MARKET ENABLING INTERFACE TO UNLOCK FLEXIBILITY SOLUTIONS FOR COST-EFFECTIVE MANAGEMENT OF SMARTER DISTRIBUTION GRIDS

Deliverable: D3.1

Flexibility Toolbox

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Abbreviations

ADMS	Advanced Distribution Management System
BRP	Balanced Responsible Party
CAES	Compressed Air Energy Storage
CSP	Concentrating Solar Power
DSO	Distribution System Operators
ECs	Electrochemical Capacitors
EDLC	Electro Chemical Double Layer Capacitor
EVs	Electric Vehicles
FQD	Fuel Quality Directive
FSP	Flexibility Service Provider
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
HGS	Hydraulic Gravity Storages
HTF	Heat Transfer Fluid
IoT	Internet of things
LAES	Liquid Air Energy Storage
LCOS	Levelized Cost of Storage
LHS	Latent Heat Storage
MPPT	Maximum Power Point Tracking
MV&LV	Medium Voltage and Low Voltage
OHL	Over Head Lines
OLTCs	On Lead Tap Changers
P2H2P	Power-to-Heat-to-Power
PDA	Personal Digital Assistant

PHS	Pumped Hydro Storage
PMC	Phase-change Material
PV	Photovoltaic
R&D	Research and Development
RED	Renewable Energy Directive
RES	Renewable Energy Source
RTE	Round Trip Efficiency
SHS	Sensible Heat Thermal Storage
SOC	State of Change
SOH	State of Health
TCS	Thermochemical Storage
TES	Thermal Energy Storage
TRL	Technology Readiness Levels
TSO	Transport System Operators
UMEI	Universal Market Enabling Interface
UPS	Uninterruptible Power Supply
VRFBs	Vanadium Red-Ox Flow Batteries

Executive Summary

Energy related emissions account for almost 80% of the EU's total greenhouse gas emissions. The energy challenge is therefore one of the greatest tests which Europe has to face. Transforming the energy system towards a sustainable, net-zero and climate-friendly economy by putting consumers at its centre can increase efficiency of the energy system and strengthen social welfare. To enable this transformation, distribution grids will face new paradigms in the ways they operate by relying more on flexibility and smart-grid functionalities to safely and cost-effectively integrate more variable renewable energy sources (RES). Future complex energy system will require strong and smart flexible resources to adjust new demand profiles to the supply variations in renewable generation.

EUniversal project aims to enable the transformation of the electricity grid by resolving existing limitations in the energy system through the introduction of a universal market enabling interface called UMEI. The concept brings forward a universal, open, adaptable and modular approach to interlink active system management with electricity markets and foster the provision of flexibility services.

This document aims to design a flexibility toolbox by identifying the technologies and solutions most suitable to providing flexibility services to the distribution grid. The goal of this deliverable is to map the most promising technologies providing flexibility services such as energy storage (mechanical, electrochemical, electrical, power-to-heat, power-to-gas); digital solutions and technologies enabling demand response; flexible thermal generation, smart charging and other ancillary services provided by EVs, active power control of RES, etc. The mapped technologies are grouped according to their technical attributes: flexibility at short, medium or long term; installation at customer, distribution and transmission level. As a result, the document provides a toolbox with the main attributes of each technology and systems for different locations and flexibility needs to be identified by the relevant DSOs.

The deliverable 3.1 reports first on the creation of this flexibility toolbox with definition of solution and criteria explaining why these flexibility solutions were chosen. Based on initial literature review, two tables give an overview of the most promising flexibility technologies that will be needed to address the challenges of the energy transition. For each of these technologies, a description of its technical components, maturity, services as well as benefits and drawbacks are provided. Groupings of technologies according to their attributes (service provision- short, medium and long term and deployment location – TSO, DSO) are also included to the tables. This part covers also reasons why certain technologies are excluded from the list.

Following the mapping, limitations and policy recommendations aimed at reducing the barriers to flexibility technologies and services are put forward.

1 Introduction

1.1 Background

Flexibility has always been a key topic for the electricity sector, but it has become critical in order to enable the large scale integration of distributed generation from renewable energy sources. This trend has two major consequences: reduced predictability of the electricity supply, and decentralization of power generation capacity to the distribution network. This causes significant changes in distribution network operation and planning requiring increased flexibility that could be provided within new flexibility market frameworks.

EUniversal focuses on the connection to the market and addresses the paradigm shift in grid operation to effectively overcome the challenges posed by the energy transition in a cost-effective and inclusive way. This is to be done based on the UMEI concept, in which development and implementation relies on Flexibility enabling technologies in addition to Smart Grid Solutions, Flexibility market mechanisms, products and platforms and UMEI itself.

EUniversal proposes to prove the feasibility of flexibility technologies such as energy storage, demand response etc. One of the main outcomes will consist of a DSO toolbox with the main attributes of each solution and its applicability to different use cases, locations and flexibility needs. The DSO toolbox is the first key step to assess the technologies and services that can bring flexibility to the DSO.

A technical-economic assessment of flexibility services for distribution networks will be conducted, considering future grid scenarios of high RES integration. This will be done through different uses cases according to specific technical requirements that, in addition to the "classical" congestion management and voltage support functions, will consider other use cases like investment deferral, voltage unbalance compensation, extended asset lifetime, amongst others. This will allow to develop and to identify the best flexibility services and products.

The current document is focusing on developing flexibility enabling technologies for DSO toolbox.

1.2 Scope and content of the document

The deliverable 3.1 Flexibility Toolbox is the first document to be produced under WP 3 Flexibility solutions. As said, the toolbox is the first key step to assess the flexibility of distributed energy resources technologies for providing grid support. The technologies assessed in this toolbox are grouped according to their technical/technological attributes in order to identify the potential of a technology to solve a problem in a given time and location (flexibility at short, medium or long term, installation at customer, distribution or transmission level). The main attributes of each technology will also be evaluated according to the location and flexibility needs of the DSO, in order to be able to cover all the solutions to be provided at European level.

Following most promising flexibility solutions are taken into consideration:

- ***Energy storage***
    - Mechanical energy storage
    - Thermal energy storage
    - Chemical energy storage
    - Electrical energy storage
    - Electrochemical energy storage
- **Demand-side flexibility**
    - Residential demand response
    - Industrial demand response
    - Smart charging (EVs)

- **Distribution network flexible assets and control (Medium and low voltage control)**
- **Renewable Self Consumption and Microgrids**
- **Dynamic Line Rating (DLR)**
- **Active power control of RES – in example of German Redispatch 2.0 (schedule-based congestion management)**

For each of these technologies, a description of its technical components, technological maturity, power and energy range, discharge and reaction time, current deployment status, owner/developer information, user of technology, applicability in demo site (Portugal, Germany, Poland), cost/effectiveness, services provided, benefits, drawbacks are provided.
Table 1 Grouping of technologies according to their attributes (service provision, short-, medium- and long-term and deployment location – TSO, DSO) are also included to the tables. Icons refer to suitability of the applications: the two values chosen are suitable (green icon) or not suitable (red icon).

Table 1. The structure of Flexibility toolbox

Name of Soluti on	Attribute								
	Service provision					Deployment location			
	Flexibility at short term	Flexibility at medium term	Flexibility at long term	Reactive power	Active power	Transmissio n grid	Distribution grid	Commercial & Industrial	Residential consumers
X	☺	☺	☺	☺	☺	☺	☺	☺	☺

An explanation of why some technologies are excluded from the list is provided.

1.3 Relation to other work packages

The flexibility toolbox was selected as one of the first research topics as the findings can be of direct use for WP3 itself, but it exchanges mostly with WP4 *Smart grid solutions for a flexible and resilient distribution system* and WP5 *Identification and assessment of innovative market mechanisms for DSO* grid services and gives output to other relevant project activities including demonstration pilots within the EUniversal project. More specifically, the document gives an overview of flexibility solutions gives insights into the trade-offs between the different options and provides support to other tasks in that sense when developing UMEI. In addition, the state of play matrix provided through Table 27 as well as limitations and policy recommendations are highlighted for further actions.

2 Flexibility toolbox

The energy system and market are undergoing drastic changes. Both technological development and the evolving legislative and regulatory framework are opening up to new opportunities and perspectives for players across the energy system. While many consumers will assume a completely new role as active participants in the market, DSOs are facing new challenges as their role evolves. Flexibility technologies deployed at all levels of the energy system are becoming increasingly important tools for the DSOs and other players to manage the challenges of the future energy system.

This section focuses on putting forward the requirements for flexibility, identifies most relevant technologies that bring flexibility to the network and gives reasons of other technology exclusions.

2.1 Definition of Flexibility

Flexibility is defined as the capacity of a power system to adapt to the inherent variability in supply and the uncertainty of demand. The parameters used to characterise flexibility can include: the amount of power modulation, generation forecasts, duration, rate of change, response time and location. The delivered service should be reliable and help to ensure the security of the system.

The use of flexibility can help DSOs to shift supply and demand peaks, to prevent congestion (voltage and current issues) and avoid power quality problems. Flexibility can serve as an alternative to network reinforcement when it is more cost-efficient than traditional reinforcement of the network.

Based on the definition in the Eurelectric report (Eurelectric, 2014) flexibility can be defined: **"[…] Flexibility is the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) to provide a service within the energy system".**

The objective of flexibility is to maintain a constant balance between supply and demand that guarantee the safety and the continuity of the energy system, to the benefit of consumers. Flexibility can be quantified through the amount of supply/demand that can be adapted and qualified through the ease, the speed, and the duration of the response. The approach should be holistic and look at how flexibility in the energy system as a whole can be harnessed to achieve the objectives of balancing supply/demand in a cost-effective way while meeting the varied interests in the value chain.

Implicit demand-side flexibility is the consumer's reaction to price signals. Where consumers have the possibility to choose hourly or shorter-term market pricing, reflecting variability on the market and the network, they can adapt their behaviour (through automation or personal choices) to save on energy expenses. This type of demand-side flexibility is often referred to as "price-based" demand-side flexibility.

Explicit demand-side flexibility is committed, dispatchable flexibility that can be traded (similar to generation flexibility) on the different energy markets (wholesale, balancing, system support and reserves markets). This is usually facilitated and managed by an Aggregator that can be an independent service provider or a Supplier. This form of Demand-Side Flexibility is often referred to as "incentive driven" demand-side flexibility.

2.2 Which criteria were considered for choosing flexibility technologies?

There are many different flexibility technologies in the R&D phase and on the market today. For the purposes of this flexibility toolbox, a selection had to be made among the many flexibility technologies, since a completely exhaustive overview of every available and potential flexibility resource would have been impractical. The main criterion used for the selection of technologies in the toolbox was whether a given solution could provide flexibility services from a technical performance perspective (e.g. ability to modify generation injection and/or consumption patterns as per the definition above). That said, the document considers also common capacity of the technology such as small or medium sized distributed energy technologies that are usually connected at the distribution network.

Among the available technologies, those with a high Technology Readiness Level (TRL) or very promising market outlook in the short- to mid-term (next 5-10 years) have been chosen. It should be noted that unexpected technology breakthroughs or other developments could lead to the rapid deployment of a new battery chemistry or other new smart grid technologies that are not listed in this flexibility toolbox. Therefore, this toolbox must be considered as a snapshot of current technology performance and short-term outlook rather than a definitive list of all available current and future flexibility technologies.

Where technology variants have similar performance characteristics (for example, various types of li-based batteries), the most commonly deployed type in the short- to mid-term has been chosen. Other criteria considered were the economic feasibility (cost-effectiveness) of the technology[1] per se and the environmental impact[2]. These last two criteria are less emphasised in the document due to the inherent difficulties in finding comparable data.

2.3 Flexibility solution mapping

In this document flexibility technologies are analysed from the point of view of their capability to be employed as reliable solutions in the network planning process. The main criteria applied to the flexibility technologies can be summarized as:

- Technological maturity,
- Flexibility delivery capacity and capability,
- Economic feasibility.

Each main criteria includes technical characteristics attributed to each technology. Different flexibility resources have different technical and economic properties. To be able to consider these resources in the flexibility services and products that are being specified under the project, it is necessary to understand the techno-economic characteristics of the individual resources and their relevance for network planning. It is also worth noting that the mentioned technologies were considered for their relevance from UMEI perspective but also with regard to the flexibility market platforms, mechanisms and aggregators. The solutions should be provided with sufficient detail to capture the relevant characteristics, while at the same time keeping the framework descriptive in terms of required efforts and available data. Therefore, in this section characteristics of the individual flexible technologies that will be analysed are presented.

2.3.1 Technology maturity:

Technology Readiness Levels (TRLs) (European Commission, 2014) are indicators of the maturity level of particular technologies including flexibility ones. This measurement system provides a common understanding of technology status and addresses the entire innovation chain. There are

[1] It should be noted that defining the cost-effectiveness of flexibility technologies can be highly complex. For energy storage technologies for example, it is not possible to simply define a levelized cost of storage (LCOS) per technology, as the LCOS depends on the deployment location, service provided, etc.

[2] Chosen technologies should have a positive environmental impact by supporting integration of higher vRES while emitting few or no GHG emissions. Calculating the CO2 footprint of the whole value chain (manufacturing, deployment, decommissioning) is complex and beyond the scope of this document.

nine technology readiness levels; TRL 1 being the lowest and TRL 9 the highest. TRL serves as a reference to the development level of a specific energy storage technology. This starts from the basic principle research, continues to stages of development, and ends up with market outreach.

2.3.2 Flexibility delivery capacity and capability:

Power range: Considering all the different technologies and application of a specific solution, the power range is defined as the range of power that the solution can provide. By definition, the power is the amount of energy delivered in a certain period of time, so the higher the power the quicker the technology is in providing energy.

Energy range: The range of energy that the technology can provide or store within itself. The higher the energy capacity the higher the overall production costs.

Discharge time: The term refers to the time required by the technology to be completely discharged (also given as a range). In general, it can be stated that the discharge time is closely linked to the type of storage technology, meaning short-term, medium-term and long-term storage. The higher the discharge time, the closer the technology gets to a 'long-term storage' type.

Reaction time: This implies the time required by the technology to be fully operative (also given as a range). Needless to say, the lower the reaction time the better it is for grid stability issues: whenever the reaction time is high this could lead to longer frequency deviations in the grid.

Power modulation: The power flexibility of loads differs according to its operating cycle, characteristics and nominal power. Therefore, the flexibility potential will vary along the day. In alternative to power modulation, this measurement can be expressed as duration time for certain technologies.

Current deployment status: How deployed is the considered technology.

Applicable in demo site: Demonstration pilot owner addresses potential applicability, i.e., existence/potential of the specific technology in the demo country.

2.3.3 Economic feasibility:

Cost/Effectiveness: Feasibility of the project: by definition, the cost-effectiveness of a project can be explained as "the ability of producing good results without costing too much money". In this context, it can be referred to the amount of electricity that can be produced or stored by a certain technology compared to its cost. It must be noted that for different types of technologies performance of Cost/Effectiveness is measured in different values. The value might not be comparable between different flexibility technologies, while still provide the level of performance.

2.4 Flexibility solution mapping

Based on above-mentioned criteria, the most promising flexibility solutions are presented under eight categories and organized as follows:

- **Energy storages**
    - Mechanical energy storage
        - Compressed Air Energy Storage (CAES)
        - Liquid Air Energy Storage (LAES)
        - Pumped hydro storage (PHS)
    - Thermal energy storage
        - Latent Heat Storage (LHS)
        - Sensible Heat Thermal Storage (SHS)
        - Thermochemical Storage (TCS)
    - Chemical energy storage
        - Power to Hydrogen
    - Electrical energy storage
        - Hybrid Supercapacitors - Electro chemical Double layer capacitor (EDLC)
        - Supercapacitors
    - Electrochemical energy storage
        - Lead – Acid Rechargeable Batteries
        - Li – Ion Batteries
        - Li – Polymer Batteries
        - Li – S batteries
        - Metal – Air Batteries
        - Na-S Batteries
        - Vanadium Red-OX Batteries
- **Demand-side flexibility**
    - Residential demand response
        - Thermostatically controlled loads (TCL)
        - Time-shiftable smart appliances enabling residential demand-side flexibility
    - Industrial demand response
        - Demand-side flexibility/ Co-generation (CHPs)
    - Smart charging (EVs)
- **Distribution network flexible assets and control (Medium and low voltage control)**
- **Renewable Self Consumption and Microgrids**
- **Dynamic Line Rating (DLR)**
- **Active power control of RES – in example of German Redispatch 2.0 (schedule-based congestion management)**

2.4.1 Energy storage solutions

a. Mechanical energy storage

Compressed Air Energy Storage (CAES)

Energy is stored in the form of high pressure compressed air. Electricity is used to run compressors to store large amount of air in specific tanks (air storage reservoirs), which is going to be released afterward to produce electricity again.

In CAES system, usually the reservoirs are geological underground voids, and the air pressurised can reach pressure conditions of 100 bars. The heat generated by the compression process is also stored using Thermal Energy Storage systems (TES). The compressor discharge temperature can exceed 600 °C. In the regenerator type TES hot air passes ceramic, concrete or natural rock materials, while its heat is transferred to the storage inventory. Alternatively, TES systems (based on thermo-oil, molten salt, etc.) can be applied as well. The cooled air is then injected under pressure into the cavern. In discharge operation, the air will leave the cavern and pass through the TES before being applied to an expansion turbine coupled to a generator, without the need for co-firing any fuel.

Table 2. Characteristics of Compressed Air Energy Storage (CAES)

TRL (1-9)	8-9
Power range	few 100 MW
Energy range	100 MWh – 10 GWh
Discharge time	from few hours – to tens of hours
Reaction time	few min
Current deployment status	Today there are only two CAES plants in operation worldwide. One plant is located in McIntosch, US (110 MW), commissioned in 1991, and one in Huntorf, Germany (320 MW), commissioned in 1978.
Owner/developer	DSO, Aggregators, energy suppliers
User of Technology	Industries
Applicable in demo site	☐Demo Portugal ☐Demo Germany ☐Demo Poland ☒None
Cost/Effectiveness	400 - 2000 €/kW
Services provided	Energy storage – flexibility
Benefits	CAES is not suited for small-scale residential situations, but rather on larger-scale, closer to where the energy is being harnessed. However, CAES can benefit on smaller scales by air cars and air-driven locomotives.

Drawbacks	It represents low efficiency (around 55%) and also costly to produce. Determining efficiency for CAES systems can be hard. If we compress and decompress at a rate that is not appropriate for the specific cavern, efficiency takes a huge hit. CAES has some geographical limitations since it must generally be built with a reservoir.
References	(1) EASE. "*Adiabatic Compressed Air Energy Storage*." URL: https://ease-storage.eu/wp-content/uploads/2016/03/EASE_TD_ACAES.pdf (2) Darmani A., Jullien C. 2017. *Innovation readiness level – Energy storage technologies.* (3) Huang Y. 2017. *Techno-economic modelling of large-scale compressed air energy storage systems.* Centre for sustainable technologies, School of the build environment, University of Ulster, Jordanstown. (4) EASE. "*Diabatic compressed Air Energy Storage.*" URL: https://ease-storage.eu/wp-content/uploads/2016/07/EASE_TD_Mechanical_DCAES.pdf

Liquid Air Energy Storage (LAES)

LAES system comprises a charging system, an energy storage and a discharging system. Energy is stored in the form of high-pressure air, which liquifies below -196°C.

The charging system is an industrial air liquefaction plant where electrical energy is used to reject heat from ambient air drawn from the environment, generating liquid air (also called "cryogen"). The liquid air is stored in an insulated tank at low pressure, which functions as the energy store. When power is required, liquid air is drawn from the tank, pumped to high pressure, and evaporated. This produces gaseous air that can be used to drive a piston engine or turbine to do useful work that can be used to generate electricity. There are various categories of LAES technologies differentiated by the thermodynamic process used.

Table 3. *Characteristics of Liquid Air Energy Storage (LAES)*

TRL (1-9)	7-8
Power range	5 – 650 MW
Energy range	10 MWh – 7.8 GWh
Discharge time	2 – 24 h
Reaction time	≤ 5 min
Current deployment status	There is only one demonstration plant that has an actual liquefier for liquid air production – Highview Power Storage in the UK. On June, 2020 it was announced that the world's first commercial liquid-air energy storage facility is to begin construction this year in Greater Manchester, England, after technology company Highview Power received a £10m ($12.5m) grant from the UK government.

	The overall process has been demonstrated in two pilot scale plants (by Highview Power Storage and Mitsubishi Heavy Industries Ltd).
Owner/developer	DSO, Aggregators, energy suppliers
User of Technology	DSO, TSO, Consumers
Applicable in demo site	☐Demo Portugal ☐Demo Germany ☐Demo Poland ☒None
Cost/Effectiveness	500 – 3500 €/kW
Services provided	Energy storage – flexibility - Renewables integration - Network reinforcement deferral - Daily/weekly balancing - Security of supply (capacity provision) - Frequency control, reserve and other ancillary services - Black start - Improve energy efficiency in LNG regasification terminals - LAES can be used to increase the flexibility of conventional power plants by lowering the minimal load and increasing the maximal load due to connections between the thermodynamic processes
Benefits	Long life duration, high efficiency when heat and cold are stored from the reactions. No geographical limitations unlike CAES and pumped hydro storage.
Drawbacks	High investment costs: there is a need to identify and quantify cost reduction drivers such as modularisation. Round trip efficiency (RTE): thermal energy storage materials and systems must be thoroughly studied and optimised for LAES. RTE: minimisation of required compression work during charge and maximisation of power output during discharge is crucial to increase round-trip efficiency of LAES. RTE: an improved purification unit can help improve round trip efficiency of LAES. RTE: integration of LAES with conventional plants, as it has the potential to increase overall efficiency. Comprehensive integration studies and full-scale demonstration should be implemented. Missing optimal operation and dispatching of LAES plants: complete system analyses and optimal integration with the grid are needed to achieve the best technological benefit, maximise revenues, and improve business cases for LAES.
References	(1) EASE. "*Liquid Air Energy Storage.*" URL: https://ease-storage.eu/wp-content/uploads/2016/07/EASE_TD_Mechanical_LAES.pdf (2) EERA. 2016. "*Liquid Air Energy Storage.*" URL: https://eera-es.eu/wp-content/uploads/2016/03/EERA_Factsheet_Liquid-Air-Energy-Storage.pdf,

	(3) Durand, Jean-Michel, M. J. Duarte, and P. Clerens. 2017. "*European energy storage technology development roadmap towards 2030.*" Int Energy Storage Policy Regul Work 108. (4) Leigh Collins. 2020. "*World first as liquid-air energy storage makes commercial debut near Manchester United ground*, Recharge."

Pumped hydro storage (PHS)

PHS is a type of hydroelectric energy storage. It is a configuration of two water reservoirs at different elevations that can generate power (discharge) as water moves down through a turbine; this draws power as it pumps water (recharge) to the upper reservoir.

Pumped hydro storage facilities store energy in the form of water in an upper reservoir, pumped from another reservoir at a lower elevation. During periods of high electricity demand, power is generated by releasing the stored water through turbines in the same manner as a conventional hydropower station. During periods of low demand (usually nights or weekends when electricity is also lower cost) or excessive variable RES generation, the PHS facility uses lower-cost electricity from the grid to pump the water back to the upper reservoir. Therefore, PHS can adjust the demand supply to balance respectively reduce the gap between peak and off-peak periods and play an important role of levelling other power generation plants and stabilizing of the power grid. PHS for large scale energy storage represents more than 95 % of current worldwide storage capacity. It is undoubtedly the most mature large-scale energy storage technology.

Table 4. *Characteristics of Pumped hydro storage (PHS)*

TRL (1-9)	9
Power range	10 MW – 3.0 GW
Energy range	up to some 100 GWh
Discharge time	Some Min - some 10 hours
Reaction time	some sec– few min
Current deployment status	Worldwide with installed capacity 170 GW.
Owner/developer	TSO, DSO and other market players
User of Technology	TSO, DSO, aggregators, energy utilities etc.
Applicable in demo site	☐Demo Portugal ☐Demo Germany ☐Demo Poland ☒None
Cost/Effectiveness	70-85%

Services provided	Load following; Load shifting; Black start; Voltage support. Energy-balancing, stability, storage capacity, and ancillary grid services such as network frequency control, contingency and regulation reserves;
Benefits	Flexibility, high-efficiency, large-scale energy storage capacity, long lifetime and low self-discharge, other grid operations benefits.
Drawbacks	High investment costs; Long return of investment; Difficult identification of suitable locations; High environmental standards.
Notes	There are future developments for modified PHS concepts: **Hydraulic gravity storages** (HGS): the HGS principle is derived from PHS technology and is based on conventional pump-turbines and motor-generators. The hydrostatic head on the turbine contains a piston in a vertical shaft in the generation mode; the piston is lifted by water pressure in storage (pump) mode. Independent from the position of the piston, the head on the turbine remains constant. **Underground PHS systems**: the concept is equivalent to conventional PHS, but instead of surface reservoir/ponds the storages are arranged below ground, e.g. existing mines. Both concepts are in the development stage and are far from commercial attractiveness.
References	(1) DG ENER. "*The future role and challenges of Energy Storage.*" URL: https://ec.europa.eu/energy/sites/ener/files/energy_storage.pdf (2) International Hydropower Association. 2018. "*The world's water battery: Pumped hydropower storage and the clean energy transition.*" (3) EERA. 2016. "*Pumped Hydro Energy Storage.*" URL: https://eera-es.eu/wp-content/uploads/2016/03/EERA_Factsheet_Pumped-Hydro-Energy-Storage.pdf (4) EASE. "*Pumped Hydro Storage.*" URL: https://ease-storage.eu/wp-content/uploads/2016/07/EASE_TD_Mechanical_PHS.pdf

b. Thermal energy storage

Latent Heat Storage (LHS)

The process is very much similar to the sensible heat storage: energy (in the form of electricity or direct irradiation) is used to increase the temperature of a certain medium that stores large amounts of heat by changing its state (i.e. passing from a solid state to a liquid one).

LHS can be divided into direct and indirect systems, both of which provide critical solutions to the storage of latent heat. Direct systems facilitate heat transfer through immediate contact between the Heat Transfer Fluid (HTF) and the LHS material. Indirect systems separate the HTF and storage material with a solid heat transfer border, in which case heat can either be delivered to a container filled with Phase-Change Material (PCM) or an encapsulated material. In the first case, heat transfer occurs by way of pipes, finned tubes or flat-plate exchangers. Concerning encapsulated PCM, the material is separated in small packages which are then put in contact with the heat transfer fluid. The form of the encapsulation depends on the application and can be found in both stationary and mobile applications.

Table 5. Characteristics of Latent Heat Storage (LHS)

TRL (1-9)	Depends on the temperature range, from 4 to 9
Power range	Up to 6 MW
Energy range	10 kWh – 2.5 MWh (Low Temperature); 10 kWh – 10 MWh (High Temperature)
Discharge time	Some hours
Reaction time	Some seconds
Current deployment status	N/A
Owner/developer	DSOs and other market parties
User of Technology	Industry – Households
Applicable in demo site	☒Demo Portugal ☐Demo Germany ☐Demo Poland ☐None
Cost/Effectiveness	0.4 – 10 €/kWh (Low Temperature); 20 – 70 €/kWh (High Temperature)
Services provided	Potential services: Heat storage, use of waste heat (power plants and industrial processes, vehicles, etc.), storage of renewable heat, cold applications (central storages). There are a wide variety of building applications for LHS - Stabilising temperatures of sensitive goods (e.g. pharmaceuticals) during transport High-temperature LHS can be integrated in subcritical steam cycles LHS is also being developed for solar thermal power plants in order to facilitate a temporal separation from the solar radiation. LHS can be deployed to improve dynamics in steam power plants as well as to reduce partial load and start-up losses. In the process industry, LHS increases energy efficiency through improved use of waste heat as well as balancing intermittencies between the availability and demand of thermal energy. In the future, LHS could be part of location-independent storage systems for nearly isentropic Power-to-Heat-to-Power (P2H2P) energy storage. Promising solutions based on right- and left-handed thermodynamic cycles with phase change of the working fluid need LHS for a minimum of exergy loss and so a maximised round-trip efficiency. However, this solution would first have to be demonstrated with SHS.

Benefits	High efficiency
Drawbacks	A stable and controllable discharging power is not really developed right now, so research priorities should focus on this matter. Development of LHS with reduced temperature difference between charging and discharging through improved heat transfer. Development of systems using the same PCM for latent and sensible heat storage (extended PCM) in order to increase storage density. Very expensive to produce, the material expenditures are still too high.
References	(1) Sarbu I., Sebarchievici C., A. 2018. *"Comprehensive Review of Thermal Energy Storage, Department of Building Services Engineering."* Polytechnic University of Timisoara, Timisoara, Romania. (2) EASE, EERA. 2017. "*European Energy Storage Technology Development Roadmap."*

Sensible Heat Thermal Storage (SHS)

Electricity (or direct irradiation) is used to increase the thermal energy of a certain medium (usually water) and stored in tanks that can vary in volume, depending on the application (industrial or for a house). The thermal energy is then used for application such as district heating.

Sensible heat storages are the most deployed type of TES. From small residential water tanks to massive molten salt storages in concentrating solar power (CSP) plants or Cowper storages for blast furnaces, all systems operate by the same fundamental principle: increasing or decreasing the temperature of a solid or liquid substance with high heat capacity to store or release thermal energy, transferring the heat directly or indirectly to the process.

Table 6. *Characteristics of Sensible Heat Thermal Storage (SHS)*

TRL (1-9)	Depends on the application, in a range 6-9
Power range	0.001-20 MW
Energy capacity range	10-50 kWh/t
Discharge time	Some hours
Current deployment status	Worldwide
Owner/developer	DSOs, aggregators, etc.
User of Technology	Industry – Households
Applicable in demo site	☒Demo Portugal ☒Demo Germany ☐Demo Poland

	☐None
Cost/Effectiveness	0.1-10 €/kWh
Services provided	Power plants: grid-balancing opportunities emerge from improved operational flexibility. Both regenerator-type heat storages and molten salt storages are applicable in these cases. Steam accumulators enable balancing the steam load between steam sources and consumers, thereby saving large amounts of energy.
Benefits	Cheap mediums (i.e. water), potential to link the electricity and heating sectors
Drawbacks	Low energy density, suitable locations for large-scale thermal energy storage.
References	(1) Sarbu I., Sebarchievici C., A. 2018. *"Comprehensive Review of Thermal Energy Storage, Department of Building Services Engineering."* Polytechnic University of Timisoara, Timisoara, Romania. (2) EASE, EERA. 2017. *"European Energy Storage Technology Development Roadmap."*

Thermochemical Storage (TCS)

The process behind this technology is based on storing energy provided heat as an input, which activates several chemical reactions. Heat is used to divide some compounds "AB" in simpler components, "A" and "B". With the opposite reaction, energy is released.

TCS stockpile heat in two distinct ways: chemical reactions and sorption processes. Thermochemical reactions based on gas-gas or gas-solid reactions use thermal energy to dissociate compounds ("AB") into two reaction products ("A" and "B"). Upon subsequent recombination of the reactants, an exothermic reverse reaction occurs, and the previously stored heat of reaction is released. This allows for the theoretically lossless storage of thermal energy. The product "AB" represents a renewable form of thermal energy storage which enables a temporally and spatially independent, reversible thermal cycle.

Gas-solid reactions take place at a constant temperature for a given vapour pressure. This allows TCS to adapt to specific applications through both the selection of the reactants as well as the selection of the reaction conditions. Additionally, due to the dependency of the gas-solid reaction temperature on pressure, the temperature level of the storage can be adjusted by varying the pressure. This means that TCS may provide a higher discharging than charging temperature, otherwise known as a "thermal upgrade". Another advantage of TCS is the independent sizing of power and capacity - the reactor determines the power while the reactant container governs the storage capacity. TCS based on reactions are currently in the early stages of their development but represent a promising thermal energy storage solution.

Sorption processes can also be used to absorb and release heat through adsorption (physical bonding) and absorption (uptake/dissolution of a material). In adsorption, the reactants (e.g. zeolite and water) are separated during charging and the heat of reaction is released after recombination. The sorption principle can be applied for thermal energy storage as well as for chemical heat pumps. Whereas sorption heat pumps are commercially available, sorption-based thermal energy storage with discharging cycles of more than 1 hour are still in research and development. (1)

Table 7. *Characteristics of Thermochemical Storage (TCS)*

TRL (1-9)	3-4
Power range	Application specific.
Energy range	System dependent (chemical reactions; 2-4 MWh (sorption processes)
Discharge time	N/A
Reaction time	Less than 1 min
Current deployment status	N/A
Owner/developer	N/A
User of Technology	N/A
Applicable in demo site	☒Demo Portugal ☐Demo Germany ☐Demo Poland ☐None
Cost/Effectiveness	10 to 90 €/kWh (chemical reactions); 10 to 130 €/kWh (sorption processes)
Services provided	Seasonal storage and peak-shifting, Buffer storage in district heating, Switchable and controllable release of thermal energy, Combination of thermal energy storage and heat pumping effects (e.g. cooling)
Benefits	- Switchable and controllable release of thermal energy - Adjustment of temperature levels - combination of thermal energy storage and heat pumping effects - Low-cost and widely available materials - Long-term, loss-free storage that - can be used seasonally
Drawbacks	Low technological maturity for all types; available reaction temperatures is limited; complex reactor design.
Notes	There is a need for focus on application-oriented rather than just material aspects. Integration of gaseous reactants, scaling from prototypes to application-relevant sizes, development of new materials with tuneable reaction temperatures etc are among other challenges related to the technology.
References	(1) EASE, EERA. 2017. "*European Energy Storage Technology Development Roadmap.*"

c. Chemical energy storage

Power to Hydrogen

Electrical energy is stored by electrolysing water to produce hydrogen and oxygen. The oxygen is released, and the hydrogen is then stored. For grid electrical energy storage applications, the hydrogen is then re-electrified (e.g. via fuel cells) thus recombining hydrogen with oxygen to produce electricity. Heat and water are released as a by-product. Alternatively, gas turbines or engines can reconvert hydrogen into electricity as well.

Hydrogen is produced from (surplus) renewable energies, and unlike electricity it can also be stored in large amounts for extended periods of time. For that reason, hydrogen produced on an industrial scale could play an important part in the energy transition.

The optimal energy storage system for vehicles lies in hydrogen and battery systems. Depending on the application, the hydrogen system could provide the bulk energy storage, while a relatively small energy capacity battery would allow regenerative braking, meet peak power demands, and generally buffer the fuel cell against load changes to extend its lifetime. Alongside other demand and supply measures, energy storage can play an important part in improved system integration.

Table 8. *Characteristics of Power to Hydrogen*

TRL (1-9)	6-8
Power range	1 kW - 1 GW
Energy range	Some 10 kWh – several GWh
Discharge time	Some h – some weeks
Reaction time	<sec - <min
Current deployment status	Available in selected areas: it depends on presence of industrial customers and their willingness.
Owner/developer	TSO, DSO, energy companies, technology providers
User of Technology	Utilities, industry players etc.
Applicable in demo site	☐Demo Portugal ☐Demo Germany ☐Demo Poland ☒None
Cost/Effectiveness	50-60%
Services provided	Peak capacity management, Spinning Reserve, Ramping, Artificial inertia, Distribution voltage management, Autonomous grid service responses.
Benefits	Flexibility, large-scale energy storage capacity, long life-time and low self-discharge, it can be injected into the gas grid, mobility purposes (fuel cells), can act as chemical platform in the industry, it is well suited for large off-shore

	wind parks or in places where is there is high discrepancy (time/space) between energy production and consumption. Power-to-gas could make use of the existing gas infrastructure to extend its lifetime.
Drawbacks	High investment costs; Long return of investment; efficiency losses during conversion steps; not safest source of energy, tricky to move around in large quantities.
Notes	There are promising future developments: - *Electrolyser*: up-scaling and cost reduction to be able to compete in the energy supply and storage landscape with alternative pathways. - *Hydrogen storage*: large demonstration projects employing salt caverns are on the way. Further experience needs to be gathered on how this particular storage system could interact with wind generation and the gas and electricity networks. - *Increase of the hydrogen admixture into natural gas infrastructure* (grid and caverns) and for all connected consumers. - *Increase of the hydrogen content in conventional gas turbines*. - *Methanation step*: technological advancements (Sabatier reaction or biological process), up-scaling and cost reductions in order to become a viable chemical storage alternative.
References	(1) FCH 2 JU. 2019. "*Hydrogen Roadmap Europe: A sustainable pathway for the European energy transition.*" (2) EERA. 2016. "*Pumped Hydro Energy Storage.*" (3) Darmani A., Jullien C. 2017. "Innovation readiness level – Energy storage technologies" (4) EASE. "*Hydrogen.*" *URL:* https://ease-storage.eu/wp-content/uploads/2016/03/EASE_TD_Hydrogen.pdf

d. Electrical energy storage

Hybrid Supercapacitors - Electro chemical Double layer capacitor (EDLC)

An EDLC System is an energy storage system based on electrostatic effects that occur between two carbon electrodes with high specific surface areas per volume, e.g. activated carbons. The electrodes are immersed in an electrolyte and a separator between the electrodes is used.

By charging the capacitor, captions are accumulated at the boundary between the solid negative electrode and the electrolyte on one side and anions at the boundary between the solid positive electrode and the electrolyte on other side, forming the so-called Helmholtz-layers. In contrast to batteries, only electrostatic effects are used for the storage of the electrical energy. The differential voltage between the electrodes is limited by the dissociation voltage of the electrolyte, which is about 0.9 V for aqueous ones and about 2.7 V for organic solvent-based ones. In terms of operating temperature, EDLCs are able to work between -40°C and 70°C.

Table 9. *Characteristics of Hybrid Supercapacitors - Electro chemical Double layer capacitor (EDLC)*

TRL (1-9)	6-9
Power range	Up to some MW

Energy range	Some kWh
Discharge time	Some sec - some min
Reaction time	5 milliseconds
Current deployment status	Recently, EDLCs have been used in start/stop systems for cars. This energy storage system is able to recuperate electrical energy during breaking and can provide the power boost for a smooth start of the engine for more than 500,000 charge and discharge cycles.
Owner/developer	Technology providers.
User of Technology	Energy suppliers, aggregators, DSOs etc.
Applicable in demo site	☒Demo Portugal ☐Demo Germany ☐Demo Poland ☐None
Cost/Effectiveness	Driven by the increasing demand for large cell materials, production processes are improved to meet price targets of less than 0.01 €/Farad.
Services provided	Uninterruptible Power Supply (UPS) systems to back-up short power failures and cover peak power demand; safety electronics as a maintenance free power back up; renewable energy for smoothing voltage sags and power boost; industrial electronics.
Benefits	90% efficiency
Drawbacks	Low energy density; usually holds 1/5-1/10 of a battery. Challenging to use the full energy spectrum for some applications. Low voltage cells, to get higher voltages, serial connections are required. Voltage balancing needed; when more than 3 supercapacitors are connected in series, the circuit needs a voltage balancing element. High self-discharge as compared to electrochemical batteries.
Notes	Today, the electrodes are made of activated carbons based on synthetic or wood precursors. By developing highly porous electrodes (such as graphene-like carbons or carbon nano tubes), a further increase of the specific capacitance will be achieved. In addition, the specific energy will be increased by electrolytes which will enable higher operational voltages.
References	(1) EASE. "Electrochemical Double Layer Capacitor", URL: https://ease-storage.eu/wp-content/uploads/2016/03/EASE_TD_EDLC.pdf

Supercapacitors

Electrochemical capacitors (ECs), also referred to as "supercapacitors" or "ultracapacitors," store electrical charge in an electric double layer at the interface between a high-surface-area carbon electrode and a liquid electrolyte.

ECs, exactly like conventional capacitors, can be charged and discharged at high power rates thousands of times with low capacitance fade. The electrode surface area and the pore size distribution in ECs determines the capacitance and thus, the energy storage capability of the device. The amount of energy stored by ECs is very large compared to conventional capacitors, because of the use of a high surface area, porous carbon-based electrode material.

Table 10. Characteristics of Supercapacitors

TRL (6-9)	8-9[3]
Power range	Transmission voltages up to 12 kV and distribution voltages up to 1500 V. Power density: »10-20kW/kg (1-5s)
Energy range	Energy density: 4-8 Wh/kg EDLCs, 15-30 Wh/kg for LCAPs and 2030 target 50Wh/kg
Discharge time	Some milliseconds to some seconds
Reaction time	Milliseconds
Current deployment status	Supercapacitors have been in commercial use for decades in both transportation and grid back up applications such as wind pitch control systems.
Owner/developer	Energy suppliers, DSOs, etc.
User of Technology	All power market players.
Applicable in demo site	☒Demo Portugal ☐Demo Germany ☐Demo Poland ☐None
Cost/Effectiveness	0,3 €/W (cell basis) 0.015 c€/F with 2030 target of 0,2€/W (cell basis), 0.005 c€/F
Services provided	- Transmission line stability - Tertiary frequency control - Secondary frequency control - Renewables intermittency smoothing

[3] 8-9 for hybrid bus, rail, and automotive applications, as well as back-up power applications such as wind pitch control systems and uninterrupted power supplies. Some research and development activities are focused towards improving energy density of the core technology, developing miniaturised capacitors, and demonstrating power electronics that support the control and management of supercapacitors combined with batteries or another secondary energy storage technology.

Benefits	Very suitable for high-power applications, high energy efficiency (more than 95%), high power density, and long calendar and cycle life, cost of manufacturing ($1000/kW with expectation of $517/kW by 2021)
Drawbacks	Toxicity of electrolytes
References	(1) EASE, EERA. 2017. "*European Energy Storage Technology Development Roadmap.*"

e. Electrochemical energy storage

Lead – Acid Rechargeable Batteries

Lead acid batteries are secondary type batteries, wherein sulfuric acid functions as electrolyte and the lead and its oxides function as electrode. For the reliable operation of power systems, Pb-acid batteries have been used in the power plants and transformer substations as backup for many years. However, these batteries are not widely used in Europe for energy storage, even though they are cheaper, due to environmental pollution concerns. Moreover, they have lower efficiencies compared to Li-ion batteries and limitations on cycles.

Table 11. *Characteristics of Lead – Acid Rechargeable Batteries*

TRL (1-9)	6-8
Power range	180 W/kg
Energy range	35-40Wh/kg
Discharge time	5-hour (0.2) and 20-hour (0.05C)
Reaction time	Milli Seconds
Current deployment status	Worldwide Starter battery. Uninterruptible power supply, emergency lighting, alarm systems, communication systems, solar batteries in photovoltaic systems (stand-alone systems), electronic cash registers and cigarette, can and beverage vending machines. The cycle-proof accumulators in the areas of: golf caddies, wheelchairs, electric bicycles, toys and medical equipment.
Owner/developer	Inventor Nelson - Lee Garrett, Jr.; Current Assigned - Garrett Plante Corp
User of Technology	Industry, Services, Household,
Applicable in demo site	☒Demo Portugal ☒Demo Germany ☐Demo Poland ☐None

Cost/Effectiveness	Very Low costs ($/kWh) 300–600 75% and 85% efficiency depending on temperature; operating temperature 18-45°C
Services provided	- Starter - Storage Services for peak shaving and load levelling, voltage and frequency regulation, and (emergency energy storage is limited because of the relatively short lifetime (500–1000 cycles) and its low energy density resulting from the inherent high density of lead. In addition, a thermal management system is required for lead–acid batteries due to their poor low temperature performance.
Benefits	- Inexpensive and simple to manufacture, low cost per watt-hour - Low self-discharge; lowest among rechargeable batteries - High specific power, capable of high discharge currents - Good low and high temperature performance - Moderate safety - Established recycling system with very high recycling rates compared to li-ion batteries
Drawbacks	- High self-discharge - Toxic material - Low power density - Low life cycle - Low energy density - Low charging times
Notes	Fast charging not possible
References	(1) Breeze, P., 2019. "*Power System Energy Storage Technologies*". Power Generation Technologies, 219–249. (2) Liu, Bing, et al., 2017. "*Study on residual discharge time of lead-acid battery based on fitting method.*" AIP Conference Proceedings. Vol. 1839. No. 1. AIP Publishing LLC.

Li – Ion Batteries

Li-ion is a low-maintenance battery, an advantage many other chemistries cannot claim. The battery has no memory and does not need exercising to keep in shape. Self-discharge is less than half compared to nickel-based systems. This makes Li-ion well suited for fuel gauge applications. The nominal cell voltage of 3.6V can power cell phones and digital cameras directly, offering simplifications and cost reductions over multi-cell designs. The drawback has been the high price, but this levelling out, especially in the consumer market. Nevertheless, today Li-ion is the most commonly used storage technology. The high research and deployment for scalable and lightweight EV batteries and smart technologies (e.g. smartphones, MP3, Laptops) lead to cost reductions, which benefits the stationary storage sector.

Lithium batteries, correctly expressed rechargeable lithium-ion accumulators, can be used for the operation of small mobile devices up to electric traction for energy supply must be responsible.

Lithium is a highly reactive light metal and can cause fires on contact with water. It is therefore used in liquid or polymer electrolytes are used. Requirements for modern lithium batteries are among other things: compact and light, without heavy metal housing, free of toxic metals, reliable and inherently safe in various sizes and designs available, durable (>9000 cycles), deliver high energy densities (200 Wh/kg or 500 Wh/l), be inexpensive, function in a wide temperature range, self-discharge by less than 1% per year when not in use and high power densities and discharge voltages. Depending on the cathode material the properties of the resulting developing cell. The discrepancy between lithium-ion batteries and the fuels previously used for propulsion are conspicuous. The energy density is even with the best design, is inferior to a factor of 60. Nevertheless, the automotive industry that this will be the technology of the future and that combustion engines as the efficiency of the electric motor is significantly better. Since today's lithium-ion batteries are far from matching the energy density of petrol or diesel. Today's research on lithium air batteries and the further development of Fuel cells can play an important role in a long-term solution to climate change and the shortage of raw materials. The cost reductions from the EV research shows that they also have benefits for the stationary storage sector. They are one of the most prevalent storage technologies being deployed currently. The most promising Lithium technologies are:

- LCO 150-200 Wh/kg
- LMO 100-150 Wh/kg
- NMC 150 – 220 Wh/kg
- NCA 200 – 260 Wh/kg
- LTO 70-80Wh/kg
- LFP90-200 Wh/kg
- LiFiPo

Table 12. *Characteristics of Li – Ion Batteries*

TRL (1-9)	9
Power range	250-340 W/kg
Energy range	100-200 Wh/kg
Discharge time	LCO – 1C LMO – 1C, (10C possible) NMC – 1-2 C LFP – 1C, 25 C NCA - 1C LTO - 10C
Reaction time	Milli Seconds
Current deployment status	Worldwide commercial use.
Owner/developer	Energy suppliers, DSOs and other power market players.

User of Technology	- Mobile phones, tablets, laptops, cameras - Power tools, medical devices, powertrains - E-bikes, medical devices, EVs, industrial - Stationary with high currents and endurance - Medical, industrial - EV UPS, EV, solar street lighting
Applicable in demo site	☒Demo Portugal ☒Demo Germany ☒Demo Poland ☐None
Cost/Effectiveness	High costs ($/kWh) 600–2500, Cost efficiency decreasing due to constant research efforts. Charge discharge efficiency 80-90%.
Services provided	- Residential and commercial buildings: time shifting and self-consumption of locally produced PV energy - Distribution grids: voltage, capacity and contingency support of smart grids - Transmission grids: Ancillary services, like frequency regulation - Renewable generation: smoothing and shaping functions associated with voltage and frequency support to ensure better integration of large renewable plants into the electricity system - Congestion management - Peak shaving - Synthetic inertia
Benefits	- Negligible self-discharge - Modulable, can be installed for small-scale (e.g. residential) or large-scale (transmission services) applications
Drawbacks	- Low safety: some material combination can have high temperatures while usage, can self-ignite and explode - Raw material is scarce and limited available - Transport measurements for safety and discharge
References	(1) Battery University. 2019. "*BU-216: Summary Table of Lithium-based Batteries*". URL: https://batteryuniversity.com/learn/article/bu_216_summary_table_of_lithium_based_batteries

Li – Polymer Batteries

Polymer Li-ion batteries provide the performance characteristics of Li-ion batteries, including their high specific energy and high energy density, in a thin, high aspect-ratio form factor. The technology addresses applications such as portable communications and computing devices which require a thin, large footprint rechargeable battery. While polymer Li-ion cells utilize the same active materials as cylindrical or prismatic Li-ion cells, in polymer Li-ion cells, flat, bonded electrodes are used to enable the fabrication of thin cells packaged within a barrier film, in contrast to the steel or aluminium cell case used in other Li-ion technologies.

Table 13. *Characteristics of Li – Polymer Batteries*

TRL (1-9)	8-9
Power range	0,3 – 7,7 Ah
Energy range	100-265 Wh/kg
Discharge time	1C – 6C
Reaction time	Milliseconds
Current deployment status	Commercial use
Owner/developer	Energy suppliers, DSOs, technology providers, other power market players.
User of Technology	Industry, Services, households
Applicable in demo site	☒Demo Portugal ☒Demo Germany ☐Demo Poland ☐None
Cost/Effectiveness	Cost reduction is improving due to mass production
Services provided	- Distribution grids: voltage, capacity and contingency support of smart grids - Transmission grids: Ancillary services, like frequency regulation - Renewable generation: smoothing and shaping functions associated with voltage and frequency support to ensure better integration of large renewable plants into the electricity system - Congestion management - Peak shaving - Synthetic inertia - Uninterruptible Power Supplies (UPS): Customer and Grid storage
Benefits	- Unique thin form - Properties for desirable commercial applications - Good rate capability - Low self-discharge - Safe against physical or electrical abuse
Drawbacks	- Sensitive to full discharge memory effect - Temperature sensitive

References	(1) Linden, D., & Reddy, T. B. 2001. "*Handbook Of Batteries (3rd ed.)*". McGraw-Hill Professional.

Li – S batteries (Lithium Sulfuric rechargeable battery).

Lithium sulphur battery is one of promising candidates for next-generation energy storage device due to the sulphur cathode material with low cost and nontoxicity, and super high theoretical energy density. Sulphur is naturally enough to resource and environmentally friendly with a high gravimetric theoretical capacity of 1672 mAh/g.

Table 14. *Characteristics of Li – S batteries*

TRL (1-9)	2-4
Power range	Average Capacity 3,25 Ah at 2,36 V
Energy range	350 Wh/kg
Discharge time	2 C
Reaction time	Seconds
Current deployment status	Research, commercialize on industrial scale for Airbus Defence and Space
Owner/developer (market party, DSO, ...)	Energy suppliers, DSOs, technology providers, other power market players.
User of Technology	Renewable storage application
Applicable in demo site	☒Demo Portugal ☐Demo Germany ☐Demo Poland ☐None
Cost/Effectiveness	Can reach above 99%
Services provided	- Starter Battery - Automotive applications (EV/PHEV) - Grid services (e.g voltage and frequency regulation, emergency energy storage)
Benefits	- Environmentally friendly due to material - Promising cost effective
Drawbacks	Safety issue due to rapid discharge

Notes	The main developments are related to the scaling-up to large capacity cells and to the development of battery systems for transportation (e-bike, scooters, EV & PHEV) and for energy storage. Some R&D efforts have been launched to solve the following issues: - short-circuits due to metallic lithium dendrites during charging low cycle life - self discharge through polysulphides dissolution - ageing (corrosion, heterogeneous behaviour, etc) - safety (volatile, low boiling temperature electrolytes) - suitable structures for electrodes
References	(1) Shaibani et.al., 2020. "*Expansion-tolerant architectures for stable cycling of ultrahigh-loading sulfur cathodes in lithium-sulfur batteries*." Science Advances, 6(1). (2) Hussain, F., Rahman, M. Z., Sivasengaran, A. N., & Hasanuzzaman, M., 2020. "*Energy storage technologies*." Energy for Sustainable Development, 125–165. (3) Green Car Congress. 2020. "*OXIS Energy Li-S cells close to achieving 500Wh/kg; targeting 600Wh/kg with solid-state Li-S technology*." URL: https://www.greencarcongress.com/2020/01/20200122-oxis.html

Metal – Air Batteries

Electrochemical cell with an anode of pure Metal and an external cathode of ambient air with an aqueous or aprotic electrolyte. Higher energy density than Li-Ion batteries, so promising for EVs.

Different types of Metal-air technology material:

- Lithium–air
- Sodium–air
- Potassium–air
- Zinc–air
- Magnesium–air
- Calcium–air
- Aluminium–air
- Iron–air
- Silicon–air

Design:

- Flexible, Static and Flow

Table 15. *Characteristics of Metal – Air Batteries*

TRL (1-9)	3-7
Power range	Li: 114000 W/kg; Zinc: 100 W/kg

Energy range	Li: 40.103 MJ/Kg/ 5928 Wh/kg Zinc: 4.392 MJ/kg Sodium: 1602 Wh/kg Magnesium 3910 Wh/kg, Aluminium 2800 Wh/kg Iron: 764 Wh/kg
Discharge time	0.5 C
Reaction time	Seconds
Current deployment status	Commercialisation by Honda and Saitec
Owner/developer	Technology providers, energy suppliers, other power market players.
User of Technology	Wind energy, Solar PV, EV, Smart grids, Wearable Electronics, military, IoT
Applicable in demo site	☒Demo Portugal ☐Demo Germany ☐Demo Poland ☐None
Cost/Effectiveness	Depending on the Material the price is lower than conventional Li-Ion Batteries, cathode is air and no raw material which is gratis. Efficiency is 75%. CAPEX – energy: $ 160/kWh; CAPEX: power $ 1,000/5Wh.
Services provided	- Large-scale stationary energy storage applications - preferably in combination with renewable wind or solar power systems to compensate the intermittent nature of these renewable power sources - Transportation: due to its high energy density, M-Air batteries would increase the autonomy of the current electric vehicles. - Renewable generation: smoothing and shaping functions associated with voltage and frequency support to ensure better integration of large renewable plants into the electricity system
Benefits	- Cost effective - High energy density - Efficient electrochemical storage.
Drawbacks	- Incomplete discharge due to blockage of the porous cathode - Poor resistance to oxidation - Anode side reaction - impure gas CO2 release - electrolyte instability
Notes	Future developments are mainly devoted to the following points: - Improvement of the current performances of Zn-Air & Li-Air systems (SetPlan Materials)

	- Study & Development of new M-Air systems: Al-Air, Fe-Air, V-Air, Na-Air - (SET-Plan Materials) - The development of electrically rechargeable M-Air batteries - Improvement of the reversibility of the Metal-Oxygen reactions - Demonstration projects
References	(1) Wang, C., Yu, Y., Niu, J., Liu, Y., Bridges, D., Liu, X., Pooran, J., Zhang, Y., & Hu, A. 2019. "*Recent Progress of Metal–Air Batteries—A Mini Review.*" Applied Sciences, 9(14), 2787. (2) National Academies of Sciences, Engineering, and Medicine. 2019. "*The Power of Change: Innovation for Development and Deployment of Increasingly Clean Electric Power Technologies*." Washington, DC: The National Academies Press.

Na – S Batteries

Sodium sulphur batteries have been used as high-temperature batteries in stationary applications for a long time, see sodium sulphur thermal batteries.

Sodium sulphur batteries have the basis of molten salt technology, where molten sodium and molten sulphur are used as negative and positive electrodes, and solid ceramic sodium alumina acting as electrolyte separates these two electrodes in these batteries.

Table 16. *Characteristics of Na – S Batteries*

TRL (1-9)	9
Power range	24-48 Ah (Japanese Stationary Sodium/sulphur Battery NGK)
Energy range	206 Wh/kg
Discharge time	6h at nominal power
Reaction time	Milliseconds
Current deployment status	Commissioned and used as energy storage system
Owner/developer	Tokyo Electrical, TEPCO
User of Technology	DSO, energy companies, etc.
Applicable in demo site	☒Demo Portugal ☐Demo Germany ☐Demo Poland ☐None

Cost/Effectiveness	($/kWh) 300–500, 4500 cycles, and the efficiency is around 85%
Services provided	650 A h was successfully used for an EES operation, peak shaving, renewable energy stabilization and provision of services of secondary importance - Stabilisation of wind farms and solar generation plants - Peak shaving - Time shifting
Benefits	- Better accessible raw resources - Low price for sodium - Liquid anode concept possible due to Na - High energy density - Higher capacity - Long lifetime
Drawbacks	- The major drawback is the requirement for a heat source - Electrodes expand strong while re- and discharge - Lower energy density than Li-Ion - Lower cell voltage and higher weight than Li
References	(1) Breeze, P., 2019. "*Power System Energy Storage Technologies*." Power Generation Technologies, 219–249. (2) EASE, "*Sodium-Sulphur (NAS) Battery*", URL: https://ease-storage.eu/wp-content/uploads/2018/09/2018.07_EASE_Technology-Description_NaS.pdf (3) Nguyen, T.-T., Martin, V., Malmquist, A., & Silva, C. A. S., 2017. "*A review on technology maturity of small scale energy storage technologies*." Renewable Energy and Environmental Sustainability, 2, 36.

Vanadium Red-OX Batteries

The vanadium redox flow batteries (VRFB) are rechargeable power sources that utilise aqueous electrolytes containing vanadium cations under four different oxidation states to store electrochemical energy. The great advantage of vanadium redox flow batteries compared to other electrical power sources is the fact that electric power is related to the stack configuration while the energy is stored separately inside two electrolyte storage tanks.

Table 17. *Characteristics of Vanadium Red-OX Batteries*

TRL (1-9)	2-6
Power range	Commercialize VRFBs with a range of power outputs from 5 kW to 50 kW
Energy range	15-25 Wh/kg
Discharge time	5h from 1.4V – 1.2V
Reaction time	Milliseconds

Current deployment status	- In research and small demo use - Mature battery technologies for peak shaving and load leveling; voltage and frequency regulation; and emergency energy storage. - China National Energy Administration approved a vanadium redox battery system of 200 MW capacity in Dalian, China, in 2016
Owner/developer	Minami Hayakita Substation, Pfinztal, Baden-Württemberg, Tomamae Wind Farm, Zhangbei Project, SnoPUD MESA 2 Project, San Miguel Substation, Pullman Washington
User of Technology	Spacecraft NASA
Applicable in demo site	☒Demo Portugal ☐Demo Germany ☐Demo Poland ☐None
Cost/Effectiveness	($/kWh) 150–1000
Services provided	Storage in special surroundings, providing power in form of a large power plant (Minamihayakita Transformer Station in Abira-Chou, Hokkaido), supply–demand balance,
Benefits	- High power - Long life (5–15 years, 12,000–14,000 cycles) - High efficiency - High safety - High capacity - Low operating cost - Easy maintenance.
Drawbacks	- Critical issues for commercialization due to material - Requirement of large space - Relatively low energy density
References	(1) Hosseiny, S. S., & Wessling, M., 2011. "*Ion exchange membranes for vanadium redox flow batteries.*" Advanced Membrane Science and Technology for Sustainable Energy and Environmental Applications, 413–434. (2) Cunha, Á., Martins, J., Rodrigues, N., & Brito, F. P., 2014. "*Vanadium redox flow batteries: a technology review.*" International Journal of Energy Research, 39(7), 889–918. (3) Imperial Innovations, "*Novel energy storage technologies*", URL: https://www.imperial.tech/media/uploads/files/ElectrochemicalEnergyStorage_Whitepaper_v4.pdf (4) Xiayue Fan Bin Liu Jie Liu Jia Ding *Battery Technologies for Grid-Level Large-Scale Electrical Energy Storage* - Transactions of Tianjin University (2020) 26:92–103

2.4.2 Demand-side flexibility

In this section, different demand side flexibility resources are mapped out by showcasing related maturity levels, different timescale aspects, as well as other techno-economic characteristics. Demand-side flexibility refers to the portion of demand in the system that can be reduced, increased or shifted within a specific duration. Demand-side flexibility is harnessed to ensure the smooth integration of large shares of variable renewable energy into power systems, therefore, it plays a major role in DSO planning tool. Flexibility can be achieved on the demand side by allowing DSO to control or to provide price signals to various sources of electricity demand, including power-to-heat, electric-vehicle charging, smart appliances and industrial demand response. The concept of microgrid is also included in this chapter as this refers to a coordinated cluster of flexible resources, able to modify their consumption/production in reaction to an external signal.

The selection of relevant flexibility resources when it comes to Demand-side flexibility to be included in the planning tool as well as defining the characterization of the respective flexibility resources is discussed hereunder. The basic working principle is explained, and the relevant characteristics are listed:

- Residential demand response
  - Thermostatically controlled loads (TCL)
  - Time-shiftable smart appliances enabling residential demand-side flexibility
- Industrial demand response
  - Demand-side flexibility/ Co-generation (CHPs)
  - Microgrids
- Smart charging (EVs)

a. Residential demand response:

Thermostatically controlled loads (TCL)

With the acceleration of the heating electrification, resources converting power to heat or cold are one of the main types of flexible assets that are used at residential level as part of Demand Response (DR) programs. They are often referred to as thermostatically controlled loads (TCL).

The power to heat or cold conversion process and its required load offers a source of flexibility by controlling the intensity and the time interval of the heating process, according to:

- Local renewable generation
- Price signal / off-peak period
- Thermal characteristics of the building
- Consumer comfort and heat consumption forecast

The principle of "power to heat" is to convert electricity into heat that can be used as a commodity e.g. in hot water tanks or transported throughout a household or building for heating purposes.

3 types of equipment are generally considered as decentralized "power to heat" options [1]:

- Electric water heaters & boilers: a resistor heating domestic hot water. The flexibility depends on the size of the water tank and the customer usage profile and preferences
- Heat pumps: Extracting heat from outdoor (air or ground) via the refrigerant cycle. The flexibility depends on the comfort preferences and behaviour of users, the thermal inertia of the building, potential heat storage, the heat pump characteristics and internal control logic.
- Storage heaters (electric space heating): Resistors are used to provide space heating through different types of heating elements. There are different ways to distribute the heat, e.g. radiative, convective, filler.

Table 18. *Characteristics of thermostatically controlled loads (TCL)*

<table>
<tr><td>TRL (1-9)</td><td>5-9 (Assets are commercially viable, but it is not always the case for IoT digital technologies enabling the flexibility)</td></tr>
<tr><td>Power range</td><td>~1kW – 100kW (depending whether it is an individual or collective decentralized heating system)</td></tr>
<tr><td>Energy range</td><td>Energy consumption 500kWh/year - 110MWh/year (storage capacity from few kWh up to few hundreds kWh in collective heating systems)</td></tr>
<tr><td>Power modulation</td><td>The flexible power evolves depending on the local heating requirements during the day and has to be forecasted based on local profiles. The power available will be then within the power capacity range of the heating system
<table>
<tr><th>TCL</th><th>Power increase</th><th>Power decrease</th></tr>
<tr><td>Storage heaters</td><td>0-30 kW</td><td>0-30 kW</td></tr>
<tr><td>Electric water heater</td><td>0-7 kW</td><td>0-7 kW</td></tr>
<tr><td>Heat pumps individual household</td><td>0-5 kW</td><td>0-5 kW</td></tr>
<tr><td>Collective heat pump</td><td>5-1000 kW</td><td>5-1000 kW</td></tr>
<tr><td colspan="3"></td></tr>
</table>
</td></tr>
<tr><td>Duration time (Power modulation)</td><td>The duration time also depends on the service delivered, comfort setpoints, building inertia, and the internal control logic of the heating system. The power increase/decrease can last from few minutes to several hours during the day.
<table>
<tr><th>TCL</th><th>Power increase time (min)</th><th>Power decrease time (min)</th></tr>
<tr><td>Storage heaters</td><td>few hours</td><td>few hours</td></tr>
<tr><td>electric water heater</td><td>few hours</td><td>few hours</td></tr>
<tr><td>Heat pumps individual household</td><td>15min - few hours</td><td>15min - few hours</td></tr>
<tr><td>Collective heat pump</td><td>Hours to days</td><td>Hours to days</td></tr>
</table>
</td></tr>
<tr><td>Reaction time</td><td>sec – few min</td></tr>
</table>

Current deployment status	148 GW of demand from all electric space and water heating in ~14 m EU homes in 2013
Owner/developer	Energy companies, aggregators, ESCO
User of Technology	Consumer
Applicable in demo site	☒Demo Portugal ☒Demo Germany ☐Demo Poland ☐None
Cost/Effectiveness	N/A
Services provided	Peak shaving, energy balancing and ancillary services such as frequency reserves, congestion management
Benefits	- Can address a wide range of grid services at different locations / grid scale - Market share of TCL technologies and IOT connectivity is growing
Drawbacks	Residential power to heat is still a small market segment in demand response. Existing heaters have to be converted into smart heater with digital and remote control to unlock the potential flexible capacity. The participation of residential consumers in flexibility market/services is very limited. The customer proposition and business model for valorisation of flexibility is still under investigation. Multiple explicit or implicit barriers exist also to enable residential DR participation (metering costs, lack of BRP/FSP coordination, DSO regulations, etc.) Demand side participation depends on the installation of smart appliances or Home Energy Management Systems (HEMS). Interoperability standards would facilitate the large-scale deployment of demand side flexibility.
Notes	The optimization of a power to heat infrastructure might be specific from one site to another and requires a detailed analysis of the local use cases and technical specificities [3]. Synergies between sites / technologies can then be grouped / clustered as part of DR programs to offer flexibilities at VPP level.
References	(1) Bloess, A., Schill, W.-P., & Zerrahn, A., 2018. "Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials." Applied Energy, 212, 1611–1626. (2) Darby, S. J., 2017. "Smart electric storage heating and potential for residential demand response." Energy Efficiency, 11(1), 67–77. (3) Amblard F., Page J. Menon R.P., Brennenstuhl M. Cipriano J., 2018. « Simulation Supported Real Time Energy Management in Building Blocks ». Ref. Ares (2018)704834 - 06/02/2018. sim4blocks.eu

Time-shiftable smart appliances enabling residential demand-side flexibility

Demand side flexibility is the ability of consumption modification in response to direct control or price signals, provided externally by an aggregator/retailer/DSO or internally by a Home/Building Energy Management System (BEMS/HEMS) [1]. The main technologies providing time-shiftable smart appliances are: washing machines, tumble dryer, dishwashers)

Candidate technologies for DR are typically:

- Time-Shiftable loads – washing machines, tumble dryer, dishwashers
- Sheddable loads

The flexibility potential of these technologies is dependent on the user comfort requirements (time for the end of washing/drying cycles, amongst others). On the other hand, exploiting the flexibility of these loads assumes a local ICT infrastructure (HEMS/BEMS) with the capability of receiving external signals.

Compared to more conventional, smart appliances usually include the following characteristics:

- scheduling of cycle start
- communication interface
- user interface with remote control capabilities and additional services for scheduling, monitoring and control

Table 19. Characteristics of Smart Appliances enabling residential demand-side flexibility

<table>
<tr><td>TRL (1-9)</td><td>9</td></tr>
<tr><td>Power range</td><td>At residential level – 0.2-5 kW</td></tr>
<tr><td>Energy range</td><td>N/A</td></tr>
<tr><td>Power modulation</td><td>The power flexibility of loads differs according to its operating cycle, characteristics and nominal power. Therefore, the flexibility potential will vary along the day. The values presented in the table are average values from [2].
According to the results, the flexibility potential of time-shiftable loads is higher in weekends and during night-time.
<table>
<tr><th>Smart Appliances</th><th>Power increase</th><th>Power decrease</th></tr>
<tr><td>Time- Shiftable loads</td><td>430 kW</td><td>65 kW</td></tr>
</table></td></tr>
<tr><td>Duration time (Power modulation)</td><td>Similarly, the time these different loads can provide a power increase/decrease will also vary. The reference values are presented in the table below according to [2].
<table>
<tr><th>Smart Appliances</th><th>Power increase time (min)</th><th>Power decrease time (min)</th></tr>
<tr><td>Time- Shiftable loads</td><td>1 to 13 hours (5).</td><td>15</td></tr>
</table></td></tr>
</table>

Reaction time	The reaction time will depend not only on the load but also on the communication and control infrastructure. The load itself can be on/off in a matter of seconds.
Current deployment status	Smart appliances are already well established in the market, mostly in premium product lines.
Owner/developer	Final user, aggregator, retailer.
User of Technology	Residential consumer, building owners
Applicable in demo site	☒Demo Portugal ☒Demo Germany ☐Demo Poland ☐None
Cost/Effectiveness	N/A
Services provided	Peak capacity management, Spinning Reserve, Ramping, N-1 contingency,
Benefits	The objective of DR strategies is usually to reduce home/building energy consumption costs, either by shifting the loads to periods of lower prices, reducing peak loads and/or maximizing revenue through the provision of additional DR remunerations schemes.
Drawbacks	The flexibility potential of shiftable loads is limited and automation is required to keep customer engagement (5). Furthermore, similar challenge as with the TCL's for residential demand response can be identified.
References	(1) Federal Energy Regulatory Commission. 2011. "Assessment of demand response and advanced metering". (2) R. D'hulst, W. Labeeuw, B. Beusen, S. Claessens, G. Deconinck, K. Vanthournout. 2015. "Demand response flexibility and flexibility potential of residential smart appliances: Experiences from large pilot test in Belgium." Applied Energy, Volume 155, pp. 79-90. (3) M. Ali, A. Safdarian and M. Lehtonen. 2014. "Demand response potential of residential HVAC loads considering users preferences," IEEE PES Innovative SG Technologies, Europe, Istanbul, pp.1-6 (4) R. Li and S. You. 2018. "Exploring potential of energy flexibility in buildings for energy system services," in CSEE Journal of Power and Energy Systems, vol. 4, no. 4, pp. 434-443. (5) Belmans R. et al. 2014. "Demand Response for Families," The Linear report, Belgium

b. Industrial demand-side flexibility

Demand-side flexibility/ Co-generation (CHPs)

Industrial demand side flexibility is usually dependent on processes involved, which can be energy intensive and may be delayed from some hours to a day. The flexibility potential of industrial loads is very attractive and already considered in several countries for the provision of ancillary services such as balancing reserves, congestion management and contingency support.

According to [1] we can identify three types of industrial loads:

- Load Type Mechanical I – manufacturing process involving mechanical and hydraulic presses, forging presses, grinders, chippers, etc. This type of loads is applicable for on/off control for extended period if needed.
- Load Type Mechanical II – manufacturing process involving machine drives such as pumps, fans, blowers, air compressors, etc. These loads can be modulated with suitable control devices such as Variable Frequency Drives (VFD) or thermostats.
- Load Type Thermal – continuous manufacturing process that is only interrupted for maintenance or production scheduling purposes. Examples are smelters, continuously operating metal heat treatment furnaces, electrolytic cells, induction melting furnaces, etc. Flexibility is highly dependent on the industrial process involved.

Furthermore, CHP's (combined heat and power) is often included in this category, although strictly speaking it could not be considered demand-side flexibility. CHP's convert an energy source e.g. gasoline, natural gas, hydrogen, biomass, etc. to electrical energy and heat.

Table 20. Characteristics of Demand-side flexibility – Industrial loads

TRL (1-9)	9
Power range	Hundreds of kW to tens of MW
Energy range	N/A
Power modulation	The power flexibility of loads differs according to industrial process.
Duration time (Power modulation)	Load shedding – a few hours Load shifting – 1-24 hours
Reaction time	>1 s -15min (for some 2h)
Current deployment status	N/A
Owner/developer	Final user, aggregator, retailer.
User of Technology	Industrial consumer
Applicable in demo site	☒Demo Portugal ☒Demo Germany ☐Demo Poland ☐None

Cost/Effectiveness	N/A
Services provided	Peak capacity management, Spinning Reserve, Ramping, Congestion management, voltage control, Secondary and tertiary reserves, N-1 contingency
Benefits	Industrial flexibility can contribute to improve power system security providing key ancillary services with very high accuracy and reliability, as well as optimize the use of RES. Additionally, it generates a financial income which is often important in competitive energy intense industry.
Drawbacks	The dependence of demand side strategies on industrial processes could be considered a drawback on the deployment of specific flexibility products.
References	(1) Michael Starke, Nasr Alkadi, 2013. "*Assessment of Industrial Load for Demand Response across U.S. Regions of the Western Interconnect*", Oak Ridge National Laboratory.

c. Smart charging (EVs)

Smart charging of electric vehicles, where charging can be shifted based on grid loads and the user's needs.

Smart charging offers a number of advantages by monitoring and shifting EV loads and stands as a direct opposite of the uncontrolled charging. It works by dynamically adjusting the time and speed electric cars charge based on the available power capacity—safely balancing a charging station's energy usage with the other grid loads.

Smart Charging can often be divided into the more common type of Smart Charging – V1G or managed charging. And the more advanced V2X (vehicle to everything), a bi-directional connection between the EV and the grid through which power can flow from the grid to the vehicle and vice-versa.

Table 21. Characteristics of Smart charging

TRL (1-9)	V1G – 8; V2X – 6
Power range	2.7 kW to 400 kW per EV (though few will be up to 400kW)
Energy range	22 kWh to 100 kWh per EV
Discharge time	Discharge time is difficult to quantify in an EV, since it depends on a vast number of variables related to car usage.
Reaction time	Few seconds
Current deployment status	The first commercial smart charging programs are being implemented in Europe
Owner/developer	Flexibility service providers, energy suppliers, DSO's, car manufacturers (e.g. Tesla)

User of Technology	DSO, TSO, Retailer (through dynamic tariffs), Flexibility service provider
Applicable in demo site	☒Demo Portugal ☒Demo Germany ☐Demo Poland ☐None
Cost/Effectiveness	Case studies in Spain have demonstrated that the scale of savings in terms of distribution network cost avoidance are: at 15% of EV penetration, smart charging allows for substantial savings of more than EUR 1 billion compared to business as usual. The costs of distribution grid reinforcement with smart charging can be 3 times lower.
Services provided	Load balancing, peak shaving, voltage control, energy storage, ancillary services, energy trading, congestion management
Benefits	Reduces grid connection costs. Avoids grid investment. Shares benefit with consumers (through dynamic tariffs as well). Allows other flexibility stacks.
Drawbacks	Consumer adoption of technology. EV charging priorities are difficult to measure. A limited household connection often limits the flexibility potential of the EV. Fear to damage the life of the EV's batteries.
References	(1) Endesa, 2014 (2) IRENA, 2019. "*Innovation Outlook: Smart charging for electric vehicles*." International Renewable Energy Agency, Abu Dhabi. (3) EDSO, 2018. "*Smart charging: integrating a large widespread of electric cars in electricity distribution grids*". (4) Smart Electric Power Alliance, 2019. "*A comprehensive guide to electric Vehicle Managed Charging.*"

2.4.3 Distribution network flexible assets and control (MV and LV control)

Distribution network operation is mostly based on the control of its assets such as switches, On Lead Tap Changers (OLTCs) and capacitor banks to ensure adequate power quality and continuity of service, as well as minimize network losses.

Voltage and reactive power control are critical to ensure efficient and secure operation across all voltage levels of the power distribution grid. In order to limit grid losses, voltage levels have to be kept as high as possible, within the limits imposed the grid components and acceptable voltage fluctuations at each node.

While the frequency is managed at system level using control of active power flows, voltage control is a localized issue that relies on exchanges of reactive energy.

In distribution grids, at HV and MV, the voltage control is mainly influenced by the reactive power control. However, in the LV grids, the active power may have an important role in voltage control LV networks are typically three-phase four-wire networks. The high R/X ratio of LV cables limits the efficiency of reactive power control for maintaining voltage within limits. In a network with longer feeders, it could make sense to consider the participation of units from neighbouring nodes and active power control. For instance, the high integration of photovoltaic (PV) in LV grids can cause overvoltage. That overvoltage can be solved for both the active power and reactive power of PV inverter.

At the same time, minimizing energy losses and avoid congestions can be achieved through network reconfiguration.

In terms of DSO owned assets, the following technologies can be used for voltage control, congestion management and service restoration:

- Capacitors (reactor or self)
- OLTC
- Network reconfiguration and outage planning
- Limitation of active flows, to keep lines in capacitive range (increase active flows, inductive range)
- MVAR import from neighbouring grids (MVAR export)

These resources are controlled either by local automatic functions and/or in centralized Volt/Var Advanced Distribution Management System (ADMS) applications.

Reactive power management assets owned by the DSO are generally limited to provide voltage regulation at the secondary substations. For lower voltage levels, the cost of capacitor banks will strongly limit the adoption of such means.

On the other hand, reactive power obligations from grid users – especially decentralised production units - connected at distribution side is becoming a significant source of flexibility for voltage control.

The current regulation (Mandatory Network code for requirements for grid connection) states that non-controlling production units below 25MW (generally connected in distribution) must be able to deliver manual control, activated following grid operator request. For each participating technology assets, a specific capacity band is contractually agreed. Article 70 under the same regulation states that *any non-controlling production unit must be able to adapt its supply of reactive power to the requirements of the grid (at the very least via commutation of its reactive power production between two levels agreed between the system operator and the grid user concerned.*

When it comes to assessing the replicability of this to distribution systems, it also should be highlighted that DSO will be subject to an increased pressure to coordinate with TSO with regards to voltage management. The Network code for system operations states in Art.27 §3 that TSO can take actions on their connected DSO. They may instruct to block automatic voltage and reactive power control of transformers, but also activate on the DSO facility the remedials actions (tap changes of power transformers, switching of power-electronics-based voltage and reactive power management device). If voltage deterioration jeopardises operational security or threatens to lead to a voltage collapse in a transmission system.

In the same code, DSO are therefore legally entitled to give voltage instructions to their own users. Article 29 states that Each TSO shall agree with the transmission-connected DSO on the reactive power set points, power factor ranges, and voltage set points for voltage control at the connection point between the TSO and the DSO. To ensure that those parameters are maintained, each DSO shall use its reactive power sources and have the right to give voltage control instructions to distribution-connected significant grid users.

This code can be translated into technical requirements, taking following technical and operational aspects into account:

- Assets at a lower voltage level are less efficient to regulate a much higher level (i.e. an asset in a 10kV has very little effect on 380kV voltage).
- To automatically regulate voltage, an asset injecting or absorbing energy needs to be (electrically) close to the voltage measurement level.
- TSO will require a service at the T-DSO interface, which is the limit of its controlling & responsibility perimeter.
- DSO's need to regulate themselves to remain within certain reactive power limits at the T-DSO interface, for which they are subject to an "additional MVAR" tariff. Any action taken within their grid should be coordinated with their energy management system so that it doesn't impede with their own regulation.

Table 22. Characteristics of Distribution network flexible assets and control (MV and LV control)

TRL (1-9)	9
Power range	N/A. (expressed in MVAR)
Energy range	N/A. (expressed in MVARh)
Discharge time	Vary from seconds to minutes to cope with voltage fluctuations. Voltage band is to be respected at all times.
Reaction time	Automatic (<sec) or manual (upon request)
Current deployment status	Own DSO assets are already available but limited to initial design assumptions (example of tap changers or existing capacity banks at HV/MV secondary)
Owner/developer	DSO, DSO-connected grid users
User of Technology	TSO, DSO
Applicable in demo site	☒Demo Portugal ☒Demo Germany ☒Demo Poland

	☐None
Cost/Effectiveness	100% (in terms of reactive power)
Services provided	- Maintain voltage within operational limits at each node - Maintain voltage within operational limits at each access point - Maintain the reactive balance at 0 within limited zones - Ultimately, but not a DSO responsibility, maintain the reactive balance for the balancing zone - Avoid or solve congestion problems, - Support during service restoration procedures Automatic control (supply of reactive power in the event of slow voltage fluctuations, over a period of minutes, and quick voltage fluctuations, over a period of a fraction of a second) and manual (upon request).
Benefits	Ensure operational security
Drawbacks	Localised nature of this flexibility source prohibits to have a competitive level playing field for ancillary service providers
References	(1) Entso-e network code System operations (2) Entso-e network code for requirements for grid connection (3) Villar, J.; Bessa, R.; Matos, M. 2018. "*Flexibility products and markets: Literature review.*" Electr. Power Syst. Res. 154, 329–340.

2.4.4 Renewable self-consumption solutions and Microgrids

This subsection includes two potential flexibility resources of flexibility for DSO toolbox: **a)** Renewable self-consumption and **b)** Micro-grids. Renewable self-consumption is defined as electricity that is produced from Renewable Energy Sources (RES) for minimizing individual or collective energy consumption. Self-consumption ratio can be increased by complementing with local storage devices and demand response strategies.

Regarding the Microgrid, it is composed of the different technologies that can provide strong resilience for places (for ex, in the case if hurricane hits a region and main grid is not operational) therefore providing flexibility to larger system. Its management and control architecture allows it to be controlled with a common goal (maximizing self-consumption/minimizing costs) that increases its total load flexibility. On the other hand, it could also provide specific services such as islanding, frequency/voltage regulation, blackstart that results not only from its technology but from the microgrid control structure.

a. Renewable self-consumption

Renewable self-consumption solutions are applicable for individual residential, commercial and industrial consumers or collective consumers such as buildings and energy communities. Self-consumption includes the following technologies:

- Photovoltaic panels sized according to the load diagram.
- Maximum Power Point Tracking (MPPT) and charger controller, for maximizing panels efficiency and for controlling battery charging. This controller might not be needed if the PV and batteries are connected to distinct DC/AC inverters.
- Solar inverter converts the direct current generated by the photovoltaic panel into alternating current.
- Battery energy storage that maximizes the use of RES in cases where peak load does not occur in hours with higher RES availability. This is typically the case of residential consumers.

The main objective of self-consumption solutions is to reduce energy consumption from the grid. However, considering the mismatch between load and generation as well as the integration of local storage capacity, additional flexibility services could be envisioned.

Table 23. *Characteristics of Renewable self-consumption solutions*

TRL (1-9)	8-9
Power range	From few W to kW
Energy range	Few Wh to > hundreds kWh
Power modulation	From few W to a few kW Power modulation of PV based self-consumption solutions will depend on the difference between the power generated and the load. If storage its installed, the maximum capacity could be limited to the energy storage power capacity.
Duration time (Power modulation)	Typically for a few minutes to 1 hour maximum
Reaction time	Immediate <1s, if storage is considered or PV inverter control

Current deployment status	Individual and collective self-consumption schemes are being implemented in the majority of European countries, according to Clean Energy Package directives.
Owner/developer	Individual consumers, aggregator, retailer, energy communities.
User of Technology	Individual consumers, energy communities
Applicable in demo site	☒Demo Portugal ☒Demo Germany ☐Demo Poland ☐None
Cost/Effectiveness	N/A
Services provided	Peak capacity management, Spinning Reserve, Congestion management, voltage control, Secondary and tertiary reserves
Benefits	Self-consumption enables the use of RES and has an indirect impact on reducing loads in distribution grids. Depending on the technologies adopted it can maximize its value through the provision of additional flexibility services.
Drawbacks	As for the demand response schemes, there are still regulatory limitations that do not allow the participation of residential consumers in flexibility market/services is very limited. In most countries the minimum capacity allowed limits participation to medium-large loads connected to the MV-HV distribution or transmission networks.
References	(1) SMA. 2010. *The self-consumption bonus*. URL: https://www.sma.de/en/partners/knowledgebase/the-self-consumption-bonus.html (2) SMA. *Increased Self-Consumption with SUNNY ISLAND and SUNNY HOME MANAGER. SMA Flexible Storage System*. Germany. (3) Solar Edge. 2018. *StorEdge Solution Applications with the StorEdge Interface and LG Chem Batteries – Connection and Configuration (Europe, APAC, South Africa).*

Microgrids

Microgrids are defined as electricity distribution systems at LV level integrating loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded.

Microgrids can be defined as a single self-controlled entity which provides power and heat to its customers and meets local reliability and security needs. The Microgrid power infrastructure is overlaid by monitoring and control structure promoting a coordinate control between DER and loads for optimal operation in interconnected mode and allowing autonomous operation.

The microgrid integrates distinct DER, namely RES and low carbon generation technologies, storage and responsive loads. Storage is a key element of the microgrid, acting as a buffer for RES variability and enabling autonomous operation.

Table 24. *Characteristics of Microgrids*

TRL (1-9)	8-9
Power range	From few kW to a few MW
Energy range	Few kwh to >10 MWh
Power modulation	From few kW to a few MW The power modulation results from the aggregated control of microgrid resources. The maximum capacity is limited to the energy storage power capacity.
Duration time (Power modulation)	Typically for 1-2 hours maximum
Reaction time	Immediate <1s considering fast energy storage devices and local control strategies of flexible loads
Current deployment status	Microgrid concept has been applied to campus, neighbourhoods, industrial parks, energy communities, hospitals and remote villages.
Owner/developer	Aggregator, retailer, community microgrid owners.
User of Technology	Microgrid owner, community microgrid communities
Applicable in demo site	☒Demo Portugal ☐Demo Germany ☒Demo Poland ☐None
Cost/Effectiveness	N/A
Services provided	Peak capacity management, Spinning Reserve, Ramping, Congestion management, voltage control, Secondary and tertiary reserves, N-1 contingency, generation optimization, islanding, black start capability.
Benefits	Microgrid systems allow maximizing renewable usage, minimize global operation costs and improve resilience by enabling autonomous operation. Their decentralized control endows the system with improved flexibility for providing grid support services to both distribution and transmission system.
Drawbacks	- Electrical energy needs to be stored in batteries which require space and maintenance.

	- Re-synchronization with the main grid can be a problem. - Issues such as standby charges as well as net metering are obstacles for microgrids. - Microgrid protection is an obstacle standing against the implementation of microgrids. (difficult to detect faults in isolated mode). - To ensure consistency, interconnection standards need to be developed. - In islanding mode, the microgrids need to have proper control strategies for power-frequency control and voltage control, coordinating the operation of the storage device, microgenerators and responsive loads
References	(1) J. Peças Lopes, A. G. Madureira, C. Moreira, 2013. "A View of Microgrids", Wiley Interdisciplinary Reviews: Energy and Environment, vol.2, no.1, pp.86-103, Janeiro, (2) R. H. Lasseter, 1998. “Control of Distributed Resources,” Bulk Power System and Controls IV Conference, August 24-28, Santorini, Greece. (3) L. Che, M. Khodayar, M. Shahidehpour, 2014. “Only Connect: Microgrids for Distribution System Restoration,” IEEE Power and Energy Magazine, vol. 12, no. 1, pp. 70–81, Jan. (4) Electric Power Research institute (EPRI), 2013. "Microgrid: A Primer", Draft report, September.

2.4.5 Dynamic line rating (DLR)

Dynamic Line Rating (DLR) System is the mean for providing the flexibility of the HV power lines transmission capacity resulting from weather depending condition. In most cases, the DLR System can handle technical constraints and solve the expected short-term congestions, thus it might deliver the network flexibility service.

DLR System can also be utilized in terms of long-term perspective to improve the grid planning process based on cost-effective sources of flexibility.

The aim of DLR is to safely utilize existing Over Head Lines (OHL) transmission capacity resulted from actual weather conditions in which the power lines operate. This DLR aim can be utilized in the short- and long-term perspective. In the short term, it allows more efficient power dispatch by avoiding the so-called "bottleneck" and adjust the OHL line load, in such a way that all the time in every span the distances to the earth will be kept within the normative limits thus improving the safety of operation.

In short and medium-term perspective (from an hour, several hours to a day) it is required on intra-day and next-day markets to plan the generation volume to balance the forecast demand or to plan the resources resulting from the erroneous forecasting of renewable generation with a variable nature of work.

From a long-term perspective, DLR System can allow enhancing the capacity of the line, which may be utilized by others instead of limiting the production, especially from predictable renewable resources

Dynamic thermal rating is not a substitute of grid development, but a complementary method to better exploit existing infrastructures

Utilized by DLR system the indirect method of line temperature calculation, based on data from weather stations, constitutes the best solution, since it not only allows the cross-checking of the acquired data, but above all, allows short term (up to several hours) and in the long term the capacity of the line forecast.

The quality of the local weather forecast is therefore of crucial importance for the accuracy of permissible load estimation.

Table 25. *Characteristics of Dynamic line rating (DLR)*

TRL (1-9)	8-9
Power range	10 MW – 100 MW
Energy range	up to 1 GWh
Discharge time	few hours
Reaction time	up to 10 min
Current deployment status	Deployed in the Polish distribution and transmission network. Within the last 5 years deployed in Polish DSOs (3 out of 4 DSOs) including DSO ENERGA and Polish TSO (PSE)
Owner/developer	Institute of Power Engineering (*Instytut Energetyki*)
User of Technology	TSOs and DSOs.

Applicable in demo site	☒Demo Portugal ☒Demo Germany ☒Demo Poland ☐None
Cost/Effectiveness	20 k€ per one HV line (Significantly less in case of multiple lines)/RoI less than 4 years and less than 2 years in terms of avoided cost
Services provided	Estimation of the flexible permissive line capacity for few hours ahead Solving the short-term congestion of the load of the lines Expected short-term congestion solving and offering flexible permissive line capacity in few hours ahead Long term and contingency analysis and investment optimisation.
Benefits	Low investment costs, easy to deploy, high accuracy of permissible load estimation. No calibration is required, ageing of the line and absorptivity and emissivity coefficient of the conductor surface is considered by the DLR system.
Drawbacks	It requires SCADA/ EMS system which allows data exchange between DLR System and SCADA/EMS System
References	(1) ENTSO-E RGCE SPD WG 2015 Dynamic Line Rating for overhead lines, CE TSOs current practice. ENTSOE Report. www. entsoe.eu (2) Babś and T. Samotyjak, 2016. *Dynamic Rating of 110 kV Overhead Lines*. Acta Energetica, vol. 3, no. 28, pp. 4-9, Jul. (3) Babs A. 2015. *Weather conditions based wide area Dynamic Line Rating system for 110 kV network monitoring and contingency analysis.* In CIGRÉ Canada Conference, Winnipeg, Manitoba.

2.4.6 Active power control of RES – in example of German Redispatch 2.0 (schedule-based congestion management)

Adaptation of the feed-in from Renewable Energy Sources by a schedule-based congestion management. The active power is reduced where the feed-in has a reinforcing effect on congestions and is compensated by other generators relaxing the bottleneck. An essential basis for this is a predictive state estimation. To find the most cost-effective solution an iterative process between the System Operators is implemented, which is particularly considering the sensitivity of the generator to the congestion, starting 36h and ending 15min before the actual time.

The process is also included into the regulatory framework in Germany and in action October 2021 in order to deal with constantly increasing congestion occurrences and decreasing conventional flexibility potential in the grid.

In Germany, it is expected that by 2030 the share of RES will have increased by up to 65%. Already today there is a high RES share (~40% RES in Germany and ~100% in the German demo region since 2017), especially wind power in north eastern Germany, which requires substantial redispatch measures to avoid overloading transmission and distribution assets. As per current regulatory framework, only conventional power plants with an installed capacity of more than 10 MW are integrated in a schedule-based congestion management (redispatch). Because of these limitations the redispatch potential in the transmission grid is reaching its limits due to the minimal capacity of conventional power plants and decreasing level of installed capacity in conventional plants. Therefore, emergency measures are used to curtail RES in the distribution grid, which is leading to increasing costs. Taking this into consideration, in 2021, a new regulatory framework for congestion management will come into force in Germany.

The future regulatory framework includes RES in the redispatch process in order to deal with constantly increasing congestion occurrences and decreasing flexibility potential in the grid. For this purpose, a multi-stage and iterative process is implemented which is based on a foresighted grid state analysis. The analysis shows, first, the expected own congestions and the necessary measures to eliminate them. Secondly, the analysis provides information about the usability of redispatch capacity in the own grid for other system operators without creating new congestions or aggravating existing ones. Security and efficiency are thereby guaranteed by the coordination between the system operators.

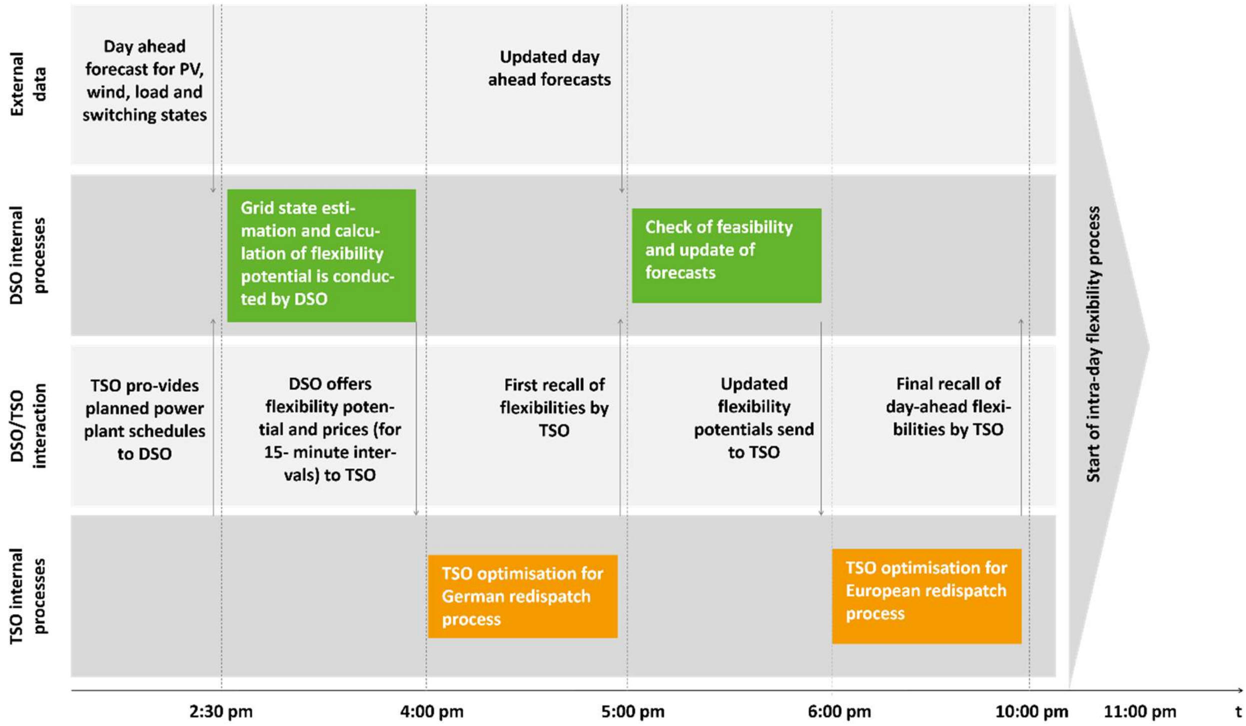

Figure 1. Redispatch Process day-ahead

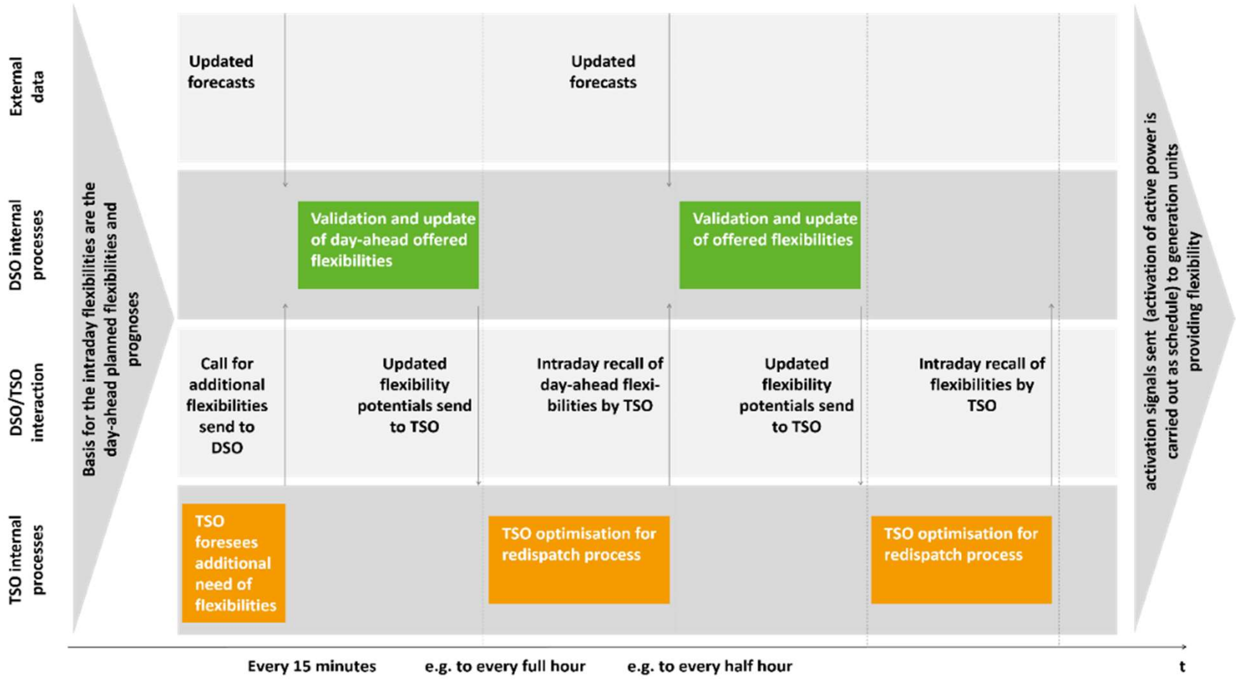

Figure 2. Redispatch Process intraday

Table 26. *Characteristics of Active power control of RES – in example of German Redispatch 2.0 (schedule-based congestion management)*

TRL (1-9)	8/ 9* (*In Action October 2021)
Assets taken into account	RES plants from 100 kW and above mandatory smaller plants voluntary
Power range	high (theoretically up to GWs)
Process Timeframe	36h - 15min before real time
Current deployment status	In implementation at German system operators
Owner/developer	Regulatory Authority
User of Technology	TSOs and DSOs
Applicable in demo site	☒Demo Portugal ☒Demo Germany ☒Demo Poland ☐None
Cost/Effectiveness	High - significant savings through the use of further decentralized flexibility resources in addition to the generators
Services provided	- To solve network congestions by re-dispatch at the lowest possible total cost - Increase the adaptability of the power system - Limit grid expansion - Prevention of imbalances
Benefits	- Cost Efficiency - plan-value based process - foresighted grid state analysis - coordination between system operators
Drawbacks	Need for coordination between system operators
References	(1) BDEW. 2020. *Redispatch 2.0. Branchenlösung im BDEW*. Berlin. URL: https://www.bdew.de/energie/redispatch-20/

2.5 Grouping of technology by attributes

EUniversal proposes to assess the feasibility of flexibility solutions such as energy storage technologies (e.g. batteries, hydrogen), power-to-heat, demand response and variable generation when operating autonomously or in coordination, as in the case of energy communities, microgrids or multi-energy systems. There is a broad set of flexibility services that can be potentially listed according to their attributes (flexibility at short, medium or long term; installation at customer, distribution and transmission level etc.).

In this section, the different technologies have been categorised following some of the main attributes that can be related to them, among which it is possible to find two main groups, namely Service provision and Deployment location. It has to be noted that flexibility technologies (such as batteries) are capable to provide flexibility for long time technically, but economically it is not cost effective.

Under service provision, the attributes can be defined as follows:

- Flexibility at short-, middle and long-term: by definition, flexibility will result from the capacity to change the load/generation and it was grouped three time-periods. Flexibility at short-term refers to a period that goes from some minutes to some hours, medium-term from some days to some months, and long-term to any longer period.
- Reactive power: Imaginary component of the power vector that allows the whole system to maintain a constant and controlled voltage supply. If reactive power does not work correctly, there could be damages to the devices used in an electric system, such as transformers, capacitors, generation, transmission, and distribution equipment.
- Active power: real component of the power vector that produces the electricity used to power devices.
-

Under deployment location, it is possible to find:

- Transmission grid: section of the electricity grid, used to transmit huge amounts of electricity, at a very high voltage (to decrease losses as much as possible). Commonly referred to as EHV, or Extremely High Voltage, the voltage in the transmission grid ranges between 220 kV and 760 kV.
- Distribution grid: section of the grid characterised by a lower voltage range, between 0.6 kV and 33 kV for Medium Voltage (MV) and 33 kV and 220 kV for High Voltage (HV). Through the distribution grid electricity is brought to residential customers.
- Commercial & industrial: attribute that refers to the feasibility of the technology to be installed in a commercial or industrial base.
- Residential consumers: attribute that refers to the feasibility of the technology to be installed in a house
-

As referred previously, this report considered technologies with high TRL. Therefore, the classification in Table 27, is based on the expected evolution of the technologies and its costs.

Table 27. Flexibility Toolbox

Name of Solution	Attributes								
	Service provision					Deployment location			
	Flexibility at short term	Flexibility at medium term	Flexibility at long term	Reactive power	Active power	Transmission grid	Distribution grid	Commercial & Industrial	Residential consumers
CAES	☺ (green)	☺ (green)	☺ (green)	☺ (red)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (red)
LAES	☺ (green)	☺ (green)	☺ (green)	☺ (red)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (red)
LHS	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (red)	☺ (green)	☺ (green)
SHS	☺ (green)	☺ (green)	☺ (green)	☺ (red)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)
PHS	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)
TCS	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)
Power to Hydrogen	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (red)
Supercapacitors	☺ (green)	☺ (red)	☺ (red)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (red)
Lead-acid Batteries	☺ (green)	☺ (green)	☺ (red)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)
Li-Ion Batteries	☺ (green)	☺ (green)	☺ (red)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)
Li-Polymer Batteries	☺ (green)	☺ (green)	☺ (red)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)
Li-S Batteries	☺ (green)	☺ (green)	☺ (red)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (red)
Metal-air Batteries	☺ (green)	☺ (green)	☺ (red)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (red)
Na-S Batteries	☺ (green)	☺ (green)	☺ (red)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (red)
Vanadium Redox Batteries	☺ (green)	☺ (green)	☺ (red)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (red)
DLR	☺ (green)	☺ (red)	☺ (red)	☺ (red)	☺ (green)	☺ (green)	☺ (green)	☺ (red)	☺ (red)
Residential DR – TCL's	☺ (green)	☺ (green)	☺ (red)	☺ (red)	☺ (green)	☺ (red)	☺ (green)	☺ (green)	☺ (green)
Residential DR /Shiftable loads	☺ (green)	☺ (red)	☺ (red)	☺ (red)	☺ (green)	☺ (red)	☺ (green)	☺ (green)	☺ (green)
Industrial loads	☺ (green)	☺ (green)	☺ (red)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (green)	☺ (red)
Microgrids	☺ (green)	☺ (green)	☺ (red)	☺ (green)	☺ (green)	☺ (red)	☺ (green)	☺ (green)	☺ (green)
Smart charging	☺ (green)	☺ (red)	☺ (red)	☺ (red)	☺ (green)	☺ (red)	☺ (green)	☺ (green)	☺ (green)
Distr. network flexible assets and control	☺ (green)	☺ (red)	☺ (red)	☺ (green)	☺ (red)	☺ (red)	☺ (green)	☺ (red)	☺ (red)
Renewable self-consumption solutions	☺ (green)	☺ (red)	☺ (red)	☺ (green)	☺ (green)		☺ (green)	☺ (green)	☺ (green)
Active power control of RES	☺ (green)	☺ (red)	☺ (red)	☺ (red)	☺ (green)	☺ (green)	☺ (green)	☺ (red)	☺ (red)

3 Limitations and recommendations

Limitations

As noted above, the development of a flexibility toolbox requires balancing the need for high level of detail in terms of technologies covered and ensuring a simple, usable overview of the different technologies.

One of the main limitations is the lack of recent, verifiable data for some technologies. For instance, it is very difficult to assess the cost-effectiveness of different flexibility solutions in a comparable way: there is no metric akin to a "levelized cost of energy" (€ per kWh) for flexibility. The best way to approach this issue would be to define a set of use cases and then assess the cost across the different solutions for the provision of this use case. However, this is beyond the scope of this paper.

Rapid technology developments also render data collection more difficult, as data that are available in literature are quickly outdated. This overview sought to collect the best available data, but not all data is available and, in some cases, information is not comparable across different technologies.

Some limitations must be taken into account when considering the flexibility technologies themselves. Many of the flexibility toolbox solutions are not yet widely deployed on the market. Additional research, development, deployment, and pilot projects are needed in order to fully support the market readiness of some technologies. In the area of energy storage, these efforts should address cost reductions; improvements in energy density and overall performance; safety and sustainability; system integration aspects; and research into energy storage business cases.

The flexibility toolbox should enable matching flexibility solutions to specific services. This first requires clearly defining the different flexibility services and their technical requirements. As far as possible, this should be done in a technology neutral way: requirements, including tendering and prequalification, for flexibility services must be designed in such a way as to allow free competition between the various flexibility solutions so that the best solution for a given service in a given location is chosen. Services should be designed and tendered in such a way that it allows for a profitable business case for flexibility solutions; e.g. energy storage facilities should be able to combine the provision of various flexibility services to ensure a robust business case.

Although the flexibility solutions identified above should be technically capable of providing flexibility, some may be limited in practice due to outdated regulation and policy decisions in some EU Member States. In some Member States, stand-alone energy storage facilities are not able to apply for a grid connection or to participate in ancillary services markets. Implementation of the Clean Energy for All Europeans package should eliminate some of these barriers, although implementation speeds will likely vary across the EU. This means that there will still be significant barriers to entry for some flexibility technologies in the years to come.

To address the limitations that must be taken into account for flexibility technologies to become deployed in the market, the following subsection will look at and consider each technology group individually. Firstly, it must be considered that in general storage technologies have high costs. When talking about **storage electrochemical technologies**, low market price volatility hinders necessary investments due to low operating costs for generation and loss of importance for day-ahead markets and long-term price signals. Optimal localisation for storage technology can be facilitated with the involvement of DSOs since they are the only party with the complete overview in the distribution system. Moreover, administrative and operation procedures are designed for generation units, and do not consider the technical particularities of batteries. The following key characteristics are needed for participation of batteries in providing flexibility service:

1) The minimum services duration should be 0,5-1 hour.
2) To include a mechanism for battery SoC (State of Charge) adjustment (this is a fundamental aspect as batteries have a limited capacity).
3) To provide bonus for fast and accurate response (e.g.: fast dynamic response of less than 1 second).
4) Distribution or transmission grid tariffs can have a significant impact on the business case.

Residential demand-side flexibility represents a very important flexibility resource for future distribution networks, particularly for low-voltage and medium-voltage with large-scale integration of renewable energy resources. However, market participation is still scarce mainly due to regulatory limitations. From the technological point of view, the participation of residential and small-scale commercial consumers, depends on the installation of smart appliances and HEMS. Compatibility between appliances potentially HEMS and interface with the aggregator/retailer needs to be ensured for enabling large scale deployment of solutions. Different improvements can be identified to incentivize residential customers to participate in DR programs, e.g. allowing aggregation, avoiding the need for additional, costly metering equipment and reducing the required amount of data transfers, a coordination mechanism for flexibility usage between the Balanced Responsible Party (BRP) and Flexibility Service Provider (FSP), lower barriers for customer acquisition such as digitalising the onboarding process, etc.

On the other hand, the flexibility potential of industrial loads is high, considering its size and power modulation capacity. However, **industrial demand side flexibilit**y is highly dependent on the industrial process, requiring dedicated management and control solutions. A specific issue can be identified for industrial DR that has a very low availability cost but a high activation cost. Non-remunerated availability tests or capped activation prices hinder these assets to provide their flexibility to the energy system.

Customers should be incentivised with demand response schemes like variable capacity agreements and price signals as well as critical peak pricing. However, with a **smart charging** system in an 'open loop' the customer decides to take the offer of off-peak periods or not. Thus, DSOs are hindered about the acceptance and effectuation of smart charging beforehand. Even though the decision should always stay with the customer and it should be kept like this 'delayed charging' offers and apps which indicate a low tariff to start charging remotely, can still cause off-peak sharp demand increases when the low tariff begins and a large number of EVs will start the charging process simultaneously. DSOs face then the issue of managing the grid within the limits of the capacity. To prevent grid reinforcements in networks with large EV shares, grid operators should be able to make offers to or buy flexibility from EV customers to modulate the power or shift the EV charge to avoid high peak load, based on agreements between DSOs and customers. Proposing a variable capacity contract to limit required capacity. Additionally, limitations on smart charging have demonstrated to be heavily cemented on the uncertainty of the number of EV's to manage (and their impact on the grid as flexibility tools) and the uncertainty around EV owner participation, since the asset is, most often, a particular owned one.

For lower **voltage** levels, the cost of capacitor banks will strongly limit the adoption of such means (for voltage regulation). Assets at a lower voltage level are less efficient to regulate a much higher level (i.e. an asset in a 10kV has very little effect on 380kV voltage). To automatically regulate voltage, an asset injecting or absorbing energy needs to be electrically close to the voltage measurement level. TSOs will require a service at the T-DSO interface, which is the limit of its controlling & responsibility perimeter.

Flexibility of controllable loads or distributed storage devices is key for increasing **self-consumption** capabilities. In this sense, additional load and storage flexibility could be used to provide additional services and maximize the value of these solutions. As for the demand response schemes, there are still regulatory limitations that do not allow the participation of residential consumers in flexibility market/services. However, considering EU market directives this should change in near future. On the other hand, interoperability issues are also relevant in this case, considering that most solutions are integrated products for solar, storage and load control.

The implementation of the **Microgrid** concept either at a community or a single commercial or industrial consumer level, will allow to increase self-consumption and at the same time improve resilience by enabling autonomous operation. The autonomous operation is quite challenging in terms of automation and protection and still requires for dedicated standards and regulation. However, it could also offer the opportunity to distribution networks improve their self-healing strategies and to develop bottom-up service restoration strategies, supported by microgrids established at the low and medium voltage networks.

The cost of the **Dynamic Line** Rating (DLR) system based on weather conditions measurement consists of: firstly, equipment cost installed on the HV line poles and secondly, the cost of software system for gathering measurement data and permissible line load calculation. Weather measurements allow very precise short-term weather forecast and calculate the scope of offered flexibility service related with the line. The reduced version of the DLR system may calculate permissible line load based only on the weather forecast delivered by a third party. In this case, will not be the feedback related to the accuracy of the weather forecast and permissible line load calculation.

The regulations for the extended **redispatch process (Redispatch 2.0)** were included in German law (NABEG) and must be implemented by all market partners in Germany, including network operators, plant operators or direct marketers from 1 October 2021. In the Redispatch 2.0 process, iterative (restricted) planning data deliveries are required for all offer-dependent assets in both the forecast model and the planned value model. Schedules have to be agreed between various system operators on distribution and transmission level. Concerning the overall process; a central limitation of re-dispatch is the exclusion of loads by regulation. If loads were available for redispatch, this could reduce the cost of redispatch. Additionally, there should be an incentive for market parties to provide good schedules with relevant locational information to the system operators, which is crucial to get a proper forecast for congestion management. Information on flexibility resources that are pre-qualified or are seeking participation in congestion management and balancing should be shared and available (typically nationally) for both TSOs and DSOs, through a flexibility resources register. TSOs and DSOs jointly recommend that the concept of flexibility resources register should be acknowledged at the European level and the implementation should be decided on a national level.

Recommendations

Most relevant flexibility solutions are identified and analysed from the point of view of their capability to be employed as reliable alternatives and to provide flexibility services to the distribution grid. It can be deduced that most of the evaluated flexibility technologies do have a sufficient technology maturity to be considered as solutions today. Majority of energy storage resources look quite promising as most of them moved forward from Research and Development phase. Still few technologies involve testing new ideas, as in case of battery technology, with approaches ranging from using cheaper, more available input components; to improving energy density of existing designs or extending the lifetime and performance ranges of storage options.

Overall, wide assortment of solutions (Metal-Air, LHS, TCS, Red-Ox etc.) have reached Demonstration and Deployment phases by benefiting government funding support and entrepreneurially-led technology start-up companies. A few of these options have reached a sufficient state of technological and commercial development so that they can be considered by DSOs. These include pumped hydropower energy storage systems (PHS) and most of battery energy storage systems (Supercapacitors, Li-Ion etc.). These technologies have characteristics that make them suitable for consideration by the grid. It is worth noting that both pumped hydro and compressed air systems can provide large-scale electricity storage and load-shifting capacity, typically in the hundreds of megawatts (MW), but their deployment is limited by the availability of suitable sites and seasonal variations - for reservoir development at differentiated altitudes in the case of pumped storage and for the limited commercial experience, system complexity, and geographical requirements of the technology. For grid scale applications, battery storage solutions could also be used, such as conventional lead-acid and sodium-sulphur batteries, as well as more recently developed lithium-ion batteries. However, these do not seem to be as suitable for larger loads.

Based on characteristics and criteria, the most prominent flexibility resources would include battery energy storage systems, pumped hydro, demand response, smart charging and hydrogen storage systems. Although few evaluated flexibility resources do have a sufficient technology maturity, almost all the selected flexibility resources will be readily deployable from 2030 onwards and to be considered as “off-the-shelf” solutions.

Based on the findings from the toolbox, DSOs can consider in which applications, electricity storage can be deployed to reinforce existing grid-based systems. On the other hand, the efficient use of flexibility resources may change in accordance with national or regional differences. This will likely require working with regulators to jointly agree on the framework and return implications while considering the expected improvement of system performance. Following framework, not exhaustive, can be considered:

> *The regulatory framework should enable the development of a full range of possible flexibility resources, while also ensuring that it is robust enough to deliver the best outcomes for stakeholders and the system as a whole. National Regulatory Authorities should ensure that no options are prematurely ruled out.*
>
> *All flexibility solutions that benefit the grid, including storage and demand side response, should be treated in a non-discriminatory manner when procured by network operators. Regulatory incentives should avoid any bias towards specific technologies that deliver flexibility.*
>
> *The relevant regulatory framework should be non-discriminatory and should not hinder or unduly disincentives DSOs from facilitating the development of flexibility.*

Since there is no one-size-fits-all-model because of national and regional differences (even between the DSOs in the same Member State) a framework based on common principles should be preferred.

Further recommendations will be provided as follows to different technology groups, because individual characteristics and aspects must be considered. For starters, a clear definition for **electricity storage** in the EU legislation is currently missing; thus, authorities should apply fair fees and avoid double taxation, once when stored in the storage facility and once when consumed by the final consumer. Second, selling flexibility services should be left to the market and buying flexibility services should be also allowed for network operators.

When talking about **Demand-side flexibility technologies,** enabling flexibility services requires the adoption of standard interfaces in order to ensure interoperability between the flexibility technologies, monitoring and control devices, market platforms and DSO systems.

To make **smart charging** feasible it is needed to implement standardised requirements aligned with regulation governing the electricity network to reduce and mitigate power quality issues. Furthermore, active involvement of DSOs in the planning and development of LV/MV networks is required to effectively forecast and integrate electric vehicles' loads and other flexible resources. Charging infrastructure should be equipped with the necessary technical and communication devices to manage the charging process particularly at the low-voltage level, where most of the charging is taking place (EDOS, 2018). The additional electricity consumption (kWh) from charging EVs is not the challenge, but the instantaneous capacity demand (kW) on low-voltage grids. In case of quick and ultra-fast chargers (>350 kW), the impact on the network can be considerable. A proactive dialogue with DSOs could speed up the installation of these chargers at MV connections, as well as maximise renewables and/or integrated storage capacity. With the operational model of 'grid-to-vehicle' (G2V) by shifting charging to periods of lower electricity demand and 'vehicle-to-grid (V2G) by discharging power from the car battery to the grid additional flexibility can be brought to the grid. Interoperability of data and coordination between all charging infrastructure and e-mobility management systems is critical to communicate with all parties. A key issue is communication of available capacity between the DSOs' and, respectively, the charging point operators' control systems, as defined in open standard interoperability protocols. Additionally, the biggest use case surrounding smart charging from the DSO point of view is to avoid an over-dimensioned grid and the costs associated with its reinforcement. The regulatory framework should allow to provide incentives (e.g. flexible tariffs) to control the amount of energy drawn by EV's or remotely control it in emergency situations.

In order to cope with congestions and volatile DER generation and manage the network load and **voltages** locally, DSOs should have access to flexibility for their own use. DSOs may increase network capacity to integrate storage capacity in a congested area, to activate additional local demand, or even to reduce the injected power by renewables at the local level. Due to its fast ramp up time, energy storage plays an important role in frequency containment reserve of balancing services and voltage control services. Moreover, to ensure that DSOs are able to use flexibility to manage their network and have the necessary architecture and framework some regulations are needed:

1) Technical solutions from DSOs' own assets, connection agreement, network tariffs and market-based procurement should be allowed.
2) DSOs should be able to choose technologies based on cost-efficiency without legal obligations and avoiding market disturbance.
3) Support the development of new distribution network tariff structures that are cost-reflective, more capacity based and oriented to the efficient use of the distribution system capacity.
4) Prevent the double use of flexibility resources when used for congestion management in distribution network. Flexibility providers shall have the possibility to simultaneously offer flexibility services for distribution congestion management, transmission congestion management and system balancing but flexibility should be only used once in the same timeframe. The regulatory framework should clearly avoid that flexibility providers profit from the creation of grid congestion and must also be adapted to detect and prevent this.

Regarding the **DLR**, it has been recommended by ENTSOE - citation: *The indirect method (with the weather station) constitutes the best solution, since it not only allows the crosschecking of the acquired data, but above all, allows the forecast of the load capacity of the line in the short term (up to several hours) and in the long term. The quality of the local weather forecast is therefore of crucial importance which may vary correspondingly.* Low investment costs, easy to deploy, esp. in case of forecasted permissible line load based on weather forecast only. High accuracy of permissible load estimation, no calibration required. DLR systems are widely deployed in the Polish DSO/TSO network. DLR system is installed in 3 out of 4 Polish DSO and on the TSO critical lines.

Flexible loads occasionally have a greater sensitivity to grid bottlenecks than adapting the generation of power plants. Therefore, it would be advisable to include loads in the regulatory framework of congestion management to make further cost saving potential conceivable. Active System Management is a key set of strategies and tools performed and used by DSOs and TSOs for the cost-efficient and secure management of the electricity systems. It involves the use and enhancement of smart and digital grids, operational planning and forecasting processes and the capacity to modulate, in different timeframes and distinct areas, generation and demand encompassing flexibility instruments (toolbox) to tackle challenges impacting system operation, thus ensuring proper integration of Renewable Energy Sources (RES) and a high share of Distributed Energy Resources (DER), as well as the integration with energy markets. Moreover, a necessity to fluctuating power flows, to perform **active power and reactive power management** significantly improve the supervision of their grids at reasonable costs due to ICT. System operators should always exchange all the relevant information from their grid and the relevant connected assets, from structural data (potential flexibility services and their characteristics) to more dynamic data (forecast and activation of bids): this is needed to allow efficient flexibility procurement without creating issues on the grid.

4 Conclusions

In this document, relevant flexibility technologies have been studied and mapped to propose a toolbox for DSO. The deliverable put forward flexibility solution technical characteristics, technology maturity, economic aspects and flexibility service delivery capacity as main criteria. Therefore, most promising technologies providing flexibility services were organised according to their attributes under - Energy storage, Demand-side flexibility, Smart charging, Distribution network flexible assets and control (Medium and low voltage control), Renewable Self Consumption, Dynamic Line Rating (DLR) and Active power control of RES – in example of German Redispatch 2.0 (schedule-based congestion management). After detailed investigation of each flexibility technology, DSO toolbox provides an overview of the main attributes of each solution and its applicability to different use cases, locations and flexibility needs. Furthermore, the deliverable provided definition of flexibility solution and criteria explaining why these flexibility solutions were chosen. Each technology is supported with a description of its technical components, maturity, services as well as benefits and drawbacks are provided. Groupings of technologies according to their attributes (service provision- short, medium and long term and deployment location – TSO, DSO) are also included to the tables. Lastly, limitations and recommendations provide insights at ways of reducing the barriers to flexibility technologies and services are put forward.

There will be a need for relating specific characteristics of the individual flexibility resources to the generic representative characteristics when the latter is developed to represent multiple flexibility resources. For instance, energy capacity of electric battery storage system and water reservoir capacity of pumped hydro are represented by similar characteristics. In the end, meaningful and relatable input data and decision variables are attached to the individual flexibility resources.

It has to be noted that these characteristics may also evolve through time depending on DSO planning given scenario years. The deliverable identified that most of the evaluated flexibility resources do not have a sufficient technology maturity to be considered full commercial solutions today. However, almost all the selected flexibility resources will be readily deployable in future time horizons. It can be deduced that the most relevant flexibility resources include battery energy storage systems, CAES, pumped hydro, domestic and industrial demand response, smart charging and hydrogen storage systems.

The deliverable put also forward quantitative and qualitative mapping of the selected flexibility resource to potential services addressed by the EUniversal project (Task 2.1 Flexibility Services). Voltage violations and congestion management are considered to be the most relevant flexibility service based on the selected time frame / resolution (less than 1 hour). Overall, all of the selected flexibility resources are identified as suitable for congestion management. The outcomes proposed in the document open the way for the development of EUniversal planning tool and the results are also going to be used in the pre-processor for evaluating the resources as potential solutions at different stages of the DSO network planning.

5 Annex I - Reference List

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