e-HIGHWAY 2050

Modular Development Plan of the Pan-European Transmission System 2050

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D3.1	**Technology assessment from 2030 to 2050**		

Annex to D3.1 - Technology Assessment Report

Storage Technologies: Compressed Air Energy Storage

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PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	X

Document information

General purpose

This document is an annex of deliverable **D3.1** focusing on the technology assessment (technical and economic performances) of generation, storage, transmission and demand-side technologies. It deals with CAES technologies on the time horizon set by the e-Highway2050 project, i.e. from today until 2050 time horizon.

The present document is complemented by an attached Excel file providing the data compiled according to the methodology described in the next sections.

Change log

Revision	Date	Changes description	Authors
V1.0	14/01/14	Creation of the document and associated Excel file	Comillas
V2.0	21/03/14	Revision	Comillas
V3.0	29/08/14	Final revision for integration in the D3.1	Technofi

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Acronyms

Acronym	Definition
CAES	Compressed air energy storage
ESG	Energy storage generation
ESS	Energy storage system
PHS	Pumped hydro storage

Table of content

CAES technologies

1 Introduction

The main objective of the present document is to provide a collection of information on compressed air energy storage (CAES) technologies according to a homogeneous methodology developed and used for all generation, demand, transmission and storage technology areas.

The main added value of the work performed by Comillas University is:

- To document the rationale of selection of CAES storage technologies with respect to the e-Highway2050 project;
- To define in a transparent way the assumptions set for the data gathering and the appraisal of the evolutions of performances and costs from today until 2050;
- To provide a list of international references on the subject;
- To appraise trajectories of evolutions of cost and technical parameters for a selection of CAES technologies based on the available literature and above assumptions;
- To discuss the robustness and limitations of the provided data.

1.1 Scope

The e-Highway2050 project looks at an exhaustive portfolio of technologies that could contribute to electricity generation and energy storage at the 2050 time horizon. This report focuses on energy storage technologies.

Energy storage technology can be divided into chemical, electrochemical, electrical, thermal and mechanical energy storage technologies. This report focuses on mechanical energy storage technologies and in particular, on compressed air energy storage (CAES) systems.

Within the group of CAES, main attention is paid to diabatic and adiabatic CAES types. These CAESs can be considered already commercial or they are a promising candidate for the time horizon set by the e-Highway2050 project. CAES are currently used to provide a wide variety of services such as energy and renewables energy time shift, spinning reserve, frequency regulation, ramping, renewables capacity firming, black start capability, transmission congestion relief, etc. ([12]).

Within this document, current CAES characteristics are reviewed and future trends of both costs and technical parameters from today until 2050 are estimated based on the available literature.

1.2 Rationale for selection of CAES technologies

The conventional electricity generating industries have little or no storage facilities. The amount of renewable energy on the grid is increasing and will continue to grow. However, the demand for electricity varies considerably, daily and seasonally, the maximum demand may only last for a few hours each year. This leads to inefficient, overdesigned and expensive plants. ESS allows energy production to be de-coupled from its supply, self-generated or purchased. In particular, CAES is (besides pumped hydro storage) the only commercially available technology capable of providing very large energy storage deliverability (above 100 MW for a single unit) ([15], [25]). In fact, utility systems that benefit from CAES include those with load varying significantly during the daily cycle and with electricity prices varying significantly with the generation level or time of day.

The increasing amount of renewable energy will almost certainly request additional energy storage [5]. CAES might be suitable to accommodate a larger amount of renewable energy since CAES systems are designed to cycle on a daily basis and to operate efficiently during partial load conditions. This design approach allows CAES units to swing quickly from generation to compression modes. For utility or renewable energy integration, energy storage capacity, power output, and life cycle are key performance criteria. The need for long life cycle has motivated the use of storage systems from reversible physics such as CAES as an alternative to electrochemical batteries that present problems of ageing and are difficult to recycle [31].

In this report, mainly CAES technologies that are already commercial or that are going to be promising candidates for the future[1] are analyzed. Commercial technologies will be certainly used in the short term, whereas promising candidates might be used in the mid and long term as alternatives. In particular, diabatic and adiabatic CAES are chosen since:

- Today there are only two diabatic CAES plants in operation worldwide, but several CAES plants are being planned or under construction (see Table 1). One plant is located in McIntosch, US (110 MW) and one in Huntorf, Germany (320 MW)

Project	Capacity (MW)	Country
Huntdorf	320	Germany
McIntosh	110	United States
Norton	2700	United States
PG&E	300	United States
Next Gen CAES using Steel Piping	9	United States
SustainX	1.5	United States
Seneca	150	United States
Apex Bethel Energy Center	317	United States
ADELE	200	Germany

Table 1: Operational and planned CAES projects ([12], [19], [48]).

- Due to limitations of diabatic CAES plants, some improved CAES systems are proposed or under investigation, including the small-scale CAES with fabricated small vessels, adiabatic CAES with thermal energy storage, isothermal CAES and CAES with humidification, etc. [15].
- Although there are currently no adiabatic CAES of scale in operation, the main components for adiabatic CAES are already available [11]. The necessary heat storage systems are still under development. The most promising solution seems to be solid state heat storage systems above ground. A possible alternative known from solar thermal power plant developments are molten salt storage systems.

Finally, on the technology level, centralized large-scale CAES are studied. The main reason behind this is that only large CAES units connected to the transmission grids seem to be economically viable [11].

[1] Note that the maturity levels of ESS technologies are not uniformly defined in the technical literature ([3], [17], [18]).

1.3 Short overview of CAES technologies

In a CAES plant, ambient air is compressed and stored under pressure in an underground cavern. When electricity is required, the pressurized air is heated and expanded in an expansion turbine driving a generator for power production. CAES technologies can be classified into three types: isothermal, diabatic and adiabatic. Diabatic CAES plants, the only ones in use or being planned today, are essentially just conventional gas turbines, but where the compression of the combustion air is separated from and independent to the actual gas turbine process. During the compression process the air heats up; the heat is removed by a radiator. The energy is stored as compressed air in a cavern.

Adiabatic CAES plants are advanced CAES systems. In an adiabatic CAES system, the heat generated during the compression process is stored. During the discharging process, the stored heat is used to heat up the air while expanding. Heat can be either stored separately or a combined heat and compressed air storage can be used (being referred to as uncooled compression) [32]. The technical feasibility is of the latter is arguable [32]. The adiabatic CAES with independent heat storage is also called AA-CAES (advanced adiabatic CAES). The independent heat storage facilities are pressurized containers with beds of stones or ceramic molded bricks through which the hot air flows. Material issues have to be solved for the pressure vessel and the piping [33]. The ADELE project aims at testing the adiabatic CAES at a demonstration plant [34].

The concept of isothermal CAES is based on isothermal compression thereby avoiding the inherent challenges of high temperature heat storage. Isothermal CAES can minimize the compression work and maximize the expansion work done through isothermal compression/expansion by means of effective heat transfer with the vessel's surroundings, which involves slow gas pressure change by liquid piston [36]. Isothermal CAES developed by SustainX holds the air in large pipes, the same used in natural gas pipelines. That means utilities or even commercial customers could place a storage device in a range of industrial locations, rather than only where there is an underground formation available [37]. SustainX's solution uses hydraulic pumps to isothermally compress air at rates that allow the high-pressure air to exchange heat with its surroundings. However, isothermal storage is only practical for low power levels, without very effective heat exchangers ([35], [12]).

For large-scale applications, diabatic and adiabatic CAES types are most suitable. A schematic diagram of a diabatic and an adiabatic CAES plant is shown in Figure 1 [11]. The main elements of a CAES plant are (1) a motor/generator, (2) an air compressor of two or more stages with intercoolers and after-coolers, (3) a turbine train, containing both high- and low pressure turbines, (4) a cavity/container for storing compressed air, and (5) equipment controls and auxiliaries such as fuel storage and heat exchanger units, etc. A schematic diagram of an isothermal CAES plant is shown in Figure 2.

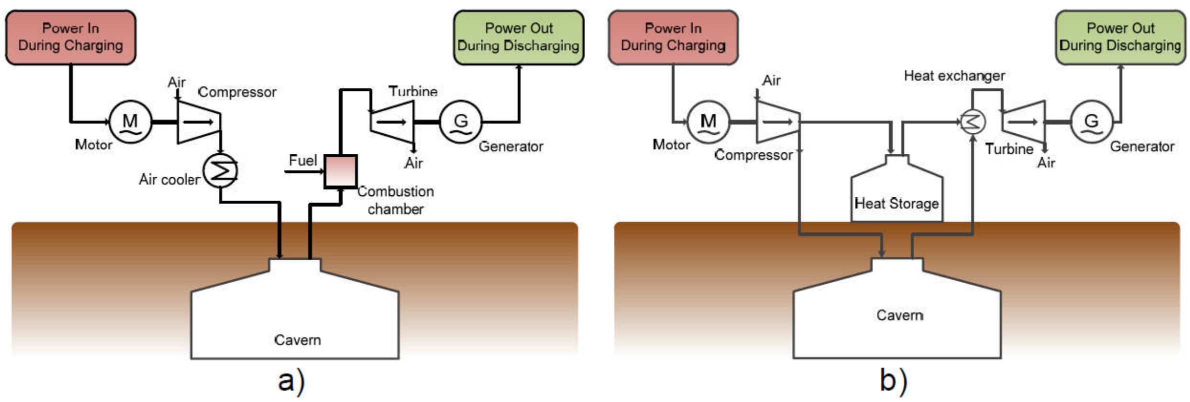

Figure 1 : Schematic diagram of a a) diabatic and b) adiabatic CAES plant [11].

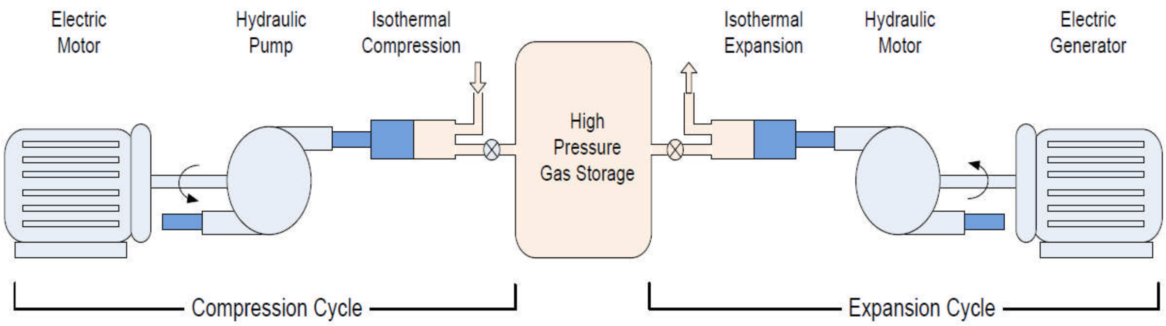

Figure 2 : Schematic diagram of SustainX isothermal CAES plant [36].

Caverns can be underground rock caverns created by excavating comparatively hard and impervious rock formations, salt caverns created by solution- or dry-mining of salt formations, and porous media reservoirs made by water-bearing aquifers or depleted gas or oil fields, e.g. sandstone and fissured lime. The compressed air can also be stored in above ground pressured vessels or near surface pressured air pipelines (including those used to transport high pressure natural gas). Both storage locations have limitations either due to availability of suitable underground formations or due to cost-related issues. Above-ground solutions are estimated to be five times more expensive than the underground solutions [38]. According to [39], decreasing storage capacity to less than 10 hours significantly reduces system net revenues. Note also that above-ground CAES are intended to store energy during 2-4 hours, whereas underground CAES can store energy representing 10 hours at full load. Finally, containments on the sea bed in deep water could serve as storage, where the water column acts as vessel [40].

CAES are able to provide load shifting, reserve, load following, voltage and black start capability, transmission and distribution upgrade deferral, congestion relief, etc. ([24], [27]). Typical technical characteristics of these services are described in references ([11], [18], [24], [25], [27]). Table 2 maps some ESS technologies, grouped according to their discharge duration and power rating, on possible applications. It can be inferred that CAES are used for large-scale applications, i.e., those applications requiring large amounts of power and energy.

	Short duration	**Medium duration**	**Long duration**	**Power (MW)**
	< 0.25h	**1 - 10h**	**50 - 500h**	
ESS technology	PHEV, EV PV-battery system	PHEV, EV PV-battery system		0.1-1
ESS technology	Flywheels Super-Capacitors SMES Lithium-ion batteries Lead-acid batteries Nickel-cadmium batteries Sodium-suflur batteries	Lead-acid batteries Nickel-cadmium batteries Lithium-ion batteries Sodium-suflur batteries Redox-flow batteries Other electrochemical batteries	Redox-flow batteries	0.1-100
ESS technology		Pumped hydro storage **Compressed air energy storage** Thermoelectric	Hydrogen storage Methanation (Pumped) hydro storage (with large water reservoirs)	100-1000
Applications	Primary/Secondary frequency control Spinning reserve Peak shaving Power quality	Tertiary frequency control Standing reserve Load Leveling Load Following	Storage for “dark calm” periods (i.e., no wind or solar generation) Island grids Energy time shift Electric supply capacity	

	Voltage control Black start capability Island grids (with e.g. diesel generator) Electromobility (Hybrid Electric Vehicles) Uninterruptible power supply Transient stability	Island grids Electromobility (Full Electric Vehicles) Residential storage systems Uninterruptible power supply Distribution upgrade deferral Transmission upgrade deferral Transmission congestion reliefe		

Table 2: Mapping of ESS technologies on possible applications ([11], [25], [27]).

Table 3 shows typical technical and economic characteristics of diabatic and adiabatic CAES. The wide range of rated power and energy is mainly due to the different sizes of operational and planned CAES. A reason for the ranges for variables such as the efficiency, the lifespan or the life cycles lies in the lack of long field experience ([3], [18]). The same reasoning can be also applied to the costs. Note that whereas for diabatic CAES plants, electrical efficiency can be measured, the electrical efficiency of adiabatic CAES plants is estimated. The electrical efficiencies reported for diabatic CAES plant correspond to the plant energy efficiencies, i.e., the electrical energy output divided by the sum of the electrical energy input (compression) and the consumed fuel (gas turbine)[2]. For the purpose of comparison, the energy efficiency of a gas turbine is around 30-35%.

		Diabatic	Adiabatic
energy rating	MWh	200-6000	150-1000
rated power[3]	MW	25-300	30-200
electrical efficiency	%	40-54	60-70
self discharge	%/day	small	0.5-1
response time	s	15-540	180-600
lifespan	year	30	25
life cycles	cycles	No limits	No limits
investment costs (power)	$/kW	425-1350	1000
nvestment costs (energy)	$/kWh	3-50	40-80

Table 3: Typical characteristics of the diabatic and adiabatic CAES ([7], [11], [14], [15], [18], [19], [23], [24], [25], [27], [55]).

Table 3 shows typical compressor and turbine power ratings of currently installed diabatic CAES plants. The ration between compressor and turbine rating usually depends on the application (duration of valley and peak demand periods and their corresponding power needs, costs and revenues, etc.). For adiabatic power plant, no figures have been found.

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[2] The description of the energy performance of diabatic CAES plants is not that straightforward as for example for conventional fossil-fueled power plants due to the presence of two energy inputs, being used at different instants of time. Electricity is needed to drive the compressors, whereas fuel is needed to heat the air for expansion. The heat rate applies to the fossil-fuel input (fuel consumed per kWh), whereas the charging electricity ratio applies to the electricity input (ratio of generator output to compressor input). Several combined indexes exist: plant energy efficiency (conversion from BTU to kWh), primary energy efficiency, « effective » energy efficiency (conversion from BTU to kWh taking into account gas turbine efficiency or a system efficiency), « Zaugg » efficiency, etc. ([41], [45]). According to the index used, the efficiency is around 50%, 35%, 88% or 66% respectively. The choice of efficiency measure for diabatic CAES plants remains an open question because thermal energy and electrical energy quantities cannot be combined by algebraic manipulation. In case of adiabatic or isothermal CAES plants, electrical efficiency can be readily derived.

[3] In the technical literature, rated power usually refers to rated turbine power.

		Diabatic	Adiabatic
compressor rating	MWh	45-110	-
turbine rating	MW	116-294	-

Table 4: Typical compressor and turbine power ratings ([42]-[44]).

2 Methodology of data production

The methodology of data production consists of two steps: first, current CAES characteristics are reviewed and second, current estimates of future trends are reviewed and compared in order to obtain consistent trends.

The assessment of current CAES characteristics is based on an in-depth literature review. The literature review reveals a certain variation of cost and technical parameters due to the very low number of operational units.

The estimation of future trends is also based on an extended literature review. Efforts are made to compare and obtain consistent future trends.

In case a specific approach is used for a certain data type, the corresponding methodology is described in the paragraph dedicated to that data type.

2.1 Methodology for data gathering

Data gathering is based on an in-depth literature review. Table 5 displays the different modes and types for data gathering. It is interesting to see that the consultation of a large amount of internal reports, published articles, State-of-the-Art studies and data bases reveals a certain variation within cost and technical parameters of current CAES technologies. For example, higher CAES performances might be available but this typically results in higher costs, too. Costs also vary with the CAES plant and its size.

Mode	Type of data gathering	Nature of data processing	Comment
Other experts of the field	Knowledge formalized in data bases	Data gathering	DOE International Energy Storage Database
	Knowledge formalized in published articles	Data gathering	Cf list of references
	Knowledge structured in State of the Art studies	Data gathering	Cf list of references

Table 5: Modes for data gathering.

2.2 Methodology for estimating future trends

The methodology to estimate future trends of CAES is mainly based on the analysis of publications partially or fully covering the time period 2020-2050. The use of several publications allows contrasting the data and trends found. The complete list of sources including reports, articles, studies and websites, can be found in the references section.

Main drivers affecting CAES deployment and evolution are:

- the technological progress within the CAES industry due to R&D activities,
- the evolution of intermittent RES and particularly, wind and solar PV generation,
- and finally, the evolution of the regulatory context (e.g., regulatory hurdles associated with environmental review).

By analyzing and comparing the published work on these CAES drivers, a unified image on future trends of CAES can be obtained. A main focus is on the consistency of the projected trends up to 2050. A detailed description of the methodology is given in section 10.

If possible, future trends for all variables described in sections 3 to 9 will be estimated. The estimations are built on the data found in the literature. For this purpose, data is temporally extrapolated or interpolated. However, there are certain variables that are more meaningful than others. These variables are highlighted in sections 3 to 9.

Finally, it is important to bear in mind that the estimation of future trends is based and therefore depends on the available literature review. Further, CAES technologies still lack of long field experience [3], [18]. Apart from the 2050 time horizon, this might constitute a limitation of the methodology.

3 Technology performance characteristics

3.1 Variables selected

Variable : ***technology performance characteristics***	**Unit**	**Definition**
energy rating	MWh	maximum storage capacity of the CAES
rated power	MW	maximum rated power of the CAES
electrical efficiency	%	overall electrical energy efficiency (kWh in, kWh out) [4]
availability	%	% of time available to store and deliver electricity
MTBF	h	mean time between failure
MTTR	h	mean time to recovery
self-discharge	% of state of charge/day	
response time	s	time from no charge to discharge at full power

Table 6: Variables describing the technology performance characteristics.

3.2 Underlying assumptions

CAES can be characterized in a generic way by a set of variables describing their technology performance. These variables are related to the available power and energy, the CAES's efficiency and losses, its availability and the response time.

Maximum and minimum values of the actual rated power and energy ranges of current CAES systems have been used in order to extrapolate current values to 2050 according to the results of section 10.3. Note that rated power and energy considerably vary within a CAES technology due to the very small number of operational CAES plants. Ratings have been assumed constant since the technology is relatively mature.

[4] The overall or round-trip electrical efficiency is not equal to the storage efficiency (also called storage efficiency or compression-expansion cycle efficiency). The former is equal to the AC/AC round-trip efficiency, whereas the latter only considers storage related processes. Usually, storage efficiency is given in the literature, and therefore motor and generator efficiencies (~ 95%) should be added. Note also that in case of diabatic CAES plants, plant energy efficiency has been used to describe the electrical efficiency.

Maximum and minimum values of the current overall efficiency values have been used to extrapolate current values to 2050 according to the results of section 10.3. Increasing efficiencies are due to the technological evolution of CAES (e.g., improvements in design, etc. for diabatic CAES). The efficiency potential of CAES is at about 70 to 80% [22].

Availability values have been found for the Huntdorf CAES power plant [15]. Although only two plants are currently in operation, 30 years of operational experience exist. Since the elements of CAES (turbine, pumps, etc.) are mature, constant availability has been assumed. It is assumed that diabatic and adiabatic CAES plants have similar availabilities.

In general, the response time varies according to the operation point. The response time from 0 to 100% output is about 10 minutes, whereas the response time from 50 to 100% is about 15 seconds [14]. Maturity of CAES implies that this range will not vary significantly. In addition, losses will not vary neither [11].

4 Technology readiness and maturity

4.1 Variables selected

Variable ***technology readiness and maturity***	**Unit**	**Definition**
technology maturity	TRL scale	
lifespan	year	
life cycles	cycles	

Table 7: Variables describing the technology readiness and maturity.

4.2 Underlying assumptions

The technology readiness and maturity of CAESs can be characterized by a set of variables related to the technology maturity, the lifespan and life cycles.

With regard to the technology maturity, it has been assumed that a technology is able to move from one to the next maturity level within at least two decades. Although a long operation experience is available, only two plants exist (the elements are mature but not the full CAES technology). More installations will be needed to confirm full CAES maturity [18].

Mean values of current lifespan and life cycles have been used to extrapolate the values to 2050 according to the results of section 10.3. In addition, values given in [11] have been taken into account. Since the elements of CAES are all mature, lifespan and life cycles remain more or less constant.

5 Possible implementation constraints

5.1 Variables selected

Variable ***possible implementation constraints***	**Unit**	**Definition**
footprint	MW/m2	Application dependent
ease of siting	-	

Table 8: Variables describing possible implementation constraints.

5.2 Underlying assumptions

Possible implementation constraints of CAESs can be characterized by a set of variables related to the plant's footprint and its ease of siting.

Only a few of these variables have been quantified, i.e., the plant's footprint and the ease of siting. In addition, only current values are given. Probably, these values won't vary drastically in the future. The footprint is also very application dependent [24].

6 Costs

6.1 Variables selected

Variable *costs*[5]	**Unit**	**Definition**
investment costs (power)	\$/kW	
investment costs (energy)	\$/kWh	
O&M costs	c\$/kWh	

Table 9: Variables describing costs.

6.2 Underlying assumptions

Costs of CAESs can be characterized by a set of variables related to the power and energy investment cost as well as the O&M costs.

With respect to power and energy costs, maximum and minimum values of the current costs have been used to extrapolate costs to 2050 according to the results of section 10.3. In addition, values given in [11] have been taken into account. Cost reductions are mainly due to the increasing demand of CAES, improvements in design, a larger market for developing dedicated equipment, etc. [48].

Current values for O&M costs have only been found for diabatic CAES. They are very small, around 0.2 c\$/kWh, and it is assumed that they will not vary drastically. O&M costs are low for adiabatic CAES too.

7 Environmental impact and public acceptance

7.1 Variables selected

Variable *environmental impact and public acceptance*	**Unit**	**Definition**
CO_2 emissions	CO_2eq/kWh	
Visual impact	high/medium/low	See [54]
Soil and geology impact	high/medium/low	See [54]

Table 10: Variables describing environmental impact and public acceptance.

[5] Most sources deliver power and energy cost in US\$. This has been maintained to avoid currency type errors.

7.2 Underlying assumptions

Environmental impact can be characterized by a set of variables related to the CO2 emissions, the visual impact and the soil and geology impact.

Current values for CO_2 emissions of diabatic CAES have been found. No estimates for future figures on CO_2 emissions have been found. However, it has been assumed that the current value will not change since gas turbines are already mature [53]. Note that adiabatic CAES do not present CO2 emissions.

Visual impact is of little concern [54]. Similarly, the impact on soil and underground geology is low too [54]. Actually, cavern integrity did not suffer during 25 years of operation of the Huntdorf CAES plant.

8 Supply chain issues

8.1 Variables selected

Variable *market and supply chain issues*	**Unit**	**Definition**
project lead time	months	Total time from permitting submission to start up when connected to the grid

Table 11: Variables describing supply chain issues.

8.2 Underlying assumptions

Supply chain issues can be characterized by the project lead time. Current values for the project lead time of CAES have been gathered from references [19] and [25]. No significant change of the project lead time has been assumed.

9 Dynamic performance of technology

9.1 Variables selected

Variable *dynamic performance of the technology*	**Unit**	**Definition**
Ramp rate	pu/s	ramp rate is related to response time; per unit (pu) of rated power
Active power control	TRL scale	
Ramp rate control	TRL scale	
Frequency control	TRL scale	
Frequency sensitive mode control	droop [%]	
Voltage control	TRL scale	
Reactive power control	U-Q/Pmax , Pmax-Q/Pmax	
Fault-Ride-Through (FRT)	U-t [p.u.-s]	
Post-fault voltage support	% of i_{rated}/% Udev	

Table 12: Variables describing the dynamic performance.

9.2 Underlying assumptions

The dynamic performance can be characterized by a set of variables related to the ramp rate, a group of power, frequency, and voltage controls, and the fault-ride-through capability.

It has been assumed that the ramp rate is strongly related to the response time. The response time is the time it takes to change from no charge to discharge at full power [2]. Note that the response time varies according to the operation point of the CAES plant. At most, the ramp rate is then the inverse of the response time. The ramp rate will not vary significantly from 2012 to 2050.

Most of the controls are currently already in a mature stage. This is due to the fact that active and reactive power controls (including automatic voltage control, load frequency control, etc.) are basically ensured by conventional excitation and turbine-governor controllers. Frequency sensitive mode control, reactive power control, fault-ride-through and post-fault voltage support depend very much on the grid codes [13].

10 Methodology for estimating future CAES trends

Currently, the largest application for storage in the US is distributed storage, primarily in the form of thermal storage used for reducing thermal heating or cooling loads [1]. Renewable energy applications constitute the second largest storage application in terms of installed capacity, primarily due to pumped hydro and CAES systems.

In the short term (i.e., the next five to ten years), based on planned investments and policies, the market for renewable integration, distributed storage, and ancillary services are likely to be the strongest growth areas in the market [1]. Development for transmission support and community energy storage is likely to be slow in the near term due to long-time horizons with adoption and difficulties in finding financing and due to the fact that the community energy storage market will likely be driven by regulated utilities, which likely indicates a slower rise to mass deployment compared to other markets.

Main drivers affecting CAES deployment and evolution at the time horizon of the eHighway2050 project are [6]:

- the evolution of intermittent RES and particularly, wind and solar PV generation,
- the technological evolution in terms of technical performance and cost reductions within the CAES industry due to multiple R&D activities,
- and finally, the evolution of the regulatory context regarding storage and possible funding schemes.

The methodology to estimate future trends of CAES is mainly based on the analysis of publications partially or fully covering the time period 2020-2050. In a first step, publications on the technological progress and its impact on the evolution of CAES are studied. Moreover, general storage prediction and market share are screened. In a second step, publications on the evolution of intermittent RES are analyzed with special focus on the impact on the evolution of CAES. Finally, the resulting CAES evolution is compared and unified.

Figure 3 illustrates the methodology.

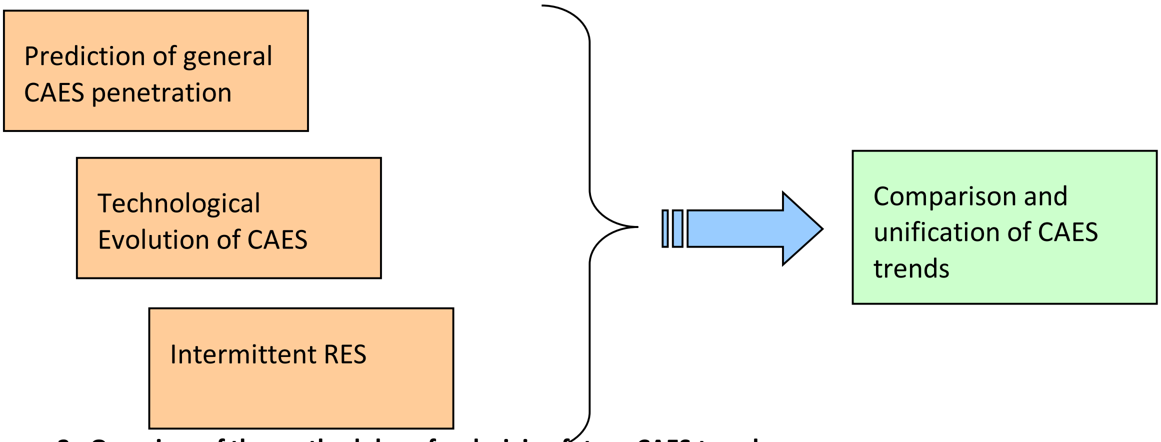


Figure 3 : Overview of the methodology for deriving future CAES trends.

10.1 Review of forecasted CAES penetration levels and technological progress of CAES

An extensive literature research reveals useful information of future trends of CAES.

A KEMA report foresees a slight increase of CAES (pumped hydro stagnates). Figure 4 shows the growth of installed capacity of various ESS technologies within the next five years. This forecast is based on information on current and planned U.S. grid-storage activities, known grid-storage market trends, and proposed energy-storage incentives. The main driver behind the growth of ESS is the renewable integration and the provision of ancillary services.

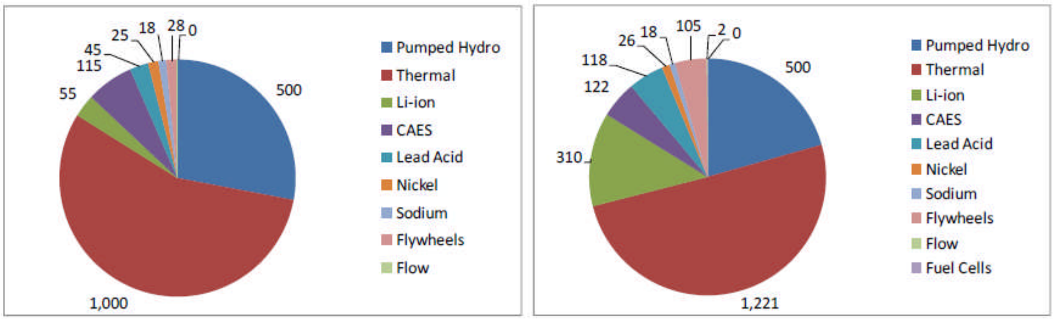


Figure 4 : Installed capacity of ESS in MW today and in five years [1].

Similarly, Pike Research forecasts that, starting from a very low base in 2012, the total capacity of energy storage generation (ESG) systems worldwide will surpass 14,000 megawatts by 2022 [8]. Key applications for long-duration energy storage include counterbalancing the intermittency of renewable energy sources like wind and solar power, leveling the loads and time-shifting periods of peak demand on the grid, and avoiding or delaying the construction of costly transmission and distribution (T&D) assets, among others. These applications will drive a total worldwide investment of just over $122 billion in energy storage projects during the period between 2011 and 2021. Figure 5 shows the yearly investment in various ESS technologies. CAES will see a significant increase in investments with respect to its current investments.

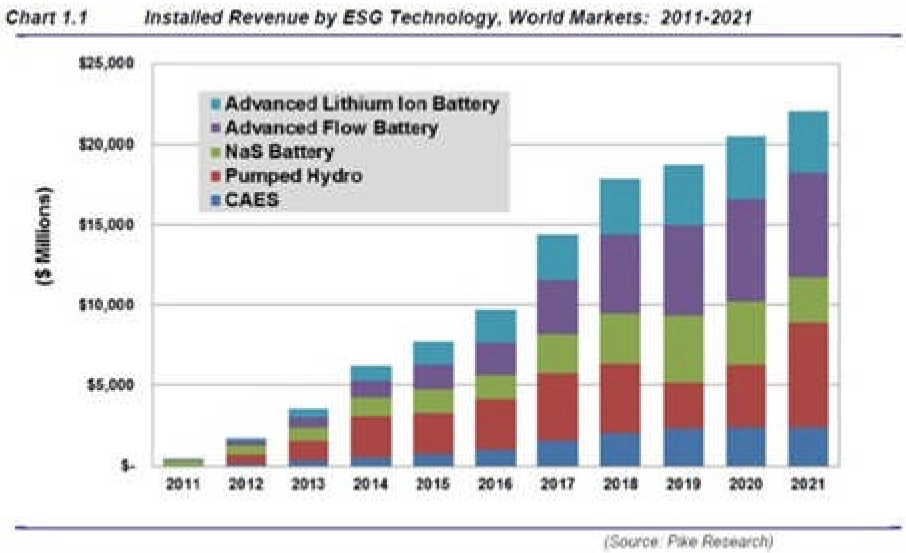


Figure 5 : Projections of the yearly investment in several ESS technologies [8].

Although diabatic CAES is based on mature technologies, there are several possible advancements in conventional CAES. Previous CAES plants used components that were not optimized for the unique characteristics of the CAES expansion cycle. This is partially due to the small market for which developing dedicated equipment would not be worthwhile. A large CAES market could drive development of custom turbo-machinery, improving the efficiency of CAES components [48]. Similarly, drivers of CAES such as the evolution of intermittent RES and particularly, wind and solar PV generation, or the ability to provide ancillary services influence the technological progress, which in turn could bring down costs due to economy of scale of greater production, incentives, R&D investments, etc.

A possible growth of CAES requires that appropriate caverns exist. Estimating the amount of underground formations available for CAES is very difficult. Some estimates indicate that more than 75% of the land area of the United States could provide suitable geology for CAES projects. However, each potential site must be individually screened, and this has proved challenging.

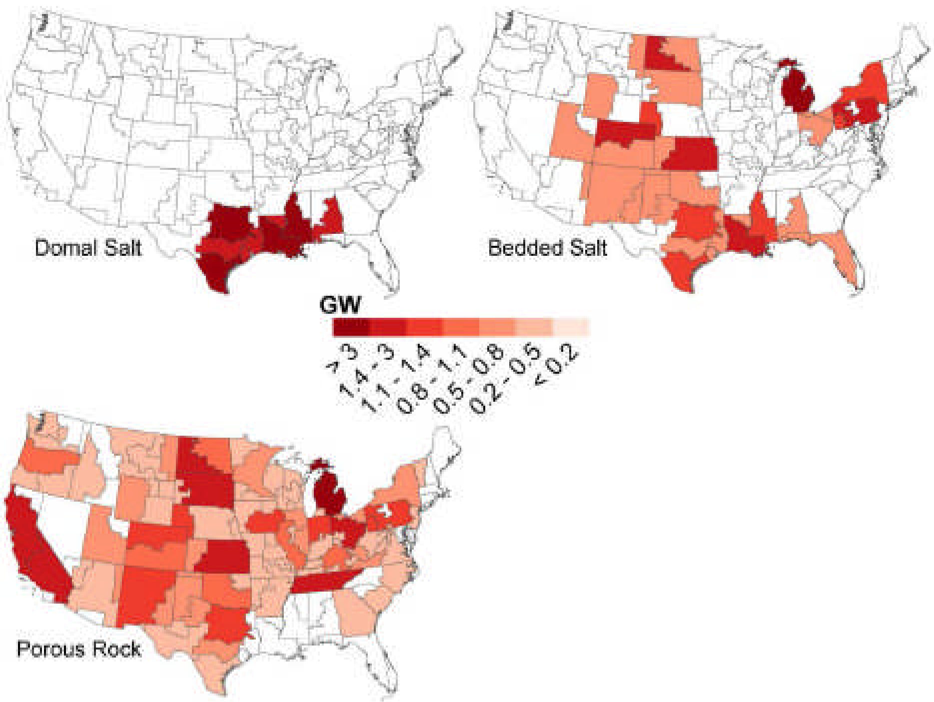


Figure 6 : Assumed availability of compressed air energy storage in domal salt, bedded salt, and porous rock [48].

CAES is receiving strong support in the US at present with one notable scheme under construction. Planning disputes have significantly delayed one large-scale project in Ohio (since 2001) [49]. CAES deployment in Europe will however be restricted by the space availability of storage caverns for the compressed air.

Figure 7 gives a rough overview of the distribution of salt formations in Europe. The symbols for existing and planned salt cavern projects indicate where salt deposits that have proven suitability for cavern construction are present; i.e. with potential suitability for the construction of future energy storages. Zechstein deposits present the most favorable conditions Europe-wide for the construction of additional storage caverns, particularly when forming large salt domes or thick salt pillows [46]. The post-Zechstein deposits allow only the development of smaller caverns. In addition, the share of insolubles is in many of these higher than in Zechstein salt. Thus, it seems that in Europe suitable sites might be available for caverns [40]. However, site specific geologic characteristics have to be taken into consideration. Similarly, reference [41] states that prospects for using cavities in salt domes as storage reservoirs may be more favorable in Europe than in the US.

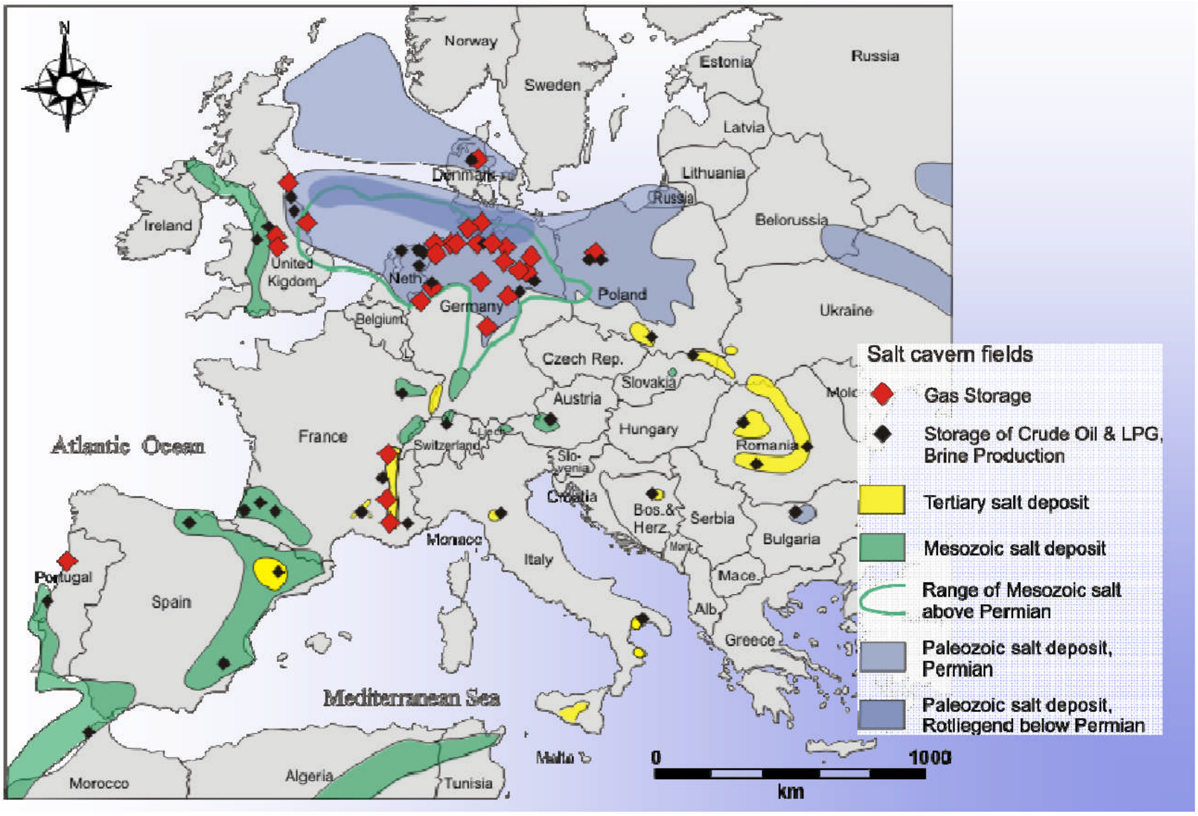


Figure 7 : Salt deposit and cavern projects in Europe [46].

Figure 8 shows the assumptions made on the characteristics of large electricity facilities for an analysis of the development of electricity sector in Europe up to 2050 [47]. Although these characteristics are generic for large ESS, they correspond to CAES characteristics reasonably well. Note that no significant improvement has been assumed although it seems that the considered CAES is an adiabatic CAES still under development today.

Technology	Year	Investment	O&M	Lifetime	Efficiency	CO_2-emissions
-	-	[€/kW]	[€/(kW*a)]	[years]	[%]	[kg/MWh]
Storage	2020	1000	10	40	80%	0
	2030	1000	10	40	80%	0
	2040	1000	10	40	80%	0
	2050	1000	10	40	80%	0

Figure 8 : Assumptions on the characteristics of large electricity storage facilities [47].

Since CAES is a mature technology (it consists of parts e.g. turbines and pumps that are used in mature technologies), a major improvement in efficiency or reduced energy input in the near future is unlikely [51]. It is possible that important changes come about through new CAES concepts (such as adiabatic CAES), but in the near-term performance/cost gains are most likely to come as a result of incremental improvements in existing designs as a result of learning by doing.

Analogous to the projections presented in Figure 8, the Danish Energy Agency (DEA) provides guidelines for the methods and assumptions which should be conducted in the energy analyses [50]. Table 13 shows the projections of diabatic CAES characteristics. Here, some improvements in the efficiency and the investment costs are foreseen.

Technology	Compressed Air Energy Storage (CAES)			
	2015	2020	2030	2050
Generating capacity for one unit (MW)	100 - 350			
Electricity efficiency (%) net	60	71	71	71
Availability (%)	95	95	95	95
Technical lifetime (years)	30	30	30	30
Construction time (years)	3	3	3	3
Investment storage, € per kWh storage volume	240	246	246	246
Investment converter, € per kW output capacity	2000	1970	1970	1970

Table 13: Projections of diabatic CAES characteristics [50].

Figure 9 shows and compares estimated costs of adiabatic CAES with Hydrogen or pump hydro storage costs. Within the next decades, a reduction of the costs of adiabatic CAES can be expected (about 50% of the present-day costs).

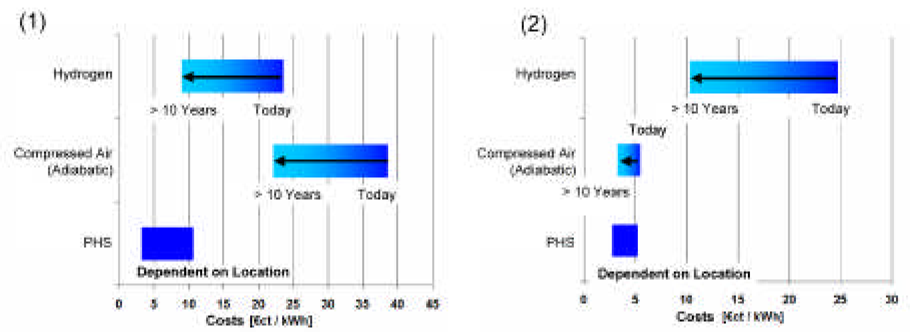


Figure 9 : Comparison of full costs of storage systems for (1) long-term storage (week storage) and (2) Load-leveling tasks (hour storage) [51].

Table 14 shows the assumptions made on the future characteristics of adiabatic CAES according to an SGU report on the future of electricity generation in Germany up to 2050. The report analyzed eight scenarios corresponding to different demand values in 2050 (500 and 700 TWh/y) and different assumptions on self-sufficiency and/or need for net import of electricity from either Denmark and Norway or from Europe-North Africa.

Parameter	Unit	Today	2020	2030	2040	2050
Round trip efficiency	%	70	78	78	80	80
Availability	%	95	95	95	95	95
Lifetime	year	25	25	25	25	25
Investment costs	€/kW	310	300	300	290	280
Variable operation costs	€/kWh	0	0	0	0	0

Table 14 : Predictions of adiabatic CAES characteristics [52].

10.2 Review of publications on intermittent RES affecting the evolution of CAES

A literature research reveals the existence of several studies analyzing the impact of increasing penetration of RES on the evolution of CAES.

In [9], the value of grid-scale storage in the future Great Britain electricity systems based on the DECC (Department for Energy and Climate Change) pathways has been modeled and analyzed. The study presented a whole-systems approach to valuing the contribution of grid-scale electricity storage in future low-carbon energy systems. However, the impact of the DECC pathways on the evolution of the costs of specific ESS such as CAES has not been determined.

The core pathway chosen to focus on the assessment of the value of storage which was characterized by a rapid increase in the share of renewable energy in the electricity supply mix. It further comprised a high rate of electrification in transport and heat sectors accompanied by ambitious energy efficiency measures, in line with DECC Pathways. Figure 10 shows that the potential system savings increase markedly as the system decarbonizes towards 2050. The composition of the value of storage is expressed in kW of installed storage capacity, for a range of assumed energy storage costs (top horizontal axis) also corresponding to different optimal volumes of energy storage deployed by the model (bottom horizontal axis).

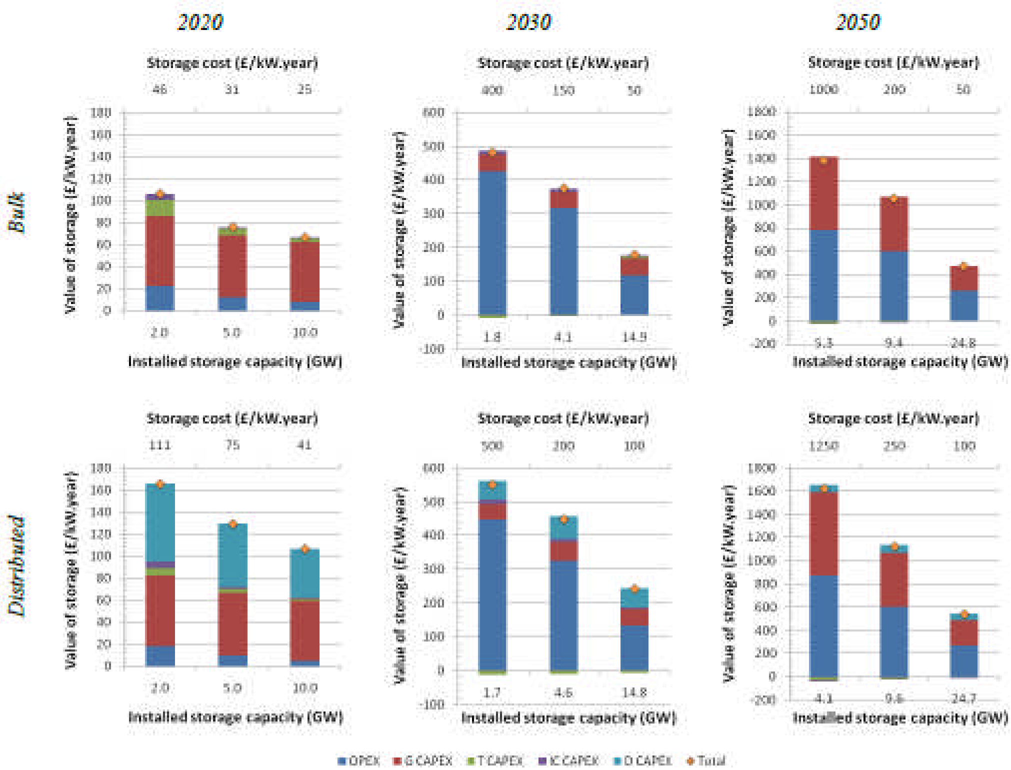
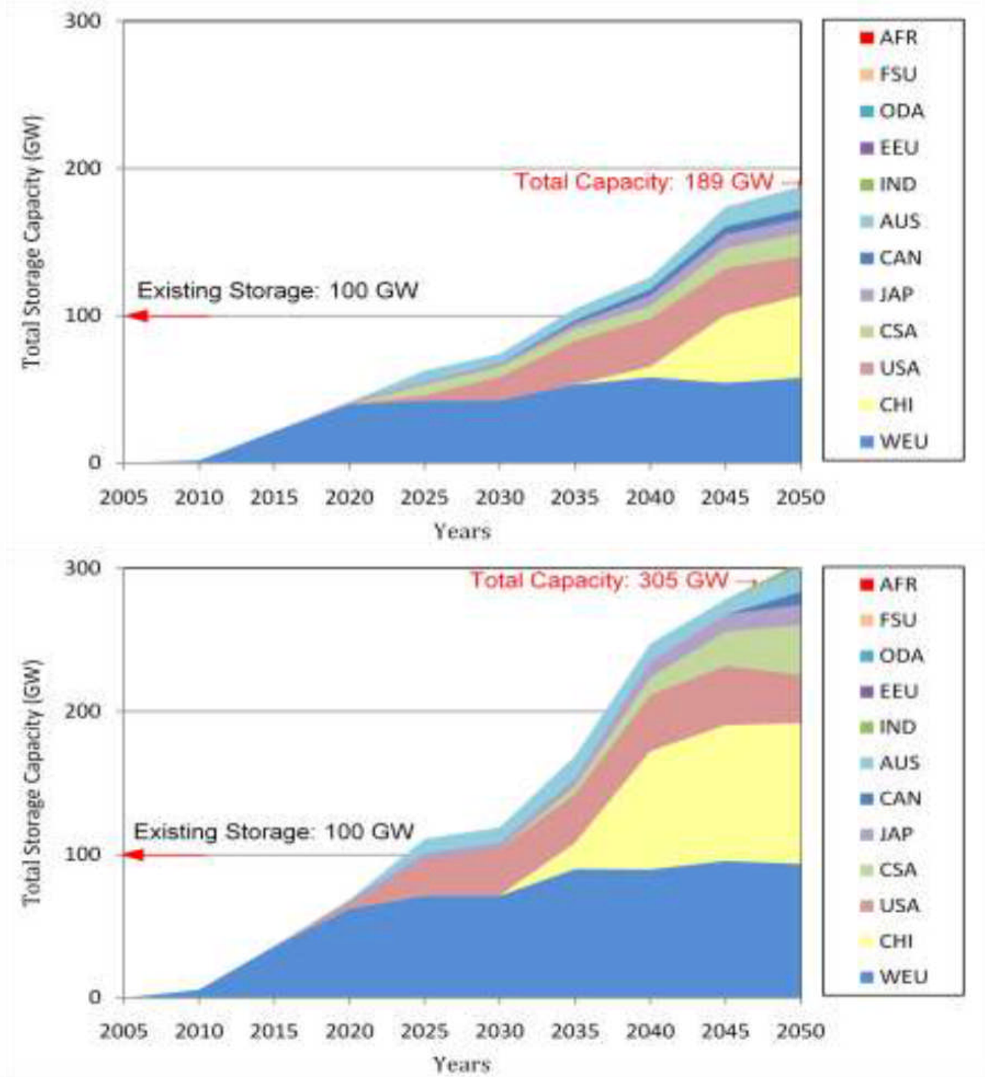


Figure 10 : Value of storage in 2020, 2030 and 2050 [9].

In [2], an estimate on the installed capacity of energy storage systems necessary to accommodate an increasing amount of wind power generation and its associated power variations.is presented The starting point was the generation mix used in the BLUE Map scenario of ETP 2008. The BLUE MAP scenario foresees an increase from about 10% intermittent RES generation in 2010 to about 30% in 2050 in Western Europe. The growth in energy storage capacities required worldwide from 2010 to 2050 to achieve the BLUE Map scenario is shown in Figure 11. It can be inferred that the installed storage capacity strongly increases until 2020 (to about 75% of the installed capacity required for 2050) and then it increases at a much slower pace.



WEU: Western Europe, CHI: China, CSA: Central South America, JAP: Japan, AUS: Australia, IND: India, EEU: Eastern Europe, FSU: Former Soviet Union, AFR: Africa

Figure 11 : Forecasted installed capacity of energy storage systems for wind power variation ratios of 15% and 30% [2].

Reference [48] examines the implications and challenges of renewable electricity generation levels—from 30% up to 90%, with a focus on 80%, of all U.S. electricity generation from renewable technologies—in 2050. The study focuses on some key technical implications of this environment, exploring whether the U.S. power system can supply electricity to meet customer demand with high levels of renewable electricity, including variable wind and solar generation.

Deployment of new storage capacity is observed in all model scenarios, and greater storage deployment is realized in scenarios with greater levels of renewables, and particularly variable renewable penetration. For the (low-demand) core 80% RES scenarios described, 80–131 GW of new storage capacity was installed by 2050 in addition to the 20 GW of existing (PHS) storage capacity. Of the six core 80% RE scenarios, the constrained flexibility scenario projected the greatest level of storage deployment (152 GW of installed storage capacity by 2050) as show in Figure 12. The constrained flexibility scenario was designed to capture greater institutional and technical barriers to managing variable generation, compared to the other 80% RE scenarios modeled. In the constrained flexibility scenario, new storage capacities occur predominantly in the first two decades (2010–2030) of the studied period, with an average annual installation rate of approximately 5 GW/yr and decade-averaged annual capital investments ranging from $4 billion/yr to $11 billion/yr between 2010 and 2030[6]. Note that the results in Figure 12 are optimistic in terms of required storage capacity, also with regard to the results reported in [2] and [47].

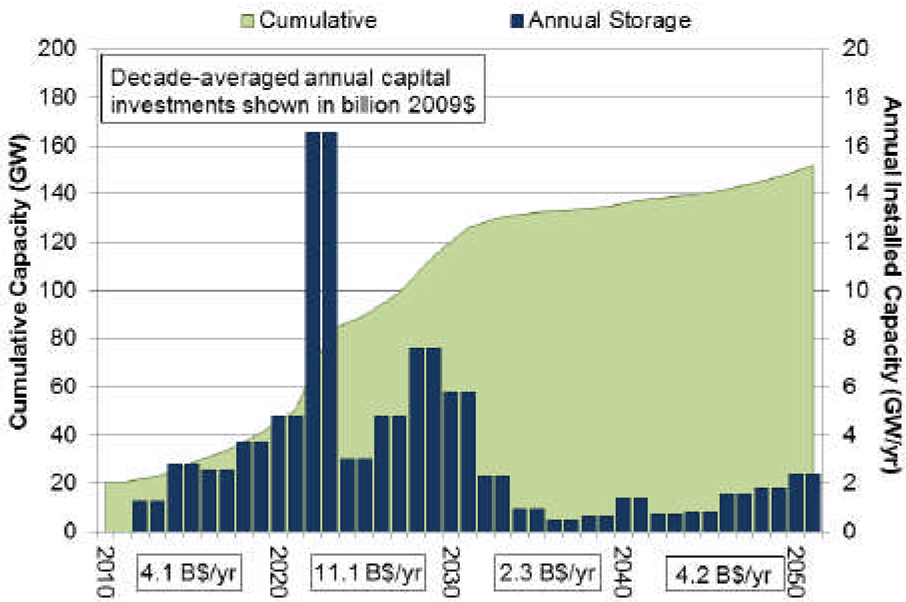


Figure 12 : Deployment of energy storage technologies in the constrained flexibility scenario [48].

In [47], an analysis of the development of the electricity sector in Europe up to 2050 has been carried out. Two scenarios were developed: Scenario A "High efficiency" presumes a very ambitious reduction of electricity demand, whereas scenario B "Moderate efficiency" is based on a moderate reduction of the electricity demand, with higher electricity consumption than in Scenario A.

Figure 13 shows the development of large storage facilities. The available storage capacity increases by ca. 7 GW. This increase is based on projects that are already planned or are under construction. Thereafter storage capacity remains constant in both scenarios. The next step takes place in 2050 when the effective RES-E share increases to more than 90%. Note that building storage facilities makes economic sense only if two conditions are met: there are many hours of excess production and additional grid connections are not feasible because countries with remaining electricity demand in these hours are too far away. In these cases, which can be observed in both scenarios A and B in 2050 for Spain and the UK, building storage capacity is a useful and economic option.

[6] As a result of the modeling assumptions, most of the new storage is CAES; however, the tradeoff between CAES and PHS is largely due to the modeling and data limitations associated with the vast majority of potential PHS in much of the United States. In addition, the relative risk associated with CAES versus PHS was not considered.

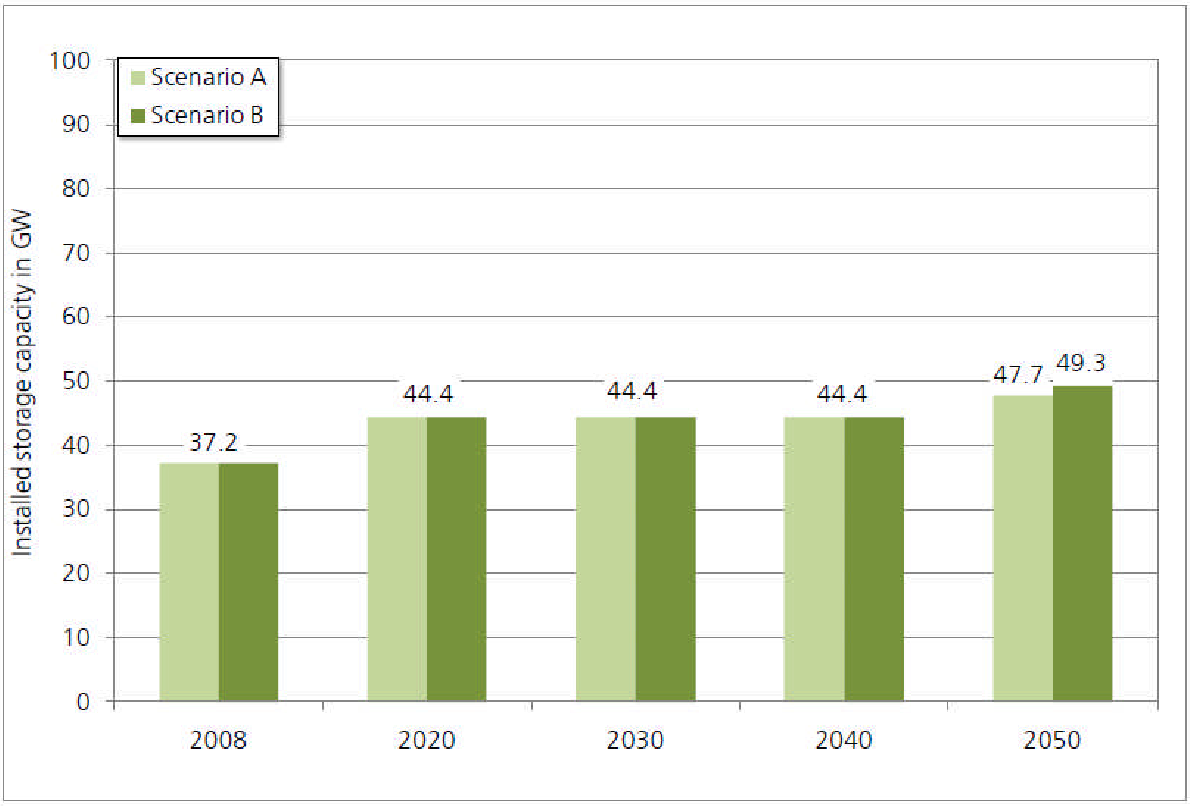


Figure 13 : Development of large storage facilities [47].

10.3 Comparison and trends

The results of the in-depth literature review presented in sections 10.1 and 10.2 are compared and unified in order to obtain an overall picture of and to estimate the future trends of costs and performance. The data for each CAES technology has been extracted from the data found throughout the literature review. Each CAES technology is analyzed separately.[7]

The estimation of the trends is primarily based on numbers obtained from the literature review. The starting point is in general the mean value of the current data range of a variable. In case of rated power and energy, the maximum value of the current data range is used for that purpose. Note also that the development in CAES certainly will slow down at a certain moment of time around 2020 or 2030 (e.g., see Figure 11 to Figure 13). Actually and since diabatic CAES is relatively mature, no significant changes are expected. However, some incremental improvements in existing designs might benefit cost and efficiency figures [51]. Adiabatic CAES are after all expected to increase the efficiency [52].

The estimated trends are used in sections 3 to 9 as a starting point.

10.3.1 <u>Diabatic CAES</u>

Figure 14 shows the projected efficiency. Note that this efficiency refers to the storage efficiency and not to the electrical efficiency. For the 2015 data (corresponding to the existing diabatic CAES plants), and assuming 95% motor and generator efficiency, the electrical efficiency is about 54% (the value reported for the Huntdorf plant). An increase in the first decade can be detected, whereas after 2020 the efficiency does not vary anymore. This trend is used to extrapolate efficiency.

[7] Unless indicated by a source, the graphics shown are a combination of data found by the literature review.

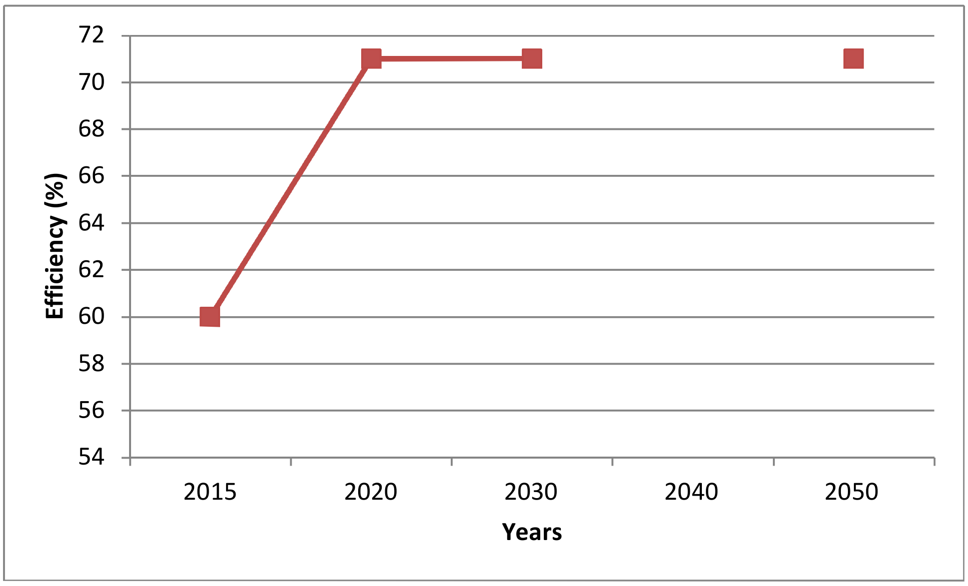


Figure 14 : Trends of efficiency of diabatic CAES [50].

Figure 15 shows the projected availability. The availability remains constant [48]. This can be basically explained by the fact the diabatic CAES consist of mature elements (gas turbine, pumps, etc.). For example, the availability of gas turbines is not supposed to increase significantly [48].

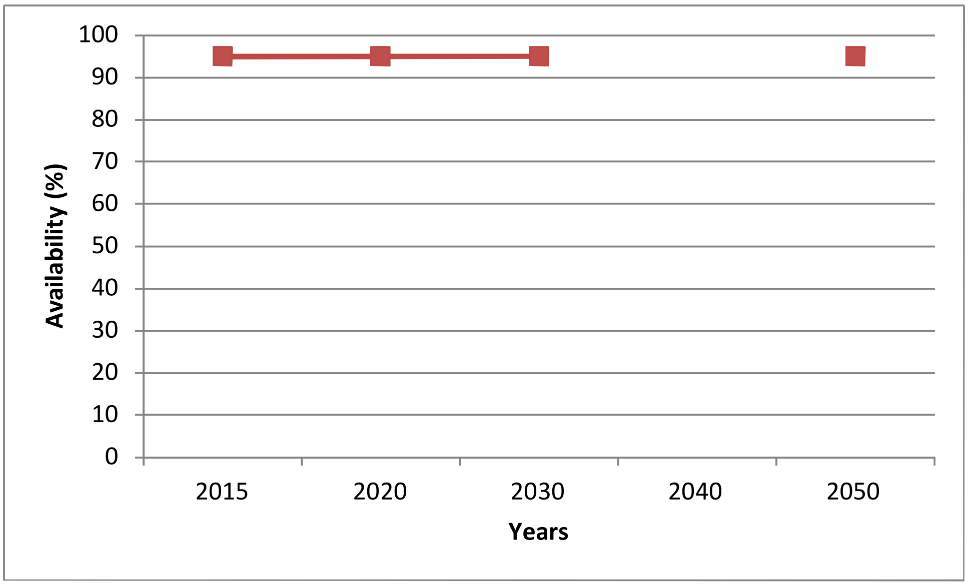


Figure 15 : Trends of availability of diabatic CAES [50].

Figure 16 shows the projected lifespan. Lifespan remains constant. This is mainly due to the fact that most elements such as turbines, pumps, generators, etc. deployed in CAES are mature. These data are used to extrapolate lifespan.

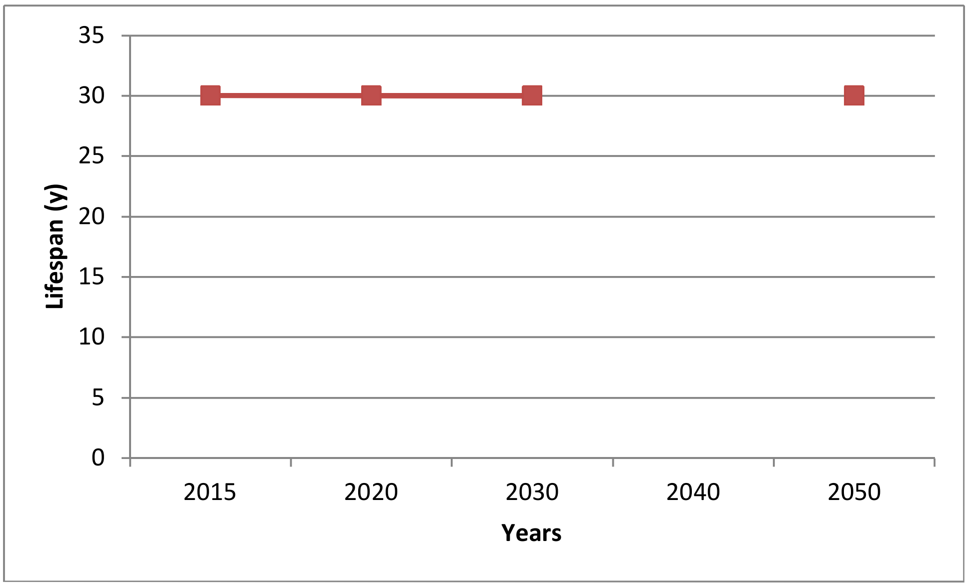


Figure 16 : Trends of lifespan of diabatic CAES [50].

Finally, Figure 17 shows the projected power costs. A clear decrease can be detected in the first decade, whereas after 2020 the power costs remain constant. The trend is used to extrapolate power costs. This is coherent with Figure 11, Figure 12, and Figure 13, where the installed capacity after all increases in the first decade, implicating that a decrease of cost (and in increase in performance) could be expected.

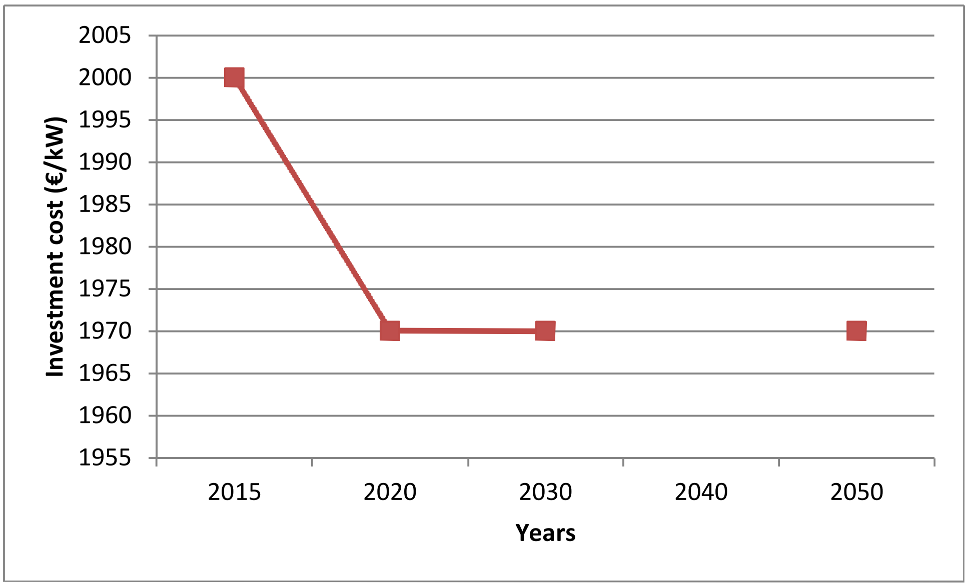


Figure 17 : Trends of investment costs of diabatic CAES [50].

10.3.2 Adiabatic CAES

Adiabatic CAES are expected to improve efficiencies. Figure 18 shows the projected efficiencies. Efficiency remarkably increases during the first decade, whereas after 2020 efficiency improvements slow down. Note that around 2050 efficiencies of adiabatic CAES reach the estimated efficiency potential of 80% of CAES [33].

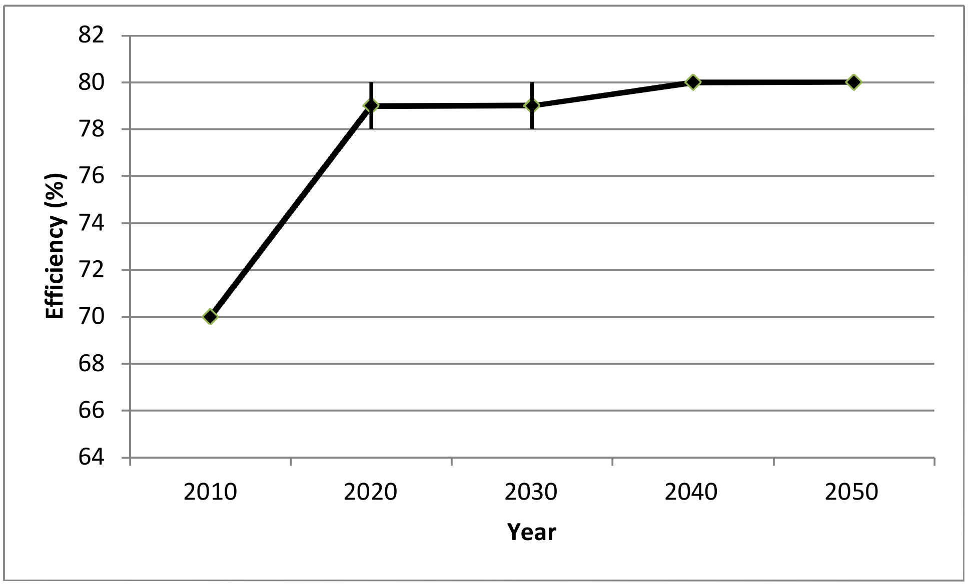


Figure 18 : Trends of efficiency of adiabatic CAES.

Figure 19 shows the projected lifespan. Similarly to diabatic CAES, lifespan does not vary.

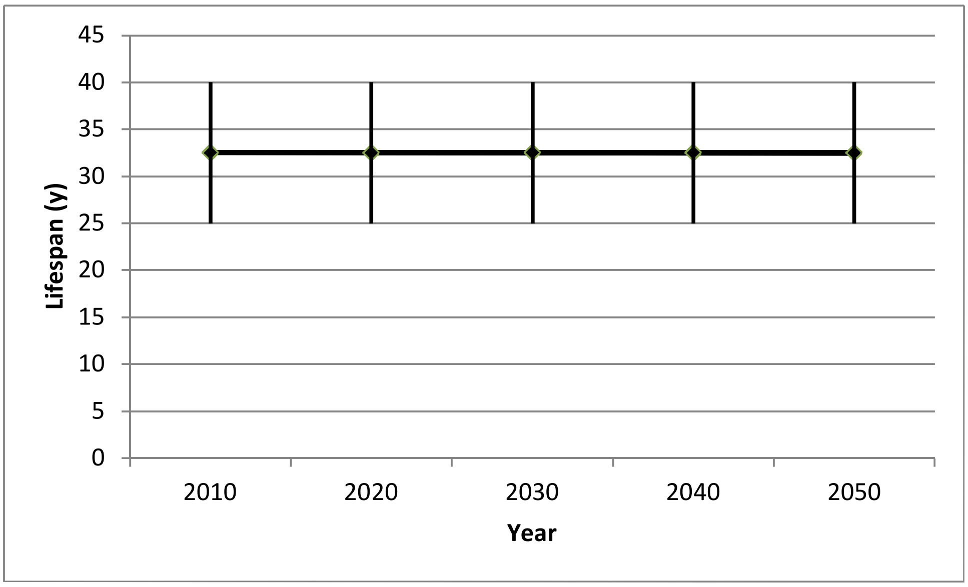


Figure 19 : Trends of lifespan of adiabatic CAES.

Finally, Figure 20 shows the projected power costs. The average value continuously decreases by about 10€/kW per decade, amounting to a reduction of about 10% in 2050 with respect to the current power costs. It is also foreseen that energy costs will also decrease, up to 50% within the next decades [51]. However, since no adiabatic CAES plant are in operation, these values must be taken with care.

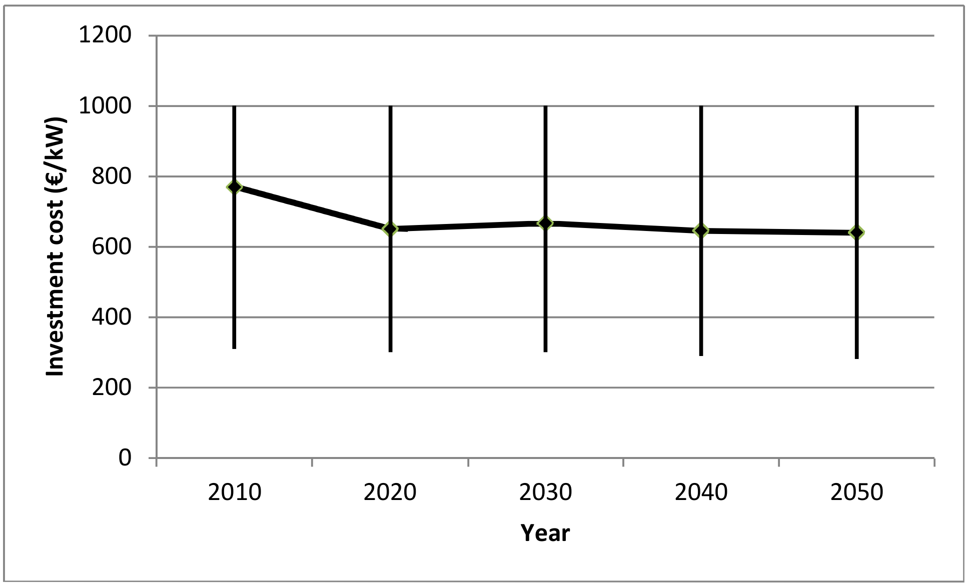


Figure 20 : Trends of investment cost of adiabatic CAES.

11 Conclusions

The main objective of the present document is to provide a collection of information and estimation of trends of compressed air energy storage (CAES) at the time horizon set by the e-Highway project.

Main attention has been paid to diabatic and adiabatic CAES types. These CAESs can be considered already commercial or they are a promising candidate for the time horizon set by the e-Highway2050 project.

Current CAES characteristics have been assessed by means of an in-depth literature review. In addition, trends of both costs and technical parameters from today until 2050 have been estimated by analyzing publications partially or fully covering the time period 2020-2050. The use of several publications allowed contrasting the data and trends found. The analysis and comparison of the published work gave rise to a unified and consistent image on future trends of CAES.

The final set of projected trends of both cost and technical parameters can be found in the accompanying document cited in section 13. Diabatic and adiabatic CAES technologies are separately treated. If possible, all variables described in sections 3 to 9 have been qualified or quantified for the five time horizons (2012, 2020, 2030, 2040, and 2050).

In general, minimum and maximum value of the range of current data has been used to estimate the future trends. The estimation has been obtained by extrapolating or interpolating the data found in the literature review. These data have been previously analyzed and compared to obtain a consistent data set. Around the estimated future trends a certain data range is also projected, accounting for variations within the evolution of the CAES drivers (mainly the evolution of intermittent RES, but also the CAES's own technological evolution and the evolution of the regulatory context). In general, relative flat profiles have been adopted to describe future trends (i.e., current values are mostly assumed for the future time horizons) since CAES technology and after its elements (turbine, pumps, etc.) are already mature. Cost and efficiency figure will see an improvement thanks to a larger market for developing dedicated equipment, improvements in CAES designs, etc.

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13 Attached document

data_CAES_Comillas