METIS Studies

Study S07

The role and need of flexibility in 2030: focus on energy storage

METIS Studies
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EXECUTIVE SUMMARY

Policy context and related challenges

The 2030 Framework for climate and energy sets as EU-wide targets for 2030 a 40% cut in greenhouse gas emissions compared to 1990 level, and at least a 27% share of renewable energy consumption. For the power system, this means a share of at least 45% of electricity demand generated from renewable sources (European Commission), compared to 27.5% in 2014 (Eurostat). A significant part of this additional renewable energy will come from variable energy, produced by wind and solar technologies, which bring new challenges in terms of security of supply and electricity price volatility.

Indeed, the variable nature of renewable energy generation driven by weather conditions induces high fluctuations of residual demand[1] and consequent needs for thermal generation: important capacity back-up is required to face periods of low Renewable Energy Sources (RES) generation while the high fluctuations in the use of these thermal units imply additional fuel and start-up costs.

In this context, interconnectors, demand response and energy storage can play an important role in increasing system flexibility and smoothing residual demand. As presented in Table 1, a portfolio of flexibility solutions with complementary time characteristics will be necessary to efficiently integrate high shares of variable energy.

Assessing the value and the needs of flexibility

The economic value of flexibility comes from several sources. First, flexibility can increase variable RES capacity value, by shifting power generation to periods of peak residual demand. An energy storage capacity can store power during periods of high variable RES generation (typically during the day for countries with high photovoltaic (PV) shares) and use it during peaks hours (e.g. in the evening when the power demand increases and the PV generation decreases). In that case, the capacity services provided by the flexibility depend on the amount of energy which can be shifted (energy storage duration) and the energy mix: a few hours of storage is sufficient to provide capacity services in countries with high PV shares while a longer storage capacity (typically 10 hours) is necessary for countries with larger shares of wind power.

Flexibility can also provide arbitrage services. Smoothing the residual demand allows to avoid expensive start-ups and use more base load units with lower variable costs. The arbitrage value is assessed by comparing the system operational costs (including fuel, CO2, unit start-up and running costs), with or without the flexibility solution, using an hourly simulation of the optimal dispatch of the European system on a full year.

Additional services can be provided by flexibility options, such as balancing services, quality/stability in the electric signal, or network decongesting. These additional services are not considered in this report.

In this report, the need for flexibility over a given period (e.g. over a day or a week) is defined as the amount of energy that has to be shifted in order for the residual demand to become constant over that period.

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[1] The residual demand (or net demand) at a given time is equal to power demand minus variable renewable energy generation.

Solar power: a minor driver for flexibility needs in 2030

Contrary to a widespread belief, a few percent of photovoltaic capacity in the energy mix tends to decrease the needs for daily flexibility. Indeed, PV generation coincides with periods of high power demand, and tends to smooth out the residual demand over the day[2]. As a result, solar power capacity does not create additional needs for flexibility as long as the PV generation is lower that 10-12% of the annual power production. According to European Network of Transmission System Operators (ENTSO-E) Visions from the Ten-Year Network Development Plan (TYNDP) 2014, the only European countries where that level should be exceeded by 2030 are Italy, Bulgaria and Spain, and only by a few percentage points.

Since this study focuses on generation adequacy at Member State level, this statement is only valid for large scale storage. Additional needs may appear at local level, in particular at the distribution level where PV can lead to local saturation effects.

Wind power: a significant driver for flexibility needs

Wind energy generation, on the other hand, varies over cycles of several days[3]. Hence, an increase in wind power capacity mechanically increases the need for weekly flexibility. For countries with high wind energy shares, a few days of generation surplus can follow periods with low wind energy generation and high back-up needs. In the studied use case, 1 GW of storage capacity in UK with 24 hours of discharge time saves from 90 to 150 M€/year by providing back-up services, storing RES surplus or nuclear energy and avoiding the start-up of gas units.

Interconnectors are an important source of flexibility

Interconnectors enable to smooth out the residual demand by aggregating the variations over larger zones. Indeed, the variability of weather conditions (and consequently of RES generation profiles) across Europe, along with the countries differences in terms of generation mix, induce lower flexibility needs if the electricity can be exchanged over large zones.

As an example, the high interconnection capacity of the centrally-located Germany divides by two the needs of the country for daily and weekly flexibility in 2030, which leaves little value for additional energy storage (below 80M€/year for a 1GW-24GWh storage capacity). In contrast, the high value of storage in the United Kingdom is related to the relative isolation of this country, as its interconnection capacity does not bring enough flexibility to cope with important wind energy shares.

[2] Even if PV can generate high fluctuations of residual demand during some summer sunny days, the cumulated impact over a year is positive.

[3] Again, this statement is only true at an aggregated (country) level. At a local level, wind conditions vary with shorter time characteristics.

Occurrence	Yearly	Weekly	Daily	Intra-hour
Historical stakes	Peak demand due to temperature (heating in winter or cooling in summer)	Higher demand during working days compared to week-end	Demand variation between peak and off peak hours	Unit outages and demand forecast errors
New stakes with high RES shares	Needs to back-up renewable variable energy with firm capacity	Variation of wind energy generation (at national level) over periods of a few days	Daily cycle of PV generation	RES generation forecast errors
Corresponding markets	Capacity market or scarcity prices	Day-ahead market	Day-ahead and intraday market	Balancing market
Flexibility characteristics requirements	3-6h for countries with high PV share 6-12h otherwise	> 12h	3-6h	High reactivity
Flexibility value	High in most countries as it can replace investments in peak units	High values for country with high wind energy share and low interconnection capacity (like UK)	Low value for most countries in Europe by 2030 Benefits appear for PV shares higher than 12%	Not studied here

Table 1: Description of the different types of flexibility needs

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1. ABBREVIATIONS AND DEFINITIONS

1.1. ABBREVIATIONS

Abbreviation	Definition
CAES	Compressed Air Energy Storage
CCGT	Combined Cycle Gas Turbine
ENTSO-E	European Network of Transmission System Operators
JRC	Joint Research Centre
MS	Member State
NTC	Net Transfer Capacity
OCGT	Open Cycle Gas Turbine
PSH	Pumped Storage Hydro
PSP	Pumped Storage Power plant
PV	Photovoltaic
RES	Renewable Energy Sources
TSO	Transmission System Operator
TYNDP	Ten Year Network Development Plan

1.2. DEFINITIONS

Concept	Definition
Net demand	Difference between electricity demand and must-take electricity generation.
RES generation surplus	Number of hours over a year during which the non-dispatchable generation (RES generation) is larger than the demand

2. INTRODUCTION AND BACKGROUND

2.1. FOREWORD

The present document has been prepared by Artelys in response to the Terms of Reference included under ENER/C2/2014-639[4]. Readers should note that the report presents the views of the Consultant, which do not necessarily coincide with those of the Commission.

2.2. INTRODUCTION

In order to pursue an evidence-based policy making process, the European Commission has recently commissioned the development of a new piece of software aimed at modelling and simulating the European energy systems and markets. This tool, called METIS, is currently being developed by Artelys and its partners. At the same time Artelys gradually delivers a number of studies, which aims at enhancing the European Commission's understanding of the studied topics, as well as at to validate the capabilities of the METIS software modules.

This study, entitled "The role and need of flexibility in 2030: focus on energy storage", uses METIS to analyse the value of flexibility in Europe in 2030. While this study focuses on energy storage, the interplay between storage and other flexibility options will be discussed in upcoming studies.

Section 3 presents the different scenarios that will be studied, the metrics that will be used to assess them and METIS software that will run the simulations. In section 4, the different benefits that can be drawn from flexibility are listed in the form of topic sheets. In section 5 are presented the main drivers of flexibility needs for a country. Each of the sections 6, 7 and 8 studies the impact of installing energy storage in specific countries with different characteristics: United Kingdom, Germany and Austria. Then, section 9 aims to present and compare the different existing storage technologies and their costs. To conclude, section 10 presents the conclusions of this report about installing flexibility where the needs are creating enough value in order to make the project valuable.

MODELING SETUP

METIS VERSION	METIS v1.1
MODULES	Power system
SCENARIOS	ENTSOE TYNDP 2014 – 2030 Visions 1 and 3
TIME GRANULARITY	Hourly
ASSET MODELLING	Cluster level No reserve constraints Country granularity
UNCERTAINTY MODELLING	50 years of weather data which influence 1. *Demand* 2. *Wind power generation* 3. *Solar power production*
BIDDING STRATEGY	Bidding at marginal cost

[4] http://ec.europa.eu/dgs/energy/tenders/doc/2014/2014s_152_272370_specifications.pdf

3. CONTEXT AND MAIN ASSUMPTIONS

In 2014, 27.5% of power demand was served by renewable energy (Eurostat). The 2030 Framework for climate and energy sets an EU-wide target of 40% cut in greenhouse gas emissions compared to 1990 level, and at least a 27% share of renewable energy consumption. For the power system, this means a share of at least 45% of power demand should be generated by renewable energy sources (European Commission). Following the current development, an important share of the additional renewable energy will come from variable sources, e.g. wind and solar. The variability and non-controllability of this type of production make it difficult to ensure security of supply and price stability.

Flexibility is a way of dealing with these issues, it is defined as the ability of a power system to maintain continuous generation and prices when experimenting quick variations in supply or demand. Flexibility can be brought by the supply side (energy storage, interconnections …) but also by the demand side. In this study, the need for flexibility in 2030 will be assessed by focusing on energy storage.

3.1. STUDIED SCENARIOS

3.1.1. GENERATION MIX ASSUMPTIONS

The two 2030 scenarios which are considered in this study are based on the ENTSO-E Visions set out in the 2014 Ten Year Network Development Plan (TYNDP 2014) (ENTSO-E's 10-year Network development plan 2014). The main characteristics of both scenarios are presented below.

- Scenario 2030 Vision 1, "Slow progress"

"Vision 1 reflects slow progress in energy system development with less favorable economic and financial conditions. Vision 1 fails to meet the EU goals for 2030. Compared to the present days, the consumption and generation mix have evolved by less than in other Visions entailing a lower pressure for more market integration and interconnection capacity" (ENTSO-E's 10-year Network development plan 2014). Vision 1 is a scenario with a relatively low level of RES development, although wind and solar capacities constitute a great share of the new build, especially in Germany. Besides, Germany, Belgium, and Switzerland are assumed to be phasing out of nuclear power while other countries are expected to build new units. On a European level, the share of RES in the power generation reaches 41% of the demand. Vision 1 will sometimes be referred to as V1 in the following.

- Scenario 2030 Vision 3, "Green transition"

"Vision 3 reflects an ambitious path towards the 2050 European energy goals, where every Member State (MS) develops its own effort achieving overall 50% of European load supplied by RES in 2030. Vision 3 meets the EU goals by 2030. However in this Vision, every country tends to secure its own supply independently from the other, resulting probably into an overinvestment in generation assets at European level." (ENTSO-E's 10-year Network development plan 2014) Compared to Vision 1, this scenario is characterised by a significantly larger RES development and a more important decrease in nuclear power capacity, including a phase-out of the Netherlands and a reduction of capacity in France. This scenario is also characterised by high CO_2 prices (93€/ton compared to 31€/ton in Vision 1), resulting in coal units becoming more expensive than Combined Cycle Gas Turbine (CCGT) power plants. On a European level, the share of RES in the power generation reaches 50% of the total demand. Vision 3 will sometimes be referred to as V3 in the following.

The installed capacities and generation mix of both scenarios are illustrated on the figures below. The higher level of demand and the larger share of RES in V3 result in a more important total installed capacity compared to V1. On the generation side, as a consequence of the permutation between coal- and gas-fired power plants in the merit order, coal represents 18% of the generation in Vision 1 and only 1% of the generation in Vision 3. CCGTs produce 10% in Vision 1 and 24% in Vision 3.

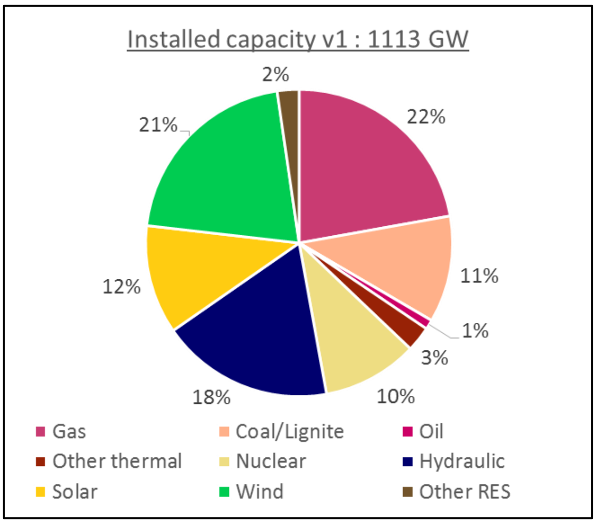


Figure 1. Installed capacity for scenario 2030 v1

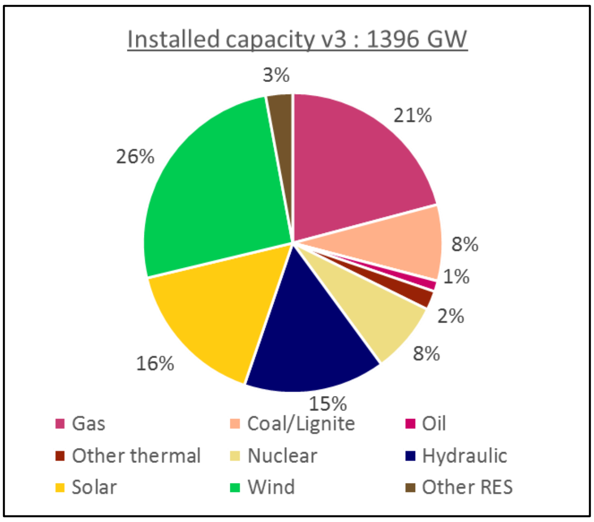


Figure 2. Installed capacity for scenario 2030 v3

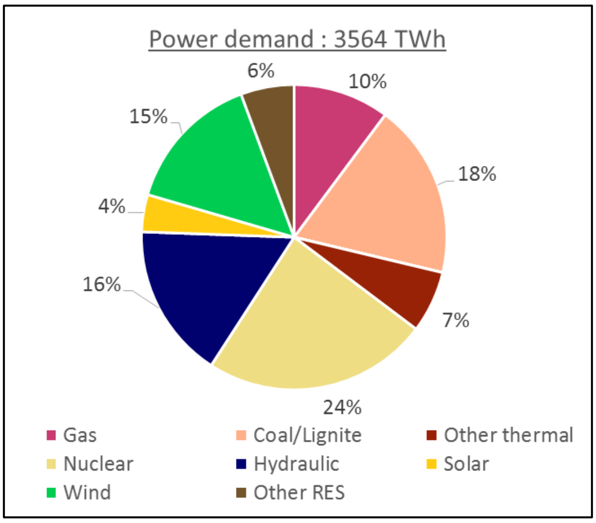


Figure 3. Generation mix for scenario 2030 v1

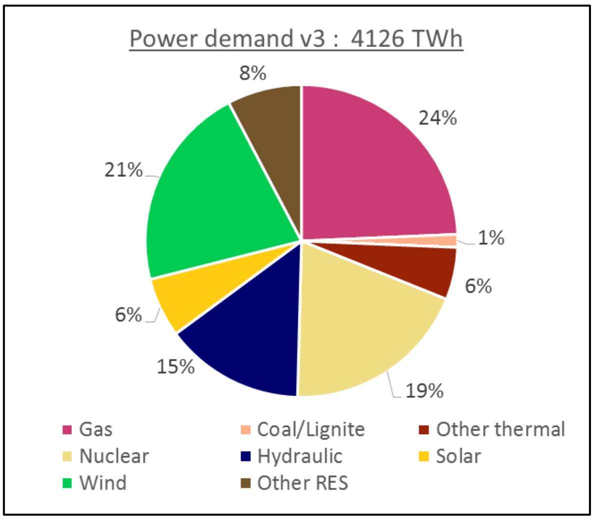


Figure 4. Generation mix for scenario 2030 v3

3.1.2. ENERGY STORAGE INSTALLED CAPACITIES

The purpose of this study is to estimate the value of further investments in energy storage capacities by 2030. In order to capture this value, one has to compare the two situations: a first one without any investments in storage capacities between 2014 and 2030, and a second one with new storage infrastructure.

The 2014 storage capacities are given below.

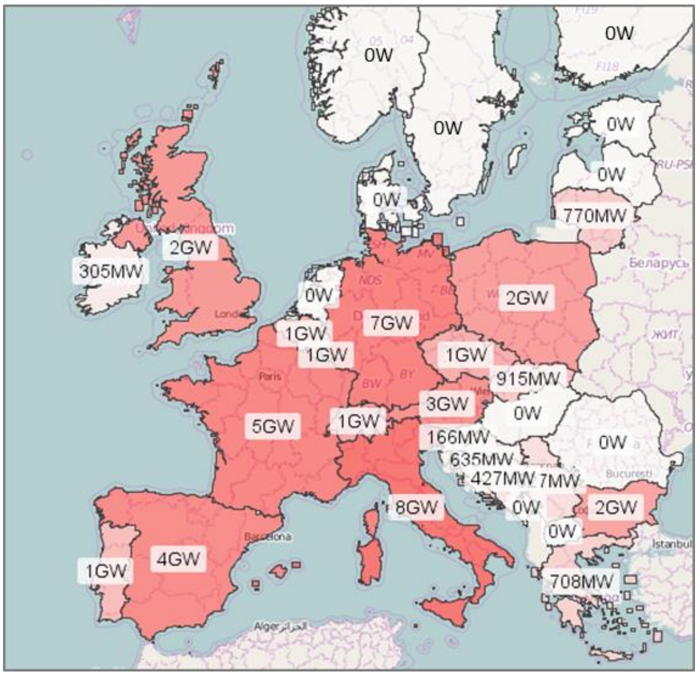


Figure 5. Pumped-storage hydro power capacity in Europe in 2014 (ENTSO-E's Scenario Outlook & Adequacy Forecast 2014)

A total of 44.5 GW of pumped-storage hydro are installed throughout Europe in 2014. France, Germany and Italy have the largest capacities. Scandinavia however, Norway and Sweden in particular, has very little capacity compared to its potential, preferring classic hydro reservoir.

3.2. **FLEXIBILITY METRICS**

This section is dedicated to the definition of three metrics that are used to characterise flexibility requirements. The first one is based on RES generation surplus, while the second and third metrics consider the importance of the daily and weekly variations of the load profile.

3.2.1. RES GENERATION SURPLUS

The first metric used to evaluate the need for flexibility is the so-called "RES generation surplus", which measures the number of hours over a year during which the non-dispatchable generation (RES generation) is larger than the demand.
In terms of net demand, which is defined as the difference between electricity demand and must-run electricity generation, RES generation surplus is the duration of negative net demand.
The number of hours of RES generation surplus for the two scenarios considered in this study and the corresponding energy are illustrated below. In order to evaluate both these quantities, ten weather years have been simulated (with an hourly time resolution). These weather scenarios influence both the demand (through a thermal gradient) and the RES generation. The two figures below present the average values over the weather scenarios. Note that in order to produce an indicator that reflects the local situation, it has been assumed that interconnectors cannot be exploited.

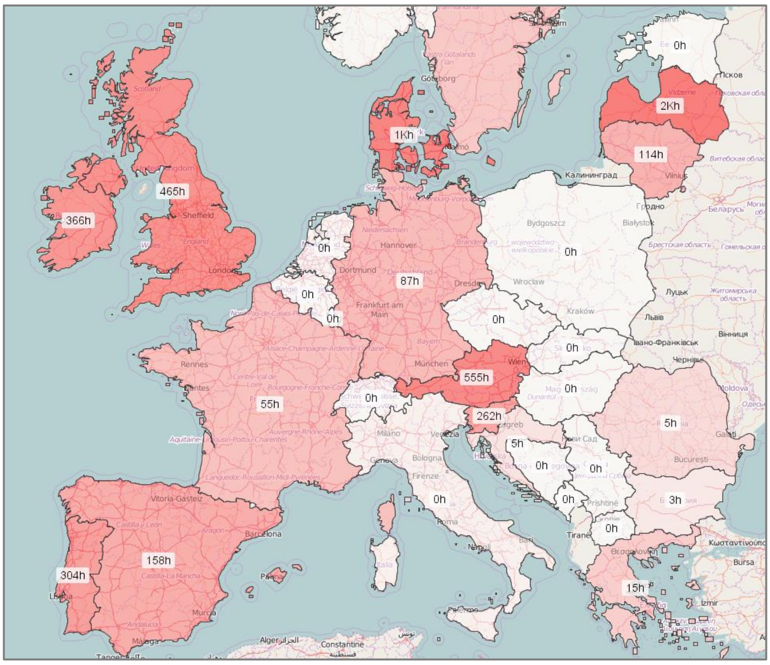


Figure 6. Number of hours per year with RES surplus (2030 V1)

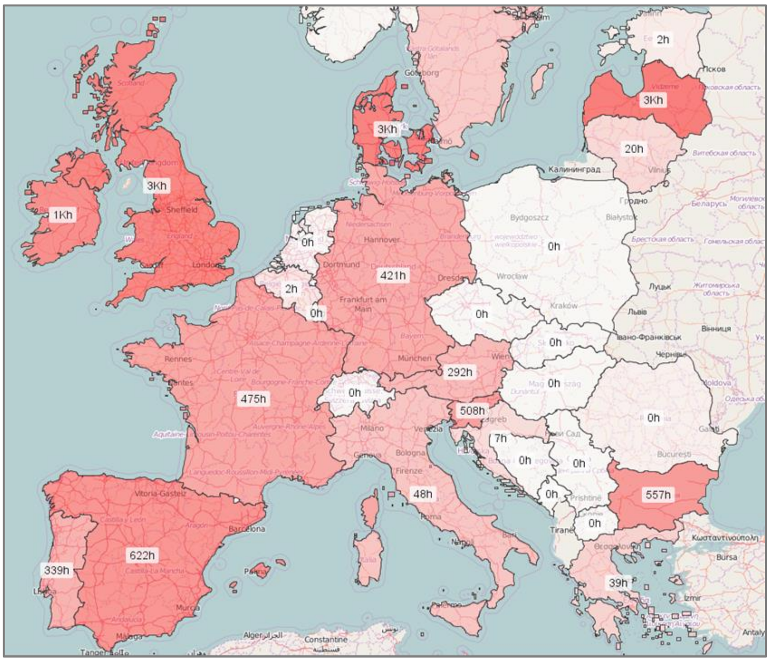


Figure 7. Number of hours per year with RES surplus (2030 v3)

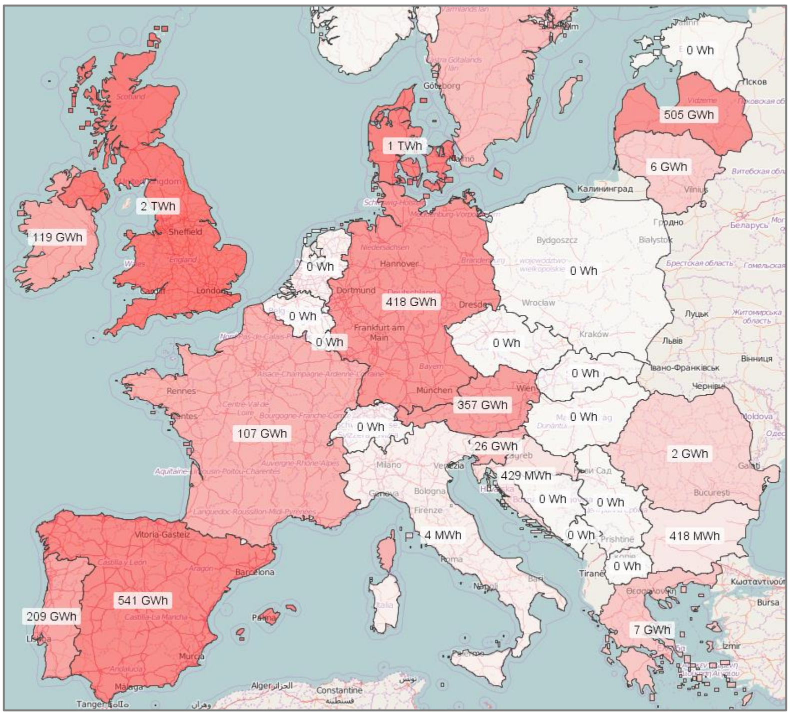


Figure 8. Total yearly RES surplus (2030 v1)

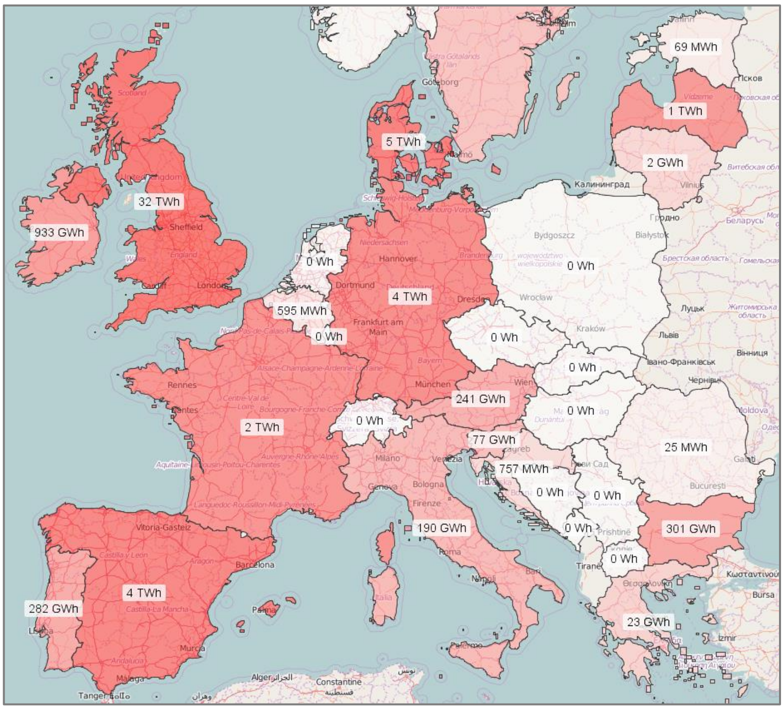


Figure 9. Total yearly RES surplus (2030 v3)

Whereas the overall RES generation surplus is rather limited in Vision 1 (5 TWh), it is substantially more important in Vision 3 (50 TWh) due to its larger share of RES. The United Kingdom is responsible for around 40% of the European surplus in Vision 1 and 60% in Vision 3, while countries like Switzerland or the Netherlands do not generate any surplus.

In order to reduce the number of hours of RES generation surplus, the flexibility of the power system needs to be increased. A number of complementary technologies can provide the required level of flexibility. Since RES generation surplus does not happen at the same time in all countries, the first possibility is to use interconnectors to share the surplus with neighboring countries. Second, if provided with well-designed signals, the demand-side can also adjust its consumption and absorb the surplus. Finally, the option that this study will be focusing on is to store energy during periods of surplus and to inject it back in the system when it is needed.

3.2.2. NEED FOR DAILY FLEXIBILITY

The second metric that can be used to determine the amount of flexibility required by the power system is a measure of the variation of net demand during a day. For a given day, it is computed as the area of the net demand that is above the net demand average on that day, corresponding to the green area on the figure shown below (Bilan prévisionnel 2015 RTE).

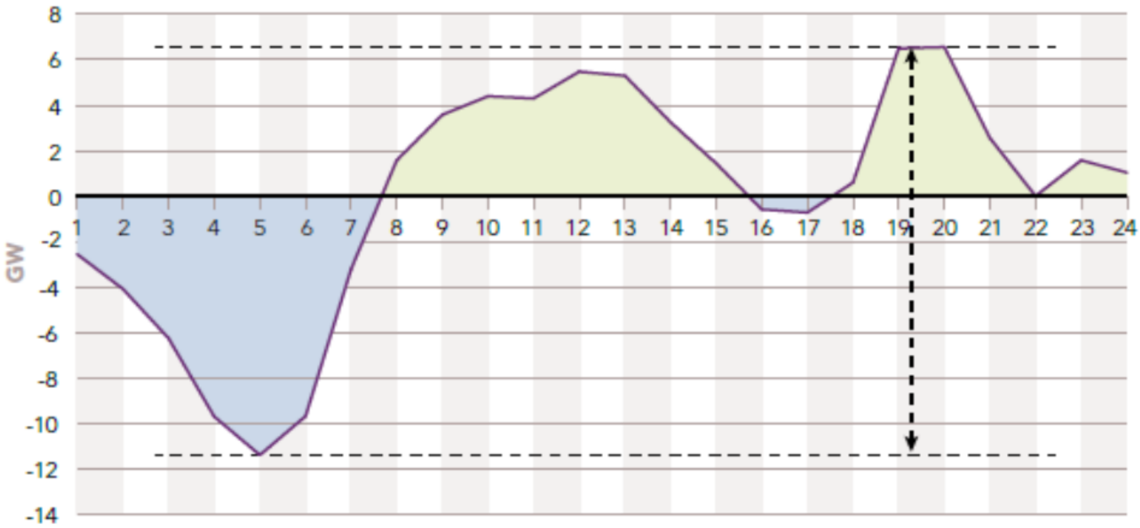


Figure 10. Variations of hourly averaged net demand around daily mean value

The need for daily flexibility is computed for each day of the 10 years of weather data, and then averaged to produce the "need for daily flexibility" indicator.
By construction, this metric evaluates the need for short-term flexibility (e.g. storage with 1-6 hours of discharge duration).

3.2.3. NEED FOR WEEKLY FLEXIBILITY

The third and final indicator that will be used in this study is the need for weekly flexibility. This indicator is very similar to the previous one. The indicator is obtained by computing the area of the daily average net demand that is above the weekly net demand average, corresponding to the green area on the figure shown below (Bilan prévisionnel 2015 RTE).

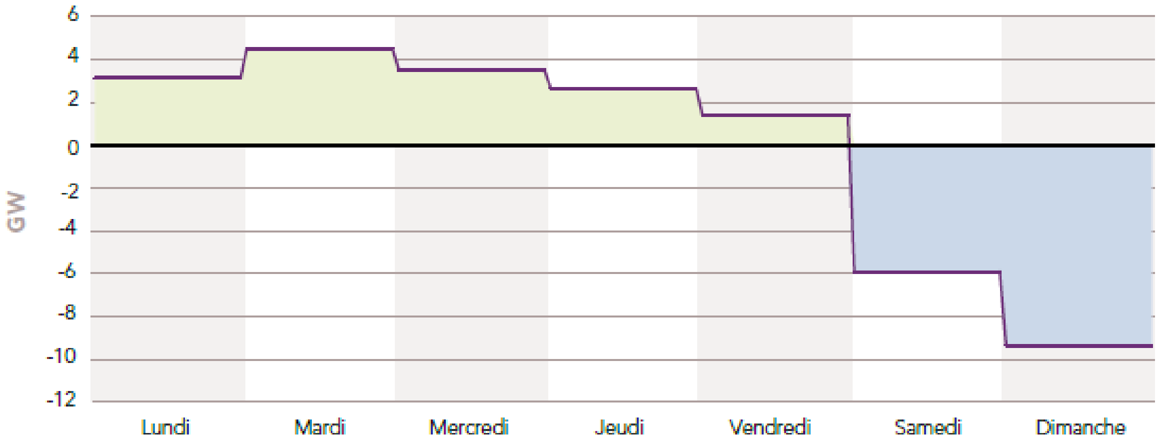


Figure 11. Variations of daily averaged net demand around weekly mean value

As for daily flexibility, the need for weekly flexibility is computed for the 520 weeks of studied weather data and then to produce the "needs for weekly flexibility" indicator.
The need for weekly flexibility that is shown on the above picture exhibits a clear pattern of higher net demand during the working days than during the weekend. The challenge for weekly flexibility technologies is to lower the net demand during the working days and to increase it during weekends. The associated characteristic time is generally counted in days.

3.3. **THE METIS MODEL**

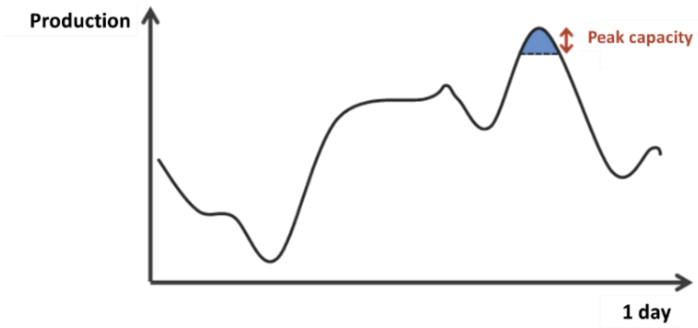
METIS works complementary to long-term energy system models (like PRIMES from National Technical University of Athens and POTEnCIA from the Joint Research Centre (JRC)), by providing a more detailed analysis of the impact of (higher shares of) variable renewables or infrastructure questions on an hourly level. Installed capacities are consequently inputs for METIS and, for this study, are based on ENTSO-E 2030 v1 and v3 scenarios from the 2014 Ten Year Network Development Plan (TYNDP 2014).
More specifically, METIS is a modular energy modelling software covering with high granularity (geographical, time) the whole European energy system for electricity, gas and heat. Simulations adopts a MS-level spatial granularity and an hourly temporal resolution (8760 consecutive time-steps per year). Uncertainties regarding demand and RES power generation are captured thanks to 50 years of temperature scenarios, which influence the demand (through a thermal gradient), and 10 years of wind and irradiance, which are translated into PV and wind generation hourly time series. The historical spatial and temporal correlation between temperature, wind and irradiance are preserved.
Generation plans are simulated using an optimal dispatch using an hourly time resolution, taking into account the contribution and constraints of storage along with interconnectors between countries. Thermal units are modeled at cluster level taking into account technical constraints of assets (minimum stable generation, efficiency at Pmin and Pmax, starting costs, minimum off times, etc.). The merit order depends on fuel and CO2 prices. Country-specific constraints (e.g. maximum annual use of coal units) or market distortions are not included within the model. Moreover, reserve constraints are not modeled in this study.
Cross-border interconnectors are modeled with Net Transfer Capacities (NTC, provided with ENTSO-E scenarios). Network constraints within each country are not modeled.

4. MAIN BENEFITS OF ENERGY STORAGE

This paragraph is based on previous work undertaken in collaboration with Enea Consulting in 2013 on energy storage potential for France (ADEME, Etude sur le potentiel du stockage d'énergie, 2013) and lists the main services provided by flexibility for interconnected power systems. The quantitative analyses of Sections 6 to 8 focus on arbitrage and capacity values. Additional analysis of the benefits of flexibility for balancing and ancillary services will be studied in study S1.

4.1. CAPACITY VALUE

Capacity coverage, crossing of consumption peaks



DESCRIPTION OF THE SERVICE

In order to ensure security of supply, it is necessary to ensure supply-demand equilibrium at all times, therefore to provide enough capacity to face electricity peak demand. This capacity can be provided :

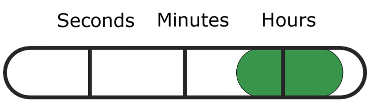
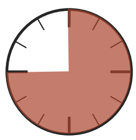
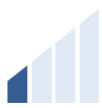
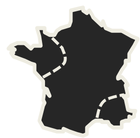
- By guaranteed generation capacity (dispatchable power plants)
- Statistically, by non-dispatchable generation capacity
- By interconnectors with neighboring countries
- By storage or demand response

Flexibility can address this issue by :

- Supplying electricity during peak periods
- Smoothing out consumption peaks (peak shaving)
- Consolidating available capacity for variable energy

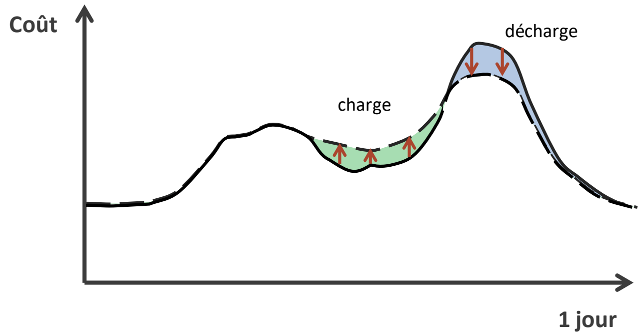
The value brought by flexibility strongly depends on the characteristics of energy shift. (one hour shift versus peak erasing on the entire day)

TECHNICAL CHARACTERISTICS OF THE REQUIRED FLEXIBILITY SOLUTION

Discharge time :	Reaction time	Frequency of use	Scale
			
Hours to tens of hours	Tens of minutes	Annual	National and Local

4.2. ARBITRAGE VALUE

Arbitrage, valorization of energetic transfers



DESCRIPTION OF THE SERVICE

Variations in electricity demand lead to price variations, with off-peak periods during which electricity is available at low price, and peak periods when prices are high. These price differences are determined by the typology of electricity generation means according to the « merit order » method (or economic precedence), namely from the generation means with low marginal cost for the base (such as nuclear power plants) up to peak power plants, requested only during consumption peaks.

The intermittency of some RES generation (such as wind power), emphasizes these price variations, therefore increases the need for flexibility.

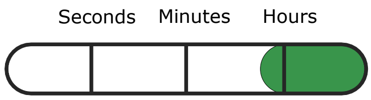
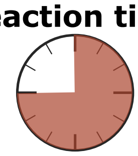
The flexibility operator makes earnings on the market by optimizing energy consumption: economic arbitrage between charge (purchase) and discharge (sale) for a storage, or the shifting of electricity consumption for the consumer, enables to take advantage of price differences to valorize the installation.

From a system point of view, flexibility has the advantage of smoothing the load curve, therefore reducing the use of peak power plants with a high marginal cost. More generally, it has the effect of reducing the variable cost of generation.

Generally, energy transfer has the effect of using units with lower fuel costs. It also affects the behavior of the units in order to reduce their marginal generation cost, such as operating at full power to improve heat rates and avoid unit start-ups.

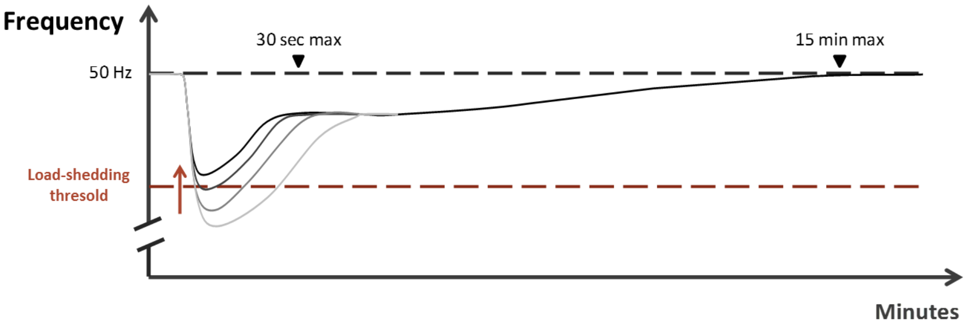
For countries that have enough RES capacity to experience periods of RES curtailment, flexibility enables to reduce this curtailment by increasing electricity consumption during these specific periods.

TECHNICAL CHARACTERISTICS OF THE REQUIRED FLEXIBILITY SOLUTION

Discharge time :	Reaction time	Frequency of use	Scale
			
Hours to hundreds of hours	Tens of minutes	Daily to weekly	National

4.3. ANCILLARY SERVICES

Frequency control

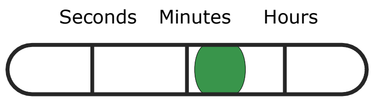
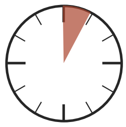
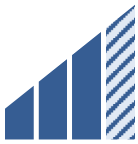


DESCRIPTION OF THE SERVICE

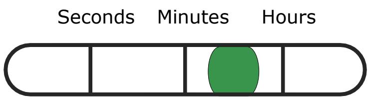
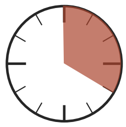
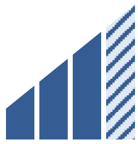
Maintaining in real time the balance between electricity consumption and generation requires to adjust quasi-instantaneously the power injected in the network. This is done by a constraint on frequency (To keep in an interval situated around 50Hz in Europe) that the Transmission System Operator (TSO) is mandated to enforce.
In order to react to unexpected variations of the load, the TSO can use reserve capacities, defined by the activation time that they have to respect. Three levels of reserve are generally used to maintain the balance between load and generation:

- Primary reserve for an instantaneous adjustment (system service), activated automatically
- Secondary reserve that follows primary reserve after few minutes (system service)
- Tertiary reserve, manually activated

TECHNICAL CHARACTERISTICS REQUIRED FOR PRIMARY RESERVES

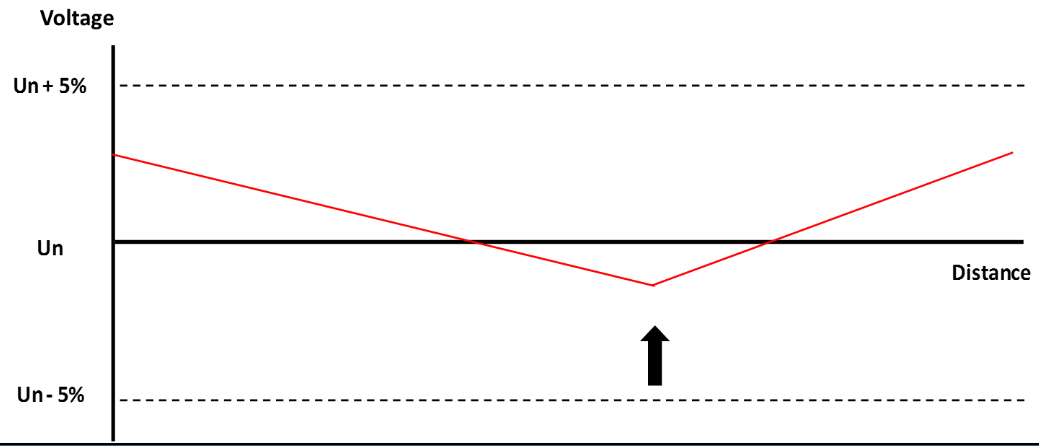
Discharge time :	Reaction time	Frequency of use	Scale
			
15 minutes	Seconds	Daily to weekly	Continental

TECHNICAL CHARACTERISTICS REQUIRED FOR SECONDARY AND TERTIARY RESERVES

Discharge time :	Reaction time	Frequency of use	Scale
			
Around 30 minutes	Minutes	Daily to weekly	National

4.4. NETWORK SERVICES

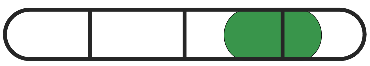
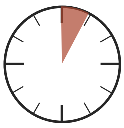
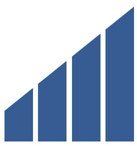
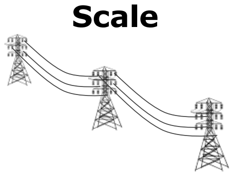
Voltage regulation



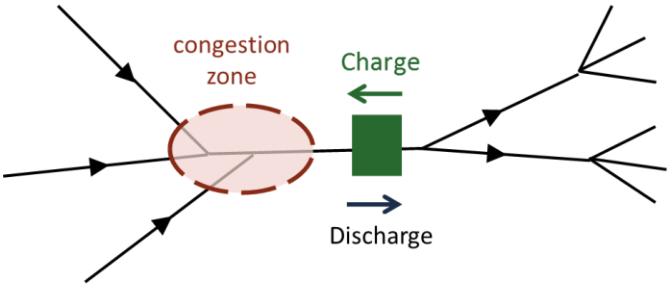
DESCRIPTION OF THE SERVICE

Maintaining the voltage level throughout the different parts of the network is a system service sought by network operators. While frequency stability characterizes an equilibrium of active power between supply and demand, tension level characterizes an equilibrium of a power that is called reactive.
The TSO is usually responsible for controlling the voltage level in the transport network, this is done via reactive power sources distributed on the network. This adjustment occurs on a local level, automatically and instantaneously (primary adjustment) and centrally managed at the regional level (secondary adjustment). Each generation unit connected to the grid contributes to voltage regulation as it is established in its system service contract with the TSO by making available the capacities of supply and absorption of reactive power.
The connection of variable generation sources (wind and solar) to the grid increases the risks of crossing voltage level threshold.

TECHNICAL CHARACTERISTICS OF THE REQUIRED FLEXIBILITY SOLUTION

Discharge time :	**Reaction time**	**Frequency of use**	**Scale**
Seconds Minutes Hours 			
Tens of minutes to hours	Seconds	Daily	Segments of network

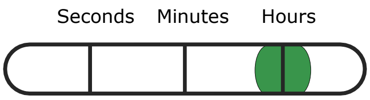
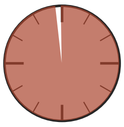
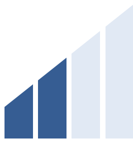
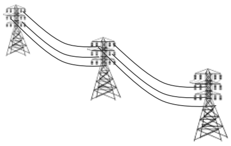
Congestions handling



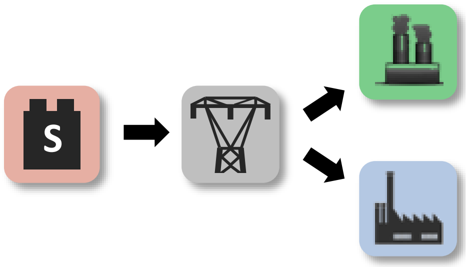
DESCRIPTION OF THE SERVICE

Electric networks are dimensioned to assure power transmission from producer to consumer by anticipating risks of incident and saturation.
Evolution of local electricity consumption can create congestion zones at some points of the network. These situations cause a non-optimal network operation (losses in transmission, increase of operation cost, etc..) and may require a network upgrade.
Flexibility makes possible to avoid network strengthening, on the short term (postponement of network investment) or on the long term. It enables to gain from load shedding benefits while keeping overall load and produced energy. The economic interest of flexibility will therefore depend on its additional value compared to load shedding.

TECHNICAL CHARACTERISTICS OF THE REQUIRED FLEXIBILITY SOLUTION

Discharge time :	**Reaction time**	**Frequency of use**	**Scale**
			
Hours	Hours	Monthly	Segment of network

Black start (Network restoring)



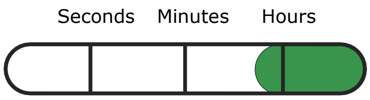
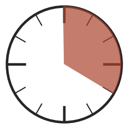
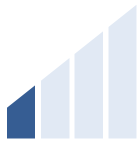
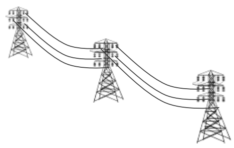
DESCRIPTION OF THE SERVICE

In case of a widespread incident leading to a shutdown of some part or all of the electric network ("black-out"), it is necessary to quickly reconstruct the network. However, the reconstruction needs an initial power supply to restart generation at regional levels.

This initial power input can come from a part of the network that is not affected by the black-out and that can supply enough power supply (at a national or international level).

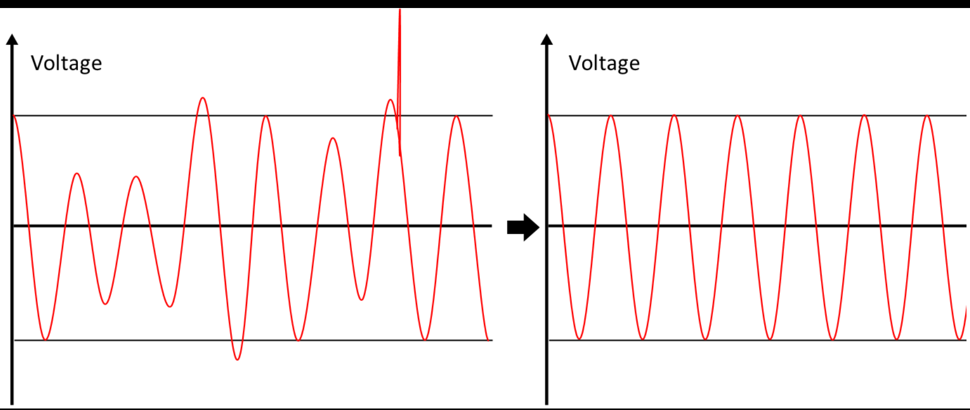
In addition or if there is no such network, it can be necessary to use generation means that can operate in condition of islanding (i.e. to decouple from the network and power the auxiliaries) or to startup autonomously ("black-start") for example using small diesel generators or energy storage.

TECHNICAL CHARACTERISTICS OF THE REQUIRED FLEXIBILITY SOLUTION

Discharge time :	Reaction time	Frequency of use	Scale
			
Several hours	Minutes	Yearly	Segment of network

4.5. SPECIFIC SERVICES FOR CONSUMERS

Quality of the voltage wave



DESCRIPTION OF THE SERVICE

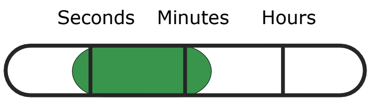
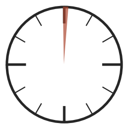
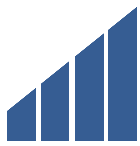
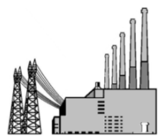
Different defects can occur on the electrical signal and affect the quality of energy supply for the consumer. These defects in quality appear at very short timescales, from milliseconds to seconds. It includes for example the presence of harmonics on the signal, dephasing between current and voltage or short voltage peaks.

Poor quality of the voltage wave has several possible consequences:

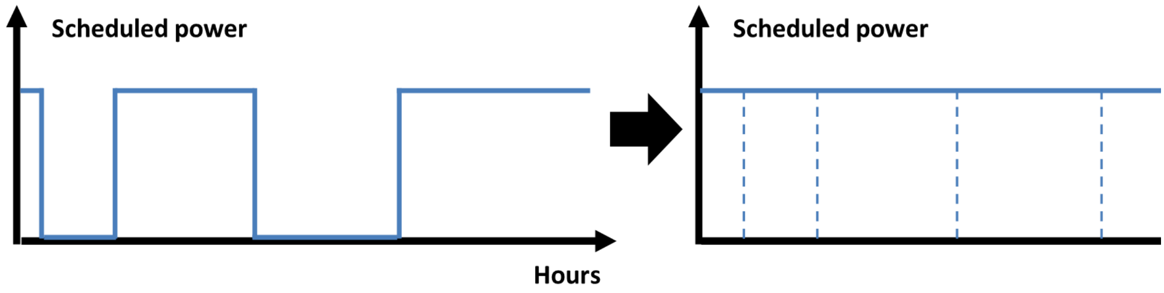
- Dysfunction of some electrical devices
- Drop in voltage ("brownout")
- Premature aging of some electrical devices and long term damages
- Indirectly, decrease or stop of possible generation for industrials

Flexibility enables to maintain the quality of the electric signal delivered to the consumer, quality that is necessary to ensure the optimal operation of some electrical systems or devices that are particularly sensitive.

TECHNICAL CHARACTERISTICS OF THE REQUIRED FLEXIBILITY SOLUTION

Discharge time :	**Reaction time**	**Frequency of use**	**Scale**
			
Seconds to minutes	Milliseconds	Daily	Site

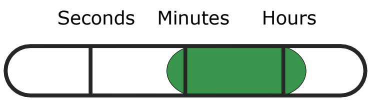
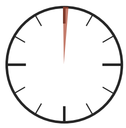
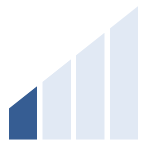
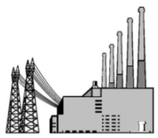
Security / Continuity of supply



DESCRIPTION OF THE SERVICE

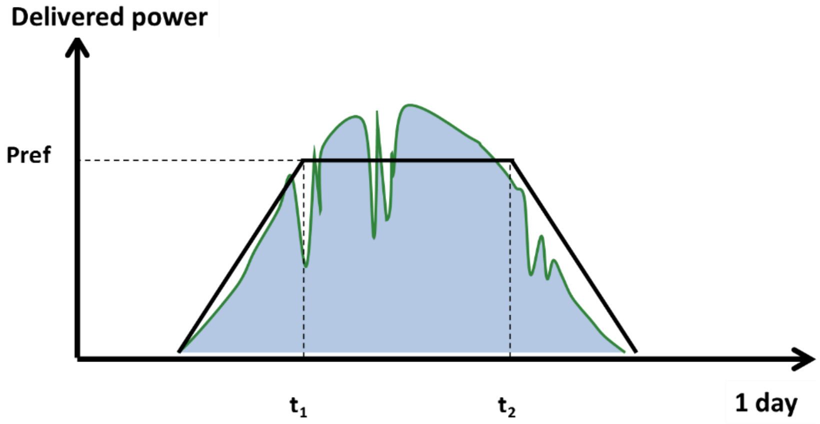
On the distribution network, yearly average duration of power cuts amounts to more than 70 minutes, most of them being unscheduled, the rest is exceptional occurrence. For numerous economic actors, these cuts represent an operational risk and/or revenue shortfall.
These clients need supply security, therefore acquire alimentation continuity systems (UPS for Uninterruptible Power Supply). Current systems commonly rely on power generators coupled with storage UPS, mostly batteries, sometimes flywheels.
When electricity supply from the grid is interrupted for a consumer (load shedding, incident), electricity storage can take over and ensure continuity of supply.

TECHNICAL CHARACTERISTICS OF THE REQUIRED FLEXIBILITY SOLUTION

Discharge time :	Reaction time	Frequency of use	Scale
			
Minutes to hours	Milliseconds	Yearly	Site

4.6. SPECIFIC SERVICES FOR PRODUCERS

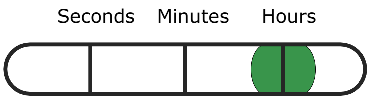
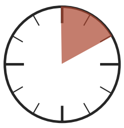
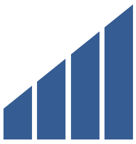
Flattening and shaping of generation



DESCRIPTION OF THE SERVICE

Coupling an electricity storage system to a generation site enables to shape the load curve according to consumption or exchanges on the market.
This enables, for example, the injection on the grid of a standardized load curve, tradable on the market (typically a step). These blocs do not reflect real power system operation: the use of electricity storage enables to optimize the dynamic aspects.
In the same manner, electricity storage enables to adapt the constraints of a power generating unit to a specific load curve through the optimization of the dynamic aspects.
Coupled to variable RES (Solar PV for example), electricity storage enables to deliver on the network a "flatter" power, less relying on meteorological hazard.

TECHNICAL CHARACTERISTICS OF THE REQUIRED FLEXIBILITY SOLUTION

Discharge time :	Reaction time	Frequency of use	Scale
			
Hours	Tens of seconds	Daily	National

5. MAIN DRIVERS FOR FLEXIBILITY NEEDS

This Section is devoted to the identification of the drivers influencing the level of flexibility requirement as measured by the indicators introduced in Section 3.2. The composition of national energy supply mixes (in particular the share of PV and wind power production) and the ways these systems are interconnected are shown to be the two main factors determining how flexible the power system ought to be.

5.1. RENEWABLE ENERGY MIX

5.1.1. SOLAR POWER

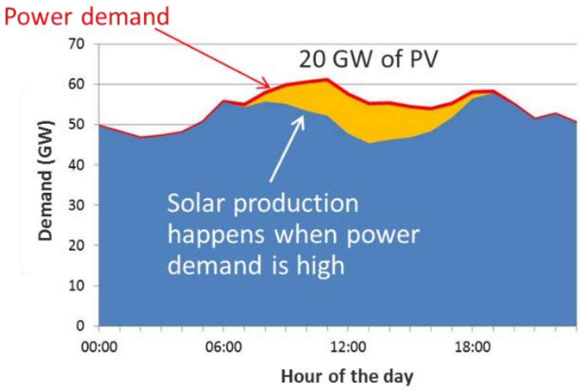


Figure 12. Correlation between PV generation and daily power demand

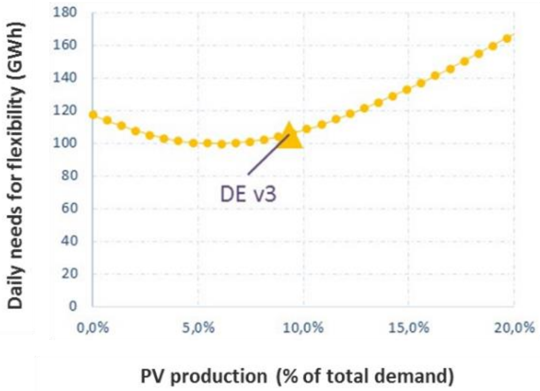


Figure 13. Influence of installed PV capacity on daily flexibility needs

Solar power generation varies within a day. It is therefore expected that installed solar capacity has an impact on the need for daily flexibility. Figure 13 shows how the need for daily flexibility evolves in Germany as the share of PV increases. It should be noted that for small shares of PV, the need for daily flexibility decreases as PV capacity increases. This phenomenon is due to the fact that PV generation occurs at times of high demand as is illustrated on Figure 12. For relatively low shares of PV generation, the system benefits from this additional capacity, net demand is smoothed and there is less need for flexibility. When the share of PV gets above 6 to 8%, the need for daily flexibility increases again as the high PV generation leads to lower net demand during the day (the excess PV generation needs to be shifted to the evening or to be shared with neighbors). It is only when the share of PV gets above 10-12% that the daily need for flexibility increases significantly and reaches levels higher than the flexibility needed without any PV generation[5].

As illustrated by Figure 14, only a very small number of European countries will have shares of PV large enough to create flexibility needs by 2030 (i.e. Italy, Spain, and Bulgaria), even in the V3 scenario.

[5] Figure 55 (Appendix 11) shows the same indicator for different countries and scenarios. The decreasing of flexibility needs for the first few percent of PV share is a result common to all cases.

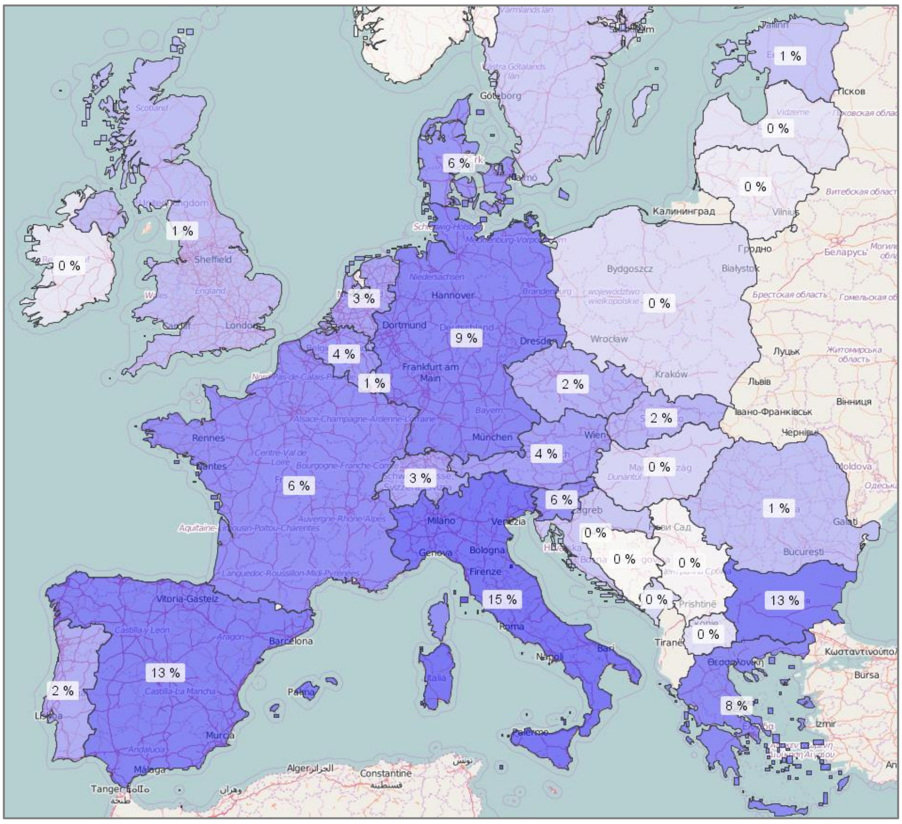


Figure 14. PV generation (2030 V3) (% of national demand)

5.1.2. WIND POWER

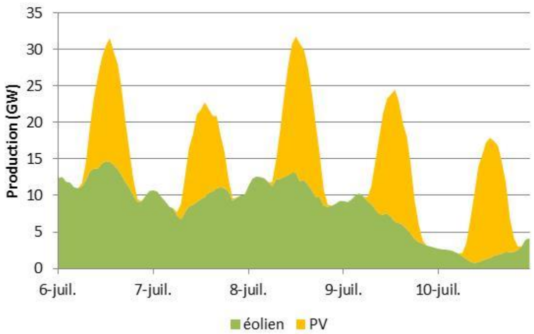


Figure 15. Wind and PV generation over several days

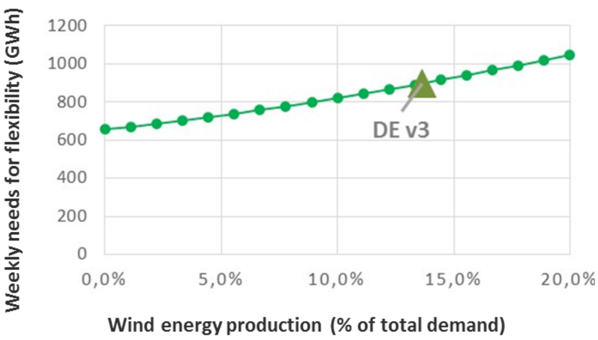


Figure 16. Weekly needs for flexibility as a function of wind power generation (Germany)

Unlike PV, wind power generation varies over cycles of several days, as illustrated on Figure 15 and is only mildly correlated with power demand, therefore an increase of wind power capacity increases the need for weekly flexibility. Figure 16 illustrates this phenomenon in the case of Germany. Investing in weekly flexibility options should therefore be beneficial for countries such as Denmark, the United Kingdom, Ireland, Latvia, and Germany, whose 2030 shares of wind electricity production are shown Figure 17 for the 2030 Vision 3 scenario (ENTSO-E's 10-year Network development plan 2014).

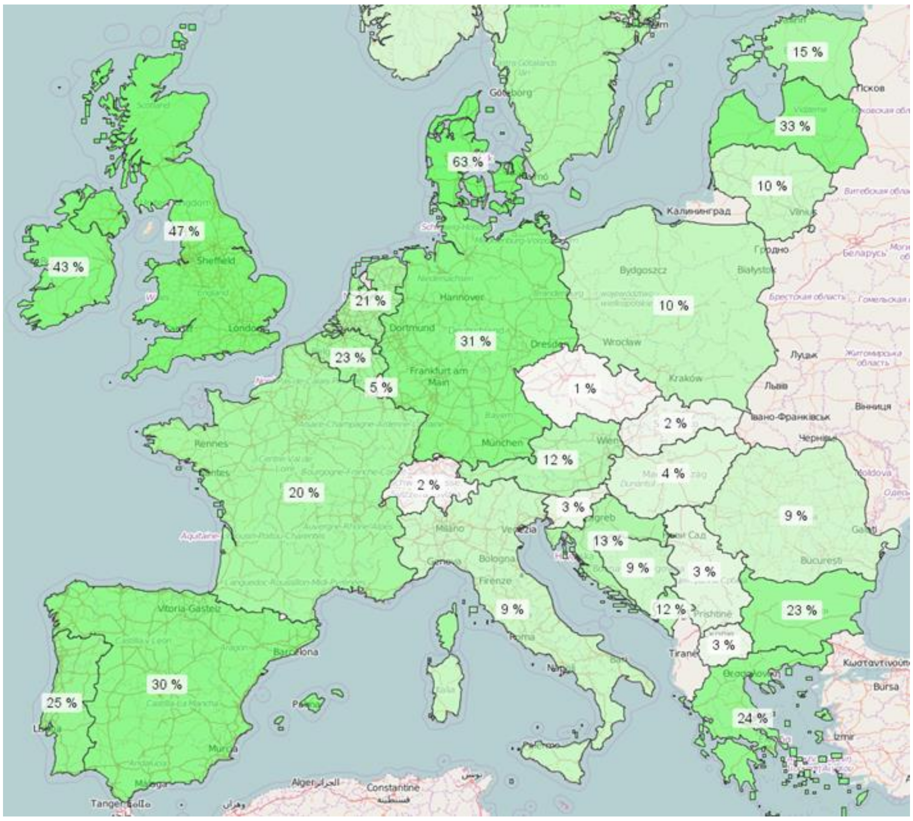


Figure 17. Wind electricity generation (2030 V3) - % of national demand

5.2. INTERCONNECTION CAPACITIES

In the previous section, the flexibility metrics have been used to characterise the situation at national level, without taking in account the role that could be played by interconnectors. In this section the contribution of interconnection to flexibility is investigated: electricity can be exported during periods of low or negative net demand and imported during periods of high net demand. Consequently, the more a country is interconnected to its neighbors, the less it needs to invest in other flexibility options (storage and DR).

Figure 18 and Figure 19 illustrate the reduction of daily and weekly flexibility needs when interconnectors are taken into account. These results have been obtained by replacing the net demand by the net demand minus the net imports when computing the flexibility indicators defined in Sections 3.2.2 and 3.2.3. This leads to a decrease in flexibility needs, to a greater or lesser extent depending on the interconnection capacity.

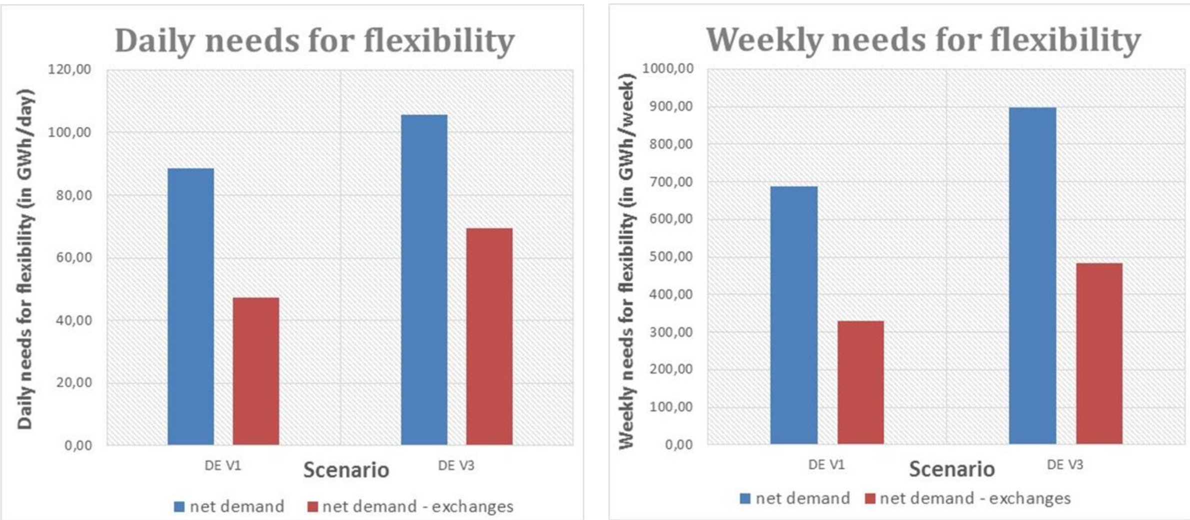


Figure 18. Flexibility needs for Germany in 2030 using net demand minus import/export balance

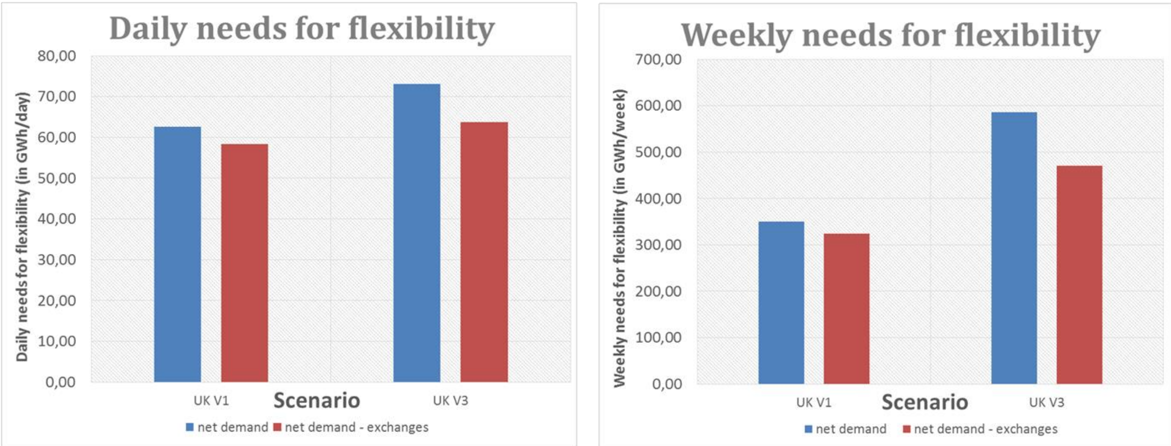


Figure 19. Flexibility needs for UK in 2030 using net demand minus import/export balance

The use of interconnectors divides Germany's needs for daily and weekly flexibility in 2030 by a factor of two. Its geographical situation at the centre of Europe and its strong exchange capacities (36.6 GW import capacity in V1, 37.7 GW in V3 (ENTSO-E's 10-year Network development plan 2014)) contribute to lessen the need for domestic flexibility in Germany.

When analysing the situation of the United Kingdom, one should not only consider its total interconnection capacity, but rather interconnection capacity of the UK/Ireland system with the Continent (7.1 GW import capacity in V1, 10.9 GW in V3 (ENTSO-E's 10-year Network development plan 2014)). The analysis above shows that such a level of interconnection capacity does not provide a significant amount of flexibility to the power system. During both periods of peak demand and periods of high wind power generation, the quantity of electricity that can be imported/exported from/to neighbouring countries is limited by the interconnection capacities, keeping the needs for flexibility at a high level.

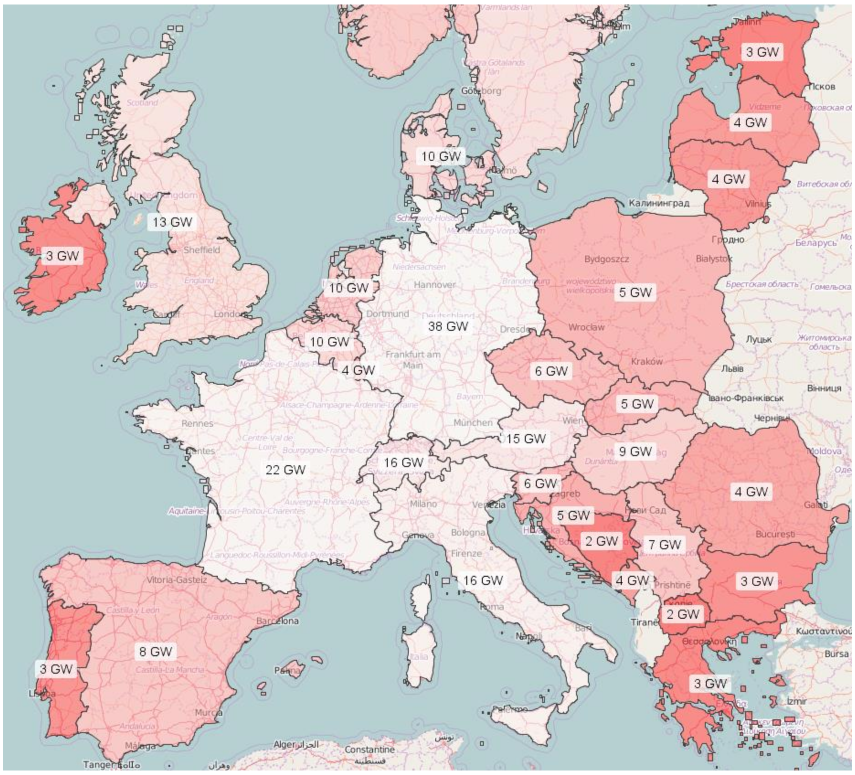


Figure 20. Interconnection import capacities in the scenario 2030 V3 (ENTSO-E's 10-year Network development plan 2014)

Figure 20 shows the importing capacities in Europe for the scenario 2030 V3 and illustrates the disparities in Europe of the potential flexibility brought by interconnectors.

6. FIRST USE CASE: ENERGY STORAGE IN THE UK

6.1. USE CASE DEFINITION

As explained in Section 3, the analysis presented below is based on ENTSO-E 2030 scenarios V1 and V3 from 2014 Ten Year Network Development Plan (TYNDP 2014) for demand, interconnection capacity, and generation (see Figure 21), and on current values for energy storage. The objective is to assess the benefits of adding 1 GW of energy storage in UK, for different discharge times.
The UK V1 and V3 scenarios are both characterised by an important wind power generation and a low penetration of PV. RES respectively generate 43% and 60% of UK power production.
The interconnection capacity, which respectively amounts to 8 and 12.5 GW, is rather small compared to the net demand peaks and does not provide much flexibility (see Section 5.2).

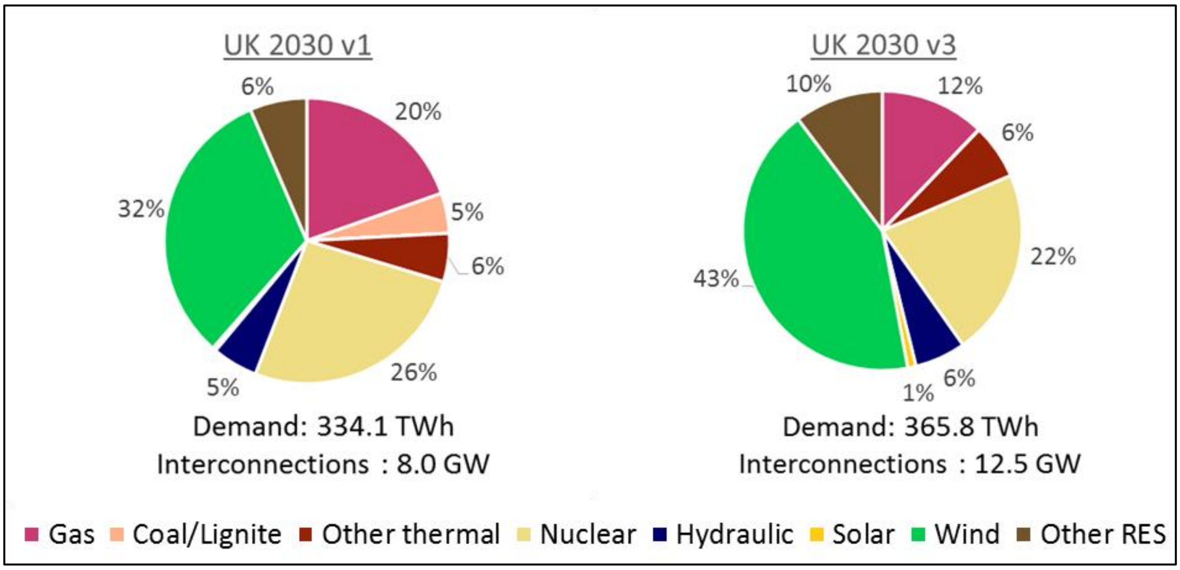


Figure 21. Power mix (in % of TWh), annual demand and interconnection capacity for UK scenarios

In V1 and V3, the hydraulic power maximum capacities are respectively 8.4 GW and 11.0 GW. In addition, 2.4 GW of pumped-storage hydroelectricity are already installed.
The results presented in this Section have been obtained by simulating a whole year with an hourly time step (see Section 3.3). Using a one year time horizon is essential to capture seasonal effects, strongly influenced by the different weather regimes. An hourly time resolution with consecutive time steps (8760 time steps per year) are important to capture storage charge/discharge dynamics.
The following chart shows a cumulative view of electricity generation in UK during a week of June. Each color is associated to a given type of generation unit, the imports are shown in grey, and the demand is represented by the solid red line. If the total energy (generated + imports) exceeds the demand, the excess energy is either exported, stored or curtailed.

The impact of the important wind power deployment is visible, the associated production varying over cycles of several days. The marginal generation cost (variable cost of the most expensive running unit) is clearly influenced by the wind load factor: nuclear tends to be the marginal producer when wind production is high, and gas units when it is low. One can expect that a storage unit with a discharge time of several days could exploit the price difference between nuclear and gas and reduce the overall system’s costs.

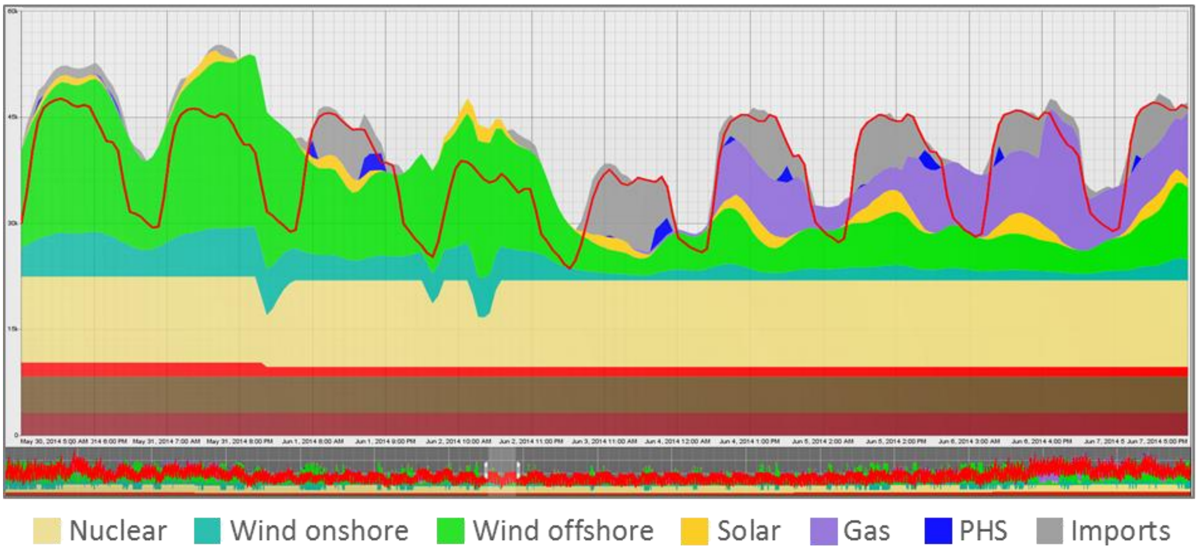


Figure 22. Cumulative generation curve of UK in the scenario 2030 v3

6.2. CAPACITY VALUE

The definition of capacity value and the methodology used to assess it in the context of this study is presented in Appendix.

Figure 23 presents two days of the 2030 V1 scenario. These days are characterised by a high level of demand and a low wind energy generation. Due to the absence of daily variation from wind power and the low level of PV generation, the net demand tends to be relatively constant over extended periods of time, potentially leading to an important number of consecutive peak hours.

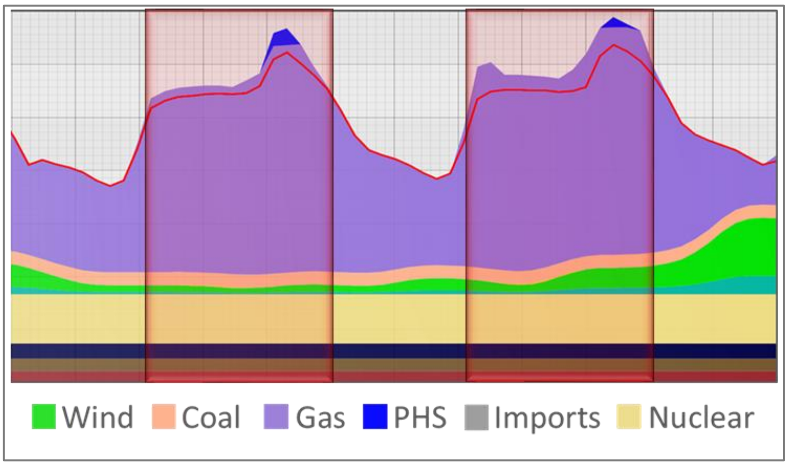


Figure 23. Peak hours during two days in UK in the scenario 2030 v3

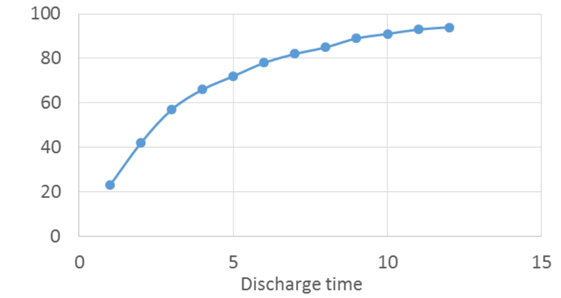


Figure 24. Storage capacity value in UK for 2030 V1 (in % of peak hours)

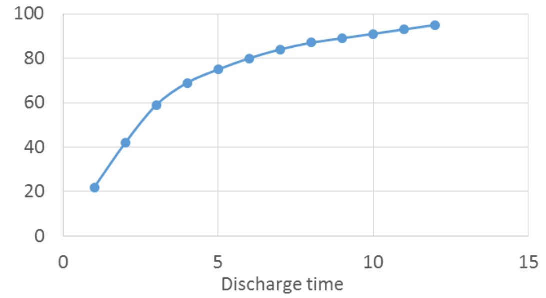


Figure 25 : Storage capacity value in UK for 2030 V3 (in % of peak hours)

Figure 24 and Figure 25 illustrate the way in which increasing discharge time progressively allows storage equipment to capture its full capacity value (see Section 11.3 for a precise description of the methodology). 80% of the capacity value of storage can be captured with storage units with 6 to 7 hours of discharge time. Twelve hours is not long enough a discharge time to capture 100% of the capacity value, which confirms the occurrence of long lasting peak periods.

6.3. ARBITRAGE VALUE

The operational costs of the power system can be lowered thanks to the exploitation of new storage units in the UK. Indeed, storage provides the power system with more flexibility and the ability to better exploit renewables and thermal units, hence cutting costs. The methodology used to assess arbitrage value is explained in Section 11.2. The impact on European generation which results from adding 1 GW with 3 hours of discharge time in the UK is depicted in Figure 26.

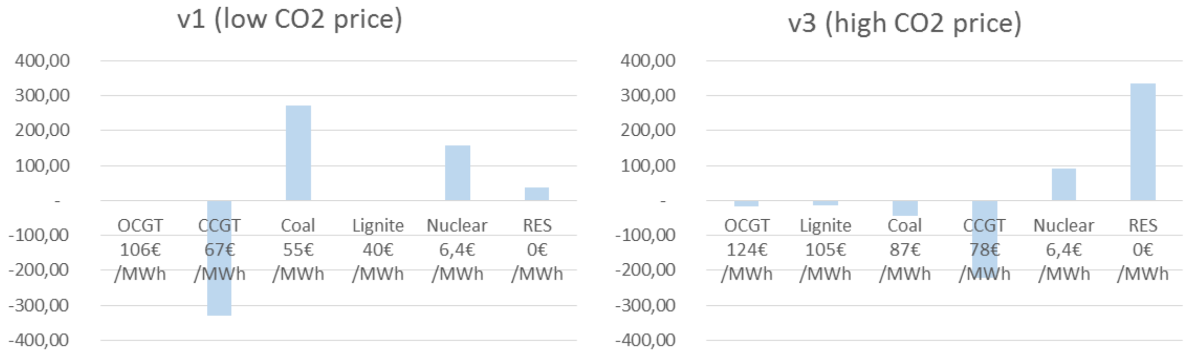


Figure 26. Impact on yearly generation in Europe of adding 1GW of 3h storage in UK in 2030 (in GWh)

In scenario V1, storage enables to use more base-load generation (coal[6], nuclear) and discharge the energy during peak load hours, leading to a decrease in use of plants with higher variable costs, such as CCGT. The total generation increases when storage is added to the system since not all the energy can be recovered.

As a result, this leads to:

- 10.1 M€ reduction in fuel costs due to a lower price of coal and nuclear compared to gas.

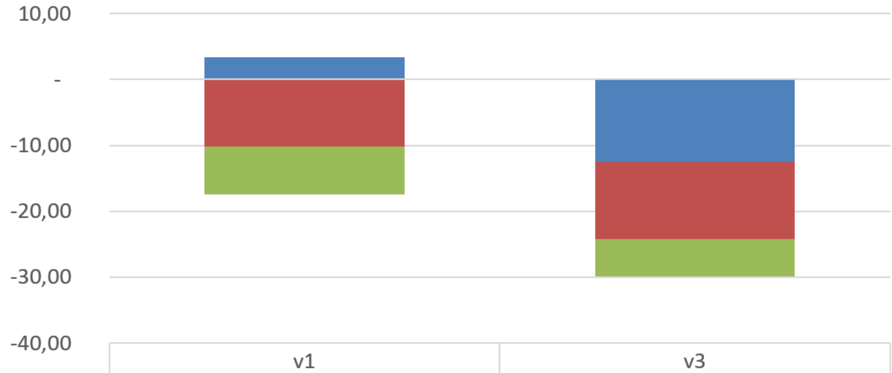
[6] As described in Section 3.3, specific constraints enforced by Member States on coal generation (for example annual quotas or specific CO2 price for UK) are not modelled in this study. Such constraints may result in a different merit order and impact the arbitrage value of storage.

- 3.4 M€ increase in CO2 costs (110 000 t of additional CO2 emissions) due to the higher CO2 content in coal than in gas.
- 7.2 M€ savings in startup costs due to the new storage flexibility

In scenario V3, nuclear generation increases at the expense of all other thermal production units and wind power curtailment is reduced.
As a result, this leads to:

- A 11.7 M€ reduction in fuel costs due to a lower fuel consumption
- A 12.5 M€ decrease in CO2 costs (130 000 t of CO2 emissions savings)
- 5.6 M€ savings in startup costs due to the new storage flexibility

These results are summed up in Table 2. Impact on costs of adding 1GW of 3h storage in Germany in 2030, in M€



	v1	v3
Startup Costs	-7,23	-5,64
Production Costs	-10,17	-11,73
CO2 Costs	3,40	-12,48

Table 2. Impact on costs of adding 1GW of 3h storage, in M€/y – UK 2030

The next couple of figures illustrate the arbitrage value of storage through cumulative generation curves, and how flexibility is used to save costs during periods of high net demand as well as during periods of low net demand.
Figure 27 illustrates days of high net demand due to low wind power generation in the scenario 2030 V1. Coal is used as peak load generation during the second peak of the day (2) but not during the first one (1) as the pumped-hydro storage capacity is large enough to handle the peak. Savings originate both from cuts in generation costs and in startup costs.

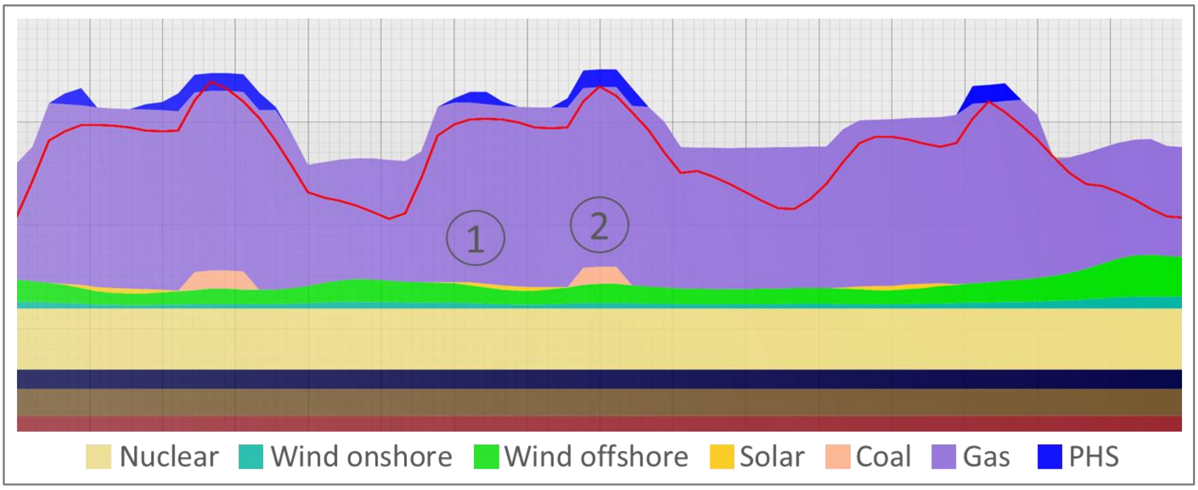


Figure 27. Example of cumulative generation during peak period – UK 2030 v1

Figure 28 illustrates a few days of low net demand due to high wind power generation in the scenario 2030 V3. In the first hours that are illustrated, conventional thermal power plants are not running, nuclear power is generating at minimal capacity, fixed at 40%, and electricity demand is lower than total generation minus export capacities. In this kind of situation, the excess energy is either curtailed or stored. In this situation, electricity is stored and used at (2), thus avoiding to start a conventional power plant.

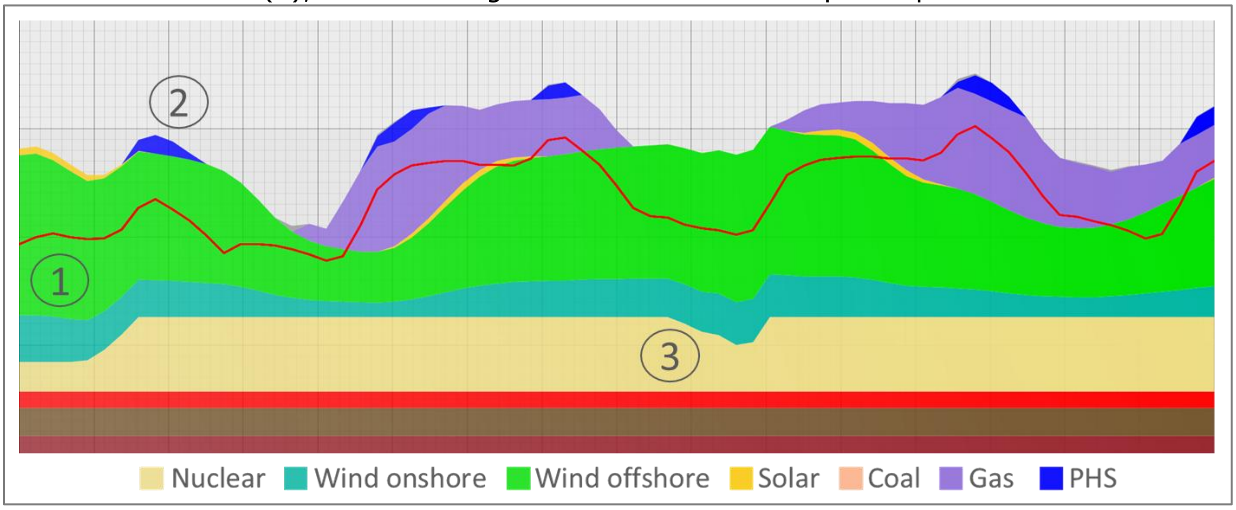


Figure 28. Example of cumulative generation during off-peak period – UK 2030 v3

6.4. TOTAL BENEFITS

The value of storage for UK in 2030 for different values of discharge time is presented in Figure 29. It is the sum of capacity value and arbitrage value; these separate results have been calculated using the methodology defined in Section 11.
The first part of the curve indicated by (1) shows the fulfilment of daily flexibility needs while the second part indicated by (2) shows the fulfilment of weekly flexibility needs.
In scenario V1, the overall value is dominated by the capacity value (see Section 6.2).
In scenario V3, additional value comes from arbitrage, in particular for high discharge times. This results from a significant need for weekly arbitrage in a scenario with a lot of wind power curtailment and limited interconnection capacity.

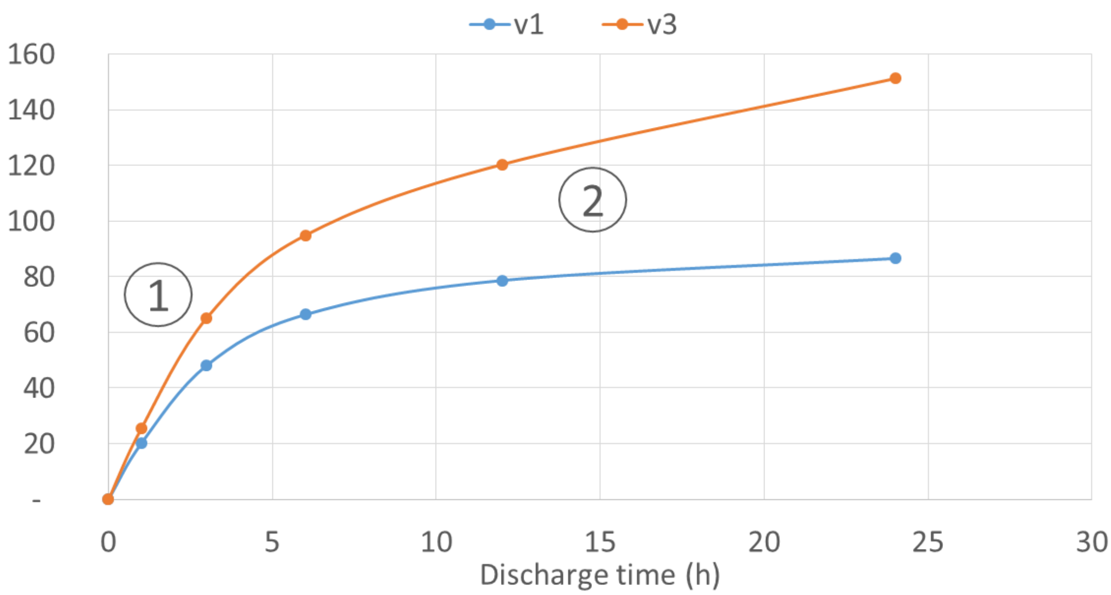


Figure 29. Storage value in UK in 2030 as a function of discharge time (M€/MW/y)

6.5. SENSITIVITY ANALISYS TO INTERCONNECTION CAPACITY

Interconnections have a significant impact on a country's power system flexibility (see Section 5.2). The relative isolation of the UK is one on the reasons explaining why flexibility is so highly valued in UK. A further development of interconnectors would however impact the flexibility needs, and the value of flexibility.
A sensitivity analysis has been performed by varying homogeneously all interconnection capacities of the UK with continental Europe (the interconnection between UK and Ireland has been kept unchanged).
The analysis has been performed with 1GW of storage with a discharge time of 12h and the interconnection capacities presented in the following table:

Scenario	V1	V3
Original interconnections capacity	7.2 GW	11.4 GW
Reduced interconnection capacity	4 GW	6.3 GW
Increased interconnection capacity	10.4 GW	16.5 GW

Figure 30 is illustrating the results of the sensitivity analysis. As expected, increasing the interconnection capacity leads to a decrease of the value of flexibility, and vice versa.

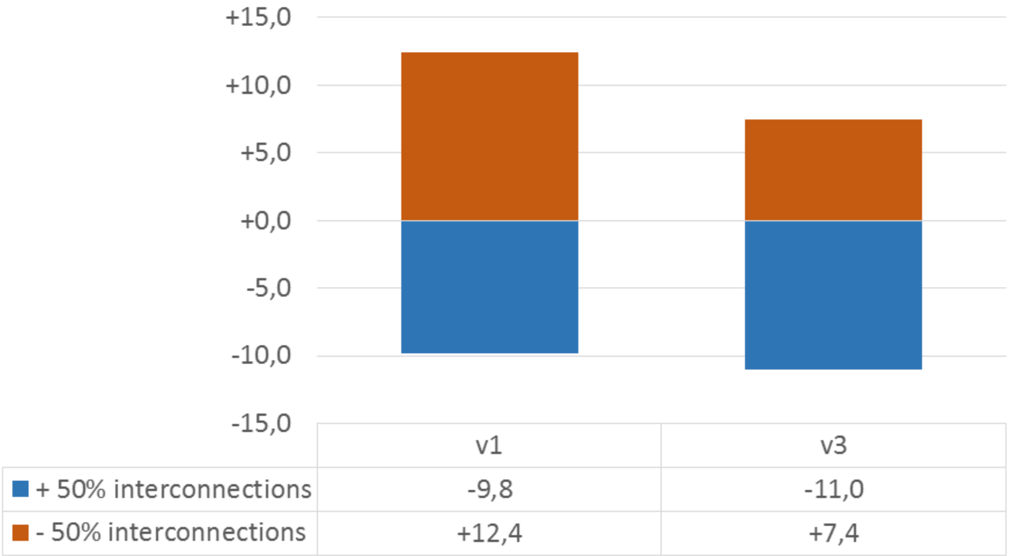


Figure 30. Evolution of the value of a 12h storage due to a change in UK's interconnection capacity in M€/MW/y

7. SECOND USE CASE: ENERGY STORAGE IN GERMANY

7.1. USE CASE DEFINITION

As explained in Section 3.1, the following results are based on ENTSO-E 2030 scenarios V1 and V3 from 2014 Ten Year Network Development Plan (TYNDP 2014) for demand, interconnectors and generation (illustrated in Figure 31), and on current values for energy storage. The objective is to assess the benefits of adding 1 GW of energy storage in Germany, with different discharge times.
The German scenarios are characterised by large shares of PV and wind generation, with a total RES share of respectively 45% and 65% of generated energy in V1 and V3. The German power supply mix is particularly impacted by the level of CO2 price, which significantly impacts the merit order: nearly half the energy is generated by coal or lignite in V1 compared to only 2% in V3, while generation from gas is multiplied by 7.5 between V1 and V3.
The high interconnection capacity, which is of the order of 35 GW in both scenarios, satisfies half of Germany flexibility needs as was illustrated in Section 5.2.

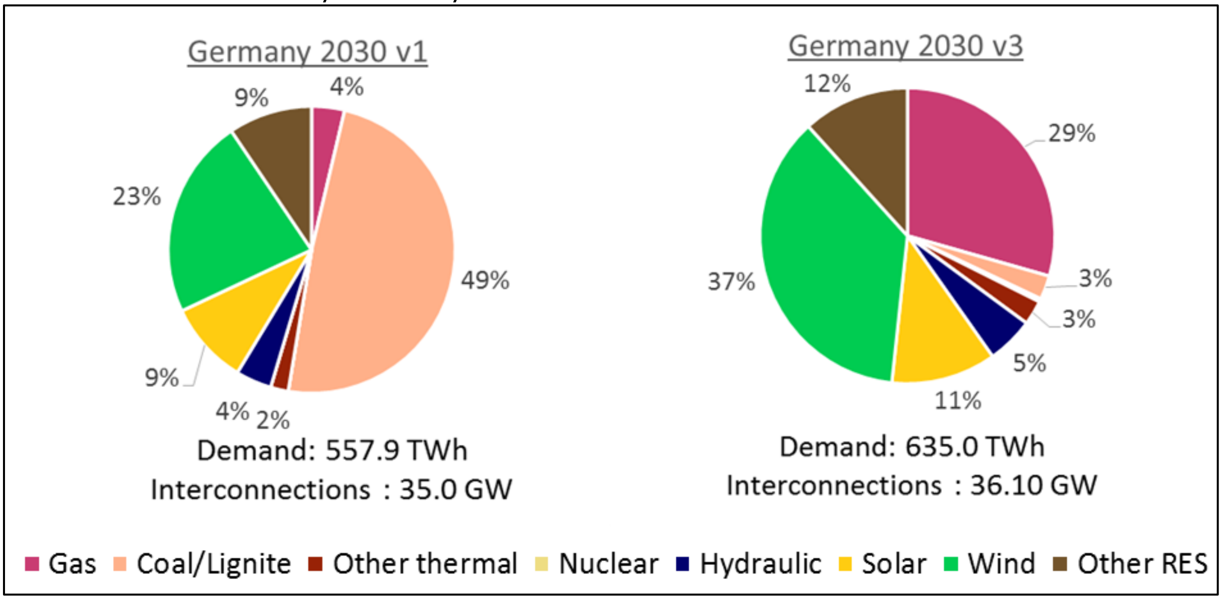


Figure 31. Power mix (in % of TWh), annual demand and interconnection capacity for DE scenarios

In V1 and V3, the hydraulic power maximum capacities are respectively 7 GW and 7.2 GW. This includes run-of-the-river capacity (5 GW and 5.2 GW) and conventional hydro reservoir (2 GW in both scenarios). In addition, 7.0 GW of pumped-storage hydroelectricity are already installed.
The following figure presents a cumulative view of electricity generation in Germany during a week of June in scenario V3. The important installed capacity of wind power and PV are clearly visible, with production respectively varying over several days and within the day. As a consequence of the high share of RES, during some times of low demand and high wind power, the marginal generation unit may be RES itself.
The high interconnectivity of Germany is also clearly visible on this figure. Electricity is not only imported during peak periods, but also used to import electricity from neighbouring countries instead of starting more expensive local power plants.

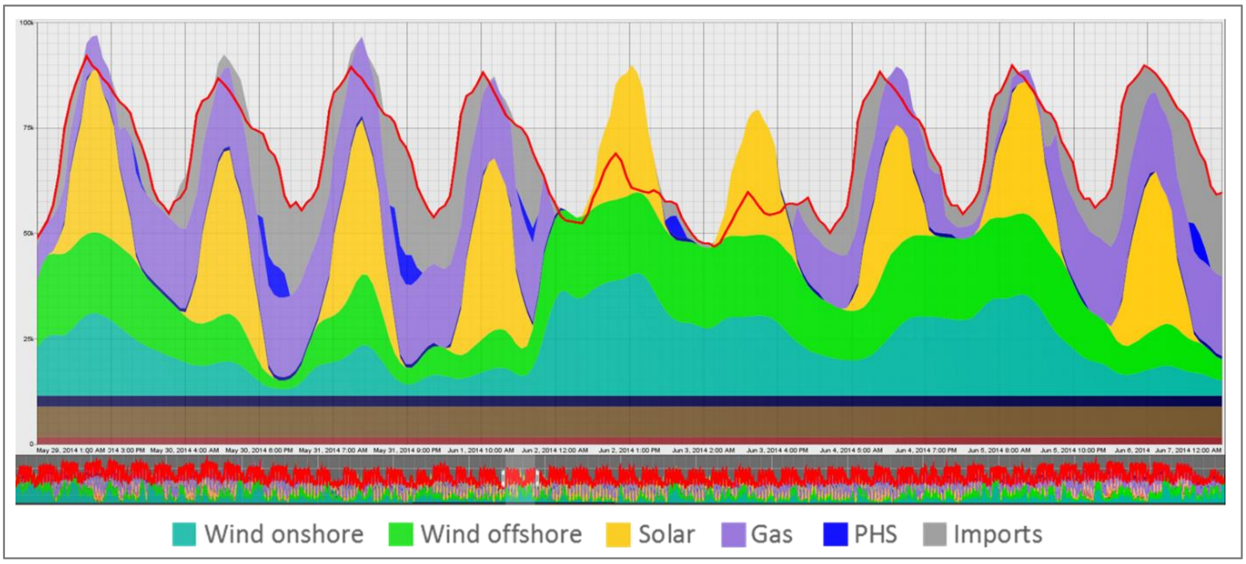


Figure 32. Cumulative generation curve of Germany in 2030 v3

7.2. CAPACITY VALUE

The definition of capacity value and the methodology used to assess it in the context of this study is presented in Section 11.3.

Figure 33 illustrates two days which are characterised by a high demand and low wind power production in the V1 2030 scenario. PV generation however lowers the net demand decrease during daytime. The consequence is that the peaks of net demand tend to occur at the beginning and at the end of the day, and are separated by a period of lower net demand.

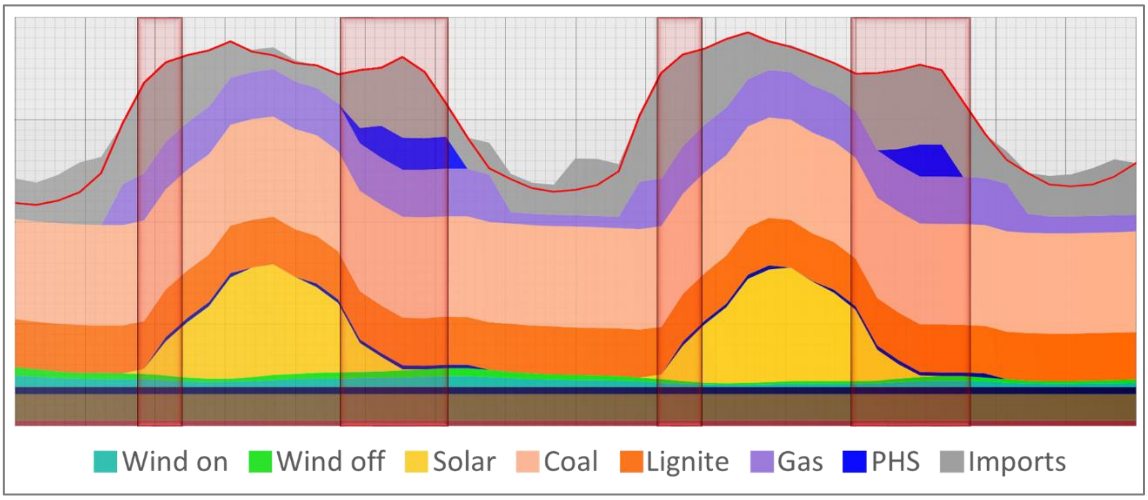


Figure 33. Peak hours during two days in Germany in scenario 2030 v1

Figure 34 and Figure 35 illustrate the way in which increasing discharge time progressively allows storage equipment to capture its full capacity value (see Section 11.3 for a precise description of the methodology). 80% of the capacity value of storage can be captured with storage units with 4 hours of discharge time. In scenario V1, capacity value reaches its maximum for discharge times of 6 hours, while in scenario V3 this maximum is reached for discharge times of 12 hours as a consequence of the higher wind power capacity, which tends to increase the flexibility needs over longer periods.

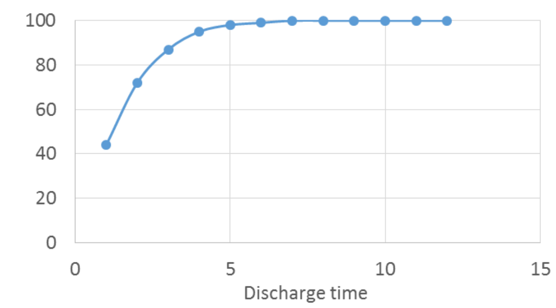


Figure 34. Storage capacity value in DE for 2030 v1 (in % of peak hours)

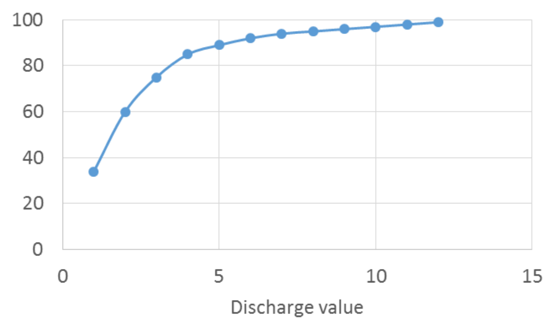


Figure 35. Storage capacity value in DE for 2030 v3 (in % of peak hours)

7.3. ARBITRAGE VALUE

The operational costs of the power system can be lowered thanks to the exploitation of new storage units in Germany. Indeed storage provides the power system with more flexibility and the ability to better exploit renewables and thermal units, hence cutting costs. The methodology used to assess arbitrage value in explained in Section 11.2. The impact on European generation which results from adding 1 GW with 3 hours of discharge time in Germany is depicted in Figure 36.

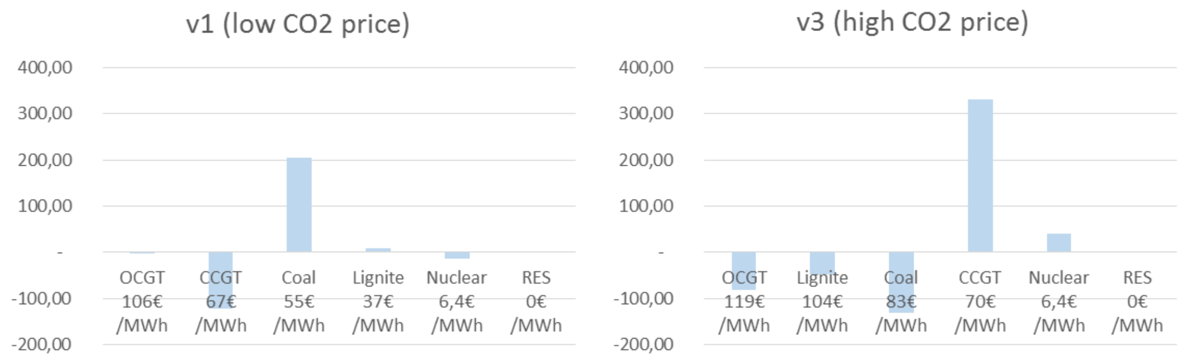


Figure 36. Impact on yearly generation in Europe of adding 1GW of 3h storage in Germany in 2030 (in GWh)

In scenario V1, storage enables to generate more base-load generation overall (coal mostly) and to discharge this energy in period of higher demand, leading to a decrease in the use of more expensive power plants such as CCGT.

As a result, this leads to:

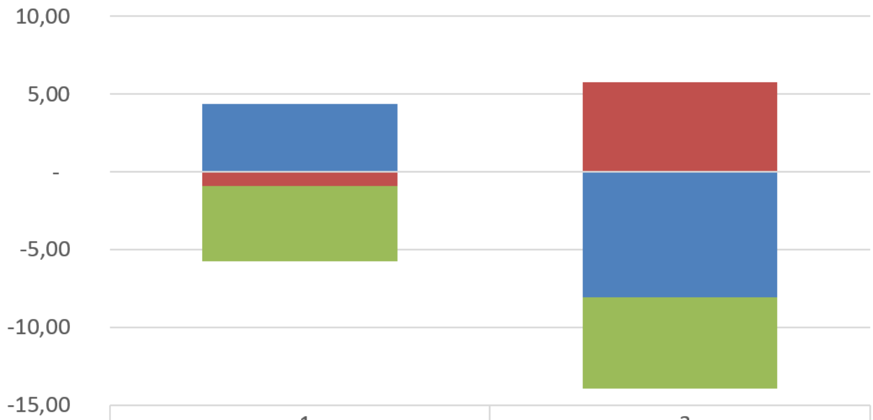
- 0.9 M€ reduction in fuel costs due to a lower price of coal compared to gas.
- 4.3 M€ increase in CO2 costs (140 000 t of additional CO2 emissions) due to the higher CO2 content in coal than in gas.
- 4.8 M€ savings in startup costs due to the new storage flexibility

In scenario V3, following the same logic, base-load generation increases at the expense of medium load and peak load generation. The main differences with scenario V1 are the amplitude of the shift and the impact on the merit order. The amplitude of the generation shift (almost the double the one in V1) is explained by the higher installed wind power capacity (64% more wind power in V3 compared with V1), which results in additional needs for flexibility. However, this generation shift materialises in a different manner, since the CO2 price of the V3 scenario modifies the merit order. As a result, CCGT and nuclear generation, used as base-load in this scenario, increase while medium and peak generation decrease (OCGT, Coal and Lignite).

As a result, this leads to:

- 5.8 M€ increase in fuel costs due to a price difference higher price of gas compared to coal/lignite
- 8.1 M€ reduction in CO2 costs (87 000 t of CO2 emissions savings) by using more CCGT/nuclear and less coal/lignite
- 5.9 M€ savings in startup costs due to the new storage flexibility

These results are summed up in Table 2.



	v1	v3
Startup Costs	-4,84	-5,88
Production Costs	-0,94	5,77
CO2 Costs	4,33	-8,06

Table 2. Impact on costs of adding 1GW of 3h storage in Germany in 2030, in M€

The next couple of figures illustrate the arbitrage value of storage through cumulative generation curves, and how flexibility is used to save costs during periods of high net demand as well as during periods of low net demand.

Figure 37 shows days of high net demand, which are due to both low PV and low wind power generation in the scenario 2030 V1. In order to satisfy the afternoon peak demand, and for three consecutive days, open cycle gas turbines (OCGT, in red) have to be started in order to generate enough power (1), which is characteristic of peak hours. PSH is charging during the night (2) and discharging during the day hence reducing costs in several ways: first it enables to generate less power with OCGTs, which results in savings in generation costs, second it also generates in the morning (3), to avoid generating with OCGT at all, therefore induces savings in both in generation costs and in startup costs.

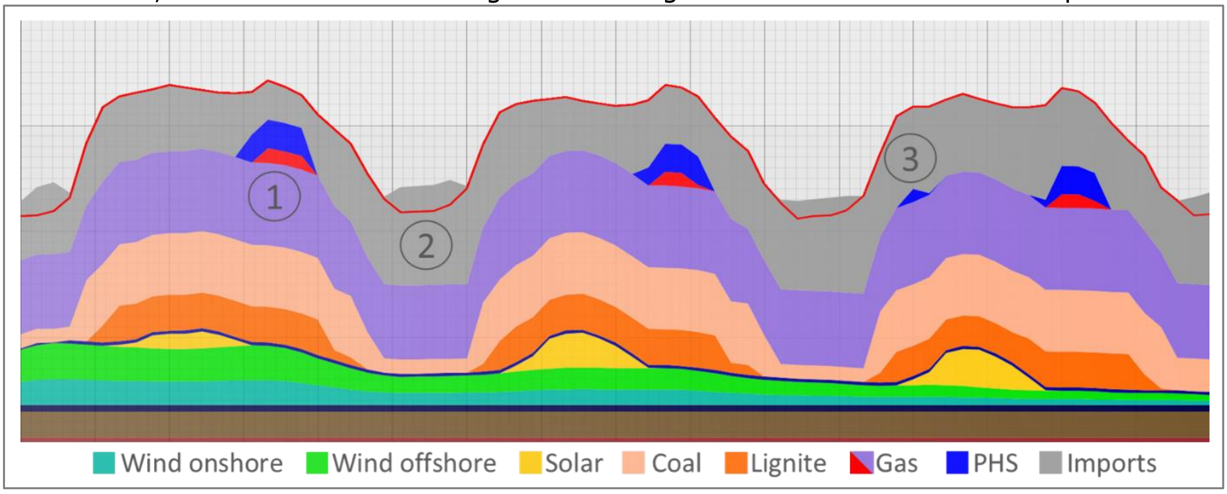


Figure 37. Example of cumulative generation during peak period – DE 2030 v1

Figure 38 illustrates days of low net demand, which are due to high wind power and PV generation in the scenario 2030 V3 in Germany. At (1), generation costs are saved by discharging the Pumped Sotrage Hydro (PSH) instead of generating more power from gas. At (3), both generation and startup costs are saved because PSH, that was able to charge during generation surplus (2), avoids starting up gas power plants.

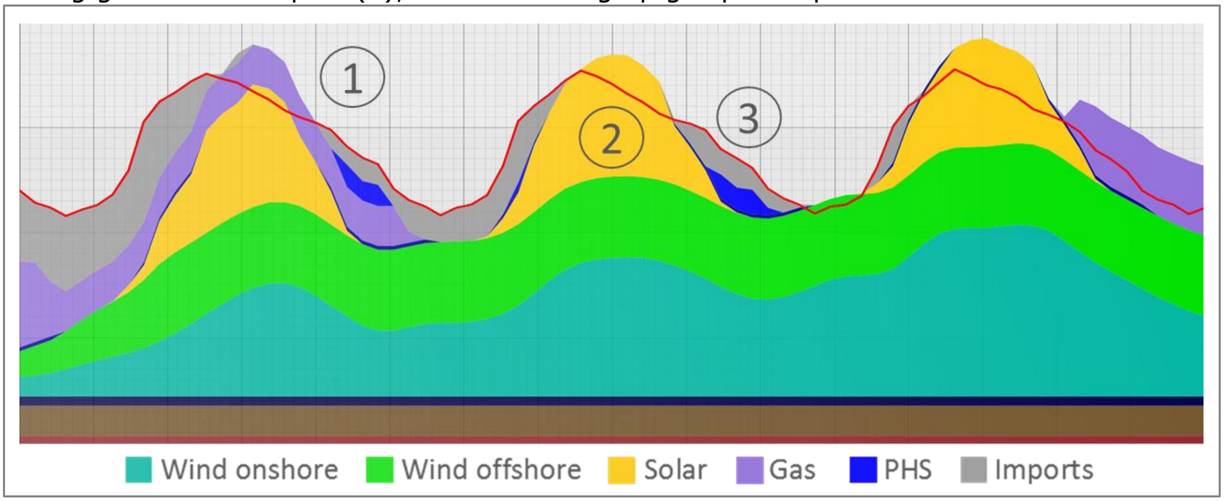


Figure 38. Example of cumulative generation during off-peak period – DE 2030 v3

7.4. TOTAL BENEFITS

The total value of storage for Germany in 2030 for different discharge durations is presented in Figure 39.

The first part of the curve indicated by (1) shows the fulfilment of daily flexibility needs while the second part indicated by (2) shows the fulfilment of weekly flexibility needs.

In scenario V1, the biggest part of the value is reached in a few hours of storage. Furthermore, the overall value is dominated by the capacity value.

In scenario V3, the shape is similar. The high wind power installed capacity increases the storage arbitrage value for discharge times longer than 10 hours, but the additional value remains limited compared to the UK use case. This is mainly due to the high interconnection capacity (discussed in Section 5.2).

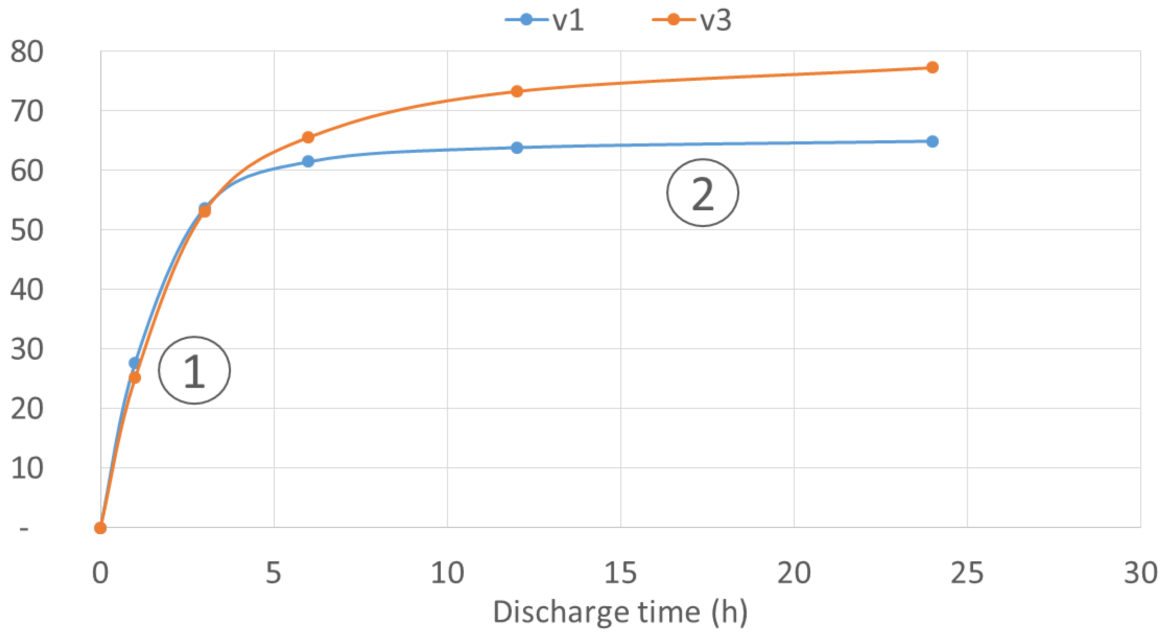


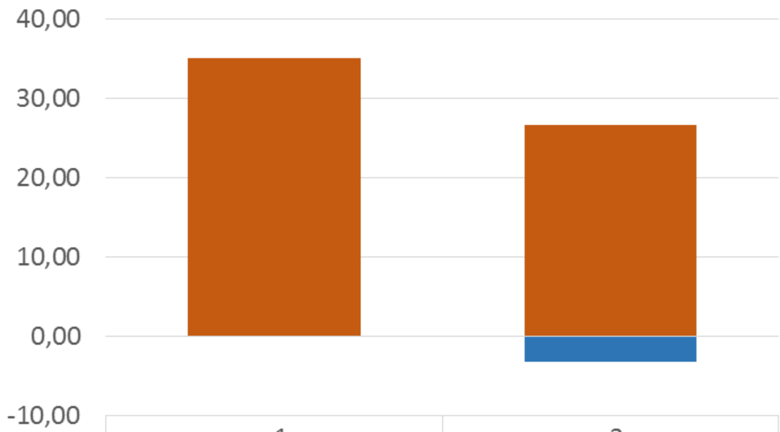
Figure 39. Storage value in Germany in 2030 as a function of discharge time (M€/MW/y)

7.5. SENSITIVITY ANALYSIS TO INTERCONNECTION CAPACITY

Interconnections have a significant impact on a country's power system flexibility (see Section 5.2). The analysis concludes that the interconnectivity of Germany is one on the reasons why the value of flexibility is low in this country. A sensitivity analysis has been performed by varying homogeneously all interconnection capacities of Germany with its neighbors.
The analysis has been performed with 12h of storage discharge time the parameters presented in the following table:

Scenario	V1	V3
Original interconnections capacity	36 GW	37 GW
Reduced interconnection capacity	18 GW	18 GW
Increased interconnection capacity	54 GW	55 GW

Figure 39 illustrates the results of the sensitivity analysis. As expected, an increase in the interconnection capacity has only a minor impact on the storage value, as the original interconnection capacity is high enough to fulfill most of the flexibility that can be brought by neighbor countries.
On the other side, when interconnector capacities decrease, the storage value increases sharply, which illustrates once again the competing role between interconnectors and storage for bringing flexibility.



	v1	v3
+ 50% interconnections	0	-3,10
- 50% interconnections	35,03	26,62

Figure 40. Evolution of flexibility needs due to a change in Germany's interconnection capacity in M€/MW/y

8. THIRD USE CASE: ENERGY STORAGE IN AUSTRIA

8.1. USE CASE DEFINITION

As explained in Section 3.1, the following results are based on ENTSO-E 2030 scenarios V1 and V3 from 2014 Ten Year Network Development Plan (TYNDP 2014) for demand, interconnectors and generation (see Figure 31), and on current values for energy storage. The objective is to assess the benefits of adding 1 GW of energy storage in Austria, with different discharge times.
The Austrian scenarios are characterised by a very important hydro power generation and quite low wind and PV installed capacities, with a total RES share of respectively 84% and 76% generated energy in V1 and in V3.
The interconnection capacity (15.3W in both scenarios) is very high for a country of this size (close to half of Germany import capacities for a demand 7 times lower). It is expected that the need for flexibility of Austria can be largely fulfilled by importing and exporting electricity, even more significantly than for Germany.

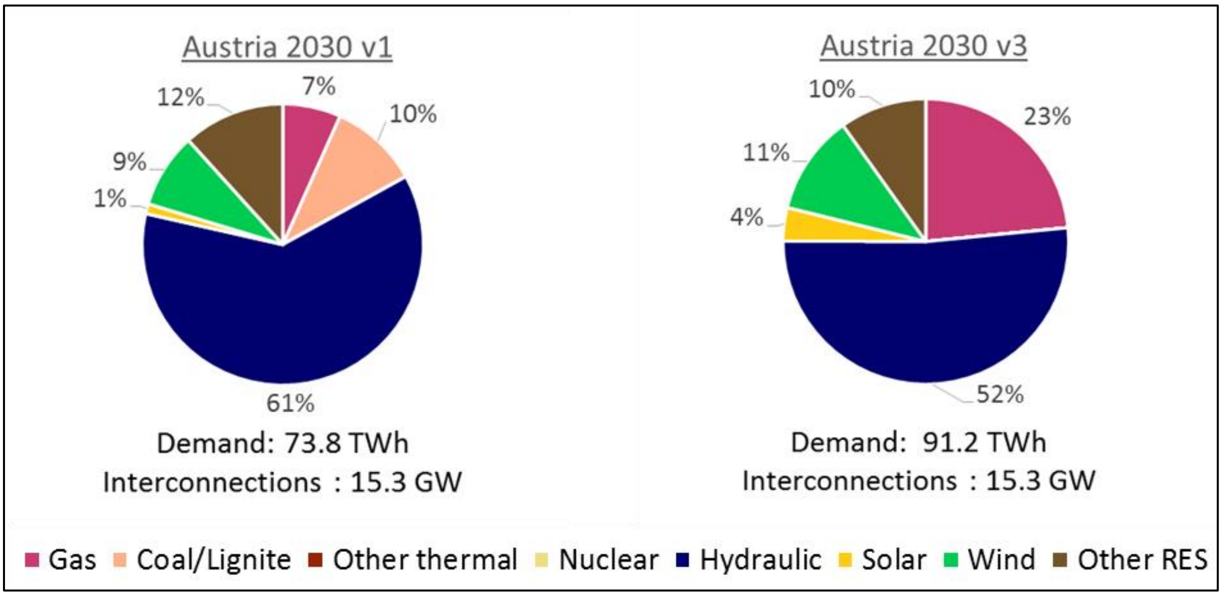


Figure 41. Power mix, yearly demand and interconnection capacity for the original Austria scenarios

In V1 and V3, the hydraulic power maximum capacities are both equal to 14 GW. This includes run-of-the-river capacity (8.1 GW and 7.9 GW) and conventional hydro reservoirs (5.9 GW and 6.1 GW). In addition, 3.4 GW of pumped-storage hydroelectricity are already installed.
Figure 42 represents a cumulative view of electricity generation in Austria during a week of June in scenario V3. One can immediately note the importance of hydropower in the Austrian energy mix, not only run-of-the-river or traditional reservoirs, but also pumped-storage hydro (capacities of 2014).
The high interconnection capacity is clearly visible as well. Up to half of the country's demand can be satisfied by interconnectors during a number of hours.

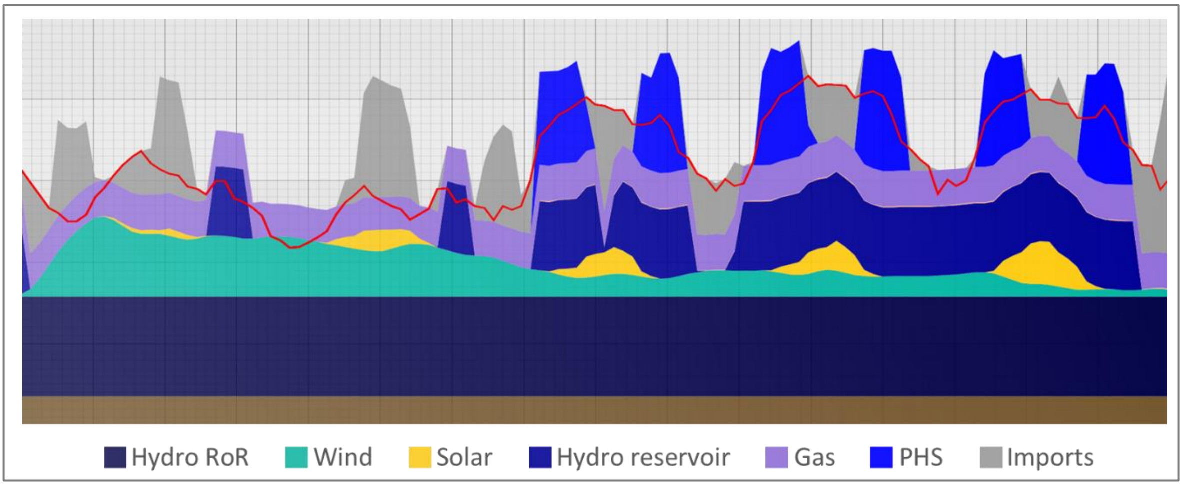


Figure 42. Cumulative generation curve of Austria in 2030 v3

8.2. CAPACITY VALUE

The definition of capacity value and the methodology used to assess it in the context of this study is presented in Appendix.

Figure 42 illustrates two days that are characterised by both a high demand and low run-of-the-river power (typically week days in winter) during a period of low wind in scenario 2030 V1. Due to the absence of daily variation of wind power and the absence of PV generation, the net demand through the day tends to be relatively constant, resulting in potentially long periods of peak hours (indicated in red).

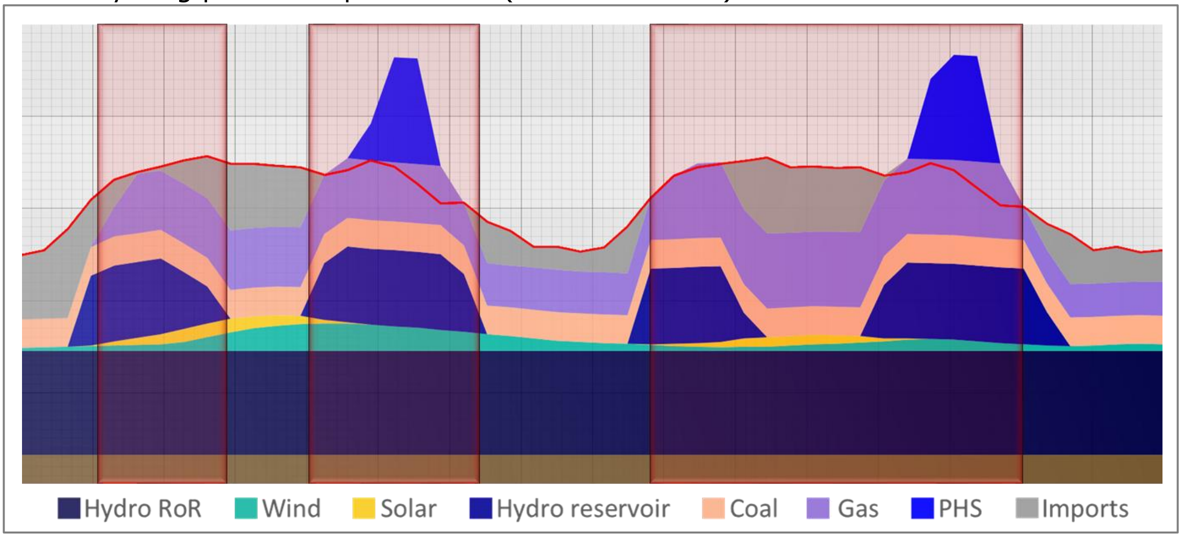


Figure 43. Peak hours during two days in Austria in scenario 2030 v1

Figure 44 and Figure 45 illustrate the way in which increasing discharge time progressively allows storage equipment to capture its full capacity value (see Section 11.3 for a precise description of the methodology). 80% of the capacity value of storage can be captured with storage units with 9 hours of discharge time in scenario V1, and of only 5 hours in scenario V3. This is related to the occurrence dynamics of peak hours. In scenario V3, with includes 4 times more PV than scenario V1, the hours in the middle of the day may not be considered as peak hours during some days (low net demand). The less successive peak hours there is, the more the storage is able to provide capacity services.

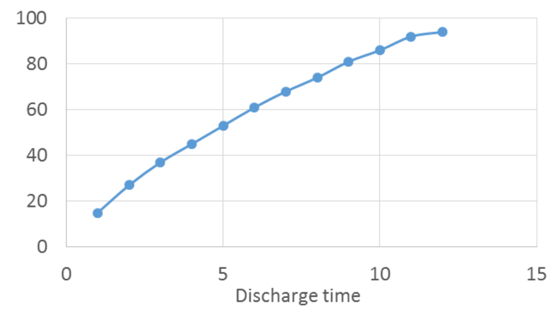


Figure 44. Storage capacity value in Austria for 2030 v1 (in % of peak hours)

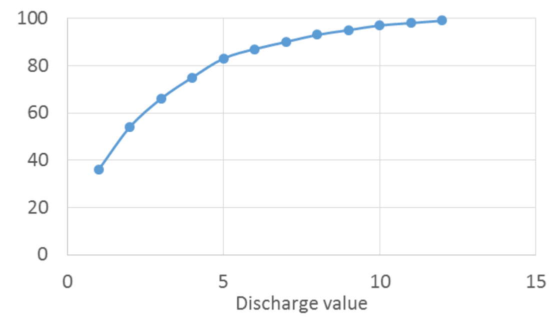


Figure 45. Storage capacity value in Austria for 2030 v3 (in % of peak hours)

8.3. ARBITRAGE VALUE

The operational costs of the power system can be lowered thanks to the exploitation of new storage units in Austria. Indeed storage provides the power system with more flexibility and the ability to better exploit renewables and thermal units, hence cutting costs. The methodology used to assess arbitrage value in explained in Section 11.2. The impact on European generation which results from adding 1 GW with 3 hours of discharge time in Germany is depicted in Figure 46.

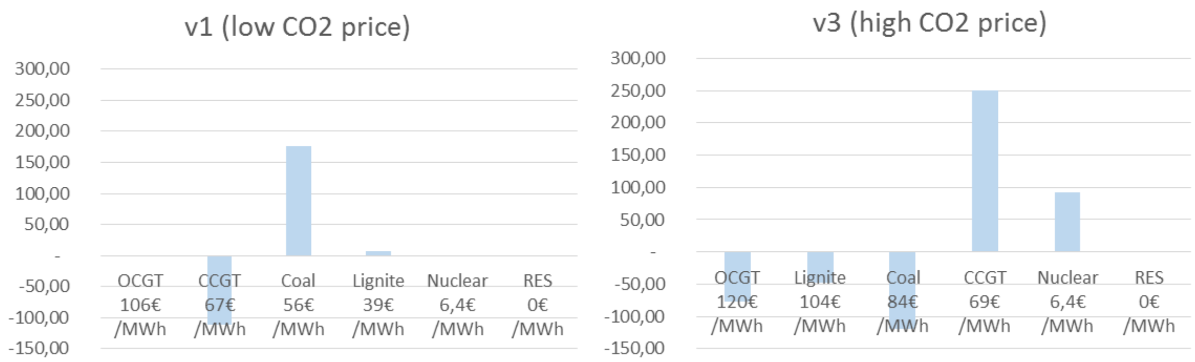


Figure 46. Impact on yearly generation in Europe of adding 1GW of 3h storage in Austria in 2030 (in GWh)

In scenario V1, storage enables to generate more base-load generation (coal mostly) and discharge this energy in periods of high demand, leading to a decrease in the use of more expensive power plants such as CCGT.
As a result, this leads to:

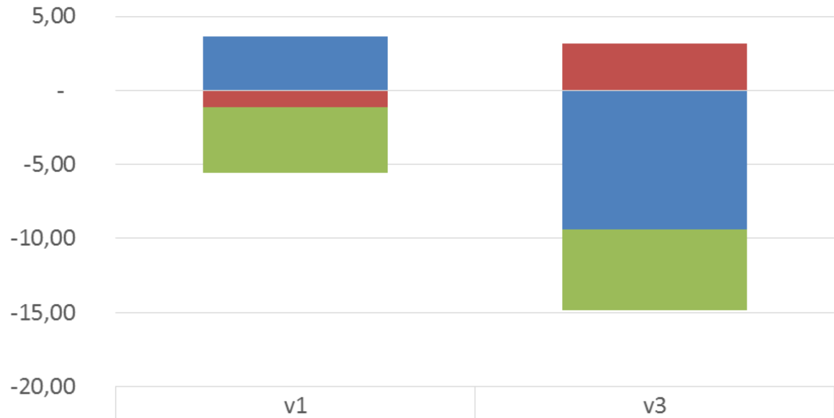
- 1.1 M€ reduction in fuel costs due to a lower price of coal compared to gas.
- 3.6 M€ increase in CO2 costs (120 000 t of additional CO2 emissions) due to the higher CO2 content in coal than in gas.
- 4.4 M€ savings in startup costs due to the new storage flexibility

In scenario V3, following the same logic, base-load generation increases at the expenses of medium load and peak load generation. The main difference with scenario V1 is impact of CO2 price on the merit order. CCGT and nuclear generation, used as base-load in this scenario, increase while medium and peak generation decrease (OCGT, Coal and Lignite).
As a result, this leads to:

- 3.1 M€ increase in fuel costs due to a price difference higher price of gas compared to coal/lignite

- 9.3 M€ reduction in CO2 costs (100 000 t of CO2 emissions savings) by using more CCGT/nuclear and less coal/lignite
- 5.5 M€ savings in startup costs due to the new storage flexibility

These results are summed up in Table 3.



	v1	v3
Startup Costs	-4,43	-5,46
Production Costs	-1,11	3,14
CO2 Costs	3,64	-9,36

Table 3. Impact on costs of adding 1GW of 3h storage in Austria in 2030, in M€

The next figures illustrate the arbitrage value of storage through cumulative generation curves. It shows to what extent implementing flexibility is saving costs during periods of high net demand and periods of low net demand.
Figure 47 illustrates some days of high net demand due to both low PV and low wind power generation in the scenario 2030 V1. Electricity is imported almost continuously during the day, both during peak periods and off-peak periods and peak power plants are not generating. This shows that national generation depends mostly on the cost of electricity in the neighboring countries rather than national demand.
Even in the scenarios in which no investment in energy storage is performed PSH are used to engage in arbitrage in the markets: importing and storing during off-peak periods and generating during peak periods. Therefore the expected value of adding extra storage is low as flexibility already exists.

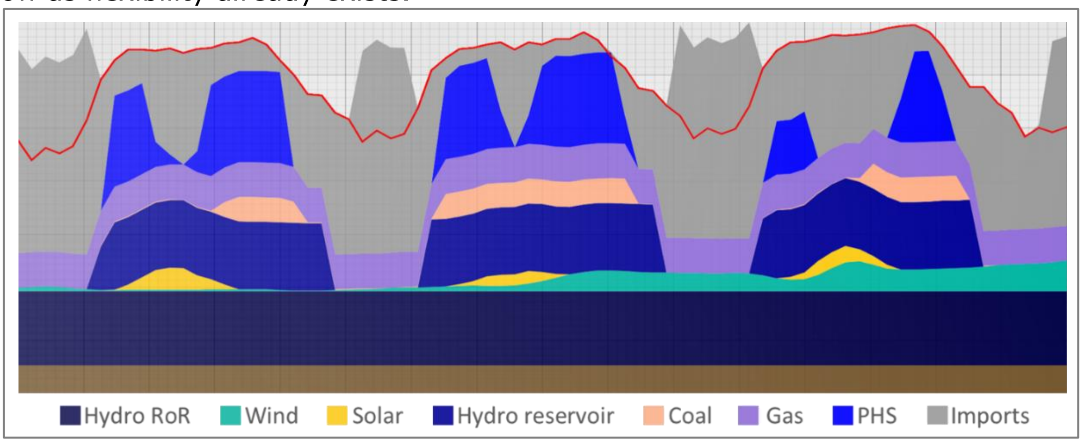


Figure 47. Example of cumulative generation during peak period – Austria 2030 v3

In periods of very low net demand, when demand is almost entirely satisfied from RES generation, PSH is not generating, as illustrated in Figure 48. However, it is storing with imports from neighbor countries in order to discharge during days where electricity is more expensive.

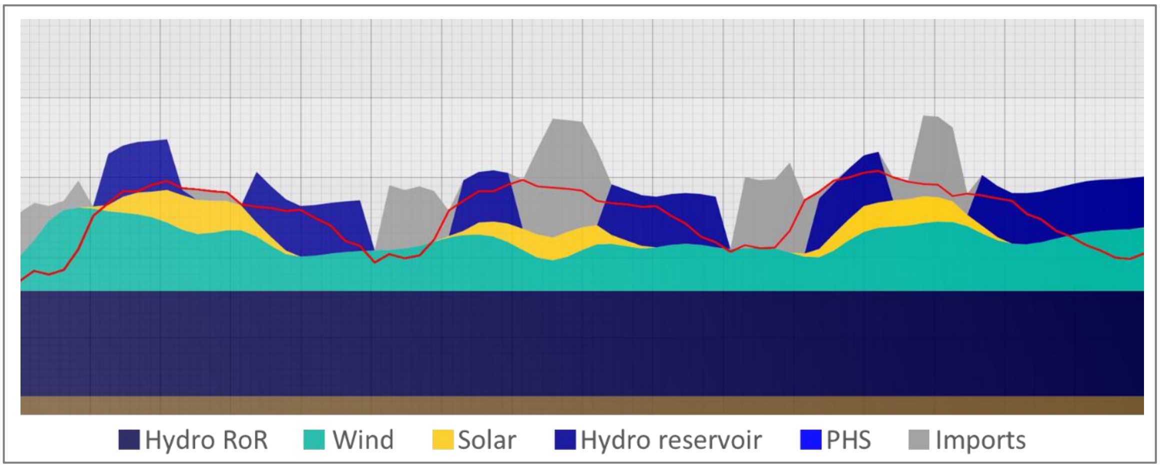


Figure 48. Example of cumulative generation during off-peak period – Austria 2030 v1

8.4. TOTAL BENEFITS

The total value of storage for Austria in 2030 for different values of discharge time is presented in Figure 49.
The first part of the curve indicated by (1) shows the fulfilment of daily flexibility needs while the second part indicated by (2) shows the fulfilment of weekly flexibility needs.
For both scenarios, the overall value is due to a large extent to the capacity value. Indeed, Austria has sufficient flexibility resources: the pumped storage capacity in 2014 and the interconnection capacity are too important for additional storage to bring a significant arbitrage value.

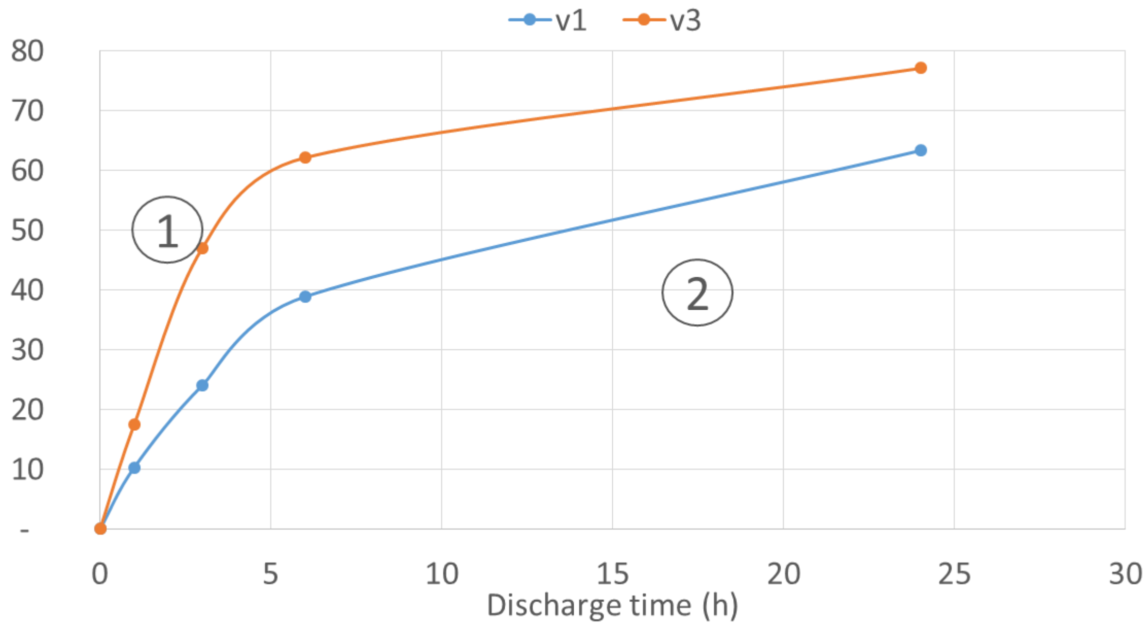


Figure 49. Storage value in Austria in 2030 as a function of discharge time (M€/MW/y)

9. ENERGY STORAGE TECHNOLOGIES

This section survey is driven from previous work realised with Enea Consulting in 2013 (ADEME, Etude sur le potentiel du stockage d'énergie, 2013) and aims to provide a state of the art of available energy storage technologies, or in development. The studied technologies have been selected to cover all the existing typologies of energy storage systems. Furthermore, for each family of energy storage and wherever possible, both mature technologies and more prospective ones have been considered.

- Gravitational storage
  - Conventional overland PSP
  - Marine PSP
  - Underground PSP
  - Energy transfer system by marine ballast
- Thermodynamic storage
  - Underground adiabatic isochoric CAES
  - Surface isothermal CAES
  - Surface adiabatic isobaric CAES
  - Hydropneumatic and oleopneumatic storage
  - Electricity storage by thermic pumping
- H_2 chemical storage
  - Alkaline electrolysis – surface gas storage – PEMFC
  - PEM electrolysis – surface gas storage – PEMFC
- Electrochemical storage
  - Lead-acid battery (Pb-A)
  - Nickel-zinc battery (Ni-Zn)
  - Lithium-Ion battery (Li-ion)
  - Zinc-air battery (Zn-Air)
  - Sodium-sulfur battery (Na-S)
  - Sodium-nickel chloride battery (ZEBRA)
- Electrochemical storage with flow
  - Zinc-Bromine flow battery (Zn-Br)
  - Vanadium redox battery (VRB)
- Electrostatic battery
  - Supercapacitor
- Inertial storage
  - Low-speed Flywheel
  - High-speed Flywheel
- Power-to-gas
  - Hydrogen production by PEM electrolysis
  - Hydrogen production by alkaline electrolysis
  - Methane production by CO_2 direct catalytic conversion

9.1. COMPARATIVE SYNTHESIS OF THE TECHNOLOGIES

The different parts of this section aim to provide comparisons of the different electricity storage technologies based on several technical and economic parameters.

9.1.1. DESIGN AND TECHNICAL PERFORMANCES

For an electricity storage technology, the capacity and efficiency to provide a specific service will depend, to a large extent, on its technical performances, namely:

- Possible discharge time, corresponding to the energy/power ratio.
- Lifetime of the system, or the amount of permissible cycles
- Response time
- Global efficiency of the electricity storage cycle (charge, discharge)
- Power range and available energy capacity, that will also have an impact on the possible positioning of this technology on the chain: transmission – distribution –

consumer, thus on the relevance of this technology for a certain operator, or another.

In a first approach, electricity storage systems are often mapped depending on their power design and their typical discharge time. These two parameters enable to compare technologies in a quite relevant manner, making a direct connection between the main characteristic of the corresponding applications. In order to move large quantities of energy on a period of several hours, it will be necessary to use massive electricity storage mediums, like PSP or CAES for example. In order to perform rapid regulation on the network, power designed systems will be preferred, like flywheels or super-capacitors. Figure 50 is showing the positioning of studied technologies on these two axis.

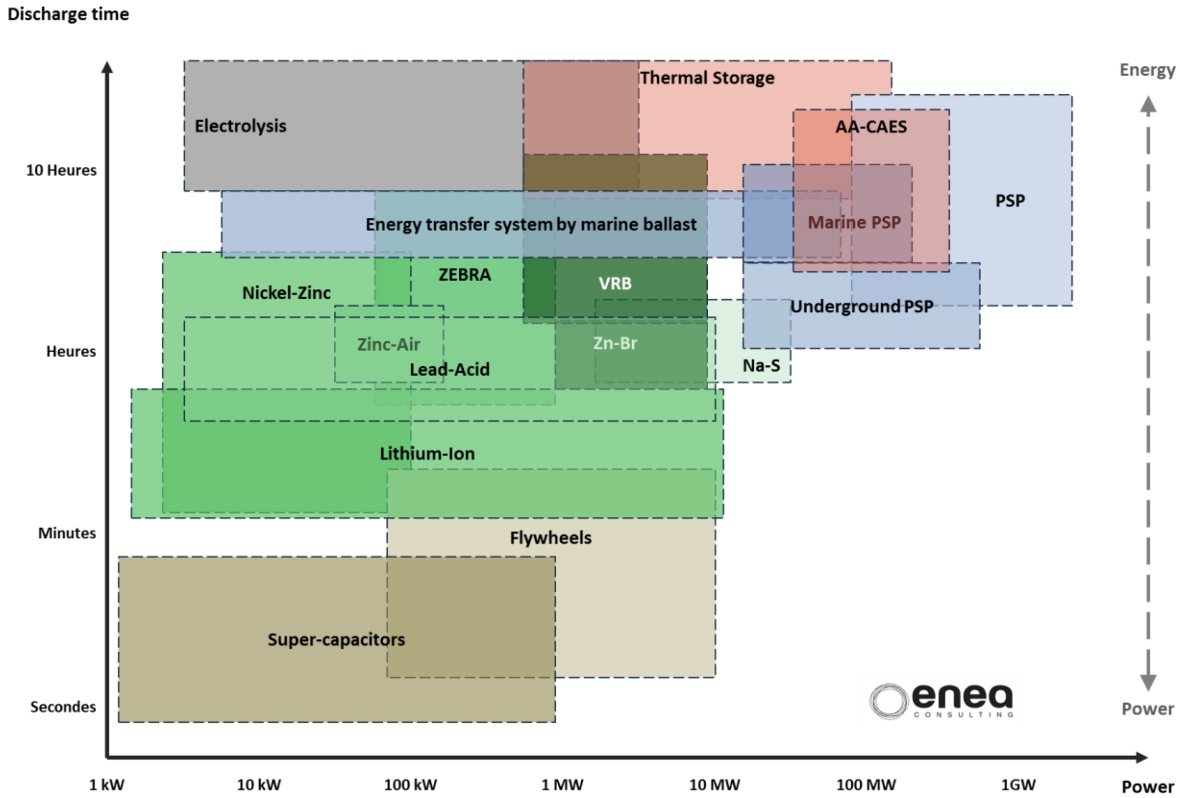


Figure 50. Positioning of the energy storage technologies depending on their discharge time and their "typical" power range

9.1.2. MATURITY LEVELS

Even though the range of technological solution is vast, only PSP reached a real market maturity at this point. PSP plants constitute more than 99% of grid connected storage power plants in the world. (cf. Figure 51)

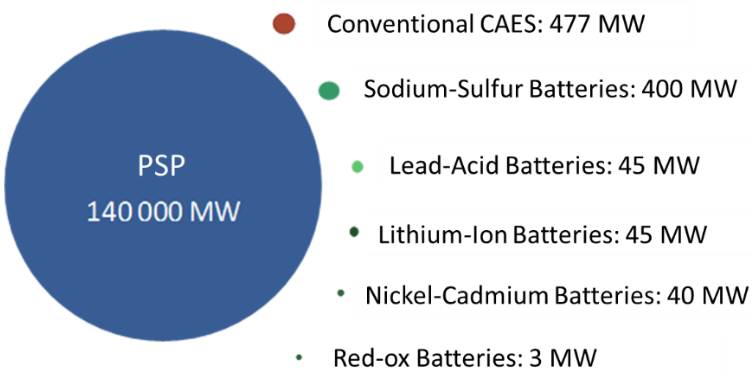


Figure 51. Grid connected installed capacity of electricity storage, in the world

Despite a still limited commercial development, several sectors reached a level of technological maturity relatively advanced. This is the case of some battery technologies proposed as turnkey solutions by several suppliers: SAFT (France) for Lithium-Ion batteries, NGK (Japan) for Sodium-Sulfur batteries and Cellstrom (Austria) for VRB flow batteries.

In anticipation of a mass market, these technologies are finding early opportunities in territories that are already sensitive with supply/demand equilibrium, or that have implemented incentive policies:

- Island territories such as Japan, Hawaii or French non-interconnected territories
- Territories having aging networks and bad interconnections (New York State in the USA for example)
- Territories having generation sites of variable renewable energy that are particularly distant from high demand sites. (Germany for example)
- Territories that implemented a favorable regulatory environment (California State in the USA for example)

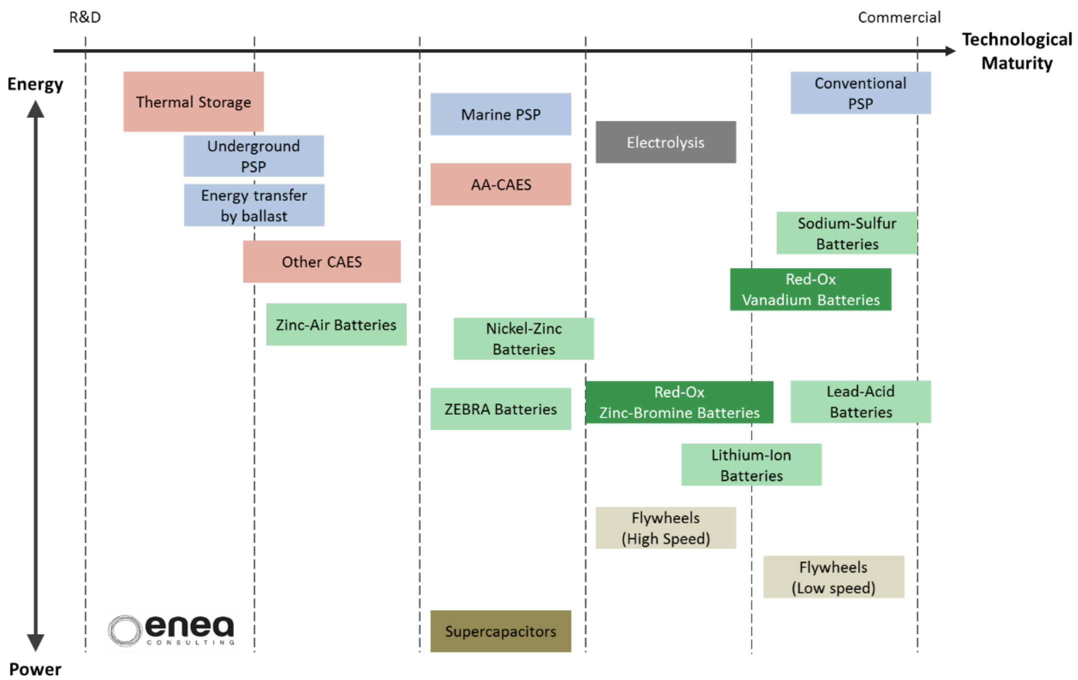


Figure 52. Technological maturity levels of electricity storage medium

Technologies that are at research and development phase are multiplying, notably pushed by new actors (start-ups, research labs spin-offs), an evidence of the dynamism of the sector. Technology developers focus on better performances (better efficiency, extended lifetime, etc.) and cost reduction.
Figure 52 summarizes the different level of technological maturity of each solution, from the status of conceptual project in research and development to the commercialization stage. The positioning of the technologies on the energy/power scale is reminded.

9.1.3. COST OF TECHNOLOGICAL SOLUTIONS

Economical comparison of energy storage technologies is a difficult exercise. Indeed, for many sectors there is few feedback thus few ways to evaluate the existing costs in an accurate way, especially operation costs. More generally, the high density of applications and technical applications often makes the only comparison of investment cost inappropriate.
A first approach consists of comparing the different systems according to their investment costs relative to energy (CAPEX in €/kWhCAP) and relative to power (CAPEX in €/kW). Figure 53 is proposing a cartography of the energy storage technologies according to these two criteria.

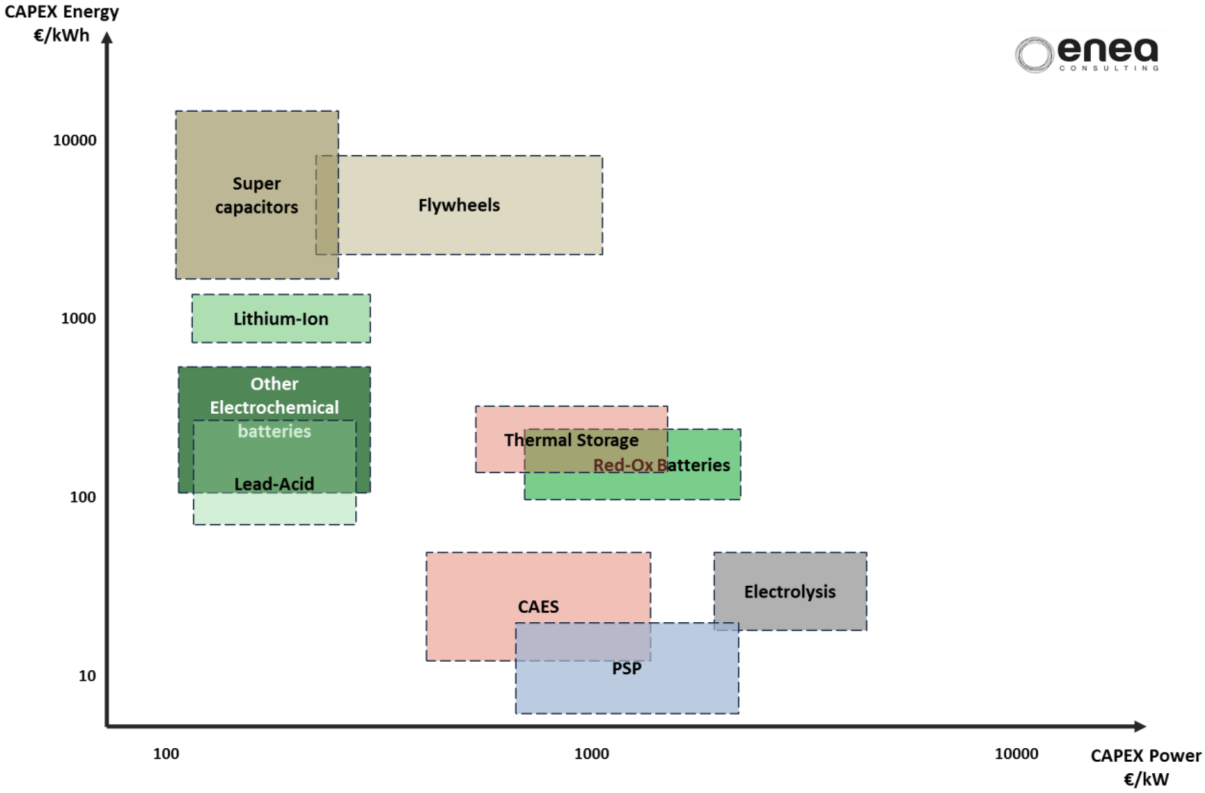


Figure 53. Positioning of energy storage technologies depending on their CAPEX in energy and power

The cost of storage should be compared to the value that it brings, as it was studied in Sections 6.4, 7.4 and 8.4 in order to draw conclusions on the profitability as such an investment.
As an example, in Figure 54 the estimated costs for battery and PSH are compared to the storage value in UK for the two studied scenarios presented in Part 1.1. No thorough cost/benefit analysis is undertaken in this study, however it is clear that PSH (and some

other gravitational-type storage) are the most adapted storage technology for a country like UK in 2030 with a major need for flexibility.

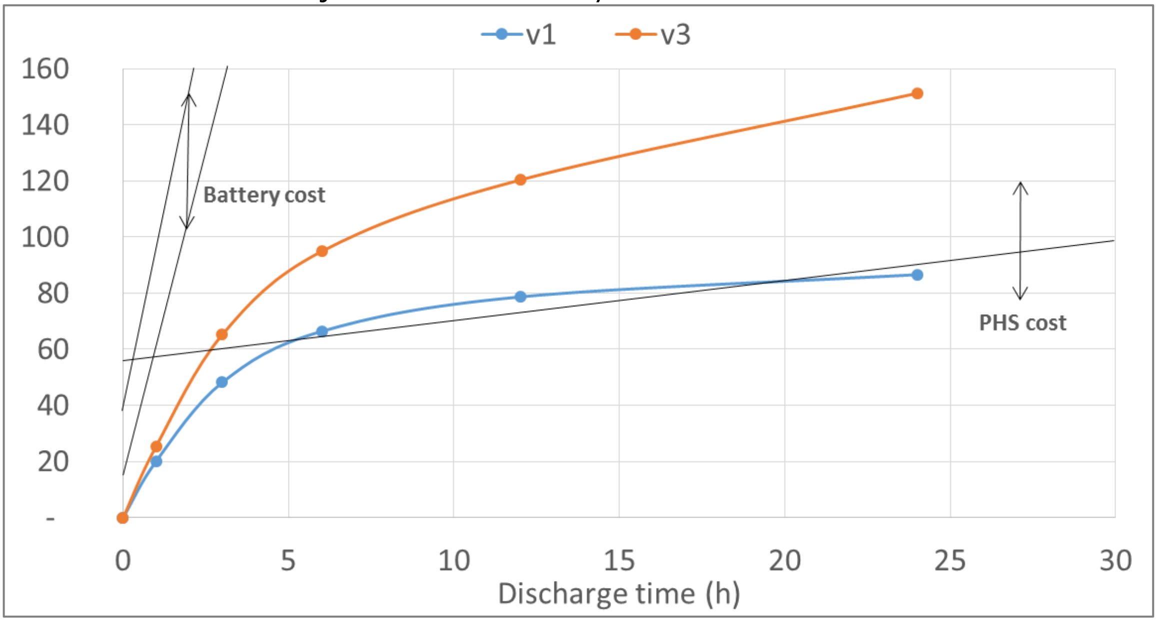
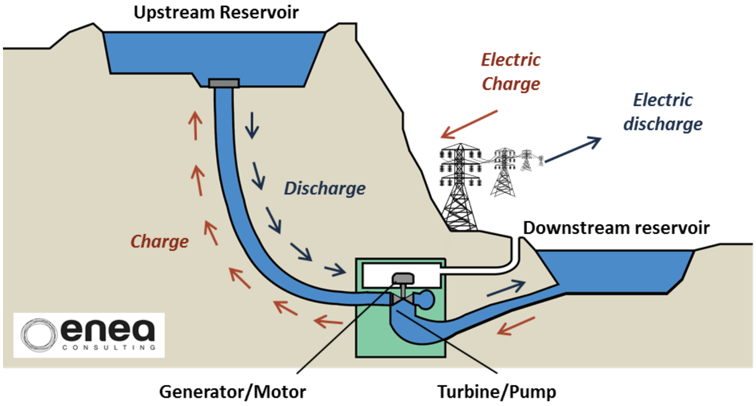


Figure 54. Comparison between storage value and storage cost for UK in 2030 (M€/MW)

9.2. STORAGE TECHNOLOGIES CHARACTERIZATION

9.2.1. GRAVITATIONAL STORAGE

Conventional land PSP (Pumped storage plant)



TECHNOLOGY DESCRIPTION

Traditional pumped storage power plants (PSP) are made of two reservoirs with different heights. Water from the downstream reservoir is pumped to the upstream reservoir (typically during periods of low demand) in order to store electricity in a gravitational way. The reverse operation, generating power by releasing water through the turbines, is carried out to generate electricity during periods of high-demand.

Turbine/generator systems are generally reversible and are used both for pumping and generating power. The most common turbine-pump systems for PSP are Francis type, mono or multi-stage. A decoupling is possible between pumping and generation power.

The pipe connecting the two reservoirs can be external or below the ground, as well as the system pump / turbine / generator. (With an substantial impact on investment costs)

New technologies of variable-speed pumps (that tend to become the norm) enabled to extend the range of use of PSPs which are not limited to binary exploitation anymore. The adjustment of charge on a larger range brings new functionalities (quick frequency response, tension and frequency adjustment during pumping and releasing, efficiency enhancement)

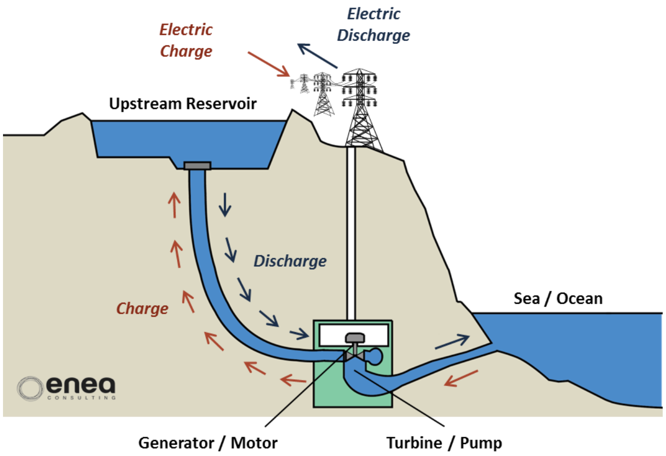
TECHNICAL ADVANTAGES

- Well-proven technology
- Good energy efficiency
- Flexibility, quick response time
- Significant lifetime
- Easy load monitoring (with variable speed systems)
- Little maintenance
- Installation on existing reservoirs: Minimization of investment

DRAWBACKS / TECHNICAL CONSTRAINTS

- Very little extra potential
- Scarcity of suitable sites (water reservoir and elevation)
- Investment costs growing with the rarefaction of suitable sites
- Difficulty of electrical connection (For new sites)
- Environmental acceptability: Physical footprint, ecosystem and hydrology alteration
- Social acceptability
- Long duration of projects development

Marine PSP



TECHNOLOGY DESCRIPTION

Based on the same principle as traditional PSP, marine PSP enables to store electricity in a gravitational manner by pumping sea water to an upper reservoir. Electricity will then be generated again by releasing the sea water through the turbines.

Eligible sites for this type of system are coastal areas with a significant elevation between the plateau and the sea level (For a given amount of energy, the height determines the volume of the upstream reservoir). As the upstream reservoir is often naturally absent, it should be created through the construction of a dike. A particular attention should be paid to avoid any sea water infiltration in the ground.

As for overland PSP, the pipe connecting the reservoir to the sea and the system pump / turbine can be external or buried. In case of a buried system, only the inferior part of the pipe will be visible.

A first specificity of the system lies in the equipment resistance to sea water. The water salinity and the presence of marine organisms induce a significant deterioration of the equipment, specifically the system pump / turbine. Furthermore, there are important risks of sea water infiltration in soils below the upper reservoir that can then affect groundwater. The sealing of the upper reservoir is thus also a key parameter.

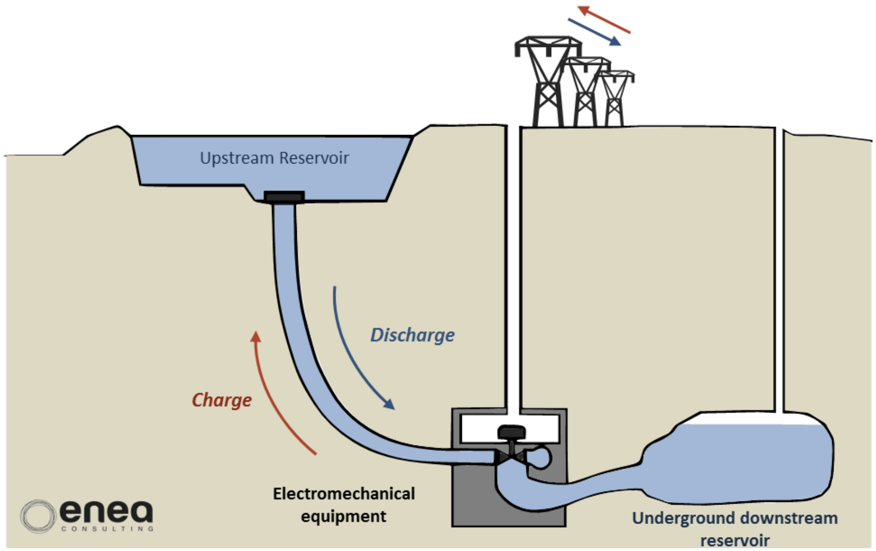
TECHNICAL ADVANTAGES

- Enables to extend the range of eligible sites for the development of PSP
- Possible proximity of sporadic energy generation sites (offshore wind, marine energy)
- Civil work less complex than conventional PSP
- Limited flooded area
- Possible positive outcome on a local level (tourism, aquaculture)

DRAWBACKS / TECHNICAL CONSTRAINTS

- Difficulty to find eligible sites
- Environmental acceptability: infiltration of sea water in the soils from the upper reservoir (as well as a surface dissemination impacting vegetation): significant need for reservoir waterproofness; physical footprint, landscape alteration; adverse effects on marine wildlife near the water outlet.
- Social acceptability
- Corrosion of turbines and other equipment (necessity to use suitable hardware)
- Adherence of marine organisms to the equipment
- High maintenance costs

Underground PSP



TECHNOLOGY DESCRIPTION

The principle is similar as the one of conventional PSP, the difference is the use of an underground cavity (artificial reservoir, geological reservoir, former mine, etc...) as a downstream reservoir. The upstream reservoir can be a basin (natural or artificial), or a watercourse, even sea water.
An air pipe makes the connection between the underground and the surface: air replaces the water that has been pumped and is expelled when the reservoir is filled during the electricity generation.
The system pump / turbine / generator is situated underground.

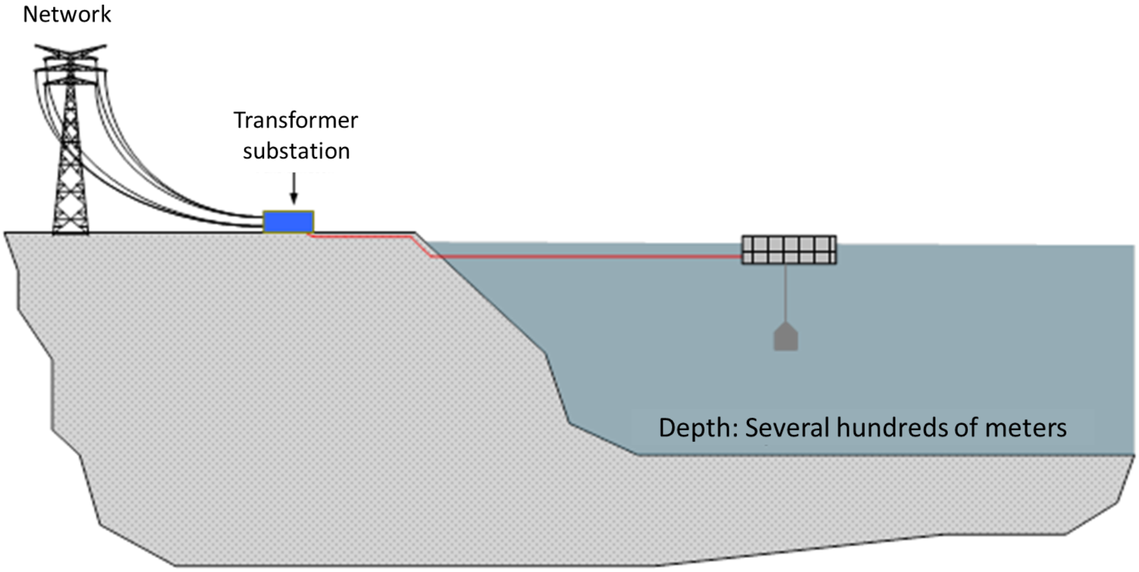
TECHNICAL ADVANTAGES

- Physical footprint reduced (underground)
- Enables to emancipate from the need of elevation / dam
- Good efficiency
- Flexible, quick response time
- Significant lifetime
- Easy load monitoring
- Little need of maintenance

DRAWBACKS / TECHNICAL CONSTRAINTS

- Few feedback
- High investment costs
  Lower efficiency compared to conventional PSP
- Need to find a suitable site (geological cavity), or/and to dig the ground/rock
- Diverse geotechnical issues:
  - Rocky mass permeability
  - Water contamination (minerals)

Energy transfer system by marine ballast



Source SOPER

TECHNOLOGY DESCRIPTION

A ballast is attached to a floating platform, with a cable.
To store energy, the ballast is brought to the surface, driven by an electric motor. To unload the energy, the ballast goes down while driving a generator.

TECHNICAL ADVANTAGES

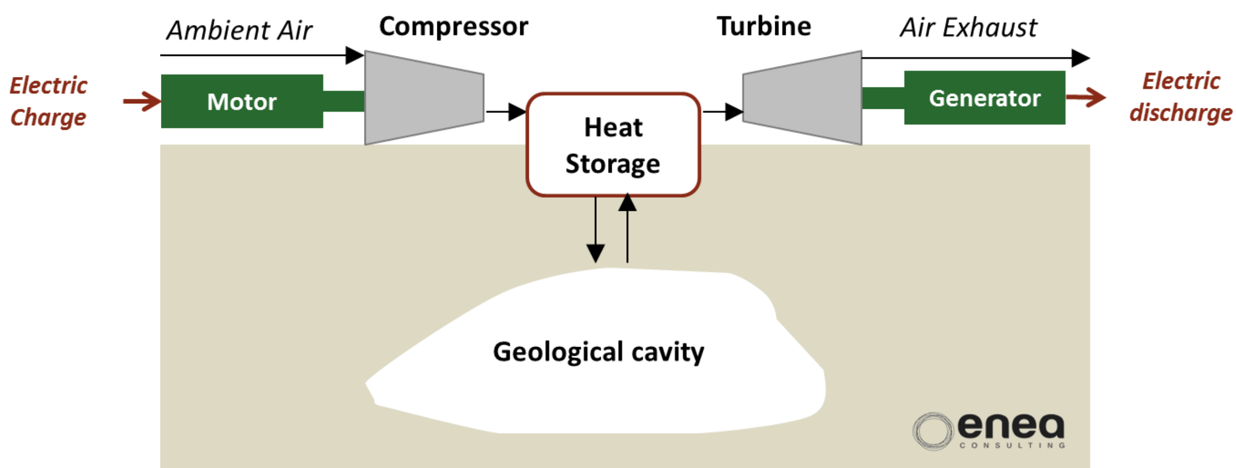
- Limited environmental footprint and social acceptation risks
- Good efficiency
- Flexible technology
- Technology based on well-proven offshore components
- No self-discharge

DRAWBACKS / TECHNICAL CONSTRAINTS

- Site constraint due to the sea depth
- Installation in deep sea
- Transmission costs

9.2.2. THERMODYNAMIC STORAGE

Underground adiabatic isochoric CAES



TECHNOLOGY DESCRIPTION

Underground adiabatic isochoric Compressed Air Energy Storage (CAES) technology, often designated with the abbreviation A-CAES or AA-CAES (Advanced Adiabatic Compressed Air Energy Storage) has the same basic principle as conventional CAES while limiting thermic losses, therefore without the need of fossil fuel.

In order to make the system adiabatic, the heat unloaded during air compression (electric load) is recovered and preserved in a thermic energy storage unit. The compressed air is stored in a geological cavity. During the unloading process, the stored heat is restored to the compressed air before expansion and electricity generation via the turbine / generator system. All this without the need of injecting gas (or any other fossil fuel) in the process. The overall efficiency is therefore significantly increased compared to conventional CAES.

The AA-CAES is a complex technology, especially for the preservation of the adiabatic-ness. The efficiency highly depends on the quality of the equipment, notably in term of temperature and pressure losses along the process.

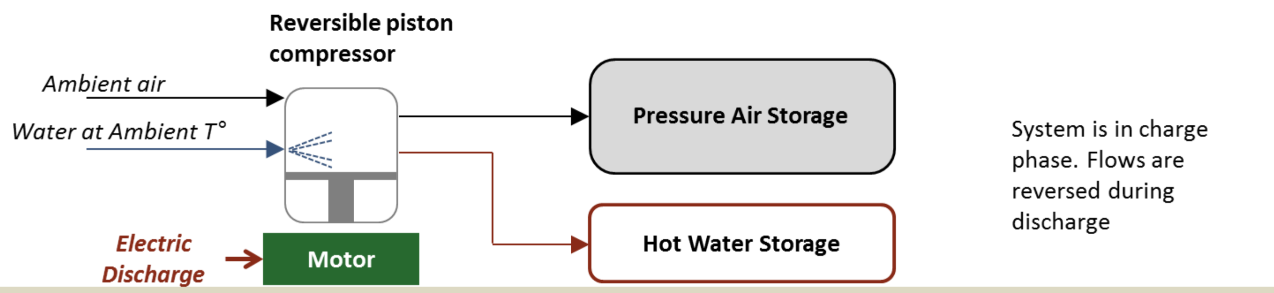
TECHNICAL ADVANTAGES

- Increased efficiency compared to conventional CAES
- No need of fossil fuel, no emission compared to conventional CAES
- Important quantity of storable energy
- Quick response time
- Possible long period electricity storage
- Significant lifetime

DRAWBACKS / TECHNICAL CONSTRAINTS

- Need to find suitable geological sites
- Technical complexity due to possible high pressure and temperature imposed on rotating machines and heat storage
- Operation complexity for heat sensible configurations
- Controllable power ranges more limited than for conventional CAES
- Efficiency depends highly on the heat storage technology
- Heat losses is a function of storage time
- No feedback yet

Surface isothermal CAES



TECHNOLOGY DESCRIPTION

This CAES technology is based on a compression and isothermal expansion of the air. During the charge, a heat-transfer fluid, generally water, is injected in the compressor and enables to recover compression heat so that the air is kept to a constant temperature.
The compression of the air-water mix is thus diphasic, which involves the use of technologies alternative to the traditional compressor/turbine couple (piston engine for instance). Several configurations exist for compressed air and water storage. They can be stored separately, with water storage as heat storage (LightSail Energy technology), or together. The water generally flows in a closed-circuit loop, limiting the need for supply. The storage is generally situated on surface, at a pressure around 200 bars, for example in pipe sections.
During the unload process, the expansion is performed with the same equipment as for the compression, operating in a reversible manner. Water is injected again in the system during the expansion, in order to restore the stored heat to the air.

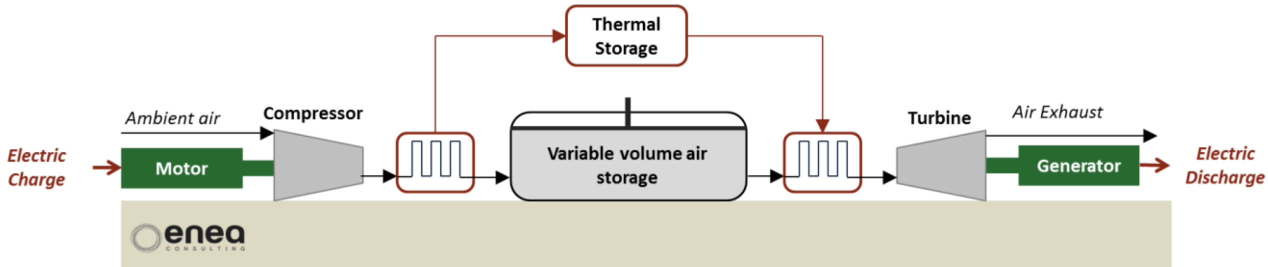
TECHNICAL ADVANTAGES

- Dissociated power and storage capacity – large range of capacity
- Modular
- Good lifetime
- Higher efficiency than conventional CAES

DRAWBACKS / TECHNICAL CONSTRAINTS

- Safety (High pressure equipment)
- Corrosion / Risk of frost
- Still high investment costs
- No feedback
- Self-discharge due to heat losses

Surface adiabatic isobaric CAES



TECHNOLOGY DESCRIPTION

Surface adiabatic isobaric CAES technology has the same basic principle as conventional CAES without the storage cavity: the air is stored at high pressure in surface tanks with constant pressure

In order to make the system adiabatic, the heat released during air compression (storage phase) is recovered to be stored then restored during expansion (unloading phase). Different heat storage systems can be considered.

The isobaric storage enables the operation of compressors and turbines at a fixed compression rate.

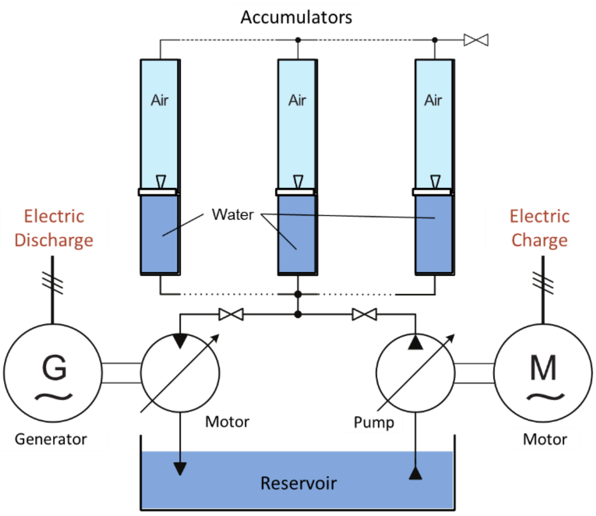
TECHNICAL ADVANTAGES

- Easy to implement (No site constraint, no geological constraint)
- Short development and installation time
- Higher efficiency than conventional CAES
- No need of fossil fuel, no emission compared to conventional CAES
- Possibility of recovering available low temperature heat energy, not used otherwise
- Very modular storable energy quantity
- High flexibility and possibility of instantaneous power variation
- Good lifetime

DRAWBACKS / TECHNICAL CONSTRAINTS

- Few feedback
- Relatively long cold-start
- Medium efficiency
- Storage cost in energy higher than conventional CAES, which doesn’t include heat storage

Hydropneumatic and oleopneumatic storage



Source Enairys Powertech

TECHNOLOGY DESCRIPTION

Hydropneumatic storage (respectively oleopneumatic) is an energy storage technology using compressed air that has the specificity of using water (respectively oil) as an intermediary fluid for compressing and expanding air.
The usage of the intermediary fluid enables to limit the temperature increase of air during compression, thus to operate closer to the isotherm. In some configurations, the intermediary liquid is directly in contact with the air, which improves heat exchanges and the isothermality of the process.
Hydraulic pumps, connected to the motor (for the electric charge) and to the generator (electric discharge) enable to compress and expand the air. The technology manufacturers usually use pistons motor pumps that provide both compression and expansion of the intermediary liquid, in a reversible manner, and enable to reach pressures of more than 200 bars. The pressure of the liquid is then transfer to the air via a hydropneumatic conversion. An air/liquid separator can be required before the compressed air storage in a way that the intermediary fluid is in contact with the air.
The systems that have been studied provide the storage of air in surface storage units (high pressure cylinders; there is not yet a discussion about geological storage)

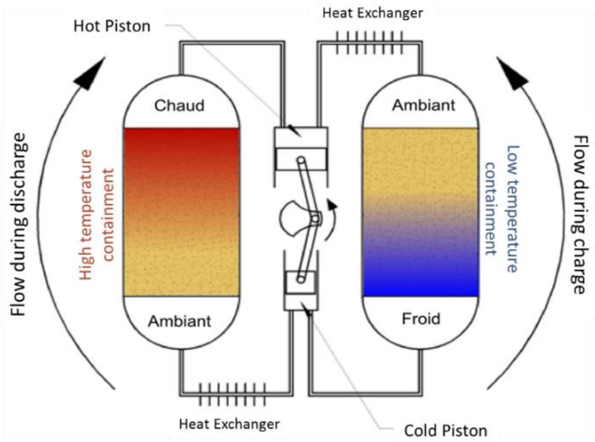
TECHNICAL ADVANTAGES

- Modular
- No self-discharge
- Good lifetime
- Easy knowledge of the load state (pressure)
- High reactivity of the hydraulic system

DRAWBACKS / TECHNICAL CONSTRAINTS

- Safety (High pressure tanks)
- Corrosion / Risk of frost
- Low efficiency
- No feedback yet

Electricity storage by thermal pumping



Adapted from Isentropic Ltd

TECHNOLOGY DESCRIPTION

Electricity storage is here achieved with two containments of refractory materials, respectively at high (between 500°C and 800°C, depending on the technology) and low temperature (between -160°C and -80°C depending on the technology), that serve as warm source and cold source to a thermodynamic cycle. The energy storage is achieved in the form of sensible heat, exploiting temperature variations inside the material.

During the charge, the circuit works as a heat pump: a heat transfer fluid (a neutral gas like argon) is put in motion through a compressor or a piston (powered with electricity) and enables to pump the heat from the low temperature containment to the high temperature one, via a compression/expansion cycle). During the discharge, this heat is released and the circuit works as a thermal machine. The heat transfer fluid drives the turbine or the piston, connected to a generator that produces electricity.

The refractory materials considered for thermal storage are gravel or ceramics (more expansive but less cumbersome than gravel)

Configuration of turbo-motors can differ among technologies. In some cases, a unique reversible circuit is used both for charge and discharge of the storage system (Isentropic Ltd process). In other configurations, two circuits are used, one for the charge and the other for the discharge (project SETHER process)

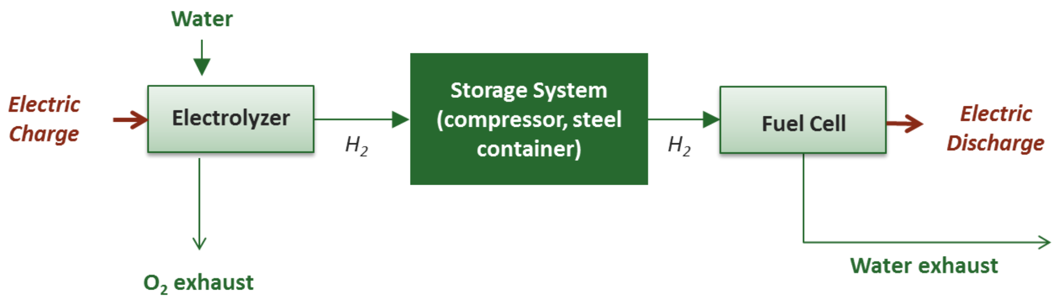
TECHNICAL ADVANTAGES

- Good energy density: low physical footprint
- Good efficiency
- No localization constraint
- Low environmental impact
- High quantity energy storage

DRAWBACKS / TECHNICAL CONSTRAINTS

- No turbo-motor available at the moment (because of high temperatures, frequent stop and start): necessity of developing specific rotating machines.
- No feedback
- Resistance to an important number of thermic cycles from refractory materials
- Very narrow range of operation for processes involving compressors (SETHER project) due to the necessity of maintaining fixed compression ratios (for maintaining storage temperature)
- Ineffective for small systems due to bigger thermal losses

Electrolysis - H_2 Storage – Fuel Cell



TECHNOLOGY DESCRIPTION

Storing electricity in the form of hydrogen lies on the reversibility of the chemical reaction linking water, oxygen and hydrogen.
During the charge, electric energy enables to dissociate oxygen and hydrogen from water, via an electrolyzer. The hydrogen is used as an energy storage vector and can be stored in a gaseous form in surface for example.
During the discharge, the hydrogen is supplying a fuel cell (FC) that is generating electricity. Different technologies of fuel cells are commercially available. Fuel cells with proton exchange membrane (PEMFC) are considered here.

TECHNICAL ADVANTAGES

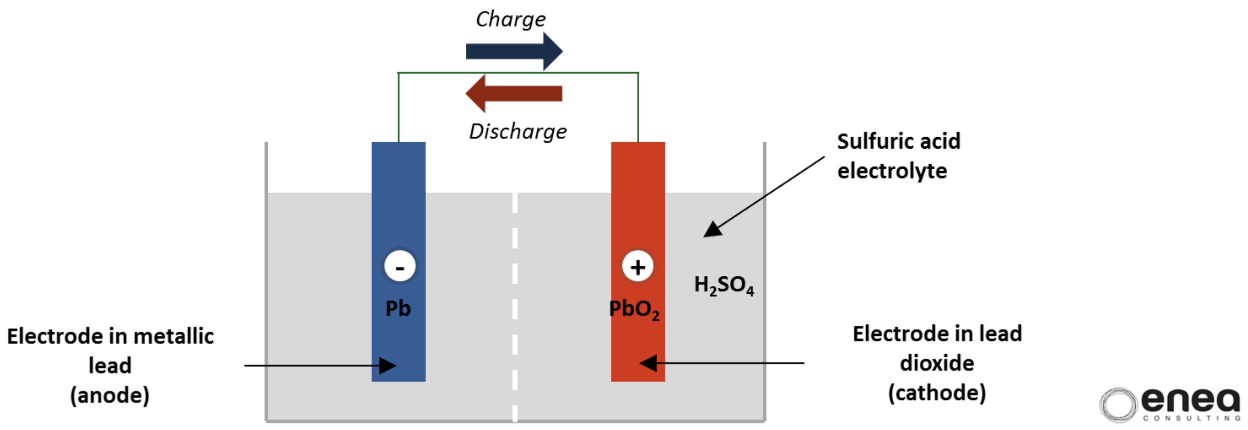
- High energy density (100 times higher than compressed air)
- Technologies (electrolysis, H_2 storage and FC) relatively mature
- Modularity: power and energy characteristics are independent (design of the electrolyzer insensitive to the fuel cell or the storage characteristics)
- Large depth of discharge

DRAWBACKS / TECHNICAL CONSTRAINTS

- Low efficiency compared to the other technologies
- High initial investment costs
- Safety and social acceptance of hydrogen
- Seveso classified

9.2.3. ELECTROCHEMICAL STORAGE

Lead-acid battery (Pb-A)



TECHNOLOGY DESCRIPTION

Lead-acid systems, the oldest and most mature battery technology, ensure an electrochemical storage via accumulators consisting of a sulfuric acid electrolyte and lead electrodes.

Although this technology is well-proven and commercially available for decades, its performances are still limited, especially in term of lifetime. Lead-acid batteries are also sensible to the discharge depth (compared to other electrochemical systems)

In order to improve the lifetime and consider new applications, new "advanced" lead-acid battery technologies are studied, with the use of electrodes made of a combination of carbon and lead for example

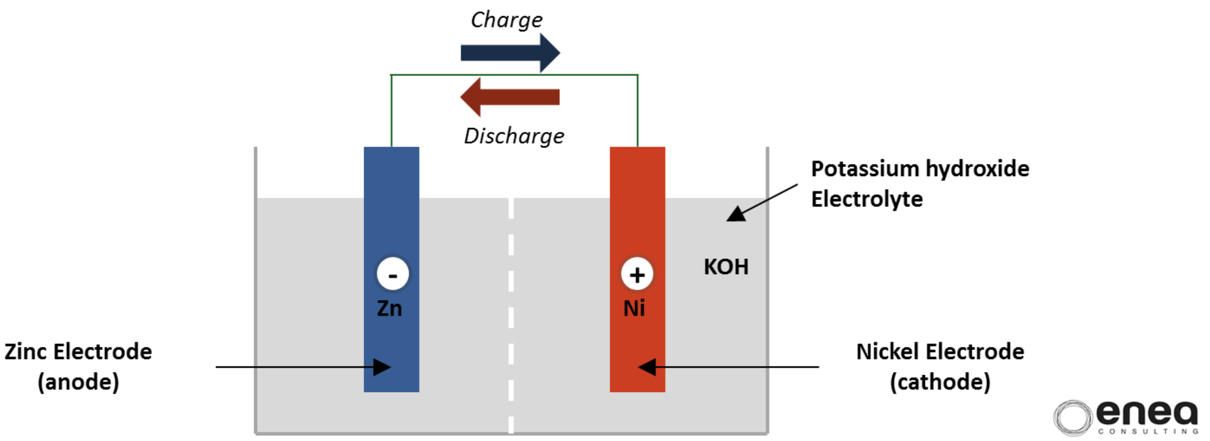
TECHNICAL ADVANTAGES

- Well-proven and mature technology (most widely used battery technology in the world)
- Safe technology
- Large capacity available
- Low self-discharge
- Electrochemical system with the lowest investment costs
- Recyclable materials (close to 100% for lead)

DRAWBACKS / TECHNICAL CONSTRAINTS

- Lifetime depends on the conditions of use
- Bad cycling capacity with a high discharge depth for "classic" technologies
- Acceptable discharge depths but depends on the battery type
- Low energy density
- Difficult awareness of the state of charge
- Toxic materials (lead)
- ICPE classified (France)

Nickel-zinc battery (Ni-Zn)



TECHNOLOGY DESCRIPTION

Nickel-Zinc battery is an electrochemical accumulator composed of a nickel cathode, a zinc anode and an alkaline electrolyte. The potential difference at the terminals of the open circuit is about 1.65V at full charge. The technology is quite old and used for portable applications (AA and AAA batteries) but it has a limited cycling capacity (typically < 200 cycles)
During the discharge, zinc is oxidized to zinc oxide $Zn(OH)_2$ nonconductive and potassium zincate K_2ZnO_2 soluble in the electrolyte. Inversely, during the charge, these oxidation products are reduced to metal zinc.
During the charge, metal zinc is recovered in an irregular manner on the electrode and generates random growing (called "dentrites") that can lead to a short circuit of the battery. The last models use an electrolyte made of polymers in order to limit the development of these "dentrites". Current research deals in priority with systems cycling capacity.

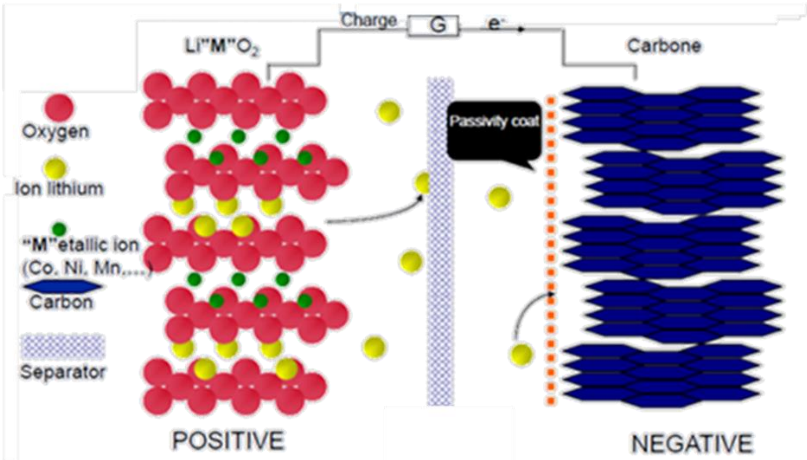
TECHNICAL ADVANTAGES

- Nominal tension higher than other similar technologies (30% higher than NICd and NIMH)
- Highly recyclable systems (>90%)
- Cost of zinc is low
- Possible high discharge depth
- Low temperature sensitivity (low impact of temperature on lifetime)
- Technology adapted to quick charges
- Safety
- Low need for battery management (compared to LI-ion technologies for example)
- Low need for maintenance
- High robustness (included in surcharge and sur-discharge)

DRAWBACKS / TECHNICAL CONSTRAINTS

- Low cycling capacity for some types of Ni-Zn batteries
- Nickel cost
- Stationary systems not mature enough

Lithium-Ion battery (Li-ion)



Source SAFT

TECHNOLOGY DESCRIPTION

Current Lithium-Ion batteries are electrochemical accumulators composed of a cathode made of lithium metallic oxide, a cathode made of graphite and an electrolyte made of lithium salt dissolved in organic carbonates (ionic solution). During the charge, lithium ions migrate through the electrolyte, from the cathode to the anode. By combining with external electrons, ions become lithium atoms that deposit between the graphite layers. The process is inverse during the discharge.
Lithium-Ion accumlators can handle large discharge depths with a limited impact on their lifetime Unless otherwise stated, the elements listed below describe LFP/C technology: cathode in lithium ferrophosphate and anode in graphite. This choice originates in the inherent characteristics of the technology (relatively low cost, cycling capacity and high lifetime). The other cathode options are less likeley to meet with the issues of energy storage. About the anode, two other materials can be used: titanium (LTO) or silicium.

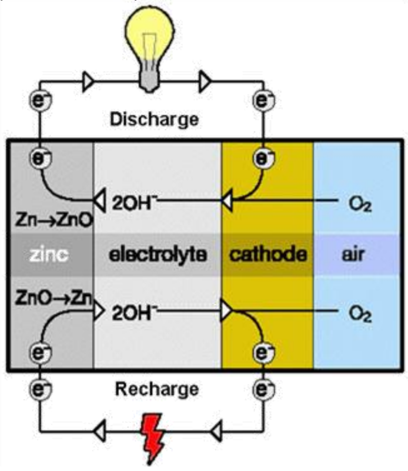
TECHNICAL ADVANTAGES

- Good discharge depth without affecting lifetime significantly
- Excellent efficiency
- High energy and power density
- Long lifetime
- Low self-discharge
- Adaptable to multiple applications

DRAWBACKS / TECHNICAL CONSTRAINTS

- High costs (but going down)
- Safety problems for some chemical contents
- Need of thermal regulation
- Need of individual monitoring and balancing of cell charges
- Issues about lithium resources (producers cartel, geographic concentration, geopolitical context, cost of alternative generation methods)

Zinc-air battery (Zn-Air)



Source EVionyx

TECHNOLOGY DESCRIPTION

In zinc-air batteries, the anode is made from zinc, a metal with a high energy density (other metals such as aluminium, lithium, calcium, magnesium or iron can also be used for metal-air type batteries). The cathode, or "air electrode", is often made of a porous carbone structure or mettalic meshes covered usinig catalisys. Oxygen from the air is the only chemical reagent of the cathode. The electrolyte is a good OH^- ion conductor, such as potassium hydroxyde. It can be in a liquid form or made of a solid polymer membrane saturated with KOH.
Thanks to their high energy density these batteries are very compact, however they are currently difficult to recharge electrically and have a low efficiency. Most common solutions consist in replacing mecanically the metal that has been consumed. New electrically rechargeable metal-air batteries are being developed though can only be used on a few hunderds cycles, with an efficiency of about 50%.

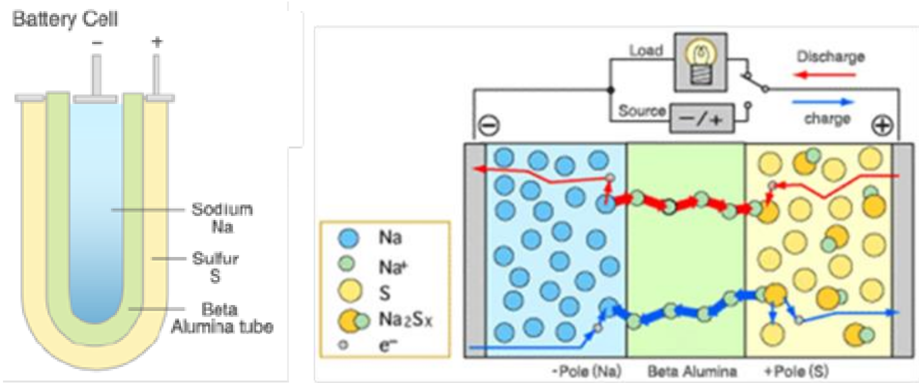
TECHNICAL ADVANTAGES

- High energy density
- Almost no self-discharge
- Low investment costs compared to other batteries
- No toxic components
- No need to replace the components regularly (membrane, cells...)

DRAWBACKS / TECHNICAL CONSTRAINTS

- Currently difficult to recharge electrically: low efficiency and bad cycling capacity for existing systems
- Issues from carbonation with wet air
- Not mature technology

Sodium-sulfur battery (Na-S)



Source A. Nekrassov

TECHNOLOGY DESCRIPTION

Na-S batteries are made of a positive electrode in sulfur and a negative electrode in sodium, both being above their fusion temperature, thus in a liquid form. The electrolyte, used to isolate the two electrodes, is a solid ceramic made of an aluminium derivative (β-alumine). The global structure of each cell is generally done as cylindric layers.
During discharge, sodium ions produced from sodium ($Na = Na^{+} + e^{-}$) migrate through the elctrolyte to the sulfur to form sodium polysulfide. The electrons move though the external circuit to the battery and generate an electric current. During discharge, the process is inversed.
In order to keep the electrodes in a liquid form, the Na-S batteries should be maintained at a temperature higher than 300°C, hence the necessity of an independent heating system for the startup of the battery and the conservation of the heat during inactive periods. This implies a significant energy consumption (up to 20% of the nominal capacity per day) for maintaining the temperature when in ilotage. However, during charge or discharge, the activity of the battery enables to self-sustain the temperature of the system.

TECHNICAL ADVANTAGES

- Good efficiency
- Mature technology
- Low need of maintenance
- Important discharge depth
- Good cycling capacity
- High energy density
- Relatively low investment costs
- Low physical footprint
- Easy awareness of the charge / discharge level

DRAWBACKS / TECHNICAL CONSTRAINTS

- Necessity of maintaining at high temperature (>300°C), consumption of auxiliary equipment
- High self-consumption during inactivity periods (up to 20% of nominal capacity per day)
- High response time at cold-start
- No flexibility of the ratio Energy/Power
- Explosion risk (21st September 2001 incident)
- ICPE classified (France)

Sodium-Nickel-Chloride Battery (ZEBRA)

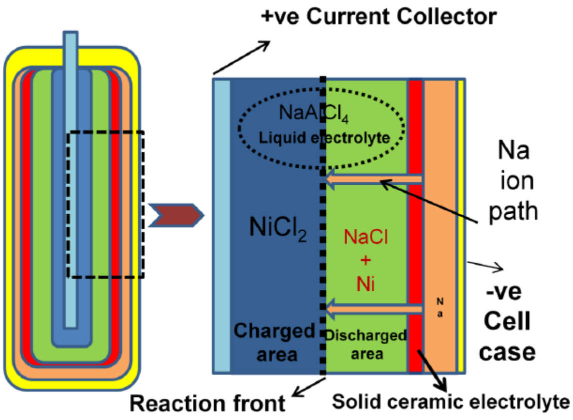


Schéma d'une batterie ZEBRA lors de la décharge

TECHNOLOGY DESCRIPTION

Na-$NiCl_2$ batteries, most commonly called ZEBRA batteries (Zeolite Battery Research Africa Project or Zero Emission Battery Research Activity) are made of a cathode in nickel chlroride ($NiCl_2$) and an anode in sodium. These electrodes are divided by a ceramic membrane of β-alumine enabling the exchange of ions Na^+ (The same membrane as for NaS batteries).
During discharge, sodium ions derived from the liquid sodium ($Na = Na^+ + e^-$) migrate through the membrane towards the cathode to form nickel and sodium chloride ($NiCl_2 + 2Na^+ + 2e^- = Ni + 2NaCl$). During the charge, the reaction is reversed. ZEBRA batteries have a significant resistance to large discharge depth. The porous « cathodique » material is immerged in a liquid electrolyte ($NaAlCl_4$) that ensures the transit of Na^+ ions. In case of membrane rupture, this electrolyte cause the appartition of solid aluminium that leads to a short-circuit of the cell. The battery can therefore continue to operate with the loss of the nominal tension of the corresponding cell (out of a total that can reach several hundreds of cells per module)
As for the NaS battery, a high temperature (around 300°C) is necessary to maintain the electrolyte $NaAlCl_4$ in a liquid state, and ensure a good ionique conductivity of β-alumine. One of the limiting characteristics of ZEBRA batteries is their large consumption (up to 20% of nominal capacity per day) in order to maintain the battery temperature during inactivity periods (ilotage)

TECHNICAL ADVANTAGES

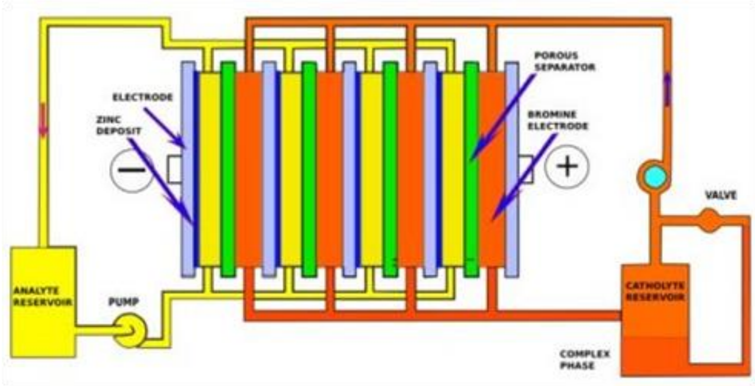
- Good efficiency
- High discharge depth
- Intern auto-protection system in case of membrane rupture
- High theoretical energy density (790 Wh/kg)
- Long lifetime
- Easy to recycle
- Easy awareness of the charge/discharge level
- Low need of maintenance

DRAWBACKS / TECHNICAL CONSTRAINTS

- Operating at high temperature (250 – 350°C)
- Necessity of maintaining at high temperature during inactivity period, leading to a consumption of 10 to 20% of nominal capacity per day
- High response time at cold-start
- No flexibility of the ratio Energy/Power
- ICPE classified (France)

9.2.4. FLOW BATTERIES

Zinc-Bromine flow battery (Zn-Br)



Source ESA

TECHNOLOGY DESCRIPTION

Zn-Br technology is part of the Redox batteries family (or flow based), which have the distinguishing feature of storing energy in two electrolytes (here Zn^{+} and Br^{-}), contained in distinct tanks. The electrochemical reactions of charge and discharge occur in a set of similar cells. In each cell, the two electrolytes flow in two chambers divided by a porous membrane and surrounded by two electrodes in a carbon-plastic composite material. During the charge, a zinc coating is forming on the negative electrode. During this same phase, bromine is converted in bromide (Br^{-}) on the positive electrode, then stored in the electrolyte tank. The inverse operation occurs during discharge. Two hydraulic pumps ensure the electrolyte circulation.
One advantage of this technology lies in the fact that electrodes do not intervene as such in the chemical reactions. The results is a limited deterioration of the equipment. Therefore, Zn-Br batteries can endure a frequent cycling with large discharge depths, without impacting significantly the lifetime of the system.
Furthermore, a characteristic of redox batteries is to be able to dissociate energy capacity, related to the quantity in electrolyte, and the power capacity, related to the exchange active surface of the cells. This modularity is however limited in the case of Zn-Br technology, as a result of the accumulation of zinc on the negative electrode during the charge.

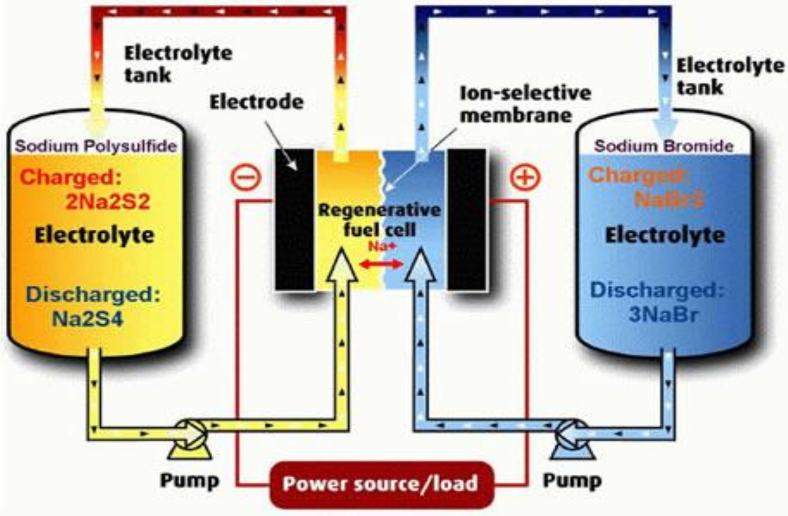
TECHNICAL ADVANTAGES

- Relatively low investment costs for energy
- Relatively mature technology
- Low self-discharge
- Handle very well deep discharges
- Modular technology (vast application range for power)
- Inexpensive materials (zinc and plastic)

DRAWBACKS / TECHNICAL CONSTRAINTS

- Low energy density
- Medium efficiency
- Complex architecture (pumps, piping, control systems, etc..)
- Energy consumption inherent to auxiliary equipment (especially the pumps)
- Important physical footprint
- Discharge time limited by zinc coating on the negative electrode
- Complete discharge needs every 5-10 cycles to enable an homogeneous zinc coating on the negative electrode during charge, then maintaining system efficiency
- Hazardousness of bromine

Vanadium redox battery (VRB)



Source EDF

TECHNOLOGY DESCRIPTION

In Red-Ox VRB batteries (a flow based type of battery), the energy is stored in ionic solutions (electrolytes) associating Vanadium in different forms (4 different oxydation states) and a diluated solution of sulfuric acid. Each electrolyte (positive and negative) is stored in a distinct tank and is sent, through pumps, to the cells where the redox reactions occur (exchange of hydrogen ions). The cells divided in two separate chambers by a porous polymer membrane (permeable to H^+ ions), surrounded by the two electrodes. During charge and discharge, the electrolytes are successively oxydized and reduced, creating differences of potential between the two electrodes and enabling to accumulate and restore electric energy.
As for all the flow-based battery technologies, VRB systems have the advantage of being able to dissociate their energy capacities (only limited by the volume of stored electrolyte) and power capacities (relative to the exchange surface of the cells). The VRBs also have a major advantage: the usage of one and only electroactive element, Vanadium, enables to emancipate from the risk of contamination by electrolyte diffusion (reducing the sensibility of the system to fatigue). The cycling ability of VRBs is therefore very high, with high supported discharge depths.

TECHNICAL ADVANTAGES

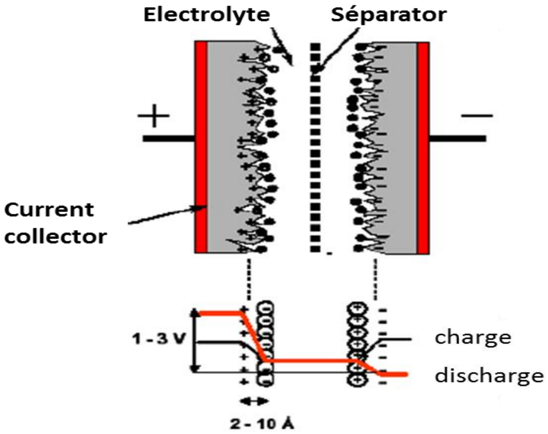
- Dissociation between power and energy, high flexibility for discharge time
- Unique electroactive element: no risqué of contamination by diffusion
- Good cycling ability and long lifetime
- High efficiency
- Very good reactivity
- Very low self-discharge
- Good handling of deep discharges
- Modular technology (large range of applications)
- Low need of maintenance

DRAWBACKS / TECHNICAL CONSTRAINTS

- Low energy density (Weakest of all redox technologies)
- Requires a high number of cells for a given power of the storage system
- Technology not adapted to small scale storage (complex design)
- High cost of the electrolytes (Growing storage capacity strongly affects investment costs)

9.2.5. ELECTROSTATIC STORAGE

Supercapacitor



TECHNOLOGY DESCRIPTION

Elaborated on the basic principle of capacitors, supercapacitors store the energy in the form of an electric field created between two electrodes, with the difference of achieving energy and power densities far more important, close to those of batteries, as well as having a very short recharge time. (Static charge, no chemical reaction)
A significant part of commercialized supercapacitors is made following a model of double electrochemical layer: an ionic electrolyte is placed between two electrodes with a large exchange surface (this characteristic enables to reach very high capacities). The electric energy that is stored enables to split the charges that accumulate at the interface between the electrode and the electrolyte, creating a difference of potential between the two electrodes. The use of this difference of potential in the external circuit enables to recover energy in the form of electric discharge, without any constraint on the discharge depth.
The quantity of stored energy depends on the size, the distance and the materials used for the conception of the electrodes and is one of the main limit for the large scale use of supercapacitors.
Unlike for batteries whose charge and discharge speed is limited by the use of liquid electrolyte, In the case of supercapacitor, this speed is only limited by the temperature increase at the electrodes.

TECHNICAL ADVANTAGES

- Excellent reactivity
- High specific power (>10kW/kg)
- High efficiency
- Easy charge monitoring (charge state available via tension measuring)
- Can be charged with variable power
- No influence of discharge depth on lifetime
- Long lifetime (high cycling capacity) compared to electrochemical batteries
- Works under a large range of temperatures
- Modular system (serial association)
- Low need of maintenance
- No use of pollutants (carbon, aluminum)

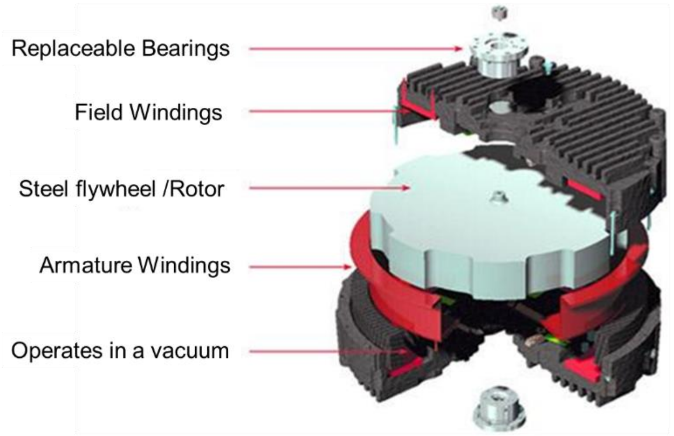
DRAWBACKS / TECHNICAL CONSTRAINTS

- Low specific energy (low discharge time)
- High cost for installed kWh
- High self-discharge (totally discharge in 24-48h)
- High voltage drop in discharge phase
- Safety problems (potentially inflammable)
- Voltage variation increases with installed capacity

9.2.6. INERTIAL STORAGE

Low speed flywheel

Source Active Power



TECHNOLOGY DESCRIPTION

Low speed flywheel is an electricity storage system in the form of kinetic energy. The energy is stored via a disk or a rotor, rotating on its axis in an environment aiming to minimize the friction: vacuum chamber and the use of bearings, generally magnetic, for the connection between the rotor and the stator. The coupling of the rotating mass to a system generator/alternator enables to store and produce electricity. The interface of power transmission also includes a variable speed electronic converter and a controller.

The high modularity of flywheels enables to design storage systems in a large range of power.

The low speed systems are the most mature flywheel technology. They are generally built in solid steel and are characterized by rotational speeds below 10 000 rpm due to the limits of the steel rotor in term of mechanical constraints.

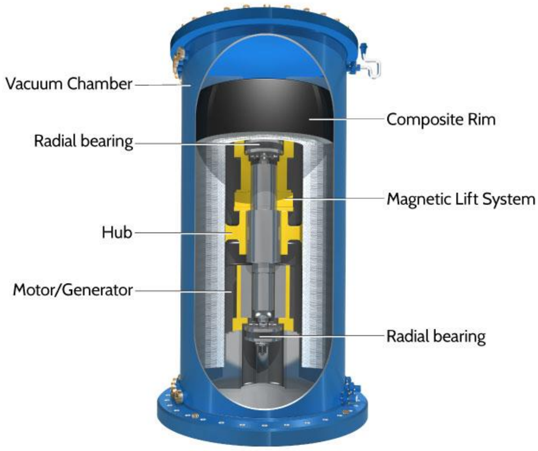
TECHNICAL ADVANTAGES

- Excellent response time
- Long lifetime
- High efficiency
- Easy awareness of the charge level
- High power modularity
- Low need of maintenance
- Possible recycling at the end of life

DRAWBACKS / TECHNICAL CONSTRAINTS

- Complex conception: magnetic bearings, vacuum
- Few available energy
- Very high self-discharge due to different losses (mechanic, magnetic..)
- High investment cost
- Potential safety issues (high speed rotating mass)
- Noise

High speed Flywheel



Source BeaconPower

TECHNOLOGY DESCRIPTION

High speed flywheel is an electricity storage system in the form of kinetic energy. The energy is stored via a disk or a rotor, rotating on its axis in an environment aiming to minimize the friction. Vacuum chamber and use of bearings, generally magnetic, for the connection between the rotor and the stator. The coupling of the rotating mass to a system generator/alternator enables to store and produce electricity. The interface of power transmission also includes a variable speed electronic converter and a controller.

The high modularity of flywheels enables to design storage systems in a large range of power. This technology is also characterized by a stored energy (related to the mass and rotating speed of the rotor) independent from the power. This modularity energy/power is however limited by mechanical constraints.

High speed systems are the most recent flywheel technologies. They are generally made of composite materials (carbon fiber and fiberglass mainly) to resist to constraints resulting from very high rotational speeds. The high speed systems are characterized by rotational speed higher than 10 000 rpm (generally several tens of thousands of rounds per minutes)

TECHNICAL ADVANTAGES

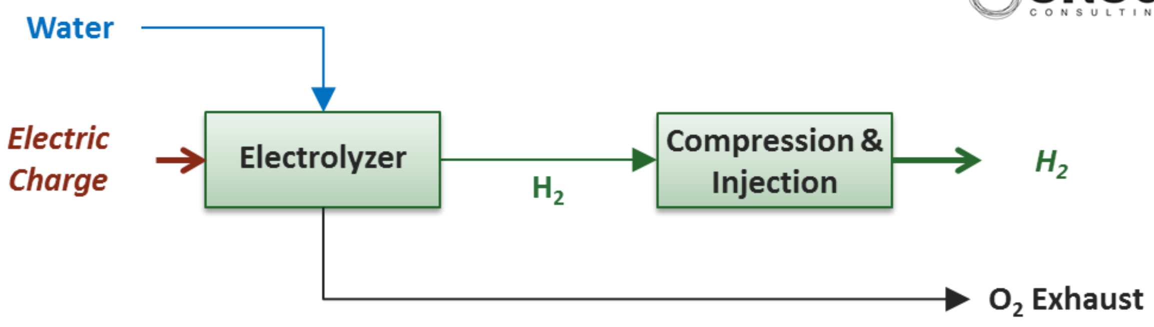
- Excellent response time
- Long lifetime
- High efficiency
- Easy awareness of the charge level
- Large range of possible regimes (+ modularity)
- Low need of maintenance

DRAWBACKS / TECHNICAL CONSTRAINTS

- Complex conception: magnetic bearings, vacuum
- Few available energy
- Very high self-discharge due to different losses (mechanic, magnetic..)
- High investment cost
- Potential safety issues (high speed rotating mass)
- Noise

9.2.7. POWER TO GAS

Hydrogen production by PEM electrolysis



TECHNOLOGY DESCRIPTION

Production of hydrogen by water electrolysis or "Power to Hydrogen" is a storage technology by conversion: electricity to store is converted into hydrogen and the hydrogen produced is injected directly in the gas network. The natural gas network as well as the associated storage sites then constitute a significant energy storage medium. Dioxygen is also produced during the electrolysis and can be expoited.

Several possible technologies of electrolyzer can be used, the most developed being alkaline technologies and PEM (Proton Exchange Membrane).

The alkaline electrolyzers use a solution of potassium hydroxide (KOH) or of potash depending of the service temperature. The potash is preferred to caustic soda for its better conductivity and for a better control of potential impurities.

The PEM electrolyzers work in an acid medium, with a solid electrolyte with a proton conducting polymer membrane. This technology has the following advantages: no liquid electrolyte, compactness, design and operation simplicity, limitation of corrosion issues and better performances than alkaline technology. In contrast, it is less mature and is currently the most expensive of the two.

For both technologies of electrolyzers, it is necessary that water is pure (no mineral or ions). Generally speaking the purification is performed by ion exchange resins, directly included in the commercialized systems.

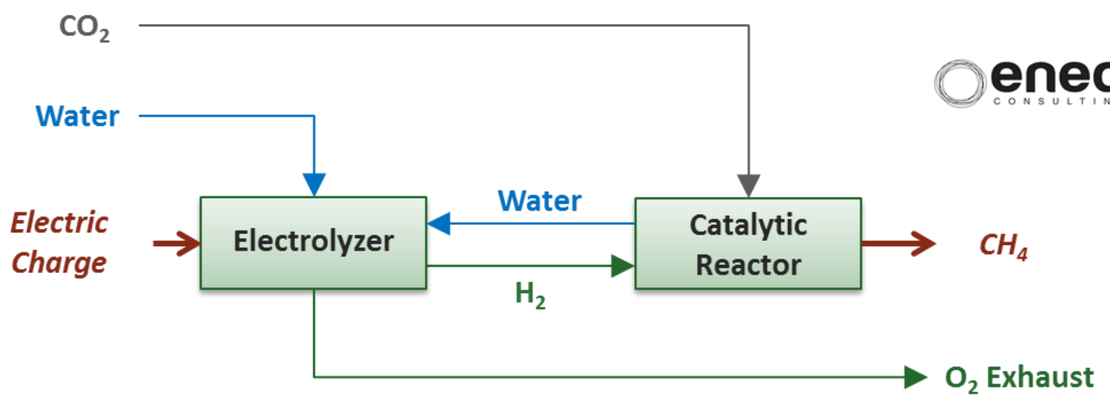
TECHNICAL ADVANTAGES

- Direct electricity conversion (No charge/discharge) in a directly usable product
- Possible coupling of electric and gas network
- Use of gas network flexibility
- Mature technologies (electrolysis and gas injection in the network)
- Conversion of electricity in a "green" gas

DRAWBACKS / TECHNICAL CONSTRAINTS

- High investment cost
- Limitation of the acceptable level of hydrogen in the network
- Necessary proximity from the gas network
- Safety and social acceptability of hydrogen
- Limited efficiency
- ICPE classified (France)

Methane production by catalytic conversion of CO2



TECHNOLOGY DESCRIPTION

Direct catalytic conversion of CO_2 pursues the production of synthesis methane from electricity. Water and carbon dioxide are also necessary inputs for this technology. The process consists of two main steps: the production of hydrogen by electrolysis, followed by the production of synthesis methane by catalytic hydrogenation of carbon dioxide.

As the process requires carbon dioxide, it can be interesting to couple this technology with sites of CO_2 sequestration. Dioxygen is also produced during this conversion chain and can be exploited.

The methane produced is injected in the natural gas network. The natural gas network as well as the associated storage sites then constitute a significant energy storage medium. Unlike for hydrogen, synthesis methane is a much less constraining vector in term of maintaining gas specifications in the network (calorific value especially)

Several possible technologies of electrolyzer can be used, the most developed being alkaline technologies and PEM (Proton Exchange Membrane). Catalyzers that are able to achieve this reaction are robust and have a low sensitivity to impurities; hence alkaline electrolyzers, more mature and less expensive, can be favored.

TECHNICAL ADVANTAGES

- Direct electricity conversion (No charge/discharge) in a directly usable product
- Reduction of energetic losses compared to Power-to-Gas-to-Power solutions
- Coupling of the electricity network with the gas network and reduction of electricity network congestion
- High flexibility on synthesis methane volumes injectable in the network, unlike for hydrogen
- Mature individual technologies
- Use of gas network flexibility and high associated storage capacity
- CO_2 valuation

DRAWBACKS / TECHNICAL CONSTRAINTS

- High investment costs
- Lower efficiency than some electricity storage solutions
- Lower efficiency than Power-to-Gas solution with hydrogen vector
- Temperature management of the reactor depending on intermittencies
- Management of catalyzers and associated risks during discharge
- Catalyzers replacement required every 5-10 years
- Necessity of a CO_2 source, captured and purified

10. CONCLUSION

This report aims to identify the benefits of flexibility in different countries of Europe, with a special focus on storage. It highlights the impact of the timescale over which the flexibility options are active on the value flexibility brings to power systems. This value is also shown to depend on characteristics such as the level of interconnection capacity and the structure of the electricity generation mix. Some of the main conclusions that have been drawn are summarised below.

Short term flexibility, with a typical discharge time of one to three hours, can be provided by storage technologies such as batteries. The study shows that, at a national scale, the benefits start to be significant when the share of installed PV in a country's energy mix reaches a level of around 12% of the annual power demand. According to ENTSO-E visions for the TYNDP 2014, the only European countries in which that level is exceeded by 2030 are Italy, Bulgaria and Spain, and only by a few percentage points. An additional value may appear at local level, in particular for PV saturation situations at the distribution network level, but are out of the scope this study. Further work on balancing services and distribution networks is planned for next METIS studies.

Mid-term flexibility, with a typical discharge time of 6 hours to 4 days can be provided by storage technologies such as PSH or CAES. Its value increases with the installed capacity of wind energy and this report shows that it can provide significant savings in 2030 in countries with high wind energy shares and a low interconnection capacity, for example the UK and Ireland.

Finally, interconnectors can smooth out the residual demand by aggregating the RES variations over larger zones and consequently can provide flexibility to the power system. This is particularly clear for Germany where interconnectors with neighboring countries allow to halve the remaining flexibility needs that have to be provided by flexible generation, storage and Demand Side Response.

With the increasing share of variable renewable energy, it is key to set up a portfolio of flexibility solutions adapted to the local characteristics (national generation mix, topological characteristics…). While interconnectors appear to be efficient solutions in central Europe countries, a mix of interconnectors, storage and demand response will be necessary for border countries. Such a cost/benefit analysis requires a detailed simulation of the European power system operations on a full year of weather data, to capture the different time scales of flexibility needs.

11. APPENDIX: MAIN ASSUMPTIONS AND METHODOLOGY

11.1. ENERGY STORAGE MODELING

The storage used in this study is a pumped-storage hydro type. It is modelled as an asset taking electricity as input and output and storing water, described as an energy. The input and output efficiency are both fixed and equal to 0.9, which lead to a total storage/discharge efficiency of 0.81.
The PSH plants are characterized by two parameters, a power capacity that describes the maximum power that the plant can deliver, and a discharge time that describes the amount of time necessary to empty the storage at maximum power. The product of these two parameters gives the total energy capacity of the storage.

11.2. METHODOLOGY TO ASSESS ARBITRAGE VALUES

Arbitrage value of storage is calculated at a European level but will strongly depend on the country where the storage is installed and the considered scenario.
For each considered scenario, the methodology used to assess storage value is the following:

- The reference case is built with storage capacities of 2014, as explained in Part 1.1.2
- For each studied country, test cases will be created from the reference by adding a storage unit in that country
- The added units have a fixed power capacity of 1GW and differ on the discharge time, varying from 1h to 24h among the test cases.
- For each test case (defined by a scenario, a country and a discharge time) and for the reference, optimal dispatch is performed over a year and the overall cost is calculated.
- The arbitrage value of storage in a test case is calculated as the difference of overall cost in the reference case and the overall cost in the test case.

11.3. METHODOLOGY TO ASSESS CAPACITY VALUES

Capacity value of storage depicts how energy storage (with a maximum charging/discharging duration) can help the system to ensure supply-demand balance during peak hours for different weather events (cold day, several consecutive days without wind over Europe…). This value is calculated at a country level based on national net demand time series (without considering interconnections impact).
For each considered scenario and each country, the methodology to assess this value is the following:

- Identify the 200 peak hours with the highest net demand, based on 50 years of data
- The 200 dates and hours of these events are identified as high-risk hours during which a unit has to guarantee availability ex-ante, in order to get capacity credits.
- Storage capacity value is computed as the ability of storage to generate continuously during these high-risk hours: considering that the storage charges 1h during 1h of off peak periods (if the storage limit is not reached) and discharges 1h during 1h of peak period (if the storage is not empty), it is possible to calculate the proportion of peak hours that can be handle by the storage unit.

Capacity value is expressed either:

- As a percentage of peak hours that the storage unit can address
- As a cost savings, taking the cost assumption for capacity: 60k€/MW/year

12. APPENDIX: FLEXIBILITY NEEDS WITH RENEWABLE PRODUCTION

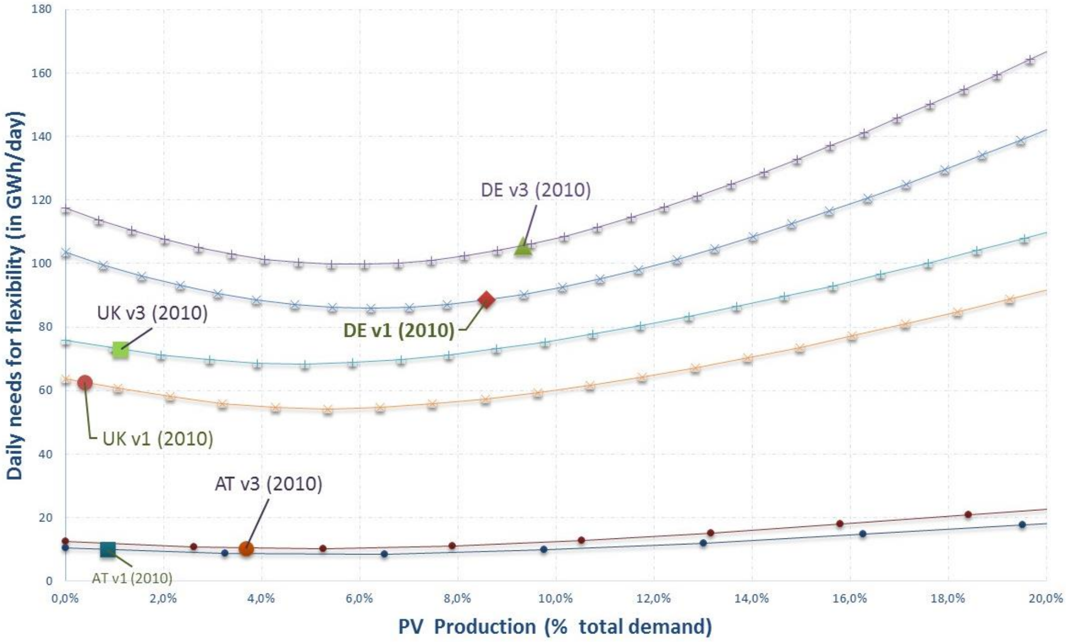


Figure 55. Daily needs for flexibility as a function of PV generation for different countries and scenarios

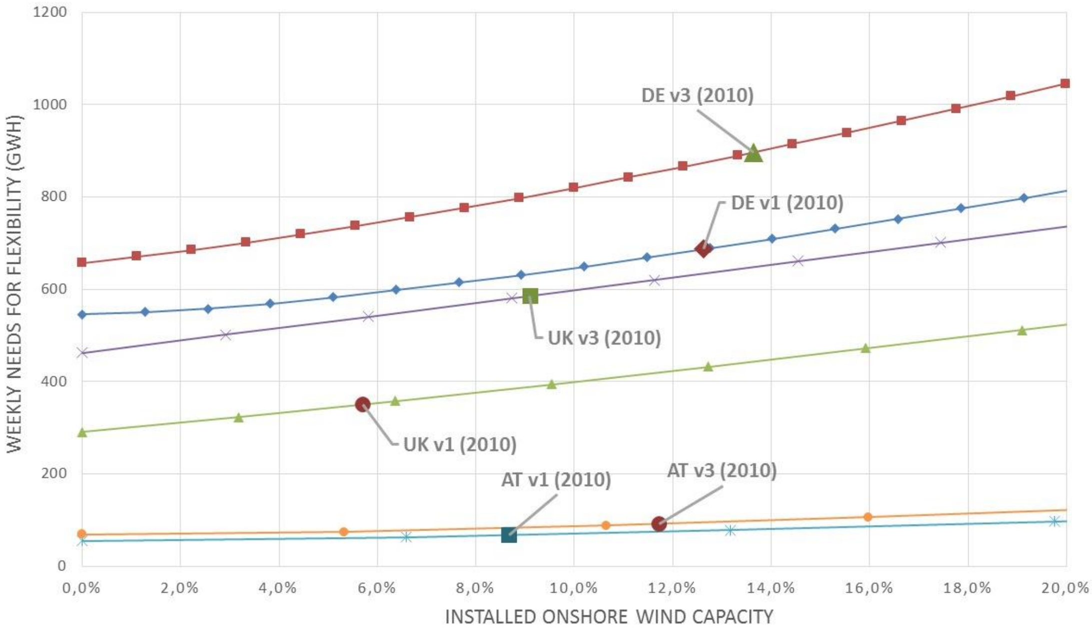


Figure 56. Weekly needs for flexibility as a function of onshore wind capacity for different countries and scenarios

13. BIBLIOGRAPHY

European Commission, COM(2014) 15 final - A policy framework for climate and energy in the period from 2020 to 2030.
http://ec.europa.eu/smart-regulation/impact/ia_carried_out/docs/ia_2014/swd_2014_0015_en.pdf

Eurostat, Electricity generated from renewable sources (code tsdcc330).
http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=tsdcc330&plugin=1

ENTSO-E’s 10-year Network development plan 2014.
https://www.entsoe.eu/Documents/TYNDP%20documents/TYNDP%202014/141031%20TYNDP%202014%20Report_.pdf

ENTSO-E's Scenario Outlook & Adequacy Forecast 2014.
https://www.entsoe.eu/Documents/TYNDP%20documents/TYNDP%202014/140602_SOAF%202014-2030.pdf

Bilan prévisionnel 2015 RTE.
http://www.rte-france.com/sites/default/files/bp2015.pdf

ADEME, Etude sur le potentiel du stockage d’énergie, 2013.
http://www.ademe.fr/sites/default/files/assets/documents/91172_rapport-potentiel-stockage-energie.pdf