearing. Holistic service allocation models identifying the optimal service allocation are hardly available as of today. Particularly, the inclusion of novel ancillary services such as grid forming in these models has hardly been done. In this study field further research is required.

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[2] Referring to the services that do not necessarily have to be activated, as long the system does not exhibit contingency events, such as island mode capability, fault current contribution, fault ride through and black start capability services.

1 List of acronyms and abbreviations

In the following table are listed the acronyms and abbreviations used in this document.

Acronym	Meaning
AC	Alternating current
ACE	Area control error
aFRR	Automatic frequency restoration reserve
CAES	Compressed air energy storage
DC	Direct current
DSM	Demand side management
EB GL	Electricity balancing guideline
ED	Economic dispatch
FACTS	Flexible AC transmission systems
FCR	Frequency containment reserve
G2P	Gas-to-power
HVDC	High voltage direct current
MSC	Mechanically switched capacitors
LFC	Load frequency control
mFRR	Manual frequency restoration reserve
P2G	Power-to-gas
PV	Photovoltaic
RES	Renewable energy sources
ROR	Run of river
RR	Replacement reserve
SMES	Superconducting magnetic energy storage
TATL	Temporarily admissible transmission loading
TSO	Transmission system operator
UC	Unit commitment
V2G	Vehicle-to-grid
WP	Working package

2 Introduction

Changing the energy system towards integrating more variable renewable energy sources, whose availability is fluctuating, implies an increasing demand for flexibility. Such flexibility for the electrical power sector can be provided by many different technologies. However, the generic definition as “the ability to adapt the planned development of the power system, quickly and at reasonable cost, to any change, foreseen or not, in the conditions which prevailed at the time it was planned” (E-CIGRE, 1995) is difficult to translate into a single meaningful definition for the energy system. So far no commonly agreed definition has emerged in the scientific literature (Cochran et al., 2014; Hillberg et al., 2019; IRENA, 2017; Ulbig & Andersson, 2012). To tackle this shortcoming and to categorize the topic, frameworks have been established to better analyze different dimensions of flexibility. For example, Zinaman & Sadamori (2018) distinguish between different layers of flexibility. They differentiate between the following aspects without separating the physical concepts of energy and power:

- Technical layer, e.g., dispatchable generation, variable renewable energy, demand side resources, energy storage
- Economical layer, e.g., economic incentives
- responsibility-related layer, e.g., roles and responsibilities

Besides qualitative considerations, a variety of quantitative scores were introduced to compare contributions to power system flexibility. Amongst others, Zhao et al. (2016), as well as Elsner et al. (2015) consider the following metrics:

- maximal usage time of the option if applicable
- response time of the action, i.e., time to enable and start-up time or trading frequency
- uncertainty
- cost

This document is based on the definition of “flexibility” as capability of energy system connected units to change its behavior close to real-time to adapt to new given requests of delivery a certain service. This work contrasts the different (technical) flexibility providers and their flexibility usage in the context of short-term network operation from an allocation point of view. Chapter 3 briefly discusses the energy system units and their capabilities to provide real-time flexibility. Then, chapter 4 reviews possible usages of close to real-time flexibility. Particularly (ancillary) system services that are already procured currently, as well as capabilities whose supply is requested by network codes that may form entrance barriers and/or create over-provision of capabilities. Next, chapter 5 depicts which flexibility providers are applicable for which usage. Flexibility demand is shortly discussed in chapter 6. Then, in chapter 7 literature about optimal allocation of flexibility providers of the energy system is identified. Particularly, literature about combining flexibility options to obtain synergies, particularly relevant techno-economic models concerning operational flexibility allocation are reviewed. Finally, chapter 8 concludes this document.

3 Flexibility sources

Different technologies may be used to provide flexibility services in the power system. In the following, different sources of operational flexibility are briefly discussed.

3.1 Generation

The generation side of the energy system comprises elements that are able to inject power into the system. This generation may be either fully dispatchable, e.g. conventional power plants, or its availability may depend on some time-variable input energy flow such as solar energy. A higher amount of installed capacity increases both long-term flexibility and total energy system cost. Concerning operational flexibility, availability, power output ramping and start-up times are important metrics for the technologies that have to be assessed when considering participation in different short-term markets for energy and ancillary services (Oree & Sayed Hassen, 2016). Besides active power, some generation units may provide reactive power, voltage regulation or inertia during normal operation and further services in regular system states (cf. section 4).

3.2 Load

Load may provide flexibility on the demand side. First, temporal shifting of already present-day demand may contribute to better balancing of supply and demand. Second, additional flexible demand – or replacement of old inflexible demand – could be incentivized and this may alter power consumption patterns. For example, fostering the use of electric vehicles or electric heating, grid usage during nighttime would change (Grunewald & Diakonova, 2018). Besides such use cases of market-based demand response, where market participants decide about load shifting themselves, reliability-based demand response allows system operators to interrupt load during critical grid operation modes (Jabir et al., 2018).

3.3 Storage

Electricity cannot be directly stored as such. Yet, conversion back and forth to other forms of energy allows to separate production and consumption in time. Available technologies use different energy forms as buffer: potential (as for example pumped hydro), kinetic (fly wheel), thermal (high temperature storage), electrical (super cap), electrochemical (lithium-ion) or chemical (power-to-gas) energy. The use of super-conducting materials as energy storage is researched. Limiting factors for energy storage are space and weight, given the characteristic energy densities of the materials used. One drawback of storage technologies in general is that converting energy from one form to another induces energy losses. Besides losses directly linked to energy conversion which induce a limited round-trip-efficiency, self-discharging processes induce further losses over time for some technologies (Nadeem et al., 2019).

3.4 Grid

The electricity grid and its operation also may be regarded as source of flexibility. In the high voltage power grid, active elements, such as high voltage direct current (HVDC) converter stations or phase-shifting transformers support increased transmission line usage in case of parallel lines. Flexible alternating current transmission systems (FACTS) may moreover provide reactive power. Besides the deployment of active network assets, switching of circuit breakers impacts the grid topology. In this way, power flows through transmission lines can be governed to some extent. In low voltage grids, tap changing transformers may facilitate more power injection, particularly responding to different states of local power injection. Still, observability in distribution grids – in comparison to transmission grids – is reduced, as the system state was mostly defined by the transmission system interaction. Increased decentralized power injection raises uncertainty and thus requires more network state estimation. Research in this field is ongoing (Dehghanpour et al., 2019). Accurate knowledge about the system state of the distribution grid enables the system operator to change the operating point such that power flow limits can be ensured while power transmission is optimized (Prettico et al., 2019).

4 Flexibility usages

Operational flexibility can be used differently in the power systems. First, it can be used e.g. to obtain arbitrage profits on different markets or to optimize in-house energy use. Second, the decrease in conventional power plant capacities requires new sourcing and remuneration mechanisms for some system services. E.g. for the German power market, regulation changes have been recommended such that a larger variety of technologies can be contracted for ancillary services (dena, 2014). Different system states have been framed that allow more flexible actions by TSOs if the system operation is in danger. Exemplary system states and possible transitions between them are illustrated in Figure 1.

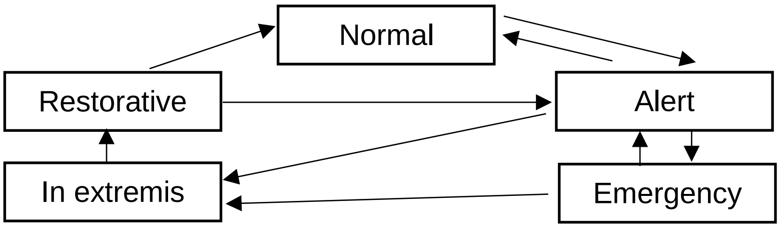


Figure 1: Power system operation states (Kundur, 1994)

Keeping these general system states in mind, during the normal system state the energy market and different system services are designed to keep the system within the normal state. However, acknowledging technical definitions, in this work we classify the demand for flexibility as partially required on a continuous basis and other capabilities that solely are kept available if contingencies arise.

4.1 Flexibility required during regular operation

Given our definition of flexibility as capability of units to change its behavior close to real-time to deliver a certain service, as well as continuous demand, the energy market and some system services (i.e. the present definition of ancillary services) fall into this category. System services ensuring grid operation may be distinguished into frequency related and non-frequency related services, whereas the first category requires local frequency measurements to deduce its magnitude of reaction and the others do not.

4.1.1 Energy market (A)

Active power and energy products can be traded on different market platforms or bilaterally. Intraday products for active power provision can be as short as 15 minutes and gate closure may be only five minutes before delivery, as observed in Germany respectively Belgium (European Commission, 2016).

4.1.2 Frequency related system services (B1)

The set of frequency related system services and their definitions differed between coordination areas, countries or control areas (Pirbazari, 2010). Yet with the Network Codes that were drafted by the ENTSO-E and enacted by the European Commission, substantial harmonization has been achieved at least within the EU and neighboring countries. Therefore, here we refer to these codes if applicable. Further information about ancillary service standardization and country specific differences can be found in the deliverable WP 8.6.

Frequency Containment Reserve (FCR)

This system service is legally defined as “active power reserves available to contain system frequency after the occurrence of an imbalance” (Guideline on Electricity Transmission System Operation, 2017, Art. 3). Frequency deviations due to abrupt power injection or load changes are handled by all TSO in a synchronous grid area jointly via FCR. Currently, FCR is the fastest reserve service that is based on frequency measurement. The system operation guideline states publication requirements and responsibilities concerning FCR. Also, the size of the reference incident and the share in overall FCR to be provided by each member country is addressed. Moreover, mandatory technical requirements for TSOs are listed in the document. Furthermore, a prequalification process for market participants is requested, and provision standards are addressed in art. 153ff, such as the maximum activation time of 30 seconds depending on the frequency change (Guideline on Electricity Transmission System Operation, 2017). Specific conditions about the balancing product are specified in in the Electricity Balancing Guideline (Guideline on Electricity Balancing, 2017). Art. 18ff lists how balancing service providers should define their preconditions for balancing providers and standards are introduced, which the procurement processes need to fulfill. Art. 25 lists recommendations on requirements for standard balancing products and art. 28 refers to fall-back procedures. The TSOs rejected the proposition of transnational FCR procurement, as initially stated in the Electricity Balancing Guideline (EB GL) (ENTSO-E, 2018b). Yet, in Austria, Belgium, France, Germany the Netherlands, and Switzerland a common market got implemented. Here, the FCR product is symmetric, its procurement is performed in blocks of four hours (ENTSO-E, 2018e). The restricted participation of renewable energy sources for FCR is criticized (Sanduleac et al., 2017). The benefits of a new system service, fast frequency response (FFR), that must be ready within a short activation time (e.g. 500ms that are needed for frequency change detection) is discussed (Meng et al., 2020).

Automatic Frequency Restoration Reserve (aFRR)

After the frequency deviation is detected and initially mitigated with FCR, the aFRR serves to replace missing generation or demand within the same load frequency control (LFC) areas where the imbalance occurred. Often one LFC area consists of a single European country, but multiple TSOs can be in one LFC area. One or more LFC areas – which each are responsible for the LFC process within their geographical scope – jointly form a LFC block. This block defines the geographical scope for which reserves have to be dimensioned. Power imbalances between two LFC areas cause the corresponding area control errors (ACE) to be nonzero. It is the task of the aFRR to shift the balancing error back into its original region. Technical principles for aFRR are defined on an European level (Guideline on Electricity Transmission System Operation, 2017, Art 157ff) yet market designs vary in each member country. As requested by regulation, the ENTSO-E published a proposal on how to implement the aFRR balance energy exchange market. This proposal is called PICASSO (Platform for the International Coordination of the Automatic frequency restoration process and Stable System Operation). PICASSO enables TSO-TSO interaction to transport balancing energy to LFC areas where the ACE is located. The platform is cleared by a common merit order list, considering cross-zonal capacity (ENTSO-E, 2018c). Minimum standardization requirements are stated in art. 24 (Guideline on Electricity Balancing, 2017). Full activation time shall be five minutes, the minimum quantity is set to one minute, the product duration is 15 minutes (ENTSO-E, 2018c).

Manual Frequency Restoration Reserve (mFRR)

In a similar fashion, the mFRR service activates reserve power in the bidding zone, where an energy imbalance occurred. Its slower activation phase allows further technologies to participate in balancing markets. Similar to the aFRR ancillary service, TSOs are pushed by European regulation to establish cross-zonal markets for mFRR provision. The corresponding project is called MARI (Manual Activated Reserves Initiative). Activation time is set to 12.5 minutes, the minimum quantity is one Megawatt and the least delivery period is set to five minutes (ENTSO-E, 2018a).

Replacement Reserve (RR)

Finally, the RR can be called to replace the previous activated reserves. Its activation time is defined as 30 minutes, while its duration range is at least 15 minutes (ENTSO-E, 2018d). This allows even slower technologies to offer capacity for reserve. Not all TSOs in Europe apply RR. In this case, planning and procurement of sufficient reserves is done only with FCR, aFRR and mFRR. The TERRE project aims at implementing a common European platform, called LIBRA, to acquire the planned amount of RR. Project members are the countries where RR is in use: Czech Republic, France, Great Britain, Italy, Poland, Portugal, Spain and Switzerland.

4.1.3 Non-frequency related system services (B2)

The system services of this category may be activated without frequency measurement. They react instantly inherently, given their physical characteristics or control properties.

Inherent inertia

Most conventional generation units in the power system provide inherent inertia through their rotating generator shaft and thus dampen frequency changes when the power balance in the energy system is not intact. This delayed frequency response provides sufficient time to actively diminish power imbalances. In a network with an high share of inverter-based technologies, the network frequency will behave more volatile. One potential solution could be the release of “virtual inertia” by fast-reacting inverter technologies within few milliseconds. However, the instant shift of the inverter operating point based on external currents makes the inverter very vulnerable, since it blindly follows grid conditions that may lead to over-currents within the inverter (Tamrakar et al., 2017).

Synchronizing Power

Generation units that exhibit synchronizing power inherently attain to synchronize with the network, particularly after connecting them to the grid during their synchronizing process. System stability depends on the existence of both synchronizing and damping torque for the synchronous machines. If not provided sufficiently, oscillatory instability occurs (Mondal et al., 2014). Besides intended synchronization of generation units turned on and off, sufficient synchronizing power needs to be provided by the grid from its generation units to respond to faults that include phase jumps.

4.1.4 Grid operation (C)

The Guideline on electricity transmission system operation (Guideline on Electricity Transmission System Operation, 2017) fosters harmonization in operation processes performed by the European TSOs. According to Part II of the guideline, tasks for TSOs are voltage control, reactive power management, short circuit current management, power flow management (congestion management through remedial actions), contingency analysis and protection. In regular system operation, external stakeholders may deliver flexibility in terms of voltage control or congestion mitigation. Grid operation during alert or emergency mode requires topological actions (switching), altered HVDC-link schedules or remedial actions (intended load interruption).

Voltage control

Steady state voltage control is necessary to keep the voltage level within its limits at all locations in the network. Overvoltage results in equipment failure and low voltage may induce overcurrents in the grid. Control action can be applied on generators or HVDC systems to inject reactive power to boost or lessen the voltage. Furthermore, tab change transformers can directly change the voltage between their primary and secondary side. Depending on the network operating point, grid elements require certain amounts of inductive or reactive power. Ideally, this local reactive power demand is served by reactive power provision through generation or compensation units nearby. The latter units are referred to as Flexible AC Transmission Systems (FACTS). If voltage control is inaccurate, fast increasing load would trigger voltage collapse within the power grid.

Congestion management

Network operators have to ensure system functionality; thus they have to apply measures if power injection and power withdrawal would result in overloaded system equipment. In zonal market clearing mechanisms, after economic dispatch, physical redispatch is triggered when necessary. Possible measures to alter the utilization of different network elements are either transmission capacity related, e.g. turning power switches to (de)activate lines or changing phase shift transformer taps. Other measures are congestion alleviation measures, e.g. reducing or shifting power injection at different busbars (Androcec & Wangensteen, 2006).

4.2 Flexibility required to mitigate contingencies

Another set of system services needs to be provided at all times, yet they will be only called after a contingency event in the electrical energy system. This distinction is proposed, as these services and/or capabilities are rather characterized by a particular level of provision and demand.

Island mode capability

This capability refers to the ability of an electricity generator to participate of an electrical island. At present time, active splitting up the coordinated grid does not occur during normal operation. In abnormal system states, such as locally measured low voltage or short circuiting of the grid side, generators separate themselves for protection if they are pushed into operations points exceeding their limits (Bian et al., 2020). Generator backup protection relays are implemented with delay, such that the primary fault protection within the transmission system may detect and mitigate the disturbance first (see also Fault ride through capability). Furthermore, abnormal operating conditions increase stress on generators (Patel et al., 2004). From a technical perspective, islanding requires grid forming. That is, eaFEB GLch separated region needs units that keep frequency, voltage through power balancing within their accepted ranges (cf. section 4.1.3). The reduced availability of synchronous machines during e.g. system split events challenges frequency mitigation. Today, no intended islanding is performed. New control and communication strategies are researched for low-inertia or even inertia-free micro systems (Espina et al., 2020).

Fault current contribution

Detection of faults in the electric power grid is essential. If faults occur, they need to be localized such that the defective grid element can be shut off selectively. Therefore, energy sources have to continue their power injection for a short time, even if local voltage and current measurements refer to an irregular grid operating point. In contrast to synchronous generators that inherently provide higher current in fault situations, inverter-based energy sources have rather limited fault current levels (Masaud & Mistry, 2016). Therefore, in the past inverter-based technologies were not of scope for fault current provision. However, with an increasing share of inverter-based technology in the power generation portfolio, these current sources are in need to participate in fault detection, as well as local voltage stabilization in fault mode. Applying adequate software, inverter-based technologies can be used as fault current contributors. However, in comparison to synchronous generators, fault current is much less and the response time is longer. Fault detection and its isolation may not trigger (Hodge et al., 2020). Deploying an alternate grid protection design is hindered by the high amount of infrastructure that is already in use.

Fault ride through capability

This behavior, also known as low voltage ride through, counteracts against shut-off cascades when faults occur. Other than decoupling from the grid, generators have to remain connected to the grid for a short time, even if the voltage is unusually low. All Type B power-generating units (connection point 110 Kilovolt or below, capacity of one Megawatt or below) need to provide a fault-ride-through profile as seen in Figure 2. Generators are only allowed to disconnect from the grid if the network voltage enters the area below the characteristic. The fault ride through mechanism ensures that generation units do not disconnect instantaneously but remain online throughout the time automatic fault detection, mitigation (and isolation) actions are executed.

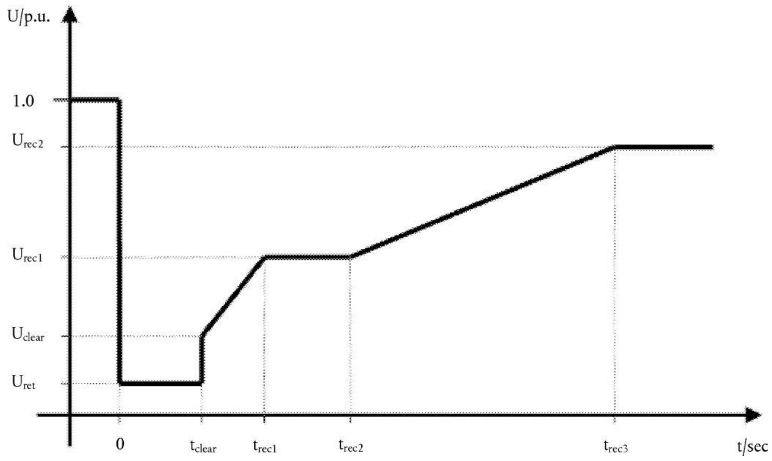


Figure 2: Fault ride through characteristic
(Network Code on Requirements for Grid Connection of Generators, 2016)

Black start capability

This service is activated when the power system is deenergized. In such a situation, power plants which can start by themselves without external power are required. Even though this service is used extremely seldom, it needs to be hold available permanently. TSOs are required to design and keep up system restoration plans, which contain information about re-energization, frequency control and resynchronization (Network Code on Electricity Emergency and Restoration, 2017). The restoration plan has to be executed if the grid is in the emergency state according to the system operation guidelines (Guideline on Electricity Transmission System Operation, 2017). When updating their restoration plan, the TSOs must consider the different availability of re-energization sources, the duration of re-energization time, the power system condition, and the system condition of neighboring TSOs. Top-down, bottom-up approaches or a combination of both may be used. The provision of enough black start capability in the restoration plan has to be managed economically efficient. Currently, TSOs implement their restoration plan in different manners, e.g. applying distinct remuneration strategies, forced or contracted participation, or use different technologies (ENTSO-E, 2017).

5 Matching flexibility providers and usage

In order to identify potential multi-service usage cases for novel flexibility providers, the possibilities to provide the various system services using the different flexibility sources are summarized in Table 1. Distinction between balancing (A), frequency-related services (B), non-frequency-related services (C) is made for normal model. The circle filling indicates the market readiness of the combination. Differentiation is made between research (1/4), prototypes (2/4), some applications (3/4) and mature technology (4/4).

Generation units can be used for economic dispatch, ancillary services – both frequency related, and non-frequency related – as well as ancillary services in abnormal system states. Apart from conventional generation, renewable generation units, e.g. wind turbines can make use of their distributed nature to provide of ancillary services with locally high impact (Debouza & Al-Durra, 2019). Prototypes for Hydrogen fuel cells exist, but hydrogen production and use is relatively expensive compared to current fossil fuel prices (Abdalla et al., 2018).

Load units can generally be used for ancillary services in normal system states. The shift of consumption or substitutes, such as alternative fuels instead of power-to-gas (P2G), may support flexibility both for dispatch and reserve markets. Likewise, shifted load can relieve congestions locally. However, whenever active power injection is required, load is not suitable as flexibility provider.

The different types of energy storage can participate in energy markets and are technically capable to provide ancillary services in normal and other system states. Depending on their physical properties, different amounts of energy, respectively power, are installed per unit. The technologies do not always satisfy today’s capacity requirements to participate in ancillary service markets.

Flexibility in system operation is de jure only capable to provide non-frequency related system services. Given the unbundling regulations in place, devices owned and operated by grid operators may not participate in markets. Many technologies of the types mentioned above are technically able to provide non-frequency ancillary services. Yet, the non-frequency ancillary service providers are usually selected in a central fashion by the TSO itself, where system operation elements are core elements, and some flexibility is procured externally.

Table 1: Flexibility providers and services to be served

Legend:
◔ research
◑ prototypes
◕ some applications
● in regular use

		Continuous demand during regular operation								Provision for contingencies			
		(A)	(B1) Freq. rel. Services			(B2)		(C) Grid operation					
		economic dispatch	FCR	aFRR	mFRR	Inherent inertia	Synchronizing power	Voltage control	Congestion management	Island mode capability	Fault current contribution	Fault ride through	Black start capability
Generation	Variable RES: PV, Wind, ROR	●	◑	◕	◕		●	◑	●			●	
	Dispatchable RES: Hydro reservoir, Biomass	●		●	●	●	●	●	●	●	●	●	●
	Conventional power plants	●		●	●	●	●	●	●	●	●	●	●
	H_2-to-power (Single units)	●		◑	◑		◑	◑	◑			◑	◑
	H_2-to-power (Virtual cluster)	●	◔	◔	◔		◔	◔	◔			◔	
Load	planned shifting	●	◕	◕	◕			◑	●				
	P2G, P2H, EV (Virtual cluster)	●	◕	◕	◕			◑	◔				
Storage	Potential: Pumped Hydro	●	◕	◕	●	●	●	●	●	●	●	●	●
	Potential: Compressed air	●	◕	◕	●	●	●	●	●	●	●	●	●
	Chemical: Battery plant, V2G	●	◕	◕	◕		◑	◑	◑			◑	
	Electrical: Supercap, SMES		◑	◑	◔		◔					◑	
	Kinetic: Flywheel			●		●					●	●	
Grid devices	Tap changer							●					
	Switching lines							●	●				
	FACTS, StatCom, MSC					●		●	●				
	Phase shift transformer							●	●				
	Dyn. Line Rating, TATL								●				
	HVDC links					◔	◔	◑	●		◑		

Source: own assessment

6 Demand for Flexibility

The demand volume for flexibility is driven by different factors. Frequency related ancillary service demand is set by reference incidents. The European wide reference for FCR is 3000 MW, shared among the TSOs according to the sum of their net generation and consumption (Network code on system operation, 2017, Art. 153). Minimal requirements on dimensioning rules for FRR and RR are stated in Art. 157 and 160. The contracted volume is decided by the TSOs themselves. Uncertainty, power system size, generation characteristics, consumption characteristics, transmission capacity and market structures are relevant dimensioning parameters (Akrami et al., 2019; van der Veen & Hakvoort, 2016). TSO procurement preferences for frequency ancillary services vary. National markets have not offered procurements options for all frequency related ancillary services in the past, as some are optional (Merina et al., 2016). Table 2 shows the different volumes of contracted frequency-related services of some countries in Europe. TSO collaboration aims at establishing harmonized procurement markets in larger parts of Europe to increase technological participation (cf. section 4.1.2).

Table 2: Average volumes of contracted ancillary services in MW, 2019

Country	FCR ↗&↘	aFRR↗	aFRR↘	mFRR↗	mFRR↘	RR↗	RR↘
AT	64	205	205	80	44	--	--
BE	81	139	139	196	68	--	--
CH	105	337	337	--	--	430	235
DE	620	1811	1811	1254	907	--	--
ES	--	620	620	--	--	--	--
FR	513	646		663	--	135	--
NL	35	385		549	634	--	--
PT	--	178	178	--	--	--	--

Source: (ENTSO-E, 2020)

Apart from frequency-related ancillary services, where markets are established, auction-based procurement markets are rare and corresponding data on market volumes is hardly publicly available. Contents of the individual contracts between the TSOs and flexibility providers are usually not public and can only be roughly estimated. Using the current demand as reference, research about future ancillary service needs to be with high-level trends of the energy system. Until 2030, the following future developments are expected for Germany (dena, 2014), yet the general trends are also valid for most other European countries:

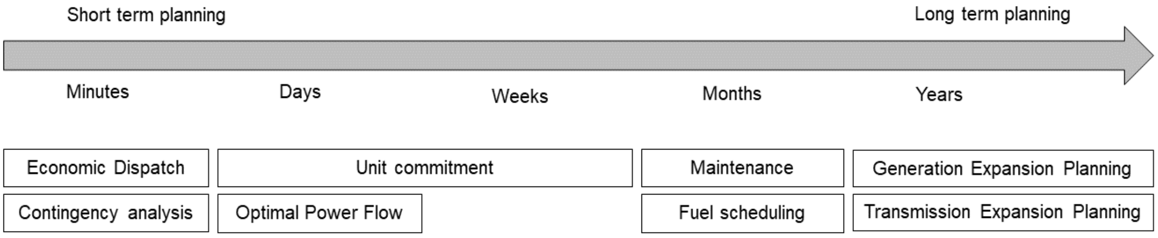
- Contracted capacity for frequency-related ancillary services will increase, as the high share of renewable infeed in the energy system implies higher forecast uncertainties which are only partly compensated by higher forecast accuracy.
- Voltage control on transmission grid level requires changes, as renewable energy sources mostly are located at the distribution grid level without voltage controllability. The required local amount for voltage control, respectively reactive power depends on

the geographic location of the power plants. Long-distance power transport over AC lines will require more reactive power in future.

- Fault current contribution from conventional power plants will decrease due to the change in the power plant portfolio towards inverter-based technologies. However, this reduction will be overcompensated by grid extension. Meshed networks reduce reactance and thus higher currents will flow during fault events.
- Black start capability: No major changes in volume are expected in the future, but increased communication will be necessary if decentral concepts are applied.

7 Technology-to-usage allocation modelling

Planning in the power sector uses analysis tools for different time horizons. Models applied in research look forward several decades to evaluate climate mitigation scenarios whereas industrial power system planning often covers time horizons up to ten years. Operational tools focus on power plant and network operation for intraday and day-ahead planning, with time ranges from minutes to weeks, and technical network studies concerning system transients provide analyses in the range of milliseconds (Seifi & Sepasian, 2011). The different model types are illustrated in Figure 3.



Source: **(Lin et al., 2018)**

Figure 3: Power system optimization models

The models differ in geographical and temporal scope and thus also in their level of detail. Long-term generation and transmission extension models (often abbreviated as GTEP) estimate endogenously the optimal future power plant portfolio. Only models of rather small scope include more technology-oriented constraints and binary decision variables This is typically the case in unit commitment models (UC), as the planning horizon is thereby typically only a few days. However, when short computation time is required, e.g. for repetitive very short-term economic dispatch modelling (ED), binary decisions are again omitted. The model types mentioned above are often used separately, model detailedness and computational effort must be in a reasonable relation. However, the use of such decoupled models may lead to oversight and misplaced concern among policy makers (IRENA, 2017). Combined use of different model types may help to indicate new synergies between different flexibility options. Yet, the context and scope of each model must be considered.

Furthermore, two major trends have to be reflected in future models: digitization and sector coupling. Digitalization allows enhanced information sharing within the energy industry. With sector coupling heat and mobility are getting more and more served by the electrical energy system. Furthermore, automatization makes processes easier, e.g., short-term trading. This all results in more stakeholders who can make use of flexibility potentials to increase the system's efficiency, yet this increases the models' size.

Considering the basic market structures as set in Europe, modeling market clearing and dispatch is a two-step process. Energy markets in the United States are organized in a centralized market fashion, where generator status and network limitations are considered during the market clearing process. Likewise, ancillary services, balancing and reserve markets are all allocated through a co-optimization, ensuring that the resulting market result lays within the allowed technical system states, still models for these types of markets are computationally challenging. In contrast, in Europe different markets for different flexibility usages are implemented. This fosters competition through transparent processes on energy and reserve markets where bidding is unrelated to technical aspects. Still, system constraints must be ensured afterwards. This leads to rescheduling if market results turn out technically infeasible, particularly due to missing transmission capacity. Models that clear parallel markets are found to yield in higher costs than co-optimization (Krishnan et al., 2016).

The increasing share of renewable generation and its decentral characteristics yet ask for both an adaptation of market mechanisms and the establishment of enhanced modelling and planning approaches. Subsequently, major existing modelling approaches are discussed. Especially, to what extent they depict different flexibility services and they model the allocation of technologies to services. This knowledge is relevant for enhanced research on multiple service modelling to determine promising flexibility synergies within the OSMOSE project.

7.1 Pure energy-market balancing approaches

Long-term scientific models designed for identifying optimal capacity mixes in the future European Energy system often only consider energy-market balancing, such as the models Perseus (Rosen, 2008), ELMOD (Leuthold et al., 2012), REMix (Scholz, 2012), and PowerACE[3] (Bublitz et al., 2014). These investment models use few time steps, include intertemporal capacity extension constraints and assume exogeneous fuel prices for the future years to estimate the efficient future power plant portfolio.

7.2 Frequency related ancillary services

The way, frequency related ancillary services are represented, varies depending on the model types mentioned in Figure 3. Besides models with a perspective of central market clearing, including UC and ED models for North American markets, optimization models for business case identification have been developed that search for optimal energy and ancillary service bidding strategies.

Some of the long-term economic models only account for generation capacity adequacy though generalized reserve provision. For example, ELTRAMOD (Ladwig, 2018) and PowerFlex (Koch et al., 2017) include minimum reserve capacities as a constraint. Other long-term models including E2M2s (Swider & Weber, 2007), E2M2 (Sun, 2013), and DIETER (Zerrahn & Schill, 2015) depict the provision of different frequency related ancillary services in European energy systems, partly in a simplified manner. Sufficient spinning and standing reserves need to be provided to ensure a reliable operation of the energy system from a central planner perspective. Other models rather focus on market mechanisms and market outcomes. These models depict market clearing processes, while assuming given exogeneous power plant capacities for a certain future time interval. The JMM (Meibom, 2006) covers primary and secondary reserve in the day-ahead and intraday electricity market for one year. Also, PowerACE[4] (Renz et al., 2014) includes reserve market modelling. Other market models facilitate research concerning strategic behavior. However, serving different markets with different gate closure times – as currently implemented in Europe – requires multiple optimization calls in a rolling

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[3] Initial model publication

[4] Publication after model improvements

planning fashion. Another stream of research specifically investigates co-optimization of energy and reserve provision and emphasizes that it increases economic efficiency and system synergies (Read, 2010). Such market designs are established in North America. They often consider reserve requirements notably through ramping constraints and ramping products in their energy market clearing optimization (Q. Wang & Hodge, 2017). Generally, efficiency of such set-ups is higher, yet the high computational requirements make it difficult to offer very short-term products of few minutes and the short time between market clearing and delivery may cause operational issues.

Business strategies of flexible power generation units – from an individual market participant perspective – serving different markets are modelled e.g. for virtual power plants or storage systems (H. Wang et al., 2020). The provision of frequency ancillary services from comparably small units is often treated in literature about smart grids (Behrangrad, 2015). Yet, local techno-economic models representing markets on distribution grid level currently do not seem viable due to the passive power flow management of distribution grids, but this might change in the future (Eid et al., 2016). A model that builds on discrete power plant operating modes to be active on both energy and reserve markets is currently developed by the Universität Duisburg-Essen.

With the increased penetration of inverter-based technologies, new ancillary services related to frequency are discussed, notably grid forming. Research has focused so far on how grid forming abilities could be integrated efficiently in today’s network structures. Control theory has been applied to assess the interaction of grid-forming as well as grid-following inverters in the grid. Suitable parameter settings and adequate placement of inverter-based technologies allow to enable virtual inertia for low inertia systems (Poolla et al., 2019). Implementing inverter-based generation technologies on the transmission grid level induces increased stress on equipment, but grid forming using inverter-based technologies is currently actively researched (Denis et al., 2018). Likewise, multi-service provision of grid forming and other ancillary services is researched. In case of island operation and system splitting, each part of the network needs at least one grid forming unit as prerequisite. Even though today’s regulation does not support intended island operation, its application is discussed in literature (cf. section 7.4.1). However, the interaction of intended islanding and other ancillary services both in operation and planning has not been further addressed yet.

7.3 Non-Frequency related ancillary services

Power flows in the transmission grid are dependent on the operating state of the network, notably the power input and output at the grid nodes, as well as the network topology, represented by information about the on- or off-state of network elements (Cetinay et al., 2018). Power flow equations are nonlinear. Their solution can be found numerically with the Newton-Raphson method. However, convergence is not guaranteed and computational effort is high (Bergen & Vittal, 2000). Approximations of the power flow equations, particularly the DC power flow which abstracts from voltages and reactive power flows, make linear optimization possible and are widely used in research and operation (Stott et al., 2009). Optimization for non-frequency related ancillary services is generally done from a central planner perspective and features such as stochasticity may be included (Gomez-Exposito et al., 2017). In contrast to economic dispatch, often only few time steps are considered.

7.3.1 Voltage control

Static voltage control can be primarily achieved by tap changers of generator units or network transformers. The voltage level at different positions of the grid is also influenced by the reactive power consumption of loads, generators, or network elements. For example, augmented amounts of variable distributed generation alter reactive power injections at specific locations in the grid and consequently shifted power flows influence the reactive characteristics of the lines as well (Sarkar et al., 2018). A mismatched reactive power balance results in unsafe voltage elevation or drops. Given the complex interrelation of active and reactive power, non-linear optimization techniques are required. A convex optimization model formulation including reactive power is published by Lavaei & Low (2012). Assessing voltage control with mathematical optimization may identify new means to enhance grid operation, as trade-offs between real and reactive power can be identified. However, applications of such optimization are only found partially in industry (Elizondo et al., 2017). Much research applying meta-heuristic optimization has focused on planning and placement of static VAR compensators (Shaheen et al., 2018) and optimal dispatch (Mohseni-Bonab & Rabiee, 2017). In the absence of established market frameworks, no models considering reactive power markets are implemented so far (Anaya & Pollitt, 2020).

7.3.2 Congestion management

In a zonal price system, congestion management is used to ensure system security. Similarly to voltage control, a holistic optimization approach depicting reactive power flows is necessary and thus synergies between voltage control and congestion management are expected. Models that include switching operations and the subsequent altered utilization of grid components already exist (Yusoff et al., 2017). A major challenge of such combinatorial models is their computational complexity (Korad & Hedman, 2016). Still, in energy systems with high shares of renewable energy sources, total system cost can be reduced through topology changes (Little et al., 2021). Further topics of interest for congestion management in the future grid are going to be HVDC lines. These assets increase operational flexibility through power flow dispatching possibilities in normal system state, as well as in fault state, where curative measures (post-fault switching in combination with additional storage units) can be applied (Hoffrichter et al., 2019). HVDC dispatch strategies have been developed both with technical (Marten et al., 2015), as well as economic focus (Castro et al., 2020).

7.4 Grid operation in abnormal system state

Some literature and optimization models about sufficient ancillary service provision in abnormal system states exist (Harish Kiran et al., 2016; Liu et al., 2016; Richard et al., 2020; Yusoff et al., 2017). However, these optimization models do not offer long-term economic insights. Instead, they focus on how assets need to be dimensioned to handle these system states. Optimization of both normal state and abnormal state does not seem promising, as the system states do not occur at the same time and due to its rare occurrence, participation in abnormal system state ancillary service provision will not be economically beneficial.

7.4.1 Island Mode capability

In a broader context as disconnecting generators for safety reasons, intended islanding based on information exchange is assessed for augmented grid resilience. In such applications, island mode capability is not only triggered by generators themselves for safety reasons, but wider parts of the grid, such as micro grids (Jufri et al., 2019). Intended islanding decision making requires global information about the network state. Intended splitting could be deployed within the transmission grid (Mureddu et al., 2016) or at the boundary to the attached distribution grids (Mahat et al., 2011). Literature focuses mainly on micro grid applications (A. Rahman et al., 2015). Intended system splitting on the transmission system level causes implementation challenges (Braun et al., 2020). However on both grid levels, a major challenge for intended islanding is safe and reliable communication between the network assets to proactively change the grid operating points (Braun et al., 2020).

7.4.2 Fault current contribution

As fault current contribution of renewable energy sources is lower, adequate allocation mechanisms are necessary to meet today's system demand. Synchronous condensers on transmission level would be an option to free energy within a short period of time. An optimization model formulation minimizes investment costs for such a system (Marrazi et al., 2018). However, as power injection shifts from high-voltage levels to low-voltage levels, the locality of generation is important. Approaches are developed to integrate fault level constraints in optimal power flow studies. Optimization models with non-linear (Vovos & Bialek, 2005) and linear constraints (Rueda-Medina et al., 2013) exist, however they have topological limitations. Short-circuit limiters have to be put in place if limits would be exceeded due to increased distributed generation or increased use of transmission lines (Sharma & Sahay, 2016). A co-optimization model is elaborated to assess unit commitment decisions while satisfying acceptable fault current levels (Lin et al., 2019)

7.4.3 Fault ride through

Fault ride through of decentral generators was initially not considered relevant, yet nowadays it is listed as generator requirement in the grid code. No literature about sufficient provision, respective required volumes could be identified. Different network topologies and characteristics imply different voltage responses to faults, therefore time constants and voltage levels of the fault ride through characteristic differ between TSOs (Hagh & Khalili, 2019).

7.4.4 Black start capability

From a system security point of view, black start capability cannot be combined with other service provision, as the generator units and their fuel need to be hold ready and thus redundancy is recommended (Esmaili et al., 2019). However, there is literature available about how optimal re-energization of the power system may look like. Different scientific models and restoration planning designs can be identified. Some consider sequential energizing of the network (Chakrabarty et al., 2020). Top-down restoration plans need to be flexible and simple, such that also partial blackouts can be handled adequately, bottom-up approaches could be an alternative (Henderson et al., 2012). Black start studies require technical detailedness, such that static and dynamic operation constraints are maintained (Feltes & Grande-Moran, 2008). Depicting switching events and nonlinear physical characteristics increases the model complexity. Ancillary service synergies concerning optimal placement of black start units can be identified, when considering intended islanding as grid resilience improvement (Patsakis et al., 2019).

8 Conclusion

This deliverable discusses the role and provision of flexibility within electrical systems in which renewable energy sources replace fossil fuel power generation. Literature about energy system flexibility contains research in many different dimensions, e.g. temporal or responsibility related. Possible origins of increased operational flexibility of the future power system could be altered generation, modified load patterns, increased storage utilization and new manners of grid operation. The Guideline on Electricity Transmission System Operation and the Guideline on Electricity Balancing, passed by the European commission, aim at harmonizing the member states' ancillary service procurement processes towards common energy and ancillary service markets. Likewise, grid operation with increased international cooperation is fostered, yet operational decision making remains locally organized. Besides, in Europe, energy market participation and ancillary service provision are handled separately in sequential processes. This is different from regions like North America where energy and reserve products are cleared simultaneously in the same market clearing processes.

The broad scope of the concept of flexibility and the generally accepted use of the word as umbrella term is one reason for a very wide range of modelling approaches. So far, different techno-economic models to match system flexibility provision to different usage applications have been developed. To detect promising flexibility allocations, in the long-term scope, both investment models and market models have been applied and provide insights for future system planning and operation. Whereas some models include stylized reserve requirements besides energy markets, others use more detailed co-optimizing market clearing approaches to depict various types of frequency-related ancillary services. In areas where market-based procurement is absent, e.g. non-frequency related ancillary services, research assesses the technical feasibility of alternate ways of system operation. This is equally true for system operation in abnormal system states. The identified models have evolved over time, getting more detailed and sophisticated. Increasing computational performance allows more holistic modelling approaches.

Energy policy will shift the value of short-term flexibility both in the energy and ancillary service markets. The increasing share of renewable technologies requires them to participate more in ancillary services in future. The EU and national governments search suitable manners to integrate them by adapting relevant rules. For this to take place, research in this field is necessary to identify suitable solutions and synergies between different flexibility services. This is equally important for both: the global perspective focusing on market designs, as well as the market-participant perspective to identify new business cases or bidding strategies. In this context, a model representing an aggregated power system and its economic operation concerning energy and balancing services is currently developed in the context of WP 1.5. It illustrates the shift in provision of energy and ancillary services with increasing shares of renewable energy.

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