FlexPlan

Advanced methodology and tools taking advantage of storage and FLEXibility in transmission and distribution grid PLANning

Flexibility elements identification and characterization

D2.2

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About FlexPlan

The FlexPlan project aims at establishing a new grid planning methodology considering the opportunity to introduce new storage and flexibility resources in electricity transmission and distribution grids as an alternative to building new grid elements. This is in line with the goals and principles of the new EC package *Clean Energy for all Europeans,* which emphasizes the potential usage of flexibility sources in the phases of grid planning and operation as alternative to grid expansion. In sight of this, FlexPlan creates a new innovative grid planning tool whose ambition is to go beyond the state of the art of planning methodologies, by including the following innovative features: integrated T&D planning, full inclusion of environmental analysis, probabilistic contingency methodologies replacing the N-1 criterion as well as optimal planning decision over several decades. However, FlexPlan is not limited to building a new tool but it also uses it to analyse six regional cases covering nearly the whole European continent, aimed at demonstrating the application of the tool on real scenarios as well as at casting a view on grid planning in Europe till 2050. In this way, the FlexPlan project tries to answer the question of which role flexibility could play and how its usage can contribute to reduce planning investments yet maintaining (at least) the current system security levels. The project ends up formulating guidelines for regulators and for the planning offices of TSOs and DSOs. The consortium includes three European TSOs, one of the most important European DSO group, several R&D companies and universities from 8 European Countries (among which the Italian RSE acting as project coordinator) and N-SIDE, the developer of the European market coupling platform EUPHEMIA.

Partners

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List of Abbreviations and Acronyms

Abbreviation/Acronym	Meaning
BESS	Battery energy storage system
CAES	Compressed Air Energy Storage
CAPEX	Capital expenditure
CCUS	Carbon Capture, Utilization, and Storage
CHP	Combined Heat and Power
COP	Coefficient of Performance
DR	Demand Response
EVs	Electric Vehicles
FACTS	Flexible AC Transmission Systems
FCEV	Fuel Cell Electric Vehicles
LAES	Liquid-Air Electricity Storage systems
Li-ion	Lithium ion
MPC	Model Predictive Control
Na-S	Sodium-Sulphur
OPEX	Operational expenditure
OPF	Optimal Power Flow
PEM	Proton Exchange Membrane
PSH	Pumped Storage Hydro
PV	Photovoltaic
RES	Renewable Energy sources
SOC	State of Charge
SOEC	Electrolysis and solid Oxide Electrolyser Cell
V2G	Vehicle-to-Grid

Executive Summary

The technological maturity and the economic viability of flexibility technologies together with their steadily increasing volume has reached a level where network planning activities should reflect whether it could be opportune no longer to rely only on traditional network infrastructure. The consideration of flexibility resources in network planning tools, however, requires significant reformulations to accommodate for the uncertainties and the specific characteristics of the technologies. Depending on the specific network challenges addressed by the planning tools, proper simplified models and acceptable level of aggregated considerations need to be carried out.

This deliverable presents the thought process in the selection of flexibility resources to be considered in the FlexPlan planning tool. More importantly the report presents detailed characteristics, models and qualitative assessment of service capability for the selected flexibility resources.

Justifications are needed for the selection of certain flexibility technologies as a relevant resource in the FlexPlan network planning tool for the scenario years 2030, 2040 and 2050. The assessments may include flexibility capabilities, technology maturity, costs and environmental impact. Although as of today most of the assessed flexibility resources have not yet reached a sufficient technology maturity level to allow using them 'off-the-shelf', the assessment indicates that most of them will be ready to be used from 2030 onwards. The selected flexibility resources are presented in Table 0-1. Their respective flexibility potential assessments and their respective typical values are also included in this report. In some cases, while the flexibility resources theoretically are capable of providing the required service, they can be ruled out due to infeasibility for geographical and infrastructural limitations. These limitations can be expressed as energy density or other footprint parameters. Typical values for these parameters are provided in this report to be used in the assessments prior to decisions of the network planning tool.

Technologies identified as flexibility resources have their own technical characterizing parameters. These parameters are essential in the development of models representing them in the formulations of the network planning tool. The level of detail of the characterizing parameters is highly dependent on the level of dynamics set to analyse the operation of the technologies. Congestion management in transmission system is mainly realized in the zonal day-ahead energy market which is traded for every hour of the 24 hours of the next day. In FlexPlan planning tool congestion is identified as the main driver for grid extension and, therefore, for network planning. Hence, flexibility resources are selected for the primary flexibility service of congestion management and characterized and modelled with consideration of 1-hour resolution operational analysis. Some of the parameters are decision variables of the planning tool while other characterizing parameters are fixed and represented by typical values. These typical values are gathered from the reviewed references.

In FlexPlan, generic flexibility models are developed for two groups of flexibility resources: storage and demand response. Each flexibility resource will hence be modelled by using one of these two generic models based on the similarities of their respective characteristics. Consequently, the characteristics of each of the flexibility resource/technology are mapped to the characterizing parameters of one of the two models. Table 0-1 shows with which flexibility model matches the respective flexibility resources in the planning tool.

The selected flexibility resources are also evaluated for their suitability for the selected flexibility service in FlexPlan project, i.e. congestion management. Congestion management can happen at demand side or at generation side. The type and nature of flexibility required for the different congestion scenarios are also different. In general, the selected flexibility resources are assessed to be capable of delivering congestion management service as it is also illustrated in Table 0-1.

Flexibility resource		Modelled as Storage or Demand Response (DR)	Suitability for demand congestion	Suitability for generation congestion
Battery energy storage system		Storage		
Demand Response	Domestic	DR		
	Industrial	DR		
Electric vehicles		DR		
Hydrogen	To distributed energy across sectors and regions	DR		
	To act as a buffer to increase system resilience	Storage		
Pumped hydro		Storage		
Thermal loads	Space heating /cooling	DR		
	Cold storage	DR		
Compressed air storage		Storage		
Liquid-Air Electricity Storage systems		Storage		
Thermo electric storages		Storage		
Key: Green indicate very suitable while yellow indicate low suitability				

Table 0-1 Summary of flexibility resources selection, modelling, and service capability

Although the results presented in this report are primarily aiming at preparing the development of the FlexPlan pre-processor and of the planning tool, the approach used to methodically select, characterize, model and assess service capabilities is applicable for other network planning tool development efforts. Nevertheless, the level of detail in the models remains to be highly dependent on the type of service the flexibility resources are envisioned to provide.

1 Introduction

The increasing integration of variable forms of generation, the increasing peak load demand and the ageing network infrastructure in the power system are demanding more economical solutions than the traditional infrastructure investments. Flexibility resources have been discussed as alternative players in support of network planning by several European and local research activities [1] [2]. The FlexPlan project, however, endeavours to develop a network planning tool with applicability to both high-voltage transmission backbones and regional distribution networks, where flexibility technologies are core members among the alternative economical solutions. Before considering flexibility resources in the planning tool, one must identify, characterize and model them. This deliverable provides the specification and characteristics of selected technologies identified with the capability to provide flexibility services. Besides, generic flexibility models representing the diverse technologies will be presented and discussed.

There is no unified and agreed definition for the term 'flexibility' in power systems. However, there are many studies and authoritative documents providing definitions that noticeably have been evolving throughout the years. A good compilation of definitions provided by various reports and documents is presented in [3]. The IEA report released in May 2019 defines flexibility as [4]:

"the ability of a power system to reliably and cost effectively manage the variability and uncertainty of demand and supply across all relevant timescales, from ensuring instantaneous stability of the power system to supporting long-term security of supply"

For the purpose of this deliverable, this definition is adopted as clarifying enough to define flexibility. There are also other terms related to flexibility which shall be defined for clarity in the remaining part of the deliverable.

- ***Flexibility resources***: are technologies or components which are parts of the power system infrastructure and which exhibit flexibility potential. Alternatively, the terms "flexibility technologies" and "flexibility components" are used in this deliverable representing similar meaning.
- ***Flexibility services***: are services provided by flexibility resources for reliable and secure operation of the power system.

Traditional network infrastructure such as transmission lines or substation transformers can be planned for long time with relatively reliable and predictable capacities. For example, loading capacity of an overhead line can safely be estimated for 10 years ahead. Nevertheless, when flexibility resources are to be considered as alternative or supportive to the traditional network infrastructure, the planning process will increase in complexity.

- There is a larger degree of uncertainty regarding the amount of flexibility which will be available at different points in time and at different locations. This is partly because many of the resources are owned by third parties and not by system operators themselves. The flexibility resources related to demand side flexibility (demand response) are dependent on user behaviour and the willingness of the end-users to make flexibility available for the system operator.
- For flexibility resources there is a greater time-dependency of the capacity availability than for transformers, overhead lines, and cables. The available energy and power capacity of an Energy Storage System at a time *t*, depends on how the ESS has been operated at time *t-1*. When

dimensioning an ESS for solving a congestion it is hence necessary to know how often the ESS must be charged and discharged and how much power which is needed each time in order to solve the congestion.

In network planning process, the inclusion of flexibility resources can be seen from two perspectives. The first one is making sure that there will be enough transfer capacity for the required flexibility in the system to balance variable renewable generation. The second perspective is the use of flexibility resources to solve challenges in the power system as alternative or supporting resource to the traditional solutions such as building new lines. In both cases, the issue remains on how to accommodate flexibility resources in the existing planning tools and practices. While the FlexPlan grid-planning tool is still an on-going work, one can see in **Figure 1-1** what possible new activities can be envisioned on top of the traditional planning activities [5]. In **Figure 1-1**, the dark blue boxes highlight the traditional planning activities while the light blue boxes indicate where flexibility related planning activities should be integrated.

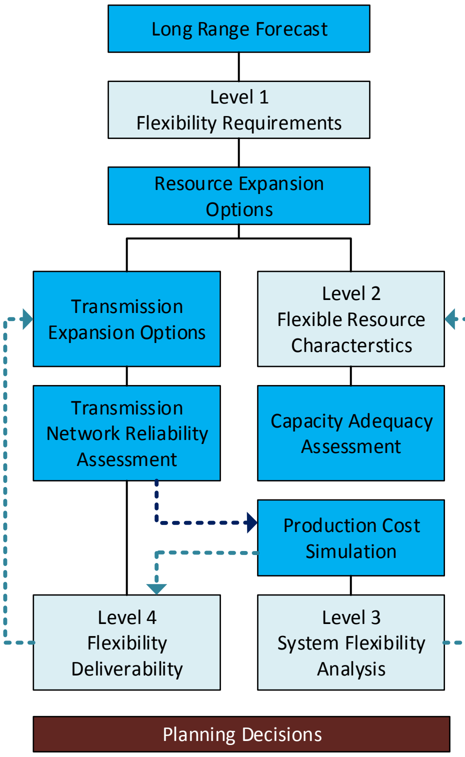

Figure 1-1 Relevance of flexibility to many aspects of utility planning process [5]

In this document, the use of the expressions 'characterization of flexibility' and 'characterization of the flexibility technologies' need to be clear from the beginning. 'Characterization of flexibility' refers to description of the flexibility capability of the specific technologies. This particularly refers to the power capacity, energy capacity, response time, payback time, service capability and others. 'Characterization of the flexibility technologies', by contrast, refers to the technical parameters of the considered technologies. For a battery energy storage system, these parameters can be, for example; energy storage capacity, maximum and minimum discharging power, state-of-charge and others. Chapter 2 of this report characterizes flexibility potential of the different resources for the purpose of selection of the relevant ones for the FlexPlan planning tool. Chapter 3, however, details the technical characteristics of the selected flexibility resources aiming for model harmonization and data gathering for the scenario years.

The flexibility resources, which are selected, characterized and modelled in this deliverable, are going to be significant input in the development of the pre-processor. The pre-processor is tasked to prepare viable alternative solutions for the FlexPlan planning tool which makes optimal investment decisions. The characterizing parameters listed for each of the flexibility resources are going to be the basis for gathering of scenario data specific to the different regional cases and the additional information provided in this deliverable also support the screening of the flexibility resources for geographical feasibility at different bus locations of the concerned network.

Chapter 2 of this deliverable presents the flexibility resources deemed relevant to be considered for the long term, large-scale network planning in the FlexPlan project. It justifies the selection of the flexibility resources based on their technical capability, operating and investment costs and technology maturity in the current and future scenarios in 2030, 2040 and 2050. Chapter 3 presents the technical and economic characterization parameters for the selected flexibility technologies while Chapter 4 presents the generic flexibility models developed in the FlexPlan project. Chapter 5 presents the mappings of the characteristics of the individual flexibility resources to the characterizing parameters outlined in the generic flexibility models presented in Chapter 4. Chapter 6 presents the qualitative mapping of the selected flexibility resources to the selected services in the network. The last chapter, Chapter 7, summarizes the main conclusions highlighting the further potential use of the results presented in this deliverable.

2 Flexibility technology listing and selection in relevance of the planning tool

Conventional planning activities focus on generation capacity, network reinforcement, power factor limitation and assert life by techno economic validation for the peak demand in the given future scenarios. The investment on network reinforcements to accommodate peak demand can be avoided or postponed by utilizing the flexibility existing in the demand and by adding new flexibility resources in the planning activity [6]. In this chapter, a list of flexibility resources and their techno economical characteristics are presented in a qualitative way. The flexibility resources are selected based on the fact sheets produced by the European Commission initiative BRIDGE, which gathers Horizon 2020 Smart Grid and Energy Storage Projects to create a structured view of crosscutting issues, which are encountered in the demonstration projects and may constitute an obstacle to innovation [7]. Section 2.1 details properties of different flexibility resources and the possible ways of modelling them. Section 2.2 lists the techno economical characteristics, their possible ranges, environmental impact, and geographical location dependency for their deployment.

2.1 List of flexibility resources

In this section, the characteristics of the flexibility resources, which are important for their selection in electrical network planning tools perspective, are described. A broad selection of flexibility resources considered for modelling and a brief description of each of the resources and different options for modelling are listed below.

2.1.1 Battery energy storage system

Due to high efficiency and easy installation, operation and maintenance, battery energy storage systems (BESS) are attractive flexibility resources. There are different battery chemistries, which have their own characteristics in terms of energy capacity, charging and discharging power rating, life span, number of equivalent full cycles, energy and power density. The battery model can be a generic model that can be tuned to specific type by varying the parameters for the characteristics of the individual type (chemistry of the battery).

BESS applications in the power systems can follow a centralised and distributed approach. Centralised batteries are installed at substation level with higher power and energy capacities to handle substation level congestion problem. The distributed BESS are those installed in individual houses, industrial sites or at secondary substations. In general, distributed BESS are operated by the owners for effective utilization of local PV generation. There are researches that proposes aggregators who manage other demand response capable equipment at household level to manage the distribute BESS [8]. Therefore, in the scope of FlexPlan, distributed BESS will be considered as a part of aggregated domestic demand response flexibility service.

2.1.1.1 Types of battery technologies

Though there are many battery chemistries available in the market and in research, the most promising technologies for grid application are Li-ion, NaS and flow batteries [9]. The proposal is based on battery's ability to act quickly for the power system service and the duration they can hold the energy with low self-discharge.

In the following some more details about the battery technologies which may be relevant for power system purposes is given, namely for lithium ion, NaS batteries and flow batteries:

Li-ion batteries are constructed with graphite anode and lithiated metal oxide cathode. They are suitable for a wide range of applications ranging from stationary storage application to mobile gadgets and electric vehicles. Li-ion batteries are available in the power range from 1 kW to 100 MW and have an energy capacity above 200 MWh depending on the application requirement. They have a calendar life up to 10 years and their round-trip efficiency is decreased at the rate of 0.5 % per year. The average cost ranges from € 660 to € 1,261 per kWh depending on the supplier, and the overall average cost is € 960 per kWh [10]

NaS batteries use molten-salt of sodium (Na) and sulphur (S) that operates at high temperature ranges. NaS batteries are suitable for applications that demands more than 4 hours of continuous operation as they can tolerate high temperatures during operations. NaS batteries are available in the power ranges from several kW to few MW and in energy capacities of 100 kWh or higher. Their calendar life is around 15 years. The round-trip efficiency loss in NaS batteries is at the rate of 0.34 % per year. The average cost of NaS batteries ranges from € 291 to € 912 per kWh depending on the supplier and the overall average cost is € 602 per kWh. It is estimated that their cost will reduce by 30 % in 2025 [10].

Flow batteries uses electrolyser tanks as energy storage units and modular ion exchange membranes through which the electrolysers are pumped to produce power as power units. The modular construction of energy and power units allows their scalability in power and energy capacity independently which makes flow batteries attractive. Flow batteries have more number of cycle and long calendar life compared to other battery technologies. Flow batteries have power capacity ranges from several kW up to 30 MW and energy capacity ranges from 100 kWh to 120 MWh. They have a calendar life of upto10 years. Flow batteries lose their round-trip efficiencies at the rate of 0.4 % per year. The average cost of flow batteries ranges from € 267 to € 1095 per kWh and their overall average cost is € 681 per kWh which is expected to drop by 30 percent to € 358 per kWh in the year 2025 [10]. A comparison of different parameters of the three different technologies is given in Figure 2-1. The plot shows the comparative values for the three different technologies by normalizing them to the maximum value among the three. The outer most circle represent the maximum value.

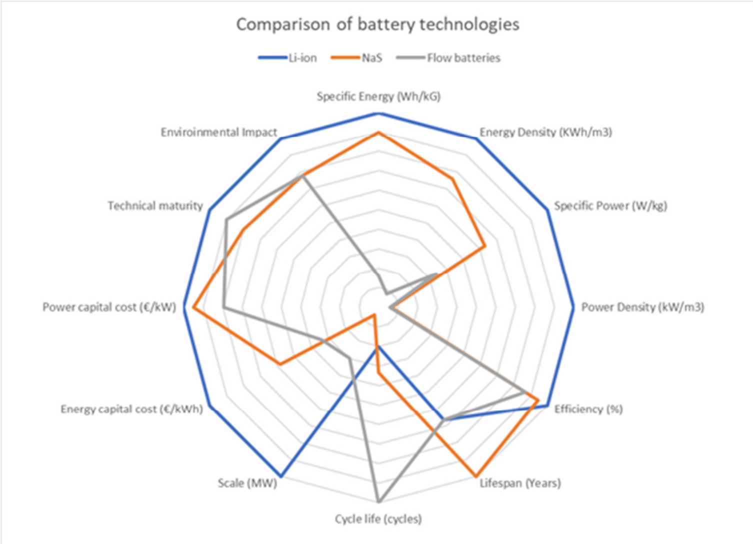

Figure 2-1 Comparison of three different battery technologies based on their characteristics [10] [11]

2.1.2 Demand Response

The US Federal Energy Regulatory Commission, FERC, defines demand response as *"Changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardised"* [12]. Demand response can be classified as Interruptible/Curtailable, reducible and shiftable [13]. In interruptible/curtailable demand response, the demand can be reduced to zero for a previously agreed duration of time [14]. In shiftable demand response, the total energy consumed is not altered, at the same time the demand is flexible to be preponed or postponed. In the domestic segment, loads which cannot be interrupted once they are started like cloth washing machine, dishwashers and dryers are shiftable demands. Batch process industries like steel plants are examples for shiftable demands in the industrial segment. In reducible demand response, the demand can be adjusted to a value between its maximum and zero. The difference between reducible and curtailable demand is that curtailable demand can be switched either ON or OFF, but the reducible demand can be operated at a power value which is in between its maximum and minimum values.

2.1.3 Electric vehicles

The focus on emission reduction in the transport sector is the main drive for electrification of mobility. There are different categories of e-mobility, namely domestic EVs, taxies, public transport buses, trucks, and other light commercial vehicles.

Domestic /distributed charging infrastructure:

Though domestic EVs are stationary during 95 % of the day, they are connected to the charging infrastructures mostly at home and during night-time or at work during the daytime, depending on availability and cost which affects the extent of the required domestic charging activities. The domestic EVs in individual houses will be considered as a component of domestic demand response resource.

Public / centralized charging infrastructure:

Public charging infrastructure and other centralized charging infrastructures for taxis, buses and other commercial vehicles can provide larger power capacity in terms of flexibility. The service duration may vary with respect to hours of the day. For example, during night hours, the availability of EV is longer than that in day hours. Their modelling can be similar to industrial demand response with variable payback time.

Large parking spaces:

In 2030, EV owners will be motivated to park their EVs in large parking spaces instead of distributed parking as it is today [15]. Similarly, todays parking places where the cars are parked for longer time (for example airport parking) will bring vehicle to grid (V2G) possibilities (in agreement with EV owners) by considering the parking lot as a large battery.

2.1.4 Hydrogen storage

Hydrogen can be generated in multiple ways and have multiple applications. Today, hydrogen is mostly produced from natural gas. However, hydrogen produced by electrolysis may become increasingly important as costs reduces and the effort to reduce greenhouse gas emission increase. In FlexPlan, electrolysis-based hydrogen is the most relevant and will be considered in the following. There are three main electrolysis technologies. . These are alkaline hydrogen generation, proton exchange membrane (PEM) electrolysis and solid oxide electrolyser cell (SOEC).

Alkaline hydrogen generation is the electrolysis of an alkaline solution (commonly potassium hydroxide (KOH) or sodium hydroxide (NaOH)) water in a cell equipped with cathode and anode. Alkaline hydrogen generation is very mature technology and the cheapest electrolysis method to produce hydrogen among the three electrolysis technologies. Similarly, PEM is electrolysis of demineralized water instead of alkaline solution. Alkaline electrolysis has a disadvantage of electrode corrosion in comparison with PEM. However PEM demands high level of purity of water, which increases the cost of the process. Alkaline hydrolysis and PEM are irreversible processes, which means hydrogen can be produced, stored and utilized as a fuel in other processes, but these methods cannot use hydrogen as a fuel to produce electricity.

SOEC is a reversible process, i.e. SOEC technology can produce hydrogen using electricity and hydrogen can be used as fuel in SOEC to generate electricity. SOEC demands the cells to be preheated to 600 °C for operation.

Alkaline hydrolysis and PEM can be modelled similar to thermostatically controlled load, where electricity is used to produce heat and SOEC can be modelled similar to battery with or without self-discharge as the produced hydrogen can be used for other purposes.

2.1.5 Pumped Storage Hydro (PSH)

Pumped storage hydro uses the geographical advantage of the height difference between upper and lower reservoirs to store electricity in the form of potential energy by pumping water from a lower reservoir to an upper reservoir. The potential energy of stored water in the upper reservoir can be converted into kinetic energy to drive a hydro turbine to generate electricity. Pumped hydro has energy density 0.2-2 Wh/l, which is the lowest among the energy storage technologies. Pumped hydro is modelled similar to battery energy storage system.

2.1.6 Thermal loads

Thermal loads use the heat capacity of the storage material to store the electricity in the form of thermal energy and difference between the upper and lower limits of the service temperature provides the flexibility.

- **Domestic thermal loads:** Water heaters, space heaters, air conditioners, refrigerators and freezers are the major thermal loads in the domestic segment. Similar to distributed BESS and domestic EVs, domestic thermal loads are considered as a part of domestic demand response flexibility resources.
- **Large commercial buildings:** The major share of electricity used in larger commercial buildings like supermarket, hotels and other commercial establishments is for heating ventilation and air conditioning (HVAC) activities. They can be treated and modelled as industrial demand response flexibility resource.
- **Cold storages:** Another major thermal load with major electricity demand and flexibility is cold storages and warehouses. Cold storages can be treated as industrial demand response flexibility resource.

In this document the thermal loads from large commercial buildings and clod storages and warehouses are also referred to as **tertiary sector loads.**

2.1.7 Combined heat and power

Combined heat and power plants serve both electrical and heat demands. CHPs can be part of process industries or serving district heating demands. CHPs can be modelled with or without thermal storages. As heat recovery is the principle for CHP, there are wide range of CHPs depending on their size and technology. In the micro and small segment, external heat engines, internal combustion engines and fuel cells from which the heat can be recovered are considered. In this project, the CHPs considered are large scale CHPs which are primarily external heat engines and gas turbines. If they are driven by thermal energy availability, which is normally the case in the industry, their flexibility is linked to that of industrial processes.

2.1.8 Compressed air storage

In compressed air storage, the stored compressed air can be serving an industrial pneumatic system demand or it can be a bidirectional flexibility unit in which the excess electricity is stored as potential energy in the form of compressed air and the pressurized air is used to run a turbine to generate electricity at the time of higher electricity demands. For the first option, compressed air storage is modelled as industrial demand response. The bidirectional compressed air storage is modelled similar to BESS.

2.1.9 Renewable energy sources

Among the renewable energy resources, wind and solar photovoltaic (PV) energy are considered due to their dominance in the total energy share. They are classified as distributed solar PV, centralised solar and wind farms and hybrid parks (with solar wind and storage). The distributed solar PV at individual houses is included in domestic demand response program similar to distributed BESS. The large centralised solar and wind forms are modelled as curtailable generation. Their inverters sizing could be a possibility for voltage control with reactive power control. As RES has a flexibility for curtailment, they are considered as hybrid parks with local storage either with the landscape advantage for energy storage (wind and solar form with pumped hydro) or with BESS is modelled as conventional power plants and not as a separate flexibility resource.

2.1.10 Liquid-Air Electricity Storage systems (Cryogenic energy storage)

Liquid-Air Electricity Storage systems are bidirectional energy conversion and storage unit in which electricity is stored by compressing and condensing air into liquid. Liquefied air can be expanded and to drive turbines to produce electricity, whenever needed. LAES system is modelled like BESS.

2.1.11 Thermo electric storages

Thermo electric storages stores electricity as thermal energy at very high temperatures (in the range of 700˚C) using compressors. The storage elements are in general pebble stones, rocks or ceramic membranes. Electricity generation is done by expanders where the working fluid drives the rotary generator. Thermo electric storages are developed to accept both electricity and heat as energy feed for storage and similar design is adapted in the discharge phase. Thermoelectric storages are modelled similar to BESS.

2.2 Characterization of flexibility

In this section, different techno economical characteristics of the flexibility resources are detailed. The possible value ranges are presented in qualitative manner to compare between different flexibility options. The values are in ranges due to many factors, for example the capital expenditure varies widely between different countries and regions. However, the pre-processor tool can select specific values depending on the location.

2.2.1 Power capacity

In conventional planning, power capacity means, meeting peak demand with the net generation. The objective of considering the flexibility resources in planning is to avoid oversizing the network, for a rarely occurring peak demand, and to support the fluctuations in RES generation and demand variation. In this perspective, the power capacity of the flexibility resources must be capable to provide network services during the hours of generation consumption imbalances, congestion and voltage deviation. The following Table 2-1 provides a qualitative indication of power capacity of different flexibility resources.

Flexibility resource		Power capacity range
Battery energy storage system [16], [17] [11]		kW - MW
Demand Response [18],	Domestic	kW
Demand Response [18],	Industrial	kW- MW
Electric vehicles [15]		kW-MW
Hydrogen [19], [20]	Alkaline	kW - MW
Hydrogen [19], [20]	PEM	kW - MW
Hydrogen [19], [20]	SOEC	kW - MW
Pumped storage hydro		GW
Thermal loads [21]	Space heating /cooling	kW-MW
Thermal loads [21]	Cold storage	MW
Combined heat and power [22], [23], [24]		kW-MW
Compressed air storage [25]		kW-MW
Liquid-Air Electricity Storage systems [26]		kW-MW
Thermo electric storages		kW-MW

Table 2-1 Power capacity range for different flexibility resources

2.2.2 Energy capacity

In conventional planning, energy capacity in generation units are considered to meet average demand in a year. The primary source of supply (fuel) is continuous and sufficient to meet the average demand except during the planned and unexpected outage periods in which the backup resources may serve. In the case of flexibility resources, one of the important characteristics which decides the duration of flexibility service at the desired power rate is their energy capacity. The larger the energy capacity of the flexibility resource, the larger the flexibility can be activated to provide network services. At the same time, the served flexible energy will be harvested back by the flexibility resources from the same network. As FlexPlan considers the service duration of minimum period of 1 hour, flexibility resources that can provide flexibility only for periods shorter than one hour are not considered. **Table 2-2** provides a qualitative indication of energy capacity of different flexibility resources considered for analysis.

Flexibility resource		Energy capacity range
Battery energy storage system [16], [17], [11]		kWh to MWh
Demand Response	Domestic	kWh to MWh
Demand Response	Industrial [27]	kWh to MWh
Electric vehicles [15]		kWh to MWh
Hydrogen [19], [20]		MWh
Pumped storage hydro		TWh
Thermal loads	Space heating /cooling	kWh to MWh
Thermal loads	Cold storage	MWh
Combined heat and power [22], [23], [24]		kWh to MWh
Compressed air storage [25]		MWh
Liquid-Air Electricity Storage systems [26]		MWh
Thermo electric storages		MWh

Table 2-2 Energy capacity range for different flexibility resources

2.2.3 Response time

Response time describes, how fast the flexibility resource can adjust its consumption to the flexibility activation signal [28], [29]. Response time of the flexibility resource is one of the important parameters to be considered. Some flexibility resources cannot be activated as and when needed though they have high flexibility potential. For example, industrial demand response potential is associated with the processes in the specific industry which may not be interrupted once started. A prior planning is needed for activation. On the other hand, flexibility resources like BESS can respond to activation in very short time (in seconds). Another perspective is long-term impact of flexibility activation. For example, flexibility activation on pumped hydro power plants will affect their capacity in long term, if the planning is not considered [28]. **Table 2-3** lists response times of different flexibility resources in qualitative manner.

Flexibility resource		**Response time**
Battery energy storage system [11]		seconds
Demand Response [18]	Domestic	seconds to hours
	Industrial	Hours to days
Electric vehicles [15]		Seconds to hours
Hydrogen [19], [20]	Alkaline	Hours
	PEM	Hours
	SOEC	Hours
Pumped storage hydro		minutes
Thermal loads [21]	Space heating /cooling	Seconds to hours
	Cold storage	minutes
Combined heat and power [22], [23], [24]		minutes
Compressed air storage [25]		minutes
Liquid-Air Electricity Storage systems [26]		Hours
Thermo electric storages		minutes

Table 2-3 Flexibility activation response time range for different flexibility resources

2.2.4 Payback time

The flexibility activation will alter the power consumption. The change may reduce or increase the energy demand during the flexibility activation period. In the case of DR programs, the energy consumption reduced must be paid back. For example, if an EV charging power is reduced to manage congestion in the network, the charging duration to serve scheduled energy delivery will increase. Also, this energy must be delivered before the EV is disconnected from the charge post. The disconnection time is not elastic. The time between the flexibility activation and EV disconnection time is the payback time. Similarly, for BESS, the batteries must be charged/discharged back to prepare them for next flexibility activation. The typical full cycle usage time of the BESS is its payback time. The following **Table 2-4** give a qualitative indication of payback time of different flexibility resources. (Hydrogen generation is considered as industrial DR)

Flexibility resource		Payback time
Battery energy storage system		6 – 8 hours
Demand Response	Domestic [18]	1 - 24 hours
	Industrial [18], [27]	1 - 12 hours
Electric vehicles [15]		1 – 8 hours
Hydrogen	Alkaline	Within 24 hours
	PEM	Within 24 hours
	SOEC	Within 24 hours
Pumped storage hydro		4 – 12 hours
Thermal loads [18]	Space heating /cooling	1 - 12 hours
	Cold storage	1 - 12 hours
Combined heat and power		**
Compressed air storage		Within 6 hours
Liquid-Air Electricity Storage systems [26]		< 6 hours
Thermo electric storages		< 2hours

** Not applicable.

Table 2-4 Energy payback time range for different flexibility resources

2.2.5 Physical constraints

For flexibility technologies being considered as alternative solutions in the network planning process, the geographical and environmental limitations have paramount importance. This will be the case when a flexibility resource is the theoretical optimum solution at a specific location while requirements regarding to the land area or lack of other resources in the surrounding area makes it infeasible. Hence, overview of the requirements for the physical placement of certain flexibility resources is presented in **Table 2-5** to screen out infeasible alternatives.

Flexibility resource		Energy density (kWh/m³)	Site dependencies
Battery energy storage system [16]		10.5 - 500	Sufficient space for battery pack placement near the substation.
Demand Response	Domestic	**	Presence of residential and industrial customers and their willingness.
	Industrial	**	
Electric vehicles [30]		200 - 300	Presence of public/ private charging infrastructures and their willingness.
Hydrogen [31]	Alkaline	30 -2550	Presence of industrial customers and their willingness.
	PEM	30 -2550	
	SOEC	30 -2550	
Pumped hydro [16]		1 -2	Availability of river inflow, geographical terrain with differential height, and political and environmental clearance.
Thermal loads	Space heating /cooling	**	Presence of residential and industrial customers and their willingness.
	Cold storage	**	
Combined heat and power		**	Geographical land potential and accessibility to fuel supply and heat despatch. Environmental regulations.
Compressed air storage [16]		3 - 6	Geographical accessibility of large underground cavities and rock structure
Liquid-Air Electricity Storage systems [31]		32 - 230	Sufficient space for Liquid-Air Electricity Storage systems.
Thermo electric storages [11]		25 - 300	Presence of industrial customers and their willingness.

** Not applicable or no data available.

Table 2-5 Energy density and site dependency for different flexibility resources

2.2.6 Technology maturity

Some of the flexibility resources are not off the shelf usable today. There are cost and technological barriers. For example, hydrogen generation by PEM is a costly method and not used for hydrogen generation as hydrogen generation by methane (natural gas) cracking process is low cost alternative method today. Similarly, SOEC method of hydrogen generation is not at industry scale as electrode corrosion is a major technological barrier today. However, the flexibility resources like DR are seeing grid observability in the network as barriers for full scale implementation due to lack of sensors and measurements and data availability. The following **Table 2-6** lists the present and expected status of technological maturity of different flexibility options and their barriers in the time plan considered in FlexPlan.

Flexibility resource		Technology maturity 2020	2030	2050
Battery energy storage system [16], [17], [11]				
Demand Response [32]	Domestic	Sensor, ICT and data visibility		
	Industrial	Sensor, ICT and data visibility		
Electric vehicles [32]		Sensor, ICT and data visibility		
Hydrogen [19], [20]	Alkaline			
	PEM	Lab/Pilot	Cost	
	SOEC	Cost and technology (Lab scale)	Electrode Corrosion issue	Cost
Pumped hydro				
Thermal loads [21]	Space heating /cooling	Pilot scale		
	Cold storage	Pilot scale		
Combined heat and power [22], [23], [24]				
Compressed air storage [25]				
Liquid-Air Electricity Storage systems [26]		Cost		
Thermo electric storages		Cost		

Table 2-6 Technology maturity of different flexibility resources at different time horizon

2.2.7 Cost

Two types of costs are considered: CAPEX and OPEX. The capital expenditure (CAPEX) and operational expenditure (OPEX) can be calculated for both power and energy capacity. For flexibility resources like BESS[1], the CAPEX is calculated for their energy capacity as their maximum power rating is function of their energy capacity and C-rating (A measure of the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in 1 hour). For flexibility resources, such as DR and EVs, CAPEX and OPEX are the maximum incentive that can be provided as an alternative to the investment in new power plants and network expansion. Therefore, the CAPEX and OPEX and calculated for in terms of kW/year. European Commission DG Energy report on "Impact assessment study on downstream flexibility, price flexibility, demand response & smart metering" analyses the different demand scenarios, network reinforcement cost, DR potential and prescribes CAPEX and OPEX for DR [18]. In resources where the power and energy capacity are independent of each other, for example pumped hydro storage, hydrogen, compressed air storage, liquid-air electricity storage and thermo electric storages CAPEX and OPEX are considered for their power rating. Their storage cost depends on different parameters. For example, storage cost for hydrogen is

[1] The cost information for BESS are taken from EU funded project e-Highway2050. More information about the project can be accessed at https://www.entsoe.eu/outlooks/ehighways-2050/

calculated in terms of cost per kWe, kWh, kg of hydrogen or m³ of hydrogen. An indicative CAPEX and OPEX for different flexible resources are presented in **Table 2-7** and **Table 2-8** respectively.

Flexibility resource		**CAPEX (€/kW(h))**		
		2020	**2030**	**2050**
Battery energy storage system [16], [11], [33]		278 - 1475	95 - 505	67 - 226
Demand Response [18]	Domestic	54/year	29/year*	15/year*
	Industrial	54/year	29/year*	15/year*
Electric vehicles [18]		54/year	29/year*	15/year*
Hydrogen [19], [20]	Alkaline	0.5 k – 1.5 k	0.3 k - 0.7 k	0.2 k- 0.6 k
	PEM	1.2 k – 1.8 k	0.6 k – 1.4 k	0.2 k – 0.8 k
	SOEC	2.5 k - 5 k	0.7 – 2.5 k	0.5 k – 0.9 k
Pumped hydro		40 -150	21.5-80.8*	16-43.5*
Thermal loads [21]	Space heating /cooling	54/year	29/year*	15/year*
	Cold storage	54/year	29/year*	15/year*
Combined heat and power [34]		0.88 k – 2.244 k	0.88 k – 2.155 k	0.88 k – 2.068 k
Compressed air storage [16], [2]		40-80	40-80	40-80
Liquid-Air Electricity Storage systems [26]		60 - 600	32.3-323*	17.4-174*
Thermo electric storages				

*values are calculated by taking discount rate of 6% per year as recommended by [35]

$$\text{Value at 'n'th year} = \text{Value at year at first year} \times \left(1 - \frac{\text{discount rate}}{100}\right)^n$$

Table 2-7 CAPEX range for different flexibility resources at different time horizon

Flexibility resource		OPEX(€/kW(h))		
		2020	2030	2050
Battery energy storage system [16], [11] [2]		Very Small	Very Small	Very Small
Demand Response [18]	Domestic	32/year	17.2/year¤	9.2/year¤
	Industrial	32/year	17.2/year¤	9.2/year¤
Electric vehicles [18]		32/year	17.2/year¤	9.2/year¤
Hydrogen [19], [20]	Alkaline	2 % of CAPEX	2 % of CAPEX	2 % of CAPEX
	PEM	2 % of CAPEX	2 % of CAPEX	2 % of CAPEX
	SOEC	2 % of CAPEX	2 % of CAPEX	2 % of CAPEX
Pumped hydro		Small	Small	Small
Thermal loads	Space heating /cooling	32/year	17.2/year¤	9.2/year¤
	Cold storage	32/year	17.2/year¤	9.2/year¤
Combined heat and power (€/kW(h)) * [34]		0.01 -0.039	0.013 - 0.068	0.017 -0.11
Compressed air storage [25],		0.15 – 0.30	0.15 – 0.30	0.15 – 0.30
Liquid-Air Electricity Storage systems		Small	Small	Small
Thermo electric storages				

*Fuel cost,

¤values are calculated by taking discount rate of 6% per year as recommended by [35]

$$\text{Value at 'n'th year} = \text{Value at year at first year} \times \left(1 - \frac{\text{discount rate}}{100}\right)^{n}$$

Table 2-8 OPEX range for different flexibility resources at different time horizon

2.2.8 Environmental impact

One of the ways to measure the environmental impact of different flexibility resources is by CO_2 emission on flexibility activation. A detailed analysis of CO_2 emission for different battery technologies based on life cycle analysis is presented in [11] and compared with other energy storage technologies. Similarly, CO_2 emission due to domestic DR is presented in [36]. The indicative values of CO_2 emission on flexibility activation on different resources are listed in **Table 2-9.**

Flexibility resource		kg of CO_2/kWh
Battery energy storage system [37] [11]		0.02 to 0.1
Demand Response	Domestic [36]	0 to 1.9
	Industrial	**
Electric vehicles [2]		0.275 – 0.375
Hydrogen [11] [37]	Alkaline	< 0.01
	PEM	< 0.01
	SOEC	< 0.01
Pumped hydro [11] [37]		< 0.01
Thermal loads	Space heating /cooling	**
	Cold storage	**
Combined heat and power [38], [39]		0.45 – 0.75
Compressed air storage [11] [37] [2]		0.2-0.285
Liquid-Air Electricity Storage systems		**
Thermo electric storages		**

** Not applicable or no data available.

Table 2-9 Emission in Kg of CO2 / kWh for different flexibility resources

3 Characterization of flexibility resources

In the FlexPlan project, flexible resources are to be modelled in the planning tool and serve as alternatives to traditional grid reinforcements. The main objective of the network planning is to minimize costs (OPEX, CAPEX) of the network while keeping environmental impact at minimum as well as maintaining satisfactory power quality and system reliability.

The selection of relevant flexibility resources to be included in the planning tool as well as defining the characterization of the respective flexibility resources are discussed in chapter 2. The characteristics of the resources will then be used in the modelling of the flexibility.

Different flexibility resources have different technical, economic and environmental characteristics. To be able to model these resources in the planning tool, it is necessary to understand the techno-economic characteristics of the individual resources and their relevance for network planning. The resources must also be modelled in sufficient detail to capture the relevant characteristics, while at the same time keeping the model manageable in terms of required computational efforts and available data. Therefore, in this chapter characteristics of the individual flexible resources are presented. In Chapter 5, these characterizing parameters are harmonized with the generic flexibility model parameters as presented in Chapter 4.

This chapter focuses on the characteristics of the individual flexible resources. Each of the following subchapters present different flexibility resources considered as relevant for the FlexPlan planning tool. The basic working principle is explained, and the relevant characteristics are listed.

3.1 Battery energy storage system (BESS)

Battery energy storage is electrochemical energy storage consisting of electrochemical cells that convert chemical energy to electrical energy. A BESS comprise several battery cells that are connected and packed to modules. The modules are connected in series and parallel to form battery packs. In addition, the BESS include Battery Management System (BMS) to monitor and balance the modules/packs, estimate the battery condition (state of charge or state of health), take care of the thermal management, safety and protection of the battery, etc.

There exist numerous technologies utilizing different materials in the battery cells for anode and cathode materials, electrolytes and separators. For grid applications, several technologies are used, e.g. lithium-based, sodium-based, lead-based and flow batteries [9]. Different technologies offer different performance in terms of energy and power capacity, costs, calendar and cycle life, safety, environmental impacts etc. Hence, the parameter values may differ between the technologies and specific installations. However, the characterization can be generalized for the relevant technologies.

It is possible to model batteries in different ways, with different levels of complexity and details. The efficiency, aging and lifetime of a BESS depends on several factors which one can model with different level of detail. Amongst others, the aging of the battery and thereby the expected lifetime is dependent on the depth of each charging/discharging cycle, the ambient temperature and the temperature management of the battery cells and packs. Moreover, the charging and discharging efficiency of the battery is amongst others dependent on the temperature and at which power the battery is charged and discharged.

Furthermore, the energy capacity of the battery decreases during the battery lifetime. For different battery technologies, the aging mechanisms, and dependencies between different parameters like state of charge, discharging/charging rates and temperature vary. Hence, for different type of BESS, the optimal operating strategy for minimizing losses and aging can therefore vary.

In FlexPlan, BESS are characterized as shown in **Table 3-1** and modelled with the storage model which is presented in section 4.1. In the model it is assumed that the battery has a fixed lifetime (independently of the usage of the battery) and that the charging and discharging efficiency for a given battery is fixed (dependency of temperature, state of health and discharging/charging rates are neglected). A possible solution to take aging into account in the battery model is to introduce degradation costs as shown in [9]. The degradation costs can be implemented to take into account that the degradation depends on the depth of the charging/discharging cycles (i.e. how much of the energy is being discharged before the battery is being recharged) and the state of charge when the battery is not in use. To limit calculation efforts in the FlexPlan planning tool, a simpler model is used.

Attribute	Unit	Comments	Typical values **[2]**
Energy capacity	MWh	Maximum available MWh when a full battery is discharged at a certain C-rate until the cut-off voltage is reached. [9]	100 -375
Discharging power capacity (continuous rating)	MW		0-80 % of maximum discharging power
Charging power capacity (continuous rating)	MW		0-80 % of maximum charging power
Maximum discharging power capacity	MW	The maximum discharging capacity of the battery can only be used for a limited amount of time due to thermal limitations	100 -375 (at 1 C-rate)
Maximum charging power capacity	MW	The maximum charging capacity of the battery can only be used for a limited amount of time due to thermal limitations	100 -375 (at 1 C-rate)
Battery charging efficiency	%	The actual energy efficiency depends on the rate and duration of the charging, the SOC, the temperature, and the ageing of the battery. [40] However, in a simplified model one may assume a constant efficiency independently of temperature, SOC, SOH and charge/discharge rate. Only the battery efficiency (not power electronics and other components) are included here, the efficiency of the rest of the BESS is taken into account in the "Power Conversion System maximum efficiency" .	50 – 90 %

Battery discharging efficiency	%	Similar to the battery charging efficiency, but for the charging of the battery.	50 – 90%
Power Conversion System maximum efficiency (inverter, etc.)	%	Efficiency of the power electronics and other BESS system components. The efficiency depends on the operating point, but it is assumed to be constant here.	> 95 %
Cycle lifetime	FCE	Full Cycles Equivalent	300 - 10000
Calendar lifetime	Years		5 - 20
End of life	%	Percentage of original capacity for which the battery is considered to reach its lifetime (i.e. the battery is no longer useful for the application) Typical value is 60-80% of rated energy capacity [8]	70 %
Typical operating temperature	(ºC)		-10 to 60 (Li-ion) 0 to 40 (Flow batteries) 300 to 360 (NaS)
Maximum SOC	%	The battery should not be charged above this SOC	85-95 %
Minimum SOC	%	The battery should not be discharged below this SOC	5 – 10 %
Geographical/special constraints		BESS can be small, distributed systems located behind the meter of end-users, or be smaller or larger systems connected to the distribution system or transmission systems.	

Table 3-1 Characterization of BESS

3.2 Industrial Demand Response

Commercial and industrial customers can have many different processes defining their core business, each of which has various impacts on their ability to deliver their saleable good or service. From the point of view of the operations manager, each of these processes has two important characteristics: quantity of service (raw amount of output) and quality of service (minimum level of quality) [41].

On the other hand, for these types of customers, electricity is an input to production much like materials or labour. Their maximum demand is an important driver of fixed operating costs, while the time of consumption impacts the variable costs. Demand Response (DR) profit maximization occurs where the marginal cost of saving one kWh of electricity just equals the marginal revenue generated by the savings. However, modifying timing and the amount of the electricity consumed should still provide the same useful effect and no negative impact on the core business processes of the company [41].

Among all possible solutions, each factory needs to select the DR options that suit better their processes, services, and characteristics, as well as the tariff or contract that provides optimum economic results. Some general **consumption control methods** that can be accomplished in the industrial environment are the following [42]:

- Programming electricity consumption to reduce any "undue" consumption.
- Moving demand from more expensive to less expensive periods is performed by reorganising work activities. Rescheduling is more appropriate for facilities which operate on two or three shifts. If two or more production lines are involved, the operation cycles can be modified to avoid their coincidence at peak time. Process rescheduling is almost impossible with direct load control measures when the control periods come at random time, while it performs well with time-of-use rates.
- Disconnecting electrical appliances (or extensively limiting their use) during peak hours to maintain the maximum power under a pre-fixed threshold. The interruption practice is effective with any form of financial incentive.
- Industries with excess production capacity can use this excess to modulate the load (i.e. reduce the production during peak hours and step it up during off peak time). Instead, for industries running at their capacity limits, the reduction of electricity demand for a given time can result in a reduction in production. When this occurs, some process restructuring is required to benefit from the economic advantages of load management.
- For processes where half-finished products and materials can be stored during one or more phases of the production activity, other parts of the factory are enabled to work in periods of demand reduction.
- Energy storage (thermal, electrical…) enables a shift of consumption to off-peak periods without impacting on the operation of the productive processes and it increases flexibility.
- Backup generation or distributed generation, if available, might be used, during peak times.
- Employees should be trained and made aware of tariff rates or any load management strategy to achieve a change in consumption patterns.
- In industry, lighting usually contributes very little to the electricity bill (typically around 5-8%) and its programming could prove uneconomical.
- Space heating and cooling in large commercial buildings and cold storage warehouses in which their thermal inertia can serve as demand response flexibility to prepone or postpone electricity demand are considered as industrial thermal loads. The difference between the present thermal capacity and the maximum thermal capacity, and the rated maximum power of the heating/cooling system defines the upward flexibility. Similarly, the present thermal capacity and the nominal electricity demand defines the downward flexibility.

Attribute	Unit	Comments	Typical values
Maximum Power capacity	MW	Depends on the process type. E.g. Packaging, Chiller, Wrapping, Weaving, Sawing, chipper, Dewatering press, Electrolysis, Compressor, Grinding, Catalytic Cracking, Mixing, Mill, Electric Furnace, Crushing, Electrolysis, Metal Cutting, Final Assembly. This value can also be indicated as % of the peak load.	Typical values for individual industries are presented in [43] [27].
Minimum Power capacity	MW	Depends on the minimum number of process one can interrupt at a time.	
Minimum duration	Hours	Minimum number of hours the process can be shifted.	
Maximum duration	Hours	Maximum number of hours the process can be shifted.	
Energy payback	% or MWh	The share of the demand which has been curtailed/shifted which have to be payed back (i.e. supplied) at a later time. For thermal loads, the energy payback is 100 %	
Energy payback time window	Hours	For thermal loads, the energy payback time window depends on their thermal capacity. Similarly, for H2 as a DR, energy payback time window depends on the local storage facility of process shift time.	
Response ramp time	Minutes		
Call limits	Times per day		
Acceptability		This represents the overall acceptability of a given industrial sector to be engaged in DR projects.	
Controllability		This determines the extent that a given load or process can be controlled.	
Sheddability process		This determines whether a given processes can be shed by a typical demand response strategy.	
Sheddability device		This determines if there is any impact on device reliability and controllability (in terms of reliability, frequent modulation or shutting down/start up).	

Table 3-2 Generic model for industrial and commercial demand response

3.2.1 Industrial Demand Response assessment

By means of segmentation, loads and processes can be identified. However, consumers are the ones that should give their last word on their ability to reduce and/or shift load. The following aspects should be answered by them when DR capabilities need to be assessed [44]:

- **Capability to consume according to variable prices** (consumption habits change):
  - Make high electricity-consuming tasks coincide with low price periods.
  - Switch off or reduce the load of redundant and non-essential systems during high price periods.
  - Shift processes taking place in parallel to avoid high consumption on-peaks.
  - Carry out pre-cooling.
  - Use storage if available (charge at lower prices, discharge at high price periods).
- **Capability to respond fast to system emergencies and/or price variations**:
  - Defer work processes totally or partially: packaging, bottling, melting, moulding, cleaning, milling, printing, pumping…
  - Postpone or reduce the consumption of non-essential activities: HVAC systems, elevators, lightning, laundry activities, pools, garbage compactors, watering, cooking, non-essential motors in general, charge of batteries (forklifts and other electrical vehicles, PCs), etc.
  - Use distributed and backup generation if available.
  - Use an energy management system able to receive inputs from the system operator and control load onsite automatically.

In addition, consumers will have to assess existing constraints linked to each of their flexible loads or generation. Once the equipment controllability and existing restrictions are known, flexibility options will be assessed:

- **Loads permitting continuous demand controllability**: All loads permitting the modification of their operational settings should be identified, for example, controllable variable frequency drives. This will permit speed/demand control between certain limits: HVAC systems, pumps, elevators, conveyors, mills…
- **Loads only permitting an on/off regulation**: for example, lightning (normally), some fabrication processes, motors without speed modulation capabilities.
- **The flexibility of generation sources** should be assessed according to their characteristics and restrictions: response time, switching capability, part-load operation…

The contract with consumers should define all control options permitted by them for each of their loads and the existing restrictions:

- **Equipment restrictions**: switching on, operation and switching off possibilities and times. Operational settings ranges should also be clarified.
- **Task restrictions**: which tasks should be accomplished and in which period of time (for example, 5 000 bottles of milk should be ready each day by 17:00h).
- **Personnel restrictions** (availability, working hours, work characteristics…) that may affect the controllability of processes or loads.
- Etc.

In [45], a methodology is presented to **estimate the potential of DR** by extrapolation of data from a pilot study (TPDDL). For each customer category, the DR potential can be estimated by the following equation:

$$DR\ potential = Aggregate\ Customer\ Peak\ Demand * DR\ as\ \%\ of\ peak\ load * Participation\ Rate * Response\ Rate \quad (1)$$

Some of the considerations taken in the methodology are the following:

- The aggregated load profile of the participants in the pilot study, from each consumer category, is assumed to be representative of the aggregated load profile of the entire corresponding category in the whole DR potential study.

To estimate the total DR potential for each customer category, the peak demand for that category and the 75th percentile of the maximum DR shed determined in the pilot study are considered. That information is provided, as example, in **Table 3-3.** The data in **Table 3-3** is not provided as a reference because the pilot took place in India, and it might not be representative for the EU.

- Implicitly, it is considered that DR events happen during the same timeframe and weather conditions as the ones in the DR pilot programme.
- The response rate of the participant is considered but the participation rate is not.

From a utility's perspective, the savings through the DR programme need to be greater than its loss of revenue due to reduced energy sales, its share of costs for setting up and operating the DR programme, and the DR incentives that it has to pay the participants [45].

From a customer's perspective, benefits associated with DR need to be greater than their opportunity cost, as well as their share of the actual hardware and operating costs involved in the DR programme (especially in an automated DR programme). In [27], the industrial demand response flexibility factor (IDRFF) is defined as follows:

$$IDRFF\ (SIC, Load, Process, Device, DR\ Product) = \min(sector\ acceptability, load\ controllability) * \min(sheddability\ process, sheddability\ device) \quad (2)$$

Please look into **Table 3-2** for brief explanations of the parameters in equation (2).

Category ID	Customer Category	No. of customers in DR pilot (available data)	Peak demand May–Oct 2014 (kW)	Max demand reduction (75th percentile) (kW)	Demand reduction as % of peak demand
1	Auto parts	4	620	110	18
2	Chemicals	2	430	60	14
3	Cold Storage	6	1,100	170	15
4	Commercial	11	4,600	350	7
5	Education	3	1,900	40	2
6	Flour Mills	25	7,300	1,100	16
7	Food products	9	2,700	370	14
8	Glass Manufacturing	2	770	90	12
9	Home products	5	1,000	250	24
10	Hospitals	2	1,400	230	16
11	Medical products	3	430	50	12
12	Others	14	1,900	360	19
13	Packaging	1	170	50	28
14	Plastics manufacturing	18	2,200	300	14
15	Printing	7	1,000	140	13
16	Pumping	3	560	90	15
17	Retail stores	3	60	20	26
18	Shoe manufacturing	7	920	140	15
19	Steel industry	17	2,000	160	8

Table 3-3 Peak demand and DR estimates by consumer category form the TPDDL pilot programme (the share of demand response is not reduction over a baseline peak demand by over a six-month peak demand) [45]

3.3 Residential Demand Response

Demand response from residential customers could come from different types of thermal loads (heating, cooling) and shiftable loads (washing machines, etc.). In this section, different types of loads potentially available for demand response are presented in designated subchapters. For network planning purposes, the aggregated effect of demand response of many types of loads from many end users is of interest. In chapter 5, it will be discussed how the characteristics of these and other flexibility resources can be generalized.

3.3.1 Water heater

One type of load that can be available for residential demand response is water heaters. Water heaters consist of a water tank with a heating rod supplied with electric power, which is operated to maintain the temperature of the water in the tank within certain limits. Hot water is demanded from the tank for different purposes (showering, cleaning, etc.) and cold water is added to the heater to maintain the volume of water in the tank. The operation of the heating rod is controlled by a thermostat with a temperature setpoint and a hysteresis.

- Heating rod is turned "ON" if the water temperature drops below the lower limit of the hysteresis
- Heating rod is remained in ON state until the water temperature reaches the upper limit of the hysteresis. Then the heating rod is turned OFF.

Demand response can be achieved by price signals or other activation signals to a controller which can adjust the thermostat setpoint depending on the price/activation signal and potentially by user defined comfort settings. **Table 3-4** Characteristics of water heater is based on the water heater model in [1].

Attribute	Unit	Comments	Typical values [46]
Thermal losses coefficient	kW/°C	Thermal losses coefficient. A=UA, where U is the heat transfer coefficient and A is the surface area. Is given in technical documentation of water heaters , e.g. 1.95kWh/24h at 65°C or similar (according to Ecogrid D2.1 report [1])	0.01667
Heat capacity of water	kJ/kg K	Heat capacity of water	4.186 kJ/kg K
Rated/maximum electrical power of water heater	kW		2 -3
Efficiency of the water heater element	Wt/We		100
Cold water temperature	°C		10 - 30
Ambient temperature	°C	Room temperature where the water heater is located	22 - 24
Mass (or volume) of water in the heater	kg	m=ρV, where ρ is the density and V the volume of the water	150
Temperature setpoint	°C	Defined by customer	75
Hysteresis of electronic thermostat temperature	°C	An interval around the temperature setpoint defining the thermostat operation	5
length of timestep i	h		
Hot water demand or cold water added during timestep i	kg	Or average water demand during timestep i	User defined
Initial temperature of water at step 1	°C		
State of heating element		Status	Status {0,1}
Comfort setting		Defined by customer	
Modified temperature setpoint	°C	Calculated based on the original setpoint, comfort setting and price at	

		timestep i.	

Table 3-4 Characteristics of water heater

3.3.2 Freezer/cold storage

For freezers/cold storages flexibility can be offered by taking advantage of the thermal capacity of the food and air in the freezer. The cooling system is managed by a thermostat with a given temperature setpoint and hysteresis characteristics to maintain the temperature in the freezer within certain limits. The thermostat setpoint and hysteresis dictates the operation of the cooling system in the following way:

- If the temperature in the freezer is above the upper limit of the hysteresis, the cooling element is turned ON.
- The cooling element remain ON until the freezer temperature reaches the lower limit of the hysteresis interval.
- When the temperature in the freezer is below the lower limit of the hysteresis interval, the cooling system is turned OFF.

The flexibility potential of the freezer is hence determined by the freezer volume and heat capacity of the freezer content (food/air), the thermal losses from the freezer to the ambient and the thermostat settings. The electric power consumed by the cooling system when the system is "ON" is constant. Hence the electric power demand is either full rated power or zero. Flexibility of freezer is thus a matter of shifting this power demand to a different point in time by giving price signals or other activation signals to a controller that manages the thermostat of the cooling system. For instance, there could be an algorithm in the controller, which calculates an updated temperature setpoint based on a real-time of future price, to thereby influence the operating cycle of the cooling system. The characteristics in **Table 3-5** are based the freezer/cold storage model in [1].

Attribute	Unit	Comments	Typical values **[47]**
Heat transfer coefficient of freezer	kW/(m² K)		86
Surface area of the freezer	m²		5.8
Thermal losses coefficient	kW/°C	α=U*A. This is the thermal losses to the ambient	
Heat capacity of food/ice	kJ/kg K	(The total heat capacity of the freezer equals the heat capacity of the food times the mass of the food)	1.4 – 2.02 [48]
Rated/maximum electric power of cooling system	kW	The electric power drawn by the cooling system when the state of the cooling system is "ON".	8
Efficiency of cooling system	Wth/We	The thermal energy output vs the electric energy input	0.8 – 2.5

Ambient temperature	°C	The ambient temperature is assumed in [1] to be room temperature and to be constant during the modelled period (24-hour period in)	22 -24
Temperature setpoint	°C	User defined	-20
Hysteresis of electronic thermostat temperature	°C	An interval around the temperature setpoint. When the freezer thermostat is in on-state, the freezer is cooled down to reach the minimum value of the hysteresis interval. Then the thermostat turns off the cooling element. Once the freezer temperature rises and reaches the maximum value of the interval, the thermostat turns on the cooling element of the freezer again	3
Initial temperature of freezer at timestep i	°C		Status
Food exchange in freezer during timestep i	kg	If taking into account that food is added or removed from the freezer	Status
Temperature of the added food	°C		-18 to 24
Total mass of food in the freezer	kg		Heat capacity of food and total mass of the food
Length of timestep i	h		
State of cooling system		{0,1} on or off in timestep i. The cooling element fo the freezer is either on of off (i.e. either at rated/maximum power or at 0 power demand)	Status
Comfort setting at time step i.		User defined, floating number. It is possible to simplify the model by neglecting the possibility of choosing different comfort settings.	Status
Modified temperature setpoint	°C	Calculated based on the original setpoint, comfort setting and price at time step i.	Status

Table 3-5 Characteristics of freezer/cooling system

3.3.3 Direct space heating and cooling

Space heating is heating or cooling of a space, for instance a room or group of rooms in a building (referred to as the thermal zone in the model). Direct space heating, as oppose to space heating with storage, heats the space directly without having additional storage capabilities in the heating system.

Hence, the storage which potentially can offer flexibility (demand response) is due to the heat capacity of the space (thermal zone) and the defined maximum and minimum temperatures of that space.

The model upon which the characterization in **Table 3-6** is based is from [1]. The model is described as follows: "*The Space Heating and Cooling Model represents the direct heating of an arbitrary object by a device* with *a coefficient of performance between electrical energy and thermal energy, which may have a minimum on time (once activated, it has to run at least for a certain time span to avoid increased wear and tear due short operational cycles.). It may therefore represent a least direct electrical space heating, direct heating using heat pumps and direct heating using a CHP (in which case the COP would be negative).*"

Attribute	Unit	Comments	Typical values **[49]**
Rated power of the heating and cooling device	We		1 - 4
Coefficient of Performance between electricity and heat	Wth/We		1 -2.5
Minimum on-time of heating and cooling device	min		20
Heat capacity of the thermal zone	W/K		2000 - 6500
U-value of the thermal zone	W/K m^2	"Thermal transmittance, also known as U-value, is the rate of transfer of heat through a structure (which can be a single material or a composite), divided by the difference in temperature across that structure. The units of measurement are W/m^{2}K. The better-insulated a structure is, the lower the U-value will be"[2]	2 to 5.8 depending on the building [50]
Relevant envelope surface	m^2		22-24
Maximum change of the setpoint	°C		2 -4
Maximum temperature of the thermal zone	°C		25
Minimum temperature of the thermal zone	°C		20
Price per degree temperature deviation from the temperature			

[2] From "What is a U-value? Heat loss, thermal mass and online calculators explained" (accessed 06.02.2020) https://www.thenbs.com/knowledge/what-is-a-u-value-heat-loss-thermal-mass-and-online-calculators-explained

setpoint			

Table 3-6 Characteristics of direct space heating and cooling

3.3.4 Space heating with storage

DER capable heating units, such as heat pumps and CHP plants, are usually connected to the building using a storage tank while space heating is still one of the main purposes. Hence, modelling techniques for such types of space heating shall emphasize the storage part [1]. The heating units are characterized by a COP and a minimum run time while the storage tank may contain detail characteristics as detailed in **Table 3-7.**

Attribute	Unit	Comments	Typical values **[49]**
Rated power of heating and cooling device	We		850
Coefficient of Performance between electricity and heat	Wth/We		2.5
Minimum on-time of the heating and cooling device	min		70
u-value of the thermal zone	W/K*m^2		2000 - 6500
Relevant envelope surface	m^2	The surface through which energy is lost to the ambient.	182 (calculated assuming that the space to be heated has a cubic shape with 4 walls, floor and roof area of 7m x 7m x 3m space)
Air exchange with the outside	m^3/h		5 – 9 time the volume of the space
Volume of the tank	m^3		1.3
Minimum temperature of the tank	°C		50
Maximum temperature of the tank	°C		75
Maximum change of the setpoint	°C		10
Temperature setpoint of the thermal zone	°C		22-24
Temperature setpoint of the tank	°C		75
Hysteresis of the tank controller	°C		10

Current outside temperature	°C		

Table 3-7 Characteristics of space heating with storage

3.3.5 Shiftable loads

Shiftable loads are here referred to as loads that cannot be disturbed once the operation cycle has started, but where starting time of the operation cycle can be shifted. Examples of such loads are washing machines, dishwashers and tumble dyers.

The electric power demand is divided into I_{total} equally long timesteps for which each of them has a power demand $P_{load,i}$. The load must be activated at some time between the availability start time and end time. The cost of activation of the demand response can be different depending on whether the operation is shifted backwards or forwards. Characteristics for shiftable loads based on models from [1] are given in **Table 3-8.**

Attribute	Unit	Comments	Typical values **[51]**
Electrical power demand of the load in the timestep i of its operating cycle	kW	For each timestep $i = 1 \dots I_{total}$ the load has an electricity demand $P_{load,i}$. I_{total} is the total number of timesteps that the consumption cycle lasts.	1- 2
Total number of timesteps the cycle last	integer	Number of timesteps the consumption cycle lasts (I_{total})	1- 3 hours
Availability start time	h or timestep	Time at which the shiftable load starts to be available	Region specific
Availability end time	h or timestep	Time by which the shiftable load must have finished its operating cycle	Region specific
Status of the load at the beginning and the simulation		-1': load is already connected and operation cycle is finished already. 1: the load is already been connected but has not finished operating cycle yet. 0: the load is 'off' and is waiting to be scheduled	Status
Status of the load at current timestep		-1': load is already connected and operation cycle is finished already. 1: the load is already been connected but has not finished operating cycle yet. 0: the load is 'off' and is waiting to be scheduled	Status
Price per time period of shift forward			
Price per time period of shift backward			

Table 3-8 Characteristics of shiftable atomic loads

3.4 Electric Vehicles (EV)

There are different ways to model EV charging flexibility [40]. Depending on the controllability of the charger EV load can be inflexible, shiftable, curtailable or reducible. The bidirectional chargers allow them to discharge to network like a BESS. Though there are multiple ways to model EV flexibility at different charging infrastructures (distributed charging, small / short time public parking and large / long time parking), in this project EVs will be modelled as flexible demands like the industrial demand response with a broader view on their flexibility. Therefore, the domestic and distributed charging infrastructures capacities are aggregated to drive the total charging power. Similarly, the number of charger and their occupancy at small and large parking places provides the total charging power. The total charging power differs for different hours of the day as the number of EVs connected to the chargers varies. In the total charging power, the maximum power capacity of the flexible power is derived based on the EV owner's acceptance and the available duration of EVs for charging. The energy payback and its duration also depend of the available duration of EVs for charging which differs for three different cases. The V2X case is predominantly suitable for network operational scenarios. Therefore, V2X is not considered as a part of flexibility in planning. **Table 3-9** lists different characteristics of electric vehicle flexibility.

Attribute	Unit	Comments	Typical values **[2]**
Maximum Power capacity	kW	Aggregated amount of charging power that can be decreased at any time from EV charging demand. (Depends on the type of the EV parking location considered and number of EVs available at different hours of the day).	21 per EV
Minimum Power capacity	kW	Minimum power that need to be supplied at any time (Depends on the acceptance factor of the EV owners, available time of EVs at parking place)	0
Minimum duration	Hours		2 - 8 [15]
Maximum duration	Hours		8 - 24 [15]
Energy payback	% or MWh	The share of the demand which has been curtailed/shifted which have to be paid back (i.e. supplied) later	100 %
Energy payback time window	Hours	The time within which the curtailed/shifted share of energy that need to be supplied.	2-24
Response ramp time	Minutes		minutes

Table 3-9 Characteristics of electric vehicles flexibility

3.5 Hydrogen

Hydrogen can be generated in multiple ways and have multiple applications. Hydrogen is used as raw material in several industries (e.g. refineries, ammonia production, bulk chemicals) [52]. Other applications, which may become more relevant in the future, include injection of hydrogen into the existing gas grid to reduce emissions from amongst others heating of buildings, and to mix hydrogen with CO2 from high-emission processes to create syngas which can be fed into the gas grid. [52] Another application is transport, where hydrogen can be used as fuel for Fuel Cell Electric Vehicles (FCEVs) [52]. For long-distance heavy-duty transport, which may not be suited for battery electric systems, fuel cell technology with hydrogen fuel may be a well-suited alternative to achieve decarbonization. **Figure 3-1**, from [52], illustrates the variety of (potential) applications for hydrogen. Per 2019, most hydrogen is produced on-site for industrial applications [19].

One way to distinguish between hydrogen produced in different ways from different raw materials is to use following colors [19]:

- Black hydrogen: from coal
- Brown hydrogen: from lignite
- Grey hydrogen: from natural gas
- Blue hydrogen: from fossil fuels with use of Carbon capture, utilization, and storage (CCUS)
- Green hydrogen: production based on electricity from renewable energy sources

As per 2019, most hydrogen produced worldwide is produced from natural gas. Only 2% of the hydrogen produced is produced by electrolysis [19]. In a future low-carbon system, the green and blue hydrogen are the most relevant, i.e. hydrogen from natural gas with CCUS and electrolysis-based hydrogen production fuelled by renewable electric power.

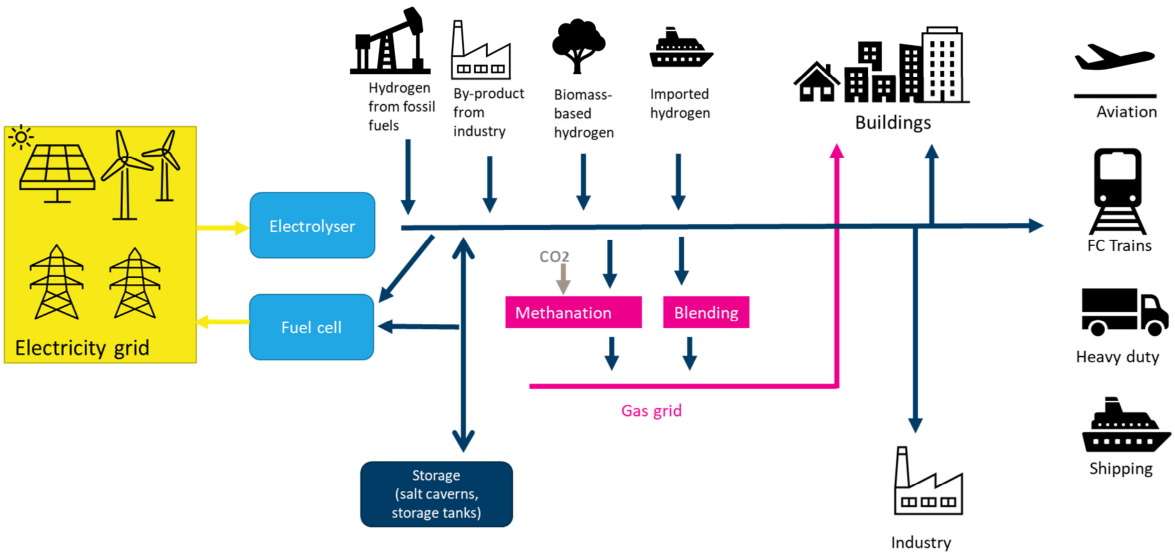

Figure 3-1 Illustration of the variety of applications for hydrogen and how electrolysis based hydrogen production can be integrated in the hydrogen value chain. The figure is adopted from [53]

In FlexPlan we consider the two following applications of hydrogen:

1. **Power-to-Gas-to-other-uses (Hydrogen as industrial load)**
    - The hydrogen is produced by electrolysis. The application for the hydrogen is either as raw material or other uses by industry, as fuel for the transport sector or for heating in buildings. Hence, the hydrogen is not transformed back to electricity but rather used for other applications in sectors other than the power grid.

For this case, the hydrogen production can be characterized as a type of flexible load and modelled as demand response, see section 3.5.1

- In the model it will be load modulation and will be accommodated within the demand response flexibility model

2. **Power-to-Gas-to-Power (Hydrogen as energy storage system)**
    - Hydrogen is produced by electrolysis and stored in a storage tank or a geological void. The hydrogen can then be utilized as fuel in a fuel cell to generate power, which is fed back into the power grid.

For this case, the hydrogen production and re-electrification facility can be modelled using the storage model, similarly as a battery or PSH, see section 3.5.2

In both the abovementioned applications, hydrogen production by electrolysis is considered. There are two commercially available electrolysis technologies for hydrogen production. A third technology is in the pre-commercial stage [53]. The three technologies are:

- Alkaline hydrogen generation (commercially available)
- Proton exchange membrane electrolysis (PEMEL) (commercially available)
- Solid oxide electrolyser cell (SOEC). (under development)

The different electrolysis technologies can be characterized using the same model, but the parameters values are different. For instance, the different technologies offer different performance in terms of efficiencies, costs, and ramp rates.

Hydrogen can be stored as a compressed gas in storage tanks or geological voids like salt caverns and depleted oil and gas reservoirs. Storage tanks are best suited for short-term small-scale storage, whereas geological voids can be applicable for longer-term larger-scale storage when larger storage volumes are necessary.

3.5.1 Hydrogen as industrial load

The flexibility in hydrogen production for industry or other sectors can be utilized by ramping the hydrogen production up or down according to the requirements from the power system and potential price signals or incentives given by the system operator to the industry. The industrial demand response characterization which will be described in section 3.2 is applicable.

3.5.2 Hydrogen as energy storage system

This type of hydrogen use is essentially for increasing power system resilience by offering buffering service. In this case, hydrogen production, storage and re-electrification can be modelled and characterized as an energy storage system. The three main components of such a hydrogen storage system is:

- Electrolyser for hydrogen production
- Storage tank or geological void for storage of the hydrogen
- Fuel Cell for re-electrification of the hydrogen

The electrolyser and fuel cell can either be two distinct units/devices or one unitised device which can be run in electrolyser and fuel cell modes (called unitized regenerative fuel cell). Similarly, as for electrolysers, also for fuel cells there exist different technologies.

Table 3-10 shows characteristics for hydrogen as a storage system. The typical values listed in the table are for electrolyser and for a unitised regenerative system. As there are three different technologies for electrolysis, namely Alkaline, PEMEL and SOEC, typical values for each of these technologies are given in the table. For unitised regenerative system, values for reversible SOEC (r-SOC) is given.

Attribute	Unit	Comments	Alkaline electrolyser	PEM electrolyser	SOEC electrolyser	**r-SOC (unitised reversible system)**
Energy capacity	MWh	Capacity of the storage tank				
Discharging power capacity (continuous rating)	MW	Fuel cell power rating for re-electrification of the hydrogen.	n/a (only charging)	0 n/a (only charging)	n/a (only charging)	0.001-1
Rated power capacity (continuous)	MW	Electricity demand for H_2 generation.	0.001-165 [54]	0.001-10 [54]	0.001-1	0.001-1
Efficiency, LHV	%	Efficiency of producing the hydrogen (LHV = Lower Heating Value)	63- 70 ([19], 2019) 65- 71 ([19], expectation for 2030) 70- 80 ([19], expectation long term)	56-60 ([19], 2019) 63-68 ([19], expectation for 2030) 67-74 ([19], expectation long term)	74-81 ([19], 2019) 77-84 ([19], expectation for 2030) 77-90 ([19], expectation long term)	Roundtrip efficiency (electricity to electricity) 55-60% [55]
Minimum SOC	%					
Maximum SOC	%					
Lifetime	hours	Operational lifetime of electrolyser.	80000 – 90000 [56], [19]	40000 - 50000	10000 - 30000	
Calendar lifetime	Years	Overall lifetime of the system.	20 [56]	20		
Electrolyser stack replacement cost	€/kW	Cost of the electrolyser stack, which need to be replaced after 80 k hours [19]	340 215 [2025]	420-210		
CAPEX	€/kW	[19]	750 480 [2025]	1200-700	2555-5111	
	€/m^3 [€/kWh]	Cost for the storage facility/tank [56]	23-195 [6.2 – 53.2]	23-195 [6.2 – 53.2]	23-195 [6.2 – 53.2]	
OPEX	€/kW	2% of CAPEX [19]	15-9.6	24-14	51-100	
Energy cost						
Geographical/special constraints						

Table 3-10: Characterization of hydrogen as a energy storage system

3.6 Reservoir Hydro

Hydropower can be divided in to three categories: reservoir hydro, run-of-the-river and pumped hydro. Reservoir hydro and pumped hydro can deliver significant flexibility with high ramping rate and predictability. Reservoir hydro, which we are discussing in this subsection, are characterized by water reservoirs storing water for long term. The flexibility available from the reservoir hydro depends on the reservoir size, the inflow to the reservoir, and various technical aspects related to the ramping rate and efficiency at different power outputs.

As oppose to the pumped storage Hydro, conventional reservoir hydro cannot be charged (by pumping water from a lower to the upper reservoir). Hence, flexibility is provided in terms of adjustment of the power output. Reservoir hydro can therefore to some extent be compared with thermal generators from which the power output can be adjusted in order to meet the power demand or provide system services. However, since the water inflow and the reservoir capacity are limited, the operational costs and generation scheduling of reservoir hydro are different from thermal plants where the operational cost (marginal cost) is mainly is determined by the cost of fuel. For hydropower scheduling, the concept of water value is used. The generation scheduling is namely related to the value of storing the water for a later point in time where the expected market price may be higher (or lower).

The characterization in **Table 3-11** is based on the characterization of Pumped Storage Hydro (section 0). The characteristics related to pumping has been excluded for the Reservoir Hydro.

Attribute	Unit	Comment	Typical values
Maximum output in generating mode	MW		Micro: 1 kW to 100 kW Mini: 100 kW to 1 MW Small: 1 MW to 10–30 MW Large: Above 10–30 MW
Minimum output in generating mode	MW		
Rough zone		Interval of rated power output which should be avoided due to high mechanical vibrations and stresses	30 – 70 %
Minimum generating time	h		
Time to start generating (startup time)	min		60 -90 seconds
Ramp rate during generating mode	MW/sec		150 MW/minute
Roundtrip efficiency	%		60 – 90 % depends

			on the operating power point.
Total maximum reservoir capacity	MWh	The maximum storage capacity to be used in pumping cycles is determined by the smallest reservoir.	20 - 1500
Initial reservoir level	MWh		**
Lifetime	Years		100
Cycle life			**
Lead time		Development and construction time before the plant is in operation	
CAPEX (power)	€/kW		1000
CAPEX (energy)	€/kWh		40 -150
OPEX		Related to water value	
Geographical/special constraints		The reservoir hydro plants are built in natural river systems. It may be different regulations in different countries with respect to how permission to build new reservoir hydro plants are given. Some river systems are protected and will not be utilized for hydro power generation. Others may be open for hydro power generation.	

Table 3-11 Characterization of Reservoir Hydro

3.7 Pumped Storage Hydro (PSH)

Pumped storage hydropower plants include an upper and lower water reservoir, a waterway to connect the reservoirs and a hydro power station equipped with turbine/pump/generator set. Energy is delivered to the grid by releasing water from the upper to the lower reservoir and running the PSH in generation mode (turbine mode). Similarly, the storage is "charged" by pumping water from the lower to the upper reservoir (pumping mode).

PSH can either be of "closed-loop" type were the PSH project is independent of naturally occurring river or lake (i.e. the reservoirs are located "off-stream"), or "on-stream integral pumped storage" where the PSH reservoirs are located on the same river. The latter type can operate as a conventional reservoir hydro plant. [57]

The energy capacity of the storage is determined by the size of the smaller reservoir and the height difference between the upper and lower reservoir (head). The maximum power generation is determined by the maximum flow of water from the upper to the lower reservoir and the head. When it comes to power capacity in pumping mode, it differs between PSHs depending on the technology used in the generator/turbine/pump sets. The different technologies also feature different degrees of flexibility with regards to ramping rate and time requirement for changing the direction from generation to pumping or vice versa.

The main technologies are the following [57] [58]. See appendix A.2 in [57] for more information about the technologies.

- Reversible pump turbine: The same turbine and generator are used in both generation and pumping mode. The shaft rotates in opposite directions in pump and turbine modes.
    - Conventional single speed synchronous motor (FS, fixed speed): Can regulate the power output in generation mode, but only run at constant power in pumping mode.
    - Adjustable speed (AS, mostly doubly fed induction machines): Can regulate the power both in generation and pumping mode
- Ternary units: Has both a pump and a turbine which can run simultaneously.
    - Single speed in pumping mode
    - Some can operate with hydraulic short circuit (pump and turbine simultaneously). This makes it possible to regulate the input power in pumping mode (as well as in generation mode)

Techno-economic characteristics for PSH are listed in **Table 3-12**. The list is based on the AS PSH characteristics from table 5.6 in [57]. Some additional characteristics are added. For some characteristics, typical values found in literature are included in the table.

Attribute	Unit	Comment	Typical values
Maximum output in pumping mode	MW		Min/max input/output: 50-500 MW (most typical: 200-350MW) [57], According to [31]: 10 MW to 3 GW. For a plant with a given rated power, the operating range is between 20-120% of rated power (AS) or 30-115% (FS) [57]
Maximum output in generating mode	MW		
Minimum output in pumping mode	MW		
Minimum output in generating mode	MW		
Rough zone		Interval of rated power output which should be avoided due to high mechanical vibrations and stresses	Fixed speed (FS): 40-60% Adjustable speed (AS): 45-55% of rated power output. [57]
Minimum pumping time	h		
Minimum generating time	h		
Time to start pumping (startup time)	min		
Time to start generating (startup time)	min		

Ramp rate during pumping mode	MW/sec		5 min from 0% to 100% pumping power [59]
Ramp rate during generating mode	MW/sec		Conventional fixed speed: 1.7-2.1MW/sec [57] 2 min from 0% to 100% generation [59]
Roundtrip efficiency	%		70-85% [31], >80% [59]
Total maximum reservoir capacity	MWh	The maximum storage capacity to be used in pumping cycles is determined by the smallest reservoir.	
Initial reservoir level	MWh		
Lifetime	Years		50-100 years [58]
Cycle life			Technically unlimited [31]
Lead time		Development and construction time before the plant is in operation	Up to 10 years [58]
CAPEX (power)	€/kW		400-1500 [31]
CAPEX (energy)	€/kWh		40-150 [31]
OPEX			
Geographical/special constraints		Some PHS are built in natural river systems. PSHs can also be developed by modifying reservoir hydro generation plants to PSHs. A third option is that the PSH can be constructed "off-stream" with man-made reservoirs and waterways. In all cases, there may be strict environmental and other restrictions and regulation which are impacting the geographical location of the PSH.	

Table 3-12 PSH Characteristics

- Typical duration of storage cycle for existing PSH in Europe (per 2013) [58]:
  - 4-9 hours in generation mode
  - 6-12 hours in pumping mode

The PSHs ability to provide flexibility depend on the type of technology as well as the power and energy capacity. In generation mode, all technologies are able to offer flexibility in terms of ramping up or down the power output. In pumping mode, the adjustable speed systems can ramp up or down the pumping power and hence offer flexibility with fast ramping times. If the flexibility required involves transition of mode (pumping to generation or vice versa), ternary systems are considerably faster than the reversible systems [57] since the shaft of the ternary system is always rotating the same direction, while for reversible systems the shaft must be stopped and then accelerated in the opposite direction to go from one mode to the other.

3.8 Combined Heat and Power (CHP)

Combined heat and power (CHP) units generate energy both in the forms of electricity and heat. CHP is one of the most efficient way to recover heat lost in the generation process by linking the cooling load of the thermal generation to the heat demand. The process is called trigeneration. In this way , the energy consumption can be maximized up to 90 % by improving the saving up to 40 % [60]. The heat is used to supply direct heat demand, for example in district heating services or by the industrial process. CHP can adjust the ratio between electricity and heat outputs. Increase in electricity generation will cause heat deficit and vice versa. The heat fluctuation is managed by local thermal storage tanks [60] or by the storage in the demand side, for example the thermal flexibility in the buildings in the case of district heating [61]. The general heat sources are biomass, biogas, waste to energy, fossil fuels (oil and gas) and geothermal [62]. Based on co-generation plant model from [1] characterizing terms are presented in **Table 3-13.**

Attribute	Unit	Comments	Typical values
Thermal capacity of CHP unit	MW	Upper limit of heat recovery unit	
Electric capacity of CHP unit	MW	Rated capacity of the electrical generator	1-50 [38] [39]
Minimum on-time of CHP	min		
Start-up time of CHP	min		10 min – 1 day [63]
Number of power steps for CHP operation	Integer	Steps defined as percentages of maximum capacity. E.g. J=4: 25% 50% 75% 100%. J=1: 100% (ON/OFF CHP)	
Volume of heat storage tank	l		Application dependent
Maximum temperature of heat storage system	°C		Application specific
Minimum temperature of heat storage system	°C		Application specific

Specific heat capacity of the fluid in the storage system	joule/gram		4.186 (for water)
Temperature margin	°C	Safety temperature margin in the heat storage system (margin to the maximum temperature)	Application specific
Time that the CHP is ON at the initial timestep 0		At the time step when the simulation starts	
Time that the CHP is ON at the current time step.	min	If value is 0 it means that the CHP is OFF	
Current temperature of the fluid in the storage system	°C		
Set-point for the CHP for the following time step	Integer (0-1)		
Geographical/special constraints		Landscape for CHP construction and accessibility for fuel and heat despatch. Environmental regulations.	

Table 3-13 Characterization of CHP

3.9 Compressed Air Energy Storage (CAES)

Compressed air storages are based on compressing air to high pressure and storing the high-pressure air in geological underground voids (salt caverns or geological formations of hard rock or porous rock).

Two types of CAES are common:

- Diabatic (conventional CAES or D-CAES): the compressed air is used in a combustion process with gas or other fuel to generate electricity using an open cycle turbine. (Commercially available. Two plants are in operation worldwide, namely Huntorf (1978, Germany) and McIntoch plant (1991, U.S.) [31])
- Adiabatic (AA-CAES or A-CAES): In the compression process, the excess heat is stored in a thermal storage in addition to the storage of the high-pressure air (i.e. there are two storages). Electricity is generated by utilization of a turbine and converting the energy from the heat in the thermal storage and the compressed air in the cavern to electricity.
  (Not yet commercially available, is in the demonstration stage. [31])

Diabatic systems have different performances than adiabatic systems, since they involve additional fuel and hence the efficiency, environmental impact and costs are different. Different characteristic specifications of CAES are given in the following **Table 3-14.**

Attribute	Unit	Comments	Typical values
Rated Energy capacity	MWh		Available (per 2103) up to 2860MWh [64]. According to [31] rang is from 100MWh to 10GWh
Power rating (discharge)	MW		Small-scale: a few kW to a few MW, Large scale: up to 1GW [64]. According to [31] some 100MW.
Recharge rate	MW	power rating for charging	
Heat rate	kJ/KWh LHV	Fuel consumed per kWh electric power output. LHV=Lower Heating Value	
Roundtrip efficiency		The cycle efficiency (charging and discharging). $\eta_{Roundtrip} = \frac{E_{input}}{E_{output}}$. For D-CAES, one must take into account that additional fuel is used in the discharge (combustion) process. Hence the energy input term, E_{input}, is the sum of the electricity consumed by the compressor and an additional term representing the energy of the fuel used in the discharging process: $E_{input} = E_{compressor} + (\eta_{ng} * E_{ng})$. The energy from the fuel, $(\eta_{ng} * E_{ng})$, is the amount of electricity that could have been made from the same fuel energy if the fuel had been used in a stand-alone power plant with efficiency η_{ng}. [64]	A-CAES: > 70% [31] D-CAES: ca 55% [31]
Operation switching time		Time needed to switch between charging and discharging operation.	The Huntorf plant (Germany, from 1978) uses 20 minutes. Faster switching times are possible with other system structures/designs. [64]
Ramp rate	MW/min	The speed of ramping up or down the power output/input	18 MW/min [64] From [10]: 10 minutes from cold start to full generation ; 5 minutes from online to full power; 3.33 minutes from full speed no load to full load; 4 minutes from offline to full load.
Partial load operation		Possibility to run the charging/discharging at partial load.	According to [64] the part-load operation ability is high
Cycle life			8000-12000 [64]
Lifespan	years		30-40 [2]

Fuel cost	€/kWh	If gas/fuel is used (D-CAES)	
Maintenance cost	€/kW year	Periodic inspection, fuelling, maintenance, component replacement, recalibration, etc.	
CAPEX (energy)	€/kWh	Cost per installed energy capacity	Large-scale CAES: 400-1000$/kWh [64]. Construction of storage reservoir comprise ca 50-60% of the capital cost. Since there are differences in costs depending on geological conditions, there may be great variations in capital costs between sites. 40-80 [2]
CAPEX (power)	€/kW	Cost per installed power capacity	According to [31]: D-CAES: 400-1200€/kW A-CAES: 1200-2000 €/kW
Lead time			
Geographical /special constraints		The compressed air is stored within geological underground voids (salt caverns or geological formations of hard rock or porous rock).	

Table 3-14 Characterization of CAES

Refer also to [10] for CAPEX and OPEX estimations. Liquified Air Energy Storage (LAES) or Cryogenic storage can also be defined as a type of CAES, as it is based on similar working principle and contain many of the same components as CAES. LAES/Cryogenic storage is discussed in Section 2.1.10.

3.10 Liquified Air Energy Storage (cryogenic storage)

LAES is similar to CAES and is often defined as a type of CAES. The working principle is similar to CAES. The main difference is that the air is liquified after compression and energy is stored in form of liquified air instead of compressed air. The plant contains three storages: a storage for liquified air, a cold storage and a heat storage. The liquified air is stored in insulated storage tanks (at low pressure and low temperature). As oppose to other CAES, there is no need for geological voids for storing the air, and therefore the choice of geographic location of LAES plants are more flexible. [31] [64]

The characterisation of LAES is equal to CAES. The characterization in **Table 3-15** is for LAES without fuel combustion. LAES in combination with gas (similar to D-CAES) is also possible [31]. Then additional characteristics related to fuel is added.

Attribute	Unit	Comments	Typical values
Rated Energy capacity	MWh		10MWh-7.8 GWh [31]
Power rating (discharge)	MW		5-650 MW [31]
Recharge rate	MW	power rating for charging	
Roundtrip efficiency			50-100% [31]
Operation switching time		Time needed to switch between charging and discharging operation.	>=5 min [31]
Ramp rate	MW/min	The speed of ramping up or down the power output/input.	
Partial load operation		Possibility to run the charging/discharging at partial load.	
Cycle life			22000-30000 [31]
Maintenance cost	€/kW year	Periodic inspection, fuelling, maintenance, component replacement, recalibration, etc.	May be higher than for other CAES due to more complex processes and components. [64]
CAPEX (energy)	€/kWh	Cost per installed energy capacity	60-600€/kWh [31]
CAPEX (power)	€/kW	Cost per installed power capacity	500-3500 €/kW [31]
Geographical/special constraints		The geographical location for LAES is more flexible than CAES since it is not dependent on geological conditions.	

Table 3-15 Characterization of LAES

3.11 Thermo-electric storage

Thermo-electric storage method accepts both electrical and thermal energy as input. Electrical energy is converted into thermal energy and uses thermal storage as energy storage form. The stored thermal energy can be extracted partly as electrical energy by expanding hot air in a gas turbine, and the other part is used in the form of thermal energy [65], [66], [67]. All the energy stored in thermo-electric storages cannot be extracted as electrical energy. Therefore, thermo-electric storage can be used most efficiently for the applications where part of the thermal energy that is not extracted as electrical energy can be used to produce process steam or hot water district heating services [65]. Thermo-electric energy storage model must be the combination of both demand response and storage models as part of the stored energy is used as heat demand. Thermo-electric storage characteristics with typical values are presented in **Table 3-16.**

Attribute	Unit	Comments	Typical values
Rated energy capacity [67]	MWh	Generally, 10 hours of storage is considered [68]	20 - 50
Power rating [67]	MW		2-5
Daily self-discharge [66]	%		0.05–1
Lifetime [66]	Years		10–20
Cycle efficiency [67]	%		~75–80
Specific CAPEX power based (per charging unit power) [68]	€/kW		797
Specific CAPEX energy based [68]	€/kW h		21
Specific OPEX power based [68]	€/kW		0.0026
Specific OPEX energy based [68]	€/kW h		11
Minimum SOC	%		
Maximum SOC	%		
Geographical/special constraints		Landscape for Thermo-electric storage construction and accessibility for heat despatch if the thermal storage uses high temperature storage	

Table 3-16 Characterization of thermo-electric storage

4 Modelling of flexibility resources

4.1 Storage modelling

In this section, we define a generic model which can apply for all kind of storages considered as candidates in the planning tool. These different storages are:

- Reservoir Hydro
- Pumped Storage Hydro (PSH)
- Battery Energy Storage System (BESS)
- Compressed Air Energy Storage (CAES)
- Liquified Air Energy Storage (LAES)
- Hydrogen as an energy storage system
- Thermo-electric storage

The first three subsections give an overview of respectively the sets, variables and parameters used for storage modelling. The two lasts subsections detail the modelling itself with respectively the constraints and costs linked to storages. The different choices which were made are discussed in these two subsections.

4.1.1 Sets

Set	Symbol	Typical value
Set of planning horizons	S_y	$\{2030, 2040, 2050\}$
Set of periods in the planning horizon	S_t	$\{1, 2, \dots, 8760\}$
Set of flexibility (storage) elements	S_j	

4.1.2 Variables

Variable	Symbol	Unit
Normalized energy storage level	$x_{j,t,y}$	-
Power absorbed from grid	$P_{j,t,y}^{abs}$	MW
Power injected to grid	$P_{j,t,y}^{inj}$	MW
Investment decision	$\alpha_j \in \{0,1\}$	-

4.1.3 Parameters

Parameter	Symbol	Unit
Maximum energy content	$E_{j,t,y}^{max}$	MWh
Minimum energy content	$E_{j,t,y}^{min}$	MWh

Initial energy content	$E_{j,y}^{init}$	MWh
Maximum absorbed energy over a year	$E_{j,y}^{abs,max}$	MWh
Maximum absorbed power	$P_{j,t,y}^{abs,max}$	MW
Maximum injected power	$P_{j,t,y}^{inj,max}$	MW
Absorption efficiency	$\eta_{j,t,y}^{abs}$	-
Injection efficiency	$\eta_{j,t,y}^{inj}$	-
Maximum absorption ramp rate	$r_{j,t,y}^{abs,max}$	MW/h
Maximum injection ramp rate	$r_{j,t,y}^{inj,max}$	MW/h
Power provided or demanded by external process	$\xi_{j,t,y}$	MW
Storage losses	$v_{j,t,y}$	MW
Status	$s_{j,t,y}$	-
Time step	Δt	Hours
Planning horizon	T	-
Investment costs	I_j	€

4.1.4 Constraints

In this subsection, we discuss the modelling of the constraints that define the behaviour of the storages. Before deep diving into the modelling, we first note the following assumptions:

- Reactive power is not considered (and so assumed to be zero) due to computational burden.
- Minimum charging and discharging times are assumed to be zero.
- Times to start charging/discharging are assumed to be zero.

The model presented in this subsection is intended primarily for candidate storage technologies, but it is also suitable for existing storage technologies. In the case of an existing storage technology, the only difference is that the investment costs should be zero and the investment variable should be forced to take 1 as value.

Then, we start the modelling with the energy balance constraints as the first set of constraints to be defined. These constraints can be stated as follows:

$$E_{j,t,y}^{max} x_{j,t,y} = E_{j,t,y}^{max} x_{j,t-\Delta t,y} + \Delta t \cdot \left(\eta_{j,t,y}^{abs} P_{j,t,y}^{abs} - \frac{P_{j,t,y}^{inj}}{\eta_{j,t,y}^{inj}} + \alpha_j \xi_{j,t,y} - \alpha_j v_{j,t,y} \right), \quad \forall j \in S_j, t \in S_t, y \in S_y \qquad (3)$$

These constraints define the dynamic of the storage as illustrated on Figure 4-1.

Each of these constraints requires three variables: one variable for the energy content of the storage and two variables for the power absorbed and injected from/to the grid. Two different variables are required for absorption and injection from/to the grid because the absorption and injection efficiencies can be different.

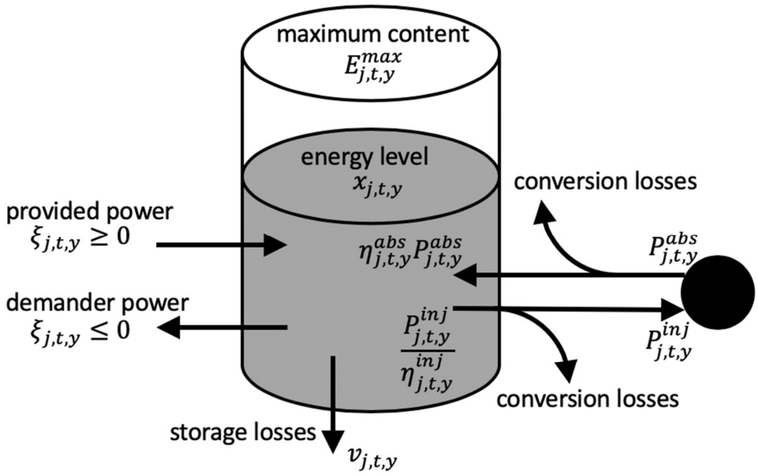

Figure 4-1 Dynamic of storage. Figure adapted from Fig. 2 in [69]

As a second set of constraints, we define the maximal and minimal energy content of the storages. For each storage, these constraints must be activated only in case we invest in the storage.

$$E_{j,t,y}^{min}\,\alpha_j \leq E_{j,t,y}^{max} x_{j,t,y} \leq E_{j,t,y}^{max}\,\alpha_j, \qquad \forall j \in S_j,\ t \in S_t, y \in S_y \tag{4}$$

Afterwards, we define constraints on the maximum power which can be absorbed or injected at each time step. These constraints also ensure that the absorbed or injected power is zero if we do not invest in the storage.

$$0 \leq P_{j,t,y}^{abs} \leq \alpha_j P_{j,t,y}^{abs,max}, \qquad \forall j \in S_j, t \in S_t, y \in S_y \tag{5}$$

$$0 \leq P_{j,t,y}^{inj} \leq \alpha_j P_{j,t,y}^{inj,max}, \qquad \forall j \in S_j, t \in S_t, y \in S_y \tag{6}$$

Moreover, we should also ensure that we are not absorbing and injecting power at the same time. Indeed, this behaviour would not be realistic and could lead to situations with the planning tool creates unnecessary power losses for free in case of overgeneration (because the storages are not fully efficient). The two classical formulations to ensure absorption and injection exclusivity are the following:

$$P_{j,t,y}^{abs} \cdot P_{j,t,y}^{inj} = 0, \qquad \forall j \in S_j, t \in S_t, y \in S_y \tag{7}$$

or

$$P_{j,t,y}^{abs} \leq V_{j,t,y} P_{j,t,y}^{abs,max}, \qquad \forall j \in S_j, t \in S_t, y \in S_y \tag{8}$$

$$P_{j,t,y}^{inj} \leq \left(1 - V_{j,t,y}\right) P_{j,t,y}^{inj,max}, \qquad \forall j \in S_j, t \in S_t, y \in S_y \tag{9}$$

However, the first formulation is non-linear and the second formulation is using binary variables. Therefore, these two formulations are not advised for our planning tool as we want to keep the model linear and as we want to keep a small number of binary variables. As an alternative, we will add this set of constraints to the model:

$$P^{abs}_{j,t,y} + P^{inj}_{j,t,y} \leq \max\left(P^{abs,max}_{j,t,y}, P^{inj,max}_{j,t,y}\right), \qquad \forall j \in S_j,\ t \in S_t, y \in S_y \tag{10}$$

These constraints will not eliminate the risk of having simultaneous absorption and injection but will limit it. Indeed, when there is overgeneration, $P^{abs}_{j,t,y}$ should be maximized and so $P^{inj}_{j,t,y}$ is pushed to zero. This principle is illustrated on Figure 4-2.

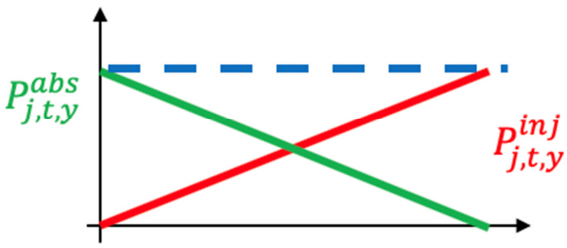

Figure 4-2 Limiting approach on simultaneous storage absorption and injection

As a next step, we have to define ramping constraints on the absorbed and injected powers. For most of the storage technologies, the ramping rate will be less than one hour and those constraints will be omitted. Nevertheless, we keep these ramping constraints in the formulation of the generic model for technologies with a larger ramping rate.

$$P^{abs}_{j,t,y} - P^{abs}_{j,t-\Delta t,y} \leq \Delta t \cdot r^{abs,max}_{j,t,y}, \qquad \forall j \in S_j, t \in S_t, y \in S_y \tag{11}$$

$$P^{inj}_{j,t,y} - P^{inj}_{j,t-\Delta t,y} \leq \Delta t \cdot r^{inj,max}_{j,t,y}, \qquad \forall j \in S_j, t \in S_t, y \in S_y \tag{12}$$

Additionally, we state constraints on the initial and on the final energy content of all storages. The second set of equations is needed to ensure that all storages do not become empty at the end of the planning horizon. It was decided to use an inequality constraint to avoid potential infeasibilities. Nevertheless, we expect the final energy content to converge towards the initial energy content as the standard behaviour. This is a desired behaviour as it permits us not to consider the water or storage value at the end of the planning horizon. It is illustrated on Figure 4-3.

$$E^{max}_{j,0,y} x_{j,0,y} = \alpha_j E^{init}_{j,y}, \qquad \forall j \in S_j, y \in S_y \tag{13}$$

$$E^{max}_{j,T,y} x_{j,T,y} \geq \alpha_j E^{init}_{j,y}, \qquad \forall j \in S_j, y \in S_y \tag{14}$$

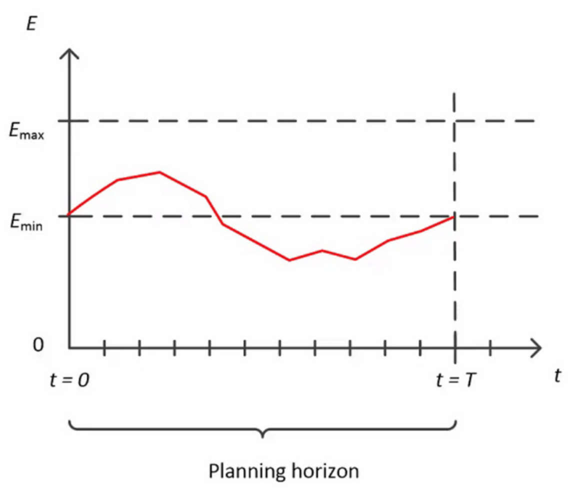

Figure 4-3 Energy content at the end of the planning horizon

Finally, we have to state how degradation of storage elements will be considered in the model. In order to avoid adding new binary variables, the choice was made to consider degradation by linearly decreasing the maximum energy content of the storages over the planning horizons. Moreover, the maximum energy content considered for each planning horizon will be the average value over the decade that the planning horizon represents. To keep these previous assumptions realistic, we also limit the total energy which can be absorbed over a year by using the following constraints:

$$\sum_{t \in S_t} \Delta t \cdot P_{j,t,y}^{abs} \leq E_{j,y}^{abs,max}, \quad \forall j \in S_j, y \in S_y \tag{15}$$

The purpose is to ensure that the storage elements are not overexploited during the first year. If needed, the maximum absorbed energy over a year as well as other parameters such as absorption and injection efficiencies or maximum absorbed/injected power at each time step can also be decreased over the planning horizons.

4.1.5 Costs

In this last subsection, we now define the costs linked to the investment (CAPEX) and the operation (OPEX) of storage elements.

- Investment costs (CAPEX):

$$\sum_{j \in S_j} \alpha_j I_j$$
$$I_j = \left(I_j^{eq} + I_j^{ins} + I_j^{env} + \cdots\right) \tag{16}$$

The global investment costs are the sum of all the individual investment costs of storage elements in which we decide to invest. These individual investment costs can be composed of different sub-investment costs. These different sub-costs can include equipment costs (I_j^{eq}), installation costs (I_j^{ins}) as well as some costs linked to environmental impact (carbon footprint) of storage construction (I_j^{env}).

- Operational costs (OPEX):

As the planning tool is considering the minimization of the costs in a system perspective, there are no operational costs linked to absorption/injection from/to the grid, nor storage costs to be considered. Moreover, there are no environmental operational costs to consider for storage (only needed for production units).

Furthermore, we do not consider any degradation costs because degradation will be accounted by pre-processing of the parameters as explained in the previous subsection.

Finally, the water or storage value at the end of the planning horizons is not explicitly considered as the constraints stated in the previous subsection should ensure that the initial and final energy contents of the storages are almost the same.

4.2 Demand flexibility modelling

In this section, we define a generic demand flexibility. This model intends to describe flexibility options in the most generic way within the planning tool. The modelling and model parameter definitions are independent of the type of the flexibility option and the used technology. The parameter values themselves reflect the type and technology.

This defined model can be used for these flexibility options:

- Electric Vehicles (EV)
- Industrial Demand Response
- Residential Demand Response
- Tertiary Sector Demand Response[3]
- Hydrogen production as industrial load

The first three subsections give an overview of respectively the sets, variables and parameters used for demand flexibility modelling. The two lasts subsections detail the modelling itself with respectively the constraints and costs linked to demand flexibility. The different choices which were made are discussed in these two subsections.

4.2.1 Sets

Set	Symbol	Typical value
Set of planning horizons	S_y	$\{2030, 2040, 2050\}$
Set of periods in the planning horizon	S_t	$\{1, 2, \dots, 8760\}$
Set of time windows	S_τ	$\{\{1, \dots, 168\}, \dots, \{8593, \dots, 8760\}\}$
Set of flexible demand elements	S_u	

[3] In this document the thermal loads from large commercial buildings and warehouses are also referred to as **tertiary sector loads**.

4.2.2 Variables

Variable	Symbol	Unit
Active power consumption	$P_{u,t,y}^{flex}$	MW
Not consumed power	$\Delta P_{u,t,y}^{nce}$	MW
Upward demand shifted	$\Delta P_{u,t,y}^{ds,up}$	MW
Downward demand shifted	$\Delta P_{u,t,y}^{ds,down}$	MW
Load curtailment	$\Delta P_{u,t,y}^{lc}$	MW
Investment decision	$\alpha_u \in \{0,1\}$	

4.2.3 Parameters

Parameter	Symbol	Unit
Reference demand	$P_{u,t,y}^{ref}$	MW
Superior bound on not consumed power	$\Delta_{u,t,y}^{nce,max}$	MW
Superior bound on upward demand shifted	$\Delta_{u,t,y}^{ds,up,max}$	MW
Grace period for upward demand shifting	$\tau_{u,y}^{ds,up,grace}$	h
Superior bound on downward demand shifted	$\Delta_{u,t,y}^{ds,down,max}$	MW
Grace period for downward demand shifting	$\tau_{u,y}^{ds,down,grace}$	h
Maximum energy not consumed	$E_{u,y}^{nce,max}$	MWh
Investment costs	I_u	€
Compensation for consuming less	$C_{u,t,y}^{nce}$	€/MWh
Compensation for demand shifting	$C_{u,t,y}^{ds}$	€/MWh
Compensation for load curtailment	$C_{u,t,y}^{lc}$	€/MWh
Compensation for load curtailment	$C_{u,t,y}^{lc}$	€/MWh
Time step	Δt	h

4.2.4 Constraints

In this subsection, we discuss the modelling of the constraints which define the behaviour of flexible loads subject to both shifting and shedding. The approach that we decided to use is to define a reference load profile and to let the planning tool decides how it deviates from it (up to some limitations which will be described in this subsection). Alternatively, one could have decided to give several load profiles to the planning tool and to let it decide which of these load profiles it wants to use. This second approach was not chosen because it would imply the use of binary variables which would slow down the resolution of the optimization problem.

Let us also note that the described model is intended first for existing loads which require an investment to make them flexible. However, it is also suitable for existing loads which are already flexible and for existing loads which cannot become flexible. In the case of a load which is already flexible, the only difference is that the investment costs should be zero and the investment variable should be forced to take 1 as value. In the case of a load which cannot become flexible, the only difference is that upper bounds on flexibility potentials should be zero or the investment variable should be forced to take 0 as value.

Before deep diving into the modelling, we first define the concepts of reference demand and flexible demand. The reference demand $P_{u,t,y}^{ref}$ is the aggregated demand for element u at time period t and horizon y (in MW), while the flexible demand or active power consumption $P_{u,t,y}^{flex}$ is the effective aggregated power consumption delivered by element u at time period t and horizon y (in MW). Figure 4-4 illustrates these two concepts.

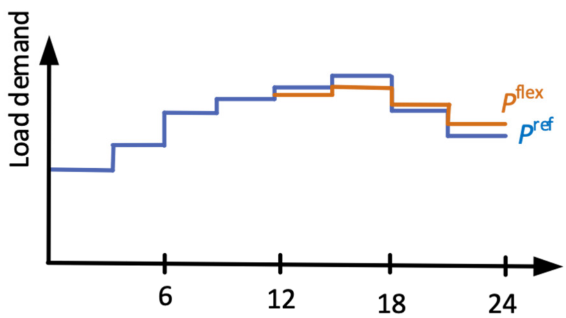

Figure 4-4 Reference demand versus flexible demand (active power consumption)

Then, we define the set of equations which link these two concepts of reference demand and flexible demand.

$$P_{u,t,y}^{flex} = P_{u,t,y}^{ref} - \Delta P_{u,t,y}^{nce} + \Delta P_{u,t,y}^{ds,up} - \Delta P_{u,t,y}^{ds,down} - \Delta P_{u,t,y}^{lc}, \qquad \forall u \in S_u,\ t \in S_t, y \in S_y \tag{17}$$

The active power consumption of element u at time period t and horizon y is equal to the reference demand of this same element at the same time to which we subtract the load shedding activation, subtract the load curtailment and add (in case of upward demand shifting) or subtract (in case of downward demand shifting) the load shifting activation. This is illustrated on Figure 4-5.

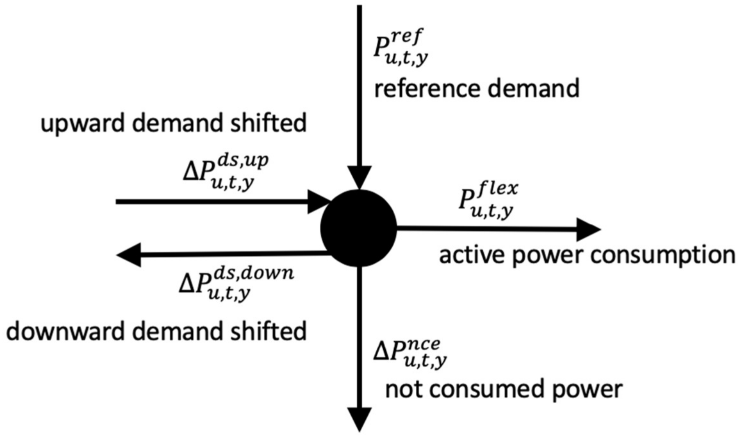

Figure 4-5 Flexible node balance

The active power consumption as well as all the four quantities (not consumed power, upward demand shifted, downward demand shifted and load curtailment) defined in the above equation are forced to be positive. Moreover, we define an upper bound for each of these four quantities. For not consumed power and demand shifting, this upper bound is active only in the case of an investment in the flexibility, otherwise the upper bound is zero.

$$0 \leq P_{u,t,y}^{flex}, \qquad \forall u \in S_u,\ t \in S_t, y \in S_y \tag{18}$$

$$0 \leq \Delta P_{u,t,y}^{nce} \leq \alpha_u \Delta_{u,t,y}^{nce,max}, \qquad \forall u \in S_u,\ t \in S_t, y \in S_y \tag{19}$$

$$0 \leq \Delta P_{u,t,y}^{ds,up} \leq \alpha_u \Delta_{u,t,y}^{ds,up,max}, \qquad \forall u \in S_u,\ t \in S_t, y \in S_y \tag{20}$$

$$0 \leq \Delta P_{u,t,y}^{ds,down} \leq \alpha_u \Delta_{u,t,y}^{ds,down,max}, \qquad \forall u \in S_u,\ t \in S_t, y \in S_y \tag{21}$$

$$0 \leq \Delta P_{u,t,y}^{lc} \leq P_{u,t,y}^{ref}, \qquad \forall u \in S_u,\ t \in S_t, y \in S_y \tag{22}$$

These constraints are used to avoid that the effective delivered charging power deviates too much from the reference demand.

In these constraints, we refer to $\Delta_{u,t,y}^{ds,up,max}$ and $\Delta_{u,t,y}^{ds,down,max}$ as shifting flexibility potentials. In order to avoid the planning tool to use too much shifting flexibility in a short period of time, we add the possibility to reduce these flexibility potentials for a coming grace period $\tau_{u,y}^{ds,up,grace}$ or $\tau_{u,y}^{ds,down,grace}$ after flexibility is activated. Therefore, in addition to the two equations (20) and (21) related to demand shifting, we add the following constraints:

$$0 \leq \Delta P_{u,t,y}^{ds,up} \leq \Delta_{u,t,y}^{ds,up,max} - \sum_{\tau \in \left\{t-\tau_{u,y}^{ds,up,grace},\ldots,t-1\right\}} \Delta P_{u,\tau,y}^{ds,up}, \qquad \forall u \in S_u,\ t \in S_t, y \in S_y \tag{23}$$

$$0 \leq \Delta P_{u,t,y}^{ds,down} \leq \Delta_{u,t,y}^{ds,down,max} - \sum_{\tau \in \left\{t-\tau_{u,y}^{ds,down,grace},\ldots,t-1\right\}} \Delta P_{u,\tau,y}^{down,up}, \qquad \forall u \in S_u,\ t \in S_t, y \in S_y \tag{24}$$

Concerning load shifting, we also have to ensure the balance between upward and downward activations. This balance between upward and downward activations is imposed over some predetermined time windows. These time windows can be different for each flexibility element.

$$\sum_{t\in\tau} \Delta P^{s,up}_{u,t,y} = \sum_{t\in\tau} \Delta P^{ds,down}_{u,t,y}, \qquad \forall u \in S_u,\ y \in S_y, \tau \in S_\tau. \tag{25}$$

Concerning load shedding, we also have to define constraints on the total allowable energy not consumed. For each planning horizon and flexible demand element, we want the energy not consumed to be positive (we cannot consume more than reference demand) and smaller than a threshold value $E^{nc,max}_{u,y}$. Moreover, we want energy not consumed to be possible only in the case of an investment in the flexibility.

$$0 \le \sum_{t\in S_t} \Delta t \cdot \Delta P^{nce}_{u,t,y} \le \alpha_u E^{nc,max}_{u,y}, \qquad \forall u \in S_u,\ y \in S_y. \tag{26}$$

In the case we do not want to allow energy not consumed for an element $\overline{u}$, we would have $E^{nc,max}_{\overline{u},y} = 0$, and then the above constraint is equivalent to:

$$\Delta P^{nce}_{\overline{u},t,y} = 0, \qquad t \in S_t, y \in S_y \tag{27}$$

4.2.5 Costs

In this last subsection, we now define the costs linked to enabling demand flexibility (CAPEX) and the costs linked to the activation of demand flexibility (OPEX). The OPEX costs are divided in three parts: costs linked to demand shifting and costs linked to demand shedding (voluntary demand reduction) and costs linked to load curtailment (involuntary demand reduction).

- Investment costs (CAPEX):

$$\sum_{u\in S_u} \alpha_u I_u \tag{28}$$

The global investment costs are the sum of all the individual investment costs of demand flexibility that the tool decides to enable.

- Compensation for demand shifting:

$$\sum_{u\in S_u}\sum_{t\in S_t}\sum_{y\in S_y} \Delta t \cdot C^{ds}_{u,t,y} \cdot \Delta P^{ds,down}_{u,t,y} \tag{29}$$

The compensation for demand shifting is only accounted for the downward demand shifted. Indeed, upward demand shifted and downward demand shifted are forced to be equal and the system should pay only when the demand is reduced but not when it is recovered.

- Compensation for demand shedding (voluntary demand reduction):

$$\sum_{u\in S_u}\sum_{t\in S_t}\sum_{y\in S_y} \Delta t \cdot C^{nce}_{u,t,y} \cdot \Delta P^{nce}_{u,t,y} \tag{30}$$

The price of the compensation for demand shedding is expected to be larger than the price of the compensation for demand shifting.

- Compensation for load curtailment (involuntary demand reduction):

$$\sum_{u \in S_u} \sum_{t \in S_t} \sum_{y \in S_y} \Delta t \cdot C_{u,t,y}^{lc} \cdot \Delta P_{u,t,y}^{lc} \qquad (31)$$

The price of the compensation for load curtailment is expected to be larger than the price of the compensation for demand shedding.

5 Link between flexibility characteristics and model parameters

In the FlexPlan planning tool, the two models presented in Chapter 4 will be used for flexibility modelling. As explained in Chapter 4, the different flexibility resources presented in Chapter 3, are grouped as shown in **Table 5-1** and they are modelled by the two different models.

Storage model	**Demand flexibility model**
Reservoir Hydro	Electric Vehicles (EV)
Pumped Storage Hydro (PSH)	Industrial Demand Response
Battery Energy Storage System (BESS)	Residential Demand Response
Compressed Air Energy Storage (CAES)	Tertiary Sector Demand Response
Liquified Air Energy Storage (LAES)	Hydrogen production as industrial load
Hydrogen as an energy storage system	
Thermo-electric storage	

Table 5-1 Model groups of flexibility resources

Hence, the characteristics of the individual flexibility resources must be mapped to the model parameters for the models. The purpose of the mapping is twofold: firstly, it is used to ensure that all relevant characteristics are included in the modelling. Secondly, it can be used in the scenario building and regional cases when the model parameters are to be populated with data.

In order to illustrate the mapping between the model parameters and the flexibility characteristics, mapping for two flexibility resources for the storage model and demand flexibility model is shown in sections 5.1 and 5.2 respectively.

5.1 Energy storage systems and the storage model

In Table 5-2 a mapping between the storage model parameters and two types of storage systems are shown, namely Pumped Storage Hydro (PSH) and Battery Energy Storage System (BESS).

Parameter	**Symbol**	**Unit**	**Pumped Storage Hydro**	**Battery energy storage system**
Maximum energy content	$E_{j,t,y}^{max}$	MWh	Maximum reservoir capacity	Minimum SOC x Energy capacity
Minimum energy content	$E_{j,t,y}^{min}$	MWh	Minimum reservoir capacity	Maximum SOC x Energy capacity
Initial energy content	$E_{j,y}^{init}$	MWh	Initial reservoir level	Initial SOC x Energy capacity
Maximum absorbed energy over a year	$E_{j,y}^{abs,max}$	MWh		Energy capacity
Maximum absorbed power	$P_{j,t,y}^{abs,max}$	MW	Maximum output in pumping mode	Maximum charging power capacity
Maximum injected power	$P_{j,t,y}^{inj,max}$	MW	Maximum output in generating mode	Maximum discharging power capacity
Absorption efficiency	$\eta_{j,t,y}^{abs}$	-	Pumping efficiency	Battery charging efficiency
Injection efficiency	$\eta_{j,t,y}^{inj}$	-	Generation efficiency	Battery discharging

				efficiency
Maximum absorption ramp rate	$r_{j,t,y}^{abs,max}$	MW/h	Ramp rate during pumping mode	Energy capacity / Charging C rate
Maximum injection ramp rate	$r_{j,t,y}^{inj,max}$	MW/h	Ramp rate during generating mode	Energy capacity / discharging C rate
Power provided or demanded by external process	$\xi_{j,t,y}$	MW	Power station self-consumption	Battery management system power consumption
Storage losses	$v_{j,t,y}$	MW	Discharge for irrigation and to maintain minimal river flow	Self-discharge
Status	$s_{j,t,y}$	-	Pumping or generation	Charging or discharging
Time step	Δt	Hours		
Planning horizon	T	-		
Investment costs	I_j	€	CAPEX	CAPEX

Table 5-2 Mapping between the storage model parameters and the characteristics of two flexibility resources; PSH and BESS

5.2 Flexible loads and the demand flexibility model

In **Table 5-3** a mapping between the demand flexibility model parameters and two types of flexible loads are shown, namely, tertiary sector demand response and industrial demand response.

Parameter	Symbol	Unit	Tertiary Sector Demand Response	Industrial demand response
Reference demand	$P_{u,t,y}^{ref}$	MW	Demand without demand response activation (Nominal demand)	Demand without demand response activation (Nominal demand)
Superior bound on not consumed power	$\Delta_{u,t,y}^{nce,max}$	MW	Nominal demand - Minimum Power capacity	Nominal demand
Superior bound on upward demand shifted	$\Delta_{u,t,y}^{ds,up,max}$	MW	Maximum rated power of the system - Nominal demand	Maximum rated power of the system - Nominal demand
Grace period for upward demand shifting	$\tau_{u,y}^{ds,up,grace}$	h	Remaining thermal capacity available / Maximum rated power of the system	Shiftable process time
Superior bound on downward demand shifted	$\Delta_{u,t,y}^{ds,down,max}$	MW	Minimum Power capacity	Minimum Power capacity

Grace period for downward demand shifting	$\tau_{u,y}^{ds,down,grace}$	h	Present thermal capacity available / Nominal demand	Energy payback time window
Maximum energy not consumed	$E_{u,y}^{nce,max}$	MWh	(Nominal demand - Minimum Power capacity) * Grace period for downward demand shifting	(Shifted period - Shiftable process time) x Nominal demand
Compensation for consuming less	$C_{u,t,y}^{nce}$	€/MWh	DR activation cost	DR activation cost
Compensation for demand shifting	$C_{u,t,y}^{ds}$	€/MWh	DR activation cost	DR activation cost
Time step	Δt	h	Resolution of one period (one hour)	Resolution of one period (one hour)

Table 5-3 Mapping between the demand flexibility model parameters and the characteristics of two flexibility resources; tertiary sector demand response and industrial demand response

6 Qualitative mapping of flexibility solutions to selected services

This section, in the first place, introduces the work developed in D2.1 to select the congestion management support service, as target for flexibility resources within FlexPlan [70]. After that, some of the characteristics of congestion are analysed to assess, in general terms, how these influence the selection of flexibility candidates in terms of sizing and location constraints.

FlexPlan report D2.1 provides a review of the services or applications that both storage technologies and Demand Response (DR) strategies can provide to the system (network, generators and customers). Even if a wide set of applications is reviewed, the final selection of the applications to be analysed in detail is done on the basis of the FlexPlan project approach:

- The focus is set on those applications able to provide network congestion support, since congestion is the primary driver for grid extension and, therefore, for network planning.
- Congestion management or support is considered from the active power control perspective.
- One hour is considered as simulation step and the services provided in shorter time scales are neglected.

As consequence, from the storage applications reviewed in D2.1, the selected main storage service is capacity *support*[4], with a final aim of deferring transmission and distribution network investments, and those DR and generator side strategies that contribute to the same objective: price arbitrage, end-user peak shaving, *time of use* energy cost management[5], *demand charge management*[6], Electric Vehicle integration, etc.

In principle, most storage technologies (probably with the exception of supercapacitors) and demand side loads (if big enough or aggregated) are suitable to provide congestion management support [71]. However, certain considerations must be taken depending on the characteristics of the congestion. Congestion occurs in the power system when [72] [73]:

- Physical power flows cannot be accommodated respecting operational constraints, such as thermal and voltage limits of assets. This is the physical aspect of the congestion where it is technically impossible to meet demand for electricity everywhere.
- Cross-zonal capacity or allocation constraints within a bidding zone limits the economic surplus for day-ahead or intraday coupling. This is the market aspect of the congestion where

[4] *Capacity support* refers that the storage can be used to shift load, normally from on-peak periods to off-peak periods, to reduce the maximum currents flowing through cables, wires and other network assets.

[5] *Time of Use pricing* refers to a systematic variation of prices, which reflects the average cost of electricity in certain periods.

[6] *Demand Charge Management* refers to the use of energy storage to reduce electricity costs by reducing demand charges during peak periods specified by the utility.

all demand can be met by changing the generator dispatch from the market's preferred outcome but with higher price.

Normally, at network operational level, physical congestion is avoided through remedial actions such as re-dispatching, countertrading (typically) or by the use of storage, DR, network assets allowing the modification of power flow through the lines (phase shifting transformers, FACTS), etc. Most of these actions (those not linked with the use of network assets) increase system operational costs and this is reflected at market level even if the physical congestion does not show up. When congestion is persistent at a specific network area, it is considered structural and a network extension might be needed to reduce physical congestion risk and the cost increase associated with it.

Since both storage and DR strategies are able to modify somehow the impact of generation and demand profiles on transmission and distribution lines, both are suitable to support congestion management. However, some characteristics of congestion should be considered to assess the ability of flexibility resources to provide this support.

The amount of power exceeding line size that cannot be transmitted from one point to another of the network, should define the **size, in power**, of the storage or, in the case of DR, of the power that should be activated through DR strategies. In the case of an excess of demand with respect to network transfer limitations, in order to eliminate congestion, the SO should act either by reducing consumption or by injecting stored power at demand side. In the case of excess of generation with respect to network transfer limitations, congestion should be eliminated by storing the excess of power that causes the congestion. Therefore, the storage technology or DR strategy should be able to meet the required flexible power to alleviate the congestion.

Two other characteristics of congestions provide insights to choose the most appropriate flexibility resource. For this purpose, we consider two dimensions in the **frequency of occurrence of a congestion**: daily and yearly. The **daily** frequency is related to the congestion behaviour along a day. If it is related to a high **demand**, one or two peaks are expected to appear during the day, according to today's conventional patterns (this is normally dependent on the region and yearly season). In this case, the flexible resource should be able to reduce the congestion for a certain number of consecutive hours. In the case of two peaks, it should be ready to act upon both periods separated by a time, in which part or the whole energy capacity level could be recovered (e.g. charging of a battery). In the case of DR, the DR contracts should specify in which conditions may the activation be performed, e.g. how many events are allowed during a day/month/season, of which duration and which is the minimum time that should pass between consecutive events.

In the case of a congestion caused by RES **generation**, the same applies. However, in this case, depending on the plant technology the optimum flexibility solution could be different. It must be considered that curtailment is always possible in a generation plant and this is currently used in some countries, e.g. Spain, to avoid congestion. Nevertheless, this is not desired, and the flexibility resources should help to avoid RES generation curtailment. In the case of a **photovoltaic plant**, the maximum production of the plant, in the absence of clouds, is expected during the central hours of the day. This causes that congestion may appear during this period in days with high availability of the resource (irradiance on the module) and in areas with high production with respect to the power evacuation capacity. The flexible resource should be active during the generation peak, normally few hours, and then it would have a longer period to be inactive or charging, in the case of a batteries. **Solar thermal** plants have a similar performance profile, however many of them have already thermal storage in their facilities to extend the generation period and provide a firmer output. This necessity to start and stop the system every day has an impact on the maintenance of the systems and some flexibility alternatives might suffer more in this context.

The case of **wind generation** is different. The variability of the resource could be high from one day to another, depending on the location of the plant. Exact predictions on the power availability are difficult to obtain, the longer the time ahead the more difficult they result. In this case, the energy availability of the flexibility resource is difficult to plan, and activation/deactivation of the resource may be required more often. In this case, the sizing of the equipment, should rely on historical data about congestions related to the power production.

In both cases, the number of storage systems coupled with RES generation plants is expected to increase in the following years, linked both to the observation of network quality requirements or/and to the provision of services to the system in return for additional incomes. This will change the injection profile of RES plants in the coming years and will provide a support for congestion management in the network.

An additional aspect to be considered is that **DR does not seem to be an available resource in the case of the** congestion **problems caused by generation**, since congestion cannot be solved at the generation point unless there is a high local demand able to increase consumption.

This daily pattern of congestion varies along the **year** with demand and generation characteristics. Congestion could appear during few days, e.g. those of highest demand in winter/summer, or it could happen during longer periods (e.g. month, season or whole year). This dimension provides information on the usage of the flexibility resource along a year, e.g. high/very low, concentrated in a period or dispersed along the year… This has an impact on the selection of flexibility options to be considered as candidate to relieve congestion. In this framework, the assessment of the feasibility of these solutions in comparison with conventional network extension practices is relevant, since above a certain usage level, building a new line (for example) could result in a lower cost solution for the system.

Sizing of flexibility resources does not need to be projected for the worst-case defining the characteristics of the congestion. The objective could be to eliminate congestion for all congested hours of the year or, for example, for a percentage of them, or to reduce congestion in a percentage, not totally, for congested hours.

An additional aspect of congestion that impacts the selection of a flexibility candidate is the **location**, even if this aspect is somehow indirect. Congestion can appear anywhere in the network and the location of flexibility resources is conditioned by that. Once the best buses for the installation of a flexibility asset are selected, it should be checked whether the location is suitable for the candidate technologies. In this case, aspects such as the following should be analysed to assess the feasibility of a new installation or the size limitations imposed by the location:

- **Availability of resources**: e.g., water, in the case of small hydro plants; existence and quantification of flexible demand (residential, industrial, EV) in the case of DR; etc.

- **Availability and accessibility of space**: underground caves, in the case of CAES; limited space to build a system, e.g. battery or hydrogen-based storage plant in an area; area with difficult accessibility to build an installation, e.g. mountainous area.
- **Environmental restrictions**: impossibility to build energy installations, including new lines, in restricted areas.
- **Safety restrictions**: some technologies might not be allowed to be installed in, or near to, certain areas or might be required to meet very strict codes if they are considered potentially dangerous, e.g. hydrogen.

These above are all aspects that should be considered in the process to select candidates for grid extension elements to be evaluated by the planning tool.

A first assessment of the flexibility options in relation to the congestion support service, considering the aspects introduced above, is presented in the following table. These aspects are the power size range; the energy capacity, represented in hours of discharge at nominal power; the type of congestion (demand, generation) they are suited for; and some of the limitations they may have. The assessment is illustrative, and it must be considered that, for example, within storage, there are diverse technologies with very different characteristics. The final mapping should be done by the pre-processor during the use case assessment.

Flexibility resource		Power: few MW	Power: tens of MW	Power: few hundreds of MW	Energy: <2 hours	Energy: 2-6 hours	Energy: >6 hours	Suited for demand congestion	Suited for generation congestion	Location related limitations
Battery energy storage system										Availability of space
Demand Response	Total (aggregated per zones)									Availability resource: industries, EV charging points, population
	Industrial (per facility)									
	EV (aggregated per zones)									
Hydrogen										Availability of space: difficult to store (caverns, high pressure tanks, cryogenic storage) Safety should be observed
Pumped hydro		high cost								Availability resource Availability of space
Thermal loads	Space heating /cooling	Included in DR								
	Cold storage									
Compressed air storage										Availability of space: caverns Environmental impact/restrictions
Liquid-Air Electricity Storage systems										Availability of space Safety
Thermo electric storage										N/A

Very suitable
Less suitable
Unsuitable

Table 6-1 Flexibility resource mapping to the congestion characteristics

7 Summary

In this deliverable, flexibility resources are analysed from the point of view of their capability to be employed as reliable alternatives in the network planning process. The main criteria considered can be summarized as:

- flexibility service delivery capability,
- technological maturity,
- economic feasibility,
- environmental impact.

These criteria may also evolve through time as the network planning is focusing on the scenario years 2030-2040-2050. It is identified that most of the evaluated flexibility resources do not have a sufficient technology maturity to be considered as 'off-the-shelf' solutions today. However, according to the assessments presented in this deliverable almost all the selected flexibility resources will be readily deployable from 2030 onwards. The most prominent flexibility resources include battery energy storage systems, pumped hydro, domestic and industrial demand response, electric vehicles and hydrogen storage systems.

As an input for the numerical evaluation, through the new FlexPlan planning tool, of the optimality to invest in flexibility resources to support grid planning, techno-economic characteristics of these resources must be preliminarily assessed. In this report, the main characteristics of the selected flexibility resources are identified. While the characteristics of some resources can be analysed in a very detailed way giving insight into the operational process, for other resources such as industrial demand response, an aggregated representation of the flexibility behaviour arising as the sum of various processes is considered sufficient in order to maintain numerical tractability of the overall mathematical model. In addition, typical numerical values for the characterizing parameters of the resources are included in the parametric tables, whenever they are available in the reviewed literature.

The formulation of the new FlexPlan planning tool must include numerical models of the alternative investment solutions, in some cases, as decision variables of the optimization problem and in almost all cases as constraints of it. For example, model of battery storage system can have size as a decision variable and number of charge-discharge cycles as a constraint. Model needs for flexibility resources depends on the level of the dynamics under investigation. For a network planning tool development, however, aggregated generic models to represent a set of flexibility resources can be sufficient. Accordingly, the selected flexibility resources are grouped into two groups for modelling purposes: the storage model group and the demand response model group. These models are presented in this report by including detailed characteristics of the resources and by considering the needs of the planning tool.

When generic models are developed to represent multiple flexibility resources, there will be a need for relating specific characteristics of the individual flexibility resources to the generic representative characteristics. For example, energy capacity of electric battery storage system and water reservoir capacity of pumped hydro can be represented by similar characteristics. In the end, meaningful and relatable input data and decision variables shall be attached to the individual flexibility resources. In this report, the mapping of individual flexibility resource characteristics to generic characterizing parameters are presented for characteristics of both model groups.

This report also presents a qualitative mapping of the selected flexibility resource to the services addressed by the FlexPlan project. Congestion management is considered to be the most relevant flexibility service based on the selected 1-hour resolution and the planning approach set up by the FlexPlan project. All of the selected flexibility resources are identified as suitable for congestion management.

The results presented in this report open the way for the development of the new FlexPlan planning tool and the results are also going to be used in the pre-processor for evaluating the resources as potential solutions at different bus locations of the network. The flexibility resources deemed to be relevant for consideration in long term network planning are presented, characterized, and modelled.

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