CRANFIELD UNIVERSITY

Emanuele BOZZOLANI

Techno-economic analysis of Compressed Air Energy Storage systems

SCHOOL OF ENGINEERING

MSc by Research THESIS

Academic Year: 2009 - 2010

Supervisors: Riti SINGH, Georgios DOULGERIS

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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science

ABSTRACT

The continuous escalation of intermittent energy added to the grid and forecasts of peaking power demand increments are rising the effort spent for evaluating the economic feasibility of energy storages. The aim of this research is the techno-economic analysis of Compressed Air Energy Storage (CAES) systems, capable of storing large quantities of off-peak electric energy in the form of high-pressure air, as an “energy stock” which allows the production of high-profit on-peak electricity when required by the grid.

Several studies of both conventional and innovative adiabatic concepts are carried out in order to identify and improve the parameters that mostly affect the plant performances. Technical models, that consider the effect of time, are developed to evaluate the parameters that reduce the electric energy spent for compressing the air and that maximize the electric energy produced.

In the conventional plant, particular attention is put on the understanding of the effects of air storage pressure range, recuperator, reheating and Turbine Inlet Temperature. For the adiabatic instead, a thorough analysis of the challenging Thermal Energy Storage (TES) is performed for understanding the advantages and drawbacks of this novel efficient concept of CAES.

In a further step the economic analyses are aimed at evaluating the different configurations proposed in the technical investigation and the effects that variations of generation train and storage characteristics have on the profitability. After an analysis of the TES impact on the profits, a final comparison is carried out against two existing technologies: Pumped Hydro Energy Storage and gas turbine.

The results of these studies confirm, from a technical and economic point of view, the reasons of the growing interest toward CAES as a feasible solution to manage the intermittent energy production. In particular they underline the conventional CAES as promising technology to undertake.

Keywords: CAES, Adiabatic-CAES, Air Storage, Energy Storage, Thermal Energy Storage, Peaking Power Plants

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SYMBOLS and NOTATIONS

c_p	specific heat (constant pressure)
c_v	specific heat (constant volume)
γ	gamma ratio (c_p/c_v)
η	efficiency
ε	epsilon (TES)
η_{PE}	Primary Energy Efficiency
η_T	thermal efficiency of a baseload plant
eq.	equation
mln	million
$	dollar
kWh_{th}	kilowatt per hour thermal
kWh_{el}	kilowatt per hour electric

A-CAES	Adiabatic Compressed Air Energy Storage
AC	Aftercooler
AEC	Alabama Electric Corporation
ANCF	Annual Net Cash Flow
BTU	British Thermal Unit (Btu)
C	Compressor
CAES	Compressed Air Energy Storage
CASH	Cascade Air Storage with Humidification
CER	Charging Electricity Ratio
CHP	Combined Heat and Power
CIT	Compressor Inlet Temperature
CO_2	Carbon Dioxide
COT	Compressor Outlet Temperature
const	constant
DH	District Heating
DR	Discount Rate

DP	Design Point
DPB	Discounted Payback Period
ER	Electricity Ratio
ESA	Energy Storage Association
ESP	Energy Storage and Power Corporation
EU	European Union
EVR	Energy Generated per unit Volume of Storage
FAR	Fuel Air Ratio
G	Generator
GHG	Greenhouse Gas
GT	Gas Turbine
HP	High Pressure
HPC	High Pressure Compressor
HPT	High Pressure Turbine
HR	Heat Rate
IC	Indirect Costs
IRR	Internal Rate of Return
LCOE	Levelized Cost of Electricity
LHV	Lower Heating Value
LP	Low Pressure
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
LPG	Liquefied Petroleum Gases
M	Motor
MP	Medium Pressure
MED	Multiple Effect Distillation
MPC	Medium Pressure Compressor
MSF	Multi Stage Flash
MPT	Medium Pressure Turbine
NPV	Net Present Value
O&M	Operation & Maintenance

PB	Payback Period
PEE	Primary Energy Efficiency
PHES	Pumped Hydro Energy Storage
PR	Pressure Ratio
press	pressure
R	Reheated
R-R	Reheated-Recuperated
SFC	Specific Fuel Consumption
T	Turbine
TES	Thermal Energy Storage
TDC	Total Direct Costs
TIP	Turbine Inlet Pressure
TIT	Turbine Inlet Temperature
TOT	Turbine Outlet Temperature
U.S.	United States
var	variable

CHAPTER 1: Compressed Air Energy Storage

1.1 CAES Overview

The continuous increments of intermittent energy represented by solar, wind, tidal power added to the grid and forecasts of increments in the peak load power required, are increasing the effort spent in order to understand the economic advantages of energy storages. The main target is to store large quantities of low-cost off-peak electric energy, produced by any intermittent power sources, but also any low cost electricity sources (nuclear power), and sell it during peak power demand periods. Compressed Air Energy Storage (CAES) is a low cost technology able to provide this, storing large quantities of off-peak electric energy in the form of high-pressure air and generating on-peak electricity when required. Nowadays, several energy storage technologies are available, but for most of them the capacity to provide energy is reduced at a short period of time (Figure 1-1) [1]. CAES and Pumped Hydroelectric Energy Storage (PHES) are the only ones suitable for long duration and utility scale applications, capable of delivering several hours of output at a plant-level power output scale at attractive costs. Differently than CAES, PHES does not require fuel combustion, but it is only economically viable on sites where reservoirs at differential elevations are available or can be constructed. In contrast to this, CAES can use different types of reservoirs for air storage and has a more modest surface footprint giving it greater site flexibility relative to PHES. High-pressure air can be stored aboveground in vessels or pipes, but if large-scale applications are necessary, underground geologic formation, such as salt and hard rock formations, saline aquifers and porous rock formations, are typically more cost effective.

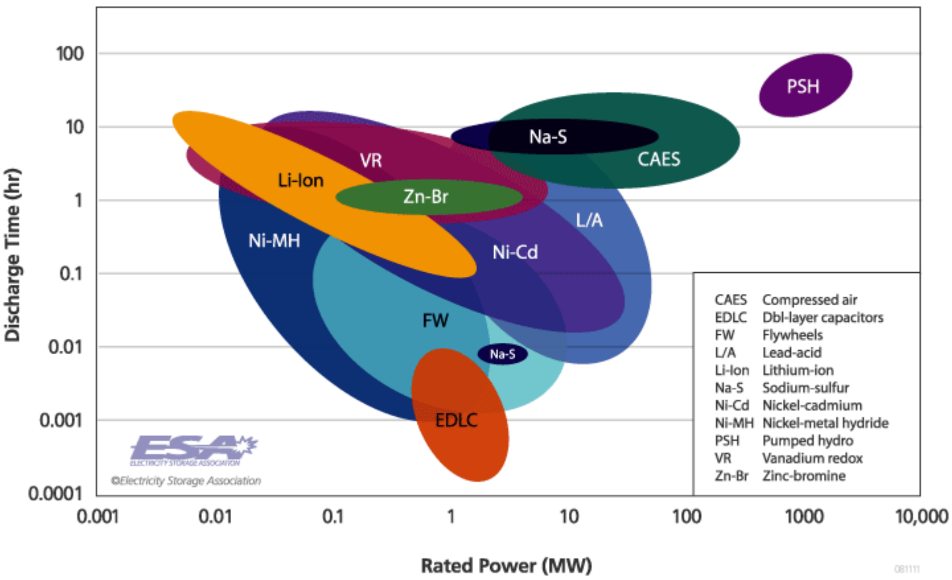

Figure 1-1 Energy Storage Technologies [3]

1.2 CAES Operation

During the compression mode operation, off-peak low-cost electricity is used to run a chain of compressors that inject air into a storage reservoir (Figure 1-2). The air is stored at the temperature of the surrounding formation and at a certain pressure, where the maximum operational value is defined by the particular underground cavern chosen. In order to improve the efficiency of the compression stage and minimize thermal stress on the storage volume walls, intercoolers among the compressors and an aftercooler before the injection into the cavern are used (Figure 1-3). During the expansion mode, for generating on-peak high-cost electricity, air is withdrawn from the storage and a certain amount of fuel (typically natural gas) is combusted. The combustion avoids icing risk for the blades at the turbine outlet and that the turbine materials and seals might become brittle. Furthermore, in the absence of fuel combustion and air temperature at the wall temperature of the reservoir, the plant would necessitate much higher air flow in order to achieve the same turbine output reducing the generation time and the power generated, so the performance indices of the plant [1].

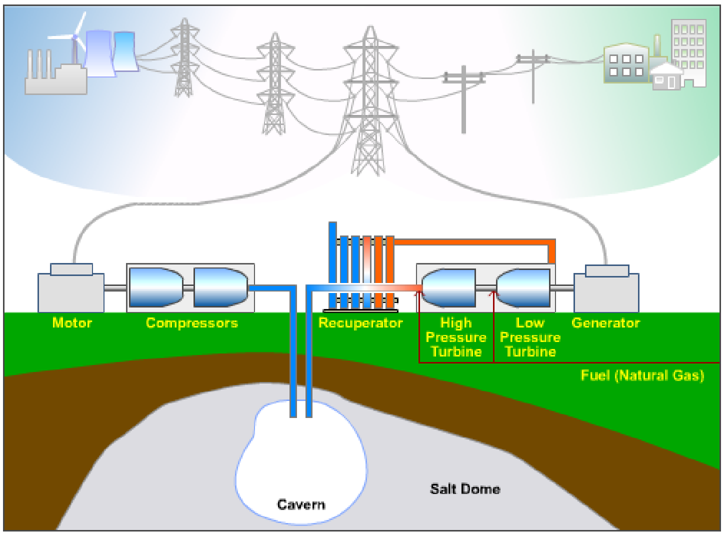

Figure 1-2 CAES concept [1]

Differently than a conventional gas turbine engine where compression and expansion happen contemporarily and two thirds (55-70%) of the output power from the expansion stage is used to run the compressor, in CAES systems they occur independently and at different times (Figure 1-4). This means that the full turbines power can be used to generate electricity during expansion, while the compressor charging system will be sized to match the electric energy sources (nuclear power plants or intermittent energy sources) and maximize the performance of the CAES (see 2.9). With regard to the turbines, being independent from the compressor train, they have a very high ramp rate, so the system can be brought on line responding to system changes very quickly and helping very slow base load plants. Because the plant is controlled by varying air flow rate, maintaining the operating temperatures well below the capabilities of metallurgy and TITs of the standard gas turbine machines, the consequence is an high reliability of the CAES [4, 6]. CAES also permits to run coal fired and nuclear units at full capacity rather than reducing or shutting down the units during off-peak power periods, with economic benefits (operating costs of the units are reduced) and improvements in the reliability and efficiency [6].

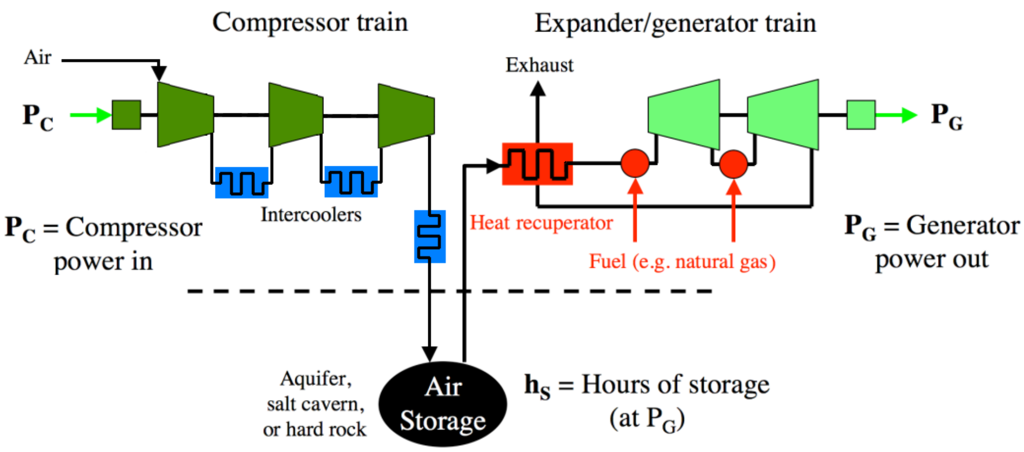

Figure 1-3 CAES System

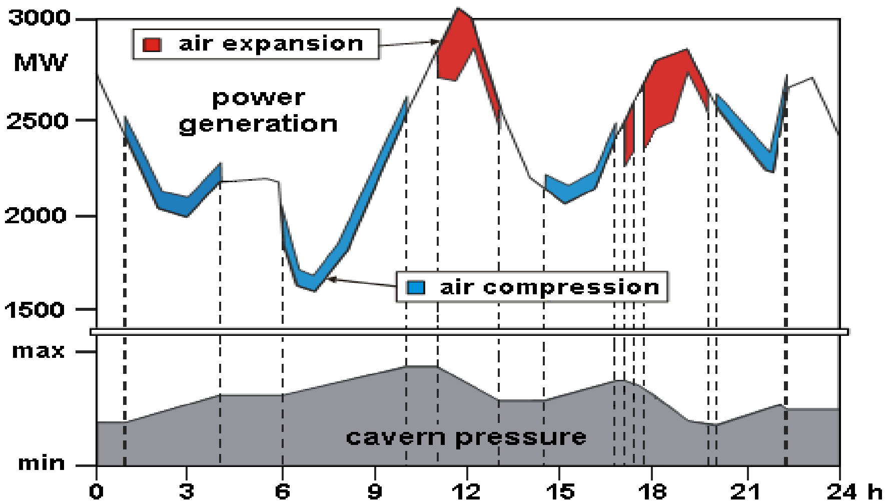

Figure 1-4 CAES operation during a day [8]

1.3 CAES plants

The technological concept of CAES is more than 40 years old and in the 1970s the first investigation about their feasibility started as a means to provide energy during the peak demand and the transition time needed from base load plant to reach the operative point. So far, 2 commercial CAES plants are present in the world: the world's first plant is the 290 MW plant belonging to E.N Kraftwerke, Huntorf, Germany, built in 1978, and the 110 MW plant of AEC (Alabama Electric Corporation) in McIntosh, Alabama, USA, commissioned in 1991 (Table 1-1). After these plants, the investigation process has not stopped and several demonstrative plants have been built and will be built, testing different CAES configurations and the feasibility with different reservoirs [1, 2]. Some pilot plants have been built in Japan, Italy and in USA; in USA the research on CAES is active and funds are available to study techno-economic aspects and the so-called "Advanced second generation CAES" [3]. In Europe, the idea to develop CAES is increasing due to the increment of intermittent energy sources [14]. Outside Europe, in Israel and Russia, plants have also been proposed [5].

Table 1-1 Existing commercial CAES plants [3]

location	Huntorf, Germany	McIntosh, USA
commissioned	1978	1991
storage volume	two cilindrical salt caverns, each of 150000 m^3	salt cavern 540000 m^3
input energy	60 MW over 12 hours	50 MW over 41 hours
output energy	290 MW over 3 hours	100 MW over 26 hours
energy required for 1 kWh_{el}	0,8 kWh electricity	0,69 kWh electricity
	1,6 kWh gas	1,17 kWh gas
pressure tolerance	43-70 bar	45-76 bar
remark	World's first CAES plant	first CAES plant with recuperator

1.3.1 Huntorf

The Huntorf plant with its 290 MW of energy produced was designed and built to provide black-start services to nuclear units near the North Sea and to provide inexpensive peak power. Designed with a storage volume capable of two hours of output, was subsequently modified to provide up to three hours of storage and help balance the rapidly growing wind output from North Germany [8].
The underground cavern used consists of two caverns (310000 m^3 total) in a salt dome formation and is designed to operate between 48 bar and 66 bar (see Figure 1-5). The compression stage composed of two compressors injects air inside the cavern with a rate of 108 kg/s, while the expansion, also composted of two stages, operates withdrawing air with a rate of 417 kg/s. The first turbine stage expands air from 46 to 11 bar, the second one from 11 bar to ambient pressure. Because the technology was not compatible with pressures so high, a steam turbine technology was chosen for the High-Pressure (HP) expansion stage, unfortunately reducing a lot the performance of the plant. The choice to maintain the HP Turbine Inlet Temperature to only 550 °C was done for two different reasons: first one due to the steam turbine technology used and the second one to facilitate the daily turbine starts needed for CAES operation [1, 8]. For the Low-Pressure (LP) turbine a conventional gas turbine with TIT of 825 °C (without cooling technology) has been used. Although the plant would be able to operate at a lower Heat Rate if equipped with heat-recuperator able to reduce the fuel

consumption as made in the McIntosh plant, this addition was omitted in order to minimize system start up time [9, 10].

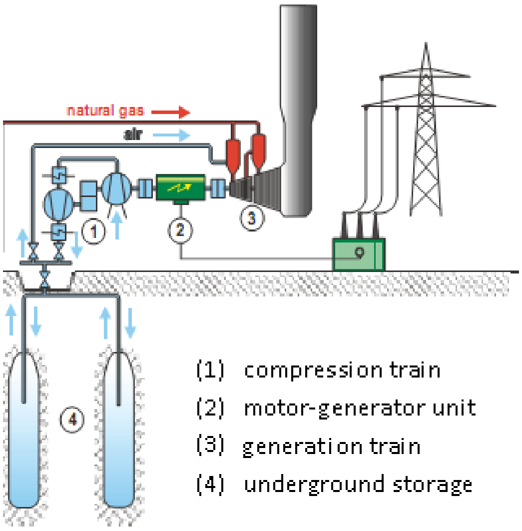

Figure 1-5 Huntorf design [8]

1.3.2 McIntosh

The 110 MW McIntosh plant, developed by Dresser-Rand, has been in operation since 1991 and has many of the operational aspects (inlet temperatures, pressures, etc) of the Huntorf plant (Figure 1-6). This plant, using a salt dome cavern of 560000 m^3 and operating in a pressure range between 45 bar and 74 bar, is able to generate 26 hours of energy at 100 MW. Differently than Huntorf plant, this includes an heat recuperator that reduces fuel consumption by approximately 26% at full load output and a dual-fuel combustor able to burn No. 2 fuel oil in addition to natural gas [1, 20].

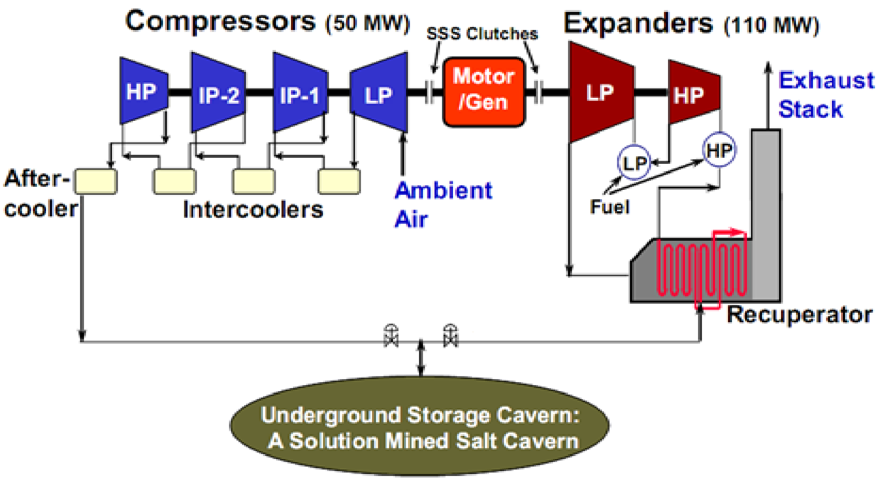

Figure 1-6 McIntosh design [20]

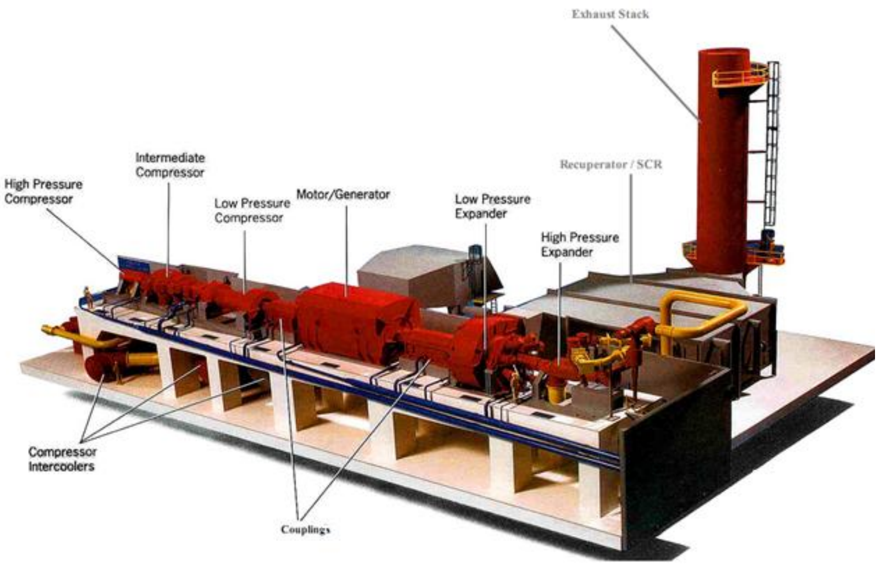

Figure 1-7 McIntosh plant [50]

1.3.3 Future plants

A series of commercial CAES plants have been proposed. The first one will use an idle limestone mine in Norton, Ohio for an 800 MW CAES facility (with provisional plans to expand to 2700 MW [9 x 300 MW]). The mine, should provide 9,6 million m^3 of storage and should operate in a pressure range between 55 and 110 bar. In Iowa, the Iowa Association of Municipal Utilities is developing an aquifer CAES project in Dallas Center directly coupled to a wind farm. The Iowa Stored Energy Park will use a 900 m deep anticline in a porous sandstone formation; the location chosen is the third studied after an initial screening of more than 20 geologic structures in the state. Studies of the chosen formation have verified it has adequate size, depth and caprock structure to support CAES operation [11].

In Texas, due to the increment of the wind penetration, the necessity to improve the electric transmissions and the presence of salt dome formations, have been announced plans to develop several CAES projects, including a 540 MW (4x135 MW) system in Matagorda County, based on the McIntosh Dresser-Rand design and utilizing a previously developed brine cavern.

Studies of the Electric Power Research Institute (EPRI) indicate that up to 80% of the United States has geology that would be suitable for an underground CAES reservoir; EPRI also believes there could be 20 to 50 CAES plants of different sizes in operation by 2020, supporting the rapidly emerging renewable energy market in America [13].

1.4 Adiabatic Compressed Air Energy Storage

The Adiabatic-CAES (A-CAES) is based on the same concept of the described CAES, but with the singularity that does not need fuel to operate [14, 15]. In an A-CAES the heat produced during the compression is not wasted, but extracted using heat-exchangers and stored inside the so-called Thermal Energy Storage (TES). During the expansion phase the stored heat is returned to the compressed air withdrawn from the cavern, avoiding the use of combustors and fuel. Due to the high pressures in the expansion train, steam turbines derivative are required (Figure 1-8). Although this process has known for 30 years, only in the last years, with developments in the technology, more and more intermittent energy usable, increment of fuel price and forecasts of CO_2 tax, has became attractive. On the basis of the system used to store the heat, two different A-CAES configurations can be defined.

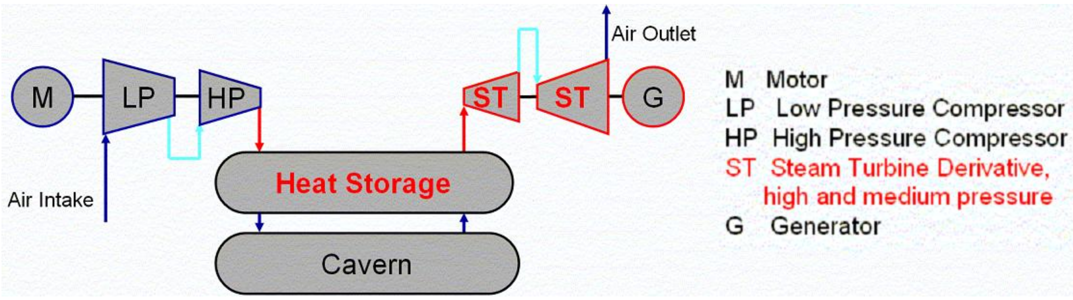

Figure 1-8 Adiabatic - CAES concept [15]

In the first one (Figure 1-9) the heat is transferred to the storage by an indirect heat-exchange [16, 17]. The heat produced during the compression is transferred to the cold medium (oil or molten salt) by heat-exchangers and stored inside the hot tank. Subsequently when on-peak power is required, the compressed air inside the formation is withdrawn and going through heat-exchangers acquires the heat previously given to the hot tank. The air is expanded through the turbines releasing electric power. During the generation the hot fluid, after having given the heat back to air, is stored in the cold tank till the next compression phase. In this configuration the temperature reached are not high and the tanks operate with fluid that is not under pressure. Disadvantages of such configuration are the requirement of two tanks, the cost of the working fluid and corrosion issues. Moreover molten salt can not change phase, so it needs to be maintained liquid using an heating system, that consumes energy [28].

A second configuration has been proposed with the European project “ADELE” [18]. The A-CAES will have a storage capacity of 1 GWh and it will be able to provide up to 200 MW within a very short time, replacing forty state-of-the-art wind turbines for a period of five hours. In this configuration the two tanks are substituted with only one where a direct heat-exchange between air and a solid medium happens. Differently than the previous case no intercoolers are used and the compressor outlet temperature has to reach the highest value possible. The maximum temperature stored in the TES defines the TIT used in the generation, and in order to get the highest output power possible, it needs to be the highest that can be reached. Value of 650 °C in a range of pressure of 6 MPa to 10 MPa is the aim for this plant [14]. The other real challenge for this plant is not represented only by the compression, but also by the TES, because this storage must be strong enough to resist at high pressures of air that exchanges the heat with the medium. Estimated costs for A-CAES are supposed less than 800 €/kW [14].

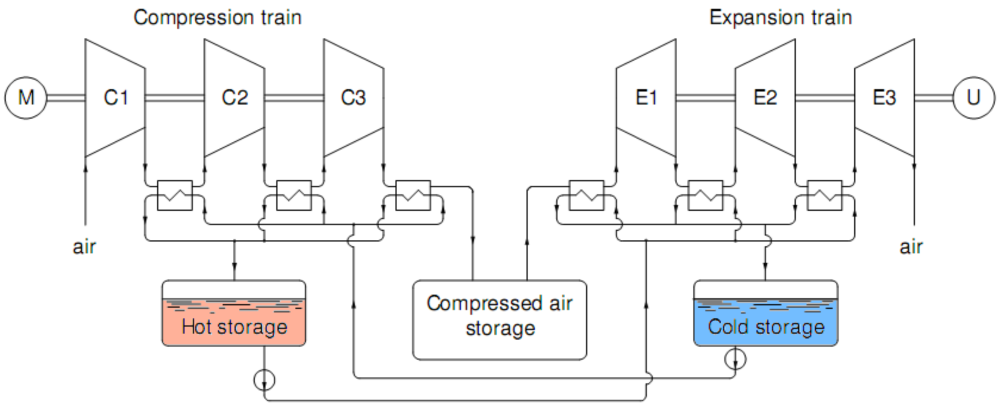

Figure 1-9 A-CAES with indirect heat-exchange [16]

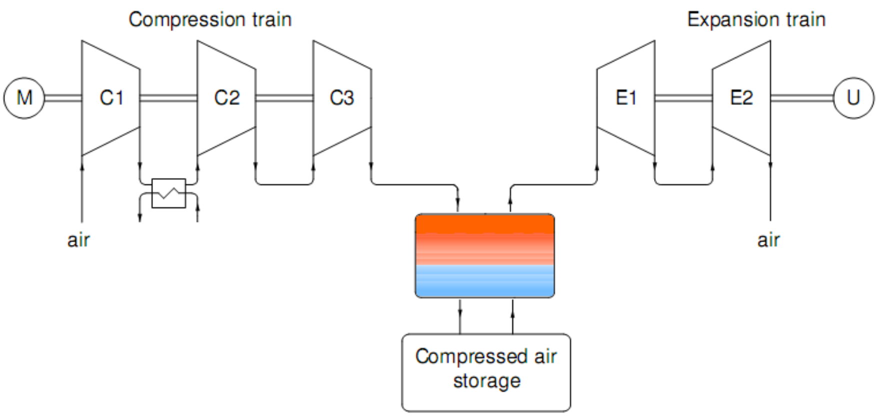

Figure 1-10 A-CAES with direct heat-exchange

1.5 Suitable storages for CAES applications

Different storages are suitable for CAES applications and they are represented by aboveground tanks and underground formations such as salt, hard rock, and porous rock formations. In Appendix A, Figures A-1 and A-3 show maps that report the availability of underground formations suitable for CAES in U.S. and Europe.

1.5.1 Salt formations

Caverns in these formations are the most straightforward to develop and operate, and the knowledge acquired in the storing of high pressure hydrocarbon products ranging from LPG's (Liquefied Petroleum Gasses) to natural gas (methane) can be easily transferred to the air storage. The underground salt deposits may exist in two possible forms: salt domes and salt beds. Salt domes are thick formations created from natural salt deposits that, over time, have realized sedimentary dome-type structures (Figure 1-11). Salt beds instead are shallower, thinner formations. Because salt beds are wide, thin formations and with higher concentration of impurities, once a salt cavern is introduced, they are more prone to deterioration. Because may also be more expensive to develop than caverns in salt domes, they are not the first option for storing natural gas or air. Salt cavern can be built with a solution mining technique, able to provide a reliable, low cost route to develop a storage volume of the needed size (typical cost is about 2 $/kWh generated from storage). The technique consists of using water to dissolve and extract a certain amount of salt from the deposit, leaving a large empty space in the formation (Figure 1-12). When this technique is used, an adequate supply of fresh water and a place to treat the resulting brine is necessary [1, 2]; due to the different composition of the formations, a series of surveys are required in order to define the right place to create the cavern. If the right composition is found, due to the elasto-plastic properties of salt, the cavern walls will have the structural strength of steel, which make them very resilient against reservoir degradation over the life of the storage facility and posing minimal risk of air leakages [8]. The cavern volume averages around 160000 m^3 to 3,2 million m^3, typically much smaller than aquifers, but with deliverability typically higher than aquifers. Therefore, air in a salt cavern may be more readily and quickly withdrawn, and caverns may be replenished with air more quickly than other storage facilities. The possibility to maintain the same mass flow both in the salt cavern and in the aquifers can be achieved using in the aquifers more wells; this increases the capital costs of the plant [7].

Figure 1-11 Storage inside a salt dome formation

1.5.1.1 Brine disposal

The biggest challenge in the solution mining and the first element to evaluate before doing this process is the disposal of the brine produced [11]. The amount is about 8 volumes of brine to make 1 volume of cavern. The solutions for the disposal could be different and depending on the environment: a solution is the injection into deeper formations, but this depends on the availability near the site of good porosity reservoirs.

Others solutions could be the transport by pipelines or by truck to ocean, low-rate release into rivers during high-water events, evaporation in ponds. The possibility to use the brine in industrial application may be considered [20].

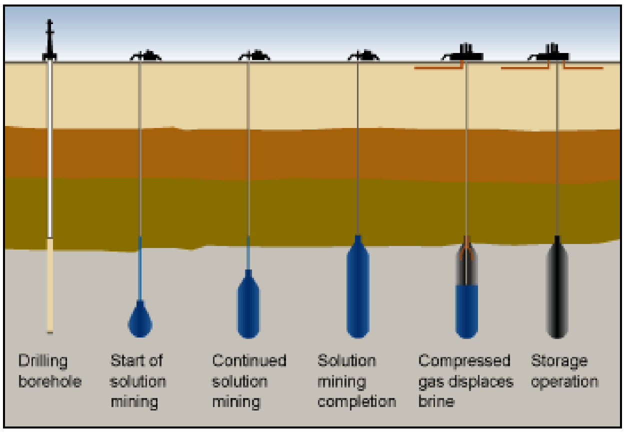

Figure 1-12 Solution mining technique [12]

1.5.2 Hard rock formations

Hard rock formation is the second possibility, even if costs of mining a new reservoir is relatively high (typically 30 $/kWh produced). Hard rock caverns usable for CAES application can be in the range 300 m up to 1500 m depth, even if depths between 450 m and 750 m are more cost-effective. The presence of existing mines might increase the feasibility, reducing the cost to about 10 $/kWh produced, as in the proposed Norton CAES plant [1, 21]. Because the availability of existing caverns and abandoned mines is limited, and the costs to develop an hard rock cavern are higher than other geologies this option is not evaluated as a first possible solution for future CAES plants. Similarly to salt caverns, hard rock formations may give revenues from the sale of the extracted material.

1.5.3 Porous rock formations

Although the previous geologies are good solutions, porous rock formations such as saline aquifers look more suitable and may offer the best near-term opportunities for CAES development. Porous reservoirs have the potential to be the least costly storage option for large-scale CAES with an estimated development cost of about 0,11 $/kWh for incremental storage volume expansion [1]. Despite its potential for low cost development, utilization of an aquifer requires extensive characterization of a candidate site to determine its suitability [22]. In saline aquifer the air is injected at pressure higher than the hydrostatic pressure in order to create a bubble which displaces from the wellbore region a certain water volume equal to the air volume injected (Figure 1-13) [23]. In this bubble a certain amount of air is not cycled (cushion) and remains permanently in the reservoir, this ensures that the water/air interface remains well away from the wells preventing coning. Once water has encroached on a well, it is very difficult to re-establish the air bubble around that well, minimizing its usefulness. Elements to evaluate in order to define the operative air pressure in the cavern, the wellhead pressure, the air mass flow injected and withdrawn, are formation thickness, rock permeability and porosity, depth and caprock characteristics [7]. Therefore, these parameters define the number of wells necessary [6]; wells that are connected to the aboveground machinery by a gathering system.

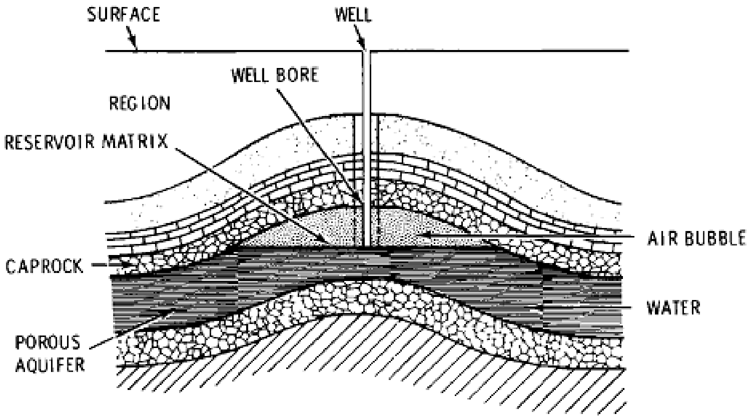

Figure 1-13 Aquifer structure [23]

1.5.4 Underground formations risk analysis

Different risks may happen when an underground formation is used for CAES applications, therefore surveys in order to study oxidation and corrosion are realized; for example, air injection into porous formations can lead to reaction of oxygen with native species and consequent reduction of oxygen concentration in the stored air. The oxygen can also lead to reactions among several mineral species with various outcomes [24]. Other risks in CAES is the deterioration of wellbore tubulars and casing cement through corrosion. Prominent corrosion types include biological, galvanic, pitting, erosion, stress corrosion cracking, fatigue and fretting corrosion. Corrosion by air injection might be further in high-pressure and high-temperature conditions, especially if significant moisture is present. Although coatings and linings might mitigate some of the corrosion effects, care must be taken to carefully monitor the condition of all piping and well materials. When particulates are generated around the wellbore, they can be carried in the air flow to the turbomachinery where they might damage the turbine blades and other sensitive equipment. The ability of the air to transport particles depends on the air flow rate, the particle size distribution and the distance of particle formation from the wellbore [7]. In the end, it can be mentioned the water effects that might enhance the corrosion rate, so it might be desirable to dehydrate the air before being injected through the generation train [7].

1.5.5 Aboveground storages

Aboveground storages have been proposed in order to overcome the problems to find the right formation in the place where the energy storage is required. As visible in Figure 1-14 there are different aboveground storage solutions, represented by vessels and pipelines. The main difference between the underground formation and the storage in HP piping is that the latter has significantly higher maximum storage pressure in order to reduce the volume required and the costs. Proposed aboveground storages for CAES able to generate 20 MW for 3 to 5 hours, are also composed of buried pipes with a diameter of about 1,2 m and with different lengths (3,7 km to 9,7 km) that define the amount of mass that can be stored. These man-made volumes can achieve values of 11300 m^3, much smaller than the volume of an underground formation; so in order to store the maximum amount of air possible the pressure values can be up to about 14 MPa, while the minimum can be till 5 MPa [37]. Risks connected to this storage are the thermal and cyclic fatigue of the structure. Moreover analysis on the corrosion due to the air that cools and deposits moisture inside the storage are still in progress [66].

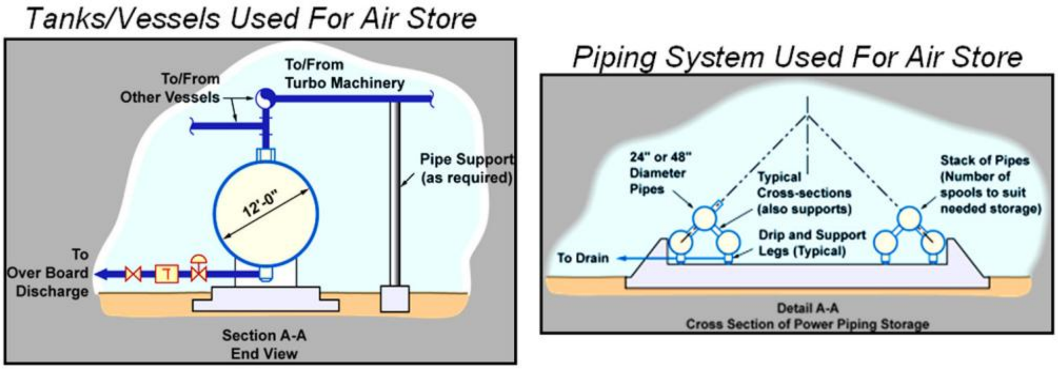

Figure 1-14 Aboveground storage configurations [66]

1.5.6 Constant Volume and Constant Pressure

For the reservoirs two possible operative modes can be chosen: constant volume or constant pressure. The most common mode is to operate the CAES under constant volume conditions: this means that the volume is fixed and the reservoir operates inside a certain pressure range. In this operative mode two different solutions can be implemented:

- allow to the HP Turbine Inlet Pressure to vary with the cavern pressure
- keep the HP Turbine Inlet Pressure constant by throttling the upstream air to a fixed pressure

Although this second option due to throttling losses requires a larger storage volume, it has been implemented in both of the existing CAES facilities due to the increase in turbine efficiency attained for constant inlet pressure operation. The Huntorf plant is designed to throttle the cavern air to 4,6 MPa, while the McIntosh system throttles the air to 4,5 MPa [8, 20].

The constant pressure operative mode instead needs to use an aboveground reservoir of water (Figure 1-15). The use of compensated storage volumes minimizes losses and improves system efficiency, but the nature of the cavern and so-called “champagne effect” must be considered [3, 25]. The cavern for this technique is hard rock caverns; in fact, since water would dissolve walls of the cavern, this technique is incompatible with salt-based caverns.

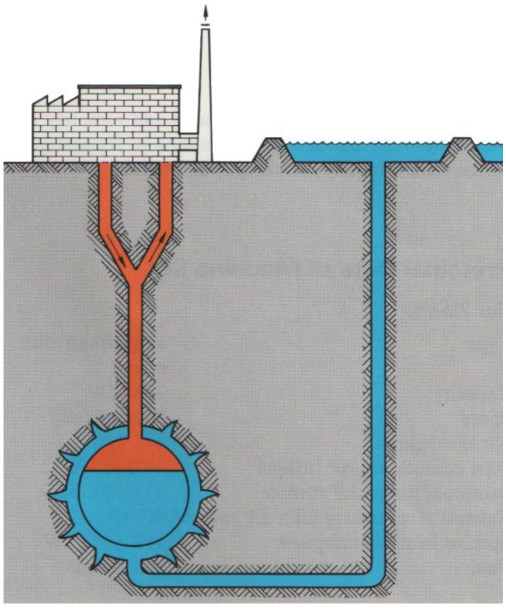

Figure 1-15 CAES with constant-pressure reservoir [59]

CHAPTER 2: CAES Components Models

In order to analyse the performance of the CAES, equations used to model conventional gas turbine engine components plus specific equations for CAES applications, have been implemented and are presented here.

2.1 Working Fluid Properties (Dry air and combustion products)

Gas properties of a working fluid have a powerful impact upon the performance of the engine, so they have to be considered as much accurate as possible. In the models, a constant value of gamma (ratio of the specific heat at constant pressure to that at constant volume, $\gamma = c_p/c_v$) for air and for combustion products are considered, while the c_p is variable and depends on the mean temperature within each component (i.e. the arithmetic mean of the inlet and outlet values) reducing the error committed [26]. A value for air gamma equal to 1,40 and for the exhaust gas equal to 1,33 are assumed. For the air c_p instead, the following equation is used inside the Matlab® models [26]:

$$\boldsymbol{cp = A0 + A1 * T + A2 * T^2 + A3 * T^3 + A4 * T^4 + A5 * T^5 + A6 * T^6 + A7 * T^7 + A8 * T^8} \quad (1)$$

Where T is static temperature divided by 1000 and the constant elements are the values reported in Appendix B (Table B-1).

When an hydrocarbon fuel is burnt in air, combustion products change the composition significantly. In order to calculate the c_p of combustion products burning kerosene the following equation is used [26]:

$$\boldsymbol{cp = A0 + A1 * T + A2 * T^2 + A3 * T^3 + A4 * T^4 + A5 * T^5 + A6 * T^6 + A7 * T^7 + A8 * T^8 + \frac{FAR}{1+FAR} * (B0 + B1 * T + B2 * T^2 + B3 * T^3 + B4 * T^4 + B5 * T^5 + B6 * T^6 + B7 * T^7)} \quad (2)$$

Where FAR is the Fuel Air Ratio using kerosene (see 2.7), T is the static temperature divided by 1000, the constants A0–A8 are the values in Appendix B (Table B-1) for dry air and B0–B8 the constant in Table B-2. The trends of c_p assumed by the combustion products in a combustion with kerosene are reported in Appendix B (Figure B-2).

Because more and more plants operating with gas turbine engine and the two CAES plants burn natural gas, less pollutant than coal or other fuels, the model of the combustion with natural gas is done. Knowing FAR and c_p in a combustion with kerosene one is able to calculate the c_p in combustion with natural gas using the experimental equation derived from [26] and presented in Appendix B (Figure B-1).

2.2 Filter and Intake

Before the compressors, a filter is considered. In the models the temperature along the intake does not change; for the pressure, a certain percentage of losses is considered by the following equation [26]:

$$\boldsymbol{compressor\ inlet\ pressure = ambient\ pressure} * (\mathbf{1} - \boldsymbol{pressure\ losses}) \tag{3}$$

2.3 Motor

In the models an electric motor operating at constant power is chosen; knowing the power transferred to the compressor train and the mechanical efficiency of the transmission, the air mass flow through the compressor train is obtained as follows [26]:

$$\boldsymbol{air\ mass\ flow} = \frac{\boldsymbol{Electric\ Input\ Power} * \boldsymbol{mechanical\ efficiency}}{\boldsymbol{Specific\ Compressor\ Work}} \tag{4}$$

2.4 Compressors

The purpose of a compressor is to increase the total pressure of the gas stream to that required by the cycle while absorbing the minimum shaft power possible. In order to calculate the temperature increment within the compressor, the following equation is used [27]:

$$\Delta \boldsymbol{T} = \boldsymbol{COT} - \boldsymbol{CIT} = \frac{\boldsymbol{compressor\ inlet\ temperature}}{\boldsymbol{isentropic\ efficiency}} * \left[\left(\frac{\boldsymbol{outlet\ pressure}}{\boldsymbol{inlet\ pressure}}\right)^{(\boldsymbol{\gamma}-\mathbf{1})/\boldsymbol{\gamma}} - \mathbf{1}\right] \tag{5}$$

Where the ratio outlet pressure to inlet pressure is the Pressure Ratio (PR) and γ is the value chosen for cold air. It is assumed that isentropic efficiency is function only of corrected mass flow. Characteristics of efficiencies in a compressor train composed of two and three compressors is represented in Appendix B (Figure B-5 and Figure B-6). For defining the corrected mass flow, the following equation is used:

$$\boldsymbol{corrected\ mass\ flow} = \boldsymbol{mass\ flow} * \frac{\sqrt{\boldsymbol{R} * \boldsymbol{inlet\ temperature}}}{\boldsymbol{inlet\ pressure}} * \frac{\boldsymbol{ref\ pressure}}{\sqrt{\boldsymbol{ref\ R} * \boldsymbol{ref\ temperature}}} \tag{6}$$

Where inlet temperature and pressure are the values taken at the compressor inlet, R (R specific) is the gas constant for air; reference pressure, reference temperature and reference R are values taken at International Standard Atmosphere conditions (for air). In order to generate the efficiency characteristics of each compressor, the following relationship is chosen to do a scaling of the corrected mass flow:

$$\boldsymbol{mass\ flow}_{\boldsymbol{Scaling\ Factor}} = \frac{\boldsymbol{mass\ flow}_{\boldsymbol{DP}}}{\boldsymbol{mass\ flow}_{\boldsymbol{DP\ map}}} \tag{7}$$

Defined the temperature rise with equation (5), the specific work [kJ/kg] and electric power [kJ/s] required to drive the compressor can be found [26]:

$$\boldsymbol{Specific\ Work = air\ c_p * compressor\ temperature\ rise} \tag{8}$$

$$\boldsymbol{Power = air\ mass\ flow * air\ c_p * compressor\ temperature\ rise} \tag{9}$$

2.5 Storage

The storage is represented by the equation that considers pressure changes in a constant volume, bearing in mind the mass flow injected and withdrawn:

$$\frac{\partial\, p_{volume}}{\partial\, t} = \frac{\gamma\, R\, T_{volume}}{Volume} * (\dot{w}_{in} - \dot{w}_{out}) \tag{10}$$

Where γ is gamma for the fluid inside the volume at a certain temperature

R is the specific Gas Constant [air] (287,058 J/kg K)

T_{volume} is the temperature inside the volume [K]

$\dot{w}_{in}$ is the air mass flow injected into the volume [kg/s]

$\dot{w}_{out}$ is the air mass flow withdrawn from the volume [kg/s]

Because compression and generation happen in different times, the equation (10) can be split in the two following ones:

$$\frac{\partial\, p_{cavern}}{\partial\, t} = \frac{\gamma\, R\, \dot{w}_{in}\, T_{cavern}}{V_{cavern}} \tag{11}$$

$$\frac{\partial\, p_{cavern}}{\partial\, t} = -\frac{\gamma\, R\, \dot{w}_{out}\, T_{cavern}}{V_{cavern}} \tag{12}$$

The equation (11) for the storage pressure increment during the compression, while (12) for the pressure decrease during the generation stage.

2.6 Heat-Exchangers

2.6.1 Intercoolers and aftercooler

Intercoolers are realized fixing the air temperature at the inlet of the next compressor, considering that a river is able to cool down the temperature to a certain value, that has to be the lowest possible in order to minimize the input energy required (3.1.5.3). For the aftercooler, the river cools down the air temperature up to the average temperature recorded in the storage; the value is due to the particular geologic characteristics of the formation (3.1.6).

2.6.2 Recuperator

The recuperator is represented using the equation of effectiveness of an heat-exchanger [26], that for CAES systems can be simplified and implemented as follows:

$$\boldsymbol{effectiveness\ \varepsilon = \frac{recuperator\ outlet\ temperature - cold\ cavern\ air\ temperature}{LP\ turbine\ outlet\ temperature - cold\ cavern\ air\ temperature}} \tag{13}$$

In order to calculate the heat-transfer area A of an heat exchanger (used in the economic analysis), the following equations have to be implemented in all the intercoolers and in the recuperator used:

$$\dot{\vartheta} = UA\Delta T_{log\ mean} = UA\frac{(T_{in\ hot} - T_{out\ cold}) - (T_{out\ hot} - T_{in\ cold})}{2}$$
$$= [\dot{m} * c_p * (T_{out} - T_{in})]_{cold} = -[\dot{m} * c_p * (T_{out} - T_{in})]_{hot} \quad (14)$$

where $\dot{\vartheta}$ is heat-transfer rate of an exchanger and depends on its design and the properties of the two fluid streams, U is the overall heat-transfer coefficient that represents the ability to transfer heat between the fluid streams and $\Delta T_{log\ mean}$ is the average effective temperature difference between the two fluid streams over the length of the heat exchanger. According to [20] and [30] a value of U equals to 310 W/m^2K is assumed.

2.7 Combustors

In order to calculate the output power produced in the generation train, c_p of combustion products and the fuel mass flow need to be defined; so FAR has to be calculated. Calculated FAR with kerosene (eq. 15), the equation in Appendix B (Figure B-1) permits to derive the FAR with natural gas. Figure B-3 and Figure B-4 present temperature rise versus FAR and combustor inlet temperature for the combustion with kerosene. The charts in Appendix B and the eq. 15 are calculated with a Lower Heating Value (LHV) of kerosene equal to 43124 kJ/kg and a combustion efficiency of 100%; if other values were used, the temperature rise or FAR should be factored accordingly.

$$FAR\ 1 = 0{,}10118 + 2{,}00376 * 10^{-5} * (700 - Combustor\ Inlet\ Temperature)$$

$$FAR\ 2 = 3{,}7078 * 10^{-3} - 5{,}2368 * 10^{-6} * (700 - Combustor\ Inlet\ Temperature) - 5{,}2632 * 10^{-6} * TIT$$

$$FAR\ 3 = 8{,}889 * 10^{-8} * |TIT - 950|$$

$$FAR = \frac{\left(FAR1 - \sqrt{FAR1^2 + FAR2} - FAR3\right)}{combustion\ efficiency} \quad (15)$$

This equation is modified for the different configurations considered: in the reheated train the temperature of the HP combustor inlet temperature is the storage temperature; in the reheated-recuperated train instead, the HP combustor inlet temperature is the recuperator outlet temperature. From now on, with “reheated” is indicated the generation train without recuperator, but supplied with the only combustor of reheating; with “reheated-recuperated” a generation train also supplied of a recuperator is considered. The inlet temperature for the combustor used in the reheating is the Turbine Outlet Temperature (TOT) of the previous turbine.

Knowing FAR with kerosene, LHV of kerosene, LHV for sample natural gas (48120 kJ/kg), the FAR with sample natural gas is represented by the following equation [26]:

$$\boldsymbol{FAR\ Natural\ Gas} = \frac{\boldsymbol{FAR * LHV\ kerosene * (1{,}0001 + 0{,}9248 * FAR - 2{,}2078 * FAR^2)}}{\boldsymbol{LHV\ natural\ gas}} \quad (16)$$

2.8 Turbines

In a conventional gas turbine engine the turbine extracts power from the gas stream to drive both compressors and electrical generator; in the CAES, the turbines drive only the electric generator, with the above mentioned benefits (1.2). In the turbine, the temperature variation due to expansion of gas is represented by the following equation [26]:

$$\Delta\boldsymbol{T} = \boldsymbol{TIT} - \boldsymbol{TOT} = \boldsymbol{isentropic\ efficiency} * \boldsymbol{TIT} * \left[\boldsymbol{1} - \left(\frac{\boldsymbol{1}}{\boldsymbol{pressure\ ratio}}\right)^{(\boldsymbol{\gamma}-\boldsymbol{1})/\boldsymbol{\gamma}}\right] \quad (17)$$

Differently than the compressors, the isentropic efficiency of the turbines is chosen constant, even if calculation with different values are done in order to evaluate the performances changes. Knowing the temperature difference, the turbine power can be calculated, using the mass flow through the machine and the gas stream c_p, by the following equation [26]:

$$\boldsymbol{Turbine\ Power} = \boldsymbol{gas\ mass\ flow} * \boldsymbol{gas\ c_p} * (\boldsymbol{TIT} - \boldsymbol{TOT}) \quad (18)$$

In the models, losses at the outlet of the generation train are considered, so a lower total expansion pressure ratio is achieved.

2.9 Performance Indices

2.9.1 Heat Rate

In order to evaluate the performances of CAES plants, some indices are proposed in the literature [1]. The first is the Heat Rate (HR) or fuel consumed per kWh of output; even if it is function of many system design parameters, the design choice that most affects the HR is the presence of a heat recovery system. The recuperator allows the system to capture the exhaust heat from the LP turbine to preheat the air withdrawn from the storage reservoir. HRs for CAES plants without a recuperator system are typically 5500-6000 kJ/kWh LHV (e.g. 5870 kJ/kWh LHV for the Huntorf). HRs with a recuperator are typically 4200-4500 kJ/kWh LHV (e.g.4330 kJ/kWh for the McIntosh). If compared with conventional gas turbine, CAES systems can achieve a much lower HR because compression energy is supplied separately [1, 2, 7]. In a conventional gas turbine the two thirds of the electric output used to run the compressor increases the level of fuel consumption at about 9500 kJ/kWh LHV. Equation 19 defines the Heat-

Rate, where η_M is the mechanical efficiency of the turbine train (which reflects turbine bearing losses) and η_G is the electric generator efficiency.

$$\boldsymbol{Heat\ Rate = 3600 * \frac{Fuel\ mass\ flow * LHV\ natural\ gas}{\eta_m * \eta_G * generated\ turbines\ power}} \tag{19}$$

2.9.2 Specific Fuel Consumption

The Specific Fuel Consumption (SFC), expressed in kg of fuel required to kWh of output, is the mass of fuel needed to provide the net power. The equation, similar to eq. 19, does not take into account the LHV of the fuel:

$$\boldsymbol{SFC = 3600 * \frac{Fuel\ mass\ flow}{\eta_m * \eta_G * generated\ turbines\ power}} \tag{20}$$

2.9.3 Charging Electricity Ratio and Electricity Ratio

The Charging Electricity Ratio (CER) is the performance index for CAES equals to the ratio of generated output energy to electric input energy (eq. 21). The CER for conventional CAES with combustion is greater than unity and typically is in the range of 1,2 to 1,8 (kWh output/kWh input) [1]. CER has to be as higher as possible, because higher will be the output power sold to the grid.

$$\boldsymbol{CER = \frac{generated\ energy}{input\ energy} = \frac{\eta_m * \eta_G * turbines\ power * discharge\ time}{electrical\ power * charge\ time}} \tag{21}$$

From CER is possible to define the Energy Ratio (ER), equal to the ratio of electric input energy to generated output (kWh input/kWh output). This index smaller than unity, gives the amount of electric energy necessary to create a kWh output (it does not take into account the fuel energy) [7]:

$$\boldsymbol{ER = \frac{input\ energy}{generated\ energy} = \frac{electric\ input\ power * charge\ time}{\eta_m * \eta_G * turbines\ power * discharge\ time}} \tag{22}$$

2.9.4 Efficiency

The simplest efficiency for a CAES plant is defined as ratio of electric energy generated to the sum of electric input energy and fuel thermal energy [7]:

$$\boldsymbol{efficiency = 100 * \frac{generated\ energy}{electric\ input\ energy + fuel\ thermal\ energy}} \tag{23}$$

$$\boldsymbol{100 * \frac{generated\ energy}{electric\ input\ energy + LHV * fuel\ mass\ flow * discharge\ time}}$$

2.9.5 Primary Energy Efficiency

When CAES is used to convert baseload power into peaking power it can be introduced the Primary Energy Efficiency (PEE), that bears in mind the thermal efficiency of the baseload plant η_T (Table 2-1). The electric input energy is replaced by the expression that considers the effective thermal input energy required to produce the electric energy.

Thus, the overall efficiency value reflects the system efficiency of converting primary energy into electric energy.

$$\boldsymbol{Primary\ Energy\ Efficiency = 100 * \frac{generated\ output\ energy}{\frac{electric\ input\ energy}{base\ load\ plant\ efficiency} + fuel\ thermal\ energy}} \quad (24)$$

Table 2-1 Thermal efficiency of baseload plants [7]

baseload power plant	**η_T (%)**
Nuclear power plant (LWR's cycle)	33
Nuclear power plant (AGR's cycle)	42
Fossil fuel power plant	42
Combined Heat and Power plant	35
Grid-averaged baseload power	35

2.9.6 Energy Generated per unit Volume of Storage

In CAES there is also an index that allows to understand the amount of electric Energy generated per unit Volume of storage capacity (EVR = $E_{GEN}/V_{STORAGE}$). The electric output energy produced by the turbines (E_{GEN}) is given by the following equation:

$$\boldsymbol{E_{GEN} = \eta_m * \eta_G * \int_0^{discharge\ time} Turbine\ Power * dt} \quad (25)$$

Discharge time is the time between the initial open of the valve at full cavern pressure and the moment in which the cavern has reached the minimum operative pressure. On the basis of the configuration applied in the storage (constant pressure or constant volume), the value of energy generated per unit volume changes following trends similar to those proposed in Figure B-7.

CHAPTER 3: CAES Technical Analysis

3.1 CAES Parameters Analysis

3.1.1 Introduction

The reference plant considered for the technical evaluation uses an underground formation and the simplest CAES configuration. The compression train is composed of two compressors, one intercooler and one aftercooler, while the generation train consists of two combustors and two turbines. Figure 3-1 shows this configuration supplied also of recuperator. The aim of this section is to collect and compare results from the different models in order to analyse the effects of each parameter on the plants performances, and to identify which are the sensitive parameters to improve. Table 3-1 shows the parameters used in the reference case [7, 8]. The analysis is based on the idea of changing only the required parameter, keeping all the others constant. In Appendix D, Tables D-1 and D-2 show some results obtained using inside the models created the values of the existing plants.

Table 3-1 Parameters of the reference model

Parameters	value	Unit
ambient pressure	101325	Pa
ambient temperature	288,15	K
compressors mechanical efficiency	0,97	
intercooler outlet temperature	298,15	K
DP compressor mass flow	110	kg/s
input electric power	60	MW
cavern temperature	308,15	K
cavern volume	310000	m³
minimum cavern pressure	4,7	MPa
maximum cavern pressure	6,6	MPa
air mass flow withdrawn	410	kg/s
LHV fuel (natural gas)	48120	kJ/kg K
combustors efficiencies	99,5	%
combustors pressure losses	3	%
1^{st} Turbine Inlet Temperature	823,15	K
2^{nd} Turbine Inlet Temperature	1098,15	K
turbines isentropic efficiency	0,85	
exhaust pressure losses	4	%
recuperator effectiveness	0,75	

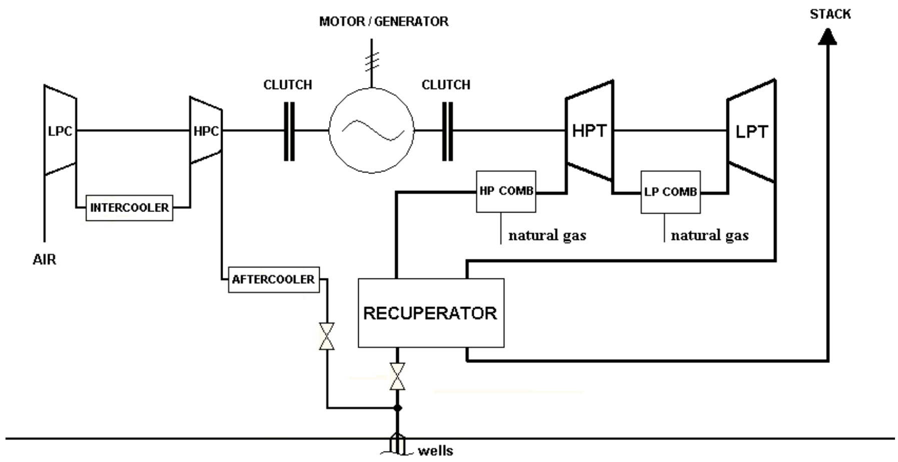

Figure 3-1 Reference case design

3.1.2 Ambient conditions

Similarly to the gas turbine power plant, the performances of CAES are affected by the ambient conditions. Figure 3-2 and Figure 3-3 show that the trends of CER and efficiency decrease with ambient temperature. This is due to the compression train; density decreases and the compressor train needs more power to compress the same amount of air mass. If the input power is kept constant, the air mass flow decreases (Figure 3-5), increasing the charge time (Figure 3-6) and subsequently input energy (Figure 3-2) and ER (Figure 3-4). Therefore, the installation of CAES in hot areas such as Texas could be characterized by lower efficiency than mild areas such as Europe. However, it is worth mentioning that this plant could operate in compression during the night when the ambient temperature is lower, reducing the input energy and increasing CER, efficiency and revenues. Unlike combustion turbines which significantly decrease the power output and increase the HR with hot conditions, in CAES, power output and HR are not sensitive, since the air is supplied from the underground storage, where the temperature is almost constant. For the above mentioned reasons, EVR does not change with ambient temperature.

Figure 3-2 shows that the CER of the reheated-recuperated cycle is lower than the only reheated one. In the models is done the assumption that the valve pressure and the air mass flow through the HP turbine are constants. Because the recuperator reduces the temperature difference between the HP combustor inlet temperature and the HP TIT, less fuel is required, reducing both the mass flow through the turbines and the exhaust gas c_p (eq. 18). Since the output power is composed of all these elements (eq. 20), the CER becomes lower for the configuration with recuperator. It should be noted that the recuperator reduces the output power also because of the pressure losses along the pipes of the heat-exchanger. According to the literature [1] and [20], an average reduction of fuel consumption of about 27% can be achieved; in the current calculation, a reduction of about 28% is found. It is obvious that this increases the plant efficiency.

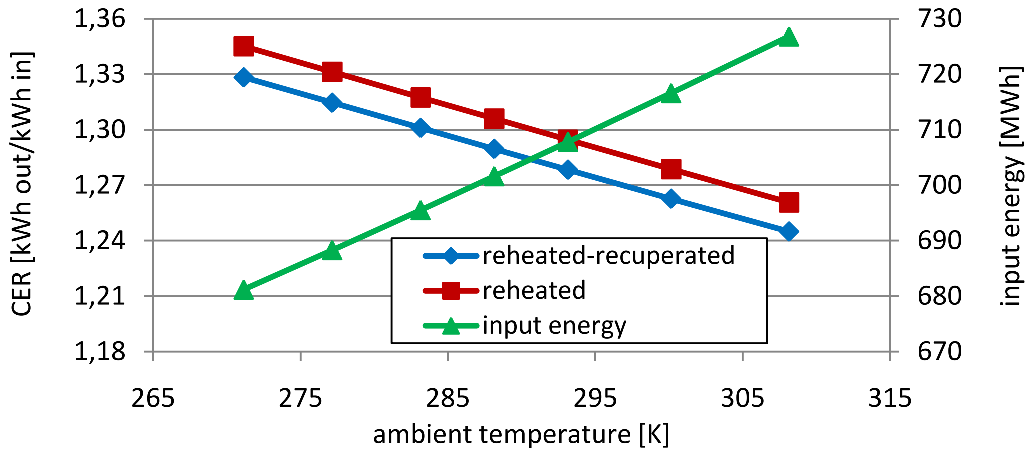

Figure 3-2 Input energy and CER versus ambient temperature

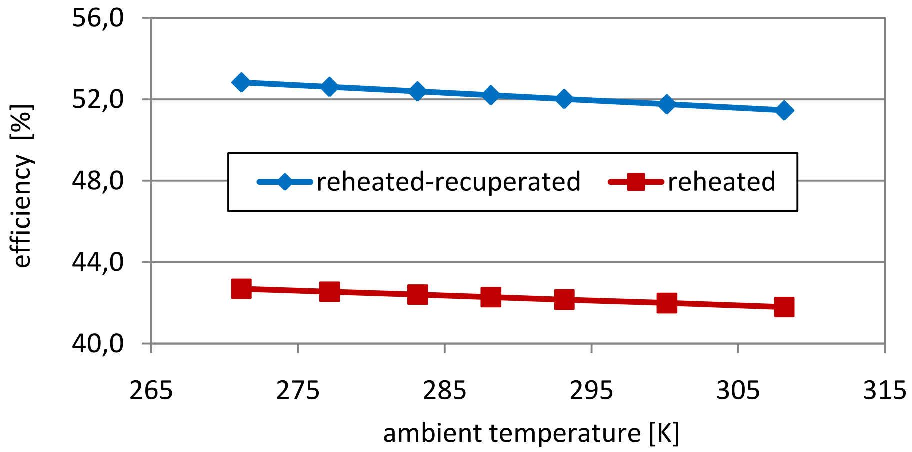

Figure 3-3 Efficiency versus ambient temperature

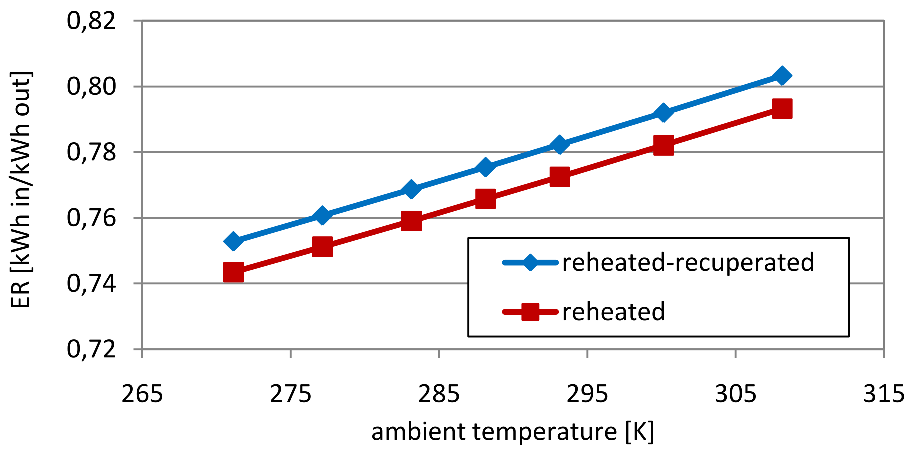

Figure 3-4 ER versus ambient temperature

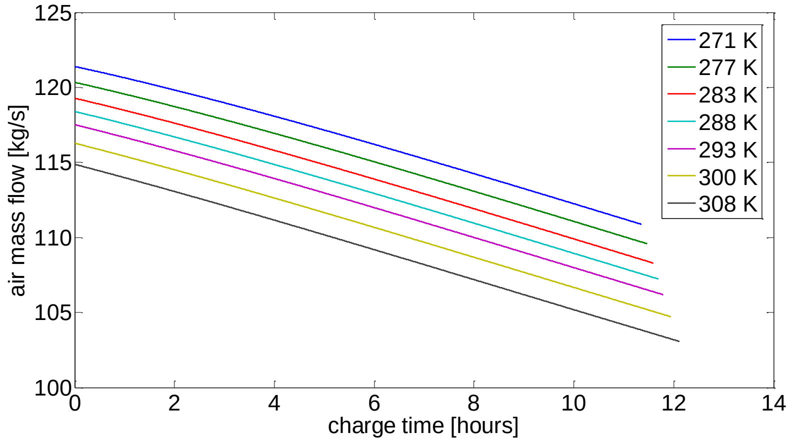

Figure 3-5 Injected mass flow for different ambient temperatures

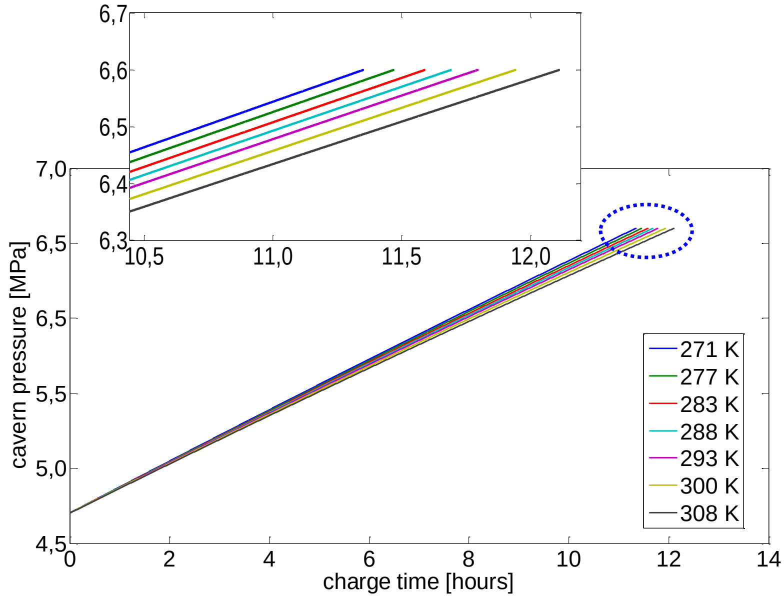

Figure 3-6 Cavern pressure for different ambient temperatures

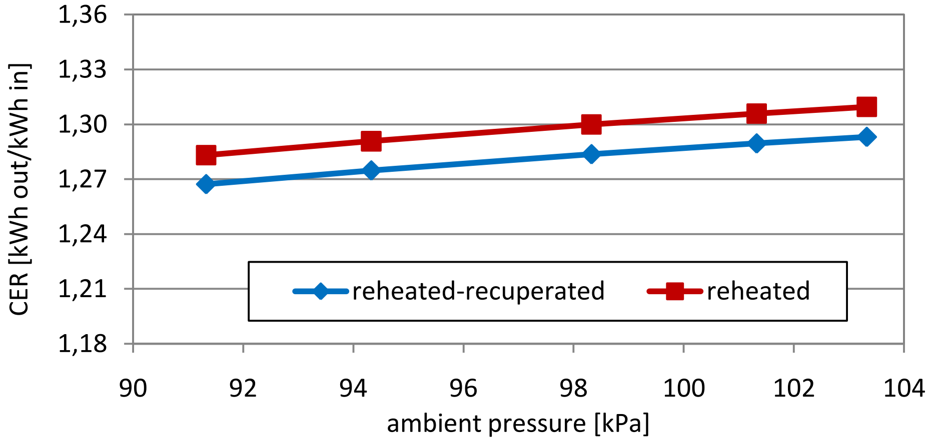

Figure 3-7 CER versus ambient pressure

Changing the ambient pressure, the efficiency does not change significantly. It assumes a value of about 42% for the reheated train and 52% for the reheated-recuperated train. Differently than ambient temperature, the increment of ambient pressure increases the CER (Figure 3-7); in fact, increments in the pressure have the benefits to reduce the input energy required to run the compressor because of higher air density. On the other hand, pressure increments reduce the expansion ratio and the output power; this is the reason why EVR goes down (Figure 3-8).

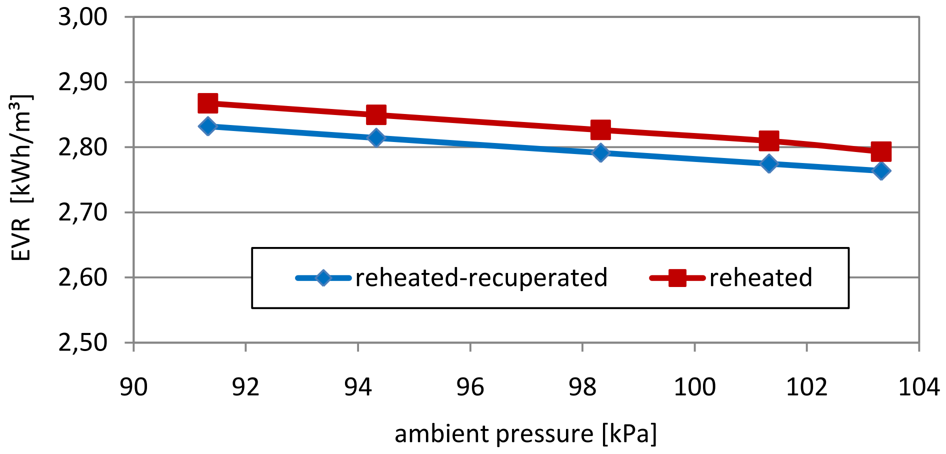

Figure 3-8 EVR versus ambient pressure

3.1.3 Filter

The filter losses slightly reduce the plant performances. The compressor inlet pressure drops down increasing the input energy required (Figure 3-9 shows the ER increment) to inject air inside the storage, and reducing efficiency and CER.

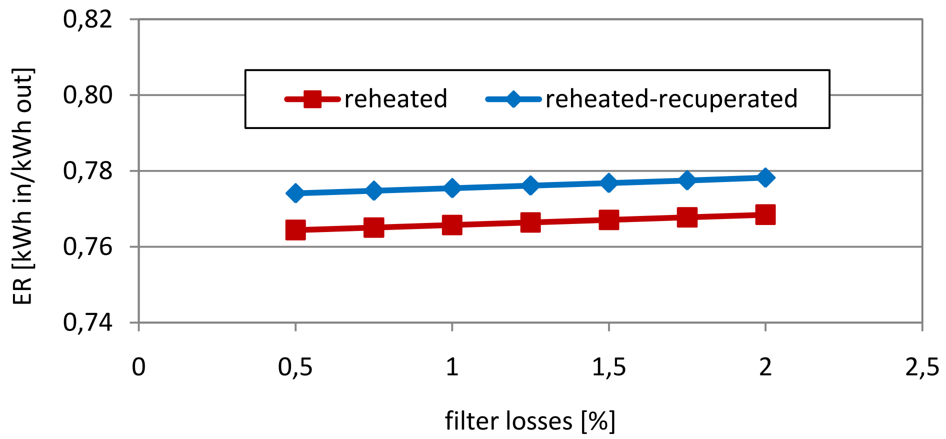

Figure 3-9 ER versus filter losses

3.1.4 Input electric power

A compressor train with the same structure of the Huntorf plant and DP air mass flow of 110 kg/s is chosen. Figure 3-10 and Figure 3-11 show the effects on the efficiency and on the CER of input electric power changes; an optimum in the region of 60 MW (similar to the Huntorf plant) is found. For the efficiency (Figure 3-10) the variation is less significant than CER because it takes into account the fuel energy, which is more important of the electric input energy. Changing the input power, the mass flow through the compressor train changes and, according to the relationship defined between corrected mass flow and isentropic efficiency (2.4), the compressors efficiencies change as well. It is obvious that the change in the injection rate affects the charge time (Figure 3-11 and Figure 3-13) and the input energy: reducing the power, the injected mass flow reduces, increasing both the charge time and the input energy required. On the other hand, increasing the input power, the charge time decreases, but due to the higher power and the effect of efficiency, the total energy increases.

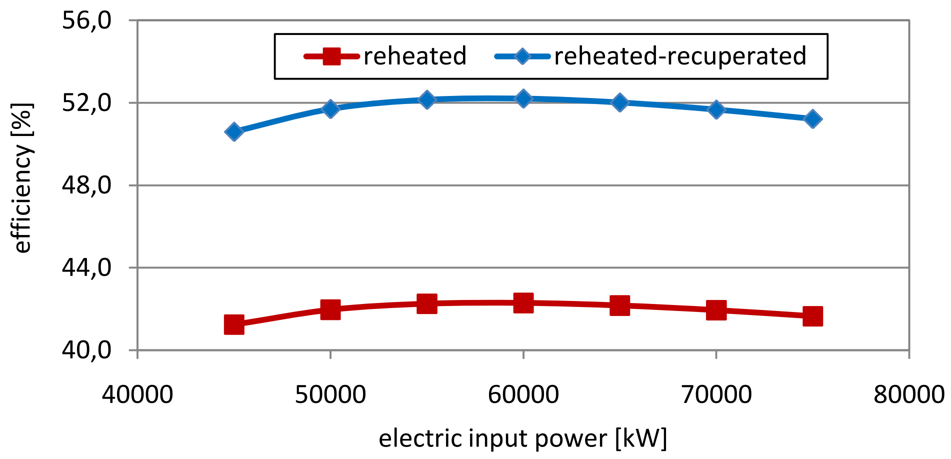

Figure 3-10 Efficiency versus electric power

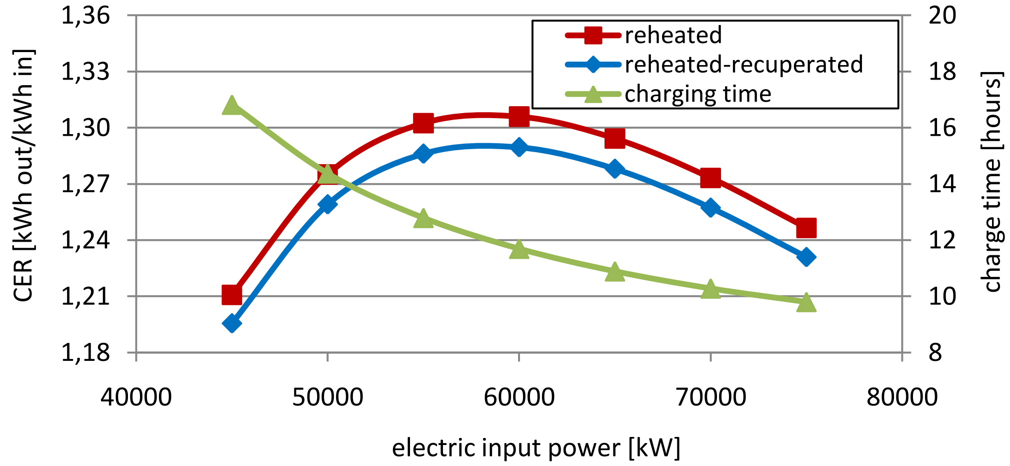

Figure 3-11 CER and charge time versus electric input power

In Figure 3-12 and Figure 3-13 is possible to see that if a power increment from 60 MW to 65 MW takes place, a mass flow increment happens and the maximum efficiencies of the two compressors is not reached increasing the effort in the compression. Similar consideration if the power is lower than 60 MW; the less mass flow and efficiencies increase the effort for the compressors to inject air. Therefore, the compressor efficiency (3.3.2) plays a key role in the performance of the plant and needs to be evaluated in the storage pressure range. Before building a plant, it is important to know the amount of energy that has to be stored and the duration of the charge time; this in order to select the compressor train with characteristics that reduce the input energy and make CER and efficiency as higher as possible.

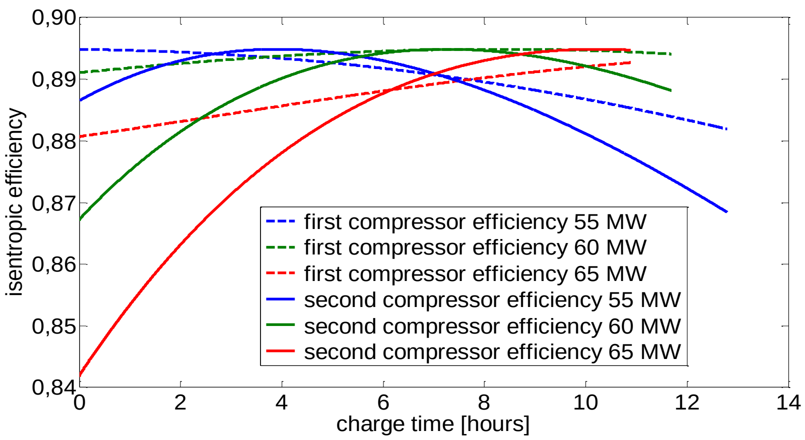

Figure 3-12 Compressor efficiency trends for different electric input power

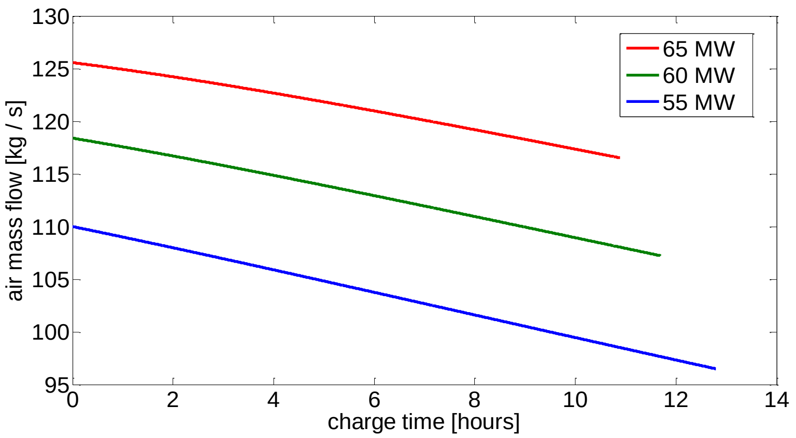

Figure 3-13 Air mass flow injected changing the input power

3.1.5 Compressor train

3.1.5.1 Alfa compression ratio

It is assumed a compressor train composed of two compressors and supplied by an intercooler. It is defined in eq. 26 a ratio of Pressure Ratios that permits to evaluate the effects of changes in the compressors characteristics on the performance indices. As reported in Figure 3-14 and Figure 3-15, the best values of efficiencies and CER are obtained for α equals to 1; optimum also achieved in literature [29]. α is equal to 1 when the Pressure Ratio of each compressor is the root square of the total PR. For α values different than unity, a decrement of the performance indices takes place; in particular CER has a significant variation, while for the efficiency can be considered negligible. Similarly to this train with two compressors, if the compressors number increases and other new ratios among the PRs are defined, the optimum continues to be found where all the ratios are equal to 1. In a train with three compressors, the optimum is for a PR of each compressor equals to the cubic root of the total PR.

$$\boldsymbol{PR_1 * PR_2 = PR_{tot}} \qquad \boldsymbol{PR_2 = PR_1 * \alpha}$$

$$\boldsymbol{\alpha\ ratio =} \quad \frac{\boldsymbol{PR_2}}{\boldsymbol{PR_1}} = \frac{\boldsymbol{compressor\ outlet\ pressure} / \boldsymbol{2nd\ compressor\ inlet\ pressure}}{\boldsymbol{1st\ compressor\ outlet\ pressure} / \boldsymbol{1st\ compressor\ inlet\ pressure}} \tag{26}$$

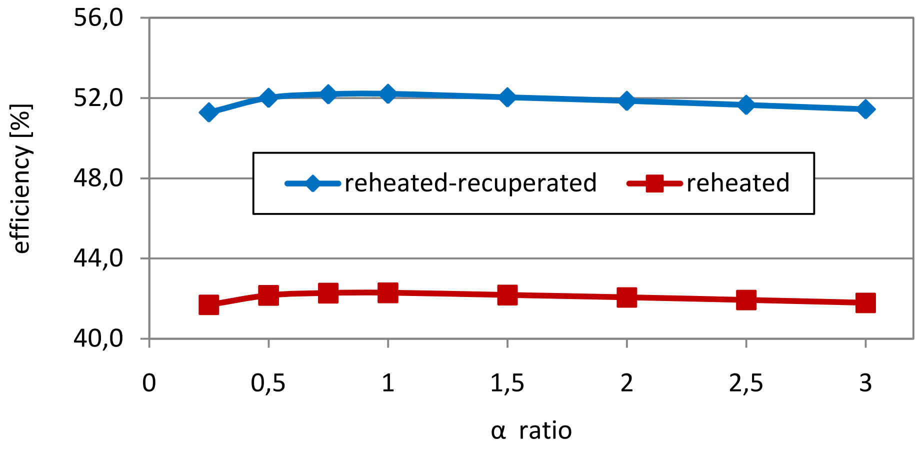

Figure 3-14 CAES efficiency versus α ratio

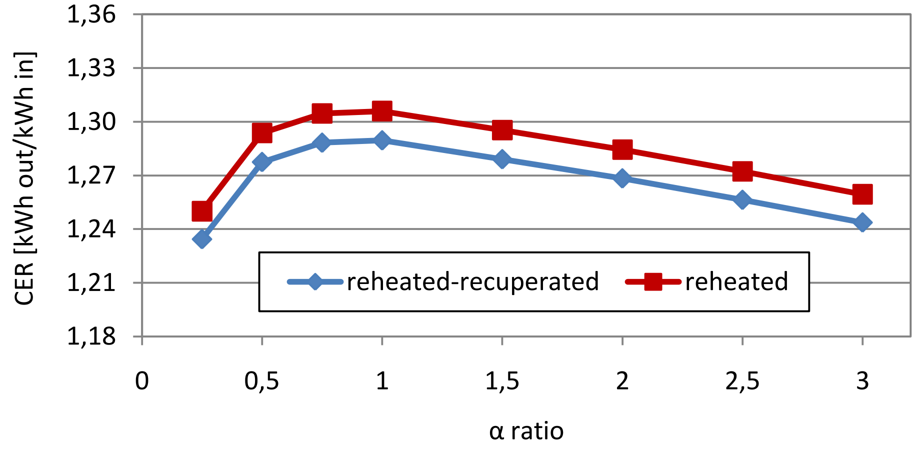

Figure 3-15 CER versus α ratio

3.1.5.2 Compressors number and DP mass flow

In order to reduce the total compressors work, the compression train includes an intercooler among each compressor. Increasing the compressors and intercoolers number, the specific work decreases and if the same constant electric input power is supplied by the grid, the injected air mass flow increases, reducing the charge time. The next two figures represent the effects of compressors increment with the same and with different DP mass flow values. Figure 3-16 shows that increasing the compressors number, keeping constant the DP mass flow, the energy required to drive the compressors reduces; hence CER (Figure 3-17) and efficiency become higher. Increasing the compressors numbers, the mass flow through the compression train increases, but because the compressors efficiency depends on the corrected mass flow (2.4), the operative point moves far from the region of best efficiency. In order to operate in the region of the best efficiency, the input power needs to be reduced. When instead the compressors number is kept constant and the DP mass flow increases, the consequence is a shift of the characteristic to higher electric input power. In fact if the power is kept constant the mass flow through the machine remains far from the optimum region of efficiency; only increasing the power (eq. 4) the mass flow increases and the machines operate closer the region of optimum. Increasing further the mass flow, the operative point moves from the region of efficiency optimum; therefore, operating at lower efficiency, more input energy is required to charge the cavern. Increments in the compression mass flow up to 340 kg/s, maintaining high efficiencies and low specific costs, have been declared achievable [6]. Figure 3-18 presents the charge time for a train composed of two and three compressors; the four compressors configuration is omitted to avoid overlapping.

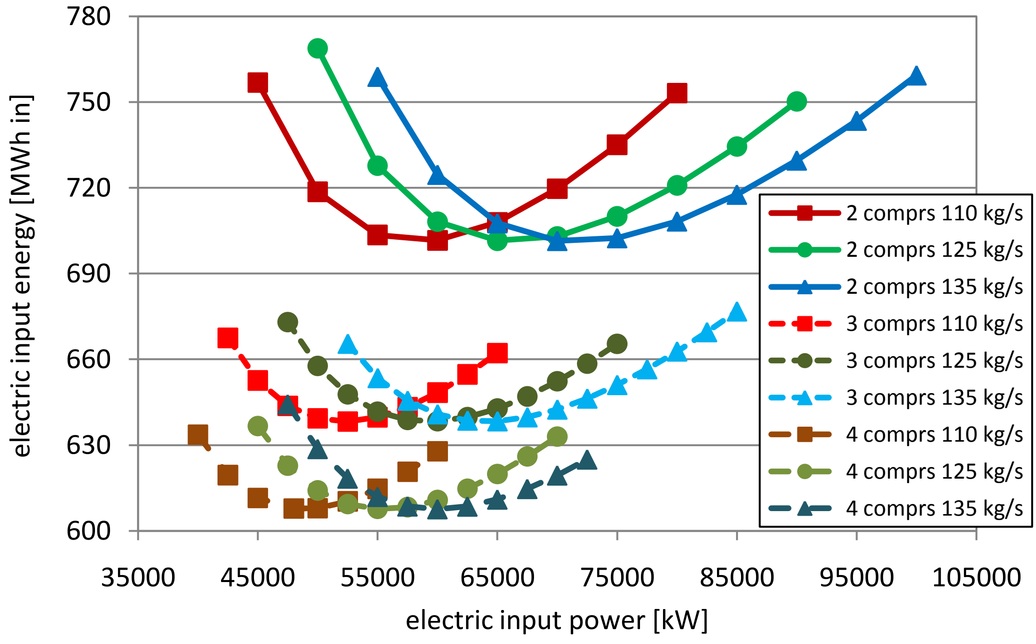

Figure 3-16 Input energy for different DP mass flow and electric input power

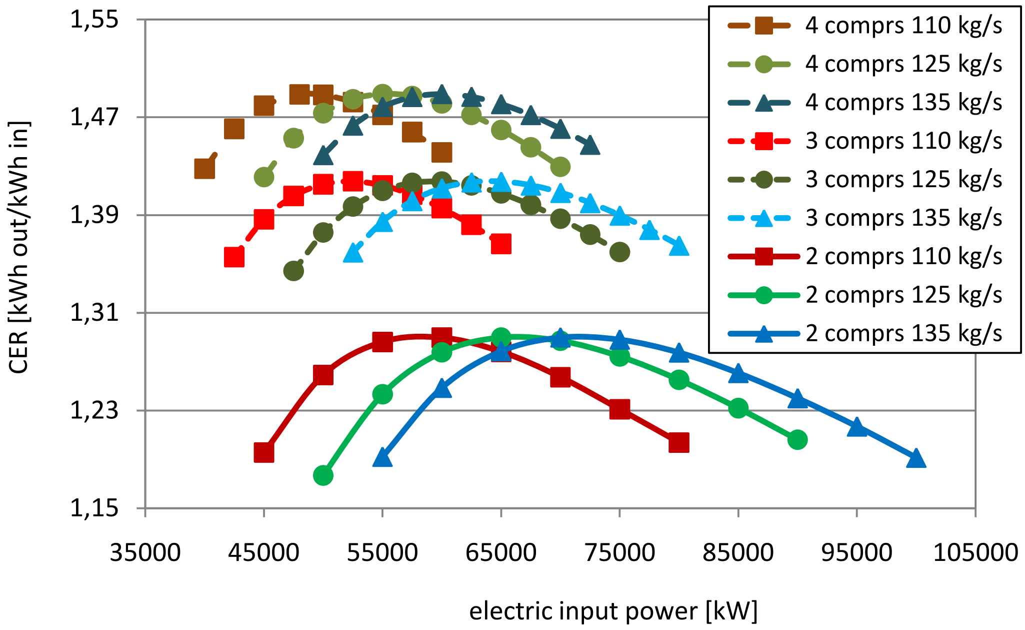

Figure 3-17 CER for different DP mass flow and electric input power

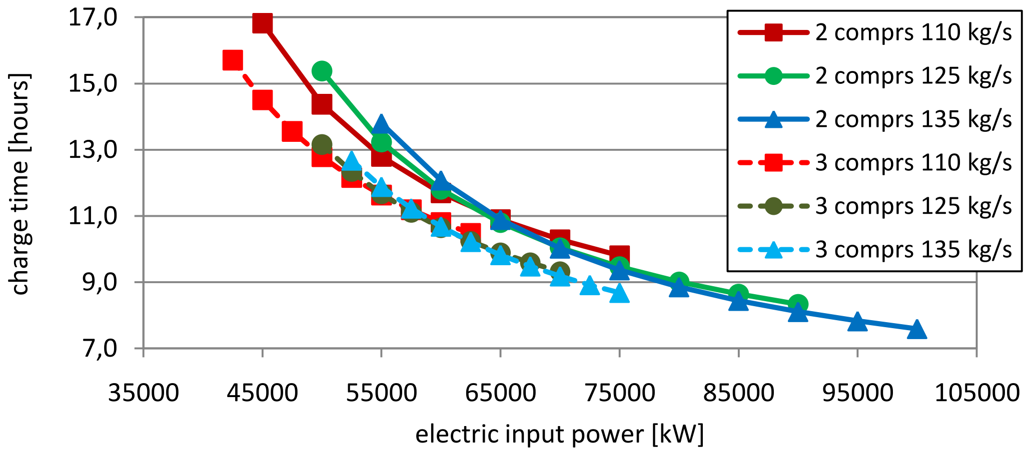

Figure 3-18 Charge time for different DP mass flow and electric input power

3.1.5.3 Intercoolers

As seen in the previous lines, intercoolers reduce the electric input energy. Figure 3-19 shows the results of the analysis of the intercooler outlet temperature changes. It is assumed that a river is able to cool the air temperature at the outlet of each intercooler; each intercooler outlet has the same temperature value. Increasing this temperature the compressor work increases and the decrement in the CER becomes significant. As a results of these trends, in conventional CAES the intercooling temperature has to be the lowest possible; this is not true anymore for the A-CAES where only a small intercooler is used (4.1.3.4).

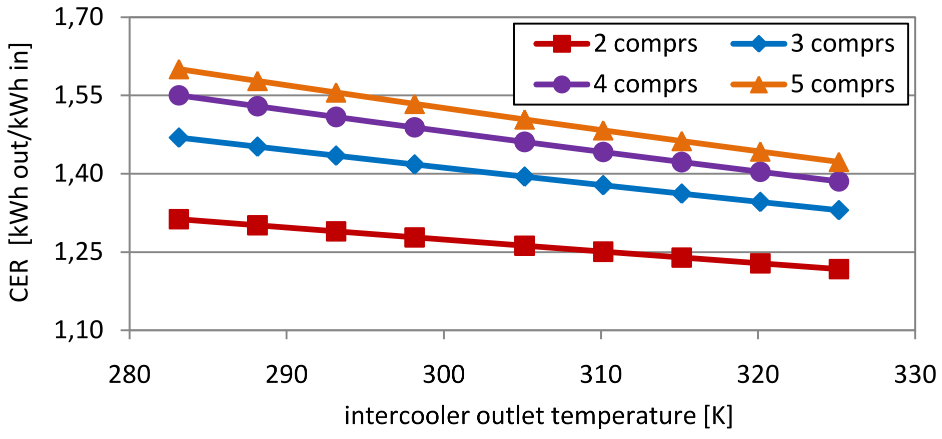

Figure 3-19 CER and intercoolers outlet temperature

3.1.5.4 Compressor efficiency

It is here presented a comparison among a compressor train with the isentropic efficiency trends previously considered (2.4) and configurations characterized by flatter and steeper isentropic efficiencies (Figure 3-20). This analysis aids the understanding of the effects, and the sensitivity on the performances, of the compressors characteristics. Constant electric input power and constant output power generated are assumed. On the basis of these two assumptions, higher the efficiency in a wide range of corrected mass flow and pressure (flat characteristic), lower the input energy required to inject air; with benefits for CER (Figure 3-21) and efficiency of the CAES. On the other hand, significant variations of the isentropic efficiencies (steep efficiency) in the operative pressure range, increase the input energy required. Therefore, this analysis shows the importance to have the maximum compressors efficiencies possible in the entire operative pressure range in order to achieve benefits in the performances. Ideally, if the compressors efficiencies were assumed constant (for example 0,9) in the entire pressure range, the CERs would be represented by constant lines with values of 1,30 in a train with two compressors, 1,43 with three compressors and 1,50 with four compressors.

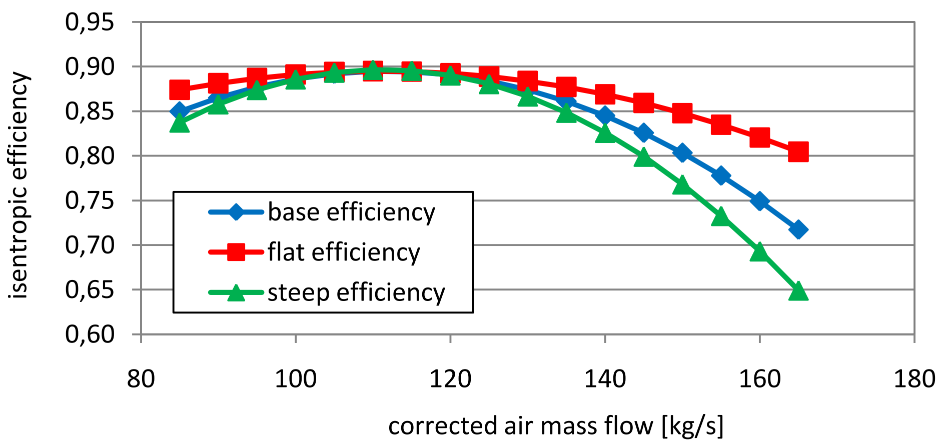

Figure 3-20 Compressors isentropic efficiencies

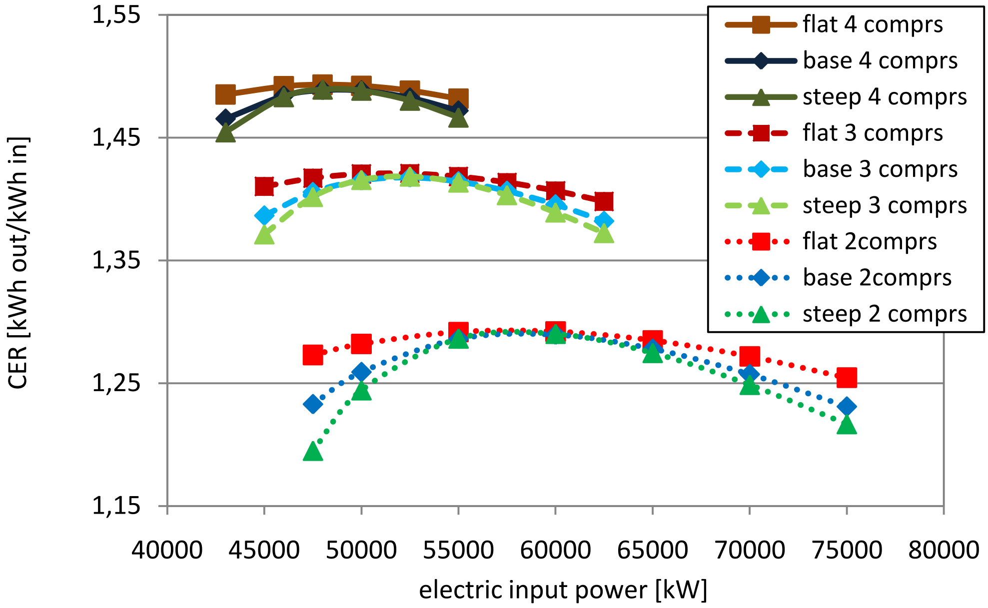

Figure 3-21 CER for different efficiencies and compressors number

3.1.6 Storage characteristics

Underground storage operating parameters and aboveground turbomachinery are interrelated; the storage may limit or even dictate the machinery operating parameters due to the limitations in the allowable stored-air pressure range and temperature. The storage may introduce possible deteriorations in the plant performances; therefore, economic evaluations have to be done before the realization of the project in that particular location. There is the risk that the injection happens in a certain pressure range, while the generation uses a different operating pressure (usually lower); this results in losses, it reduces the output power, the plant performances, thereby the revenues.

3.1.6.1 Storage temperature

In this section is studied the underground storage temperature and its effects on the storage dimensions and performances of the plant. The thermal characteristic of a cavern depends on the depth and the particular region where it is located. First of all, the geothermal gradient needs to be explained; measured in °C/km, is the rate of temperature change with depth in the earth. The rate of increment with depth varies considerably with both tectonic setting and the thermal properties of the rock. It is possible to find areas with high gradients (200 °C/km), for example where molten volcanic rock rising to the surface. Low gradients (15–30 °C/km) instead can be found in tectonic subduction zones [31]. The underground temperature starts changing after a depth of 500 m (before it is almost constant and it depends on the surface temperature) and it changes not only with depth but also horizontally (Appendix C, Figures C-1, C-2, C-3). Temperature gradient and the underground temperature present a complex

relationship; even if the gradient has a certain value, the underground temperature may not follow that trend and it may assume different values [32]. If a geothermal gradient was followed going underground, the temperatures would assume the values observed in Figure C-4. It is important to note that if the geothermal gradient is very high, probably the cavern is closed to volcanic (hence seismic) regions, so the storage construction must be avoided in order to prevent cracks [7].
According to [20] it is assumed in the models a constant cavern temperature equals to 308,15 K, also during the compression where it is assumed that the aftercooler is able to guarantee constant temperature values of the air injected and inside the storage. In the reality, the compression and the consequent pressure increment generate an increment of the air temperature inside the cavern. Therefore, on the basis of eq. 10, the maximum operative pressure is reached faster and a lower amount of air is stored, limiting the amount usable for the generation. If a certain output energy is required and the cavern temperature increases, the solution that permits to store the necessary air mass is a volume increment. It is evident that bigger volume increases the capital cost and it also needs to be found; thereby possible availability problems can take place.

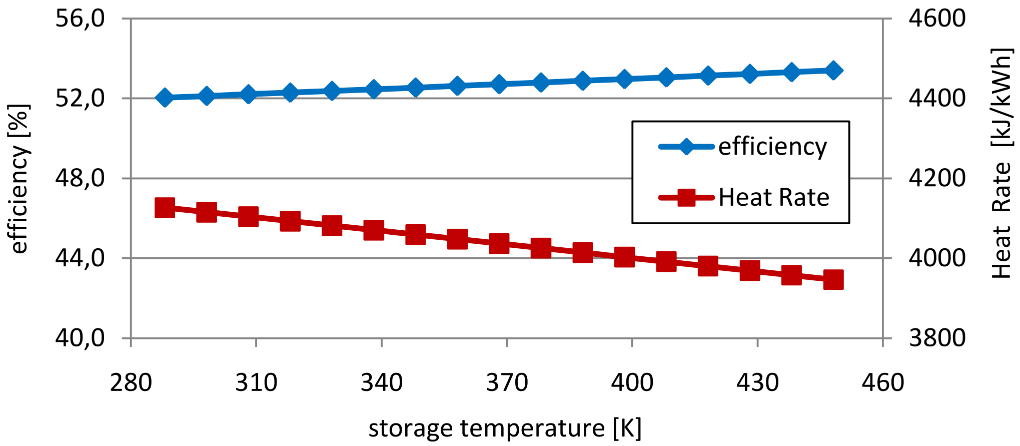

Figure 3-22 Performance indices versus storage temperature

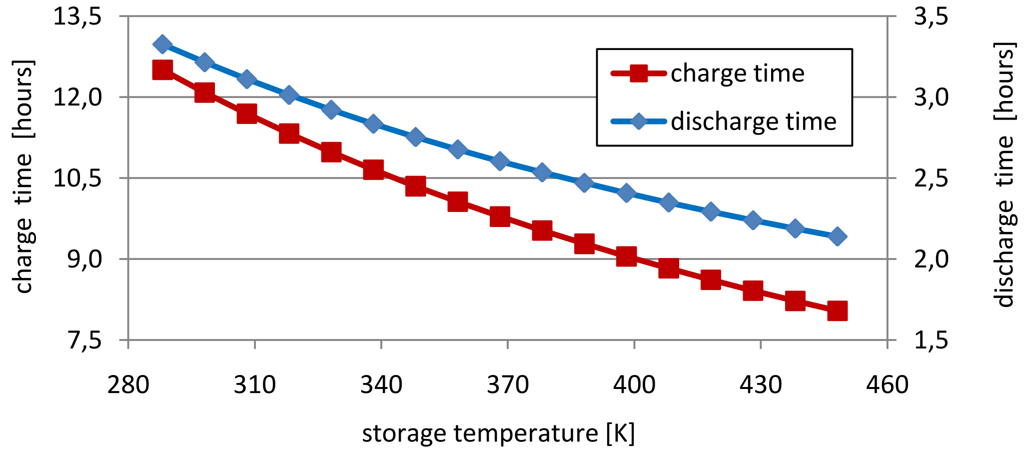

Figure 3-23 Charge and discharge times versus storage temperature

Using some parameters of the McIntosh plant and considering the effect of temperature increment reported in [20], the results show that the cavern volume needs to be about 3% bigger in order to store the same amount of air mass able to generate 100 MW for 26 hours, compared with the case where the temperature is constant at 308,5 K. If the operating maximum pressure was increased to 8,0 MPa, and similar comparison was done, the volume required would need to be 3,7% bigger. Figure 3-22 represents efficiency and HR for different underground temperatures. The increment of cavern temperature reduces the HR, because less fuel is required (3.1.7); consequently the efficiency of the CAES increases. Another advantage of high storage temperature is the smaller aftercooler required. However, the disadvantage of the temperature increment for a constant volume, is the reduction of the air mass injected and withdrawn; with consequent reduction of charge and discharge times (Figure 3-23). If a certain mass is required to ensure a certain output energy, the solution is to enlarge the volume or to increase the TITs, so with lower mass flow withdrawn is possible to generate the same output energy (3.1.10). Figure 3-24 shows the trend of air mass flow and storage pressure in the cases of constant and variable storage temperatures (the variable temperature is function of the pressure [20]).

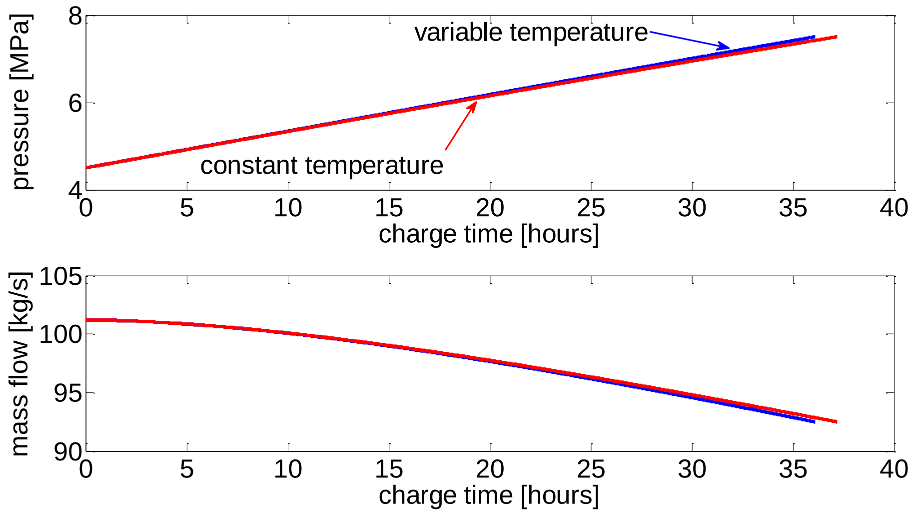

Figure 3-24 Charge time comparison with constant and variable storage temperatures

3.1.6.2 Storage volume

The storage volume defines the amount of air mass that can be injected and stored at a certain pressure, so it determines the input energy required, the output energy, the charge and discharge times (Figure 3-25). Changing the volume, CER and efficiency do not change; in fact, even if the energies change, their ratio is always constant. Moreover the EVR remains constant because of the linear relationship between time and volume. If the volume increases, the discharge time and output energy increases, but the EVR (about 2,77 kWh/m^3) does not change.

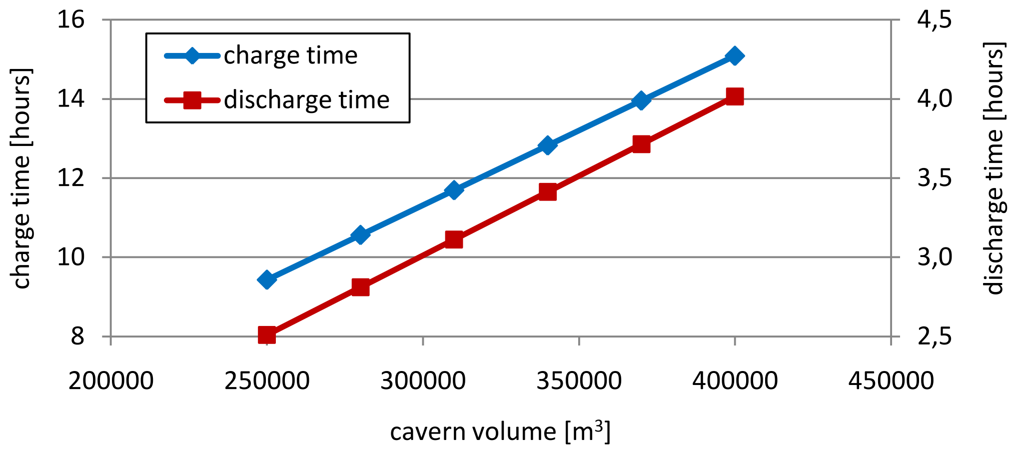

Figure 3-25 Charge and discharge times changing cavern volume

3.1.6.3 Storage pressure

The storage depth does not only affect the temperature, but also defines the maximum pressure of injection and inside the cavern. The pressure is limited for avoiding fractures in the walls of salt and hard rock caverns, while for porous formation the break of the caprock. If this happened, a leakage of air would take place and the formations would not be usable any longer. For porous rock formations average values for the threshold of the caprock are between 16,06 kPa/m and 18,55 kPa/m. In these formations also the hydrostatic pressure, equals to 9,74 kPa/m, needs to be considered in order to create and maintain the air bubble [6, 35]. For salt caverns instead, the pressure gradients are in the range between 15,83 kPa/m and 19,23 kPa/m, with depths between 182 m and 914 m [6, 34]. Usually, for salt formations, the allowable working pressure is chosen up to 80% of the fracturing threshold and the max allowable pressure is measured considering as depth the top of the cavern. In the McIntosh plant for example, a value of 18,09 kPa/m at a depth of 413 m (bottom of the last cemented casing of the production well), allows a working pressure of 7,47 MPa and a maximum pressure of 9,34 MPa [20].

3.1.6.4 Maximum storage pressure

In this analysis the maximum pressure is evaluated, doing the assumption that compressors efficiencies are equal to 0,89 and the valve pressure is constant at the minimum pressure value (3.1.6.5). When higher maximum pressure has to be reached, the amount of air injected increases, even if its rate decreases because of the pressure increment and the more work spent by the compressor. The case analysed is supplied by a recuperator with effectiveness equals to 0,8, but same consideration are verified for the only reheated train, even if with lower efficiency (about 42%) and higher HR (about 5780 kJ/kWh). Figure 3-27 shows that increasing the maximum pressure, the efficiency drops down; in fact, higher pressure leads to store higher amount of mass inside the storage providing higher output energy, but this is obtained with higher losses. Because of the valve pressure constant at the minimum storage pressure, the output power generated is constant. Since the generation train operates in a certain point, the HR is constant and consequently also the CER has trend similar to the efficiency. Differently, EVR (Figure 3-26) increases if the pressure increases, because more mass is stored inside the same volume and more output energy can be produced for the same volume.

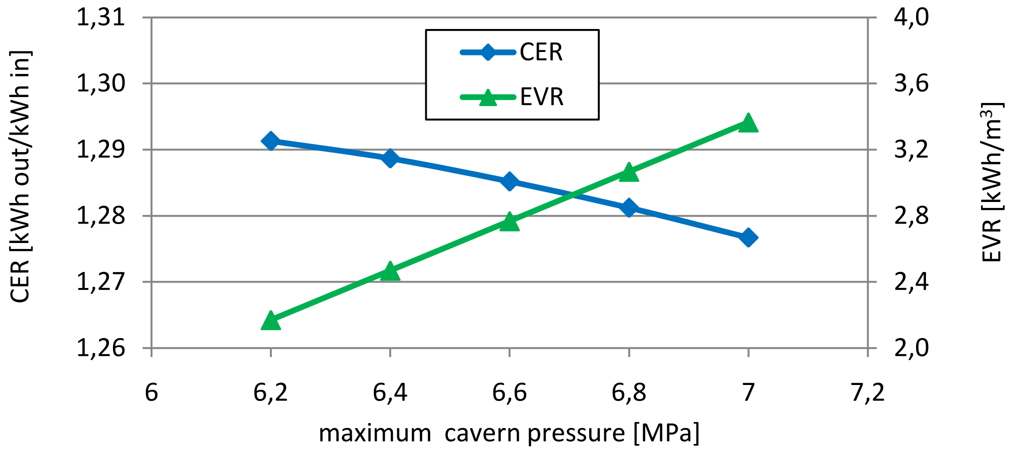

Figure 3-26 CER and EVR versus maximum cavern pressure

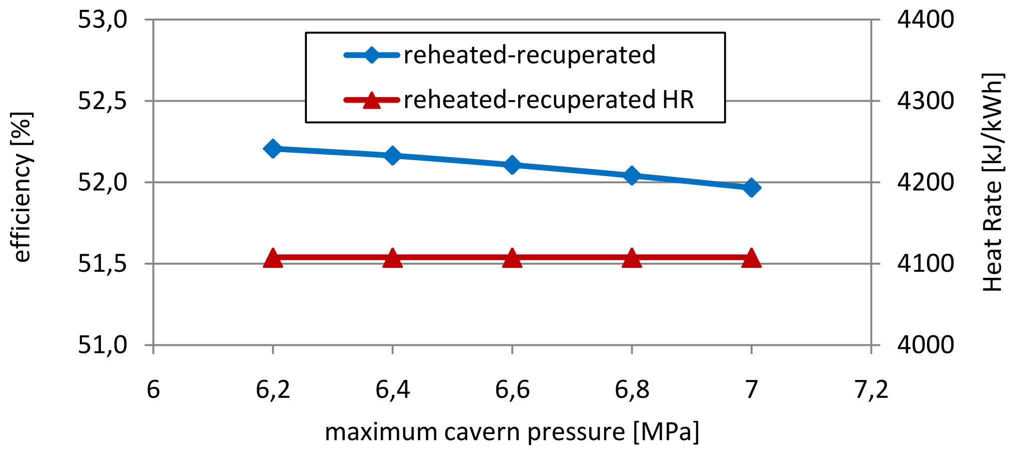

Figure 3-27 Efficiency trend versus maximum cavern pressure

3.1.6.5 Minimum storage pressure

Minimum storage pressure can define the inlet pressure of the generation train; two reasons can explain why a valve is introduced before the generation train, increasing losses and requiring bigger storage volume. The first one can be the need to adapt the storage pressure to the generation train and the other one can be due to the benefits in the turbine efficiency attained for constant inlet pressure operation [7]. The second one is the reason why a valve is applied in both McIntosh and Huntorf plants. As reported in 1.5.6, in the Huntorf plant, the valve reduces the HP TIP, with consequent reductions in the output power and performance indices. In these analyses the effect of a reduction of the minimum pressure is showed. Figure 3-28 shows the trend of CER in a train without recuperator; an optimum can be observed. This behaviour can be motivated by two factors, when the minimum pressure decreases there is an increment of losses because also the valve pressure decreases, hence the output power produced decreases. When instead the pressure range is reduced, increasing the minimum pressure, the energy required to inject air increases because of the higher pressure ratio and the higher work necessary to drive the compressor. Looking at the efficiency, the main component in the denominator of the ratio for a generation train without recuperator is represented by the fuel energy. Because of this, the efficiency does not reach an optimum, even if, again, it can be seen the effect of the electric input energy when the minimum pressure is increased. The trend curves slightly due to the electric input energy effect. Analysing the EVR, the trend goes down increasing the minimum pressure because less mass is stored and less output energy is generated. The concept is similar to the changes in the maximum cavern pressure: when inside a constant volume the pressure range reduces, the amount of mass reduces, so the output energy and EVR reduce.

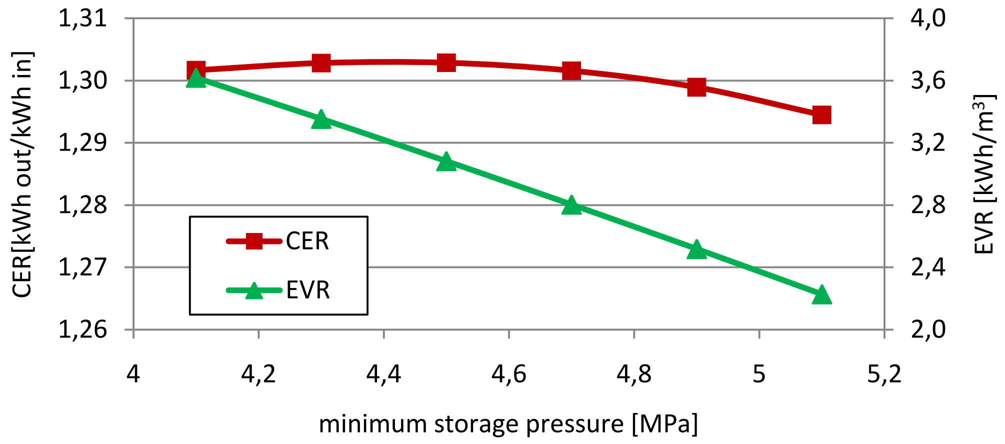

Figure 3-28 CER and EVR versus minimum storage pressure (reheated)

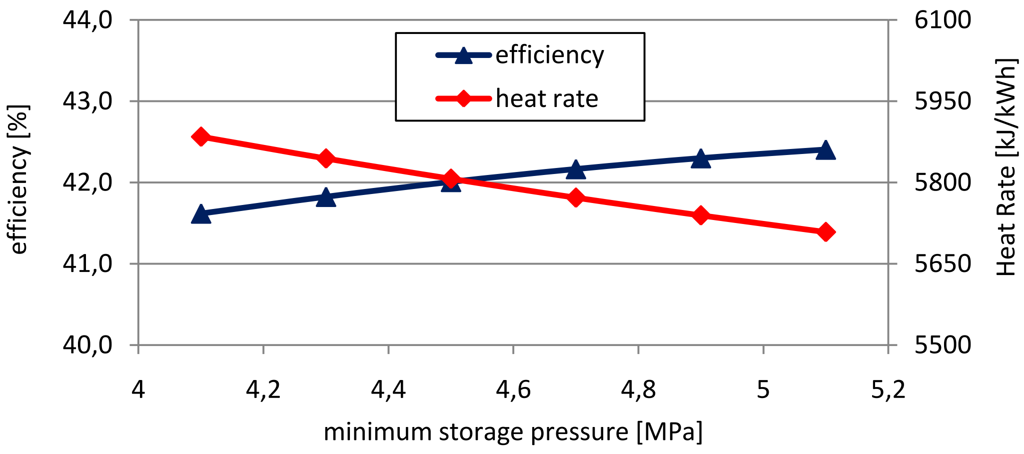

Figure 3-29 Efficiency and HR versus minimum storage pressure (reheated)

If a train supplied of recuperator is considered, the trends of CER and EVR (Figure 3-30) are similar to those presented for the only reheated train; the difference is a small discrepancy due to the less output power produced because of the recuperator. For the efficiency, the effect in the denominator of the fuel energy is less significant that the previous case, so the efficiency becomes more sensitive to electric energy variations. Because the input energy increases when the compressor injects air at higher pressure, in Figure 3-31 is visible the effect of the input energy increment on the efficiency.

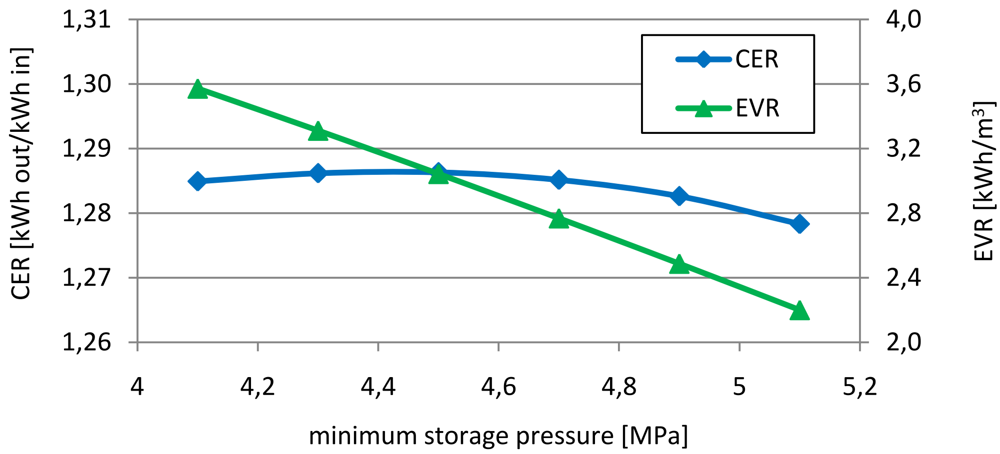

Figure 3-30 CER and EVR versus minimum storage pressure (reheated-recuperated)

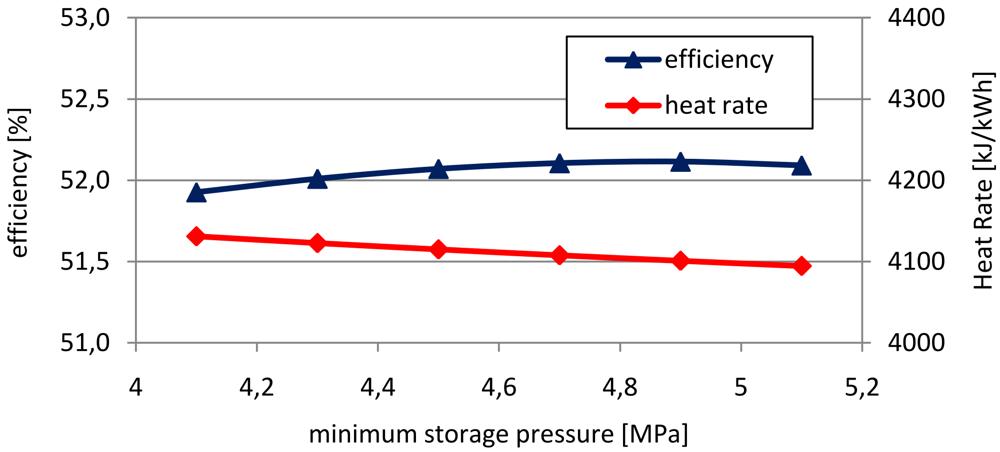

Figure 3-31 Efficiency and HR versus minimum storage pressure (reheated-recuperated)

3.1.6.6 Variable valve pressure

As seen, the use of a valve in order to adapt the machinery with the storage characteristics results in decrement of the output power (Figure 3-32) and also an HR increment takes place. For these reasons, a constant pressure valve should be avoided.

It is carried out an analysis where a variable pressure is released from the maximum value in the cavern till the minimum operating value. It is assumed that the turbines are chocked and the isentropic efficiencies are constant at 85%. When a turbine is chocked, the ratio $\frac{\dot{m}\sqrt{T}}{p}$ can be assumed constant (Appendix C, Figure C-5); defined the value of this ratio at DP, if the pressure increases and the TIT remains constant, the mass flow through the turbine increases. Figure 3-33 shows the trend of the output power when DP mass flow equals to 410 kg/s, DP pressure equals to 4,55 MPa and TIT equals to 823,15 K are assumed. Even if the variable pressure configuration discharges the storage faster that the train with constant pressure, the energy produced is higher, with improvement in CER that increases from 1,29 (constant pressure) to 1,34 (variable pressure). Since the efficiency also depends on the output power, it increases from 52,2% with constant pressure up to 53,2% with variable pressure. For the EVR, the value of 2,77 kWh/m^3 with constant pressure valve, increases to 2,90 kWh/m^3 with variable pressure valve. Figure B-7 confirms that the use of variable pressure reduces the volume required or, for the same storage volume, increases the energy generated. Figure 3-34 shows the trend of storage pressure changing the air mass withdrawn; due to the higher request of mass, the variable pressure configuration presents a faster discharge compared to a discharge with constant air mass withdrawn. Due to the higher mass flow withdrawn, the HR is higher; HR values that go from 4425 kJ/kWh in the beginning up to 4440 kJ/kWh in the end. This affects the efficiency that has not the same improvement of the CER.

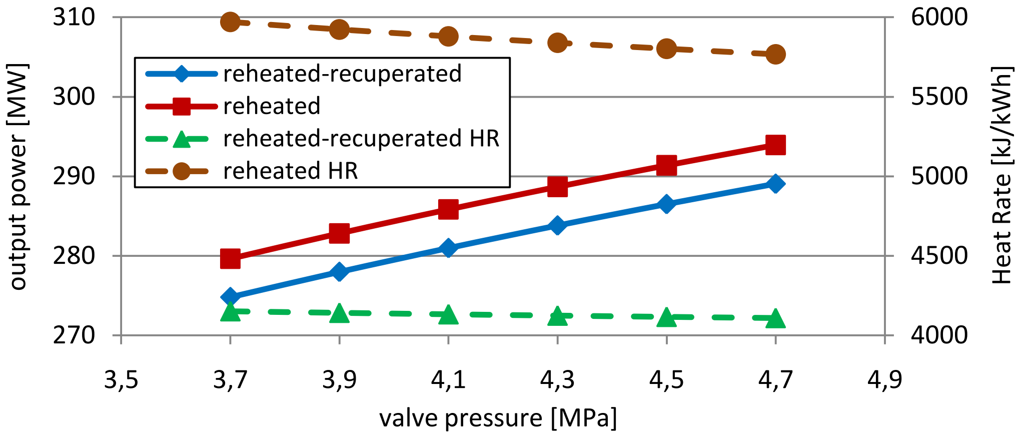

Figure 3-32 Output power and HR versus valve pressure

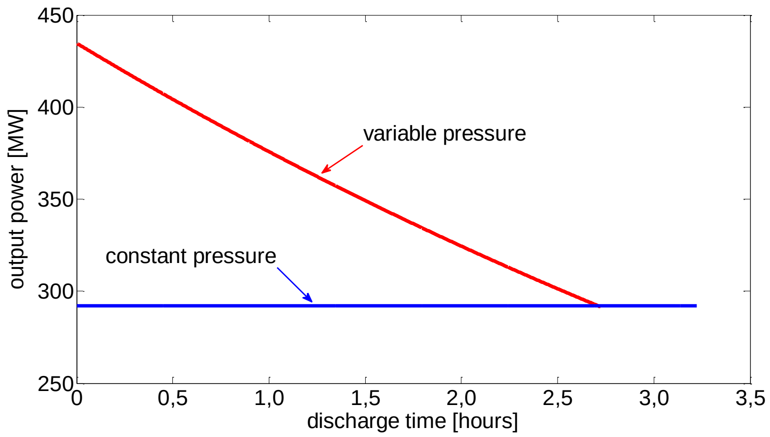

Figure 3-33 Output power for variable and constant valve pressure

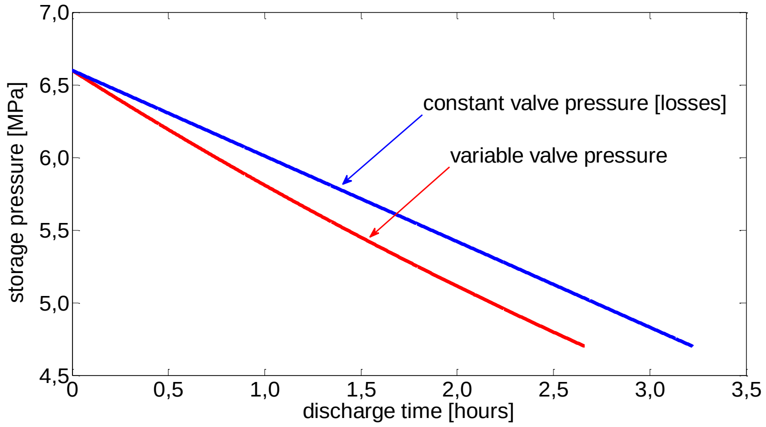

Figure 3-34 Air storage pressure with variable and constant pressure valve

3.1.7 Recuperator

In order to evaluate the effects of the recuperator, variations of the effectiveness and pressure losses are investigated. Increasing the effectiveness, the HR decreases, with consequent increment of the efficiency (Figure 3-35).

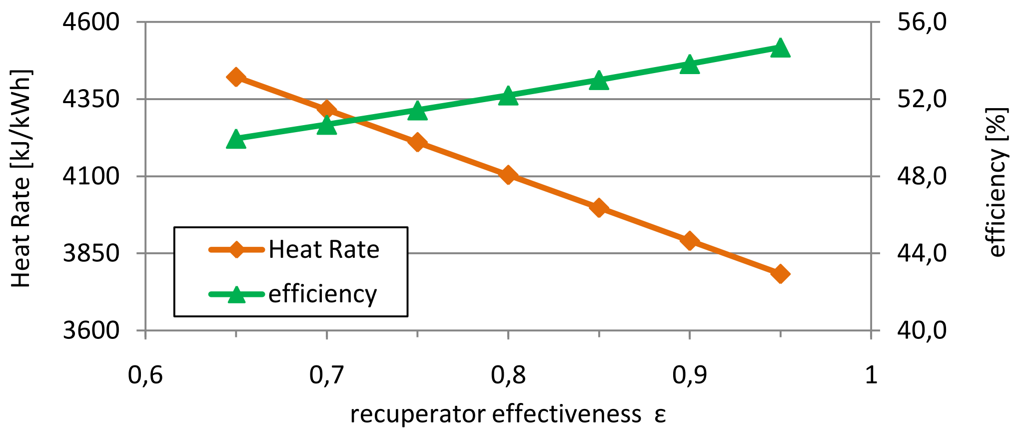

Figure 3-35 Heat Rate and efficiency versus recuperator effectiveness

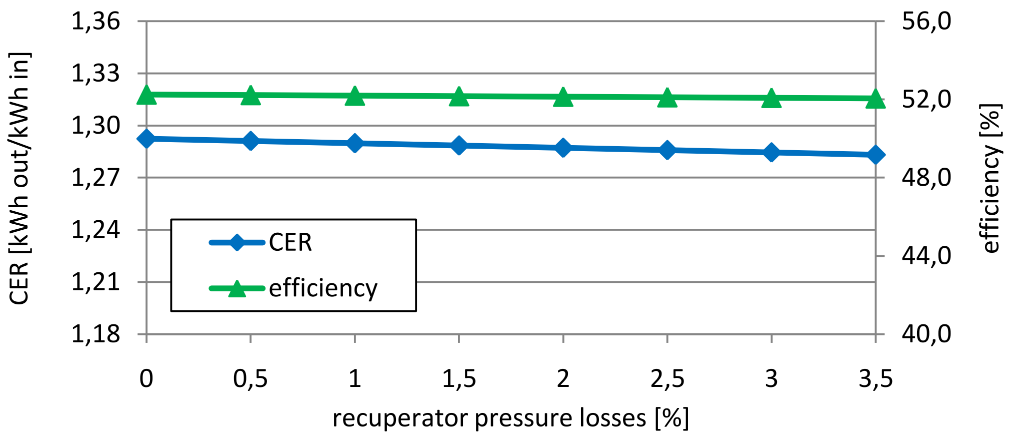

Figure 3-36 CER and efficiency versus recuperator pressure losses

Changes in the pressure losses show negligible variations in the efficiency, while in the CER a little slope can be highlighted (Figure 3-36). Thermodynamically the recuperator introduces significant benefits and reduction in the fuel consumption, but the delays that it can introduce at the start-up of the generation train have to be evaluated and reduced.

3.1.8 Air mass flow withdrawn

The variation of the air mass flow withdrawn from the storage changes the discharge time, but because the same amount of mass stored is available, it does not affect the output energy generated. Therefore, CER does not change remaining constant to 1,29 (train with recuperator). The consequence of a mass flow increment is an increase of the output power produced (Figure 3-37), power that is produced for less time since the cavern empties faster (Figure 3-38).

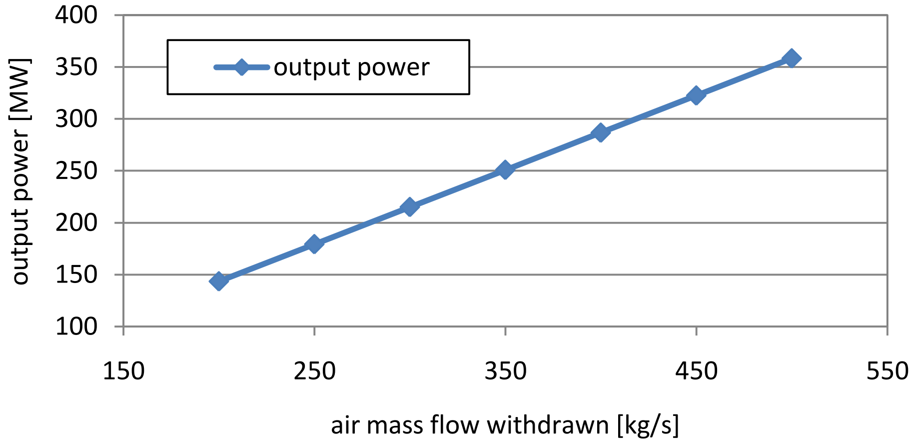

Figure 3-37 Output power trend versus air mass flow changes

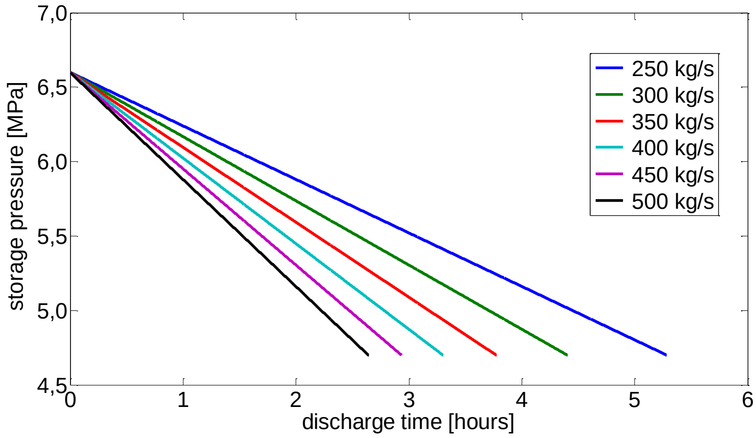

Figure 3-38 Storage pressure trend for different air mass flow withdrawn

3.1.9 Turbines isentropic efficiency

Turbine efficiency is an important parameter that characterizes the generation and it increases the output power with consequent benefits in the performance indices. Due to the more power produced with the same amount of fuel, HR reductions with consequent efficiency increments are registered (Figure 3-39); CER increments are also achievable (Figure 3-40). If the LP turbine is the component that produces the main amount of output power, it has to have the highest efficiency.

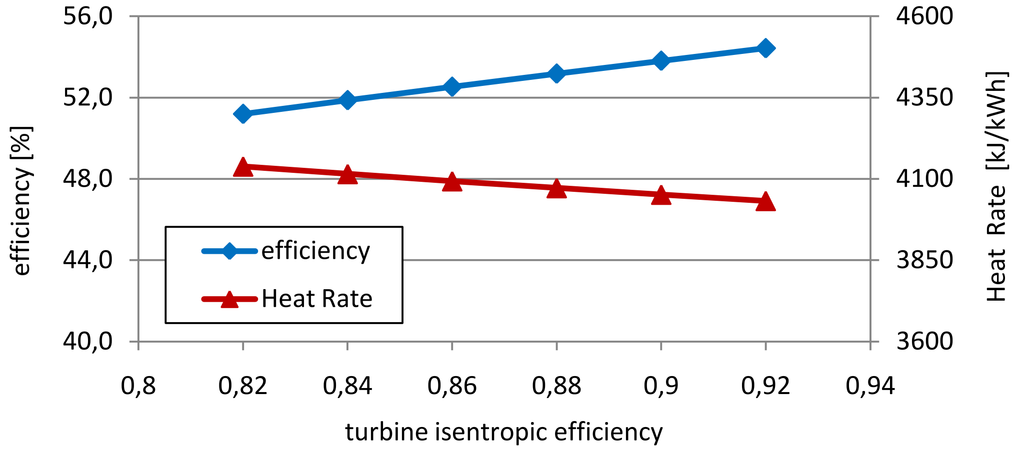

Figure 3-39 HR and efficiency changing turbine efficiency

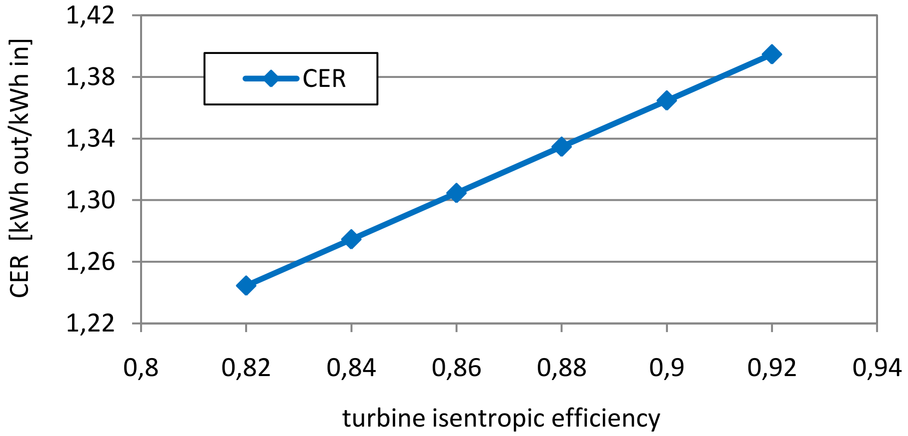

Figure 3-40 CER changing turbine isentropic efficiency

3.1.10 Turbines Inlet Temperatures

3.1.10.1 1st TIT

The 1st TIT is increased, keeping constant the 2nd TIT. The result is an increment of the output power that leads to higher CER (Figure 3-41), efficiency (Figure 3-42) and EVR (Figure 3-43). A reduction in the HR is registered, the higher 1st TIT leads to higher power produced by the 1st turbine releasing high temperature gas to the 2nd combustor that requires less fuel. The configuration with recuperator maintains the benefits above mentioned, but with the improvements that less fuel is required; increasing the efficiency.

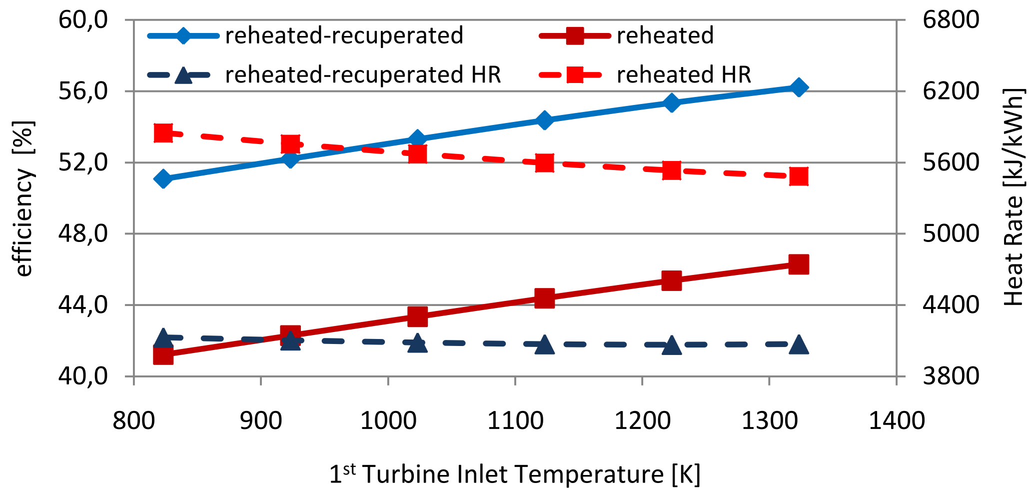

Figure 3-41 Efficiency versus 1st TIT

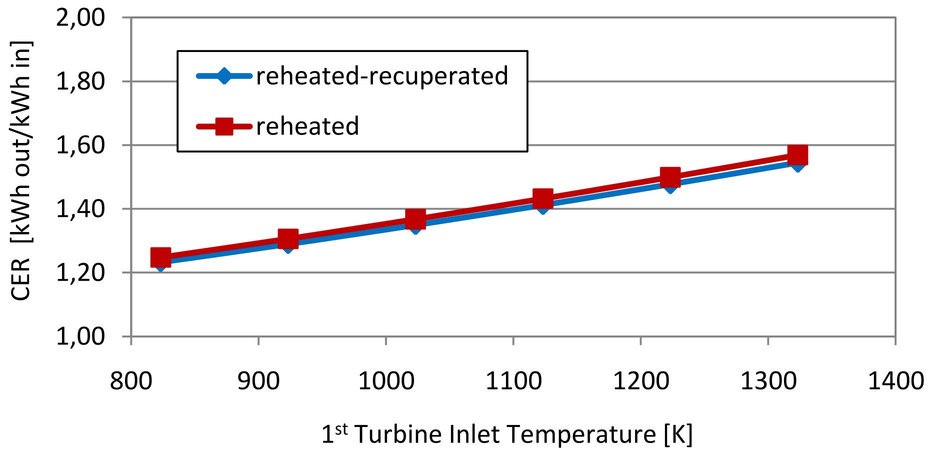

Figure 3-42 CER versus 1st TIT

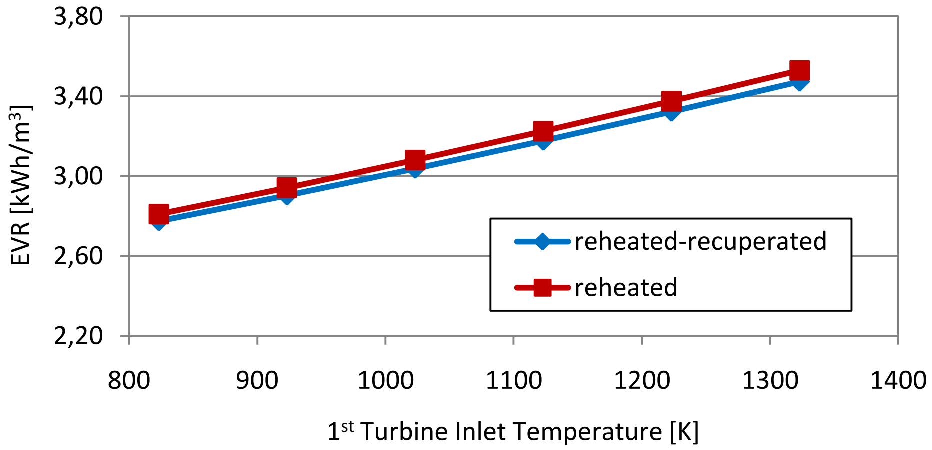

Figure 3-43 EVR changing 1st TIT

3.1.10.2 2nd TIT

Similar to the previous investigation, increasing the 2nd TIT, CER increases (Figure 3-44), while different behaviour is observed for the efficiency. In Figure 3-45, only the train supplied with recuperator presents benefits in the efficiency, because the more amount of heat in the exhaust is transferred to the air withdrawn from the cavern using less fuel to reach the 1st TIT. In the train without recuperator instead, with the increment of the 2nd TIT, the heat is wasted through the stack, more losses take place and the significant increment in fuel consumption (due to the low HP TOT and the temperature drop to cover) happens without any benefits. The efficiency in this configuration decreases increasing the LP TIT. Similar to 1st TIT increments, increasing the 2nd TIT, the EVR increases (Figure 3-46).

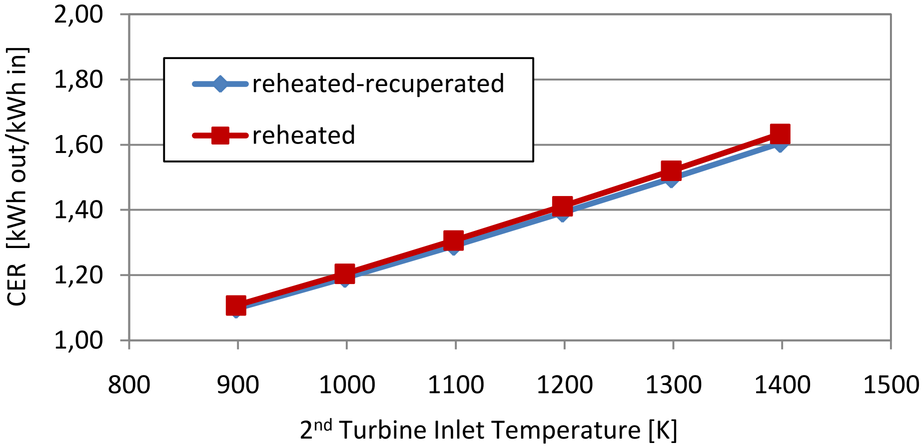

Figure 3-44 CER versus 2nd TIT

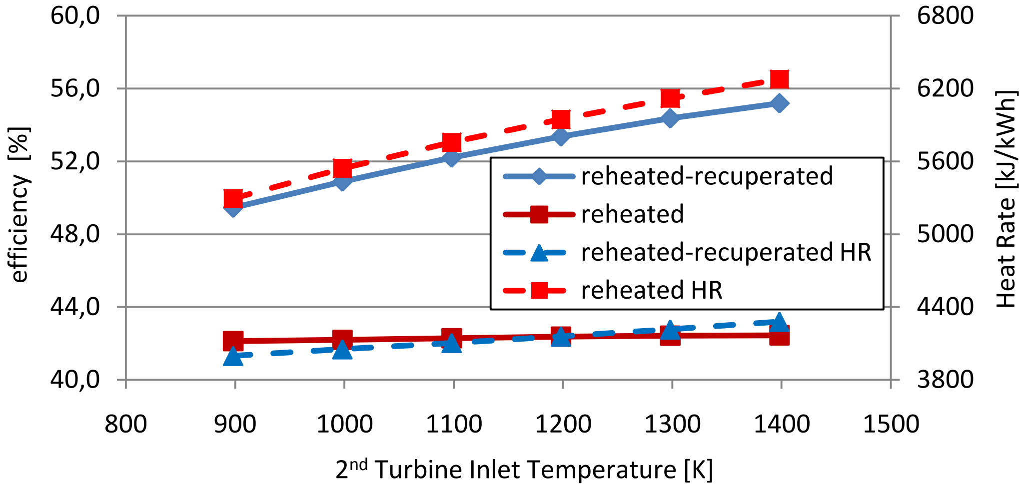

Figure 3-45 Efficiency and Heat Rate versus 2nd TIT

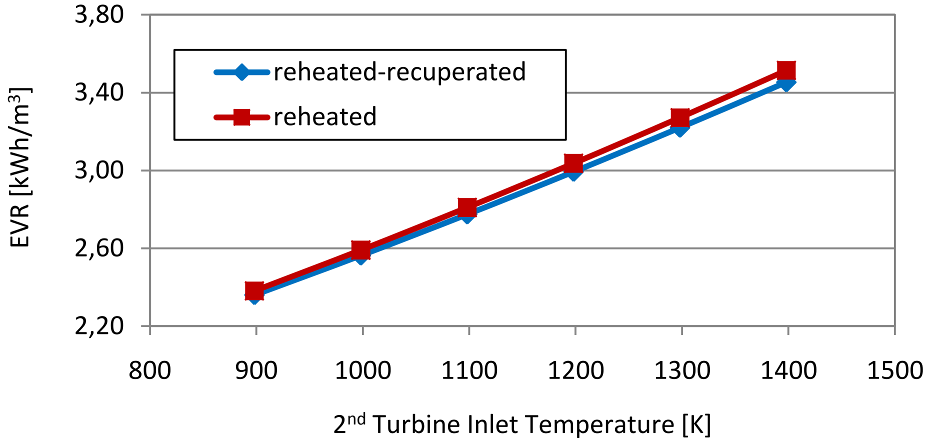

Figure 3-46 EVR versus 2^{nd} TIT

3.1.10.3 1^{st} and 2^{nd} TITs

In order to show the results of TITs increments, 3D graphs that plot the variations of temperatures versus a ratio β (eq. 27) are used. Increasing the TITs, an increment in the generated output power happens, and in order to maximize this output, the right value of β needs to be chosen (Figure 3-47); as done for both existing plants. In the existing plants, the values of β are in the region that optimizes the power generated and the CER. Figure 3-48 represents some trends of the surfaces in Figure 3-47; it can be seen that the ratio β has to be chosen on the basis of the TITs. The turbine that generates the main component of power needs to be the one with the higher TIT, this is the reason why in the Huntorf plant the LP turbine has higher expansion ratio. If the two TITs were equal, β would simple be equal to 1. In Figure 3-48, when the TITs become closer, the ratio moves to the direction of 1 and goes to higher value when the difference is more significant.

$$\boldsymbol{\beta\ ratio} = \frac{\boldsymbol{2^{nd}\ expansion\ ratio}}{\boldsymbol{1^{st}\ expansion\ ratio}} = \frac{\boldsymbol{2^{nd}\ TIP}/\boldsymbol{exhaust\ pressure}}{\boldsymbol{1^{st}\ TIP}/\boldsymbol{2^{nd}\ TIP}} \qquad (27)$$

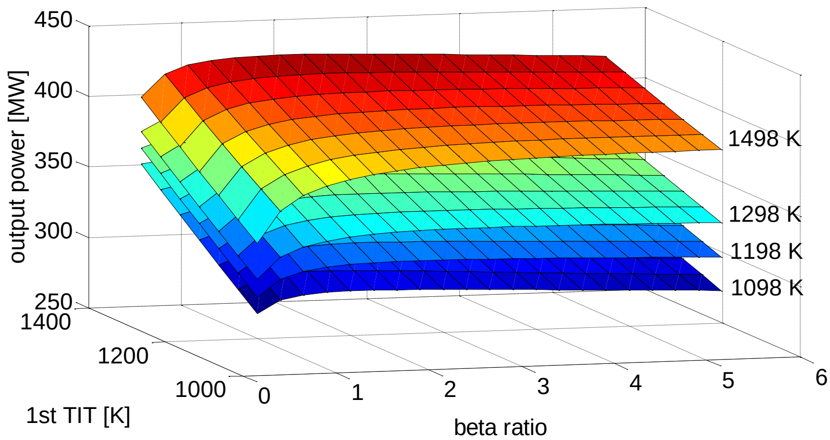

Figure 3-47 Output power analysis changing 1^{st} and 2^{nd} TITs

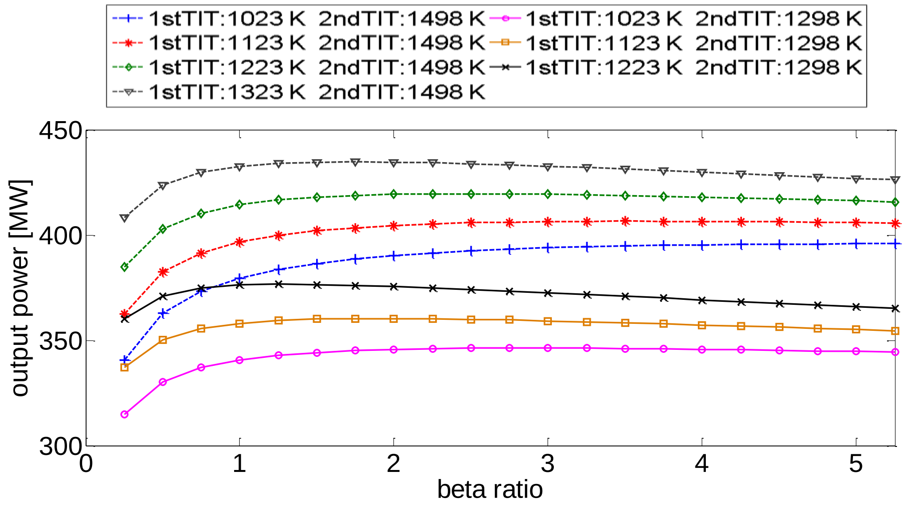

Figure 3-48 Output power optimum analysis changing TITs

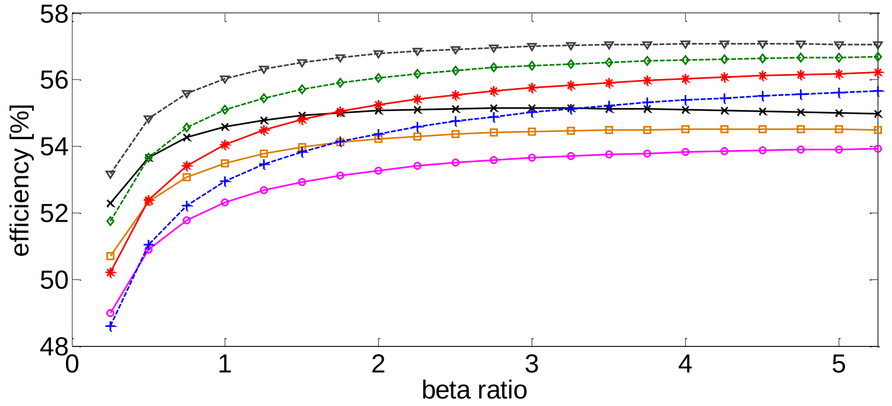

Figure 3-49 Efficiency optimum analysis changing TITs

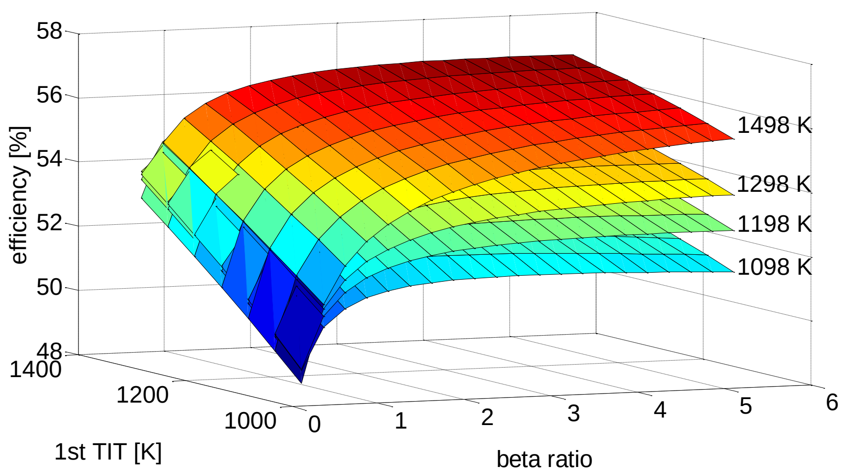

Figure 3-50 Efficiency changing 1st and 2nd TITs

Even if the output power optimum is defined for a certain β, the efficiency optimum can have different β (Figure 3-49), also due to the HR (Figure 3-51). HR shifts the efficiency optimum (Figure 3-50) to higher β compared to that one representative of the output power optimum. In the models, higher 2nd TITs are assumed, for these reasons the main component of power is produced by the LP turbine, reducing the HR. As it will be highlighted several times, all the output power improvements generated by TITs increases have the disadvantage to increase the HR. Nowadays this can represent economic problems due to the fuel price and forecasts of CO_2.

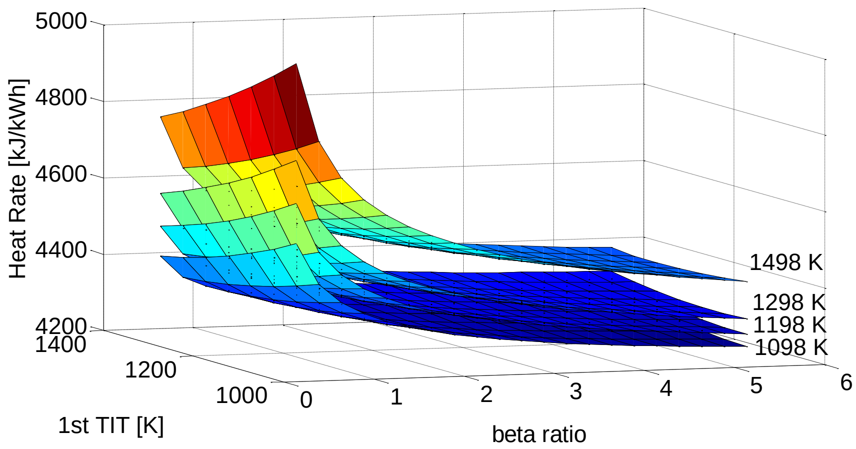

Figure 3-51 Heat Rate analysis changing 1st and 2nd TITs

3.1.11 Generation train analysis

3.1.11.1 Configuration without HP combustor

A concept that avoids the HP combustor and uses only the recuperator to warm up the air coming from the cavern, is proposed in the literature [1] and it is here investigated (Figure 3-52). In order to have enough heat that can be transferred from the exhaust gas to the cold air, higher LP TIT than the previous cases (3.1.10.3) has to be assumed. If this does not happen, significant decrement in the output power, CER (Figure 3-55) and efficiency take place. Figure 3-53 shows the CER trends for LP TITs between 1298 K and 1498 K, recuperator effectiveness between 0,75 and 0,9 and β between 0,25 and 5,25. It can be seen that effectiveness increments increase the HP TIT, this increases both output power (Figure 3-53) and CER, while the HR decreases. On the other hand, if the effectiveness is low, HP TIT decreases and the fuel consumption increases, since the gas at the outlet of the HP turbine needs to reach the higher LP TIT (Figure 3-54). Doing a comparison with configurations supplied by HP combustor (even if characterized by lower TITs), it can be seen that the trains with HP combustor can achieve better performance indices. The output power increment increases CER (Figure 3-56), EVR and efficiency. However, these benefits are reached spending more fuel (Figure 3-56). It is also evident that the HR decreases in the train without HP combustor when the effectiveness increases. But effectiveness increments are obtained with bigger transfer areas that make the recuperator bigger and slowing down the dynamic. Therefore, a configuration without HP combustor needs to be evaluated in an economic analysis due to the effects of capital costs, fuel price and CO_2 tax (5.2.4.2); while a technical analysis needs to evaluate the time required to follow the peak demand.

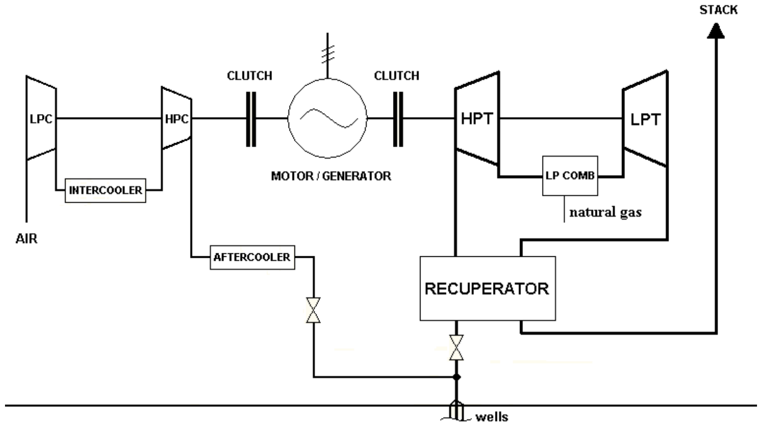

Figure 3-52 Generation train without HP combustor

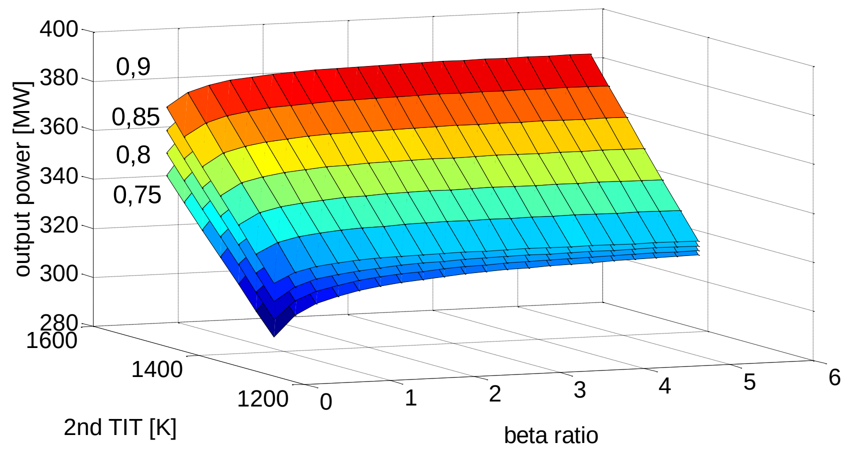

Figure 3-53 Output power generated in configurations without HP combustor

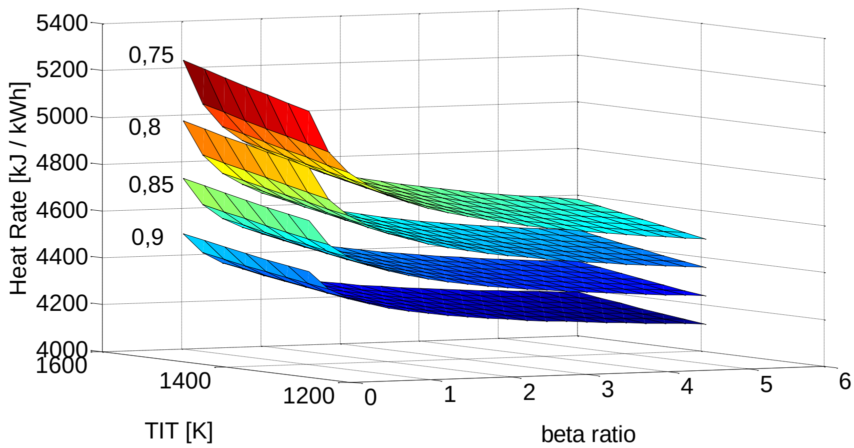

Figure 3-54 Heat Rate in configurations without HP combustor

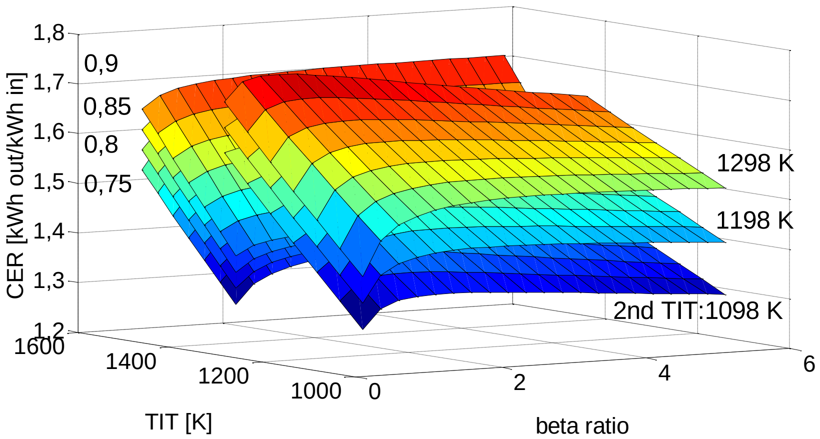

Figure 3-55 CER comparison in configurations with and without HP combustor

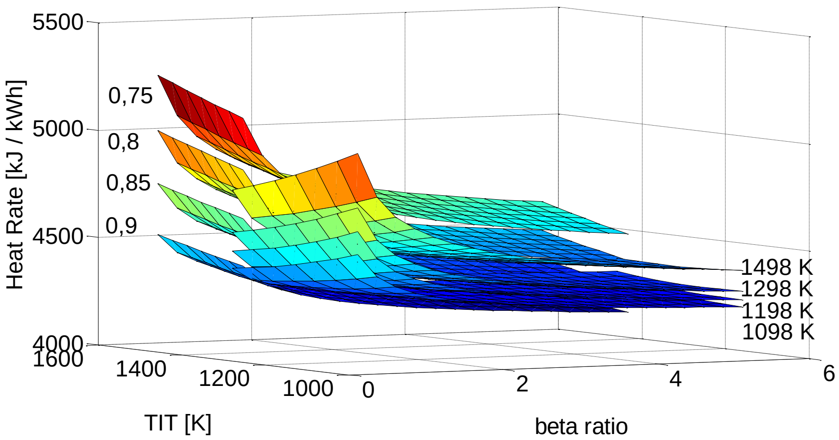

Figure 3-56 HR comparison in configurations with and without HP combustor

3.1.11.2 Generation train without reheating

A comparison among the previous configuration supplied with the reheating combustor and configurations outs of it (Figure 3-57) is analysed for evaluating the effects of the reheating. All the trains are supplied with a recuperator. In the configurations without the reheating, it is done the assumption that is possible to supply high HP TIT with a valve pressure equal to 4,7 MPa. The reheated-recuperated trains used in the comparison are the reference model (Figure 3-1) supplied by the recuperator and a generation train with valve pressure equals to 4,7 MPa and HP TIT equals to 1098 K. This is done for comparing this latter with the train without reheating. Figures 3-58, 3-59, and 3-60 highlight again that HP TIT increments increases the output power, hence CER, efficiency and EVR. While for the two reheated-recuperated trains the choice of the β ratio affects the performance indices, for the recuperated train the trends variations are negligible. If the reheated-recuperated train with inlet pressure at 4,7 MPa and HP TIT equal to 1098 K is compared with the train without reheating, it can be seen that the combustion introduces benefits in performances. However, this is achieved with more fuel consumption (Figure 3-61). This is the reason why the increment in efficiency

(Figure 3-58) is less significant than in the CER (Figure 3-59) and EVR. Comparison of the train supplied by the recuperator with a train without it, show again the significant fuel consumption reductions (of about 23%) (Figure 3-61 and Figure 3-62).

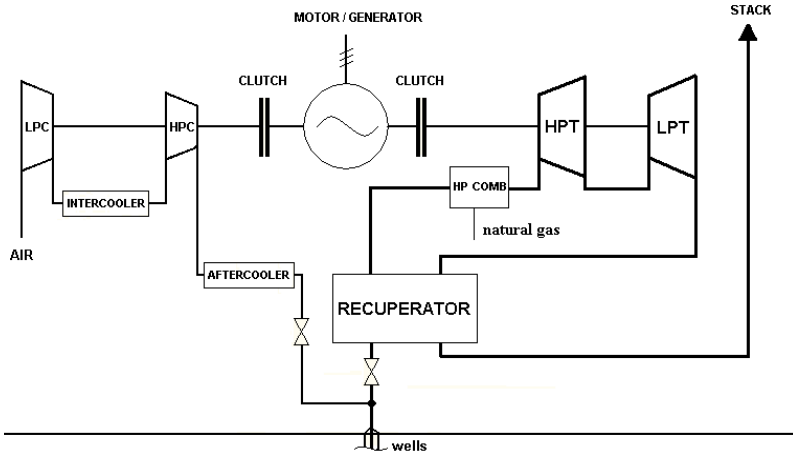

Figure 3-57 Generation train without reheating

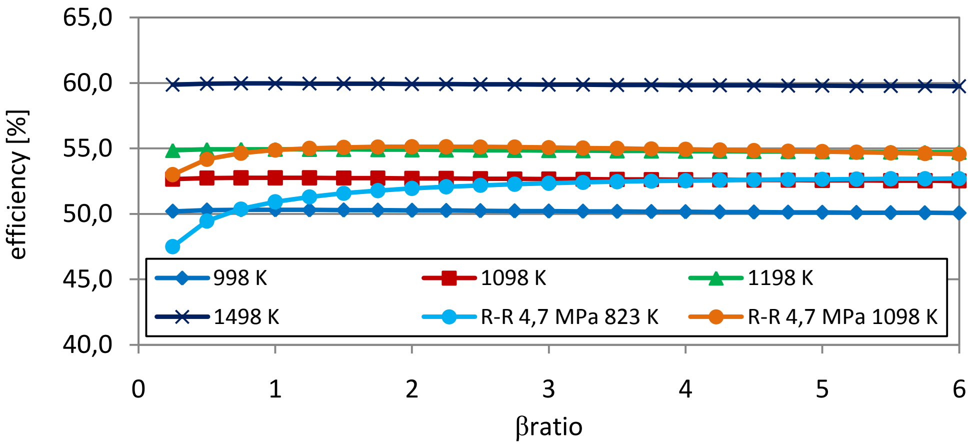

Figure 3-58 Efficiency comparison (trains analysis without reheating)

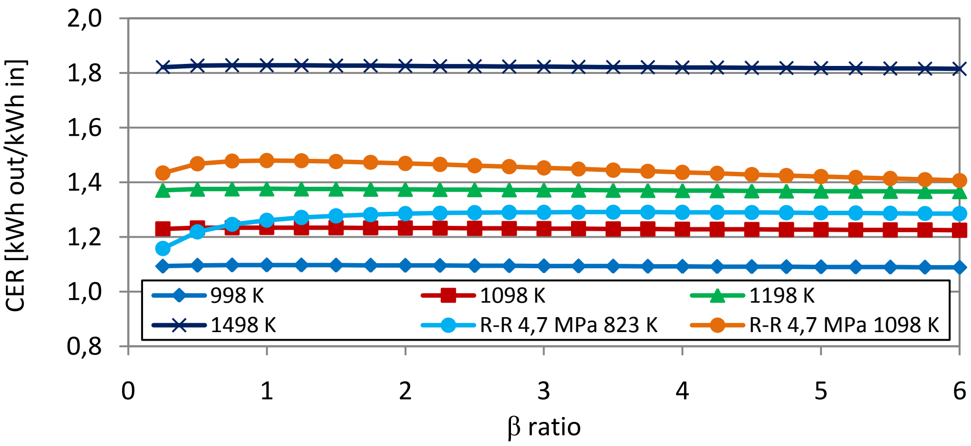

Figure 3-59 CER comparison (trains analysis without reheating)

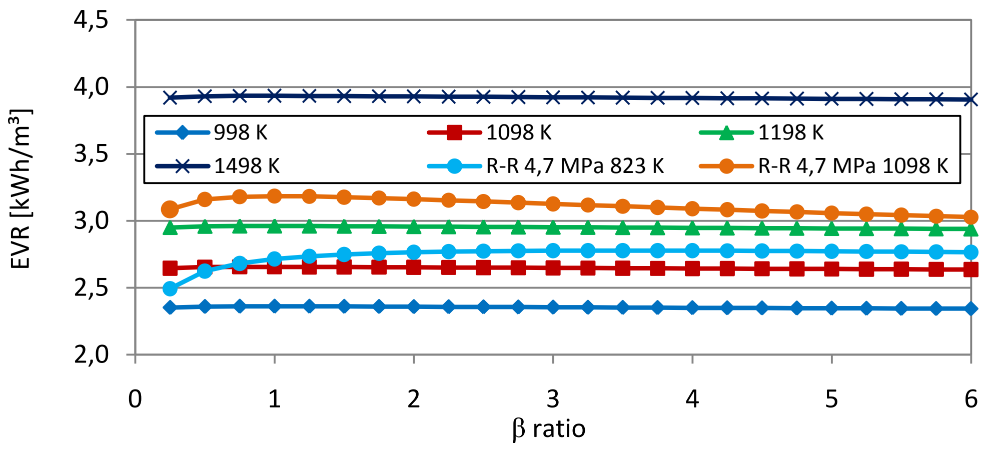

Figure 3-60 EVR comparison (trains analysis without reheating)

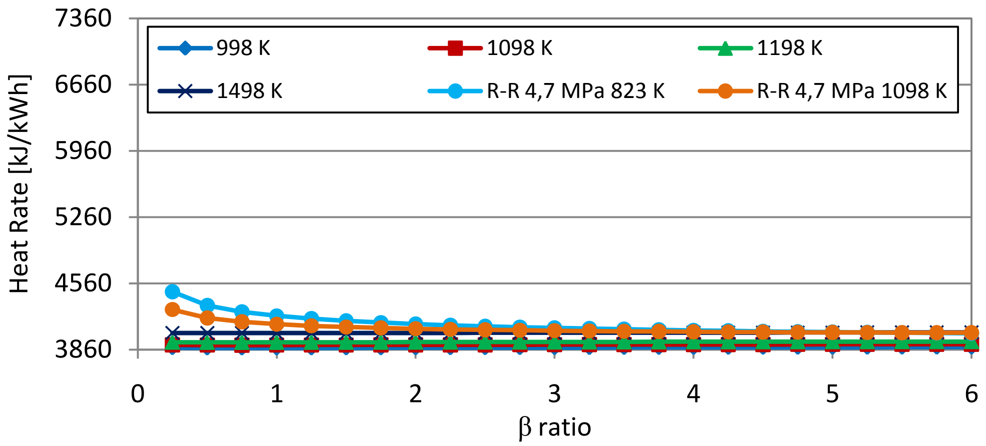

Figure 3-61 Heat Rate comparison (generation trains supplied by recuperator)

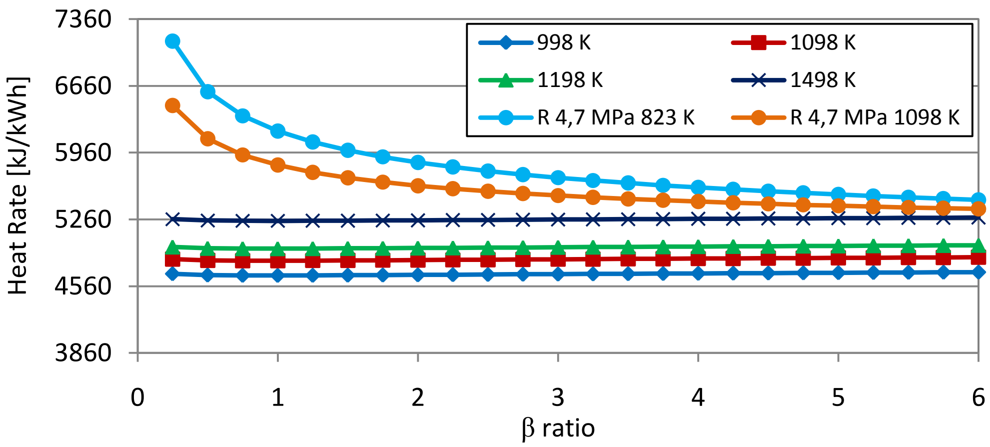

Figure 3-62 Heat Rate comparison (generation trains without recuperator)

3.1.11.3 Recuperated train with one turbine

A generation train composed of one turbine that expands from the valve pressure to ambient pressure is analysed. The train is supplied of a recuperator with effectiveness equals to 0,8 and that introduces 2% losses. The TIT increment increases output power, so CER (Figure 3-64), EVR and efficiency; but as said, these benefits are obtained with an Heat Rate increment (Figure 3-65).

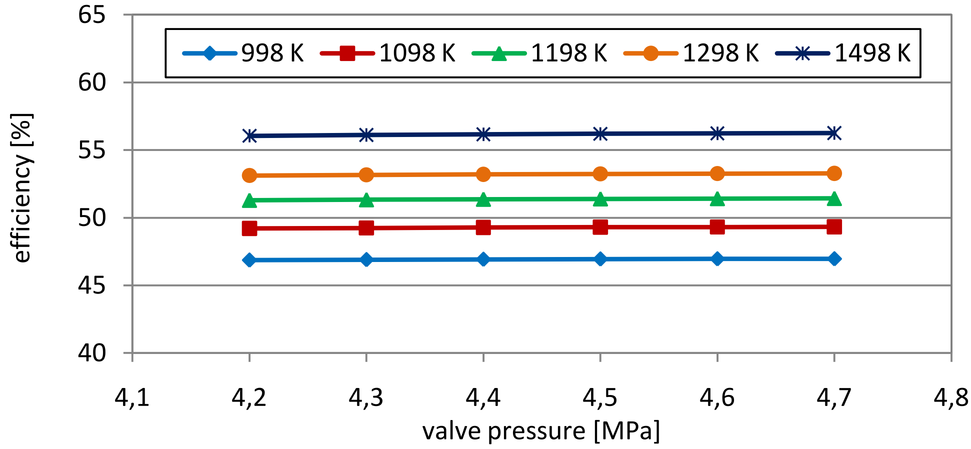

Figure 3-63 Efficiency in the generation train with only one turbine

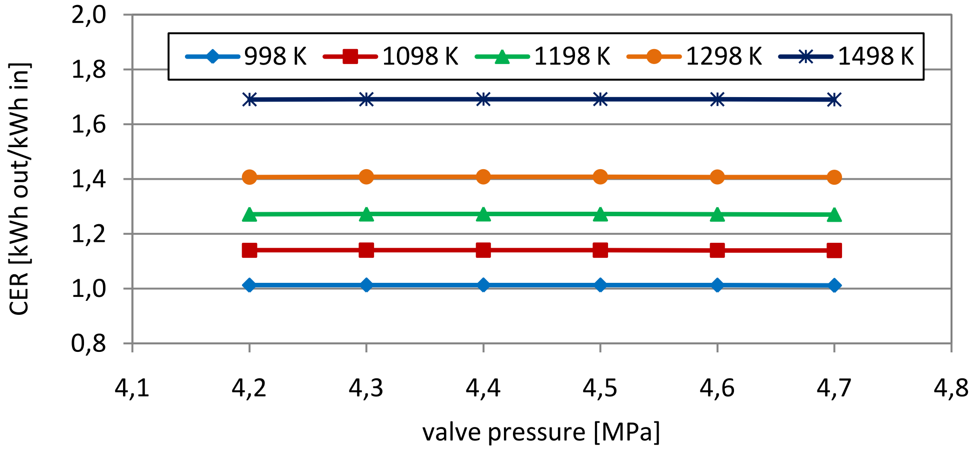

Figure 3-64 CER in the generation train with only one turbine

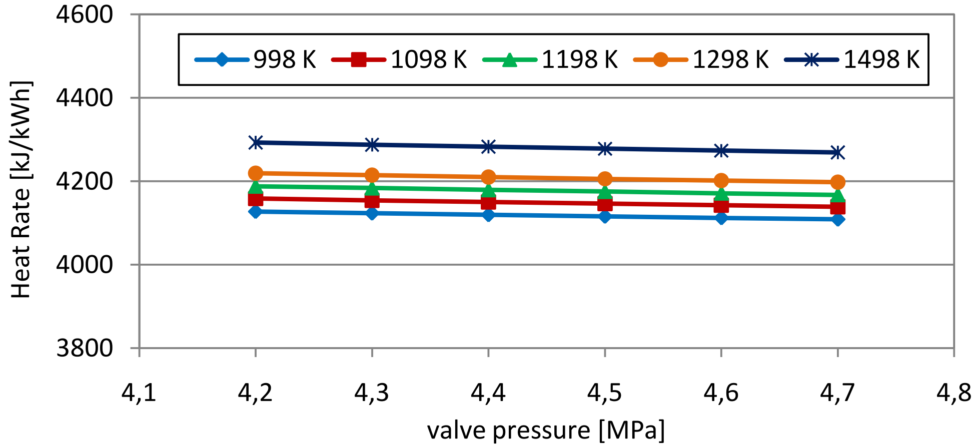

Figure 3-65 Heat Rate in the generation train with only one turbine

If these values are compared with the configurations with two turbines without reheating, it can be seen that the power output obtained with only a turbine is lower than with two, so the values of CER, EVR and efficiency (Figure 3-63) are lower. Even if the FAR is lower for the train with one turbine, the power produced is much lower, so the HR is higher than the train with two turbines. For these reasons, the configuration with one turbine should be avoided in favour of trains with two turbines.

3.1.11.4 Generation train with three turbines

Due to the improvements seen in the output power with reheating and TITs increments, it is here analyzed a train composed of three turbines (Figure 3-66). A valve pressure equals to 5,5 MPa that releases air at 410 kg/s and a train with 2^{nd} and 3^{rd} TITs equal to 1473 K are assumed. Turbine isentropic efficiency equals to 0,9 and recuperator effectiveness equals to 0,75 are assumed. The High Pressure TIT is chosen on the basis of the highest temperature for steam turbine [36] and the values proposed for CAES applications [6, 37]. In order to analyse the plant performances changing the Turbine Inlet Pressures, two ratios are defined (eq. 28 and eq. 29). Increasing the HP TIT the output power generated increases, with benefits also in the performance indices. Figure 3-67 shows the presence of an optimum of the output power generated; same optimum also for the CER and EVR. This optimum is still function of the TITs; increasing the 1^{st} TIT, the optimum moves the 2^{nd} TIP to lower pressure, decreasing both the Γ and the δ ratios.

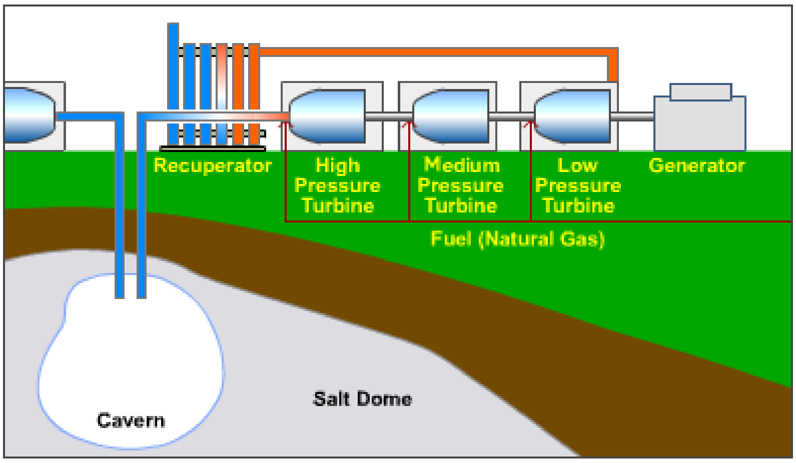

Figure 3-66 Generation train with three turbines

$$\boldsymbol{\delta\ ratio} = \frac{\boldsymbol{2^{nd}\ expansion\ ratio}}{\boldsymbol{1^{st}\ expansion\ ratio}} = \frac{\boldsymbol{2^{nd}\ TIP}/\boldsymbol{3^{rd}\ TIP}}{\boldsymbol{1^{st}\ TIP}/\boldsymbol{2^{nd}\ TIP}} \tag{28}$$

$$\boldsymbol{\Gamma\ ratio} = \frac{\boldsymbol{3^{rd}\ expansion\ ratio}}{\boldsymbol{1^{st}\ expansion\ ratio}} = \frac{\boldsymbol{3^{rd}\ TIP}/\boldsymbol{exhaust\ pressure}}{\boldsymbol{1^{st}\ TIP}/\boldsymbol{2^{nd}\ TIP}} \tag{29}$$

Low 1st TIT instead, moves the MP Turbine Inlet Pressure to higher value because the MP and LP turbines are at higher temperatures and they need to produce the highest amount of power possible. If the three temperatures are equal, the values of Γ and δ ratios are equal to 1 and the expansion ratios are equally distributed. Increments in the 1st TIT introduces the HR trends observed in Figure 3-68; for a certain train configuration (Γ and δ ratios) the HR reduces increasing the HP TIT. In Figure 3-69 and Figure 3-70, output power and HR trends for a valve pressure equal to 5,5 MPa are represented. If the 1st TIT is low, the 2nd TIP has to be the highest possible (about 4,5 MPa), if instead a 1st TIT equals to 1144 K is assumed, the MP TIP is about 3,1 MPa and the LP TIP is about 0,55 MPa. If all the TITs are equal to 1473 K the MP is about 1,5 MPa, the LP about 0,32 MPa and the power achieved reaches about 534 MW. It can be mentioned that also in this train the HP combustor could be avoided (3.1.11.1), using the energy of the high temperature exhaust gas and a recuperator.

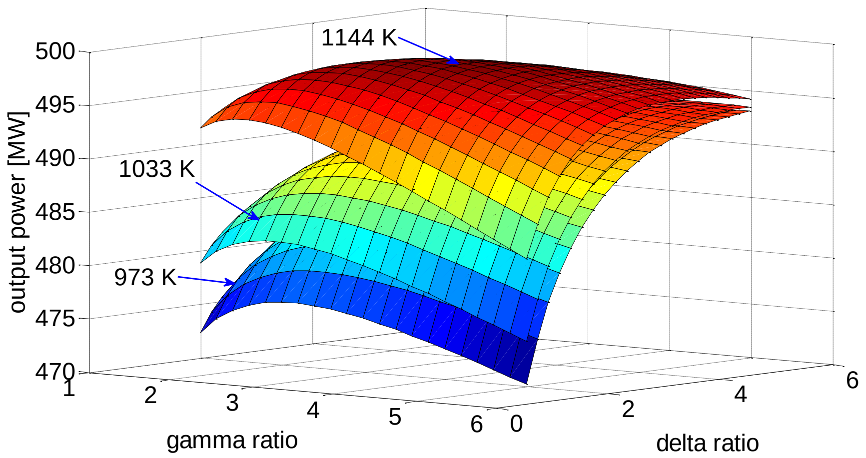

Figure 3-67Output power generated for different HP TIT

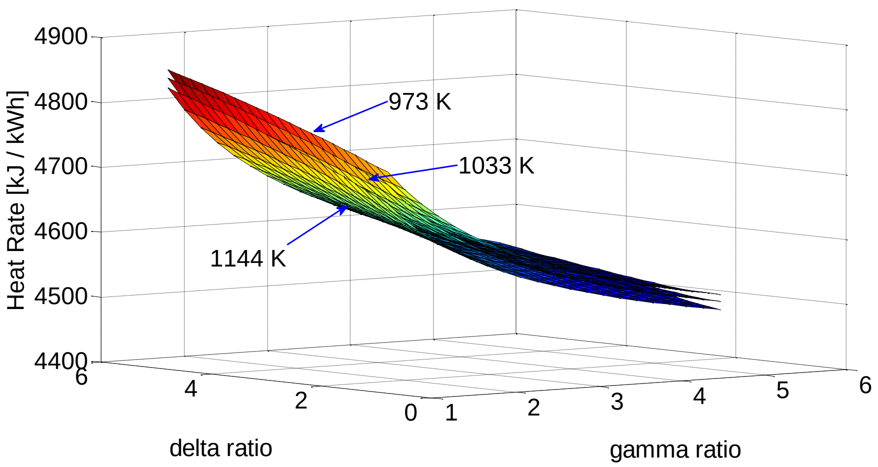

Figure 3-68 Heat Rate for different HP TIT

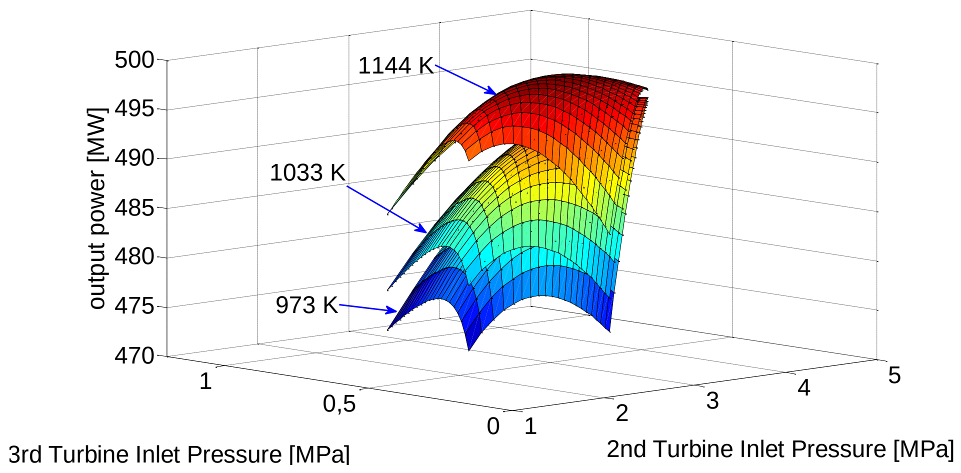

Figure 3-69 Output power for different HP TIT

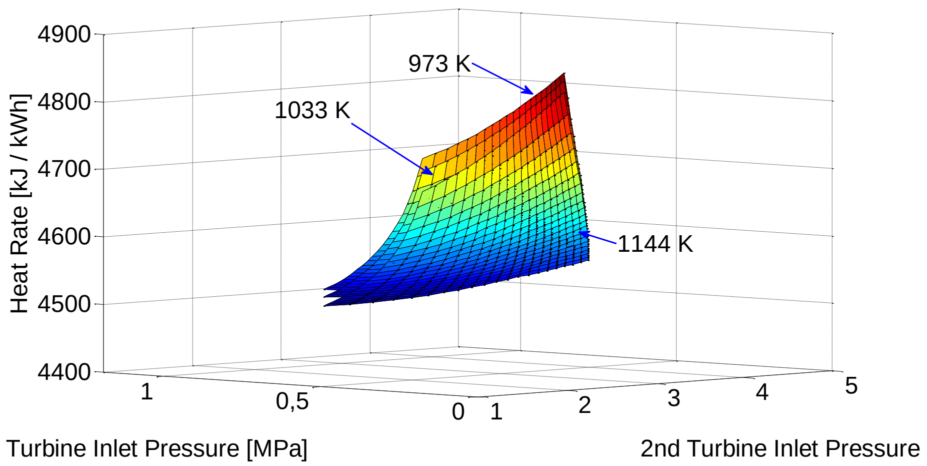

Figure 3-70 Heat Rate for different HP TIT

Seen the high temperature of the exhaust gas released into the atmosphere and the design of low temperature HP TIT, it is investigated the possibility to introduce a recuperator between HP turbine and MP combustor (Figure 3-71), in order to overcome the temperature drop. Figure 3-72 shows the HR comparison between two generation trains both with 1st TIT equals to 973 K, one supplied by one recuperator and the other with two recuperators. The effectiveness is assumed equals to 0,75. If the train is designed to produce the highest output power (red circle), hence all the power is generated by the last two turbines, the HR improvement by using the second recuperator is only about 1%, while for the efficiency about 0,5%. Therefore thermodynamically, the 2nd recuperator slightly improves the plant performances if there is a significant drop between HP TIT and MP TIT. However, it introduces economic problems, due to the space and more maintenance required, but in particular the system can become slower. An investigation also for a train composed of two turbines has been realized; the results have showed that the 2nd recuperator does not add any benefits both thermodynamically and economically compared to the simple train. Therefore, a configuration with only one recuperator is advised.

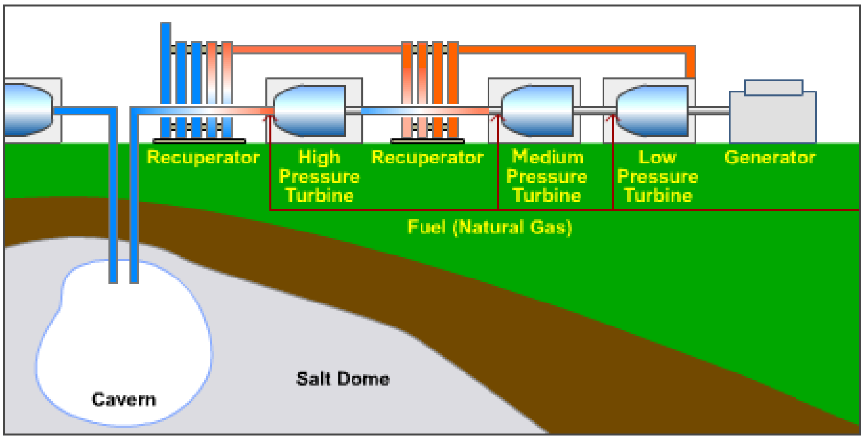

Figure 3-71 Generation train with 2nd recuperator

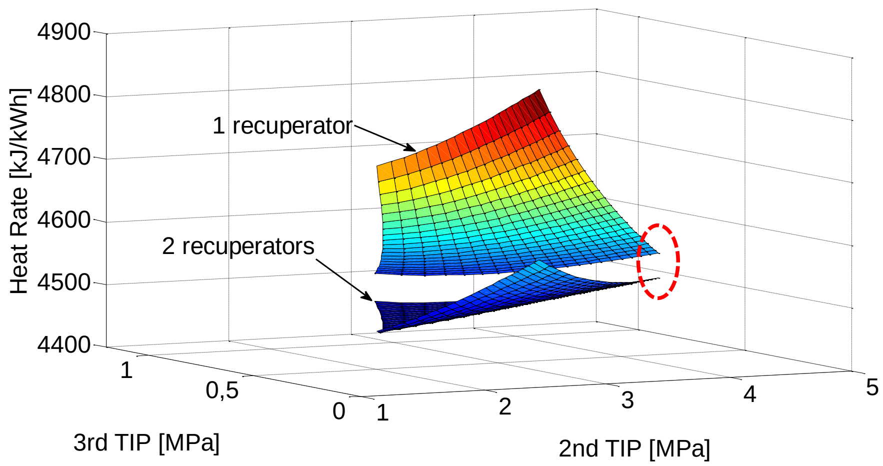

Figure 3-72 HR comparison when the 2nd recuperator is introduced

Before going ahead with the next analysis, it is presented a table that collects information about the advantages and disadvantages of the train with three turbines compared to that one with two (Table 3-2). For all the models a storage volume of 500000 m^3 with pressure range 5,5 MPa-8,5 MPa, air mass flow withdrawn of 410 kg/s and turbines efficiencies equal to 0,9 are assumed. In the table, benefits in the HR increasing the recuperator effectiveness are registered even if a reduction of the power produced happens, due to the pressure losses and less fuel used (less mass flow through the turbines). Comparing the configurations, it can be seen again the benefits achievable with TITs increments; with the same mass flow withdrawn, higher power can be achieved if three turbines are used. It is obvious that, since the train with two turbines produces less output power, the EVR is lower than that one produced with a three turbines configuration. Therefore, these results show the benefits in terms of output power, CER and EVR, introduced with the three turbines configuration, even if with fuel consumption increments.

Table 3-2 Comparison between generation train with two and three turbines

train with 3 turbines					
HP TIT [K]	LP and MP TITs [K]	effectiveness	power [MW]	Heat Rate [kJ/kWh]	EVR [kWh/m^3]
1033	1473	0,80	493,8	4440	7,88
		0,85	493,2	4309	7,87
		0,90	492,7	4190	7,86
1144	1473	0,80	498,0	4466	7,93
		0,85	497,3	4340	7,92
		0,90	496,7	4235	7,91
1144	1573	0,80	536,6	4502	8,56
		0,85	536,0	4380	8,55
		0,90	535,5	4250	8,54
train with 2 turbines					
HP TIT [K]	LP TIT [K]	effectiveness	power [MW]	Heat Rate [kJ/kWh]	EVR [kWh/m^3]
1033	1473	0,80	423,0	4328	6,75
		0,85	422,3	4223	6,74
		0,90	422,0	4120	6,73
1144	1473	0,80	437,0	4342	6,97
		0,85	436,5	4245	6,96
		0,90	436,0	4136	6,95
1144	1573	0,80	464,0	4372	7,40
		0,85	463,5	4273	7,39
		0,90	462,9	4156	7,38

3.1.12 Primary Energy Efficiency

The plant efficiency changes if the thermal efficiency of the baseload plant that produces the electric input energy is considered. Assuming the reference plant (Figure 3-1) with constant compressors efficiencies and the values of thermal efficiencies reported in Table 2-1, PEEs assume the trends proposed in Figure 3-73. AGR's cycle and fossil fuel power plant have the same thermal efficiency. It is obvious that lower thermal efficiency (LWR's cycle) produces lower PEE; lower thermal efficiency increases the electric component in the denominator of the PEE and the ratio drops down. It can be also highlighted that, in the recuperated train, the PEE variations are bigger, due to the more effect of the electric energy in the denominator of the ratio, compared to the train without recuperator (where fuel energy is more important).

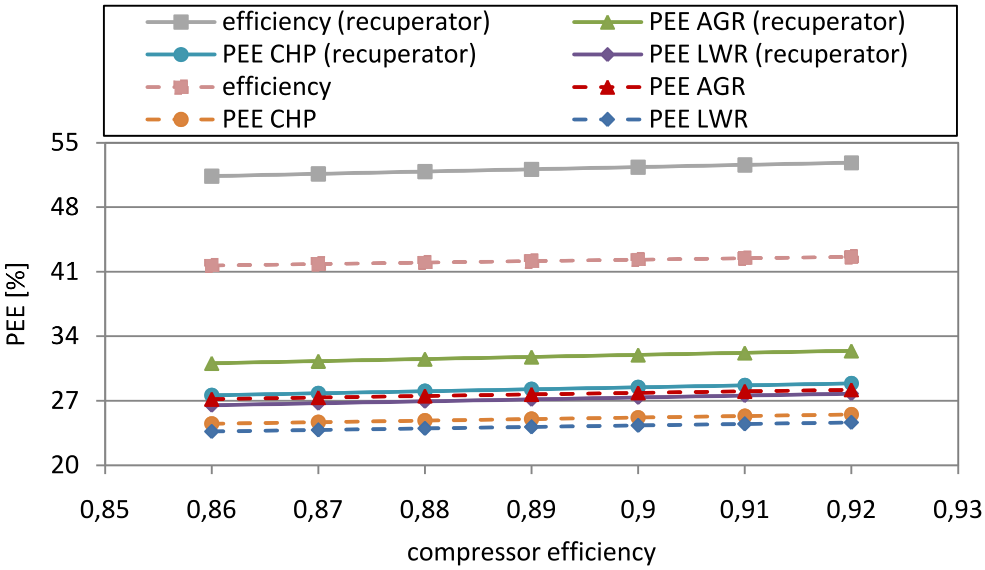

Figure 3-73 PEE for different baseload plant thermal efficiencies

3.2 Parametric Analysis

In chapter 3.1 the performance indices variations have been proposed changing each single parameter; now it is performed an investigation of the performances changing more parameters together.

3.2.1 Electric input power and intercooler outlet temperature

Analysing the intercooler outlet temperature with the input power supplied, it can be seen that the optimum of the plant efficiency and ER move to lower input power values when the intercooler outlet temperature decreases (Figure 3-74 and Figure 3-75). It is assumed to have the compression train of the reference case with two compressors and DP mass flow at 110 kg/s (Figure B-5). Reducing the intercooler outlet temperature the compressor work reduces and more mass flow for the same input power can flow through the compressor, but changing the efficiency of each compressor. If the mass flow increases, the optimum changes moving to lower input power. The reasons have been mentioned in 3.1.5.2. The intercooler temperature reduction reduces the input energy, but has as drawbacks the bigger intercooler and water source required.

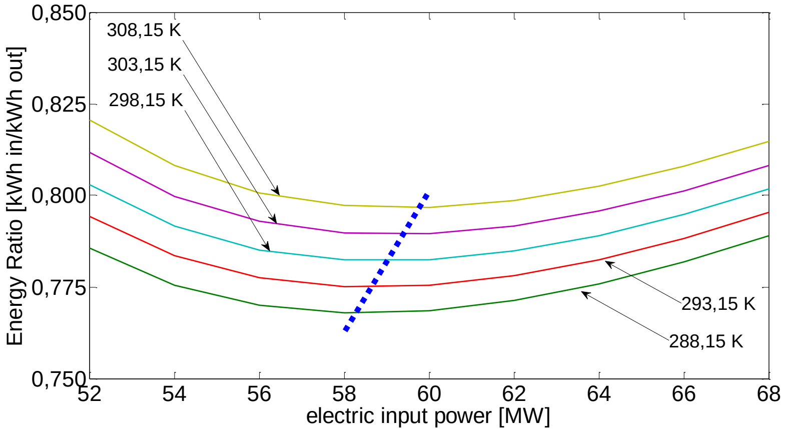

Figure 3-74 Energy Ratio changing compression parameters

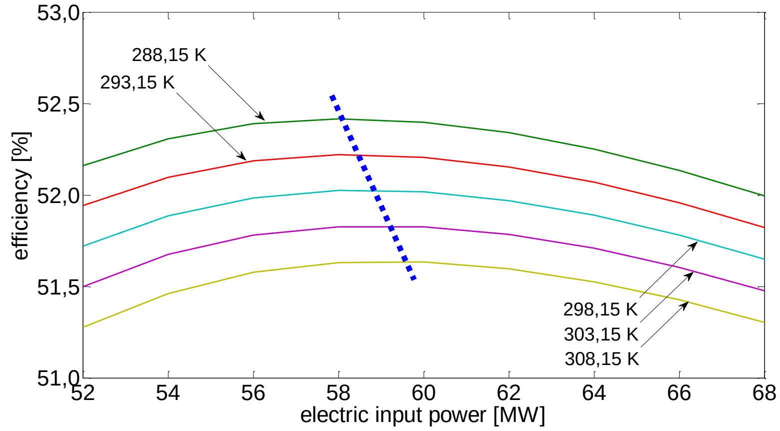

Figure 3-75 Efficiency trends changing compression parameters

3.2.2 Cavern Pressure

There is a strong relationship between the operative pressure range of the storage and the machinery (3.1.6); in these analyses, for a certain machinery design, a certain trend between the performance indices and a certain pressure range is found. Some graphs for reheated and reheated-recuperated train are presented. In order to show the behaviour of the performance indices a new index is also introduced. This non-dimensional input energy (eq. 30) takes into account the input energy required to drive the compressors, the volume and the maximum pressure. If considered without pressure, it is similar to EVR but it takes into account the input energy stored into the volume. Differently than the EVR that needs to be the highest possible, this index needs to be small because low input energy is required for defined volume and pressure.

$$non\ dimensional\ input\ energy\ =\ \frac{input\ electric\ energy}{volume*pressure}\quad \left[\frac{Joule}{m^3*Pa}\right] \tag{30}$$

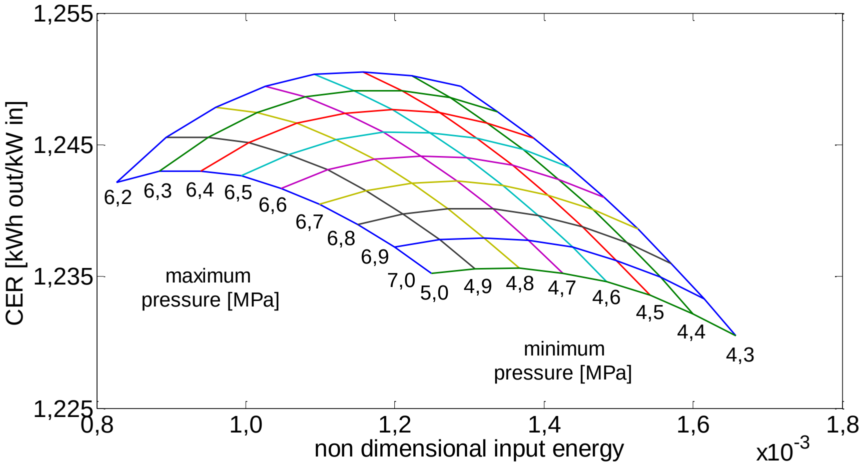

Figure 3-76 CER versus operative pressure range (train without recuperator)

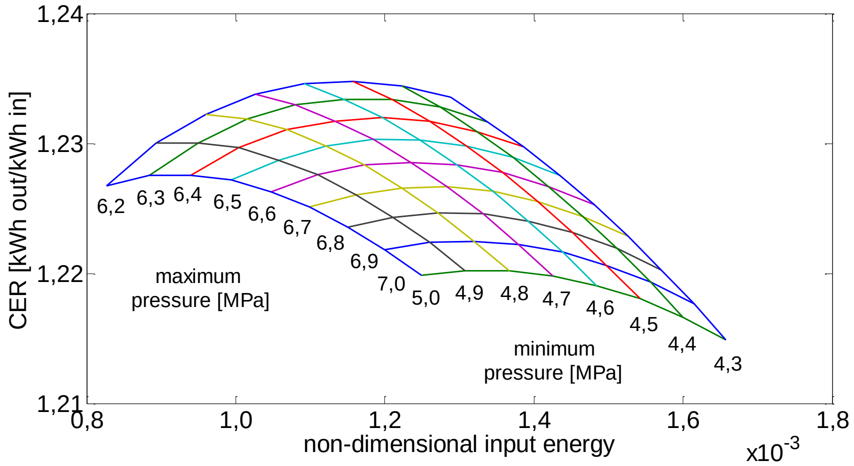

Figure 3-77 CER versus pressure range (train supplied of recuperator)

Figure 3-76 shows that for a certain maximum pressure, the CER has a certain trend and it is possible to define an optimum for a minimum value of pressure range, for example 7 MPa has optimum of the CER for minimum pressure equal to 4,8 MPa. The reasons of these trends are justified by the results seen in 3.1.6.3 about minimum and maximum storage pressures. As visible in Figure 3-76, the CER optimum for different maximum pressure goes down increasing the maximum pressure because when higher pressure needs to be reached, higher input energy is required to compress air into the storage. In fact, increments in the pressure reduces the air mass flow because more work is required by the compressor train. Figure 3-77 shows that the recuperated cycle creates negligible variations in the trends of the CER versus operative pressure range, the only difference is the lower values of CER due to the less power produced because of the recuperator.

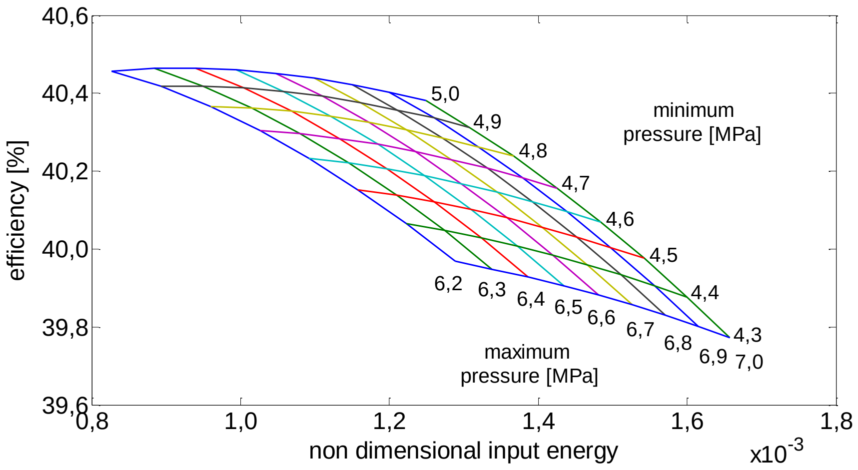

Figure 3-78 Efficiency versus pressure range (train without recuperator)

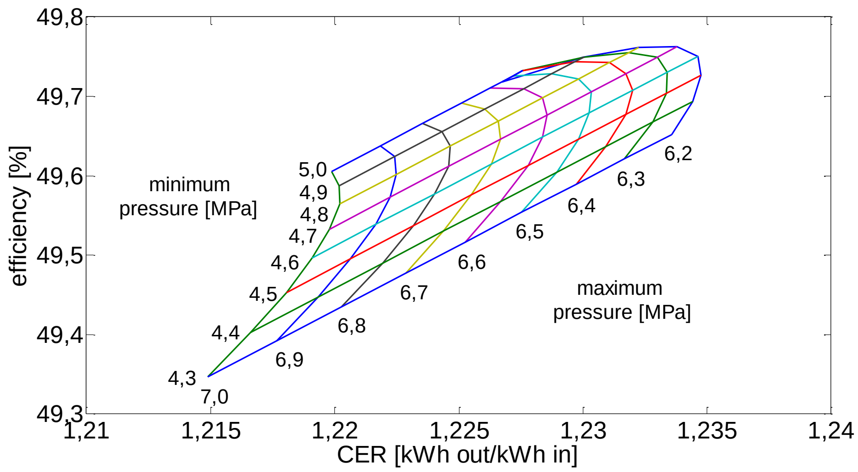

Figure 3-79 Efficiency and CER versus pressure range (train with recuperator)

Figure 3-78 shows the trends of efficiency for a train without recuperator, where is visible the effect of the minimum pressure decrement. The efficiency goes down due to the losses effect (3.1.6.5). It is also visible the effect of the increment in the input energy required increasing the maximum pressure inside the cavern from 6,2 MPa to 7 MPa; the non dimensional input energy reaches higher and higher values. The efficiency for the train supplied of the recuperator is evaluated with the CER (Figure 3-79). Because of the different machinery characteristics, the efficiency trends present optimum at different values of pressure and, as in the previous case, both the augmentation of the pressure range and the minimum pressure reduction increase the losses and the efficiency goes down. Same consideration for the CER, the increment of the pressure range with constant valve pressure, increases the losses and this ratio drops down.

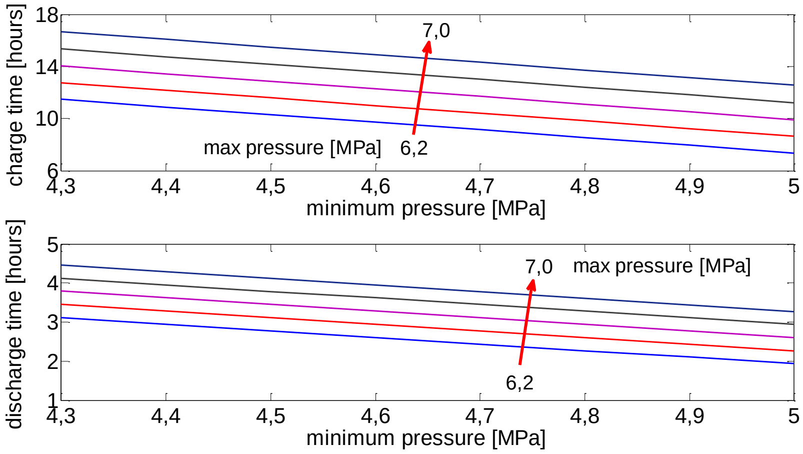

Figure 3-80 Charge and discharge times versus pressure range

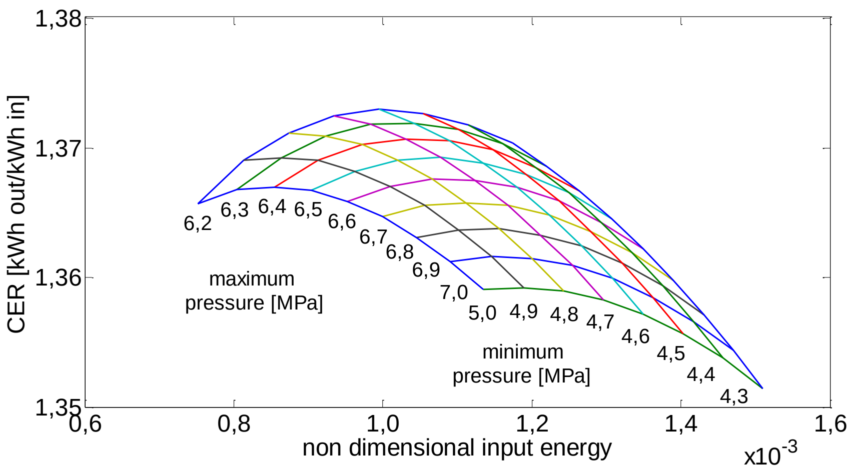

Figure 3-81 CER versus pressure range (three compressors)

The analyses of CER and efficiency optimums are proposed without considering the charge and discharge times. Figure 3-80 shows these trends and their relationship with the times. Reduction of the pressure range reduces the charge time, hence the input energy, but also the output energy is less. If a certain output energy is required, the pressure range may need to be changed and possible lower values of CER and efficiency may be achieved. If the compressor train is composed of three compressors, the trends of CER increase (Figure 3-81) compared to the configuration with two compressors (Figure 3-82) due to the less input energy required (as non-dimensional input energy shows). Looking at the efficiency, benefits are obtained from the less input energy required (Figure 3-83). Besides, as said, pressure range increments and lower minimum pressures introduce losses with consequent efficiency decrease.

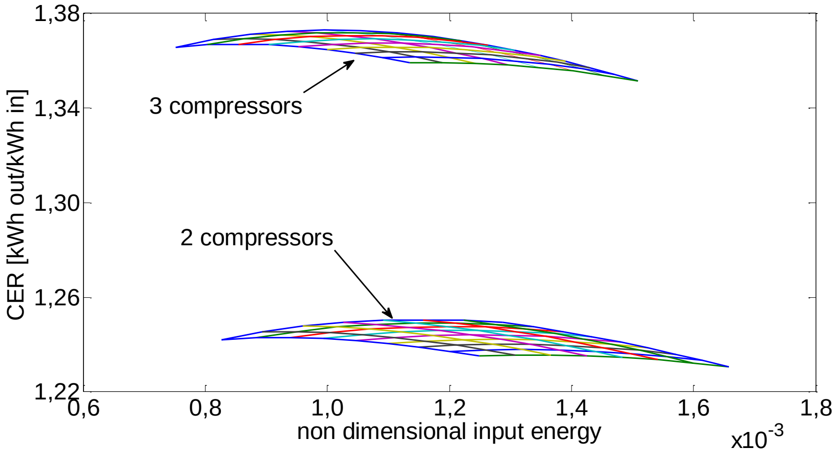

Figure 3-82 CER comparison (two and three compressors)

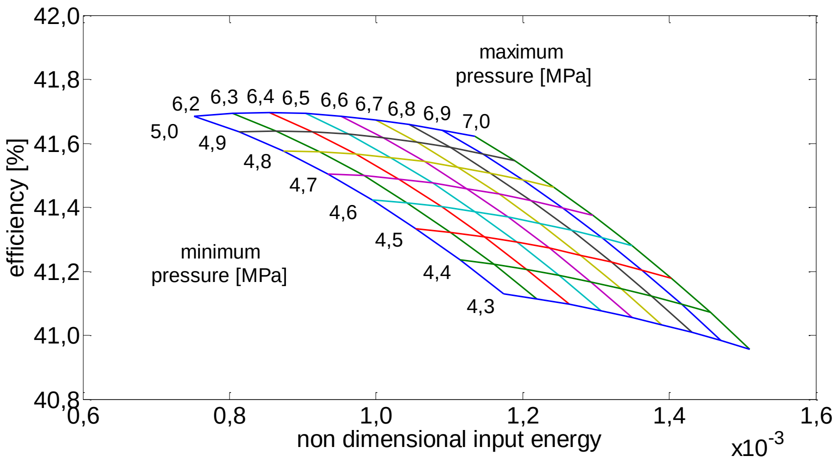

Figure 3-83 Efficiency versus pressure range (three compressors)

3.2.2.1 Minimum and maximum pressure

Before continuing with the next parametric analysis, it is done a brief interruption to propose an analysis of the performance indices changing the minimum and maximum pressure. The plant considered has a compressor train composed of three compressors (constant efficiency equals to 0,89) driven by an electric motor of 70 MW. The generation train, provided of recuperator with effectiveness equals to 0,9, is composed of two turbines that operate with an air mass flow of 410 kg/s. The 1st TIT is equal to 1298 K and the 2nd TIT is equal to 1498 K. The storage has a volume of 400000 m^3. Figures 3-84, 3-85 and 3-86 represent the trends of performance indices for certain storage pressure ranges; for each minimum pressure value (4,5 MPa to 10 MPa) a pressure range between 2 MPa and 6 MPa is evaluated. As said, if the minimum pressure increases and the pressure range is at higher pressures, the input energy required to charge the storage is higher. As Figure 3-87 shows, the charge time increases (for higher minimum pressure, but for the same pressure range), due to the higher compression work. Therefore, the CER decreases (Figure 3-84). For the efficiency, it can be seen the effect of the fuel consumption on the previous trends of Figure 3-84. In particular, when the minimum pressure increases, the output power increases and the HR decreases (3.1.6.6), leading to higher efficiency. However, the HR reduction becomes smaller and smaller increasing the pressure, so after a certain minimum pressure, the benefits in the fuel consumption reduce and the trends of Figure 3-85 are achieved. The EVR instead depends on the pressure range value (Figure 3-86); when the range increases, the amount of air stored increases and it can generate power for longer time. Also the minimum pressure increment affects the EVR since the minimum output power increases.

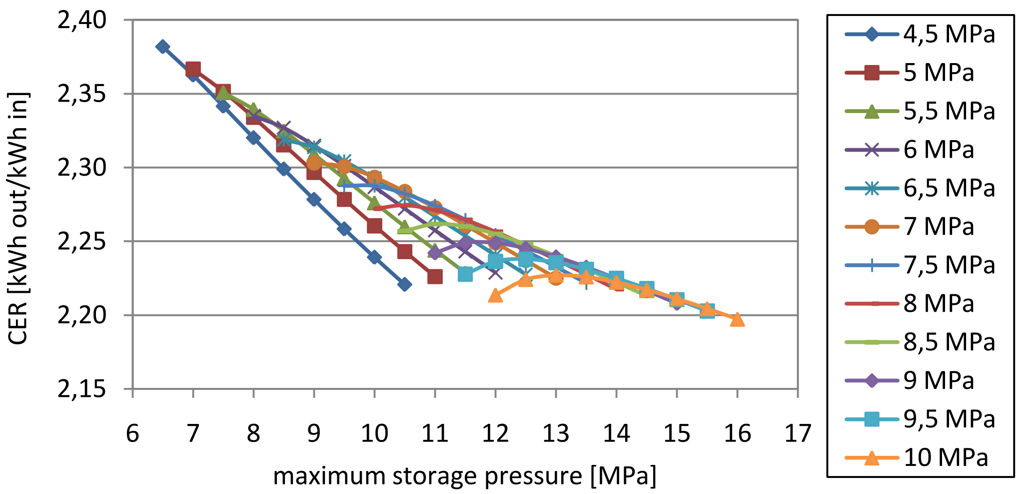

Figure 3-84 CER changing operative pressure range

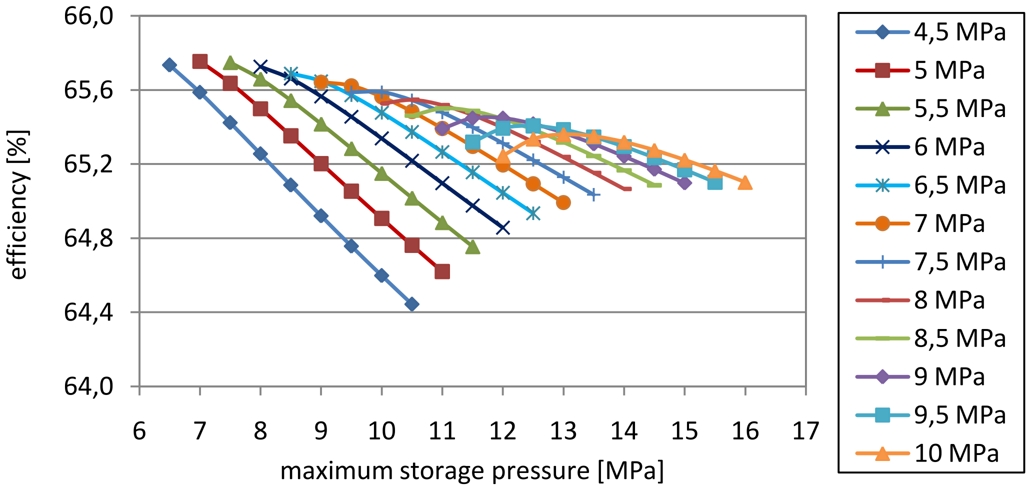

Figure 3-85 Efficiency changing operative pressure range

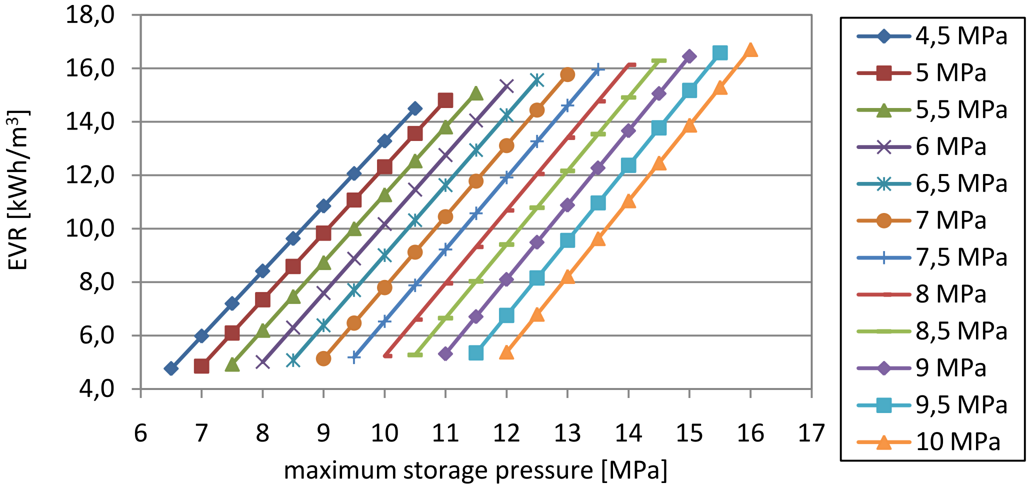

Figure 3-86 EVR changing operative pressure range

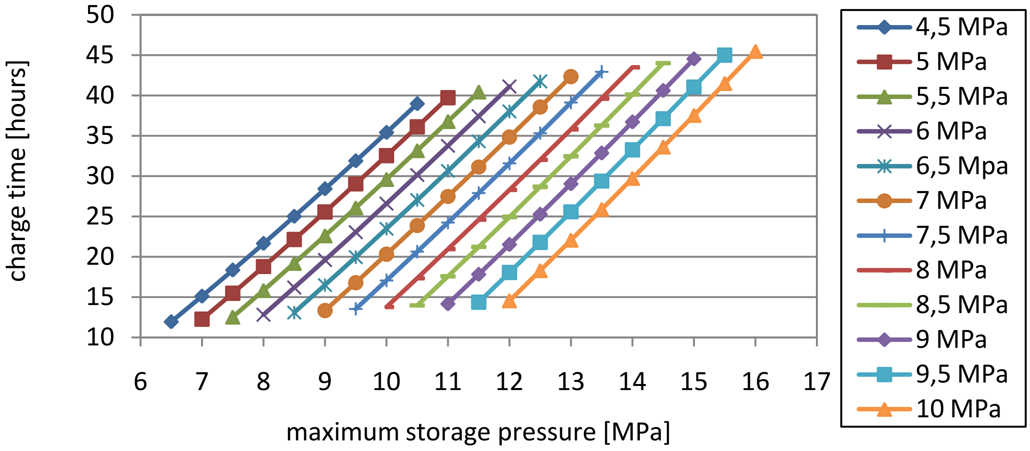

Figure 3-87 Charge time changing operative pressure range

3.2.3 Electric input power and TITs

Changing electric input power and TITs, the optimum for CER and for efficiency increase to higher values (due to improvements introduced by TITs) but it is obvious that it remains always at the same electric input power because in the region of 60 MW the electric input energy required is the minimum.

3.2.4 TITs

The performance trends changing the TITs are investigated analysing the SFC-specific work graphs (Figure 3-88). They confirm the benefits of raising both TITs, in order to increase the output power, hence the CER and EVR. However, it has to be paid attention on the SFC, sensitive to TITs variations. Increasing the HP TIT, keeping constant the LP TIT, a power increment generated by the HP turbine is registered, both in the train with recuperator and in that one without (Figure 3-88 and Figure 3-89). This increment introduces also SFC reductions; benefits that however decrease with the HP

TIT increment. When a recuperator is supplied, an optimum is reached if high HP TIT and low LP TIT are used. Reached this optimum and trying to increase more the HP TIT, requires more fuel, but because of the small HP expansion ratio, the more fuel spent gives less benefits in terms of power produced (the specific work still increase but with an higher SFC required). For the LP TIT, every increment introduces significant specific work augmentation due to the high value of expansion ratio of the LP turbine; the problem is the SFC increment. The results in Figure 3-88 and Figure 3-89 highlight the importance to increase both the TITs avoiding temperature drops between the turbines (low HP TIT and high LP TIT and vice versa need to be avoided) and the need of a recuperator for using as much as possible the energy supplied with the fuel and reducing SFC (Figure 3-89). A benefit to highlight in the increase of the TITs is that the machinery can be smaller since the specific work increases, or for the same DP mass flow the output power produced can be bigger.

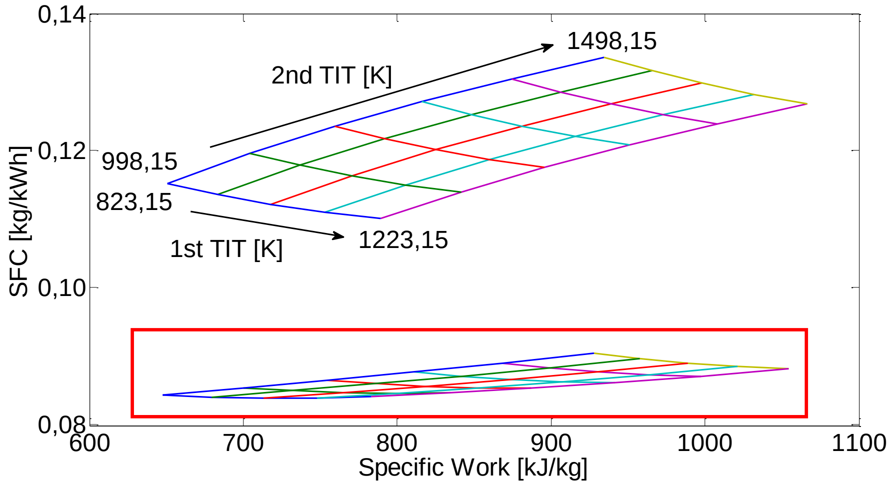

Figure 3-88 Specific Work and SFC versus TITs

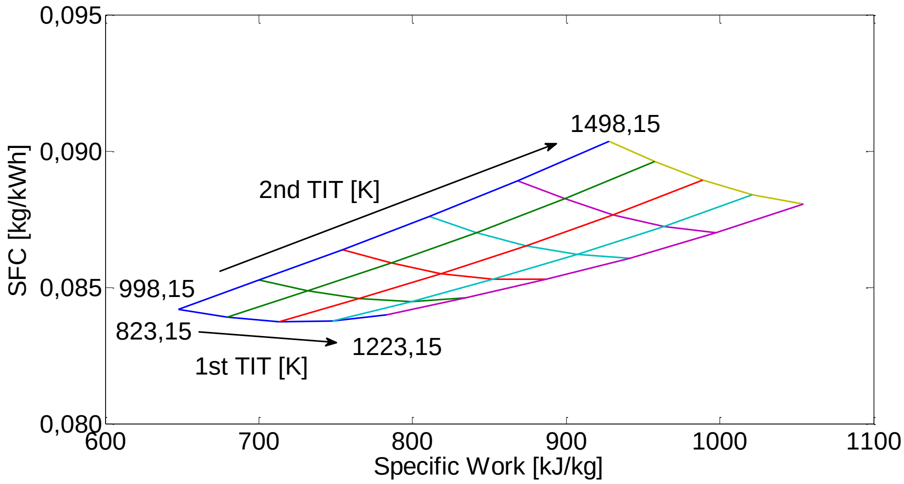

Figure 3-89 Specific Work and SFC versus TITs (reheated-recuperated train)

Figure 3-90 shows that, increasing both TITs in a train without recuperator, the SFC increases and the efficiency goes down because all the energy is wasted through the stack. It is obvious that this operative point needs to be avoided in terms of efficiency. It is clear that it may be better to have lower 2nd TIT (it reduces the losses) even if the specific work is lower. If instead a recuperator is used, significant benefits are achieved increasing both TITs; the operative point moves to lower SFC and the highest efficiency (Figure 3-91) and specific work are achieved (Figure 3-88).

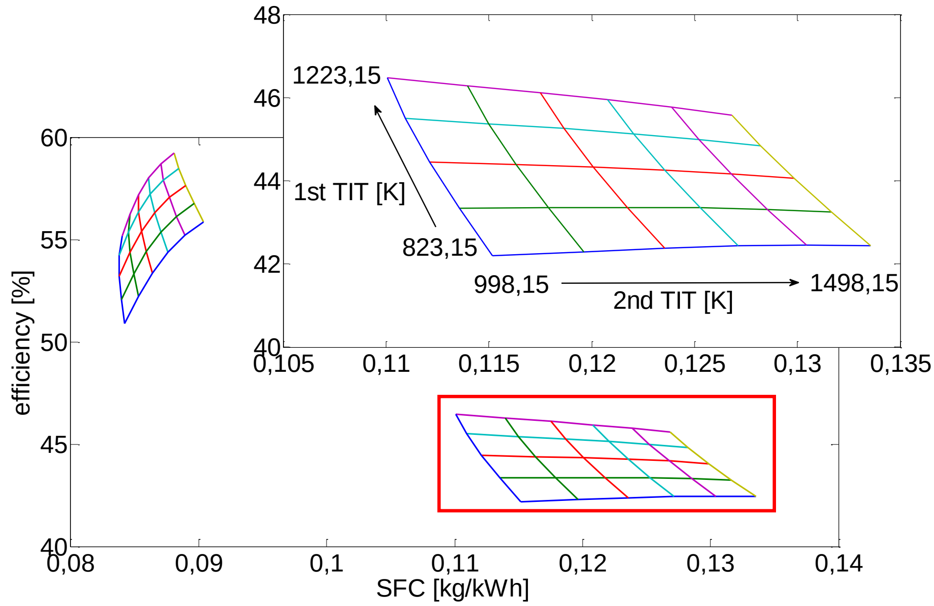

Figure 3-90 Efficiency and SFC versus TITs

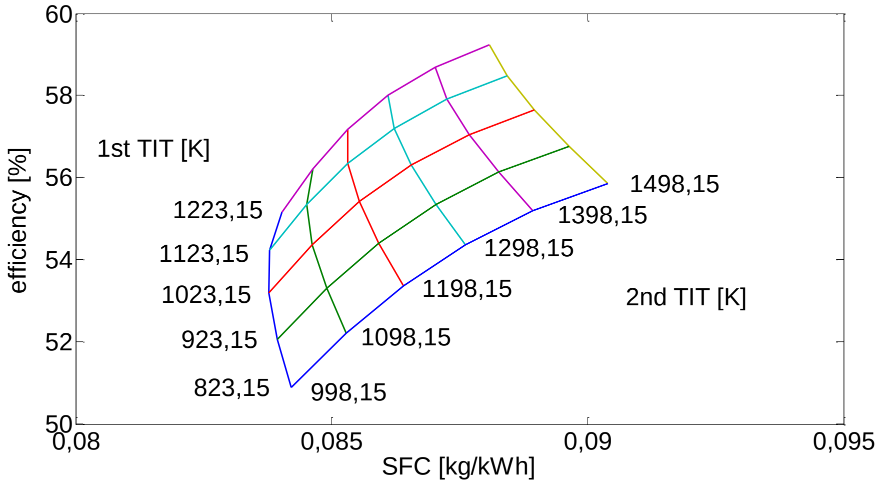

Figure 3-91 Efficiency and SFC versus TITs (reheated-recuperated train)

3.2.5 Valve pressure and generation train

Similarly to the TITs, an analysis changing valve pressure and β ratio (eq. 26) is done. As seen in 3.1.10.3, defined the TITs values, a β ratio that maximizes the output power can be defined. Even if the power optimum is reached, the value is not the optimum for the SFC that decreases if higher β ratio is assumed (Figure 3-92). This increment means that more power is produced by the LP turbine that is the turbine with higher TIT. Since the β increment after the optimum defines small specific work changes and more significant variation in the SFC, the result is an efficiency increment. This confirms that the maximum of efficiency and the output power (CER) maximum are different, in particular for the efficiency is at higher value of β respect to the output power. Because for a certain β value is reached the optimum of the output power, this is also the optimum for the CER (Figure 3-93) and EVR.

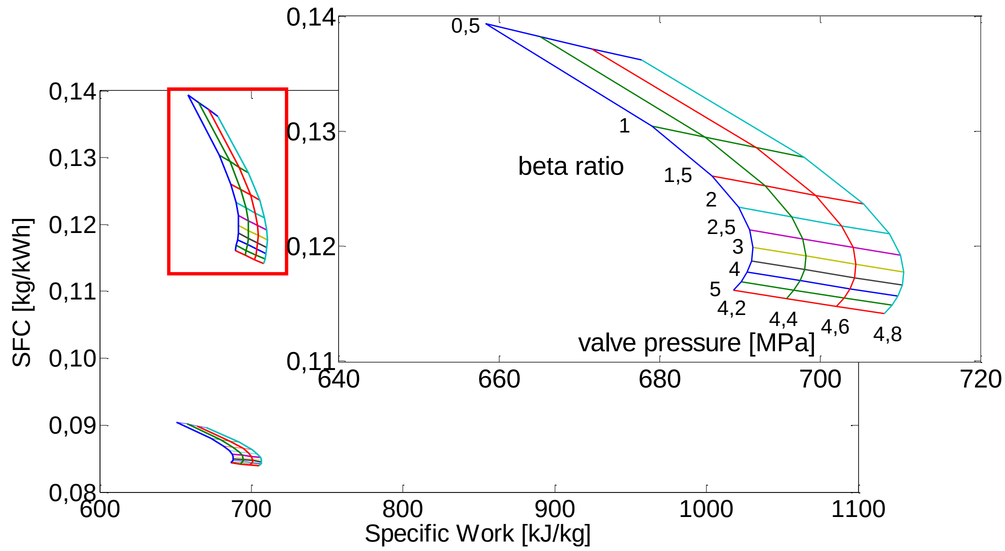

Figure 3-92 Specific Work – SFC versus β ratio and valve pressure analysis

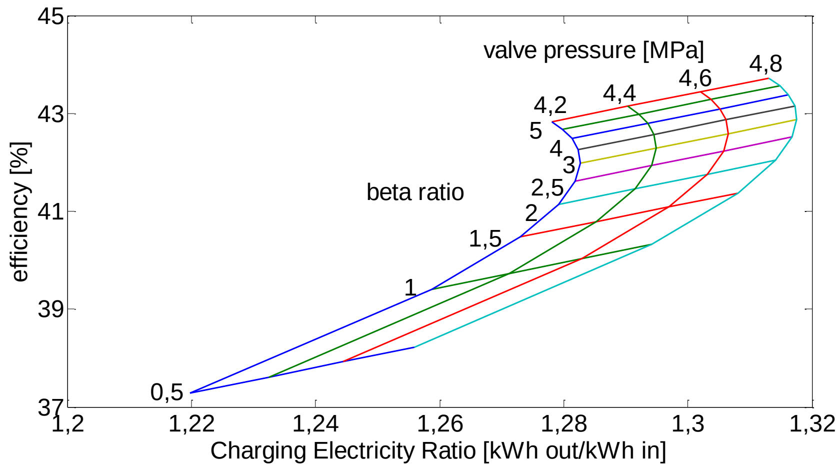

Figure 3-93 Efficiency and CER versus β ratio and valve pressure

3.2.6 Valve pressure and 1st TIT

Similarly to conventional gas turbine, it is defined the SFC-Specific Work trend, changing valve pressure and 1st TIT. In Figure 3-94 a train without recuperator (top) and another one with (bottom) are analysed. As seen, valve pressure increment improves the specific work and reduces the SFC for both the train. In the case with recuperator, for a 2nd TIT constant to 1098 K, increasing the 1st TIT a minimum in the SFC is reached; after this, other TIT increments increase the specific work but negligible increments in the fuel consumption are registered.

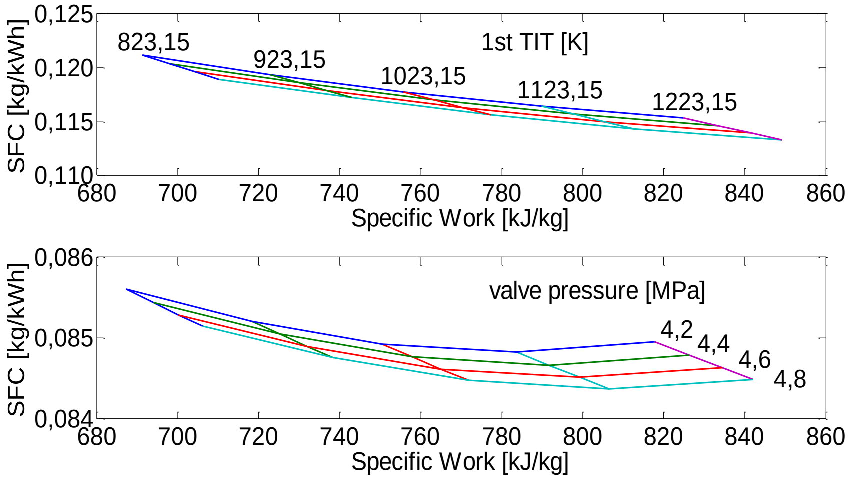

Figure 3-94 Specific Work – SFC (valve pressure and 1st TIT)

3.3 Sensitivity Analysis

It is here realized an analysis to identify the sensitivity of the performance indices changing the different technical parameters of 1%.

3.3.1 Output power analysis

The analysis shows that the main components that affect the output power are mass flow and turbine efficiency with trend almost linear. The output power is particularly sensitive also to the TITs (Figure 3-95), more the 2^{nd} TIT because it produces the main component of power. Cavern minimum pressure defines the valve pressure so the pressure of the fluid that expands through the generation train; increasing this, the power increases. The above mentioned parameters introduce improvements when increased; instead, increments in the ambient pressure and recuperator losses, reduce the index, since both reduce the expansion ratio.

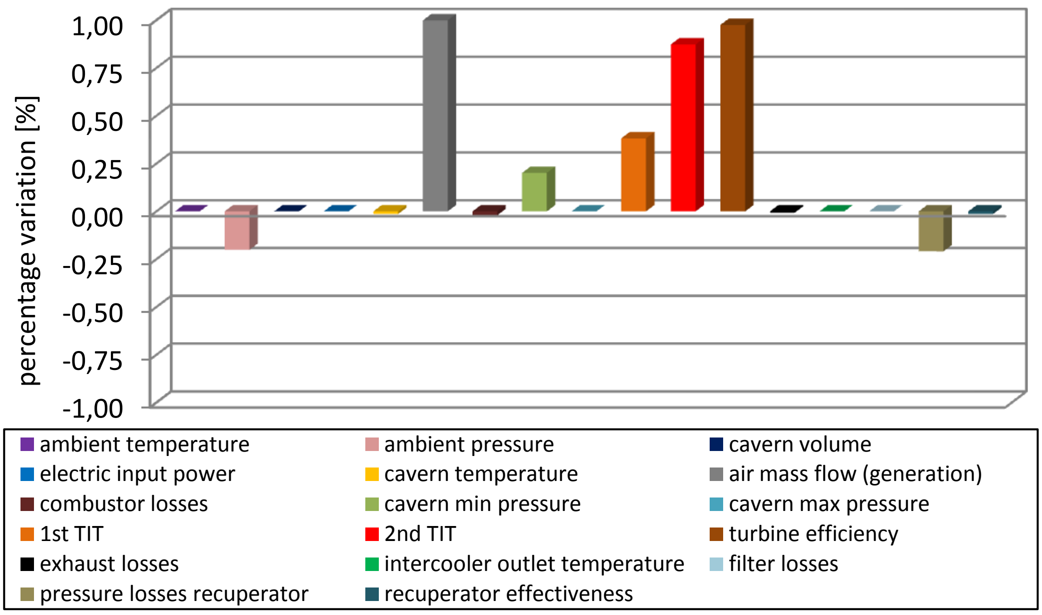

Figure 3-95 Sensitivity analysis for the output power

3.3.2 Charging Electricity Ratio analysis

Similarly to the previous case, the CER is sensitive to the turbine efficiency and the TITs (Figure 3-96). It is not sensitive anymore to the mass flow since CER is a ratio of energy. Even if the mass flow withdrawn changes, the amount of mass stored in the volume remain constant. The analysis of the compressor isentropic efficiency shows the high sensitivity of the CER on this parameter (as seen in 3.1.5.4). Other parameters that need to be evaluated in the compression are input power, intercooler outlet temperature and maximum pressure. They define the input energy and their increment introduces increments in the energy required for the injection of the air into the storage. Despite ambient pressure reduces the expansion ratio, hence the output power, it reduces also the compression ratio making easier and less expensive the injection. For the same consideration done in 3.3.1 the recuperator losses reduce the CER.

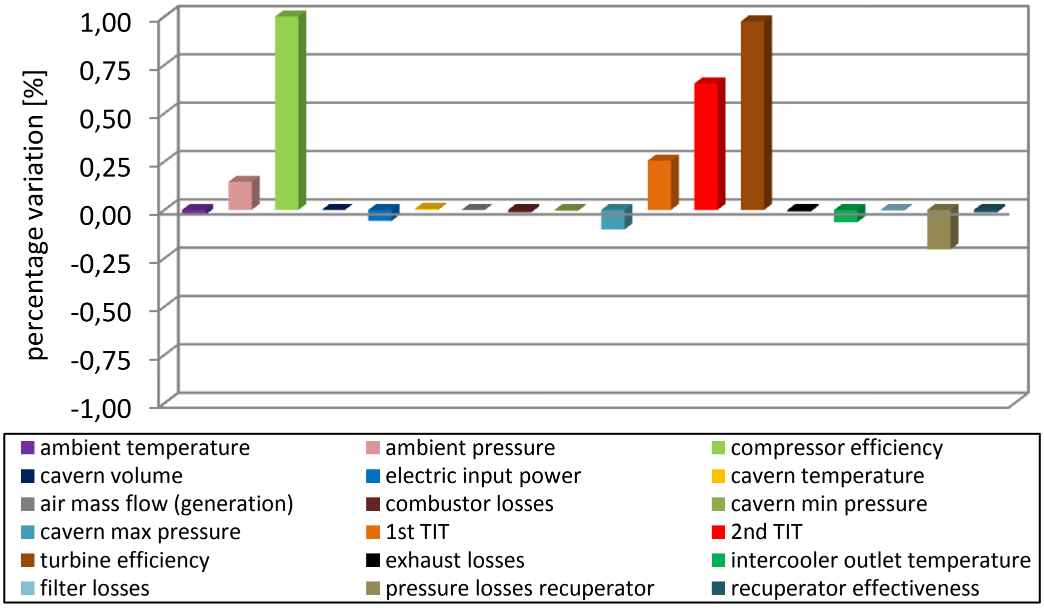

Figure 3-96 Sensitivity analysis for the CER

3.3.3 Efficiency analysis

As the previous cases, the efficiency of the plant is particularly sensitive to the turbine isentropic efficiency (Figure 3-97). The compressor isentropic efficiency still affect the efficiency even if the sensitivity decreases because of the effects of the fuel energy.

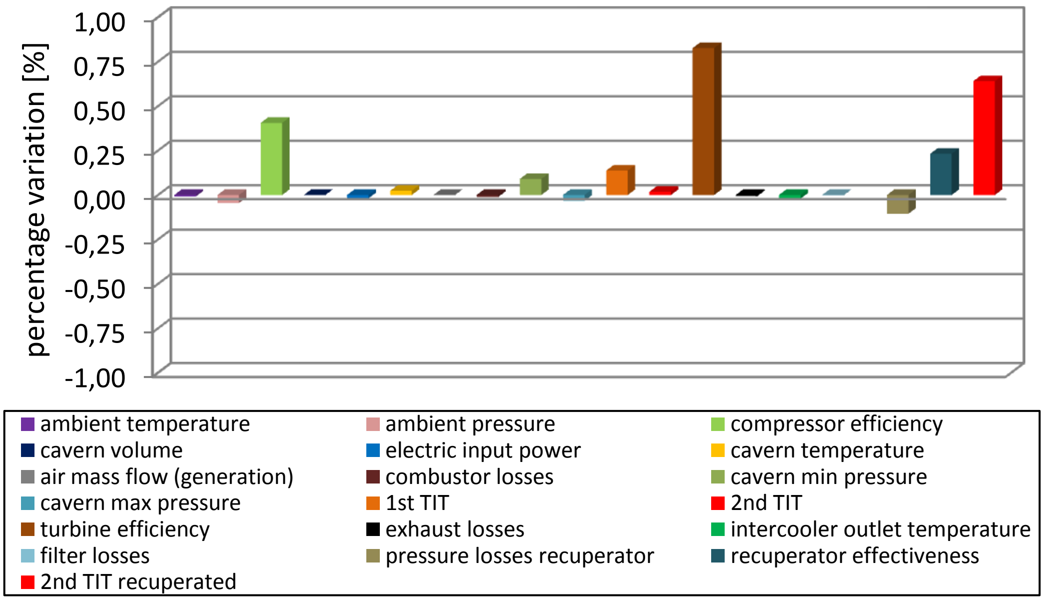

Figure 3-97 Sensitivity Analysis for the efficiency

A consideration has to be done for the 2nd TIT: if a recuperator is not supplied, a TIT increment does not bring any benefits because the energy is wasted through the exhaust gas. On the other hand, if a recuperator is used, significant improvements are achieved because less fuel is required (red bar). Benefits in the efficiency are also achieved with increment of the recuperator effectiveness.

3.3.4 Energy Volume Ratio analysis

The elements that more affect the EVR are maximum and minimum pressures since they define the amount of air that can be stored (Figure 3-98). Increasing the maximum pressure, more mass is injected and it is available to create power for longer time. On the other hand, increasing the minimum pressure, less mass can be stored and less energy is produced. Similar to the previous cases, turbine isentropic efficiency improves the index. Increments in the TITs increase the output energy produced for the same amount of air mass, but HR needs to be evaluated. Cavern temperature defines the amount of air that can be stored inside the volume and it has a small impact on the ratio; increasing the temperature, the energy reduces.

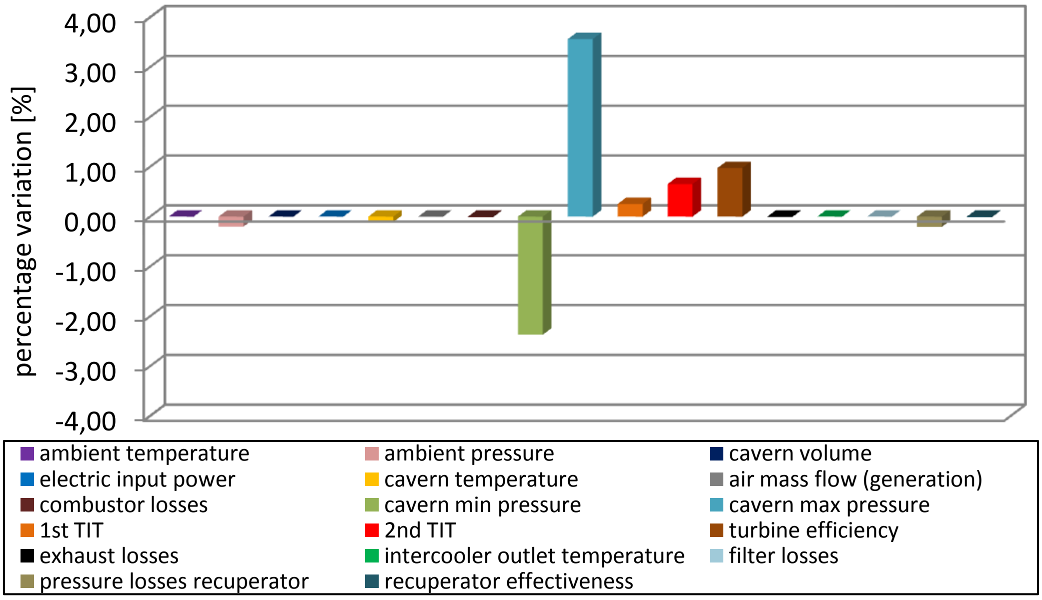

Figure 3-98 Sensitivity analysis for the EVR

3.3.5 Heat Rate analysis

Turbine isentropic efficiency still introduces benefits in the performance indices (Figure 3-99). As seen in Figure 3-97, recuperator effectiveness reduces the fuel consumption introducing efficiency increments. The 2nd TIT increases the fuel consumption, but if a recuperator is used, the heat-exchange with the cold air withdrawn reduces the fuel to reach the 1st TIT. Similar consideration can be done for ambient pressure, pressure increments reduce the expansion ratio and lower power is produced; in the recuperated train, gas at higher temperature is released and it is available for the cold air withdrawn. The last parameter is the recuperator effectiveness that reduces the HR extracting more heat from the exhaust gas.

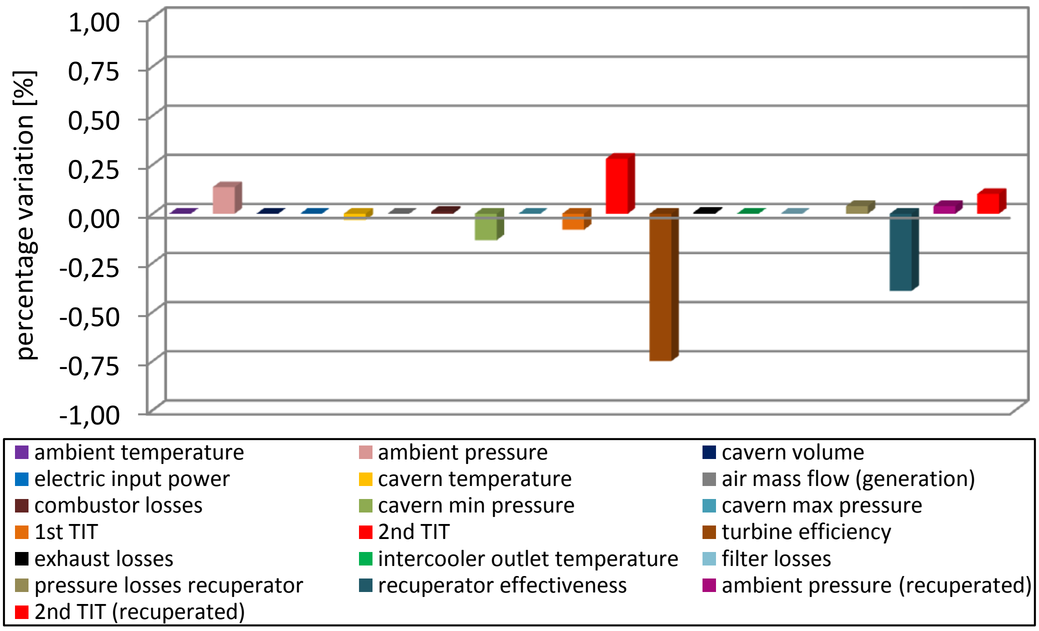

Figure 3-99 Sensitivity analysis for the Heat Rate

3.3.6 Conclusions of the Sensitivity Analysis

According to these results the turbine isentropic efficiency is the parameter that most affects the performances, and for this reason should be maximized as much as possible. The TITs also influence significantly the performances indices, but a recuperator is advised, avoiding waste of hot gas through the stack. In the compression train, compressor efficiency improvements and reduction of the intercoolers outlet temperature should be taken into account. From the analysis of the EVR, it can be seen the significant effects of pressure variations on the energy spent and produced. Since the amount of air stored inside changes, also the time of compression and generation change. In the end, ambient pressure, that should be the highest possible in order to reduce the input energy required during the compression.

3.4 CAES and wasted heat

An analysis of a CAES plant connected to a system able to use the waste heat produced during compression is done, the hot water after the heat-exchangers is not wasted but stored into a thermal energy storage. The feasibility to use aquifers as seasonal thermal energy storages [38], the possibility to find underground different layers of aquifers [39], the diffusion of the concept to use the fuel burnt as much as possible, the diffusion of District Heating [40] and the possibility of revenue from the heat sold, are some of the reasons why this investigation is done. Because the production and demand of heat are often not matching in time or space, a medium able to solve the problem and bridge the time gap (hours, days, weeks or even seasons) is required. Underground Thermal Energy Storage (UTES), with storage media that may be groundwater (aquifers, ATES) and boreholes, or man-made tanks, may be the solutions. In order to model the heat storage equation 31 is used [41]; the one-dimensional model used is for a fully-stratified tank where the entire fluid inside is assumed to have a uniform temperature which changes with time as a result of the addition or withdrawal during the charge or discharge processes. In the equation, M represents the mass of water in the tank that changes with the addition and withdrawal, $\dot{m}_{in}$ is the mass flow rate, T_{in} is the inlet temperature of the water, T is the storage temperature, T(0) defines the initial condition of the average temperature inside the storage. The losses with the surrounding environment are not considered in this equation, but a certain losses percentage is assumed between the charge and the discharge of the heat storage.

$$\boldsymbol{MC_p \frac{dT}{dt} = \dot{m}_{in}\, c_p\, (T_{in} - T)} \quad (31)$$

The plant analysed uses a compressor train composed of three compressors, DP mass flow equals to 200 kg/s and input power equals to 100 MW. The storage is a 400000 m^3 formation that operates between 5,5 MPa and 8,5 MPa. The expansion train composed of two turbines, has pressure limited by a valve to the minimum value of pressure range (5,5 MPa), while the TITs are respectively 1144 K and 1473 K. With a mass flow of 410 kg/s, it can produce 436,5 MW for more than 6,5 hours (1400 MWh of input energy is required). The idea is to store all the heat that can be extracted during the compression by heat exchangers (Figure 3-100); an amount up to about 7300 m^3 of hot water may be stored, using cold water (293 K) coming from a river. The water temperature at the end depends on the thermal energy storage characteristics; if an initial amount of water of 10000 m^3 at 373 K is stored inside a man-made tank, the addition of water at about 408 K during compression causes the trend represented in Figure 3-101. If for example an initial amount of 30000 m^3 is assumed, the temperature reached is lower, even if the same amount of thermal energy is stored (Figure C-6). In both cases the temperature is enough to be used in District Heating (DH) or in desalination plants. DH is a system for distributing heat for residential and commercial heating requirements; DH plants can provide higher efficiencies and better pollution control than localized boilers. DH with Combined Heat and Power is the cheapest method of cutting carbon and it has one of the lowest carbon footprints of all fossil generation plants. A desalination plant essentially separates saline water into two streams: one with a low concentration of dissolved salts (the fresh water stream) and the other containing the remaining dissolved salts (the brine stream). The device requires energy to operate and the two basic technologies used to remove the salts from water are thermal distillation and membrane separation. In this analysis thermal distillation is considered; around 40% of the world's desalted water is produced with processes that use heat to distil fresh water [42]. Multi Stage Flash (MSF) and Multiple Effect Distillation (MED) processes consist of a set of stages at successively decreasing temperature and pressure. MSF process is based on the generation of vapour from seawater due to a sudden pressure reduction when seawater enters to an evacuated chamber. The process is repeated stage by stage at successively decreasing pressure (Figure C-7). In MED instead, vapours are generated due to the absorption of thermal energy by the seawater; the steam generated in one stage is able to heat the salt solution in the next stage, because next stage is at lower temperature and pressure. The performance of the process is proportional to the number of stages (Figure C-8). MED plants normally use an external steam supply at lower temperature than MSF.

If it is assumed to use all the thermal energy stored inside the heat storage (5% of energy losses are considered) in a DH application operating at 368 K [73], a mass flow withdrawn at 500 kg/s can be delivered for about 5,5 hours. In the end the energy contained in the thermal energy storage is assumed to be the same of the initial condition before compression. If instead the heat is used for desalination, the possibilities are represented by MSF Once-through that requires a temperature of 363,8 K, while MED Low temperature horizontal or vertical tube designs need temperatures at about 343 K. Before calculating the amount of water that can be generated, the Performance ratio for desalination plants needs to be defined [42]. It represents the mass of desalinated water produced per unit of input energy and it is expressed in kg/MJ. Values between 3,44 kg/MJ and 5,17 kg/MJ are proposed in the literature [42]. Considering a process with performance ratio equals to 3,44 kg/MJ the amount of fresh water that can be generated is about 12100 m^3, while if a 5,17 kg/MJ ratio is used, the amount increases to about 18200 m^3. It is obvious that the amount of heat stored and used is function of the air storage volume, that defines the charge time of the CAES. The amount of heat depends not only on the storage volume, but also on the storage pressure range. If the air storage volume is reduced to 300000 m^3 the amount of water stored decreases at about 5500 m^3 and 389 K (lower than the previous case, because less thermal energy is produced), reducing to more than 4 hours the autonomy of the DH, while the water that can be desalinated is in the range 8900 m^3 (Performance ratio equals to 3,44 kg/MJ) to 13400 m^3 (5,17 kg/MJ). In the case analysed, only the heat produced in the compressor train is stored; in fact, the exhaust gas needs to maintain a minimum temperature before being released in the atmosphere [65]. Since the exhaust gas temperature after the recuperator for the preheating of the air withdrawn is about 400 K, it is not possible to extract other heat energy. It is worth mentioning that increasing the number of compressors and intercoolers, the outlet compressor temperatures decrease and lower temperature of the water are reached. However, heat storages at lower temperatures are feasible, hence higher amount of water at lower temperature can be stored and used, taking advantage of compression trains with lower temperatures. As said, this idea has been investigated due to the aquifer properties to store heat up to 120 °C [38] and because there may be different layers of aquifers also closed each others, with the feasibility to use one aquifer as air storage and the other one for the heat.

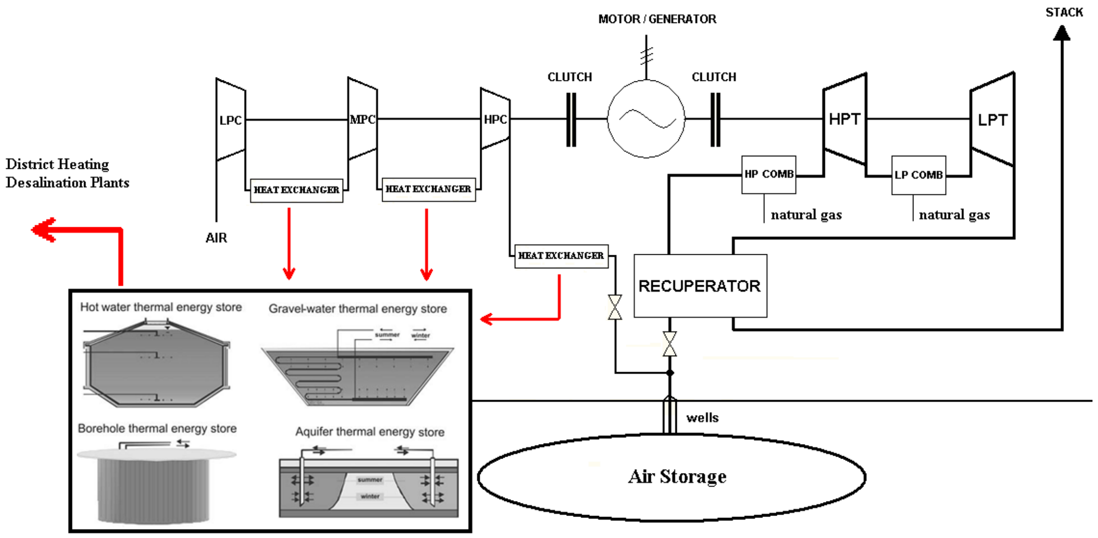

Figure 3-100 CAES with thermal energy storage of hot water

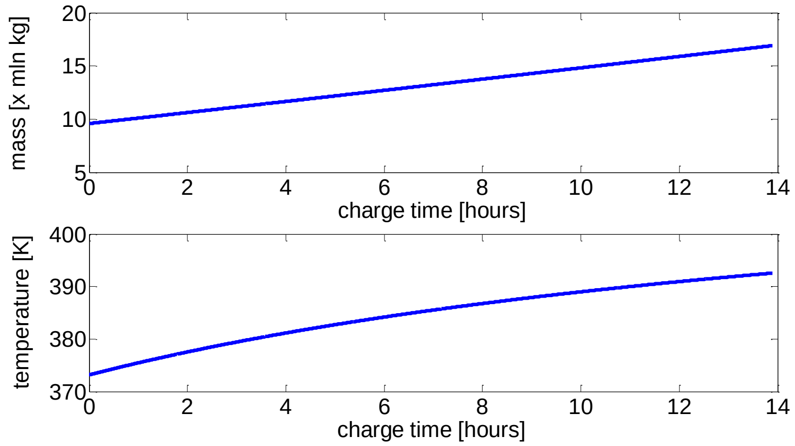

Figure 3-101 Water and relative temperature inside the TES (10000 m^3)

3.5 Conclusions

The technical analysis on conventional CAES highlights the particular benefits introduced by the increments of the compressors and turbines efficiencies (3.3.6), that have to be as much as possible constant and high in the operative pressure range. Compressor efficiency reduces the input energy consumed during the air injection: the same amount of air is stored inside the storage with less input energy. This is also achieved by increasing the number of compressors and the intercoolers among them (3.1.5.3). For the turbine efficiency increments instead, the benefits are in the generation where more power can be extracted with benefits for the performance (3.1.8). Similarly, TITs increments increase the output power and energy produced with the same amount of air stored inside the storage (3.1.10.3); unfortunately this aim is achieved increasing the fuel consumption, which effects will be studied in the economic analysis. Increasing the TITs also permits to produce the same amount of power withdrawing less mass flow, so the storage dimensions can be reduced. This is an element that should be taken into account for aboveground storages with limited volume and mass stored; TITs increments increase the energy produced for the same amount of mass.

Since a CAES is basically composed of a gas turbine engine, it is affected by the ambient condition (3.1.2); however, ambient temperature affects only the compression train, since in the generation, the air temperature is equals to the storage temperature. Ambient pressure again needs to be the highest possible in order to improve the compression, even if this reduces the output power produced. The storage defines the amount of mass that can be stored on the basis of the temperature inside and also the pressure range (3.1.6). Lowest is the storage temperature, highest is the amount of mass that can be stored inside the volume, the disadvantage is the HR increments in the combustion in order to reach the HP TIT. If the minimum pressure increases, and the pressure range is maintained constant, the input energy required to inject air increases, reducing the CER. For the efficiency instead, the minimum pressure increments introduce higher output power and HR reductions. This is the reason why the optimums move to higher minimum pressure values in the pressure range analysis (3.2.2). If the maximum pressure increases, the CER decreases since the operative pressure of the generation is at the minimum pressure value and more losses are produced and also more input energy is required to compress air inside the storage. Benefits are achievable avoiding the constant pressure at the inlet of the generation train and using a variable pressure configuration, but this requires that the turbine efficiency remains as much as possible constant and at high value in the entire operative pressure range. The best pressure ranges in order to achieve high CER, look at low pressure since less input energy is required to inject air underground (3.2.2). The increment of the pressure range increases the amount of air stored inside the storage, hence the EVR that can be produced. It is obvious that the pressure range needs to be chosen avoiding the break of the structure; if happened, the storage would not be any longer usable.

The generation train instead is composed of turbines with expansion ratios that have to maximize the output power produced, hence the turbine that has the highest TIT (LP turbine) has to produce the main component of power. The analysis of different generation train configurations, always highlight the benefits of the reheating and the TITs increments both for the HP turbine and the LP turbine; unfortunately these introduce fuel consumption increments. Consequently of these considerations, a train with three turbines shows the significant output energy increment compared to a conventional two turbines train. The configuration with only one turbine is also analysed, but the results show that it is not a good technical solution.
Similarly to the values found for the existing plant in literature, the recuperator reduces of about 28% the fuel consumption, with benefits in the efficiency and in the profitability of the plant, even if the response of the generation train has to be evaluated. The recuperator makes slower the train that instead needs to follow the peak electricity demand. No significant variation are registered in the CER and EVR when a recuperator is introduced. The possibility to install a small recuperator between the HP turbine and the next combustor, when low HP TITs are used, is investigated. No benefits are registered in the configuration with two turbines; if three turbines are used, it is registered a small benefit of only 1% in the HR (the expansion ratios are chosen to maximize the output power generated). The amount of air mass withdrawn defines the generation train dimensions, higher this value, higher is the output power generated; it is obvious that the discharge time reduces (3.1.8). Similar consideration are verified for the compression train, where bigger machine reduces the charge time but increases the power required.
The growing interest found in the Thermal Energy Storage using aquifers, has given the idea to investigate the storage of the waste heat produced during the compression in these formations, in order to sell this energy later to a DH grid or to use it in a desalination plant. The latter idea, for example, could be used if an offshore wind farm produces electricity that needs to be stored and aquifers were available near the coast, where the CAES needs to be built. Therefore the CAES would be used for storing electricity and its waste heat could be used for a desalination plant. The possibility to use also man-made tanks is feasible, but higher costs need to be taken into account [56]. Aquifers are proposed for TESs since water is a safe and good medium to store thermal energy and because using aquifers there is the only need of pipes for the injection and withdrawn of water. As mentioned, different layers of aquifers may be available underground, one on the top of the other, hence one could be used for storing air and the other hot water.

CHAPTER 4: Adiabatic–CAES Technical Analysis

Several studies of both adiabatic concepts proposed in 1.4 have been done, even if the following analysis delve more the A-CAES with a direct heat-exchange, where more interest is found in the literature [18, 19, 51, 52].

Plants with indirect heat exchange, provided with two tanks, have the benefits that the hot and cold materials are stored separately, but they present very high cost of the medium used, high cost of the heat exchangers, and the need to have two tanks instead of only one. Also there is high risk of solidification of storage fluid (molten salt), due to high freezing point, which increases the O&M costs, because it requires heating system to maintain the medium in the liquid phase. Another problem could be the material disposal; if it needs to be changed and it is not more usable because of the properties degradation, environmental and economic issues may happen.

In the other A-CAES concept, solid medium as concrete, substitutes the molten salt or the oil. It is chosen because of its low cost, availability and easy processing. Moreover, concrete is a material with high specific heat, good mechanical properties, thermal expansion coefficient near that of steel and high mechanical resistance to cyclic thermal loading. However, design of the geometry, tube diameter and number of pipes inside the concrete may affect the cost of this storage.

4.1 A-CAES with direct heat-exchange

4.1.1 Plant configuration

In an A-CAES with direct heat-exchange, the heat produced during the compression is transferred to the medium directly, and during the generation the cold air from the cavern acquires directly the energy inside the TES going in the opposite direction. The idea is to store the highest amount of thermal energy possible at the highest temperature, this means that the outlet compressor train temperature has to reach the highest value possible, in the limits of the technology. The highest temperature possible reduces the amount of air withdrawn required and it avoids icing problems. In order to achieve this, the compressor train (Figure 4-1) is not provided of intercoolers as the previous cases, only a small one could be necessary in order to limit the temperature at the outlet of the train under certain limits (about 923 K). When the air exits the compressor train, goes inside the TES, and from the top to the bottom releases the heat to the medium (Figure E-1). Because at the bottom the temperature could be still hot, it could be necessary to cool it down before being injected into the formation. Later the cold air from the cavern, going from the bottom to the top, acquires the energy to generate power through the turbines (Figure 4-2 and Figure E-2).

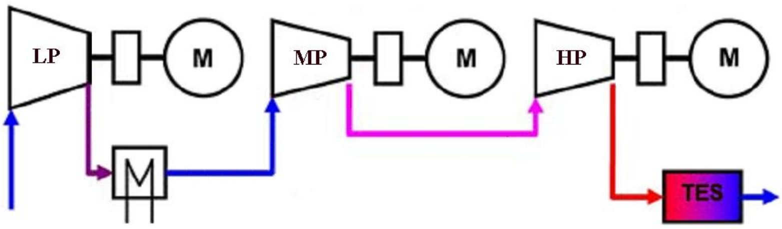

Figure 4-1 Compressor train design (A-CAES with direct heat-exchange) [14]

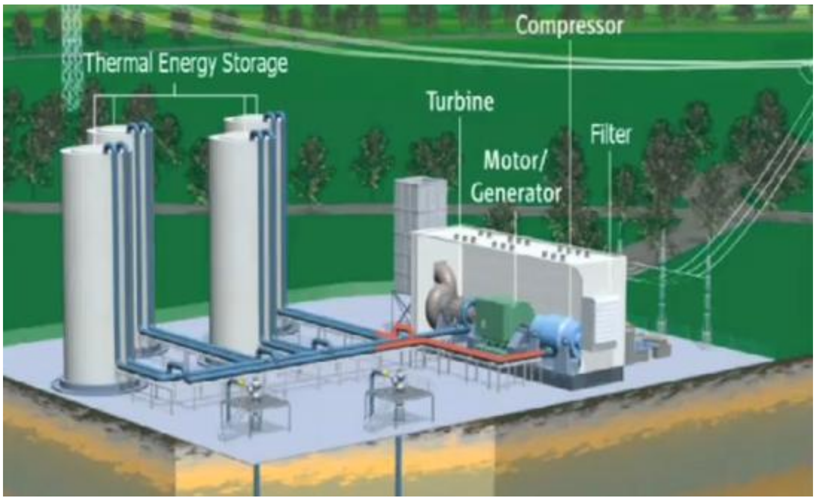

Figure 4-2 A-CAES with direct heat-exchange design [75]

4.1.2 A-CAES model

In order to overcome the above mentioned problems with liquid mediums and also to analyse the possibility to use inside the TES mediums different than concrete, cheaper pebbles and rocks are evaluated [47]. Rock or pebble-bed storages can also be used for high temperatures up to 1000 °C [56], hence no temperature problems take place. The use of rocks for thermal storage also provides the following advantages:

- rocks are not toxic and non-flammable
- rocks are inexpensive
- rocks act both as heat transfer surface and storage medium
- the heat transfer between air and rock is good, due to the large heat transfer area
- the effective heat conductance of the rock pile is low, due to the small area of contact between the rocks; then the heat losses from the pile are low

In the next lines this concept of TES is modelled and investigated, finding good results in terms of performance indices. For A-CAES the definitions of CER and EVR remain the same seen in eq. 21 and eq. 25. The efficiencies instead, assume different meaning since the fuel is not considered any longer. Efficiency for adiabatic plants can be defined as:

$$\boldsymbol{efficiency = 100 * \frac{output\ energy\ generated}{electric\ input\ energy}} \quad (32)$$

while PEE can be written as:

$$\boldsymbol{Primary\ Energy\ Efficiency = 100 * \frac{output\ energy\ generated}{\frac{electric\ input\ energy}{base\ load\ plant\ efficiency}}} \quad (33)$$

Doing this assumption, the efficiency can be easily calculate from CER, they differ of the term 100.

In order to model the direct heat exchange between solid medium and air (Figure 4-3) at a certain pressure and density inside the constant TES volume, Shumann's model [45] and the equations proposed by Ziada and Rehim in [46] for air and different solid mediums, are implemented.

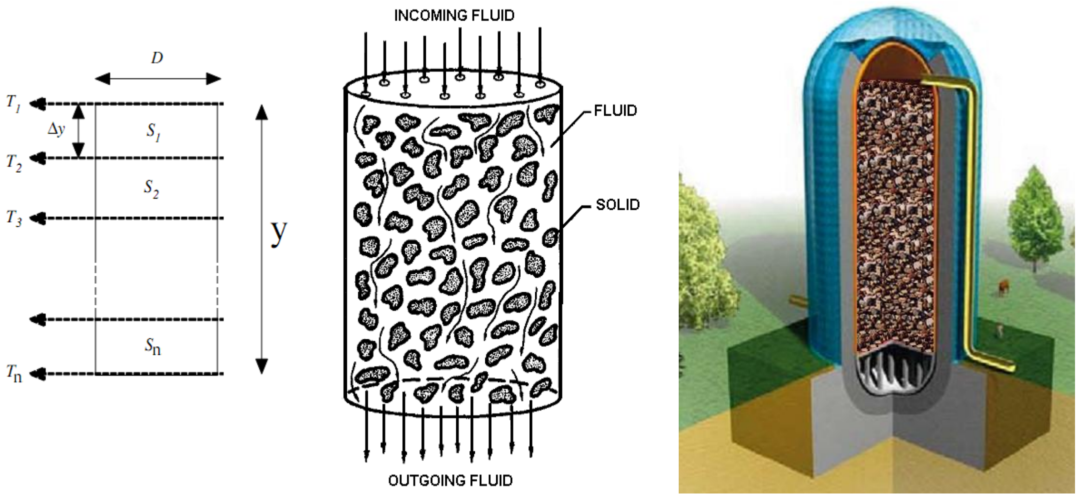

Figure 4-3 TES with heat-exchange between fluid and solid medium [54, 75]

The models take into account the thermal interaction between air and solid medium without considering losses during the exchange. The two energy equations are here presented.

Air energy equation. The energy equation that governs the thermal behaviour of the air phase, considering that the air flows axially and neglecting the heat transfer by conduction, is written as follows:

$$\boldsymbol{\varepsilon\, \rho_a c_{p_a} \frac{\partial T_a}{\partial t} + G c_{p_a} \frac{\partial T_a}{\partial y} = h_v (T_s - T_a)} \quad (34)$$

where ρ_a is the density of the air, c_{pa} is the specific heat capacity of the air, ε is the ratio of air volume in the bed to the total bed volume, T_a is the air temperature, ∂y is the portion of height of the volume considered, G [kg/m^{2}s] is the air mass flow rate express as air mass flow divided by the surface, h_v [kJ/m^{3}s] is the volumetric heat transfer coefficient between the air and solid and can be written in terms of G and solid diameter d_s (the assumption that pebbles have a constant diameter d_s is done) as follows:

$$\boldsymbol{h_v = 0.7 * \left(\frac{G}{d_s}\right)^{0.75}} \quad (35)$$

Solid energy equation. The energy equation that governs the heat transfer to the solid can be written as:

$$(\mathbf{1}-\boldsymbol{\varepsilon})\ \boldsymbol{\rho_s c_{p_s}} \frac{\partial \boldsymbol{T_s}}{\partial \boldsymbol{t}} = \boldsymbol{h_v}\ (\boldsymbol{T_a} - \boldsymbol{T_s}) \qquad (36)$$

where ρ_s is the density of the solid, c_{ps} is the specific heat capacity of the solid, T_s is the solid temperature.

4.1.3 A-CAES analysis

With the same approach used for the conventional CAES, it is carried out an investigation of the A-CAES; a reference case is considered and an analysis of the effects of parameters changes on the performance indices is done. The considered plant is composed of a compressor train with 3 compressors operating with a DP mass flow of 200 kg/s, driven with an electric input power of 135 MW (Figure 4-4). Assuming the values of Table 4-1, the trend of the temperature at the outlet of the compressor train is that one observed in Figure 4-5, where the value is limited under 923 K [15]. This characteristic of temperature at the inlet of the TES, during the charge, defines the temperatures distribution showed in Figure 4-6. In this figure, each trend represents the temperature at a certain height of the TES. During the discharge instead, the temperatures drop down and all the heat is used till the minimum pressure inside the air storage is reached. In the generation, the analysis of the energy produced by machines that operate with a constant pressure valve (Figure 4-7) and also without any throttles and turbines chocked (Figure 4-8) are carried out. If a variable pressure from the maximum to the minimum pressure at the inlet of the generation train is used, it produces much more energy than the case with constant pressure and losses (Figure 4-9), but similarly to what explained in 3.1.6.6, the mass flow is higher and the discharge time reduces. However, if a valve is used, the efficiency falls down from 68,5% to 67% (therefore the CERs assume respectively the values 0,685 and 0,67). According to [51] and [55] different representations can also show the trend of the temperatures inside the TES; one is to use in the abscissa the temperatures and in the ordinate the non-dimensional height of the TES (Figure 4-10 and Figure 4-11). The trends are considered in the beginning, in the end, and every 2 hours for the charge and 1 hour for the discharge. Looking at these two graphs and the previous proposed (Figure 4-6 and Figure 4-8), it can be seen the effect of the hot air coming from the compressor train at the top of the TES, that in the first period of charge, increases significantly the temperature. Similarly, during the first period of discharge, the cold air coming from the cavern cools down very fast the temperature at the bottom of the TES.

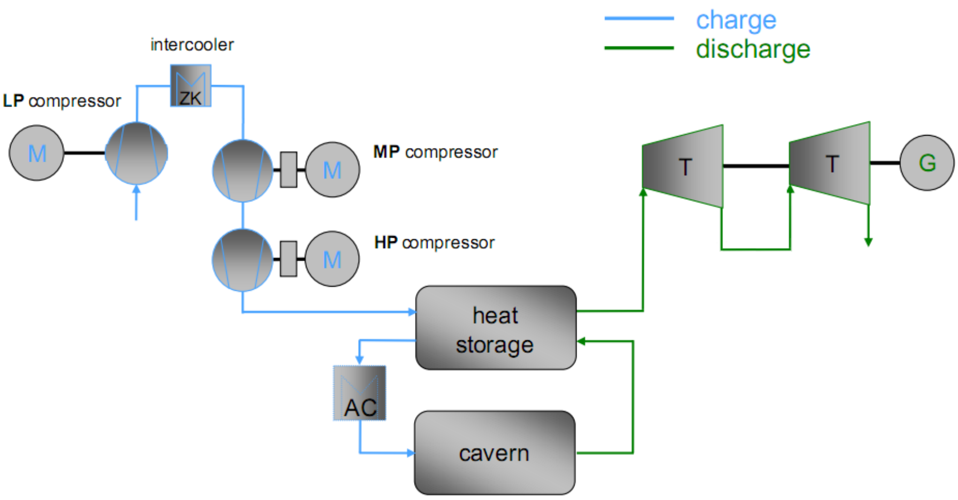

Figure 4-4 Adiabatic-CAES design

Table 4-1 Reference values for the A-CAES plant

Parameters	value	Unit
ambient pressure	101325	Pa
ambient temperature	288,15	K
compressors mechanical efficiency	0,97	
intercooler outlet temperature	340,15	K
DP corrected mass flow	200	kg/s
input electric power	135	MW
storage temperature	308,15	K
storage volume	650000	m^3
minimum storage pressure	6,0	MPa
maximum storage pressure	8,0	MPa
TES losses	4	%
ε	0,35	
specific heat medium (pebbles)	0,750	kJ/kgK
TES medium density	1870	kg/m^3
TES volume	17000	m^3
TES surface	200	m^2
DP mass flow	500	kg/s
DP pressure	6	MPa
DP TIT	853	K
turbine mechanical efficiency	0,98	
turbines isentropic efficiency	0,90	
exhaust pressure losses	4	%

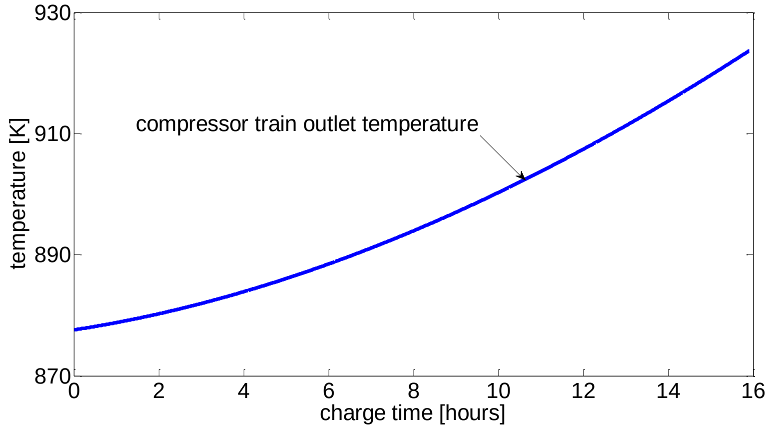

Figure 4-5 Compressor train outlet temperature (6 MPa-8 MPa)

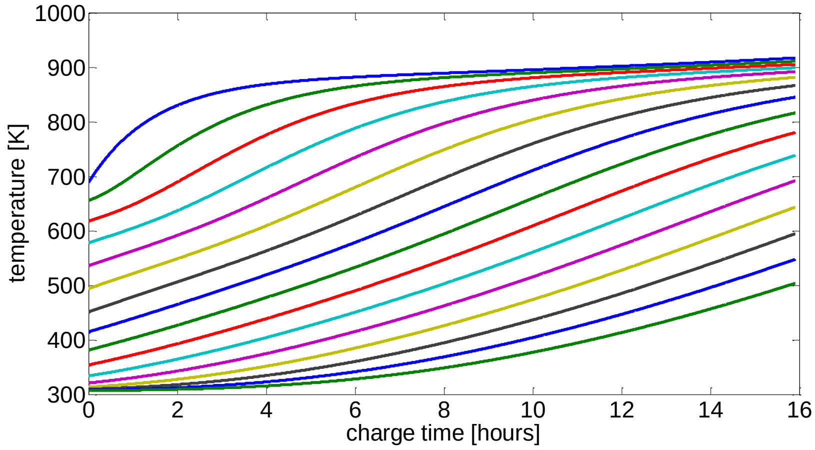

Figure 4-6 Temperature distribution in the TES during charge

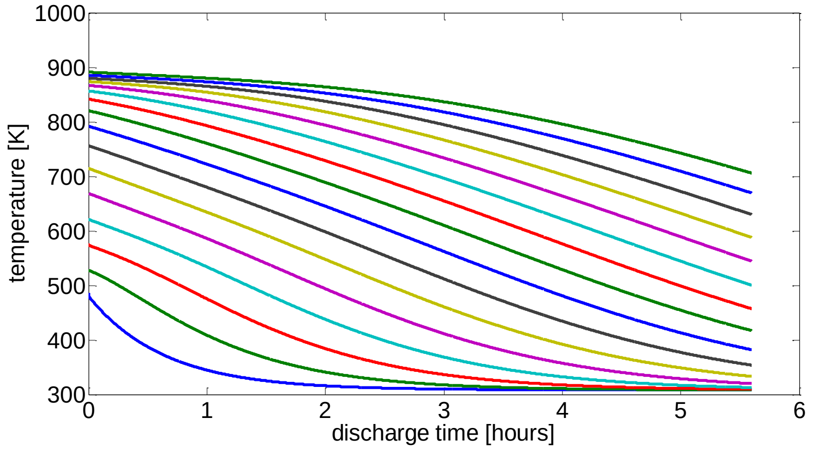

Figure 4-7 Temperature distribution in the TES during discharge (constant pressure)

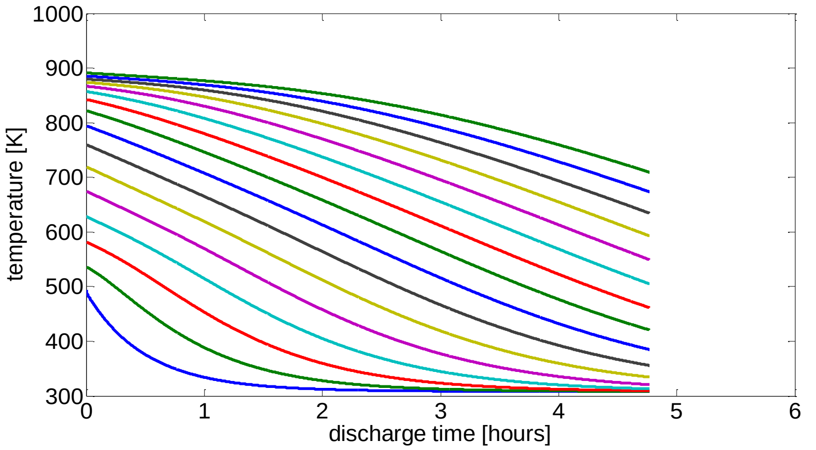

Figure 4-8 Temperature distribution in the TES during discharge (variable pressure)

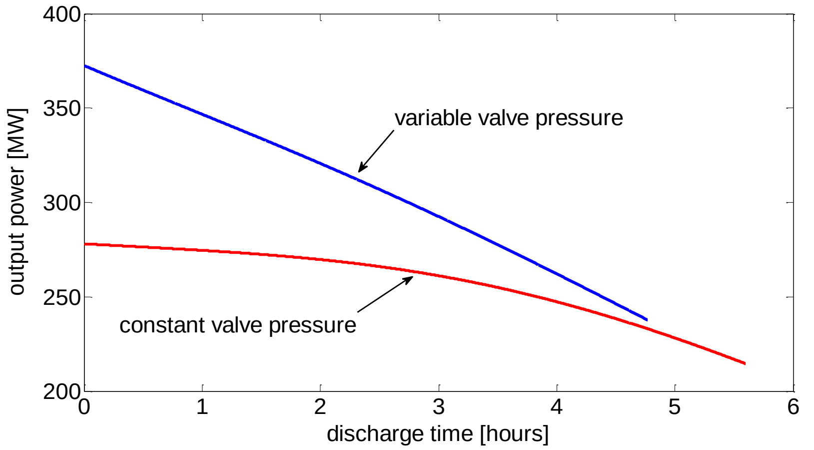

Figure 4-9 Output power generated with constant and variable pressure

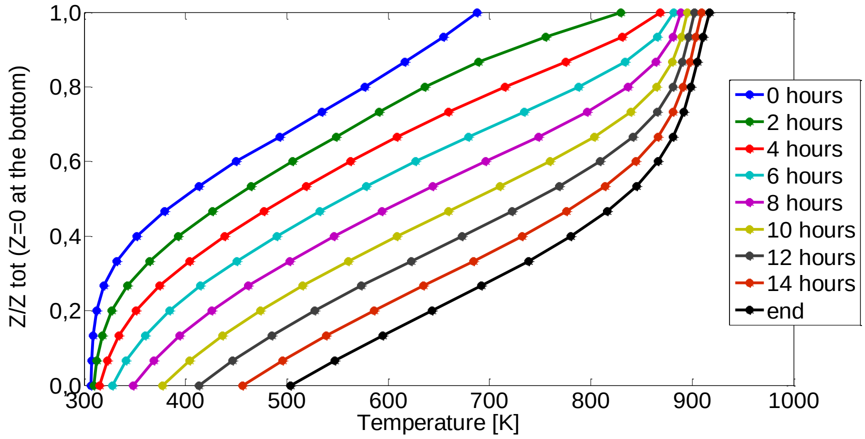

Figure 4-10 Temperature distribution function of the TES height (charge time)

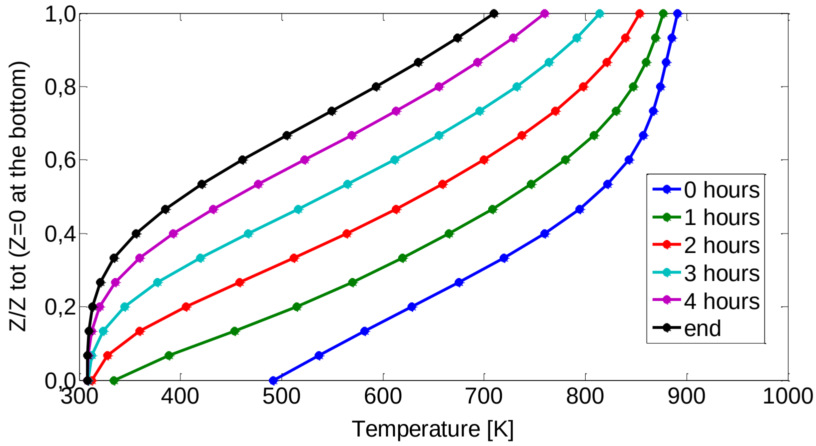

Figure 4-11 Temperature distribution function of the TES height (discharge time)

4.1.3.1 Ambient temperature

Similarly to conventional CAES the ambient temperature affects the performance of the plant since compression requires more electric input energy. Because the output energy produced during the generation is not affected by the ambient temperature (EVR remains constant), the consequence is a CER decrement (Figure 4-12).

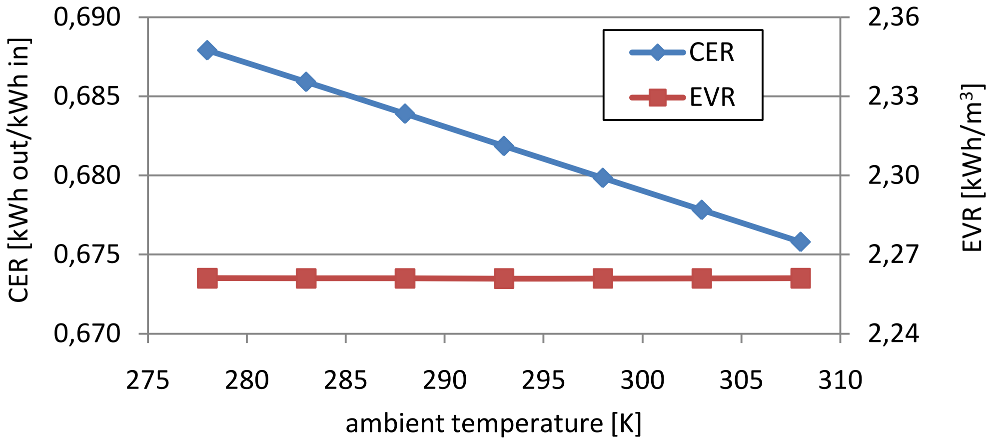

Figure 4-12 CER versus ambient temperature

4.1.3.2 Ambient pressure

The effects of ambient pressure on the performance indices are still similar to those seen for conventional CAES. The pressure increment reduces the work required by the compressor train, the mass flow increases and the input energy required decreases, hence CER goes up (Figure 4-13). In the generation instead, higher ambient pressure reduces the expansion ratio and less power is generated (EVR drops down). However, a particular effect inside the TES, introduced by the ambient pressure variations, needs to be mentioned. According to eq. 5, lower pressure ratio, due to higher ambient pressure, reduces the air temperature increment of the last two compressors, and if the intercooler outlet temperature does not change, the effect is a reduction of the compressor train outlet temperature and the energy stored inside the TES (Figure 4-14). If the thermal energy stored decreases, the lower TITs during the generation produce less electric energy (Figure 4-15).

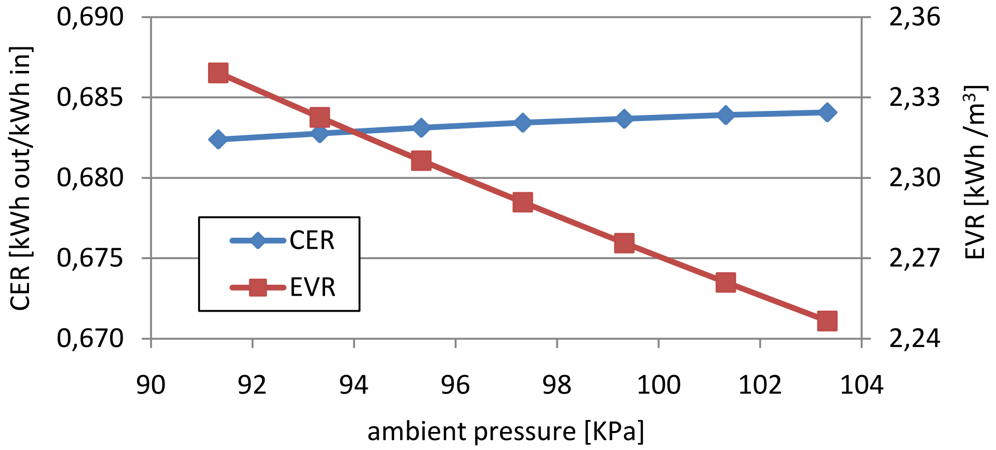

Figure 4-13 CER and EVR versus ambient pressure

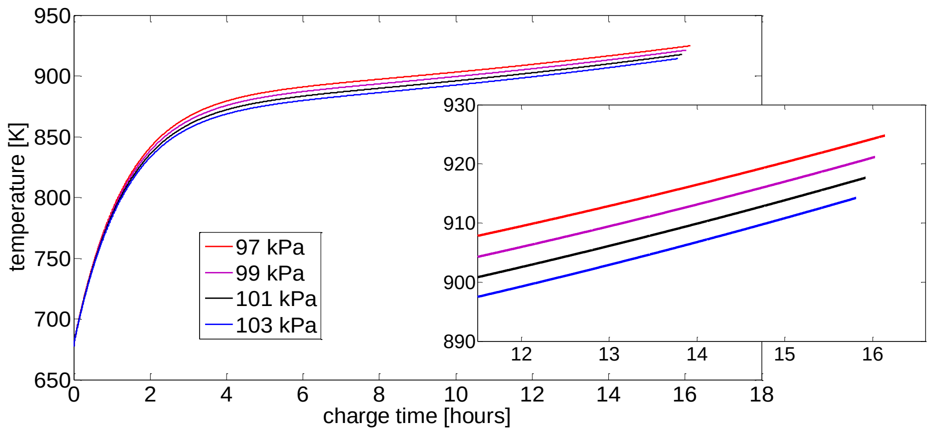

Figure 4-14 Effect of ambient pressure on the maximum temperature reached

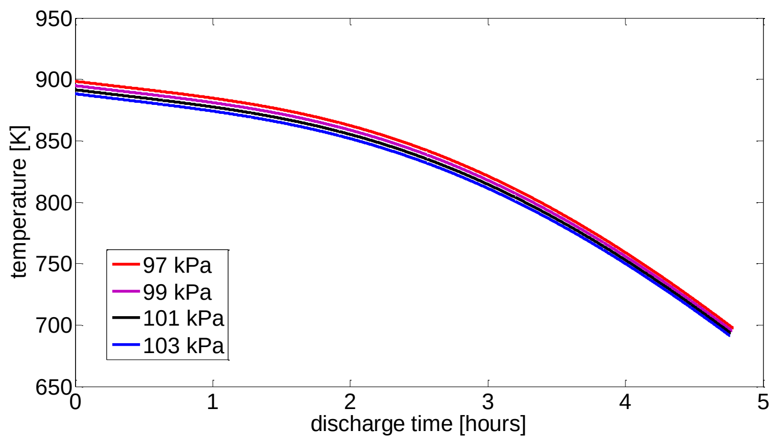

Figure 4-15 Effect of ambient pressure on the discharge temperature

In Figure 4-14 and Figure 4-15, only the top temperature of the TES is represented in order to show this effect. Therefore, because of this second effect of the ambient pressure, higher pressure reduces the output energy, but the energy saved during compression is higher than the amount lost in the generation, and the result is a slight improvement of the CER.

4.1.3.3 Electric input power

Changing the electric input power the CER assumes the trend observed in Figure 4-16, where the behaviour is also due to the compressors efficiency characteristics function of the corrected mass flow (3.1.5). Here an optimum can be highligthed, but the main observation is in the output energy generated, in fact the low electric input energy spent to run the compression train transfers less thermal energy to the storage. Therefore, the air temperature at the turbines inlet is lower and less output power is achieved, decreasing the EVR.

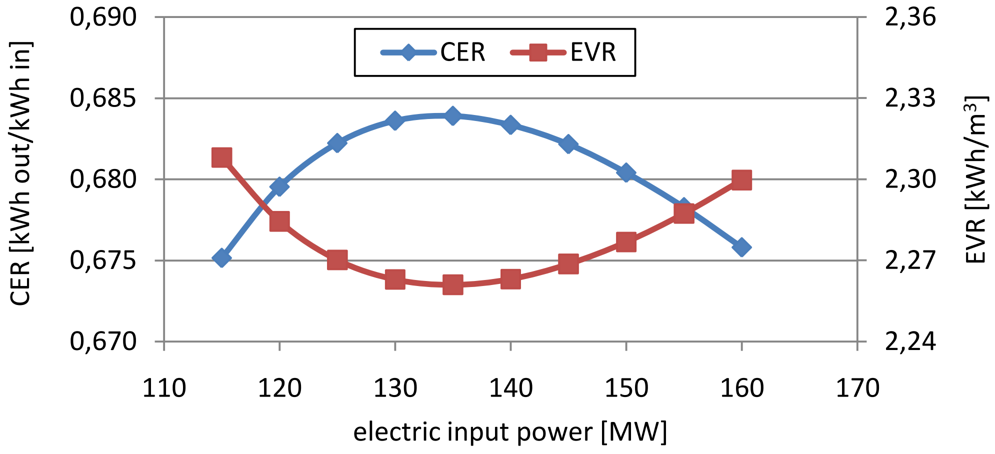

Figure 4-16 Effects of input power on CER and EVR

4.1.3.4 Intercooler outlet temperature

Despite the adiabatic approach theoretically does not include any intercooler, a realistic concept needs it and it is put in the beginning of the train to decouple charging pressure from the outlet temperature. It is obvious that increasing the intercooler output temperature, the total work required to drive the compressor train and the temperature at the outlet (Figure 4-17) increase. This causes a charge time increment and a slight CER drop (Figure 4-18). However, assuming that it is possible to overcome the limit of 923 K for the intercooler outlet temperature, the higher temperature reached permits to store higher amount of thermal energy inside the TES. It can be seen that, while the CER decrement is slight, the variation in the electric output energy produced is much more important. In one side these results show again the benefits of a low intercoolers outlet temperature, since the input energy for the charging reduces, even if for this adiabatic configuration has the disadvantage to reduce the thermal energy stored and the electric energy generated. In the other side the results show again the importance to have high TITs for increasing the output energy generated, although a slight CER reduction is registered.

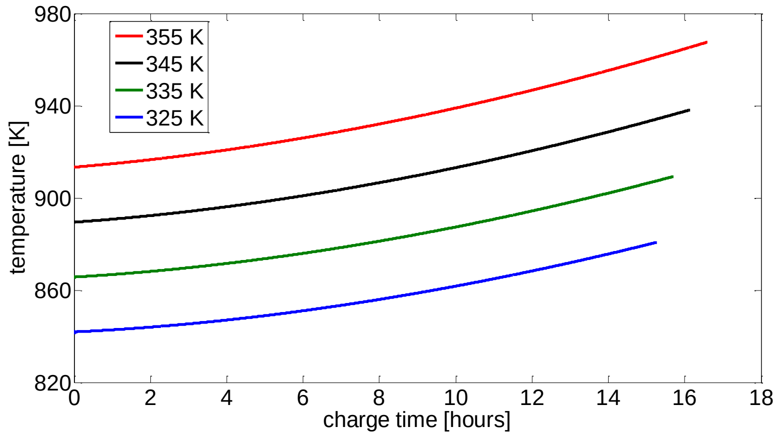

Figure 4-17 Compressor train outlet temperature changing intercooler characteristics

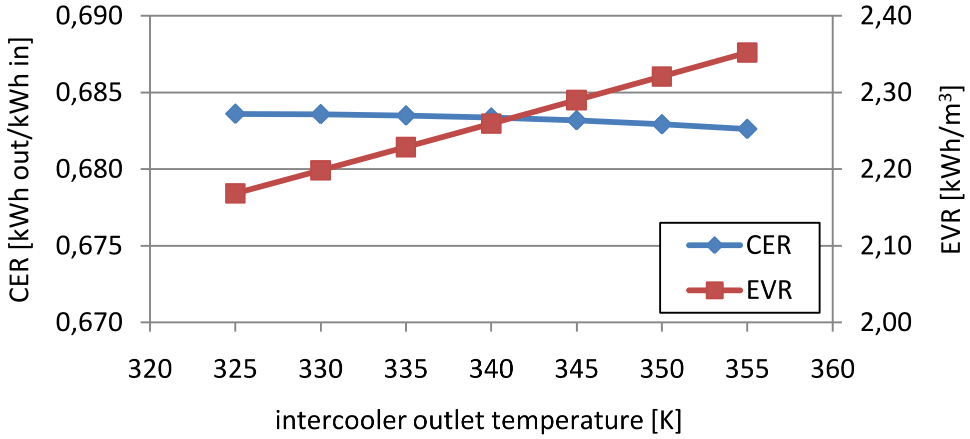

Figure 4-18 Intercooler outlet temperature effects on CER and EVR

4.1.3.5 Compressors efficiency

In order to evaluate the effect of the compressor efficiency on the performances, constant values of isentropic efficiency are set into the models. Compressor efficiency improvements introduce significant benefits in the CER (Figure 4-19), but due to the less electric input energy required (2.4), the compressor train outlet temperature (all the other parameters are kept constant) decreases and less thermal energy is stored inside the TES. Consequently, less electric output energy is generated.

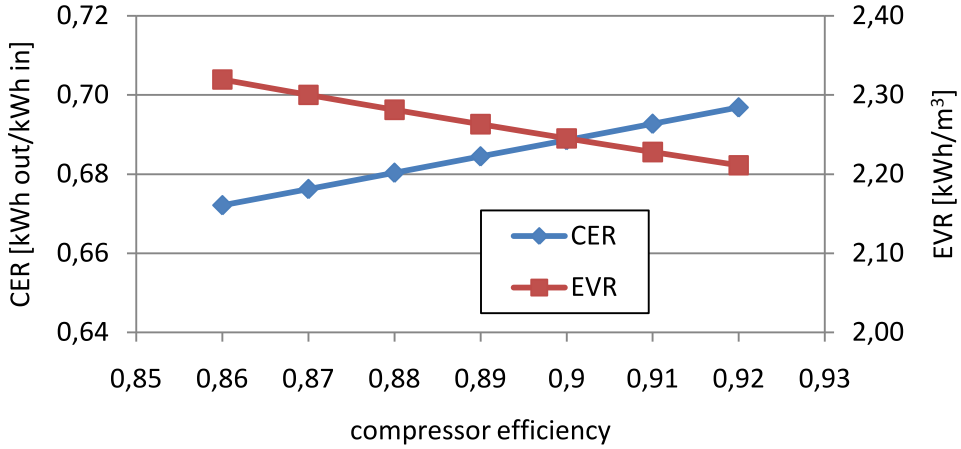

Figure 4-19 Compressor efficiency effects on the CER and EVR

4.1.3.6 Volume of the TES

Changing the volume of the TES, maintaining constant all the other parameters, the properties of heat exchange between air and solid change, with consequent variations in the CER and the EVR. Figure 4-20 shows these trends with also the presence of optimums. In fact, according to the energy equations, when the volume reduces, the temperatures of the medium inside the TES reach higher values during the charge, but the energy stored reduces. This becomes a disadvantage in the withdrawn when, due to the high mass flow, the temperatures drop down quicker even if at the beginning were higher; the output power that can be generated by the turbines drops down. Volume increments instead, reduce the temperatures reached by the solid medium during the charge due to the higher mass of the medium. During the discharge, the temperatures change slower, but because of the lower temperatures reached during the charge, a little decrement in the power produced can be registered. However, bigger volume is better than smaller, since higher is the amount of energy that can be stored.

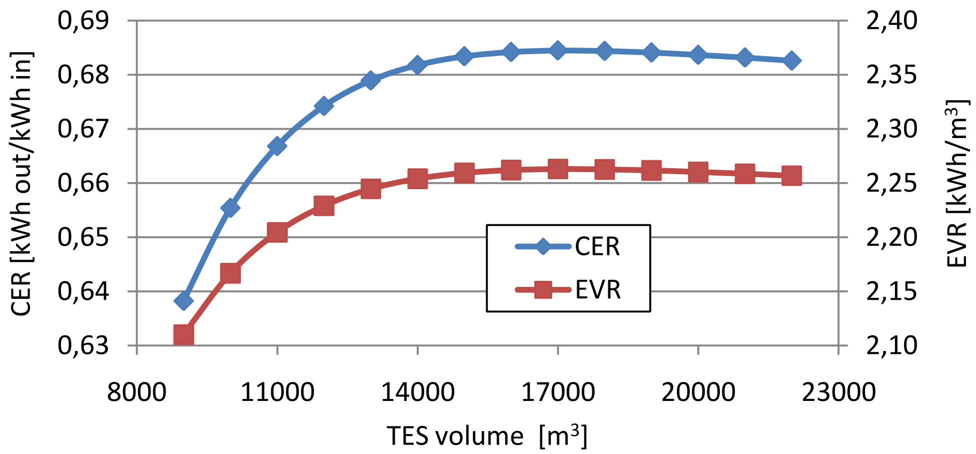

Figure 4-20 TES volume affects on CER and EVR

In Appendix E, Figure E-3, E-4, E-5, E-6 show some example of trends, during charge and discharge, of the temperatures inside the TES for small and big volumes. If compared to the Figure 4-6 and Figure 4-8, it can also be seen that the volume of the TES affects slightly the discharge time: if the turbines need to be maintained chocked, due to the variation of TITs, the air mass flow withdrawn changes and also the discharge time changes. Smaller TES reduces of some minutes the discharge time.

4.1.3.7 Surface of the TES

Figure 4-21 shows that taller storages are better than larger ones since they introduce benefits in the performance of the A-CAES. When the surface is reduced, both the air mass flow rate G and the h_v increase, this increases the temperature reached at the top of the TES and the energy stored at the end of the charge time, permitting to generate more output energy. It is obvious that the increment in the diameter, influences the heat storage in the opposite way, degrading the performances. Because the diameter reduction introduces a taller structure (for 17000 m^3 a TES of 200 m^2 becomes 85 m tall), the possibility to build more tanks (Figure 4-2) closed each other is advised. Models have been created to evaluate if the split of the flow from the compressor train in two different tanks and the next union of the flow before going into the generation train affects the heat storage and the performances of the plant, but no degradation has been found. It has been done the assumption that no pressure losses take place in the split of the flow.

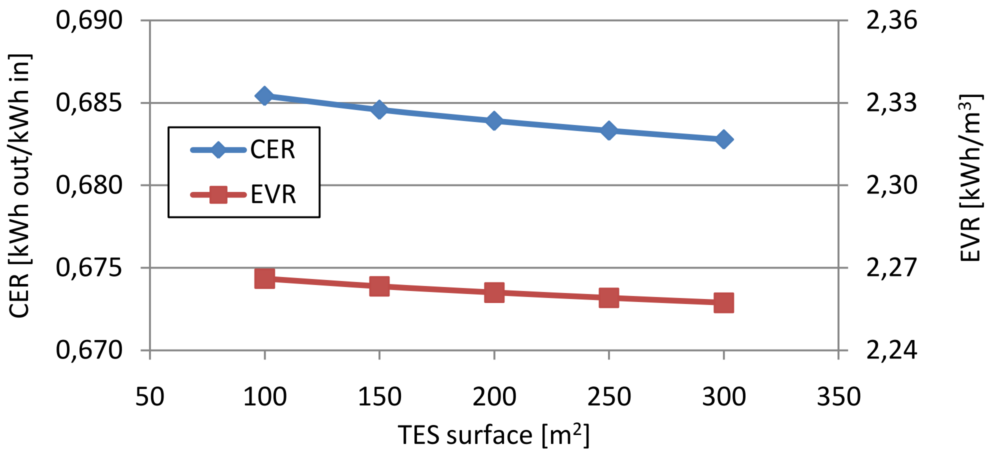

Figure 4-21 CER and EVR versus TES surface

4.1.3.8 TES losses

Even if thermal energy losses can be lower [28, 68], a 4% losses between charge phase and discharge are considered in all the models presented. If this value is changed, for evaluating the losses effect, it is obvious that less heat losses introduce significant increments of the EVR and CER; in fact, much more output energy can be generated (Figure 4-22). When the losses increase, the effect is a TIT reduction with a consequent output power and discharge time reduction (Figure 4-23). The losses reduction in the TES, improving the isolation and the thickness of the container, is one of the sensitive elements to consider in the performances improvement (4.1.4).

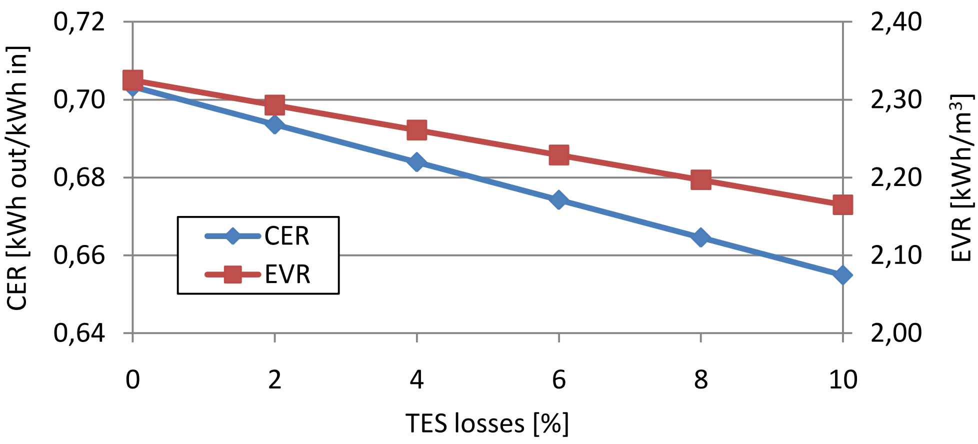

Figure 4-22 TES losses effects on CER and efficiency

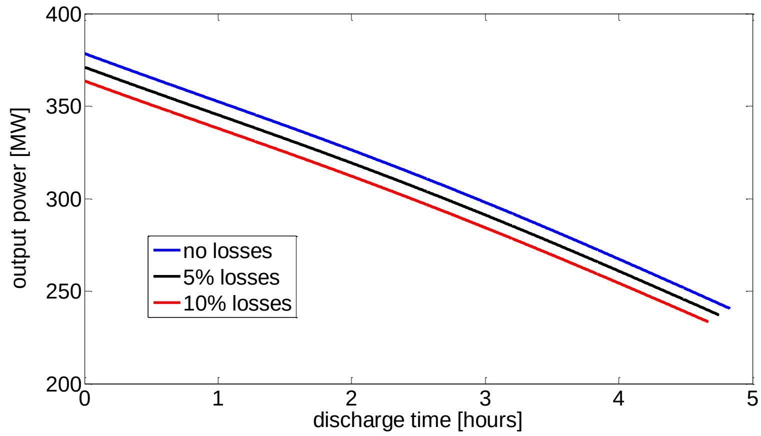

Figure 4-23 TES losses effects on output power generated

4.1.3.9 Medium inside the TES

An analysis with different mediums is performed in order to investigate the performances of the plant using different materials. Cheap materials as rock and pebbles with different characteristics of density and specific heat are compared to the proposed concrete. Table 4-2 shows the properties of the mediums used [51, 54, 56]; in the legend, the first value represents the density and the second one the specific heat of the material. The assumption that high temperature concrete may operate at these temperatures is done. With its high density and specific heat, the concrete represents a good solution in terms of the volume of the TES (Figure 4-24 and Figure 4-25); in fact, the optimums of CER and EVR are achieved for the least volume of the TES. A volume of about 10000 m^3 is found as optimum for the concrete, that is about the same value proposed in [14]; verifying the reliability of the models implemented.

Table 4-2 Medium properties

medium	density [kg/m³]	specific heat [kJ/kgK]
pebbles (1)	1870	0,750
pebbles (2)	1870	0,600
pebbles (3)	1600	0,880
pebbles (4)	2800	0,750
rock (granite)	2640	0,820
concrete	2750	0,916

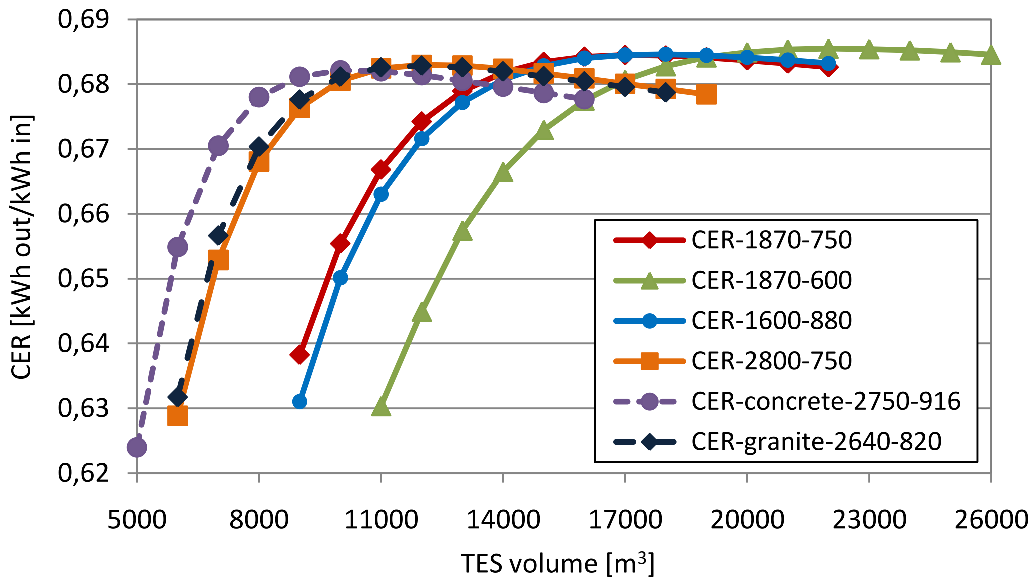

Figure 4-24 CER for different mediums

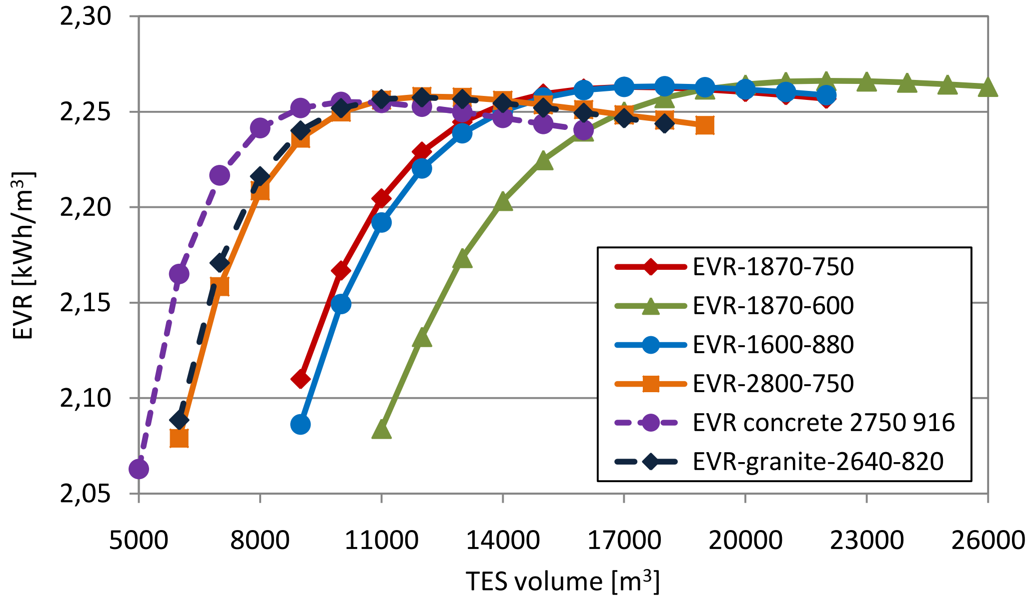

Figure 4-25 EVR for different mediums

Other good performances with small volumes are achieved with pebbles with high density (2800 kg/m^3) and specific heat equals to 0,750 kJ/kgK and with rock (granite). Going to the other types of pebbles (1, 2, 3 in Table 4-2), it can be seen that specific heat decrements require bigger volumes in order to achieve good characteristics of CER and EVR (from pebbles(1) to (2)). However, lower specific heat has the characteristic that smaller variations in CER and EVR take place changing the volume. For bigger specific heat, the variations in CER and EVR are characterized by bigger slopes; this can be seen for concrete, granite and pebbles(3); the latter characterized by a slop steeper than pebbles(1).

4.1.3.10 Spheres dimension

The dimension of the spheres of medium represents another element to evaluate in the A-CAES; in [56] Thermal Energy Storages have average diameters between 1 and 5 cm. The analysis of the diameter confirms the need of small pebbles or pieces of rock inside the TES in order to improve the energy stored and the CER (Figure 4-26). Increasing the dimensions from 1 cm up to 13 cm, it can be registered a drop of about 1,2% in the CER.

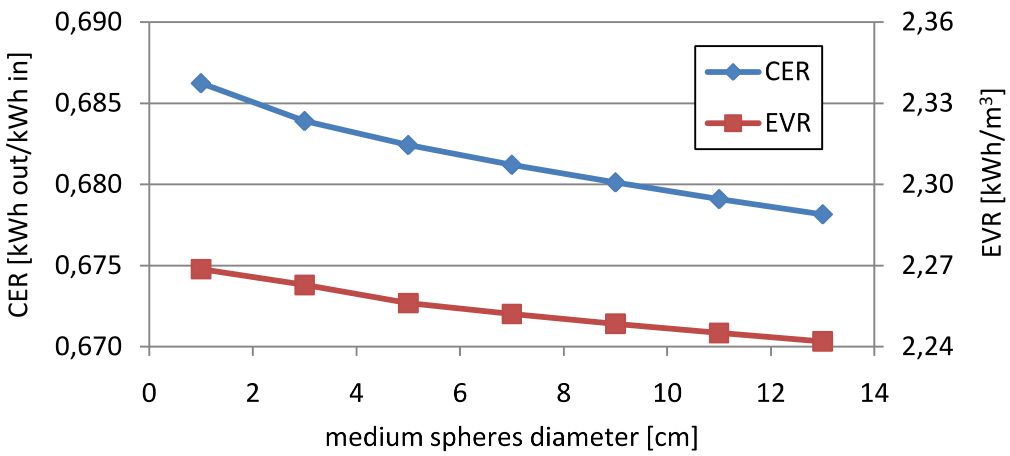

Figure 4-26 Medium spheres diameter effects on CER and EVR

4.1.3.11 Storage volume

Differently than conventional CAES where CER does not change with the storage volume variations (3.1.6.2), here there is the TES volume that affects the performance indices (Figure 4-27). As seen, there is a relationship between the TES volume and the amount of thermal energy produced during the charge that needs to be stored efficiently. The storage volume variation introduces a change in the amount of air mass stored inside, hence the amount of thermal energy. For this reason when the cavern characteristics are known, an optimum for the TES volume (4.1.3.4) can be defined. The right dimensions of the TES, do not define only the optimum of the CER, but also of the EVR. If the air storage volume increases, the amount of air mass that goes through the

TES increases, but not all the thermal energy is exchanged with the medium and stored by the TES that has not enough thermal capacity. Consequence of air storage volume increment without a sufficient TES is the output energy generated decrement. If instead the air storage volume is small, the mass through the TES decreases releasing less thermal energy. It is evident that this less thermal energy with its lower maximum temperature reached, produces less electric output energy during the discharge.

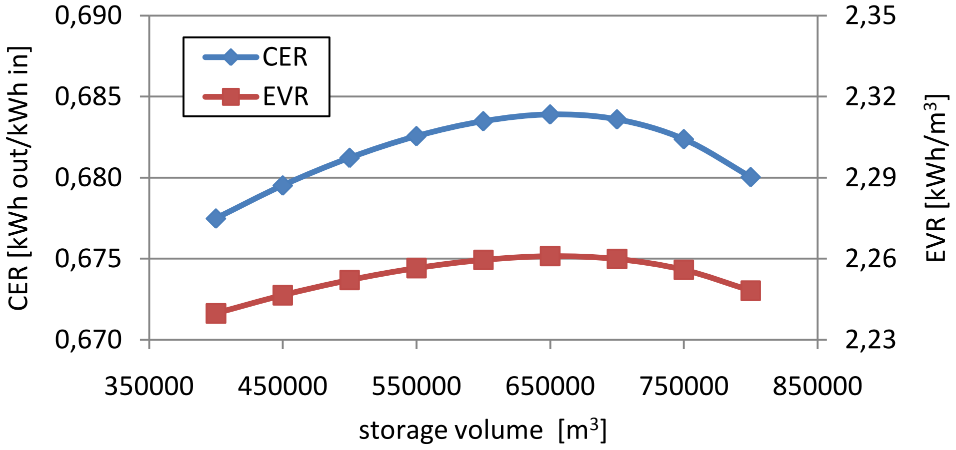

Figure 4-27 Storage volume effects on CER and EVR

4.1.3.12 Storage temperature

As seen for conventional CAES, increasing the air storage temperature, the amount of air mass injected inside the same volume reduces; therefore also the generated energy decreases. As consequence of this, increasing the cavern temperature, EVR always decreases (Figure 4-28). For the CER instead, a slight increment is registered, due to the higher temperature of the air withdrawn, therefore less thermal energy is subtracted from the TES during the discharge and the TIT remains higher for longer time producing higher energy.

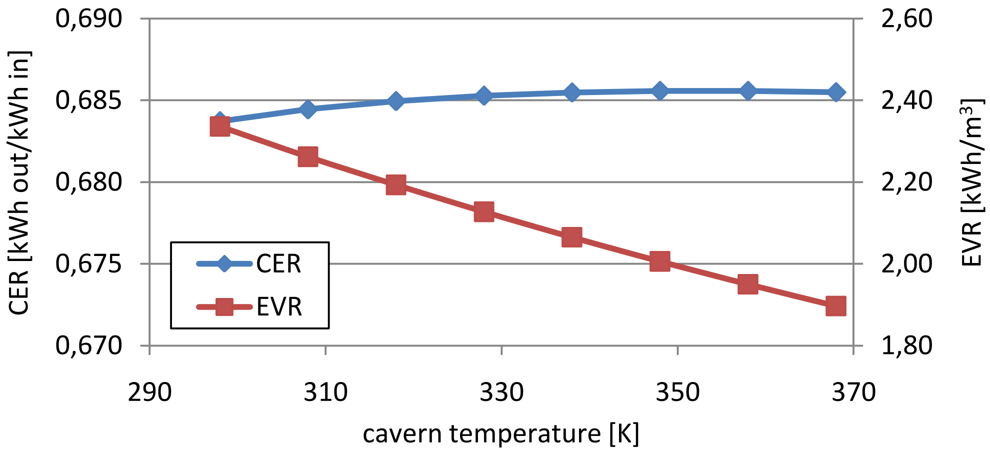

Figure 4-28 CER and EVR changing cavern temperature

4.1.3.13 Maximum storage pressure

The reference A-CAES plant (Figure 4-4) with constant compressors efficiency equals to 0,89 is assumed in order to analyse the performance indices changing the pressure range inside the air storage. The generation train operates with air released from the maximum pressure inside the cavern till the minimum operative value. Therefore, the maximum pressure increment introduces benefits in the output energy produced due to the higher thermal energy stored inside the TES during the charge and the bigger expansion ratio that produces more power during discharge. In fact, in this case no losses due to valve with constant pressure at the inlet of the train are taken into account. Increasing the pressure, the mass stored inside also increases, hence higher EVR can be generated for the same amount of storage volume (Figure 4-29).

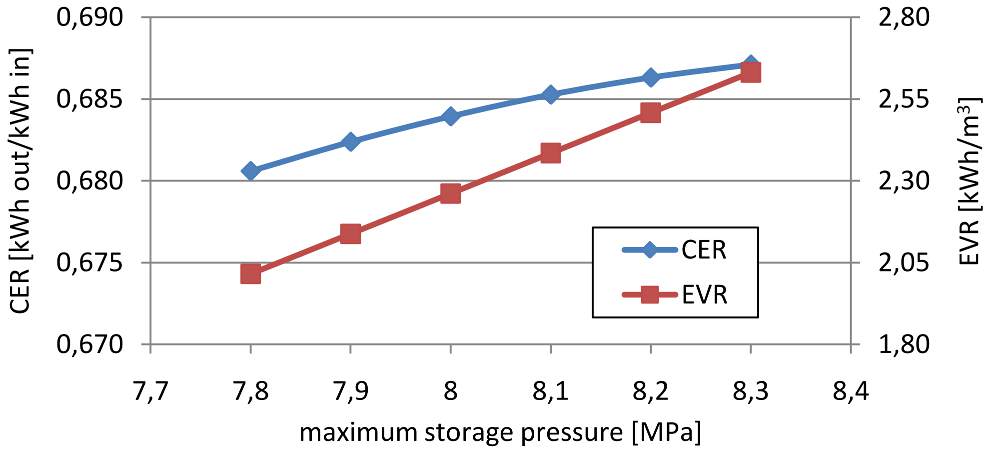

Figure 4-29 Maximum pressure effects on CER and EVR

4.1.3.14 Minimum storage pressure

With opposite trend than the maximum storage pressure, the increment of the minimum storage pressure introduces CER and EVR decreases (Figure 4-30).

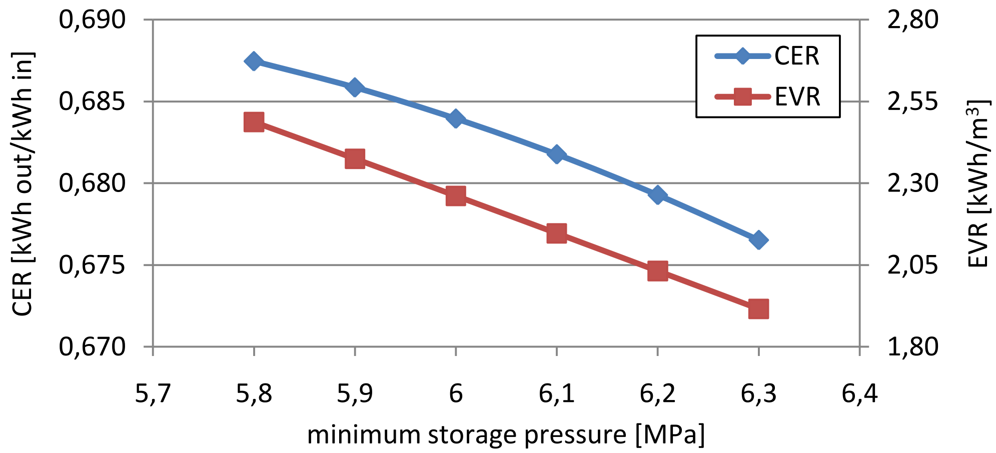

Figure 4-30 Minimum pressure effects on CER and EVR

When the pressure range moves to higher minimum pressure, for example from 6 MPa to 6,1 MPa and so on, the air mass stored inside the cavern and the thermal energy stored inside the TES decrease. However, the input energy spent does not decrease of the same amount, since higher work is required to compress the air. For these reasons, the CER reduces. The reason why the EVR decrease is instead the reduction of the mass injected and stored inside the cavern, due to the pressure range reduction.

4.1.3.15 Turbines efficiency

Similarly to conventional CAES, the turbines efficiencies have a significant influence on the performance indices of the plant and they need to be maximize as much as possible in order to produce the maximum power achievable. CER and EVR increments are registered when the efficiency improves (Figure 4-31).

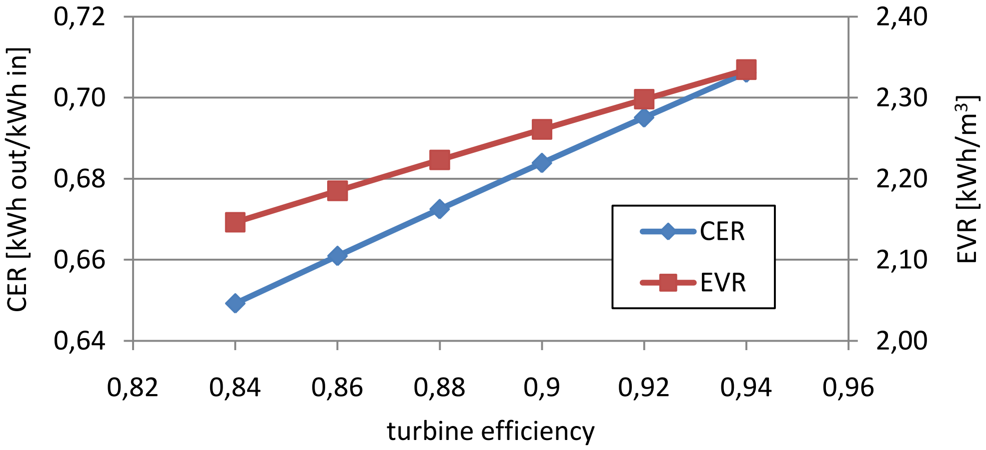

Figure 4-31 Turbine efficiency effects on the CER and EVR

4.1.3.16 Air mass flow withdrawn

The air mass flow withdrawn from the cavern affects the output power generated, but does not affect the energy produced that depends on the amount of air stored inside the storage. Thus CER and EVR remain constant, respectively to 0,683 and 2,26 kWh/m^3.

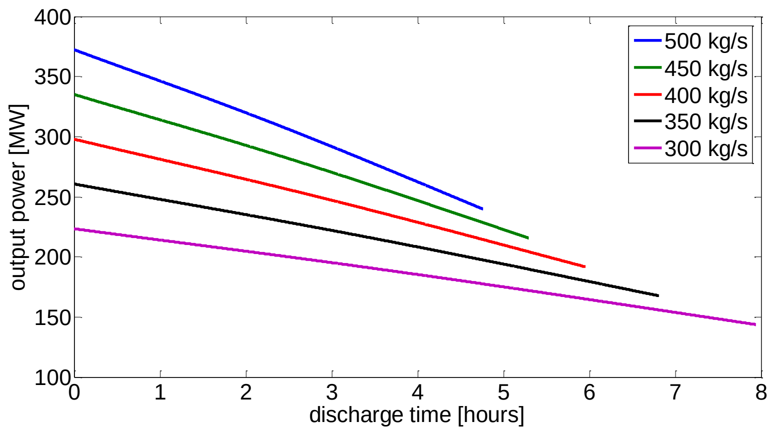

Figure 4-32 Output power and discharge time changing the air mass flow withdrawn

Because air mass flow increments generate higher output power, if the same output energy is maintained, the discharge time decreases (Figure 4-32).

4.1.3.17 A-CAES at 10MPa

A-CAES with higher pressure range are proposed in literature [14, 15] and models have been created in order to understand the performance indices variation. The values assumed are the same of Table 4-1, but the pressure range is changed between 10 MPa and 12 MPa. The intercooler outlet temperature is assumed equal to 307 K in order to have a temperature of about 923 K in the last stage of compression (Figure 4-33). In order to operate with the highest CER, an input power of 145 MW is used. Similarly to the previous case (4.1.3), a valve at the inlet of the generation train generates losses; therefore it is investigated a train with turbines chocked and a ratio $\frac{\dot{m}\sqrt{T}}{p} = const_2$. Figure 4-34 shows the output powers when constant pressures equal to 6 MPa and 10 MPa (with 500 kg/s of mass flow) are assumed and when the machines operate chocked with DP pressures equal to 6 MPa and 10 MPa. A case where the DP pressure is chosen in the middle of the range 10 MPa-12 MPa is proposed. As Table 4-3 shows, the variable pressure introduces benefits in the energy generated and in the efficiency. Increasing the operative pressure range, the electric output energy produced is higher but, because of the higher input energy required to compress the air till that pressure, the CER falls down.

Table 4-3 EVR and CER for different generation train configurations

	constant pressure		variable pressure		
	6MPa	10MPa	DP 6MPa	DP 10MPa	DP 11MPa
EVR [kWh/m^3]	2,214	2,345	2,263	2,369	2,369
CER [kWh out/kWh in]	0,670	0,647	0,685	0,654	0,654
Efficiency [%]	67,0	64,7	68,5	65,4	65,4

Because of the ratio $\frac{\dot{m}\sqrt{T}}{p} = const_1$, for DP pressure equals to 6 MPa, the air mass flow is higher than the other cases and the consequence is a faster reduction of the cavern pressure and discharge time (Figure 4-34). For the plant at higher pressure, if the DP pressure is assumed at 11 MPa instead of using 10 MPa, the mass flow reduces with benefits in the generation time that becomes longer, even if the output power decreases. In the analysis, the DP pressure is equal to 10 MPa because it is assumed that the machines that operate at constant pressure are able to operate also up to the maximum pressure producing much more energy. However, if an A-CAES is built, it is better if the DP pressure is located inside the operative pressure range. Figure 4-35 shows the trends of air mass flows withdrawn (the constant mass flows at 500 kg/s are omitted). It can be seen that the temperature reduction inside the TES (and the HP TIT reduction) affects the mass flow withdrawn, that for the train at high pressure (10 MPa-12 MPa), in the last period of generation, increases in order to maintain the constant value $const_2$.

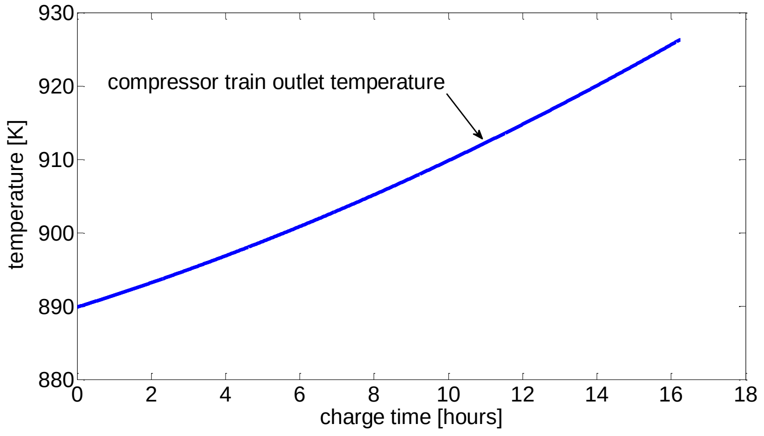

Figure 4-33 Compressor train outlet temperature (10 MPa-12 MPa)

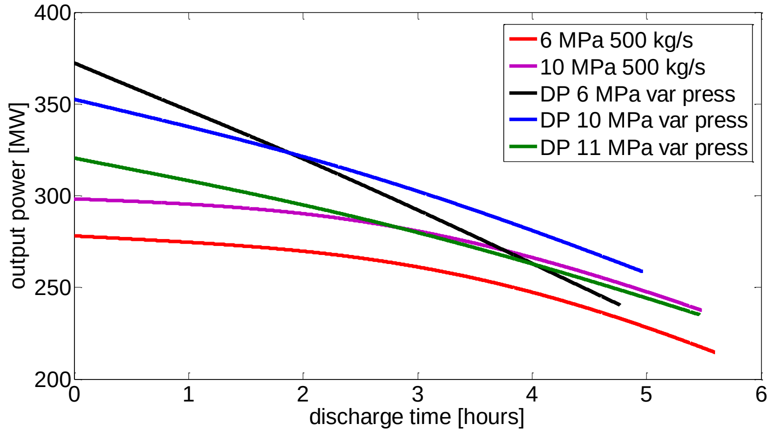

Figure 4-34 Output power comparison for different train configurations

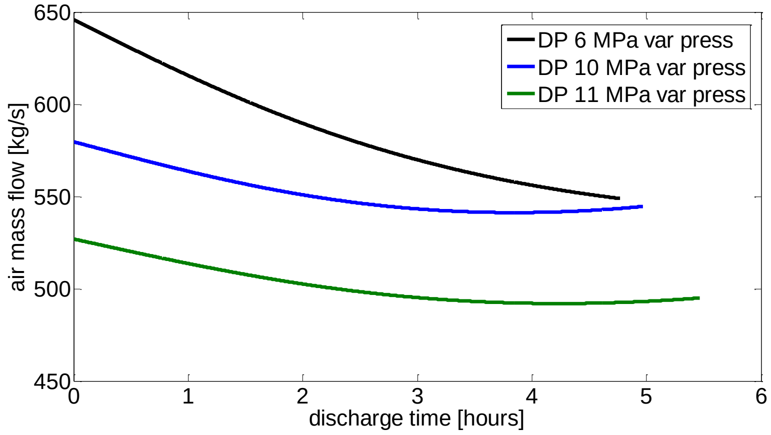

Figure 4-35 Air mass flow comparison for different train configurations

4.1.3.18 Generation train outlet temperature

Analyses on the generation train have also involved the investigation of the LP Turbine Outlet Temperature. Low TITs do not affect only the mass flow that increases (in order to produce the same power) respect to a conventional CAES, but also generates problems in the last stages of the LP turbine (1.2) since the temperature can reach very low values. Figure 4-36 shows the trend of the LP TOTs in the different configurations. It is obvious that increasing the expansion ratio (moving the range from 6-8 MPa to 10-12 MPa), the temperature drops to lower values increasing the possibility of brittleness. It can be seen the drops going from the red and black lines that represent respectively the trends at constant valve pressure and variable pressure in the range (6 MPa-8 MPa) to the higher pressure range (10 MPa-12 MPa), represented with the blue and fuchsia lines. Therefore, the last stages of the LP turbine need to be able to resist at very low temperatures. Also a system able to dehydrate the air before the generation train and able to avoid that later water drops can freeze, is recommended .

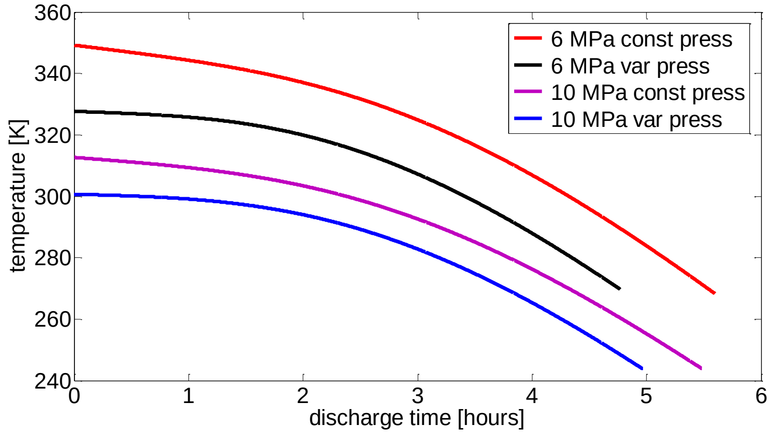

Figure 4-36 LP Turbine Outlet Temperature in different generation train configurations

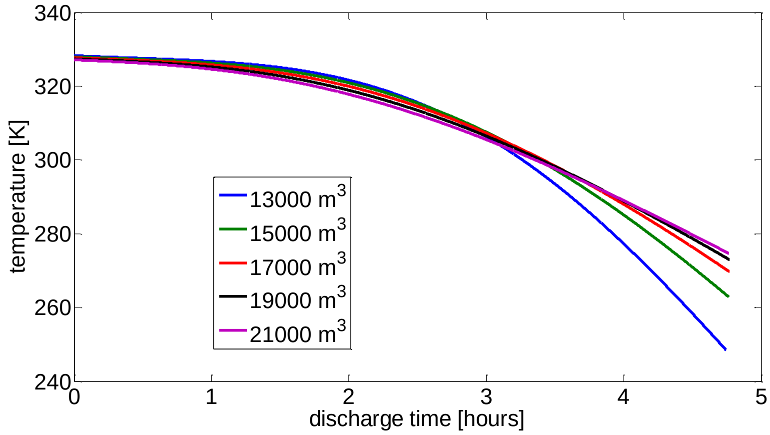

Figure 4-37 LP Turbine Outlet Temperature for different TES volume

An investigation of the effects of different TES volumes on the LP Turbine Outlet Temperatures (TOT) is done. Figure 4-37 shows the trends for a train operating with variable pressure in the range 6-8 MPa. When the volume of the TES is smaller than required, the effect is a significant drop of the LP TOT. On the other hand, when the volume of the TES increases, the outlet temperature becomes higher and it is less the probability of problems of brittleness. Therefore, between TES dimensions and LP turbine material characteristics can be defined this relationship that needs to be considered in order to avoid problems in the aboveground machinery and higher O&M costs. In particular the relationship needs to be kept into account for maximize availability and reliability of the generation train, essentials for CAES.

4.1.3.19 Generation train with two turbines in parallel

In order to overcome the problem of the low LP Turbine Outlet Temperature reached, the design of Figure 4-38 is investigated. The generation train comprises two turbines that operates in parallel instead of in series.

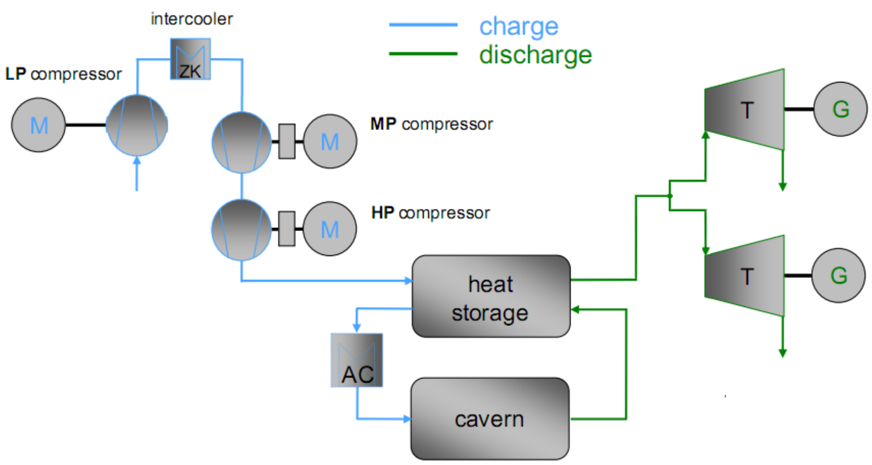

Figure 4-38 A-CAES with generation train with two turbines in parallel

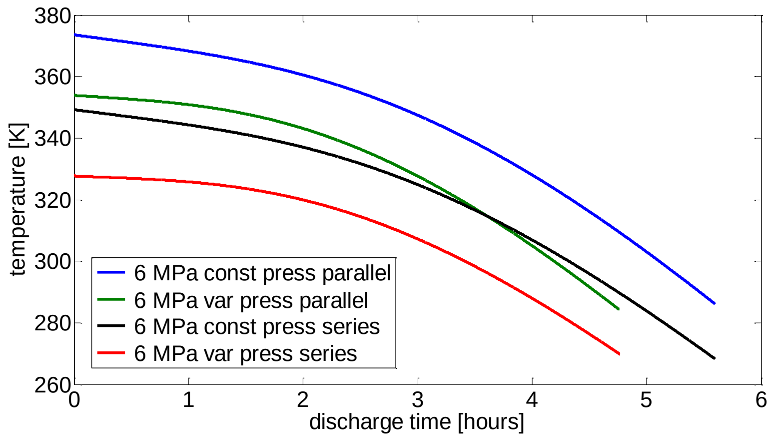

Figure 4-39 Generation train outlet temperatures for different train configurations

It is assumed that the air flow of 500 kg/s after the TES is split into two streams of 250 kg/s, each of them goes into a different turbine that expands till ambient pressure (pressure losses are considered). The analysis with machines operating at variable pressure is done supposing that each turbine operates with DP mass flow equals to 250 kg/s. This concept introduces benefits in the generation train outlet temperature (Figure 4-39), but the output energy produced is lower than the previous cases (Figure 4-40). In terms of CER and EVR, it is obvious that the configuration with turbines in parallel is worse. The following results are achieved: in the train with constant valve pressure (6 MPa) and each turbine operating at 250 kg/s, the efficiency is 64% with an EVR of 2,1 kWh/m^3; if a variable pressure is assumed, the efficiency and EVR increase respectively to 65,1% and 2,15 kWh/m^3. These values are worse than the others achievable (see Table 4-3) if a series of turbines is used (6 MPa has to be considered for the comparison). Therefore, the turbines in series represent better solution compared to the parallel one, even if the last stages of the LP turbine need to be manufactured properly (problem more significant increasing the operative pressure of the air storage).

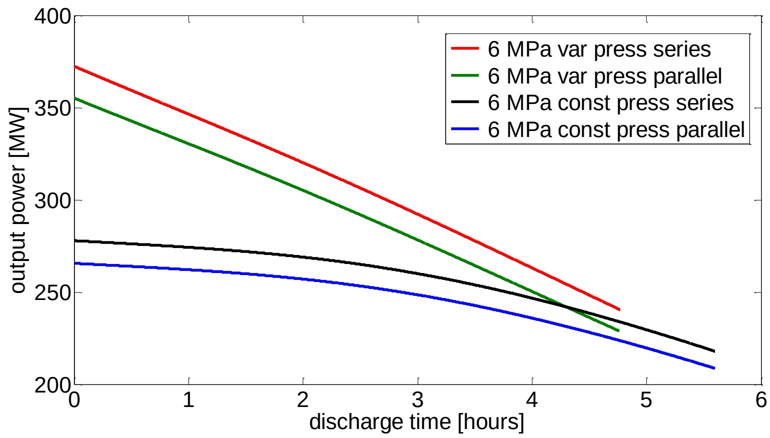

Figure 4-40 Output power for different train configurations

4.1.4 Sensitivity analysis for A-CAES

With the same methodology used for the conventional CAES, the sensitivity of the performance indices of an A-CAES, changing the parameters of 1%, is carried out.

4.1.4.1 Charging Electricity Ratio and A-CAES efficiency

Similarly to conventional CAES, the compressors and turbines efficiencies are the elements that need to be maximized in order to achieve the highest values of CER and efficiency (Figure 4-41). Other important parameter is the isolation of the container of the TES. Increasing the losses, thermal energy is wasted, and the energy transferred to the air during the generation decreases, reducing the output power generated and the generation time. Less significant parameters as electric input power and the operative pressure range of the air storage affect slightly the index.

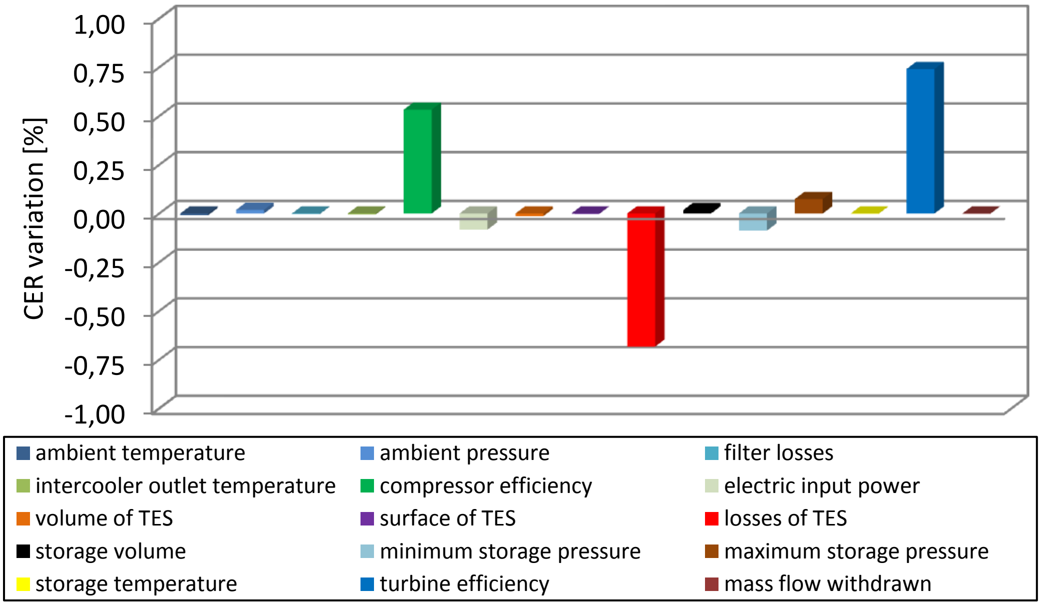

Figure 4-41 Sensitivity Analysis of CER and efficiency for A-CAES plant

4.1.4.2 Energy Volume Ratio

The main parameters that affect the energy produced are still minimum and maximum storage pressure (3.3.4) since they define the amount of air inside the volume. It is obvious that an increment of the minimum pressure, for the same maximum pressure, reduces the amount of air stored into the volume. On the other hand, the maximum pressure increment, for constant minimum pressure, permits higher expansion ratio with consequent higher power produced (variable valve pressure is assumed).

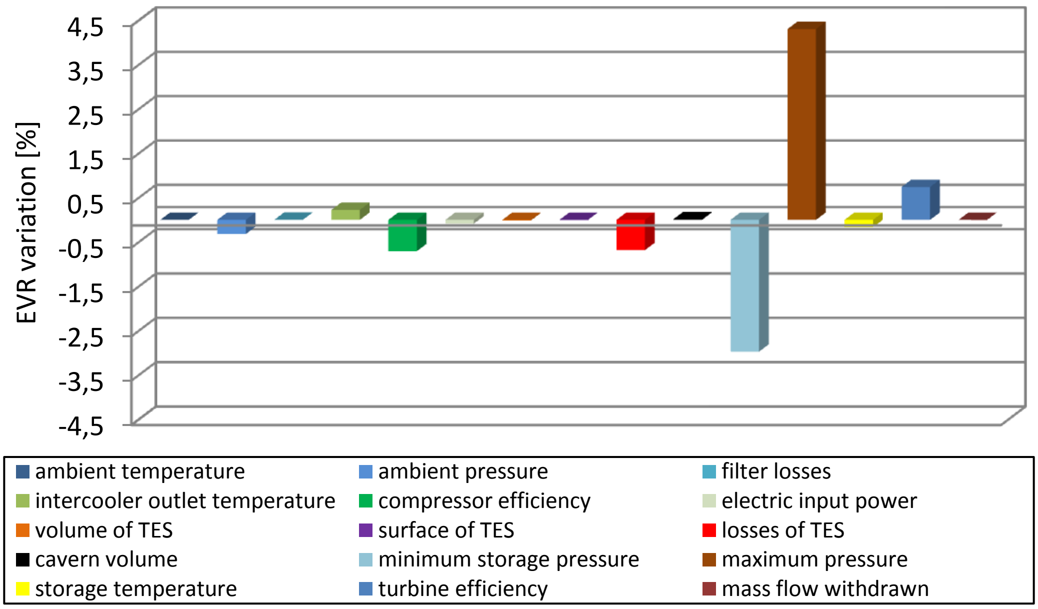

Figure 4-42 Sensitivity Analysis of EVR for A-CAES plant

Significant parameters for EVR (Figure 4-42) are still the compressors and turbines efficiencies and the thermal losses of the TES. In this case the effect of the compressor efficiency is negative because efficiency improvement reduces the compressors work required and the compressor outlet temperature. Therefore, less thermal energy is stored inside the TES and less power is produced during the generation. For similar reason, increasing the ambient pressure, the input energy required decreases, the heat produced reduces and less thermal energy is stored into the TES. In the end, the intercooler outlet temperature: if increases, the compressor train outlet temperature increases and more thermal energy is stored and it can be used for generating more output energy.

4.1.4.3 Input Energy

A sensitivity analysis of the electric input energy still shows the significant effects of the storage pressure range (Figure 4-43). It has to be mentioned, that in this analysis the energy is not divided by the storage volume; this shows how the volume variation affects the energy. In the previous sensitivity analysis (also for conventional CAES), variation of volume did not show any effects on the performance indices since they were divided by the storage volume. It is obvious that a significant parameter that affects the input energy is the compressor efficiency. Because its improvement decreases the input energy more than the EVR (Figure 4-42), the result is a benefit in the Charging Electricity Ratio (Figure 4-41). Intercooler outlet temperature and ambient pressure affect the index for the reasons mentioned in 4.1.4.2. Slight variation of the index, also registered in the CER analysis, is due to the storage temperature that increasing reduces the mass stored, hence the input energy required and the output energy produced.

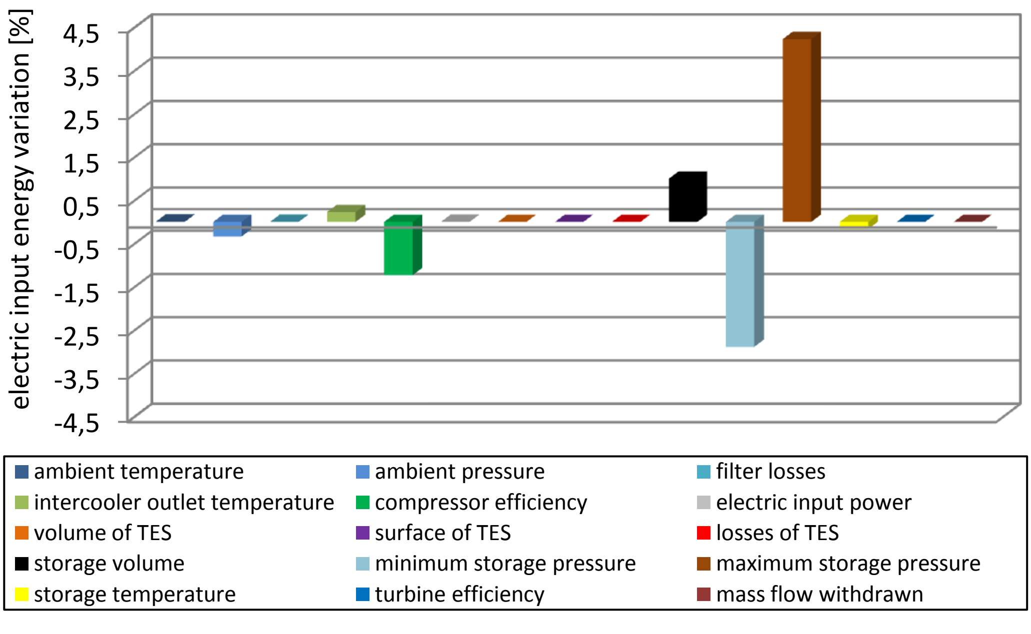

Figure 4-43 Sensitivity Analysis of electric input energy for A-CAES plant

4.2 A-CAES with indirect heat-exchange

A brief investigation also of A-CAES with indirect heat-exchange, as proposed by Energy Storage and Power LLC, is here carried out [17]. Figure 4-44 shows the plant configuration characterized by heat-exchangers that transfer the thermal energy to the tanks during the charge and back to the air withdrawn during the discharge. In the compressor train only two compressors are used in order to reach a sufficient air temperature. As seen in Chapter 3, increasing the compressors number the compressors outlet temperature decreases, hence the maximum temperature in the tank decreases affecting later the output power generated. In the compression train, after the heat-exchangers that transfer the heat to the hot tank, other heat-exchangers using cold water from a river are installed respectively for adapting the air temperature to the second compressor inlet and for the injection into the cavern. The two tanks can use molten salt (liquid sodium) or oil; heat transfer oils used for this purpose (for temperatures ranging from 100 °C to 300 °C) are Dowtherm and Therminol. As mentioned, the problem associated with these oils is that degrade with time and this becomes particularly serious if they are used above their recommended temperature limits. The use of oils also presents safety problems since there is a possibility of ignition. A further limitation to the use of oils is their cost.

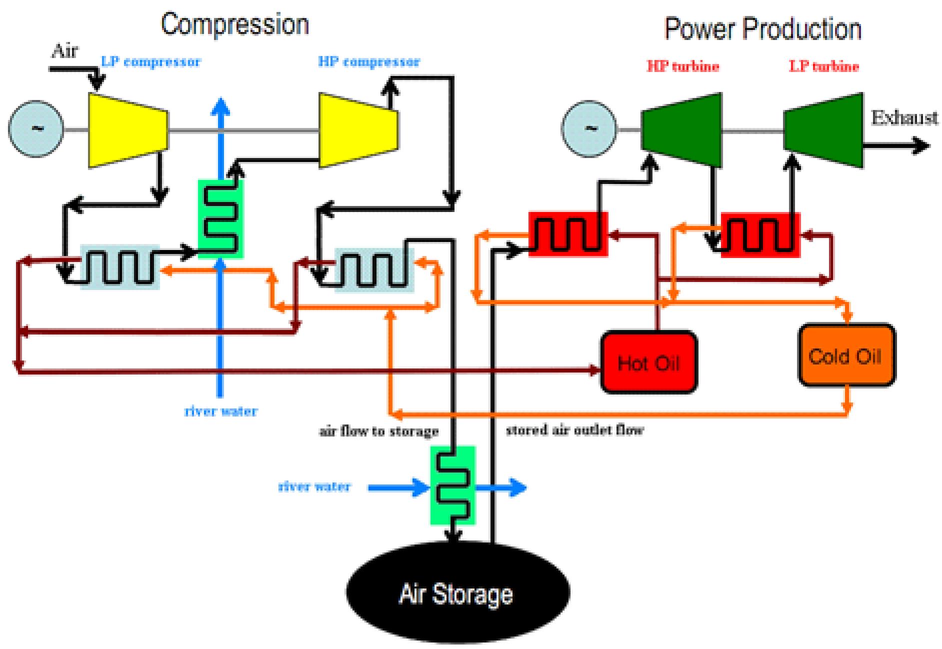

Figure 4-44 A-CAES with indirect heat-exchange

In order to model the indirect heat transfer, equation 31 already used in 3.4 for the storage of hot water in aquifer is implemented. Assuming a constant oil temperature equals to 393 K coming from the cold tank, the hot oil temperature increases on the basis of the initial conditions inside the hot tank; 2000 m^3 of oil at 518 K is assumed as initial conditions (Figure 4-45). Assuming 4% thermal losses between charge and discharge, the output power generated has the trend observed in Figure 4-46. About 545 MWh_e from an initial input energy spent of about 810 MWh_e is recovered and sold to the grid. Similar to conventional CAES and A-CAES with direct heat-exchange, the limitation for the generation train of operating at the minimum storage pressure introduces losses. Assuming the values in Table 4-4, the CER is 0,658 if the generation operates at constant pressure; it becomes 0,673 if a variable pressure is assumed.

Table 4-4 Reference parameters for A-CAES with indirect heat-exchange

Parameters	**value**	**Unit**
ambient pressure	101325	Pa
ambient temperature	288,15	K
compressors isentropic efficiency	0,89	
intercooler outlet temperature	318,15	K
DP compressor mass flow	250	kg/s
input electric power	150	MW
storage temperature	308,15	K
storage volume	300000	m^3
minimum storage pressure	7,0	MPa
maximum storage pressure	9,0	MPa
oil density [56]	750	kg/m^3
oil heat capacity [56]	2200	kJ/kgK
heat-exchangers effectiveness	0,90	
DP mass flow	350	kg/s
DP pressure	7	MPa
DP TIT	515	K
turbines isentropic efficiency	0,90	
exhaust pressure losses	4	%

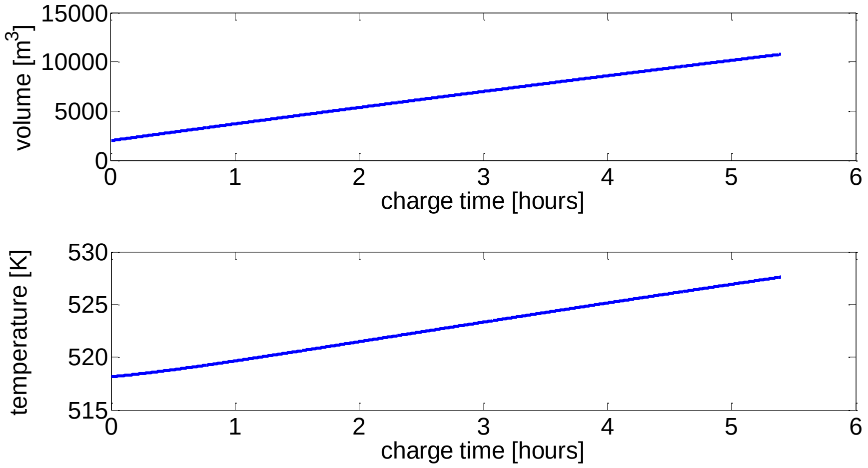

Figure 4-45 Oil mass and temperature inside hot tank during the charge

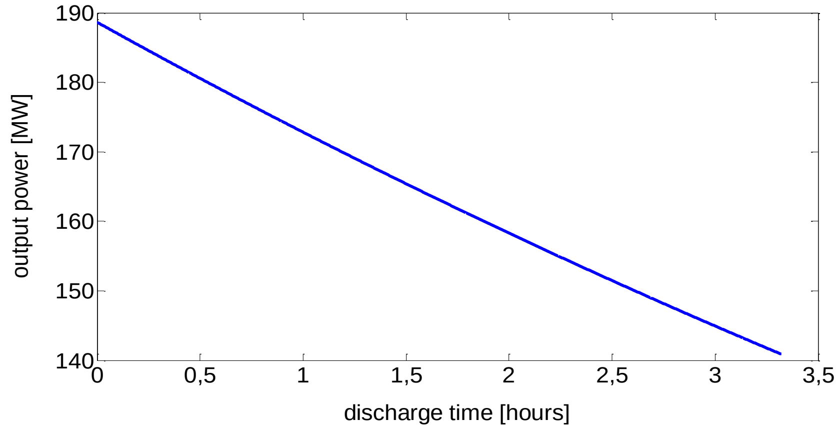

Figure 4-46 Output power produced in the A-CAES with indirect heat-exchange

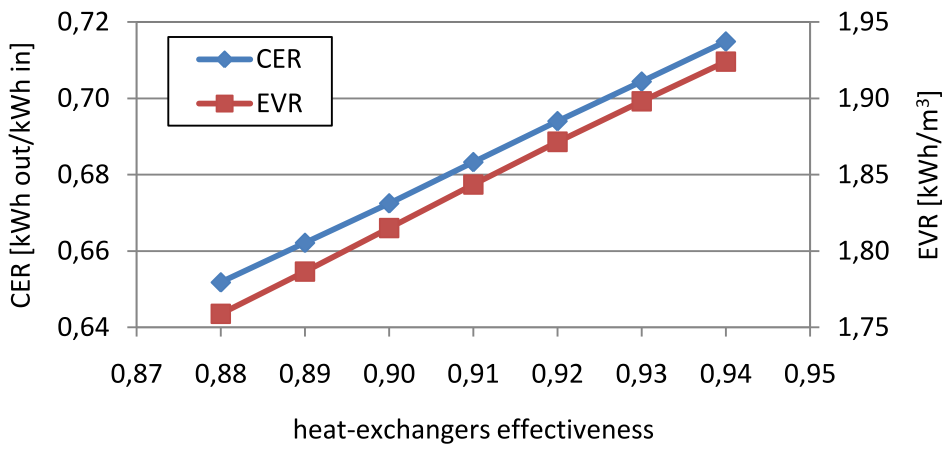

Figure 4-47 Effectiveness effects on the CER of A-CAES with indirect heat-exchange

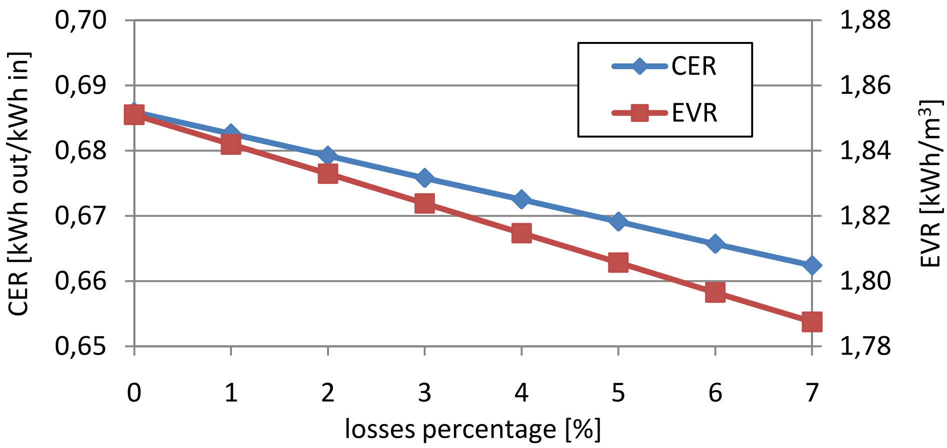

Figure 4-48 Tank losses effects on performances of A-CAES with indirect heat-exchange

As results of the simple models created, it can be seen the effect of the heat-exchangers effectiveness that needs to be the highest possible in order to maximise the thermal

energy stored, hence the EVR and the CER (Figure 4-47). It is obvious that this requires bigger heat-exchangers that may slow down the dynamic of the generation train. Other aspect that still needs to be evaluated are the thermal losses; higher the losses between charge and discharge, lower the EVR and the CER (Figure 4-48).
Because of the environmental and technical risks mentioned, this concept will not be investigated in the economic analysis. It has been briefly proposed here since the required methodology can be the same used for the CAES provided with the storage of hot water in aquifer; the concept to store energy in a liquid medium is the same, the only differences are the medium characteristics.

4.3 Conclusions

First of all, the results of the technical analysis, in terms of efficiency, are very closed to those found in literature (about 69%-70%), verifying the reliability of the models created. As seen for the conventional CAES, the results show the correlation of the performance indices to the ambient conditions. Performances improvements are achieved for low ambient temperature and high ambient pressure. The latter causes a particular effect in the adiabatic plant; since the compression energy required reduces increasing the ambient pressure, less thermal energy is transferred to the medium, thus less energy is available for the generation. However, the electric input energy saved increases the CER, therefore high ambient pressure is still recommended. Changing the electric input power, the operative points of the compressors change; operating in the region of high efficiency, the input energy required reduces, but the compressor outlet temperature is lower and lower thermal energy is transferred to the medium (the others parameters remain constant), hence the EVR reduces. However, because of the benefits in the input energy saved operating at higher compressor efficiency, the CER increases. Same results are achieved when an investigation of the compressor efficiency is realized; increasing the compressor efficiency, keeping constant the other parameters, less thermal energy is stored and less output energy is produced. However, thanks to the lower electric energy spent in the compression, CER increases. The latter element to analyse in the compression train is the intercooler. Assuming that is possible to increase the compressor outlet temperature above 923 K, the intercooler temperature affects the compressor train outlet temperature introducing increments in the thermal energy stored, thus in the TITs and EVR. CER instead slightly reduces since more effort needs to be spent when higher intercooler temperature is used.
The TES investigation highlights the strong relationship of the TES dimensions with the medium chosen and the air storage characteristics. Medium density and heat capacity define the TES volume; in order to reduce the volume, high density and specific heat values are required. The air storage volume with its characteristics of temperature and pressures defines the charge and discharge times with the amount of air that is stored inside. This defines the mass that goes through the TES releasing or acquiring thermal energy, hence a direct correlation between TES volume and air storage capacity can be

determined. An optimum for the TES volume is defined when a certain output energy is required (hence the storage characteristics are known). As seen for conventional CAES the air storage temperature affects the air mass injected inside the same volume, therefore the EVR. In the adiabatic a slight increment of the CER is also registered. Because of the higher temperature of the air withdrawn, less thermal energy is subtracted from the TES during the discharge and the TIT remains higher for longer time producing higher energy.

Filling the TES with pebbles or rocks, their dimensions should be the minimum possible in order to increase the heat transfer between air and medium. If this does not happen, significant CER and EVR reductions are registered. About the shape of the TES, taller cylinder tanks are advised. Because of the big TES volume required, more tanks are necessary; an investigation with more tanks has highlighted that no CER and EVR degradations take place if the stream coming from the compression train is split in more tanks and later the air coming from the cavern is split in different tanks and merged again before going through the generation train. Whatever is the shape and the volume of TES, the main element that needs to be maximized is the isolation of the walls. As the sensitivity analysis shows, the thermal losses with compressor and turbine efficiencies are the elements that must be taken into account in order to optimize the plant performances. Lower the losses, higher the energy available for the generation and higher the EVR and CER.

As the sensitivity analysis shows, the energy produced is still function of the minimum and maximum pressures. In particular, bigger pressure ranges increase the air stored and the EVR. If the pressure range increases to higher values (from 6 MPa-8 MPa to 10 MPa-12 MPa), an EVR improvement is still registered even if the higher electric input energy required for the compression reduces the CER. Consequently, as seen for conventional CAES, a A-CAES operating at lower pressure ranges is advised in order to maximize the CER. As reported in 1.2, low TIT requires higher air mass flow in order to achieve the same output power of a train with high TIT; this consequently needs bigger air storage volume for generating the same amount of energy. The consequence may be also in the generation train outlet, in the last stages of the LP turbine, where potentially the temperature can become very low creating problems of brittleness. Problems that can also increase if an higher expansion ratio (higher pressure range or maximum pressure) is used. It can be seen also a relationship between the generation train outlet temperature and the TES volume. Bigger TES with bigger thermal capacity permits to avoid fast reduction of the TIT (therefore of the TOT) reducing the risks of brittleness. The possibility to use two turbines in parallel that expand from the air storage pressure till ambient pressure is investigated highlighting the benefits in the TOT, but less power and energy is produced. Therefore the generation train with two turbines in series seems the better solution to undertake.

Changing the air mass flow withdrawn, the power generated changes, but since the air mass stored permits to generate always the same amount of energy, if less mass flow is withdrawn, longer is the discharge time and vice versa.

The brief analysis of the A-CAES with indirect heat-exchange shows CER and efficiency values very closed to those ones achieved with the direct heat-transfer. CER and EVR are in this case function of the heat-exchangers effectiveness, if this increases, higher thermal energy is stored and available for the generation. However, consequence of bigger heat-exchangers is that they can become big slowing down the dynamic. Also for this plant the need to reduce the thermal losses remain a priority.

CHAPTER 5: Economic Analysis of CAES

5.1 Methods and Models

When a power plant has to be built, it is required an economic analysis to evaluate its feasibility and its risks in the long-term period of time. Even if the performance analysis of a plant shows good results with particular characteristic of the parameters, it can be necessary to evaluate that the project is economically viable, because could be characterized by higher initial investment costs and O&M costs. Therefore, the plant needs to be interesting, and to make a sensible decision, methods that take into account all the costs and benefits are required. Since money is depreciated with time, it is also necessary to convert these costs and benefits to current values [57, 58]. The methods to help a company to take the decision are represented by:

- Discounted Payback Period (DPP)
- Net Present Value (NPV)
- Internal Rate of Return (IRR)

These methods, explained in the next lines, have been implemented inside mathematical models in order to evaluate the economic feasibility of both CAES and A-CAES.

5.1.1 Payback Period and Discounted Payback Period

In investment decisions, the Discounted Payback Period (DPP) is the number of years it takes for an investment to recover its initial cost after accounting for inflation, interests and other matters affected by the time value of money, in order to be worthwhile to the investor. It differs slightly from the PayBack Period, which only accounts for cash flows resulting from an investment and does not take into account the time value of money. The shorter the discounted payback period, the more desirable the investment.

5.1.2 Net Present Value

The Net Present Value (NPV) is the difference between the sum of the Discounted Cash Flow which are expected from the investment and the amount which is initially invested (eq. 37 and eq. 38). A certain Discount Rate (DR) to consider risks and interest rate is applied to the Annual Net Cash Flow (ANCF) (eq. 39). The intermediate values are called Present Values. The results obtained subtract the initial investment is the NPV. This is done by measuring all cash flows over time back towards the current point in present time.

$$NPV = initial\ cash\ flow + \frac{ANCF_{year\ 1}}{(1+DR)} + \frac{ANCF_{year\ 2}}{(1+DR)^2} + \cdots + \frac{ANCF_{year\ N}}{(1+DR)^N} \quad (37)$$

$$NPV = initial\ cash\ flow + \sum_{t=1}^{T} \frac{ANCF_t}{(1+DR)^t} \quad (38)$$

$$ANCF = annual\ operation\ profit\ -\ annual\ loan\ repayment\ -\ annual\ taxes \quad (39)$$

The major advantage of this method is that it takes into account the time value of the money. Figure 5-1 shows an ANCF and another ANCF at which a Discount Rate is applied; because of the equation 37 it is obvious that cash made in future becomes less and less. When the two sums are compared, it can be seen that even if a project looks attractive adding all the ANCF, it is not so attractive when a DR is taken into account: NPV can be negative although the cumulative ANCF is positive. Another advantage of this method is the simplicity to compare two projects; the one that has the highest NPV should be the better from the financial point of view and should be undertaken. However, this method is very sensitive to the DR: small change in the DR causes large changes in the NPV and also the estimate of the appropriate DR is uncertain. One solution is to calculate a range of NPV numbers using different discount rates and forecasts, so that one can generate, for example, best, worst and median case NPV numbers, or even a probability distribution for the NPV.

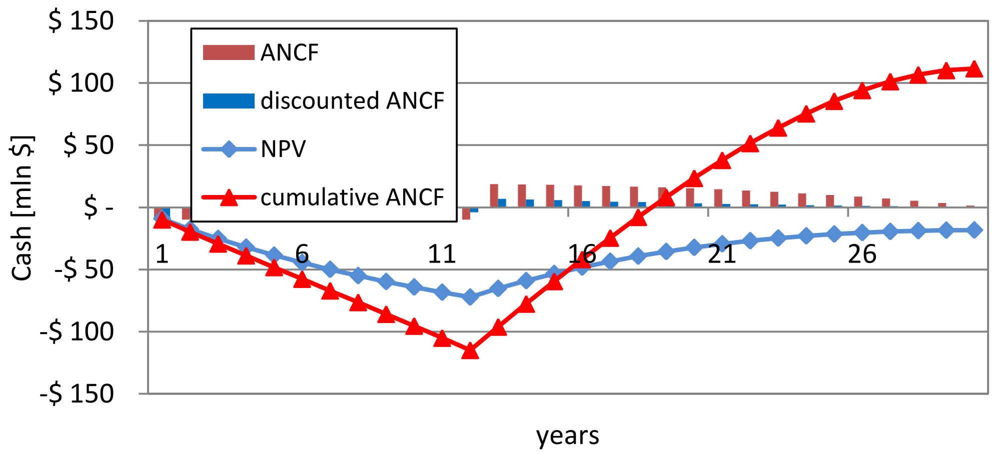

Figure 5-1 NPV and cumulative ANCF comparison

5.1.2.1 Annual Operation Profit

The annual operation profit for a conventional CAES can be defined as the revenue generated by the on-peak electricity sold to the grid minus the cost of the off-peak electricity, minus the fuel consumed by the generation train, minus the Operation and Maintenance (O&M) costs:

$$annual\ operation\ profit = \quad (40)$$
$$= sold\ electricity\ revenue - input\ electricity\ costs - \ fuel\ cost - O\&M\ costs$$

The revenue from sold electricity is defined as sold energy times the on-peak price:

$$sold\ electricity\ revenue = \ MWh\ of\ sold\ on - peak\ \ electricity * \$/MWh \quad (41)$$

The input electricity costs is defined as off-peak cost of the input energy times the off-peak price:

$$input\ electricity\ costs = MWh\ of\ consumed\ off-peak\ \ electricity * \$/MWh \tag{42}$$

The fuel cost is calculated as function of the energy produced and fuel price:

$$fuel\ cost = fuel\ consumption * MWh\ produced * \$/kg\ fuel \tag{43}$$

The O&M costs are defined as fixed plus variable costs. The variable costs are function of the output energy produced, while the fixed costs are function of the output power.

$$O\&M\ costs = fixed\ O\&M\ costs + variable\ O\&M\ costs$$

$$variable\ O\&M\ costs = variable\ O\&M\ cost\ per\ MWh * MWh\ produced \tag{44}$$

$$fixed\ O\&M\ costs = fixed\ O\&M\ cost\ per\ MWe * MWe\ produced \tag{45}$$

5.1.2.2 Annual loan repayment

The annual loan repayment is composed of two parts: the first one is the refund of the loan and the second part is the payment of the interest on the unpaid loan. In the models analysed a constant annual payment is assumed.

$$annual\ loan\ repayment = refund\ of\ loan + payment\ of\ interest\ of\ unpaid\ loan \tag{46}$$

Using the table calculated by J. Quenaut in [58] (Table F-1 in Appendix) and defined V_0 the initial capital cost, 'A' the repayment of the loan (without interest) during the year, 'N' the time of loan, 'i' the interest rate, the following equation that represents the amount to pay every year can be derived and implemented in the models:

$$amount\ to\ pay = V_0 * \frac{i}{1-(1+i)^{-N}} \tag{47}$$

5.1.2.3 Taxes

The annual taxes take into account the taxes on the profit and the possible taxes on emitted CO_2:

$$annual\ tax = tax\ rate * taxable\ income + tax\ on\ emitted\ CO_2 \tag{48}$$

5.1.2.3.1 CO_2 tax

A carbon tax is an environmental tax that is levied on the emissions produced by plants that during the process burn fossil fuels. In fact, carbon atoms are present in every fossil fuels and are released as carbon dioxide (CO_2) when fuels are burnt. Carbon tax increases the competitiveness of non-carbon technologies compared to the traditional burning of fossil fuels, and this is the reason why nowadays effort is spent in the adiabatic cycle. The CO_2 tax has very high fluctuation and it is dependent on the location. In the last few years, due to the increment of climate change problems, new countries are about to define CO_2 tax in order to reduce the GHG. Some values of carbon tax can be found in [60-62].

In order to calculate the emission tax is necessary to know the quantity of CO_2 produced when 1kg of CH_4 is burned; the combustion reaction is:

$$CH_4 + 2\ O_2 \dashrightarrow CO_2 + 2\ H_2O \tag{49}$$

CO_2 molar weight is 44,01 kg/kmol and CH_4 molar weight is 16,04 kg/kmol, therefore 2,743 kg of CO_2 are produced per kg of CH_4. Knowing fuel consumption, the tax can be computed.

5.1.3 Internal Rate of Return

The Internal Rate of Return (IRR) on an investment or project is the Discount Rate that makes the NPV of costs (negative cash flows) of the investment equal the NPV of the benefits (positive cash flows) of the investment. IRRs are commonly used to evaluate the desirability of investments; the higher a project's IRR, the more desirable it is to undertake the project. Assuming all other factors are equal among the various projects, the project with the highest IRR would probably be considered the best and undertaken first. In Figure 5-2 an example where the IRR is equals to about 13,4%.

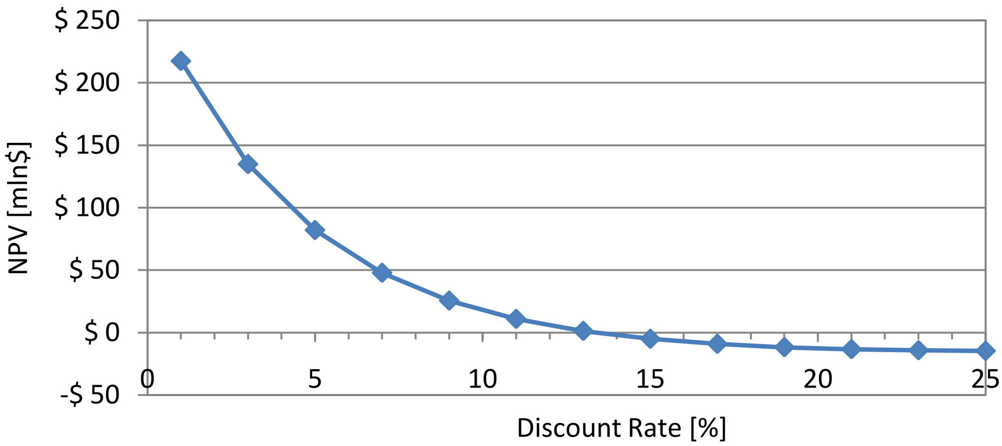

Figure 5-2 IRR Example

5.1.4 Total Investment Costs

In order to calculate the Total Investment Costs (TIC) of CAES and A-CAES, it is evaluated the procedure reported in Figure 5-3 [63]. The TIC is composed of three main components, the Total Direct Costs (TDC), the Indirect Costs (ID) and the Contingency.

The Total Direct Costs are the costs that can be directly related to producing specific goods and for this reason they take into account the costs of the components, the site development costs and the labour costs required. The Total Purchased and Installed Cost is represented by the components costs, and in order to consider eventual neglected equipment, it is added a 5% of unlisted components. With the term process buildings are considered the civil constructions that house the process equipment in the plant; service buildings are used to house, for example, the manpower and the warehouse of the spare parts; the service systems distribute auxiliary services to process equipment. The site development costs concern the activities that are required to prepare the site where the power plant will be located and the initial spare part cost is the first purchase of the spare parts at the beginning of the power plant operative life.

Indirect costs are costs, either fixed or variable, that are not directly accountable to a cost object and that include for example, the engineering activities, the project management and administration, the building yard activities, the inspection, the insurances and legal fees.

In the end, a contingency allowance needs to be considered for unpredictable and incidental events that are statistically likely to occur during a power plant construction. Since the CAES can present more unpredictable events than a combined cycle (more experience has also been acquired for these plants), it is assumed a contingency of 15% instead of 10%.

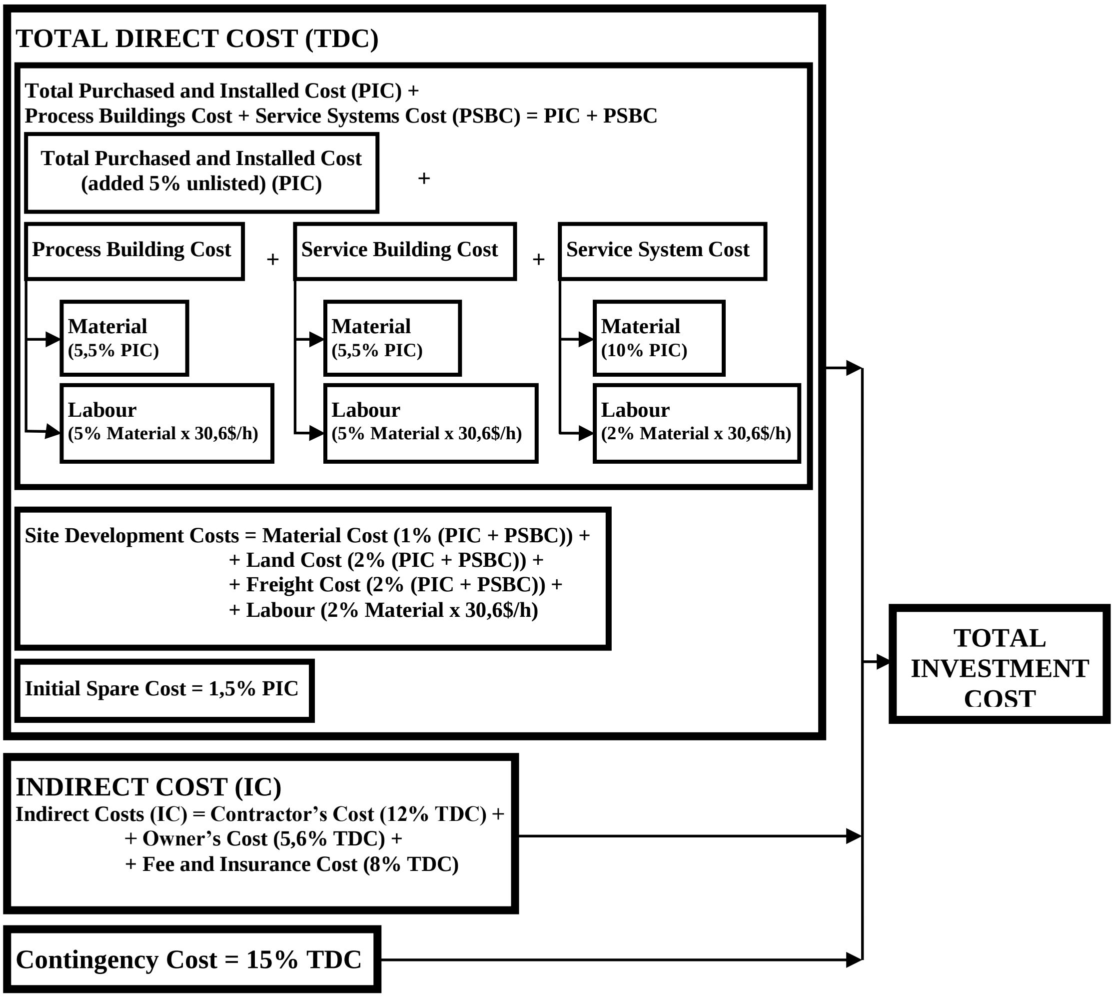

Figure 5-3 Economic model to calculate Total Investment Cost [63].

In order to calculate the TIC, the Total Purchased and Installed Costs needs to be defined; therefore the aboveground machinery costs and the storage costs are required. The functions that can be used are here presented.

5.1.4.1 Machinery costs models

The aboveground machinery of CAES and A-CAES are mainly conventional gas turbine engines, hence the following equations described in [63] for machines operating with air can be adopted. The equations are function of the main parameters of design that describe the machinery:

$$Cost_{compressor}[\$] = \frac{100}{1-\eta_{isentropic}} * \dot{m}_{air} * r_c * ln(r_c) \tag{50}$$

$$Cost_{heat\ exchanger}[\$] = 2880 * (surface)^{0,69} * (max\ pressure)^{0,28} \tag{51}$$

$$Cost_{combustor}[\$] = \frac{573}{1-f_{cc}} * \dot{m}_{air} * [1 + exp(0,02 * TIT - 31,86)] \tag{52}$$

$$Cost_{turbine}[\$] = \frac{1148}{1-\eta_{isentropic}} * \dot{m}_{air} * ln(r_{exp}) * [1 + exp(0,036 * TIT - 65,66)] \tag{53}$$

$$Cost_{electric\ generator}[\$] = 103 * power^{\ 0,94} \tag{54}$$

where:

$\eta_{isentropic}$	is the isentropic efficiency of compressor and turbine
r_c	is the compressor PR
r_{exp}	is the expansion ratio of the turbine
$\dot{m}_{air}$	is the air mass flow [kg/s]
f_{cc}	is the pressure drop in the combustor
TIT	is the temperature at the outlet of the combustor [K]
surface	is the exchanger surface [m^2]
max pressure	is the highest pressure in the heat exchanger [bar]

In order to define these coefficients in dollars ($) in 2009 and also convert all the other costs used in the economic analysis, are used the GDP index and the dollar exchange rate with the others currencies in different years [64].

5.1.4.2 Storage costs

For the calculation of the storage costs, values function of the output energy generated are proposed in the literature. Knowing the energy generated and the specific cost, the total capital cost of the storage can be defined:

$$storage\ costs = energy\ generated\ [kWh] * storage\ specific\ cost\ [\$/kWh] \tag{55}$$

As proposed in 1.5, saline aquifer has estimated development cost of about 0,11 $/kWh for incremental storage volume, salt caverns about 2 $/kWh generated from storage and in the end the most expensive hard-rock formation with 30 $/kWh produced. If existing mines were used, the costs would reduce to about 10 $/kWh. However, other elements need to be considered in the definition of the final capital cost; for example with aquifer, it needs to be considered CAES wells, well laterals, gathering system, water separator facility and initial bubble development costs. The total cost of developing a porous rock formation depends on the characteristics of the storage stratum (thinner and less permeable structures require more wells and therefore an higher development cost). CAES cost estimates indicate a capital cost of $2-$7 per kWh of storage capacity depending on the site characteristics (Table F-2) [7]. These costs are lower than those estimated for salt cavern ($6-$10 per kWh of storage capacity) which is the next cheapest option [7]. These take into account the costs for the cemented well, the costs for the solution mining, transport and disposal of the brine. Due to the different storage configurations, the cost of the cavern can increase to higher specific capital costs; value of about 12 $/kWh, has been found in the literature [37]. In [67] instead, the storage costs are mentioned in $/kW and they report salt dome as the least expensive with costs of about 40 $/kW to 80 $/kW, compared to porous formation (60 $/kW to 100 $/kW) and hard rock (up to 200 $/kW). Due to the uncertainty in the specific capital costs for the different formations, in the following analysis, it is considered a costs range.

5.2 Economic analysis

The object of this analysis is to compare some of the configurations seen in the technical investigation (Chapter 3) and see the impact that each variation has on the economic indices NPV, DPP and IRR.

5.2.1 Machinery

The reference plant considered, presented in Table 3-2 and already used in the analysis of the waste heat (3.4), uses a compressor train composed of three compressors, DP mass flow equals to 200 kg/s and electric input power equals to 100 MW. The 400000 m^3 storage operates in the pressure range 5,5 MPa to 8,5 MPa. The expansion train able to produce 436,5MW is composed of two turbines, it has pressure limited by a valve to 5,5 MPa and the TITs are respectively 1144 K and 1473 K. The input energy required in a cycle is about 1400 MWh, while that generated is about 2840 MWh. A plant provided of these characteristics reaches a cost of about 186,2 mln$. A detailed costs calculation is proposed in Appendix F, where Table F-3 represents the values used in the calculations, while Table F-4 shows the results of the calculations using the methods proposed in 5.1.4. An economic analysis of this plant without the recuperator is done for evaluating the impact of this latter on the profitability; the investment drops down to about 173,5 mln$ (Table F-5). If instead the compression train and the underground cavern remain the same, but the generation train is changed introducing a third combustor and a third turbine, the costs of the plant increases reaching about 213 mln$. The parameters chosen for this latter plant are those that maximize the output power generated. It has been developed a Matlab program to identify the optimum region in term of profits inside the surfaces observed in 3.1.11.4; because the revenues are very sensitive to the output power generated, the best point is located where the electric energy generated is the highest. The costs for the three turbines configuration is presented in Appendix F, Table F-6.

In the technical analysis the CAES plant characterized by low TITs has been presented and it is here analysed with its variants: the case without recuperator and another one with the compressor train composed of three compressors instead of two. The initial value of 150,3 mln$, decreases to 141,1 mln$ in the configuration without recuperator and to 147,6 mln$ for the compressor train supplied of three compressors. It is worth mentioning that the recuperator introduces a significant variation in the cost of the machinery due to the material costs, the space and work required for the development. However, even if the significant difference in the capital cost, the economic analysis shows that because of the high fuel price, the recuperator has a significant role in the profits.

In all the cases proposed is done the assumption that the generator can be used as a motor during the compression train (similarly to the Huntorf and the McIntosh plants). If this assumption was not verified, in the reference case should be added in the components costs 5,8 mln$ for a 100 MW motor and in the other case 3,6 mln$ for a 60 MW motor; with consequent TIC increments. The possibility to install an independent motor would introduce benefits of operating flexibility [1].

5.2.2 Storage

In order to understand the effects of the storage cost on the initial capital cost, a range of storage cost values are analysed. Because of the uncertainty found in the literature for these costs, the values ranges proposed in 5.1.4.2. for porous and salt formations are chosen adding 0,5 $/kWh to the minimum value and assuming values 20% higher for the maximum values. Therefore, for porous rock formations a range between 2,5 $/kWh and 8,5 $/kWh, while for salt caverns between 6,5 $/kWh and 12 $/kWh are considered. For hard-rock caverns instead, a range between 20 $/kWh and 40 $/kWh is chosen. In Figure 5-4 the economic impact of the storage is presented versus the machinery costs for a cavern of 400000 m^3; the reference case with its 186,2 mln$ is considered. It can be seen that, even if the machinery costs changes of about 15%, it maintains the main component of the capital costs; also if an hard-rock cavern is considered. If an analysis with constant machinery cost and different storage volumes is performed, the trends are those ones represented in Figure 5-5. It can be seen that increment in the autonomy of the cavern, increases the storage costs. As Table 5-1 shows, it is obvious that bigger caverns increase the amount of output energy available, but longer charge is required (DP mass flow equals to 200 kg/s for the compression and 410 kg/s for the generation are assumed). If the output energy is required for longer period of time, a bigger volume is necessary, increasing the costs of the storage. In the worst case of an hard-rock cavern of 750000 m^3, it can reach a cost higher than the capital costs of the machinery. These results show why aquifers and salt caverns are the first solutions studied for CAES applications. In the economic analysis, a storage with specific capital cost of 11 $/kWh is chosen as reference.

Table 5-1 Charge time and discharge time for different cavern dimensions

cavern volume [m^3]	300000	400000	500000	750000
charge time [hours]	10,4	13,9	17,4	26,0
discharge time [hours]	4,8	6,5	8,1	12,2

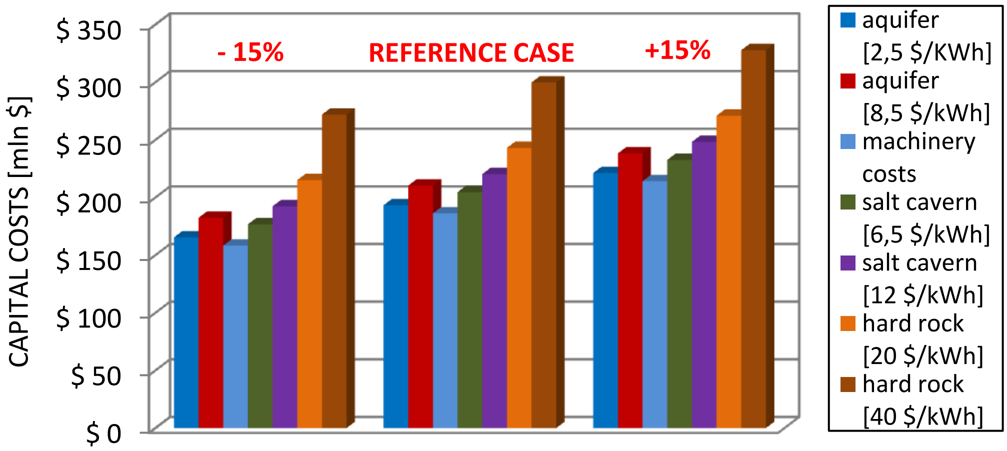

Figure 5-4 Economic impact of the cavern costs on the TIC

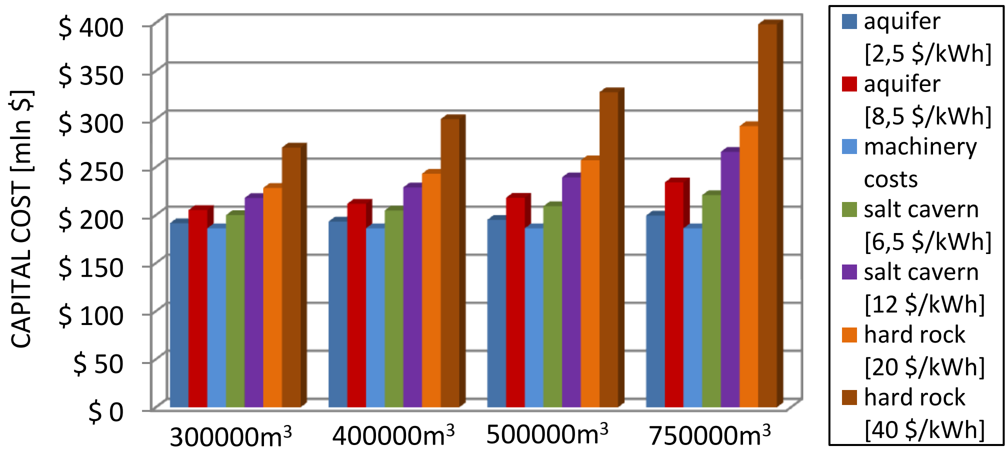

Figure 5-5 Economic impact of different cavern dimensions on the TIC

5.2.3 Electricity, fuel, O&M, tax prices

As mentioned for the storage, a certain uncertainty characterize the prices of the different parameters, prices that vary on the basis of the markets.

The off-peak electricity used for energy storage can derive from different sources as intermittent wind, solar and tidal power or the cheap nuclear energy. Figure 5-6 shows the Levelized Cost of Electricity (LCOE) for different sources in different countries. It is evident the reason why nuclear energy has been proposed for CAES, it can supply cheap off-peak electricity that can be stored and sold to the grid at higher prices getting significant revenues. However, these prices do not represent the off-peak electricity prices, the off-peak prices can be much lower and different, on the basis of the markets.

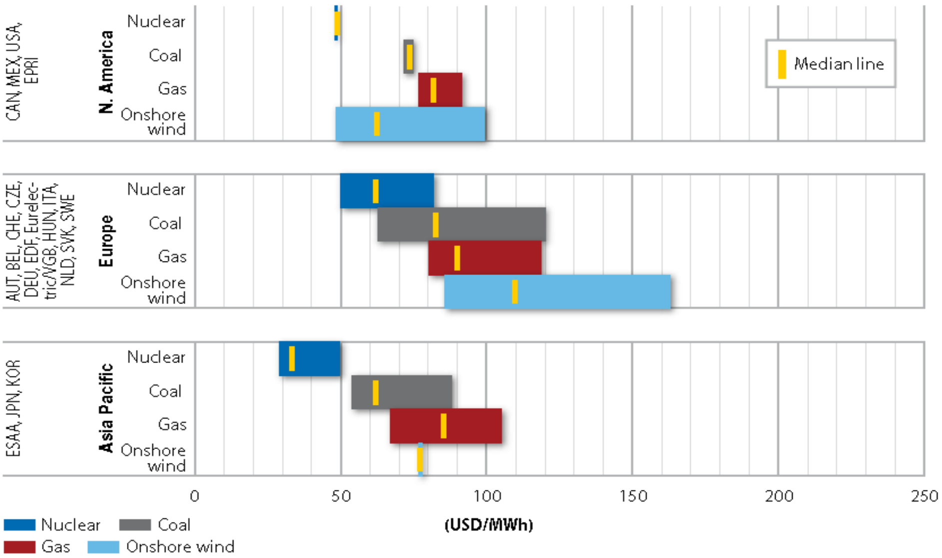

Figure 5-6 LCOE for different energy sources (5% Discount Rate) [77]

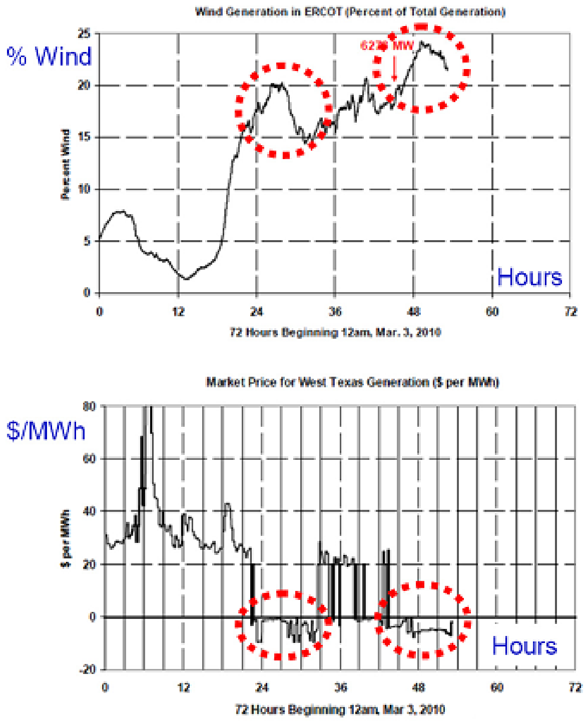

Figure 5-7 Impact of wind penetration and reduction of off-peak electricity prices [78]

In Texas, but forecasts say this will happen soon also in other states (such as California, New York, Iowa, Colorado and elsewhere), due to the high wind penetration, the price of electricity is dropped to less than zero. Figure 5-7 summarizes the situation experienced on March 3, 2010 and several times since, when so much wind energy was generated that the off-peak market price of electricity went negative. These circumstances highlight the important value of energy storage such as CAES to the use and further penetration of wind generation resources.

In this analysis a reference value of 50 $/MWh is assumed (Table 5-2).

Figure 5-8 shows natural gas prices in U.S. for electricity production in the last years. It can be seen the high variability of the fuel cost that has also touched significant peaks. Even if the HR in CAES is lower than gas turbine used for peak generation, fuel price maintains a significant role in the profitability of the plant. A value of 7 $/mlnBTU with an escalation rate of 6% every year is assumed (Table 5-2).

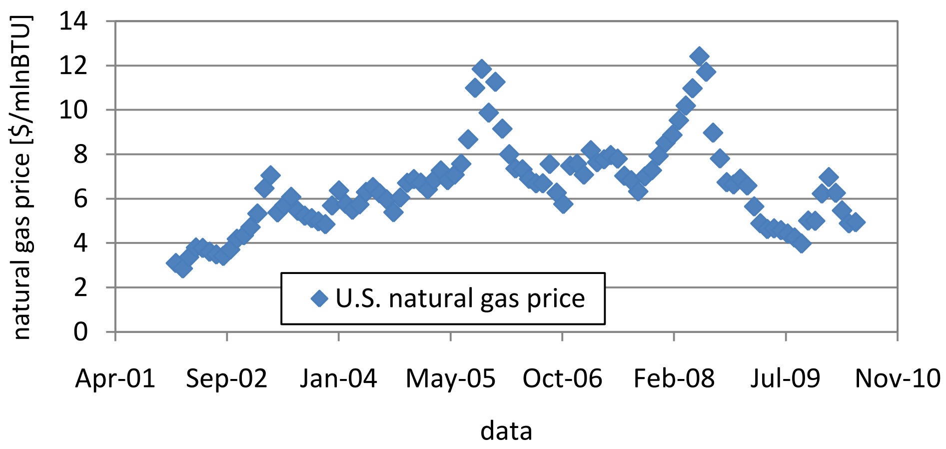

Figure 5-8 Natural gas price trend for electric power in U.S. [76]

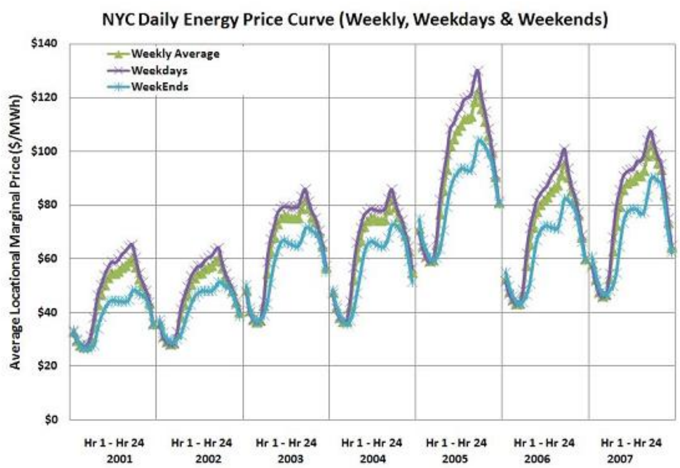

Figure 5-9 Average electricity price profiles in NYC during the week [50]

On-peak electricity price is another parameter, that similarly to off-peak electricity, is strongly dependent on the location (Appendix F, Figure F-1). Figure 5-9 gives an idea of the trend of average electricity price during the week and also during the years in New York City. It is worthy to compare the electricity price trend with the fuel price trend reported in Figure 5-8. It can be seen the obvious connection between the two prices, in particular in 2005, where a peak is registered both for the fuel price and for the electricity price. In this economic analysis, with similar approach used in the technical analysis, only one parameter varies keeping constant all the others. However, as seen, the trends are usually connected together, hence, if the fuel cost increases, the off-peak and on-peak electricity increase. A value of 105 $/MWh is assumed as reference in the analysis (Table 5-2).

In the reference case, no CO_2 taxes are considered (Table 5-2). However, similarly to the consideration done for fuel and electricity, since the prices are linked together, if CO_2 tax changes it is also probable that electricity prices will be affected by variations.

The O&M costs are also characterize by variable values in the literature [1, 2]. In this analysis fixed O&M costs equal to 8 $/kW_e$ and variable O&M costs equal to 0,004 $/kWh are assumed.

The plant life, necessary to calculate the NPV, is another parameter with a significant fluctuation; in the literature values vary between 20 to 30 years [1, 2]. It is assumed a value of 30 year. In the end, a loan period of 12 years with a loan interest of 8% are assumed [79, 80].

Table 5-2 Reference parameters used in the economic analysis

parameter	value	unit	escalation rate
Discount Rate	8	%	-
off-peak electricity price	50	$/MWh	3%
on-peak electricity price	105	$/MWh	3%
fuel price (natural gas)	7	$/mlnBTU	6%
CO_2 tax	0	$/ton CO_2	-
tax	35	%	-
Fixed O&M costs	8	$/kW	3%
Variable O&M costs	0,004	$/kWh	3%
loan repayment	12	years	-
loan interest	8	%	-
plant life	30	years	

5.2.4 NPV Results

5.2.4.1 Market conditions

A parametric analysis of the profitability of the different plant configurations is carried out. The reference CAES plant chosen presents an initial capital costs of about 217,4 mln$, achieved adding the 31,2 mln$ of the underground storage to 186,2 mln$ of the aboveground machinery. NPV variations are reported in the next figures as consequence of the parameters values changes. Figure 5-10 shows the trends of the input energies, both off-peak electricity and fuel variations; it can be seen the benefits to have low prices for both. Furthermore, the results show the more sensitivity of the NPV to fuel variations compared to the reference case, due to both the higher escalation rate of the fuel price (6%) and the higher amount of the fuel energy required to run the plant compared to the electric energy.

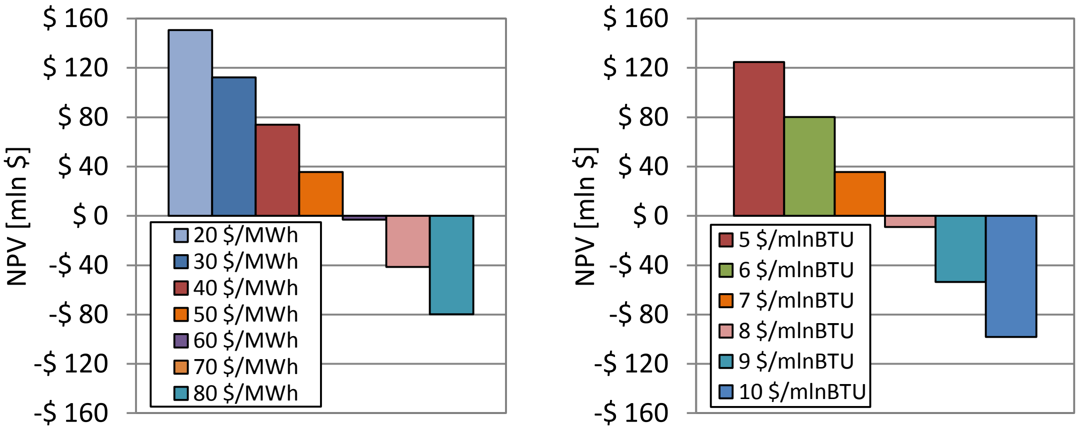

Figure 5-10 NPV changing off-peak electricity and fuel prices

In literature different values for the hours of operation of the plant in a year are proposed [1, 2]. In this analysis a reference of 280 cycles/year with 1820 hours of generation/year is assumed. Figure 5-11 shows the benefits of increasing the hours of generation since more output energy is sold increasing the revenues. The stops of the machinery need to be kept at the least value. The other results in Figure 5-11 consider the CO_2 tax; in the reference case is assumed equal to zero but if it is applied, with an escalation of 3% per year and maintaining all the other parameters fixed (this does not respect what could happen in a real market (5.2.3)), this introduces significant reduction in the NPV that becomes easily negative with a tax less than 15 $/ton, lower than the average values proposed in some real market (5.1.2.3.1) and also assumed in other economic analysis (30 $/ton in [66]). If the electricity price did not increase with the CO_2 tax increment, the plant would become no more economic attractive soon.

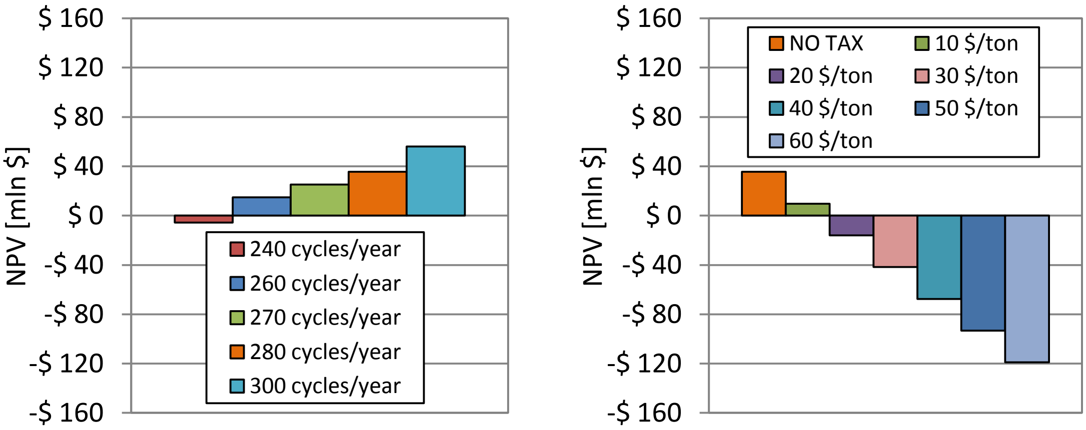

Figure 5-11 Impact of CO_2 tax and number of cycles/year on the NPV

Compared to the effects of the previous parameters, it can be highlighted the low sensitivity of O&M costs on the NPV (Figure 5-12); even so, lower O&M costs are preferred since their increments introduce NPV reductions. Besides O&M increments may mean stops of the machinery that here are not taken into account, but they may reduce the NPV because less cycles/year are realized.

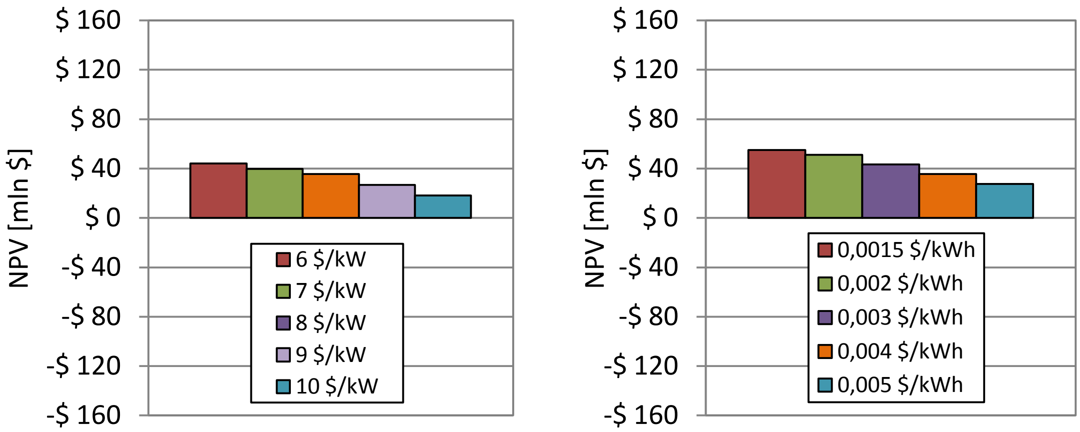

Figure 5-12 Impact of O&M costs on the NPV

In the end, the effects of the on-peak electricity price on the NPV show the high sensitivity of the NPV to the electricity. As visible in Figure 5-13, in a market with high on-peak electricity price the revenue can increase significantly. On the other hand, if the price decreases, the NPV become easily negative and the plant is not attractive anymore. A certain difference has to exist always between the off-peak and the on-peak electricity prices in order to get positive NPV for this plant.

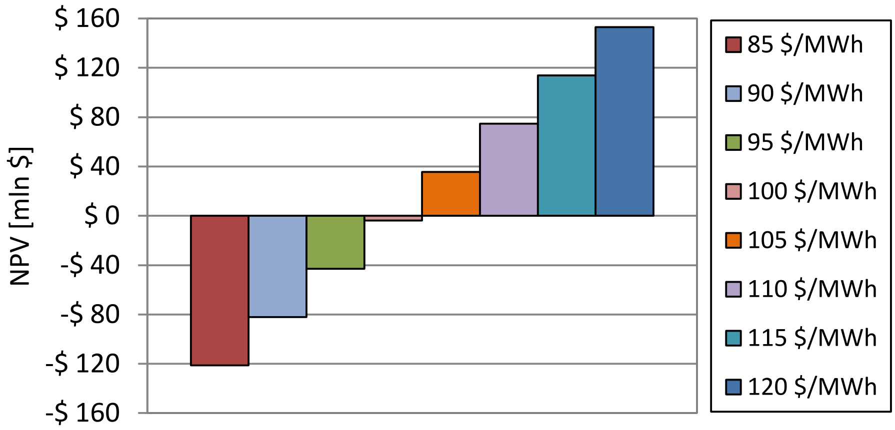

Figure 5-13 NPV changing the on-peak electricity price

Before going ahead with an analysis of the machinery, it is worthy to highlight again the strong relationship of the plant to the market conditions, and in particular the effects of different escalation rates of fuel, electricity and O&M costs on the NPV. The results show the benefits of low escalation rate of the fuel since affects significantly the NPV

(Figure 5-14). In the previous models an escalation rate for electricity and O&M costs of 3% is assumed, if decreased to 2% a significant NPV decrement would take place. The NPV could become again positive only assuming a reduction of the fuel escalation rate (5%). As will be highlighted several times, the profits are strongly related to the market conditions and the presence of a sufficient difference between off-peak electricity and on-peak electricity prices.

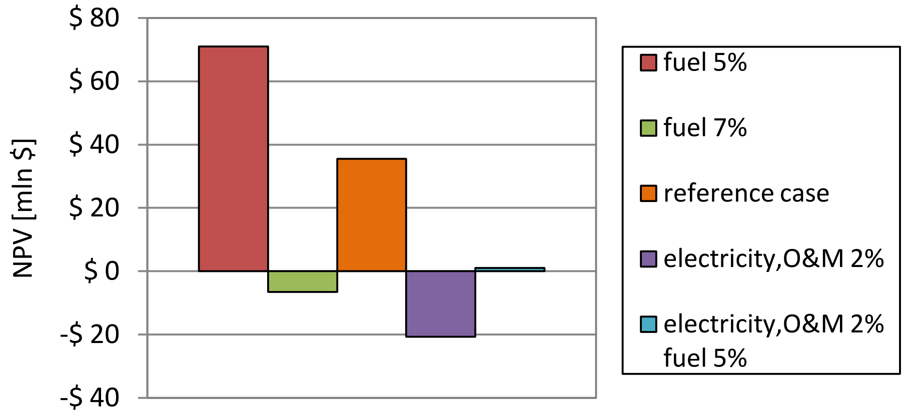

Figure 5-14 Escalation rate effects on the NPV

5.2.4.2 Machinery

If the recuperator is not installed and the same formation of 400000 m^3 is assumed, the capital cost of the plant decreases to 204,8 mln$ (Table F-5). Because of the high HR of this plant, the consequence is that with the same assumptions of Table 5-2, the NPV is negative and the DPP is over the plant life. Only if the price of the off-peak electricity fell to 30 $/MWh (-40%) or the on-peak electricity increased to 115 $/MWh (+10%) or the fuel price decreased to 5,5 $/mlnBTU (-20,5%) the NPV would become positive, even if lower than the reference case (Figure 5-15).

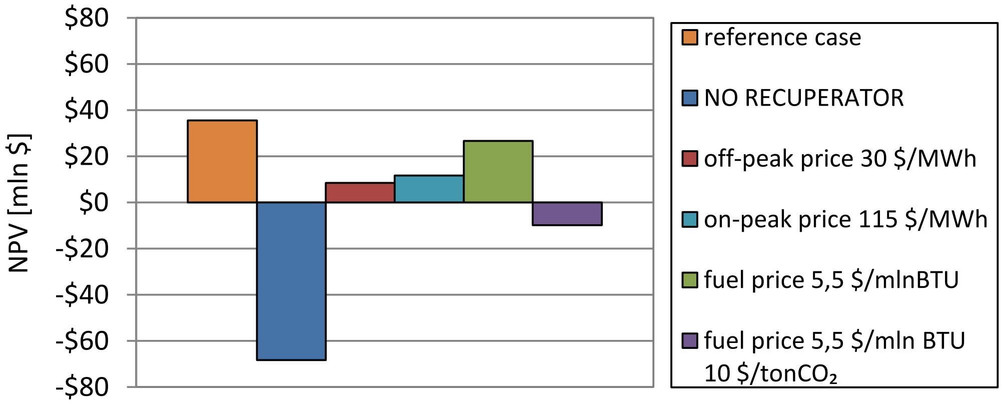

Figure 5-15 NPV for CAES without recuperator

These results show again the high sensitivity of the plant to the fuel and on-peak electricity prices. However, considering the latter case with low fuel price, if a small

CO_2 tax was added, due to the high HR and consequent emissions, the NPV would become again negative. For these reasons, even if the recuperator introduces higher initial capital cost and for big generation train can be bulky and slow the dynamic of the generation train, its installation is advised in order to reduce the fuel consumption and the consequent emissions, costs and tax.

If the generation train is instead modified adding the third combustor and third turbine, the TIC with the salt cavern of 400000 m^3 increases to 244,3 mln$ (Table F-6). Figure 5-16 shows the NPV comparison between the two turbines and three turbines trains. It can be seen that the train with three turbines has higher NPV due to the higher amount of electricity sold to the grid with the same amount of off-peak energy spent, even if with higher HR (4340 kJ/kWh instead of 4245 kJ/kWh). Changing also the fuel cost and introducing CO_2 taxes, the configuration with three turbines gives better results. It can be seen that if the fuel price increased to 8 $/mlnBTU, the NPV for the train with two turbines would become negative while for the other would be still positive. From these results the train with three turbines looks more economically attractive than the conventional; reliability and more difficult production of this train may need to be taken into account [59].

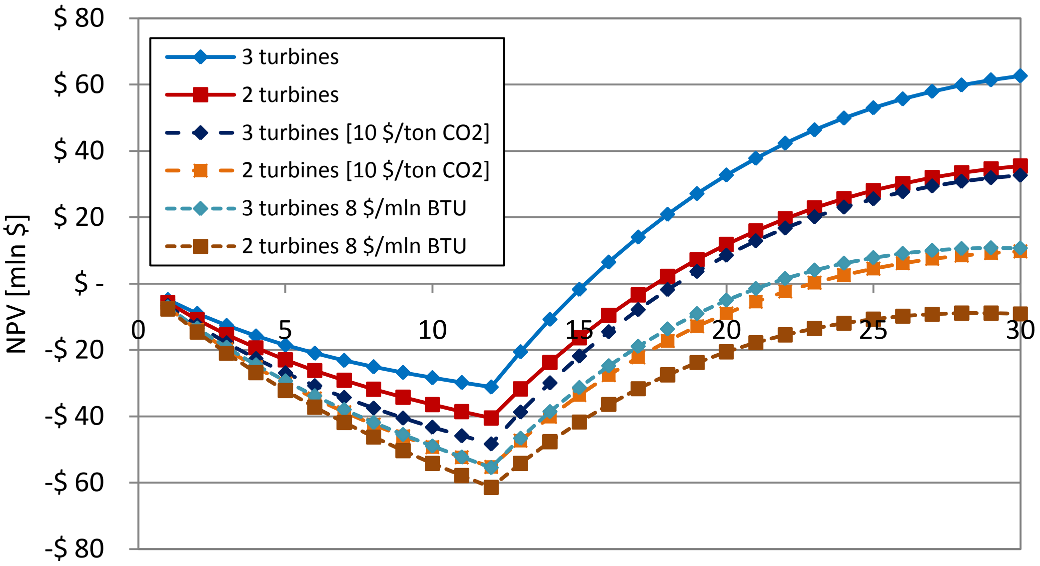

Figure 5-16 NPV comparison for a generation train with three turbines

It is here investigated the generation train with three turbines and a second recuperator (3.1.11.4). The plant characterized by an HP TIT equals to 973 K defines a TIC of about 239,2 mln$ that increases to about 242,9 mln$ when the second recuperator is added. Looking at Figure 5-17, the NPV has not any improvements, instead it reduces. In fact, as highlighted in the technical analysis, the 2nd recuperator reduces slightly the HR, but the higher capital costs and the less revenues from the electricity sold (the output power slightly reduces when the second recuperator is introduced) reduce the NPV. Therefore, for these reasons and the already mentioned delay created, it can be concluded that the second recuperator is not economically viable.

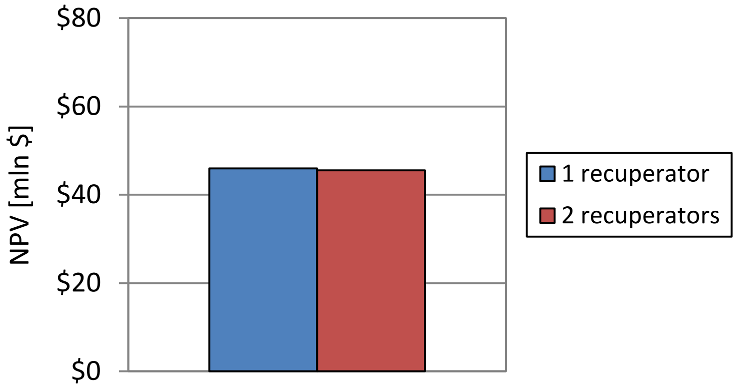

Figure 5-17 NPV comparison between generation trains with one and two recuperators

After the three turbines configuration, it is carried out the analysis of the CAES seen in 3.1.1, with two compressors, a generation train with low TITs and a less expensive cavern. Less expensive cavern because of the smaller dimension (310000 m^3) and the less depth underground (lower maximum pressure). It is assumed a specific cost for a salt formation of 9 $/kWh, defining an initial capital cost of about 168,6 mln$ (Appendix F, Table F-10 and F-11). It is evident that the long charge time and short discharge with also low energy generated, define a low CER, that consequently yields a negative NPV. Assuming for example the same condition of Table 5-2 and increasing the cycles/year to 350 (12 hours and more than 3 hours are respectively the charge time and discharge time), the NPV assumes the negative value observed in Figure 5-18.

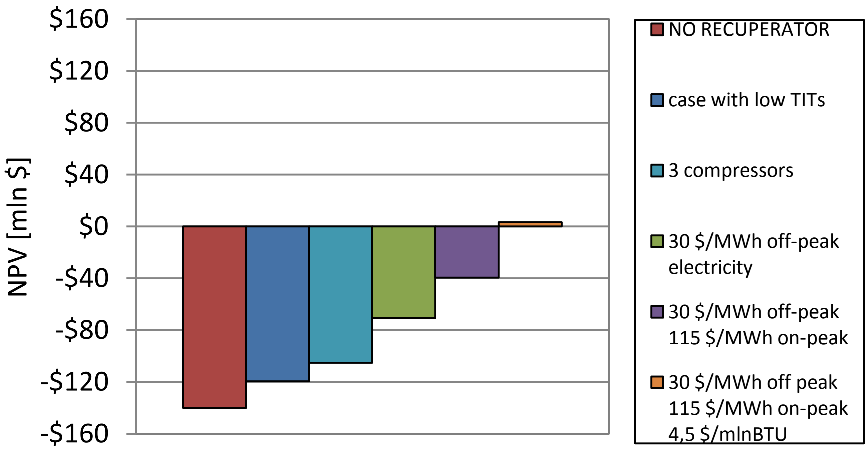

Figure 5-18 NPV for the plants with low TITs

Only changing significantly the prices of the parameters, the NPV becomes slightly positive. As expected, the introduction in the compressor train of a third compressor and a second intercooler with the consequence reduction in the input energy required, improves the NPV. If the generation train is without recuperator, the NPV falls down

more, as already found out in the previous lines. Therefore, these results show again the importance to have high CER with its high amount of energy sold to the grid.
It has been highlighted several times the technical benefits to increase the TITs. Figure 5-19 shows these benefits in the NPV trends for different HP TITs, with consequences not only on the final NPV, but also in the Discounted Payback Period.

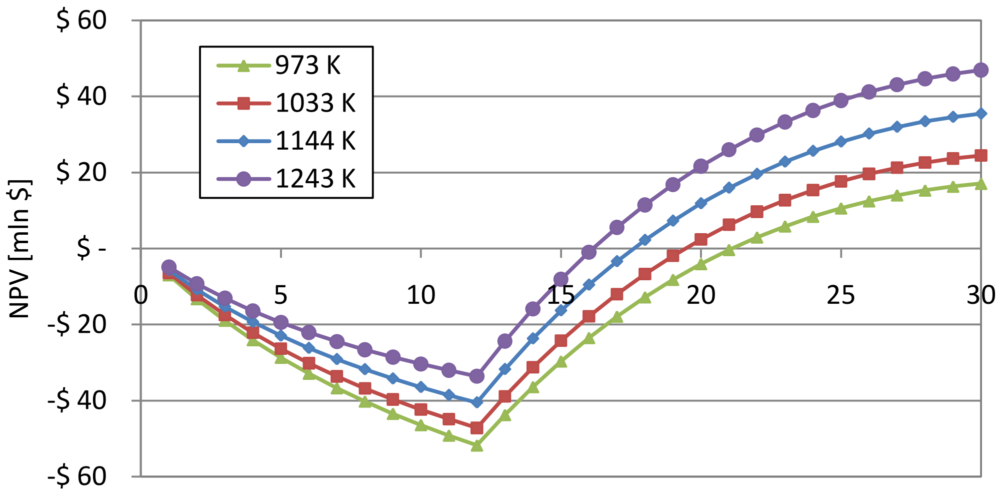

Figure 5-19 NPV for different HP TITs

Looking at the costs percentage of the components in the total components cost, it can be seen that the generation train represents the main component of the PIC (Figure 5-20). For this reason, it is evaluated here the possibility to maintain the same compressor train and underground cavern, reducing the mass flow withdrawn. This increases the generation time, reducing the power. The plant will benefit of a reduction in the cost of the generator, smaller turbines, smaller combustors and also a reduction in the recuperator dimensions, that may become faster.

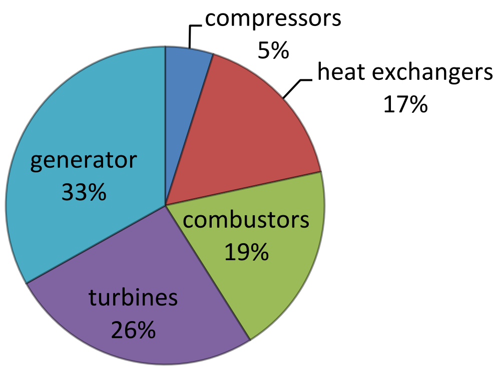

Figure 5-20 Percentage of the costs due to the different components

Looking at the NPV for four different scenarios, it can be highlighted the benefits in the NPV reducing the mass flow withdrawn. It is done the assumption that the amount of energy generated and sold to the grid in one year (making longer the hours of operation of the generation train) is the same than the reference case at 410 kg/s. Reducing the mass flow withdrawn, the initial capital cost reduces (Appendix F, Table F-7), while the costs and revenues remain the same, therefore the consequence is this increment in the NPV (Figure 5-21) of the same amount of capital cost saved in the beginning reducing the generation train.

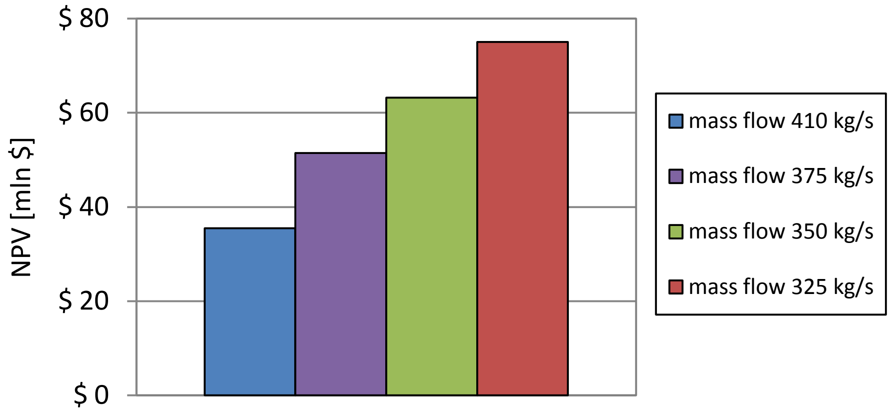

Figure 5-21 NPV comparison among generation trains with different mass flows

In Chapter 3 it has been proposed the generation train without HP combustor; it is here analysed using the generation train of the reference plant of the economic analysis. Compression train and cavern remain the same. The HP combustor is avoided and a recuperator with effectiveness equals to 0,92 is supplied in order to reach an HP TIT of 826 K. The LP turbine operating with a TIT equals to 1473 K and isentropic efficiency equals to 0,9 releases the exhaust at about 871 K. It is done the assumption to maintain the significant mass flow of 410 kg/s, even if this introduces a huge recuperator with a surface of exchange of about 19000 m^2, that has the benefit to reduce the HR to about 2086 kJ/kWh, but slowing down the dynamic of the generation. Assuming the parameters in Table 5-2, the NPV of the reference plant is higher than that one without HP combustor, benefits maintained till the fuel reaches a price of 9 $/mlnBTU, where a slight improvement in the NPV of the plant without combustor is registered (Figure 5-22). Similar consideration if a CO_2 tax of 40 $/ton takes place. These better NPVs for the plant without HP combustor are due to the lower HR. Therefore the possibility to install a train without the HP combustor could be interesting in particular markets, but the dynamic of the generation also has the priority and here it is evident the big recuperator required. In order to reduce the recuperator dimensions, a solution is the mass flow reduction (lower output power); if instead, a certain high output power value needs to be maintained, the solution can be the LP TIT increment.

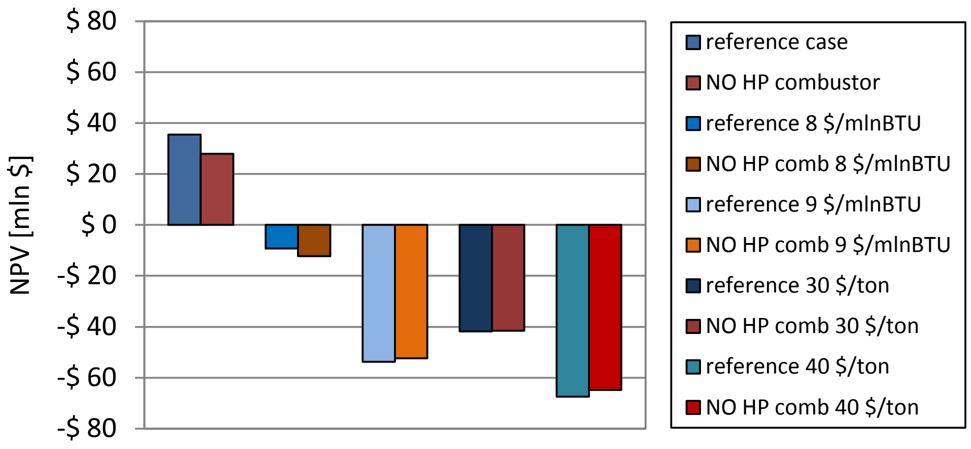

Figure 5-22 HP combustor effects on the NPV

As reported in 5.2.1, in all the models analysed the generator is also used as motor during the compression. If a 100 MW motor is introduced, it increases the components cost of about 5,8 mln$, introducing a TIC of 201,4 mln$ for the machinery and a Total Investment Cost of 232,6 mln$ with consequent decrease of the NPV of the more TIC spent (about 15,2 mln$). Introducing a more flexible system with a motor in each compressor (three motors respectively of 32,5 MW, 33,7 MW and 33,8 MW chosen at DP, are assumed), it is registered a slight reduction in the NPV than the previous case (Figure 5-23). The TIC increases of about 0,9 mln$ (202,3 mln$) respect to the previous case with only a 100 MW motor.

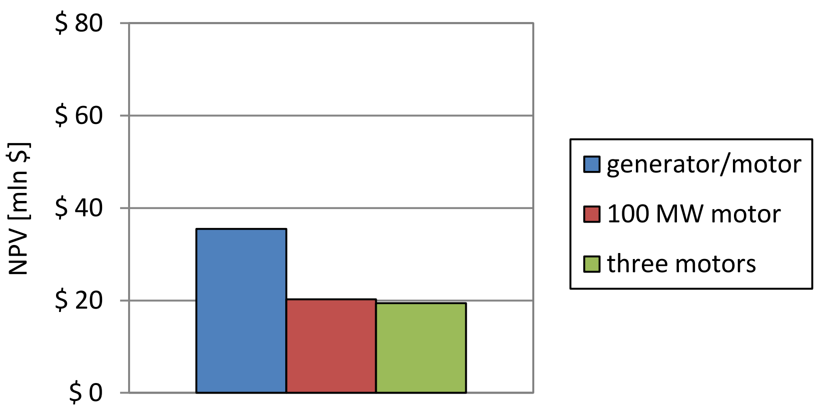

Figure 5-23 Motor cost effect on the NPV

In 5.2.1 it has been anticipated the impact of the machinery costs on the TIC and here the results on the NPV are proposed. Since the costs and revenues are the same for all the cases analysed, the NPV variations depends only on the TIC difference spent in the beginning. If the capital cost is 15% less than the reference, that amount (about 28 mln$) is added to the NPV after 30 years, otherwise it is subtracted (Figure 5-24).

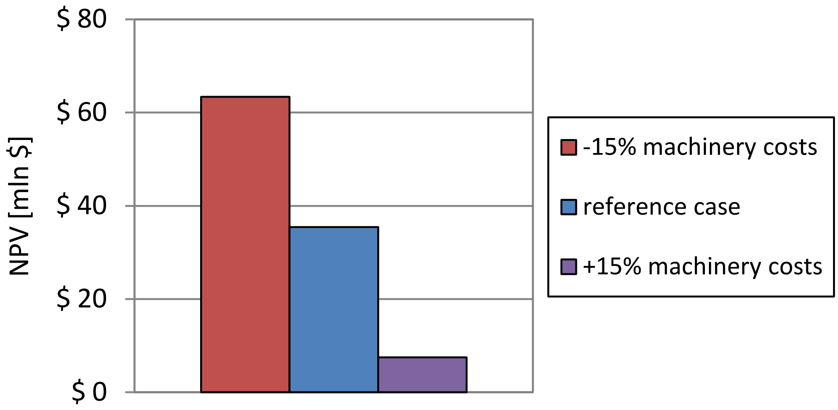

Figure 5-24 Effect of machinery capital costs on the NPV

5.2.4.3 Storage

In 5.2.2 it has been proposed the impact of the cavern costs in the initial capital cost. Figure 5-25 shows the NPVs for the machinery of the reference case with different storage specific costs. Since the costs and the revenue remain the same, the NPV vary of the same amount of initial capital cost variation spent for the cavern. Assuming a specific cost increment from 5 $/kWh to 7 $/kWh, the capital cost increases of 5,7 mln$ (from 14,2 mln$ to 19,9 mln$), that is the decrement registered in the NPV (from 52,5 mln$ to 46,8 mln$). The results show again hard-rock caverns as the last option for CAES applications.

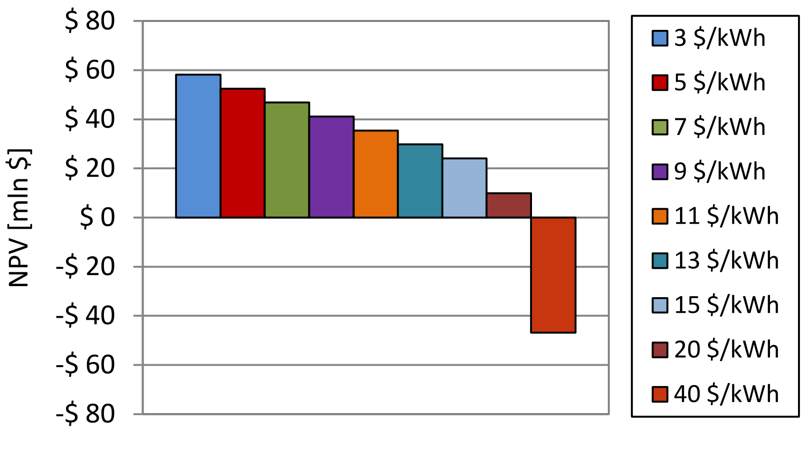

Figure 5-25 Storage specific costs effects on the NPV

It is now carried out an analysis of the profitability maintaining the same aboveground machinery with its initial costs, but changing the cavern dimensions, hence changing the charge and discharge times and the number of cycles in a year. Figure 5-26 shows the results. The assumption of maintaining the same amount of charge and discharge hours in a year is considered in all the cases analysed (Table 5-1); the number of cycles reduces increasing the storage volume. Since prices and revenue are kept constant, the input energy spent and output energy produced are the same in all the cases; the consequence is that the NPV decreases increasing the volume. The variation is equal to the more TIC spent in the beginning to build the bigger cavern.

storage volume	storage cost
300000 m^3	23,2 mln$
400000 m^3	31,2 mln$
500000 m^3	39,0 mln$
750000 m^3	58,2 mln$

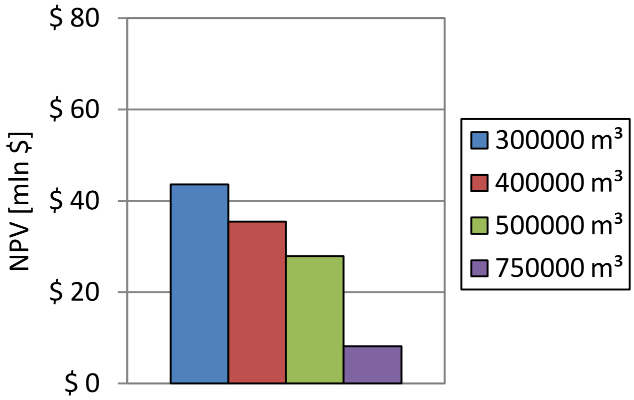

Figure 5-26 Effect of changing the cavern dimensions on the NPV

5.2.4.4 Discount Rate

In 5.1.2 it is defined the high sensitivity of the NPV to the DR. The reference case is assumed. As Figure 5-27 shows, the NPV is high sensitive to DR variations and it increases significantly with low DR since, according to eq. 37, higher discounted ANCF are added (Figure F-4 in Appendix F).

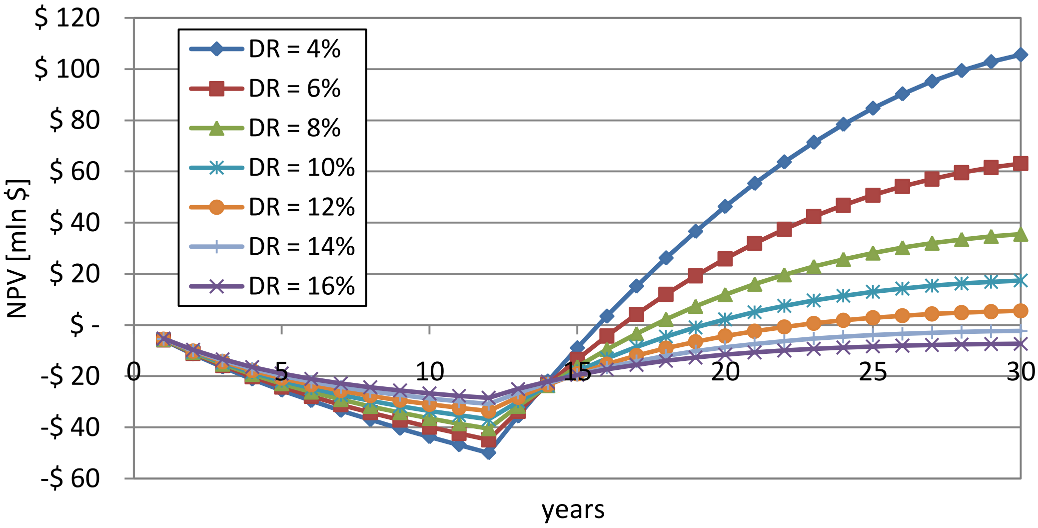

Figure 5-27 DR effects on the NPV

5.2.5 CAES with Thermal Storage of wasted heat

The storage of waste heat in aquifers or man-made tanks for using this in a DH application is here investigated. Although the growing interest in aquifer TES, no specific costs for this storage have been found, therefore, it is done the assumption to use man-made tanks with a global volume of 50000 m^3. The economic comparison is between this plant configuration and the reference case already analysed in 5.2.1. The main differences are the man-made thermal energy storage and in the compression train the more heat-exchangers required. Some heat-exchangers are used to transfer the heat to the tanks (or aquifer), but additional heat-exchangers are required for reducing as much as possible the air temperature at the next compressor inlet or at the cavern inlet. This introduces an higher initial investment, that from 186,2 mln$ of the reference case, increases to 229,7 mln$. The cost of man-made TES can vary on the basis of the dimensions and characteristics [74]; a mean value of 300 $/$m^3$ is assumed. Since the cavern remains the same formation of 400000 m^3 seen in the reference case with its 31,2 mln$, the total capital investment cost is 260,9 mln$; about 20% higher than the other one. No pipes costs to connect the TES to the main DH net are considered. All the parameters and electricity, fuel and O&M prices remain the same proposed in Table 5-2. From the analysis done, an amount up to 900 MWh thermal energy can be generated and sold. Heat energy prices found, report a price of 0,07 £/kWh_{th} [72] and 49 €/MWh_{th} [73] in 2009. In the case analysed it is assumed a lower value of 60 $/$MWh_{th}$. According to [72] 4,5 $/$kWh_{th}$ is also introduced to take into account the O&M costs of District Heating. Similarly to the O&M costs of the CAES, an escalation rate of 3% is assumed. Figure F-3 in Appendix F show the trend of costs and revenues of all the components during the plant life.

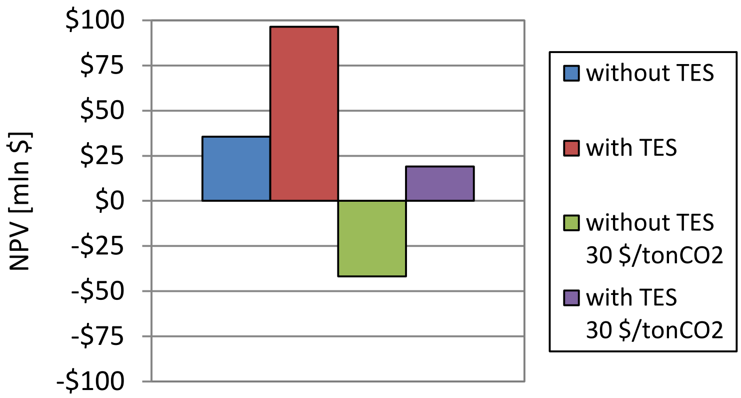

Figure 5-28 NPV comparison between the plant with TES and the other without.

Analysing the NPV for both plants, it can be seen that, although the higher initial capital costs, the profitability of the plant provided of a Thermal Energy Storage increases (Figure 5-28). Moreover, if a CO_2 tax of 30 $/ton CO_2 is applied, the NPV of the plant without TES becomes negative, while the profitability of the other remains positive. Therefore, this analysis highlights the benefit to store and sell the waste energy produced during the compression, if a man–made tank is built or an aquifer is available.

5.2.6 DPP and IRR results

Looking at the trends of PBP and DPP, the PBP of the reference plant is equal to 15 years that increases to 18 years if the DPP with DR of 8% is assumed. Information about the DPP for different DRs can be derived from Figure 5-27; the DPP is in the intersection of the NPV trend with the horizontal axis. As seen during the NPV analysis, the NPV is high sensitive to the market conditions in which it operates and this affects also the DPP. This means that if the fuel and off-peak electricity prices increase or the on-peak electricity revenues decrease or the plant reduces the number of cycles, there is an high probability to increase the time of Payback with also the risk that the DPP becomes higher than the plant life. This means that the plant is not economic feasible and must be avoided.

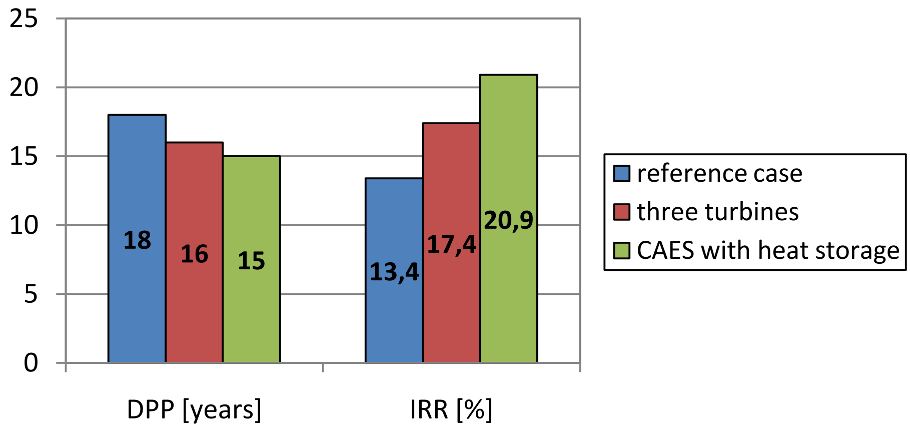

Figure 5-29 DPP and IRR for some CAES configurations analysed

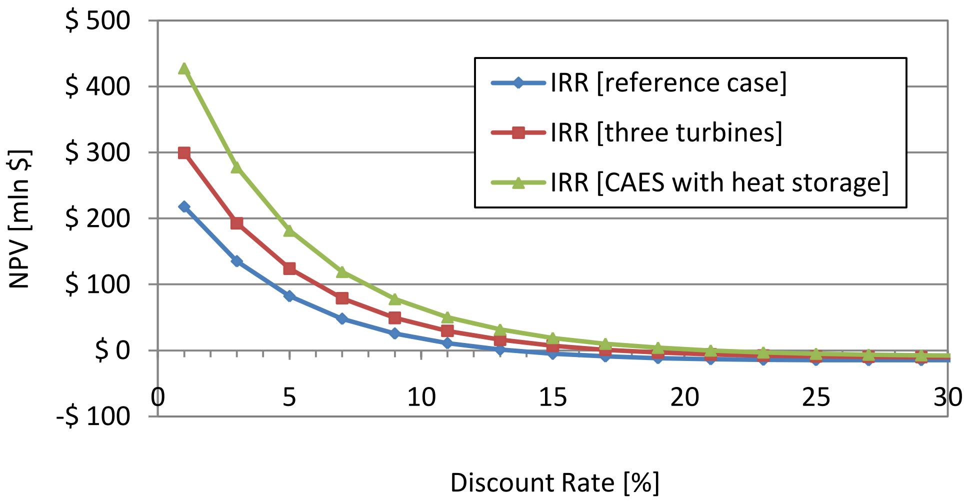

Figure 5-30 IRR of some CAES configurations analysed

As seen, the introduction of the third turbine and third combustor improves the plant profitability; if this configuration is adopted, the PBP drops to 14 years and the DPP 16 years. The possibility instead to store the heat produced selling it to a DH net, define a

PBP of 14 years and a DPP equals to 15 years. The Internal Rate of Return is another index sensitive not only to the plant configuration, but also to the market conditions. Figure 5-29 shows the benefits for the generation train modified with three turbines (more power is produced with the same mass flow withdrawn) and the plant provided with thermal energy storage for selling the heat produced. Both of them increase the revenues compared to the reference case, reducing the DPP and increasing the IRR (Figure 5-30).

5.3 Conclusions

The economic analysis has highlighted the high sensitivity of the conventional CAES to the market conditions. They affect significantly the profitability and they need to be accurately investigated before building the plant. Also the relationship among the initial capital costs, the geological area and the market scenario has to be evaluated. In fact, the particular market scenario and the proposed area with its characteristics of electric input energy that needs to be managed and output energy (both output power and discharge time) that needs to be supplied, define the machinery characteristics and the storage dimensions, hence the capital costs. If a cheap storage is not available in the region and it needs to be huge enough for supplying the energy required, higher investments are required, reducing significantly the profits. As the literature reports, the results confirm that hard-rock caverns should be the latter solutions to be used, since they decrease significantly the NPV. While aquifers and salt caverns should be the first to be investigated, if available. It is worthy to highlight that also salt caverns could represent a risk: before starting the construction it is important to make sure that there are the mediums to dispose the brine created, which quantities are function of the cavern dimensions, hence of the market characteristics. If for example, there is the need to supply a CAES in a region and it is possible to decide between a place closed to the sea and the other far away from it, in the end seems more profitable the idea to build it closed to the sea.

The parametric analysis realized for different market conditions, shows the high sensitivity of the NPV to the on-peak electricity and the fuel, fuel energy that maintains a significant percentage of the costs. Less significant than these two, but still important, the off-peak electricity. In order to reach high NPV from this plant, a significant difference between the off-peak electricity and the on-peak electricity prices are required. High CER are also recommended. Looking at the operative hours in a year, it is important to use the plant as much as possible, increasing the generation hours and the consequent revenues that permits to payback faster the initial investment. Therefore it is important to reduce to the least the periods of inactivity of the plant, reducing the maintenance periods and the unexpected stops of the machinery. O&M costs do not affect significantly the profitability, as electricity and fuel prices do, but it is evident that their reduction is advised. A significant element of the market that needs to be considered is the CO_2 tax, which impact is quite important. It can be seen that for the market conditions assumed in Table 5-2, the NPV becomes negative with tax variations (15 \$/tonCO_2) also lower than CO_2 tax already proposed in real market. It is worthy to highlight that in the analysis done, every parameter is investigated keeping constant all the others, but in a real market, the costs increment would have effects also on the revenues. Higher fuel prices mean higher off-peak and on-peak electricity prices; same considerations if a CO_2 tax is applied. Since nowadays each country is proposing its own tax value, the building of this plant in a region where the CO_2 tax is lower is obviously advised. When a market conditions analysis is performed, also the forecasts of the fuel and electricity prices in that area should be taken into account; rate variations can vary costs and revenues modifying significantly the NPV.

The analysis on the machinery costs has highlighted again the significant benefits in the TITs increments. Consequence of these are the smaller generation train, since less air mass flow needs to go through the turbines to produce the same amount of power. Smaller generation train reduces the initial capital costs of the machinery, but also reduces the air storage (that can represent an economic problem); therefore, the amount of air that needs to be stored is lower reducing charge time and input energy required. If instead the cavern dimensions remain the same, the TITs increments generate much more energy with significant increments in the revenues. In both cases, higher TITs increase the fuel consumption and the relative costs, but this is compensated by the higher amount of output energy sold and revenues achieved. Because of this, it has been seen that the configuration with low TITs analysed in Chapter 3 is not economically feasible, while the reference case analysed with its high TITs and CER represents a good viable solution. Plant with lower TITs and CER requires higher prices difference between input energy (off-peak electricity and fuel) price and output energy (on-peak electricity) price in order to compensate the low output energy generated and to pay back the initial investment. Due to the equations implemented for calculating the components costs, the intercoolers and compressors number increment reduces the compressor train costs. Consequently, the NPV increases both because of the less TIC and the less input energy required in each charge cycle.

The economic investigation on the bulky recuperator shows that it is required even if it may slow down the dynamic of the generation. In fact, even if the train without it reduces considerably the initial TIC, the higher fuel consumption in order to reach the HP TIT increases significantly the costs. Costs that are not compensated by the slight revenue increments (the train without recuperator has higher output power, hence increases slightly the revenues compared to the recuperated train). In order that NPV becomes positive, but still worse than the plant supplied with recuperator, low fuel price is required. However, if a small CO_2 tax is included, the NPV becomes again negative. Therefore, the recuperator is required, since reducing the fuel consumption, it reduces the CO_2 emissions and the consequent tax.

Although the TIC increments, the introduction of the third combustor and the third turbine with consequent TITs and output energy increments introduces significant NPV improvements, that makes this plant economically better than the reference case with two turbines. Considering again the generation train with three turbines, the introduction of a second recuperator between the HP turbine and the MP combustor when HP TIT is low, highlights that it is not economic viable since it increases the TIC and reduces the revenues; these drawbacks are also not compensated by the slight fuel consumption reduction.

The more flexibility in the compression train introducing an independent electric motor or a series of motors instead of using the generator, decreases the NPV of an amount that is equal to the more TIC spent to install these devices, which costs depend on the input power required. As seen, high power electric machine can affect significantly the components cost, therefore the motor installation should be considered accurately in each case. The concept that avoids the HP combustor using a recuperator is also investigated; the results show that, on the basis of the particular market, it can be a feasible solution. The conditions which can give better results than the conventional are high costs of the fuel and CO_2 tax; however, this analysis does not considered the dynamic of the generation train. In fact, in order to have a sufficient HP TIT the recuperator effectiveness has to be high, extracting as much energy as possible from the exhaust gas. The downside is the surface of exchange increment, hence it is required bigger recuperator volume. Using this configuration for high power, it can introduce the need of high mass flow value that, as seen, increases significantly the TIC and consequently decreases the profitability. The solution with HP combustor looks still better, both technically and economically.

In general, it can be seen that capital costs variations, both for machinery and storage, affect the final NPV that increases or reduces, compared to a reference case, of the same amount spent more or less in the initial investment.

Since the profitability of the plant is sensitive to the market conditions, consequently the PBP, the DPP and the IRR are affected. Payback periods increase and IRR decreases if the costs increase or the machine reduces the operative hours; vice versa if the costs reduce.

During the research it has been evaluated the concept of using an aquifer or a man-made tank for storing the heat produced during the compression as hot water, highlighting the benefits in the profits. Even if a significant increment in the TIC and other O&M costs increments are registered, the sale of the hot water in a DH grid can be very interesting with the possibility to make this plant also more profitable than the plant with a generation train with three turbines. However, this application has several limitations: air storage and aquifer for thermal storage (otherwise a man-made tank is required) of the right dimensions and characteristics closed each other need to be find (this may be difficult to find in the place where the CAES is required) and their location needs to match good market conditions with enough heat demand. If the heat demand is low, hence the heat price low, this plant may be not attractive anymore. About the aquifer thermal storage, it needs to be big enough to cover the heat market. The heat demand may happen after weeks, hence reducing the revenues since less heat is sold to the grid, affecting the revenues. However, even if the realization has some constrictions, this

model is presented for highlighting the opportunity that a plant with these features could introduce.
It is worthy to highlight that instead of using the thermal storage of hot water for DH, there is the possibility to create a Cascade Air Storage with Humidification (CASH) [37]. The hot water stored during the compression can be used to humidify the air coming from the storage during the generation, reducing the total airflow through the expander train. Other benefits are the intercooled compressor train and the air storage volume reduction (overcoming storage problems where geological formations have a limited capacity and are expensive). It is obvious that this reduces the costs of the existing components, but on the other hand it adds other new components. In this plant, the compressor train is optimized both for reducing the power consumption and for producing hot water. An advantage of this technology is the reduction of the NO_x emissions.
In the end, it is worthy to pay attention that in this economic analysis it is assumed that the generation train operates with a constant valve pressure fixed at the minimum operating pressure of the cavern. This generates lower CER. If the turbines were able to operate in the entire air storage operative pressure range with high efficiency, the CER and the consequent revenues could be higher.

CHAPTER 6: Economic Analysis of Adiabatic-CAES

6.1 Economic analysis introduction

The same methodology proposed for conventional CAES in the previous chapter (5.1 Methods and Models) is used here for the economic analysis of Adiabatic-CAES. Here fuel and CO_2 tax are not considered any longer, therefore eq. 40 for the annual operation profit changes as following:

$$annual\ operation\ profit = \tag{56}$$
$$= sold\ electricity\ revenue - input\ electricity\ costs - \ O\&M\ costs$$

From eq. 48 instead, the annual tax now takes into account only the tax on the profit:

$$annual\ tax = tax\ rate * taxable\ income \tag{57}$$

Because of the introduction of the TES, where no specific costs are available in the literature and in order to compare the Adiabatic CAES with the conventional, some assumptions have been done and they are here explained.

6.1.1 TES costs

In this economic analysis are investigated A-CAES plants with Thermal Energy Storages that have as mediums concrete, rocks and pebbles. For pebbles and rock, no values are available in literature; while for TES operating with concrete the data are only for low temperature. No specific costs of TES with concrete that operates at high temperature (about 923 K) have been found. Values available, for TES that operates up to 663 K, report specific costs that vary in the range less than 20 €/kWh_{th} (2006) up to 40 $/$kWh_{th}$ (1994) [69, 70]. Commercial value proposed in 1999 for a TES using concrete reports a specific cost of 26 $/$kWh_{th}$ [70]. In the analysis it is investigated a range of costs.
The proposed life time for TES with concrete operating at high temperature in A-CAES (value also required to define the plant life), averages between 25 years [71] up to over 30 years in daily cycles [14]. Same values are proposed for TES operating at lower temperature [69]. A value of 30 years is chosen.

6.1.2 Storage costs

Since no values of storage costs function of the volume [$/$m^3$] have been found in the literature, in order to calculate the capital cost of a A-CAES plant and comparing it with the conventional CAES, the following approach, with some assumptions, is defined. Using the costs range proposed in 5.1.4.2 in terms of $/kWh and using the results proposed in 5.2.2 for the conventional CAES with a cavern of 400000 m^3 (31,2 mln$ for 2840 MWh_{el}), costs ranges in $/$m^3$ are calculated for aquifers, salt and hard-rock formations (Table 6-1). With these values is easy to analyse different storages volumes for A-CAES applications. The reasons why this approach is applied are mainly two. Using the values in $/kWh proposed in 5.1.4.2, the storage costs would be lower than conventional CAES. Instead, due to the low TITs and the consequent higher air mass flow withdrawn in order to reach the required output power, the storage for A-CAES needs to be bigger than conventional plant. The second reason is the need to compare the plant with the previous conventional CAES; and even if the aboveground machinery has different costs, a cavern with same dimension has to have same costs.

Table 6-1 Specific costs for storages used in A-CAES

	minimum value		maximum value	
specific cost	$/kWh	$/m^3	$/kWh	$/m^3
aquifer	2,5	17,7	8,5	60,4
salt formation	6,5	46,2	12	85,2
hard rock cavern	20	142,0	40	284,0

6.2 Economic analysis

6.2.1 Machinery

The aboveground machinery investigated is that one already proposed in 4.1.3, where it is assumed that the generator operates also as electric motor in order to reduce the capital costs. Different sizes of the generation train (500 kg/s and 350 kg/s) and different TES characteristics are analysed. A TES operating with concrete, another one with rock(granite) and the last one with pebbles(1) are presented (Table 4-2). The TES dimensions are chosen in those points where the CER is maximum (Figure 4-24); therefore, 10000 m^3 for concrete, 12000 m^3 for rock and 17000 m^3 for pebbles. Pebbles(4) and rock(granite) are characterized by the same performance indices for the same TES volume, therefore similar conclusions can be derived from the economic analysis.

In order to estimate the cost of the TES, the total thermal energy stored inside after the compression is required: as visible in the technical analysis, the TES is divided into a certain numbers of layers (4.1.2 and 4.1.3) and for each of them the amount of thermal energy stored inside is calculated (eq. 58), using as reference value the ambient temperature (assumed at ISA conditions). In fact, if the TES was not charged, the temperature inside would be the ambient temperature. After having calculated the thermal energy stored in each layer, the addition of all the terms generate the total amount stored inside the TES (eq. 59). In eq. 58 the term ε is considered, since only the solid medium absorbs energy, the rest is void.

$$E_{th_i} = \rho_{medium} * V_i * c_{p\,medium} * \varepsilon * (T_{i-layer} - T_{ref}) \qquad (58)$$

$$E_{th} = \sum_{i=1}^{layers\ number} E_{th_i} \qquad (59)$$

For the TES using concrete, the thermal energy stored is about 1270 MWh_{th}, that would reach the value of 1540 MWh_{th} (about 21% more) if all the medium was at 923 K. In order to consider possible variations in the final thermal energy stored, due to different operative conditions, the TES capacity is oversized of 10%. Because of the uncertainty of the TES costs, an analysis of a range between 15 $/$kWh_{th}$ (optimistic case that takes into account future improvements in the TES development and materials) and a pessimistic 45 $/$kWh_{th}$, with a reference value of 30 $/$kWh_{th}$, is performed. Assuming a value of 1400 MWh_{th}, the costs are respectively 21 mln$, 42 mln$ and 63 mln$. Figure 6-1 shows the capital costs for a machinery operating with 500 kg/s (assumed as reference in the graph) and when a 15% variation of it takes place. In Appendix G, Table G-2 reports the components costs and TIC values. It can be seen in Figure 6-2 that assuming the reference specific cost for the TES equals to 30 $/$kWh_{th}$, the TES cost represents almost half of the total machinery; it becomes much lower if a 15 $/$kWh_{th}$ is assumed or higher in the pessimistic case.

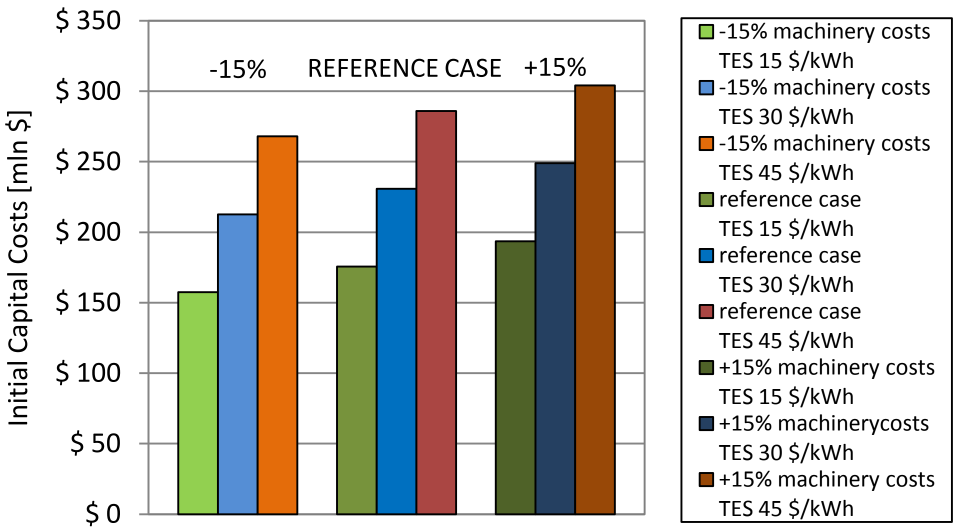

Figure 6-1 Impact of different TES specific costs and machinery costs on the TIC

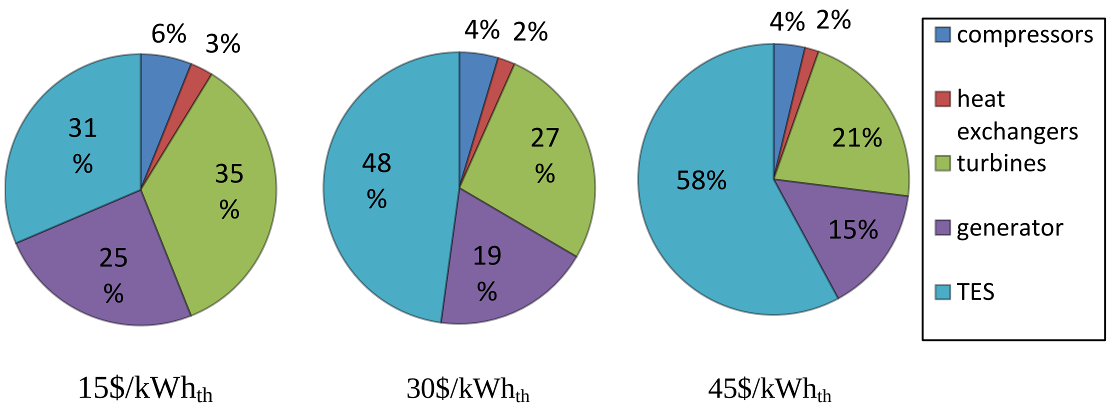

Figure 6-2 Percentage costs of the TES on the aboveground machinery

6.2.2 Storage

In order to understand the effects of the 650000 m^3 storage on the initial capital cost, the ranges of costs proposed in 6.1.2 have been analysed (Figure 6-3). It can be seen again, that even if the machinery costs changes of about 15%, it maintains a significant percentage of TIC, except if an hard rock cavern is used. In this case, the expensive caverns would assume the main component of the initial investment cost.
Since the maximum cavern pressure used in the A-CAES (8 MPa) is lower than the value assumed for the conventional CAES (8,5 MPa), it is assumed an initial price of 10 $/kWh (that defines a cost of 71 $/m^3$, based on the approach seen in 6.1.2). The 650000 m^3 storage reaches a cost of about 46,1 mln$, that represents the 17% of the total capital cost (277 mln$). This percentage is obviously higher than the conventional CAES seen in 5.2.2 where the cavern assumed about 14% of the TIC. This is due to the low TITs and higher mass flow withdrawn in adiabatic plants; thereby, it depends on the bigger storage required.
With a capital cost of about 277 mln$, the specific cost for the A-CAES becomes about 923 $/kW; value that is in the range proposed in literature [14].

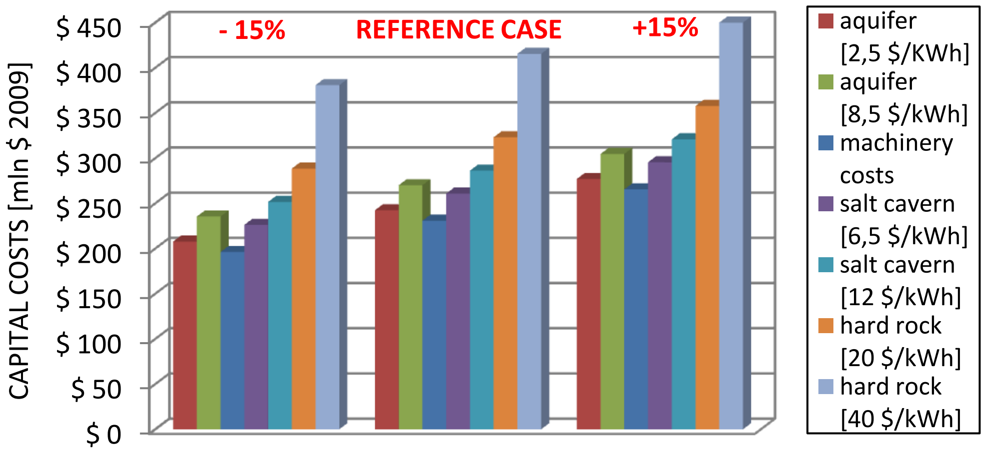

Figure 6-3 Cavern costs on the TIC of the A-CAES

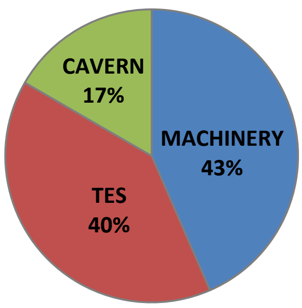

Figure 6-4 Percentage costs of the main components of the A-CAES

6.2.3 NPV results

6.2.3.1 Market conditions

The high initial capital costs and the low Charging Electricity Ratio and efficiency (averages between 68% and 70%) affect significantly the profitability of these plants, that become feasible only for particular market conditions, storage and TES costs. If the A-CAES plant operates with a charge time of about 16 hours (2150 MWh_{el}) and discharge time of about 5 hours realising up to 1500 MWh_{el} in a market characterized by the prices of Table 5-2, the NPV after 30 years will be negative (-177,6 mln$). The investment must not be undertaken. Comparing this plant with the previous conventional CAES and its 2840 MWh_{el} released to the grid in each cycle, it can be seen that almost two adiabatic plants are required in order to supply the same amount of output energy. If instead a conventional CAES plant is created in order to match the characteristics of the A-CAES, this plant requires a compressor train composed of 3 compressors operating at DP mass flow equals to 125 kg/s, a cavern of 210000 m^3 and a generation train at 300 kg/s. The TITs are assumed equal to 1144 K and 1473 K. This is able to release about 1500 MWh_{el} in less than 5 hours, spending about 762 MWh_{el} in compression (65 MW are required for less than 12 hours). The capital cost is about 155 mln$ and in the same market conditions seen in Table 5-2, the NPV is equal to -21,8 mln$ (Figure 6-5). It is still negative (red bar), but better than the adiabatic. It is worth mentioning the very small cavern required that is one third of that required for the adiabatic, with all the technical and economic consequences that may derive.

The adiabatic concept derives from the continuous increment of fuel prices, the forecasts of CO_2 tax and the concept of "green technology". Assuming constant all the other parameters and changing fuel price and CO_2 tax, the NPV becomes closed to the conventional one when both a price of 10 $/mlnBTU and a CO_2 tax of 60 $/ton CO_2 are applied. If a scenario where the fuel and CO_2 prices increments increase the off-peak and on-peak electricity prices respectively to 65 $/MWh and 135 $/MWh, the conventional remains better even if still with negative NPV (Figure 6-5).

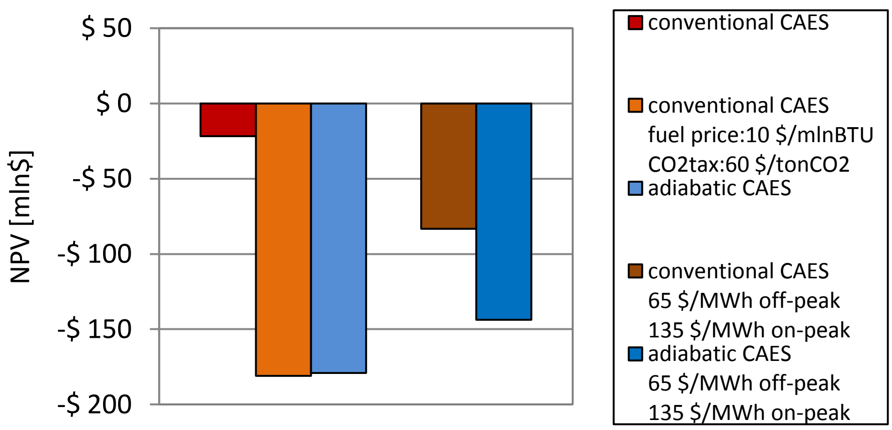

Figure 6-5 Conventional and Adiabatic CAES comparison

Since big mass flow withdrawn influences the generation train costs (Figure 6-2) a reduction of the mass flow from 500 kg/s to 350 kg/s is realized. This reduces the output power to about 225 MW that is provided for less than 7 hours to the grid. The capital cost reduction from 277 mln$ to 248,1 mln$ creates benefits in the NPV that becomes -148,7 mln$ or equals to -113 mln$, if it is assumed the scenario with 65 $/MWh for off-peak electricity and 135 $/MWh for on-peak electricity. The NPV is still negative compared to a conventional CAES able to deliver the same power and energy. A market that would create a positive NPV is one where the off-peak price is 30 $/MWh and 115 $/MWh the on-peak price. Therefore a market with high on-peak electricity price and low off-peak electricity price. From now on, a plant with generation train at 350 kg/s and the conditions of Table 6-2 are assumed in the investigations.

Table 6-2 Reference values for economic analysis of A-CAES

Parameter	value	unit	escalation rate
Discount Rate	8	%	-
off-peak electricity price	30	$/MWh	3%
on-peak electricity price	115	$/MWh	3%
tax	35	%	-
Fixed O&M costs	8	$/kW	3%
Variable O&M costs	0,004	$/kWh	3%
loan repayment	12	years	-
loan interest	8	%	-
plant life	30	years	

In A-CAES the off-peak electricity is the only source of energy, no combustion is used and the CER is low (also the revenues will be low), therefore the plant is characterized by an high sensitivity to the off-peak electricity price variations (Figure 6-6). High sensitivity that is also to the on-peak electricity, that needs to be the highest possible.

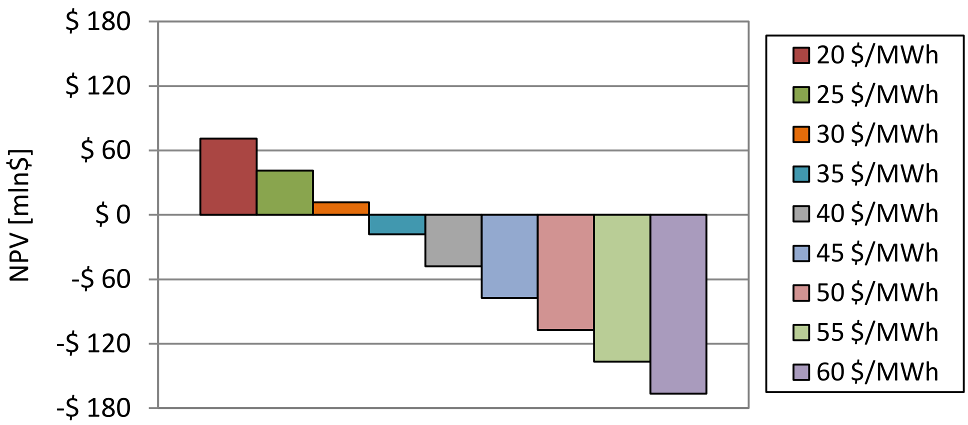

Figure 6-6 off-peak electricity prices effects on the NPV

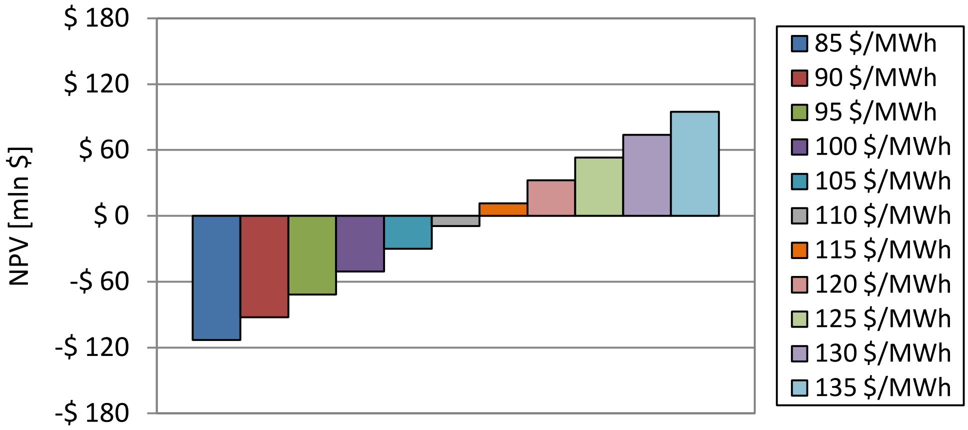

Figure 6-7 On-peak electricity prices effects on the NPV

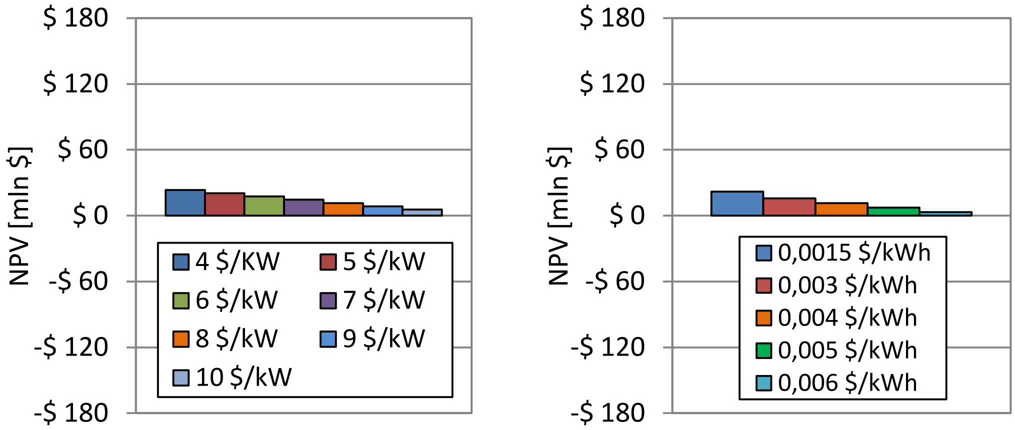

Figure 6-8 O&M costs effects on the NPV

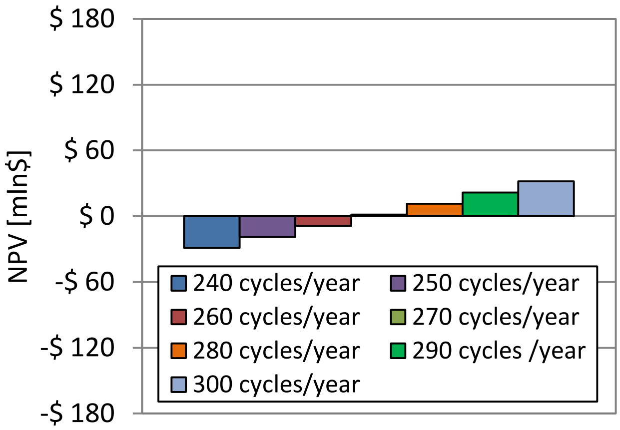

Figure 6-9 Effects on the NPV of number of cycles in one year

The need to have significant prices difference between off-peak electricity and on-peak electricity has been already highlighted in the conventional CAES, but since for adiabatic the CER is lower and the TIC higher, the difference needs to be bigger. If this does not happen, the consequences are significant profits losses (Figure 6-7) and the investment has to be avoided. No values of O&M costs for A-CAES have been found in literature, hence a costs range is investigated. As seen in 5.2.4 for conventional plants, the O&M costs do not affect significantly the profitability as electricity prices do, but it is obvious that their reductions is advised for increasing the NPV (Figure 6-8). Because of the lower output energy produced and sold to the grid with an adiabatic plant compared to the conventional one, the need to operate as much as possible reducing the periods of stop is advised in order to get a positive NPV (Figure 6-9).

6.2.3.2 Machinery

The specific cost of the TES with concrete is still subject to uncertainty, also because of technical challenges to overcome [19, 75]. Figure 6-10 shows the impact of this cost on the NPV, where it can be seen the benefits of the cost reduction. The NPV difference is represented by the Total Investment Cost variations due to the TES costs, and since these variation can be significant, the NPV differences are also important.

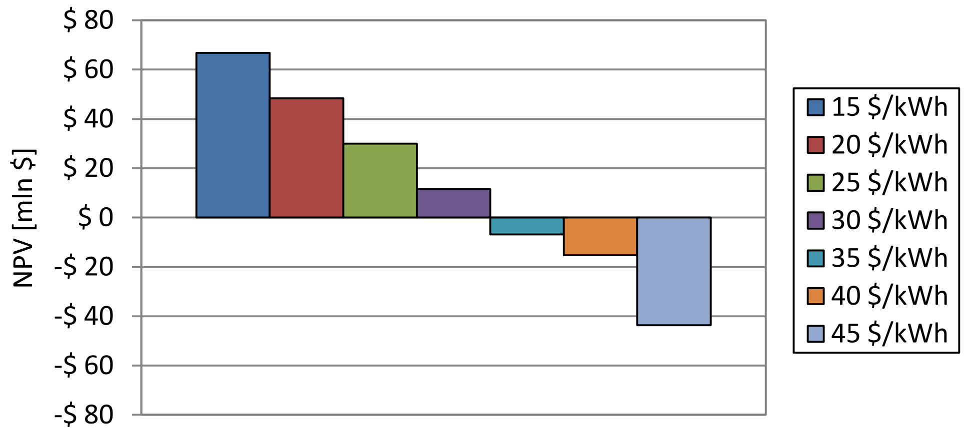

Figure 6-10 TES price effects on the NPV

In the technical analysis the possibility to use rock and pebbles instead of concrete has been investigated. The reasons are the challenges that the TES at high temperature still needs to face [19, 75]. No enough experience has been collected in TES with direct heat-exchange at so high temperature; if the medium (concrete) inside the TES degraded and needed to be changed, this process probably would require more effort than pebbles and rock which simply would need to be withdrawn from the container and substituted with other cheap pebbles. The TES with concrete also requires a system of pipes for the heat-exchange and the labour to make it (Figure G-1). If during the 30 years of operation the material changed the properties and it was not good enough any longer, unexpected O&M costs could take place, with the stop of machinery and significant revenues decrements. The pebbles and rock could potentially overcome some of these problems, but as calculated in the technical analysis, their properties produce bigger volumes. In order to compare the concrete with the others mediums, bearing in mind the effect of volume, medium cost and labour, the following approach is used. From the reference 10000 m^3 TES cost of 42 mln$ (30 $/kWh$_{th}$), it is calculated the specific cost per unit volume (4200 $/$m^3$). If this specific cost was the same for rock and pebbles the costs would be respectively 50,4 mln$ (12000 m^3, rock) and 71,4 mln$ (17000 m^3, pebbles (2)). Instead, if a certain discount percentage, due to the different mediums, was applied, the costs would assume the values presented in Table 6-3. Applying these capital costs inside the economic models, the impact on the NPV would be that one represented in Figure 6-11 and Figure 6-12. It can be seen that for rock and pebbles(4) (Table 4-2), the NPV becomes better if the TES with rock has a specific cost 20% lower than concrete (Figure 6-11), while the pebbles(2) requires a specific cost 45% lower (Figure 6-12).

Table 6-3 Possible TES costs for different volumes and mediums

	TES costs	
discount	12000 m^3	17000 m^3
%	mln $	mln $
0	50,4	71,4
5	47,9	67,8
10	45,4	64,3
15	42,8	60,7
20	40,3	57,1
25	37,8	53,5
30	35,3	50,0
35	32,8	46,4
40	30,2	42,8
45	27,7	39,3

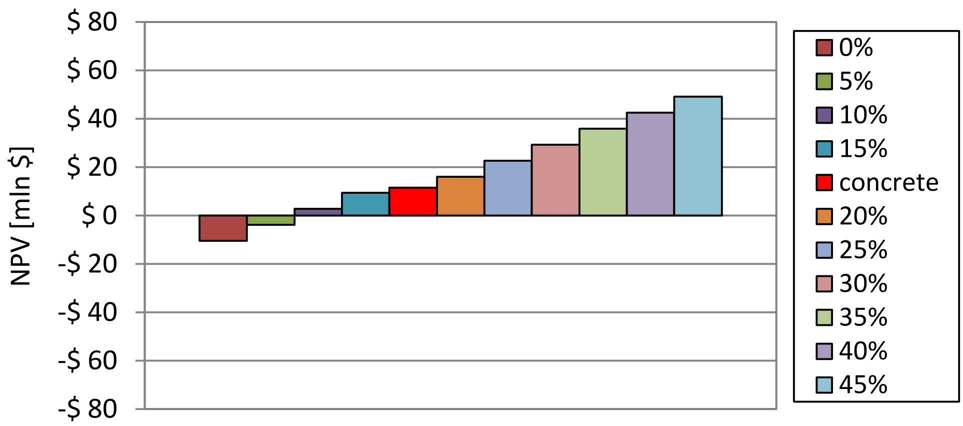

Figure 6-11 NPV analysis for TES with rock (gravel) and pebbles(4) (Table 4-2)

However, according to [14] and [19], since the TES is under pressure, the container may be the most expensive part of the TES. Hence the possibility to build bigger volumes with cheaper mediums needs to be evaluated accurately. From these results, if pebbles substituted the concrete, their specific heat and density should be high in order to reduce as much as possible the volume dimensions and the costs (medium as pebbles(2) with low density and specific heat should be avoided).

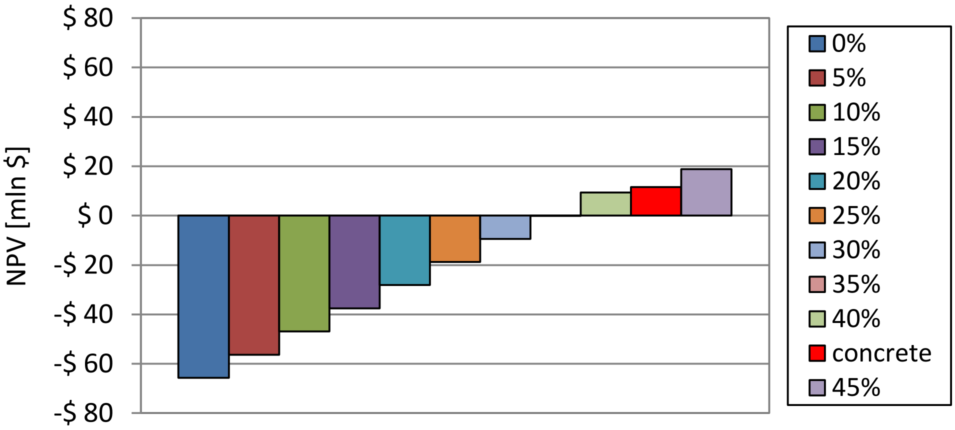

Figure 6-12 NPV analysis for TES with pebbles(2) (Table 4-2)

Similar to conventional CAES, the variations in the aboveground machinery costs influence the NPV of an amount equals to the initial investment saved. Figure 6-13 shows the NPV when variations of 15% in the only machinery costs (TES is excluded) respect to the reference case are considered.

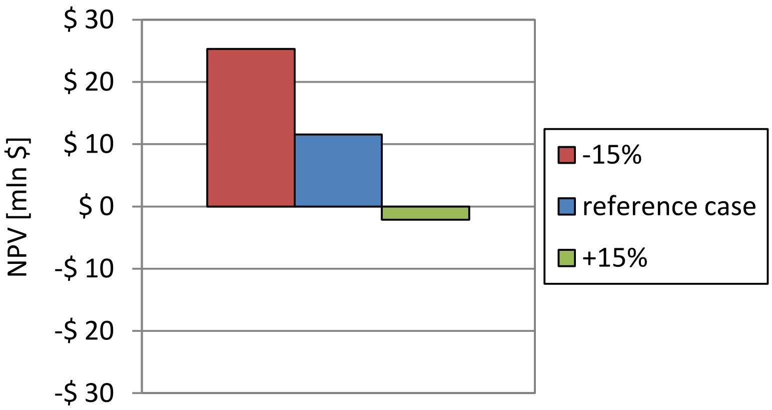

Figure 6-13 Machinery and TES effects on the NPV

6.2.3.3 Storage

Differently than the conventional CAES, air storage variations, introduces significant changes in the NPV, since it affects not only the cost of the storage, but also the TES volume that can represent a significant percentage of the TIC (Figure 6-2). Table 6-4 reports data about the air storage volumes analysed and the relative TES volume. Their values are chosen in order to maximize the CER. Figure 6-14 presents the NPVs for the different volumes, where the same amount of charge and discharge times in a year is considered. Therefore, for smaller air storage the number of cycles increases. This introduces also higher number of cycles inside the TES, where potentially the medium can degrade faster. This aspect should be taken into account investigating with a technical and economic analyses the risks. The volume reduction increases the NPV of the amount of TIC saved in the beginning, due to the smaller TES (material, space and labour) and the smaller air storage volume.

Table 6-4 Storage dimensions effects on electric energy and TES volume

storage volume	electric input energy	electric output energy	TES volume
m^3	MWh	MWh	m^3
400000	1325	925	6000
500000	1650	1150	7500
650000	2150	1500	10000

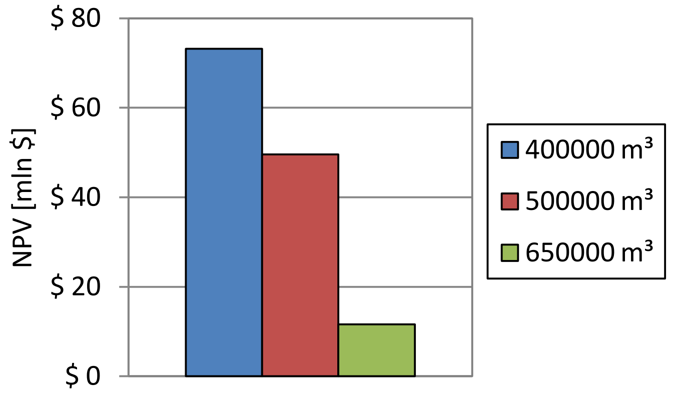

Figure 6-14 Storage volume effects on the NPV of A-CAES

In the reference case it has been assumed an air storage specific cost of 71 $\$/m^3$; Figure 6-15 shows the results of changing these costs. It is obvious that the costs reduction introduces benefits in the NPV, and for A-CAES that requires bigger air storage volume, the specific costs reduction is strongly advised. These results show again hard rock caverns with their 142 $\$/m^3$ and 284 $\$/m^3$ are not the first solutions, and because of the bigger volume required in A-CAES, they should be avoided.

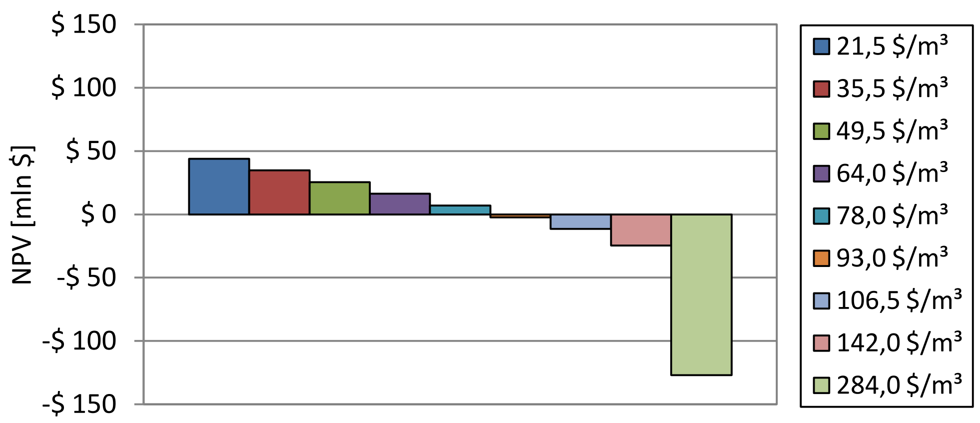

Figure 6-15 Cavern costs effects on the NPV

6.2.4 DPP and IRR

The PBP for the plant analyzed is about 18 years, that becomes 28 years if a DPP with 8% DR is taken into account. As seen for conventional CAES, the NPV remains particular sensitive to the DR (Figure 6-16).

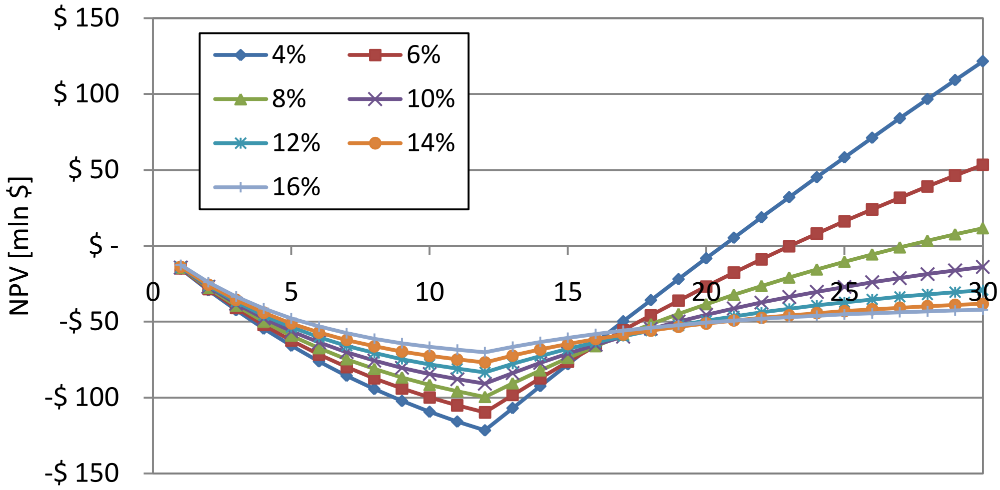

Figure 6-16 NPV versus different DRs

Figure 6-17 shows the IRRs of the three plants considered in 6.2.3.3 with different storage volume. The storage reduction with the consequent TES reduction, reduces the initial investment cost with benefits in the IRR. It is assumed that the TES is able to resist to the higher number of charge and discharge cycles in the plants with smaller storages. The smaller storage has also the benefits to reduce the payback periods, that for the 400000 m^3 storage decrease to 15 years (PBP) and 17 years (DPP), while for 500000 m^3 is 16 (PBP) and 21 (DPP).

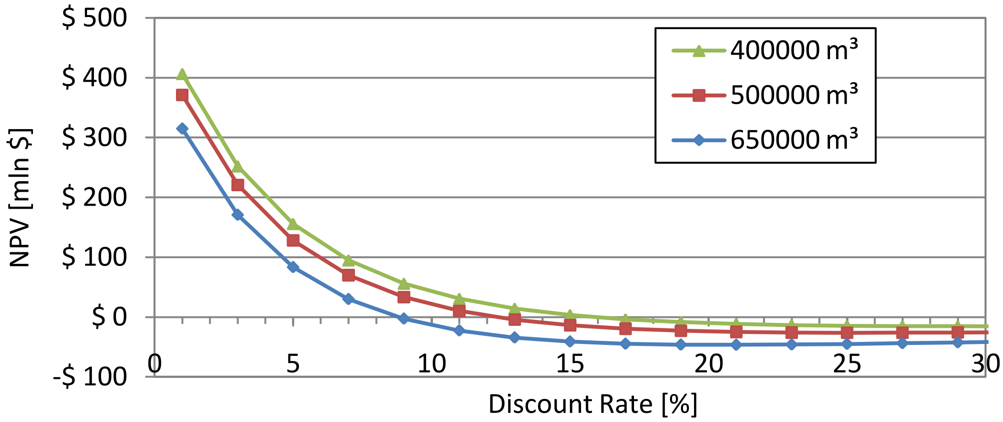

Figure 6-17 IRR of the A-CAES

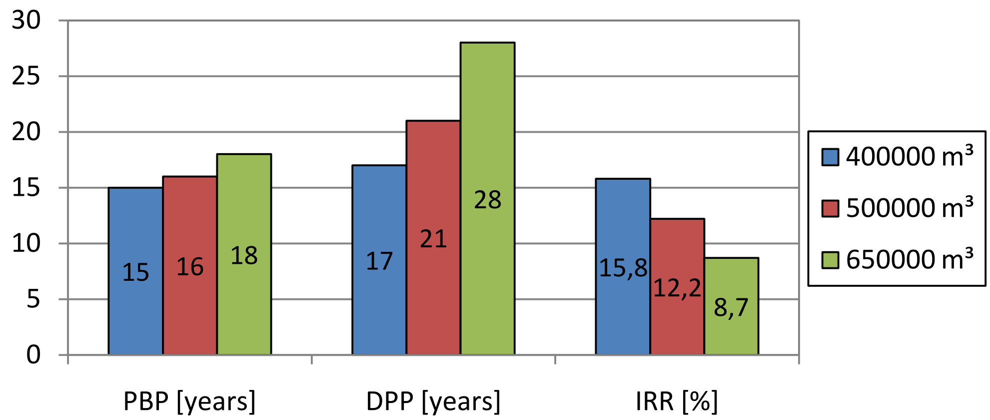

Figure 6-18 PBP, DPP and IRR for three different plant configurations

6.3 Conclusions

The economic analysis of A-CAES still highlights the strong relationship among the market scenario, the geological area and the initial capital costs. Relationship that is more significant than for the conventional plant since the air storage volume is much bigger, the CER is smaller and an expensive Thermal Energy Storage is introduced. The availability of a cheap air storage is required since it needs to be huge enough for supplying the electric output energy necessary and because of the absence of combustion the air mass withdrawn is big. Unfortunately, as seen for conventional plant, bigger mass flow can affect significantly the capital costs since more expensive machinery are required. Figure 6-4 shows that the air storage acquires an higher percentage of the total investment cost compared to the conventional plant, since bigger volume is required. If a cheap storage is not available in the location, the investment becomes affected by this drawback, with the risk that it has to be avoided. However high capital costs are not the only problem, also the availability of the right big cavern in the desired place needs to be taken into account. If the energy storage is required in that particular location, the solution could be to invest in a conventional CAES, but a suitable economic analysis of the market still needs to be performed.

The economic investigation has also highlighted the significant cost percentage occupied by the TES that, on the basis of its specific cost, can be more than 50% of all the aboveground machinery cost. Analysing the few specific costs available in literature, the trend looks decreasing, forecasting a more feasibility for A-CAES plants in the future. However, these values refer to TES with concrete at low temperatures, no information for high temperature are available. It is worthy to highlight that TES might represent not only an high initial capital cost, but also later with other unexpected costs due to the stops of the machinery for maintenance. In fact no enough experience has been acquired in this new concept that still presents technical challenges. The direct heat exchange at high temperatures and pressures and the daily cycles of charge and discharge with consequence degradation of the medium still create problems under analysis.

The parametric analysis highlights the stronger relationship of the off-peak electricity to the NPV that now represents the only input energy source of the plant. Consequently the NPV is also sensitive to the on-peak electricity. Due to the low CER and the high capital costs, bigger difference between the off-peak electricity and on-peak electricity prices are required in order to get profits. Similar to conventional CAES, this plant has low sensitivity to O&M costs compared to the electricity prices, but since the final revenues are lower, the reduction of these costs is advised. The low CER makes this plant more sensitive than conventional CAES to the charge and discharge cycles. Since higher revenues come from the energy sold, paying back faster the investment, the number of generation cycles needs to increase. This is the reason why the stops of the machinery needs to be reduced at the minimum and also the risk that the daily cycles can degrade the medium inside TES needs to be taken into account and avoided. Revenues losses do not only come from the TES maintenance costs, but also from the on-peak electricity not sold. Another issue to consider is that, while the conventional CAES is composed only of compressor and generation trains and air storage, the A-CAES comprises also the TES that introduces more possibility of unexpected stop of the machine due to maintenance.

As underlined several times, TES is still a new concept and no experience have been matured in order to say that the medium will keep the same characteristics for the plant life and no unexpected stops of the plant will happen. TES maintenance may also affect both the compression and the generation. This represents another element that put the conventional CAES in a better position than the adiabatic.

For solving the problem of medium degradation, pebbles and rock have been investigated and at the end of the economic analysis it has been observed that, in order to have more feasible the storage with rock (granite) it is required a specific cost 20% less for rock than concrete. Since the material characteristics affect the volume of the TES and the final capital cost, it is advised that are used only pebbles with high density and high specific heat. Pebbles with low density increase the volume and the specific cost should be at least 45% less than that with concrete to make this configuration more profitable.

Due to the relationship between air storage volume and Thermal Energy Storage volume, if the air storage volume reduces, significant benefits in the profits of the plant take place. It is assumed that same number of charge and discharge hours in a year, increasing the numbers of cycles. However, this assumption have the drawbacks that introduces more cycles inside the TES, that needs to be strong enough to support the mechanical stress, and also the medium inside could change its properties faster. Also for these reasons rock and pebbles might be taken into account; even if there is the possibility that the initial costs of a TES with rock or pebbles are higher, the benefits might be seen later with an easier maintenance. The plant may return online, yielding revenues, after less time.

The analysis of the payback periods is still correlated with all the economic considerations done till now, since market conditions and initial capital costs affect the profits. Due to the lower CER and bigger capital costs than a conventional CAES, the payback periods increase. For the case considered, the PBP is equal to 18 years, while a Discounted Payback Period of 28 years is found for DR equals to 8%. The DPP and IRR analysis for plants having different air storage volumes, underlines the benefits of having smaller air storage, even if the TES needs to support more charge and discharge cycles. The possibility that the TES was not able to resist to the mechanical and thermal stress and unexpected maintenance and losses take place, would make these trends no more real and the small cavern could also become the worst solution.
A first comparison between conventional CAES and A-CAES has also been carried out. In order to generate similar output energy of the conventional CAES plant proposed (436,5 MW for about 6,5 hours), two A-CAES plants with generation train at 350 kg/s are required. Due to the high capital costs and low CER, the NPV of these two adiabatic plants in the market conditions of Table 5-2 is strongly negative, therefore they have to be avoided. A conventional CAES has been created in order to match the characteristics of only one adiabatic plant, requiring smaller compression and generation trains, thus a smaller cavern (making it feasible in more locations with less problems). The adiabatic plant, still remains less attractive than the conventional. The condition which makes this plant better than the conventional one are significant fuel prices and CO_2 tax increments. Assuming an unrealistic case where the fuel price and CO_2 tax increments do not increase the electricity prices, the conditions that make the adiabatic more attractive are 10 \$/mlnBTU and 60 \$/tonCO_2. If an electricity prices increment is considered, the conventional becomes again more profitable of the adiabatic plant. Therefore, the results show that the conventional is more profitable and also more feasible, since less dependent to the geographical and geological positions. Adiabatic that is viable when a cheap underground formation and an aboveground machinery coupled with low off-peak prices and high on-peak prices are available.

CHAPTER 7: Peaking Power Plants Comparison

In this last chapter it is realised an economic comparison among the different solutions to provide peak power electricity. A brief introduction on simple cycle gas turbine power plant and Pumped Hydro Energy Storage is done.

7.1 Gas turbine Power Plants

In order to supply peak electricity, a simple cycle gas turbine composed of compressor, combustor and turbine can be used. As mentioned, the compressor connected on the same shaft of the turbine consumes a significant part of power and this is one of the reasons why there is also interest in CAES. Different gas turbine configurations are nowadays available in the market, with new improvements and new technologies that increase the efficiency reducing the significant amount of fuel required [79]. However, in this investigation it is analysed a conventional simple cycle gas turbine (Figure 7-1) implementing the assumptions proposed in Table 7-1. In order to compare the gas turbine power plants with CAES plants, it is assumed a gas turbine with compressor Pressure Ratio equals to 21,5:1 and a TIT of 1523 K. A mass flow of 540 kg/s is required to generate a net power of about 218 MW, while about 54% of the turbine power (477 MW) is wasted to drag the compressor (256 MW). Two power plants with this mass flow are required to generate the 436,5 MW proposed with the CAES. The possibility to have three plants instead would require a mass flow of about 360 kg/s each (about 145 MW). The choice to have more plants could have the benefit of more uniform electricity distribution along the grid instead of having only one big plant with the risk of overloading the grid. For calculating the Total Investment Cost, it is implemented the same methodology [63] explained in Chapter 5; a value of about 76 mln$ with a specific cost of about 350 $/kW [29] is found for the components cost. Reducing the compressor and turbine efficiencies the cost reduces, but an higher air mass flow is required. The efficiency of the plant depends on the particular scenario, if a plant runs only for a short period, it does not make economic sense to make it efficient. However, the drawback of the efficiency reduction is the Heat Rate increment. The thermodynamic efficiency of new simple cycle gas turbine power plants ranges from 30% to 42%. The plant created presents an efficiency of about 39,6% and HR of about 9070 kJ/kWh. The economic model for calculating the development power plant cost is the same proposed in 5.1.4, but a 10% of contingency is assumed [63], due to the less technical complications compared to CAES. The capital cost results equal to 193 mln$, with a specific cost of about 890 $/kW [82]. It decreases to 863 $/kW if a compressor efficiency equals to 0,88 and turbine efficiency equals to 0,89 are assumed (with the downside that HR increases to 9360 kJ/kWh). Whatever the plant design, the costs remain significant compared to a CAES, also because the costs proposed are only for one of the two plants required.

O&M costs for gas turbine are reported in the range of 0,003 $/kWh to 0,015 $/kWh [29, 83, 84]; a value of 0,008 $/kWh is assumed. Similar to the Compressed Air Energy Storage plants analyzed, a plant life equals to 30 years [85] and an escalation rate of 3% are assumed in the economic analysis.

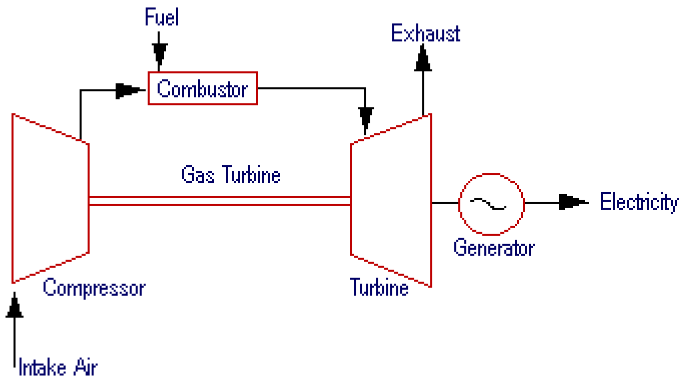

Figure 7-1 Simple cycle gas turbine design

Table 7-1 Simple cycle gas turbine parameters

Parameters	value	Unit
ambient pressure	101325	Pa
ambient temperature	288,15	K
filter pressure losses	1	%
compressor Pressure Ratio	21,5	
compressors isentropic efficiency	0,89	
air mass flow	540	kg/s
net electric power	218	MW
LHV fuel (natural gas)	48120	kJ/kg K
combustors efficiencies	99,5	%
combustors pressure losses	3	%
Turbine Inlet Temperature	1523	K
exhaust pressure losses	4	%
Turbine isentropic efficiency	0,9	
Mechanical losses	2	%

Assuming the 218 MW gas turbine power plant in the scenario with the same electricity and fuel prices proposed both in Table 5-2 and Table 6-2, the NPV is strongly negative. About -174,5 mln$ if on-peak electricity costs 105 $/MWh and -135 mln$ if it costs 115 $/MWh. Moreover, if CO_2 tax is applied (30 $/tonCO_2$ for example), the NPV drops down more (about -217,65 mln$ and -256 mln$ if an on-peak electricity price of respectively 105 $/MWh and 115 $/MWh are assumed). Therefore this investment has to be avoided. These results highlight one of the reasons of the interest in the Adiabatic

CAES, much more attractive than a gas turbine power plant in a scenario with high fuel price. The confirmation of this, can be seen comparing the results of the economic analysis of the 225 MW A-CAES (6.2.3.1) with these results found for gas turbine. An economic analysis in a scenario characterized by on-peak electricity price of 125 \$/MWh and a fuel price of 5 \$/mlnBTU (escalation rate of 5%) is carried out. The analysis shows the obvious benefits in the on-peak electricity price increment, that compensates the high fuel costs (Figure 7-2). Because of the high HR, the plant is particularly sensitive to fuel prices, which costs have to be maintained at low value in order to achieve profits. As mentioned in the previous lines and seen in Chapter 5 and 6, the numbers of hours of generation improves the NPV. As Figure 7-3 shows, the number of hours needs to reach a certain value in order to avoid negative NPV. Due to the high fuel consumption and consequent emissions, CO_2 tax can affect significantly the profits; the strongly negative NPVs in Figure 7-3 justify the growing interest in CAES.

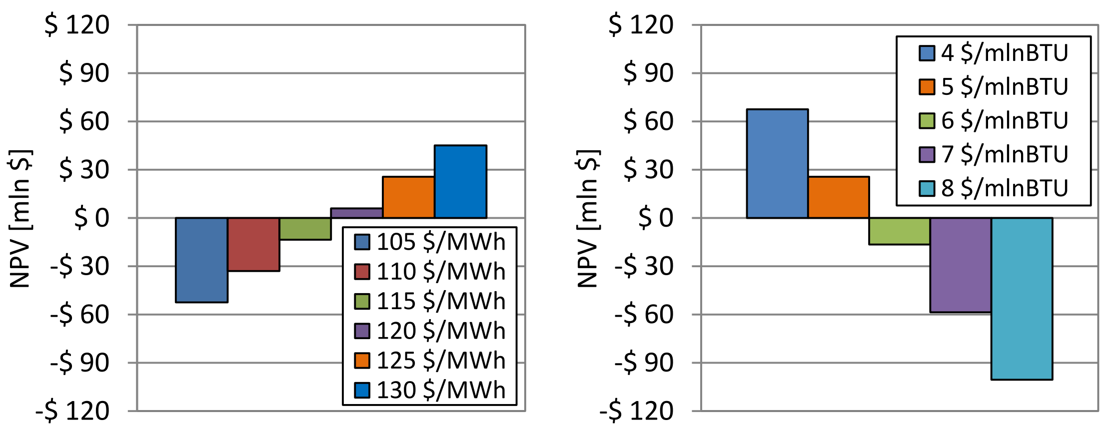

Figure 7-2 Effects of the on-peak electricity price on the NPV

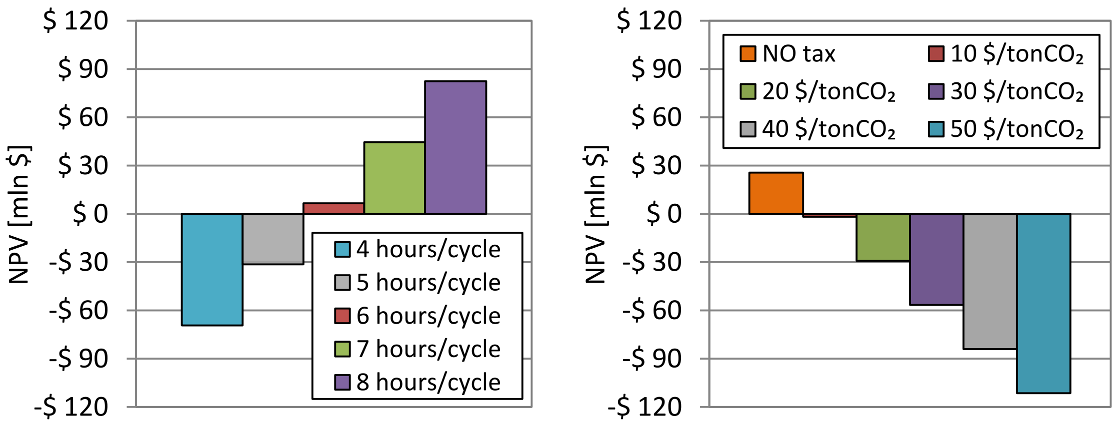

Figure 7-3 Effects of generation hours and CO_2 tax on the NPV

7.2 Pumped Hydro Energy Storage

The fundamental principle of Pumped Hydro Energy Storage (PHES) is to store electric energy in the form of hydraulic potential energy. During off-peak periods, the pumping takes place and the water is pumped from the low reservoir to the upper reservoir; when electricity demand is high, generation takes place releasing the water from the upper reservoir to the lower reservoir (Figure 7-4). Pumping and generation generally follow a daily cycle, but weekly or even seasonal cycling is also possible with larger PHES plant. PHES is an energy storage which requires very specific site conditions to make a project viable, i.e. high head, favourable topography, good geotechnical conditions, access to the electricity transmission networks and water availability. The most essentials are the availability of locations with a difference in elevation and access to water. Its flexible generation can provide both up and down regulation in the power system while its quick start capabilities make it suitable for black starts and provision of spinning and standing reserve (Table 7-2). Similar facilities are provided by the CAES and some of them also by gas turbine, even if this latter is not able to provide frequency regulation, supply reactive power and voltage control [1, 2].

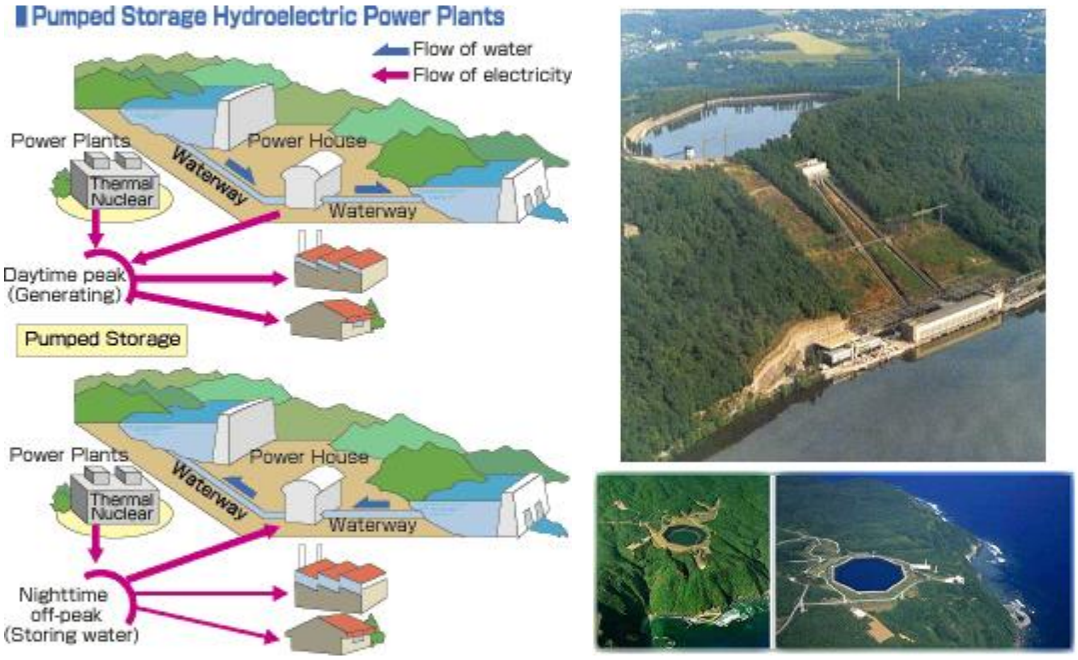

Figure 7-4 PHES operation [84] and some real PHES plants [91]

Table 7-2 Typical operating characteristics of generating plants [1, 2, 90]

	Nuclear power plant	Coal fired plant	Gas turbine-peaker	CAES	PHES
Normal duty cycle	Baseload	Baseload	Peak load	Peak-midmerit	Peak-midmerit
Unit start up-daily	No	No	Yes	Yes	Yes
Load following	No	Yes	Yes	Yes	Yes
Quick start (10 min)	No	No	Yes	Yes	Yes
Frequency regulation	No	Yes	No	Yes	Yes
Black start	No	No	Yes	Yes	Yes

Specific capital costs per MW proposed for PHES are inside a significant range due to the correlation of the cost to the specific site conditions; the head and the geotechnical conditions affect significantly the cost of the plant. Deane, Gallachóir and Mc Keogh in [90, 91] refer costs between 470 $/kW and 2170 $/kW (2009) (in Appendix H, Figure H-1 and Figure H-2), while the Energy Storage Association [3] refers less than 1500 $/kW (2001). J.G. Levine reports and uses in its analysis a value of 1300 $/kW (Figure H-3) [92]. However, it is worthy to highlight costs higher than 2170 $/kW (2009) for power bigger than 1GW and also costs lower than 470 $/kW; in 2001 the 1200 MW Guangzhou pumped storage plant (China) has been built at about 350 $/kW [88, 94], while the Kazunogowa (Japan) plant has been built at 2000 $/kW(2001) [95].
The size range of new installations ranges from 200 MW to 3000 MW, with efficiencies between 70% to 79% [84], Energy Storage Association instead, refers an efficiency between 70% to 85% [3]. J. G. Levine uses 80% [92]. As example, the 1836 MW Tianhuangping Pumped-Storage Hydro Plant presents a value of 70% [93]. This value is about the same of A-CAES plants, only 70% of the electricity spent will be recovered and sold to the grid (no fuel is used). In the analysis a range of values is analysed. The life expectation of PHES is 50 years, but could reach 100 years [84]; a plant life of 50 years and a Discount Rate of 8% are evaluated in the economic analysis. O&M costs equals to 0,5% of the initial investment cost [92] with an escalation rate of 3% are assumed. It is analysed a 436,5 MW PHES able to provide an output energy of about 2840 MWh_{el} as the conventional CAES seen in Chapter 5. The plant, with its 75% efficiency, requires a pumping energy of about 3800 MWh_{el}; 280 cycles of charge and discharge in a year are assumed. According to [92] an off-peak electricity price of 30 $/MWh and an on-peak electricity price of 110 $/MWh are assumed; an escalation rate of 3% has taken into account. Different specific capital costs highlight the high NPV variations (Figure 7-5); low investment costs in the market conditions considered makes the plant particular attractive, but becomes a wrong investment if the initial capital cost increases. Figure 7-5 shows also that low specific costs reduce the DPP. Figure 7-6 shows that lower specific costs increase also the IRR. If according to [92] a specific capital cost of 1300 $/kW is assumed (defining a TIC of about 567,5 mln$) and an analysis for different efficiencies is performed, it can be seen that the NPV increases (Figure 7-7) when the efficiency increases. This is because of the more energy recuperated from the pumping energy spent. In the other hand, efficiency decrements can define negative NPVs making the plant no more attractive. Similar to the considerations done for the previous power plants, the market conditions correlated with the plant characteristics and initial capital costs, can make the energy storage profitable and attractive or a wrong investment that has to be avoided.

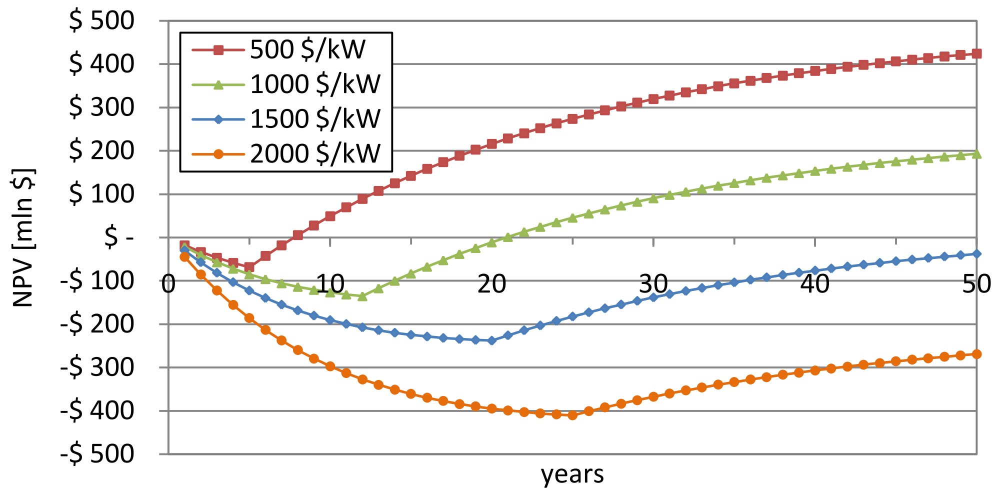

Figure 7-5 NPV for PHES with different specific costs

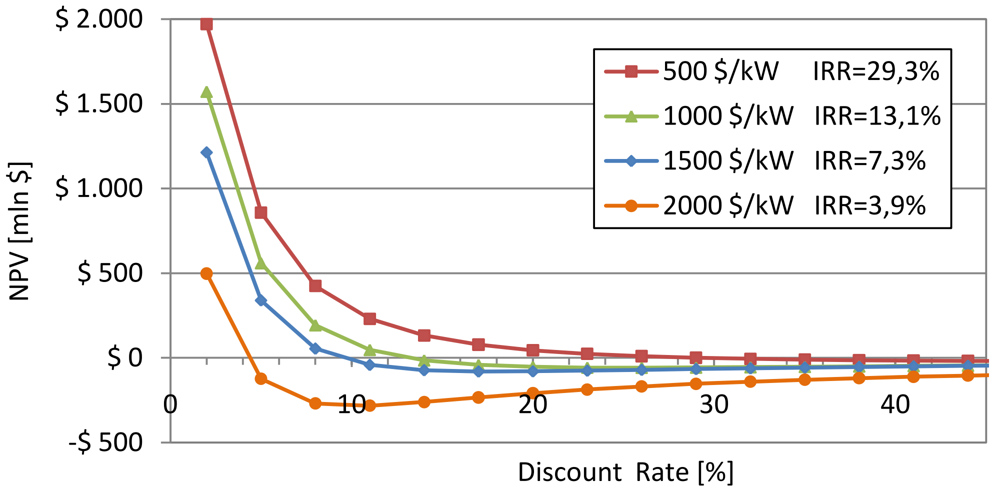

Figure 7-6 IRR for PHES with different specific costs

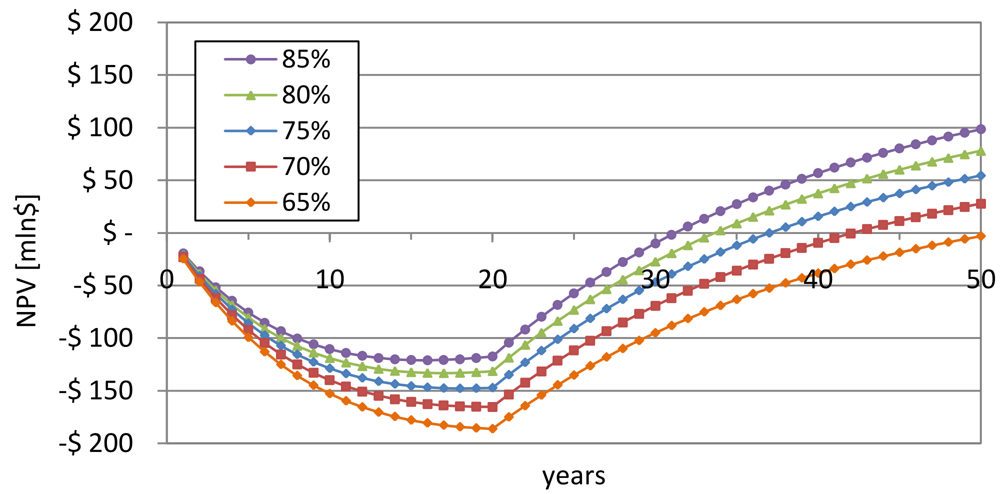

Figure 7-7 NPV trends for different PHES efficiencies

7.3 Plants comparison

The previous peaking power plants are now compared using a scenario with 40 \$/MWh for off-peak electricity price and 115 \$/MWh for on-peak electricity price (it is assumed an escalation rate of 3%). It is assumed a plant life for CAESs and gas turbine power plants equals to 30 years; 50 years for PHES. In a first comparison a conventional 436,5 MW CAES plant is compared to plants with same output power and energy. For the PHES it is assumed a plant able to supply 436,5 MW for about 6,5 hours; in all the analysis, an efficiency of 75% is assumed. In order to generate the same amount of energy with A-CAES, two independent units (see Chapter 4) operating with air mass flow withdrawn of about 340 kg/s and using a total storage of about 1,2 million m^3 are used. If a specific costs of 30 \$/kWh_{th} for the TES and 71 \$/m^3 (6.1.2) for the air storage are assumed, the initial capital cost reaches about 492 mln\$ (case 1). If instead the specific costs decrease respectively to 25 \$/kWh_{th} and 43 \$/m^3 the capital cost decreases to about 416 mln\$ (case 2). If gas turbine power plants are introduced, two 218 MW plants are required. Figure 7-8 shows the NPV trends assuming a fuel price of 5 \$/mlnBTU and an escalation rate of 6%. It can be seen that conventional CAES and PHES with specific cost of 500 \$/kW have the best NPVs after 30 years. Conventional CAES that could also have better NPV if an initial capital costs reduction took place, or worse if an economic air storage was not available. Assuming a storage specific cost of 20 \$/kWh (hard-rock formation) the NPV is lower than that of a PHES with specific cost of 750 \$/kW (Figure 7-9). Looking at the two A-CAES plants, they are less attractive than conventional CAES, but with a profitability that is better than a PHES with specific cost of 1250 \$/kW. With the following assumption of fuel price, the gas turbine power plant presents NPV closed to that of A-CAES (case 1). However, due to high sensitivity to the fuel price of the gas turbine, if the price increased, this plant would not be feasible anymore since the revenues would become less than the fuel costs. Moreover, less expensive cavern and TES would make the A-CAES (case 2) much more profitable than a gas turbine power plant (Figure 7-8).

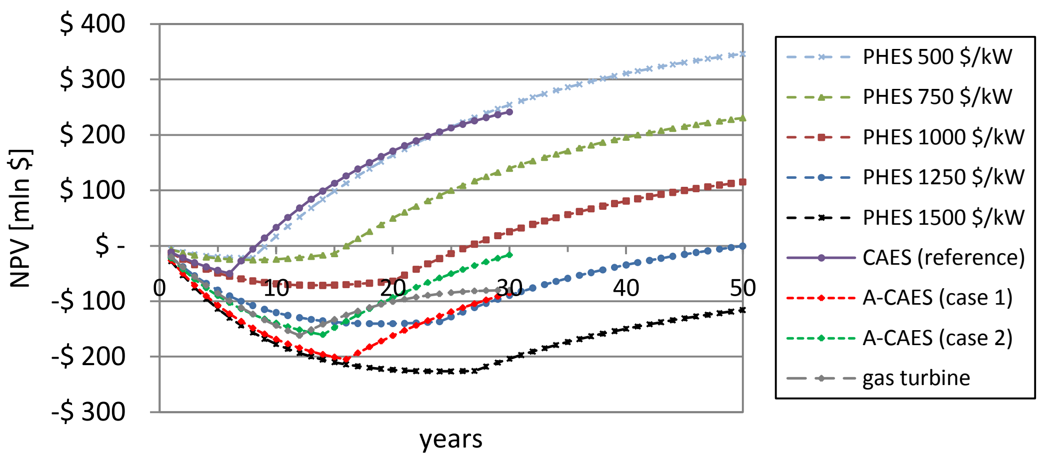

Figure 7-8 Comparison among different peaking power plants (436,5 MW)

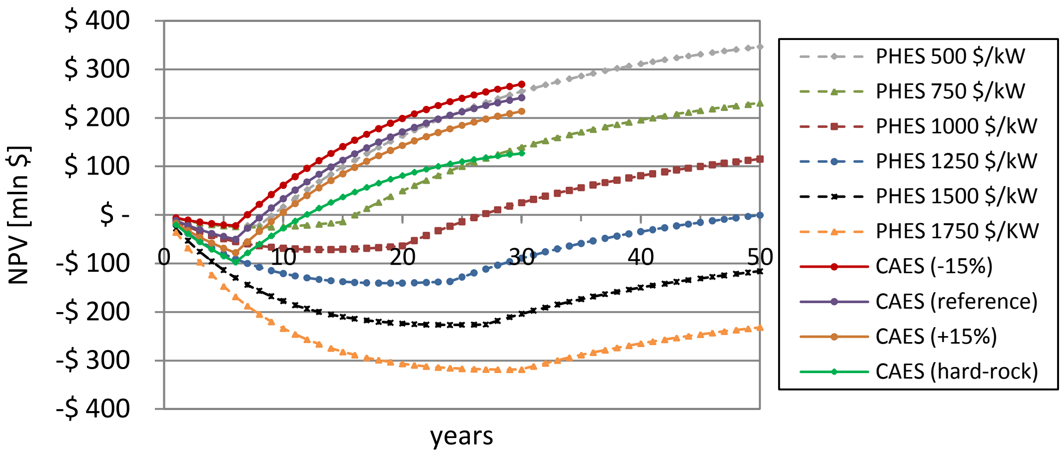

Figure 7-9 Comparison among PHESs and conventional CAESs (different capital costs)

Applying a CO_2 tax and assuming the other prices constant, it can be seen the NPV decrement of the conventional CAES, that for a tax of 30 $/tonCO$_2$ has a NPV still better than a PHES with specific cost of 750 $/kW, but that goes under it if a tax of 60 $/ton CO$_2$ is applied (Figure 7-10). Due to the high fuel consumption of gas turbine and the consequent emissions, the NPV falls down with only a small CO_2 tax, with the risk that the costs to produce the electricity become higher than the revenues achieved. Therefore, gas turbine power plants could become no more feasible.

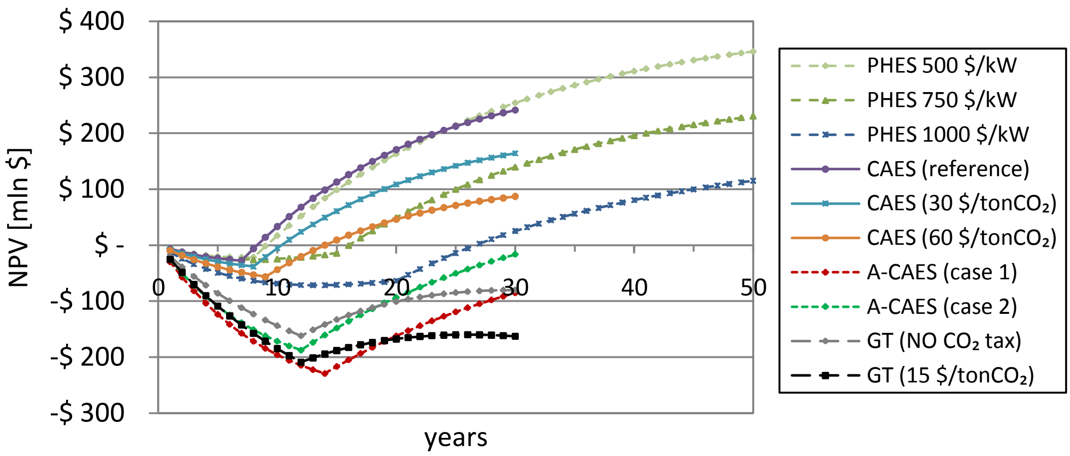

Figure 7-10 Peaking power plants comparison (CO_2 effects)

If the fuel price increases to 7 $/mlnBTU, maintaining an escalation rate of 6%, and CO_2 tax is applied, the trends are those observed in Figure 7-11. The results show that conventional CAES with significant CO_2 tax applied (higher than 60 $/tonCO$_2$) could reach the NPV of A-CAESs. Therefore, if an A-CAES plant is built using a cheap cavern and the TES specific cost decreases, there may be the possibility that it is better than a conventional one. However, it is worth mentioning that in order that A-CAES has similar NPV than conventional CAES, there is the need of high CO_2 tax, of the availability of a big and cheap formation, of a low off-peak electricity price and of a sufficient difference between off-peak and on-peak electricity prices. Moreover, unpredictable stops have not to happen; stops of the machinery that for A-CAES might be more likely than for the conventional (6.2.3.2).

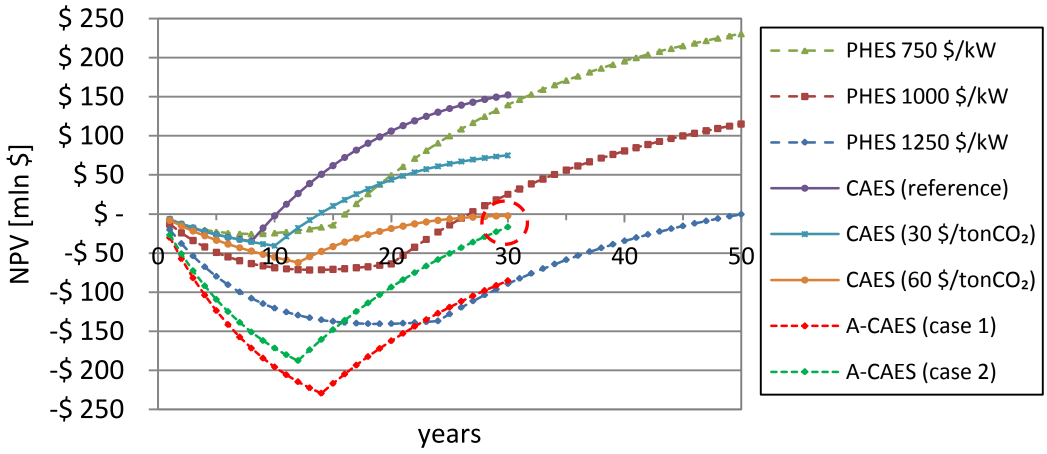

Figure 7-11 Peaking power plants comparison (fuel price and CO_2 tax effects)

If a more realistic scenario, where the CO_2 tax increases the electricity prices, is assumed, the previous trends change. It is assumed that a 30 $/ton$CO_2$ increases the electricity prices of 5 $/MWh (45 $/MWh for off-peak and 120 $/MWh for on-peak electricity), while a tax of 60 $/ton$CO_2$ increases the electricity prices of 10 $/MWh. While with these assumptions the NPVs of the conventional CAESs become positive again, for A-CAESs they go down (Figure 7-12). In fact, as seen in Chapter 6 (6.2.3.1), the profitability of A-CAES is sensitive to the electricity prices, and in this case (due to a CER lower than one) the off-peak price increment reduces the final revenues although the higher on-peak price.

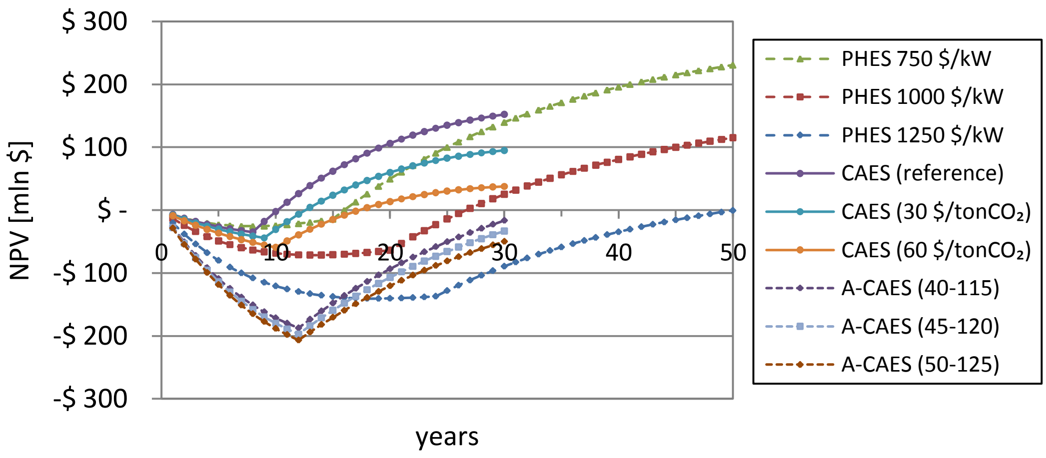

Figure 7-12 Peaking power plants comparison (CO_2 tax effects and electricity prices)

Figure 7-13 shows the NPV trends for different fuel costs (an escalation rate of 6% is assumed) and different efficiencies for a PHES with specific cost of 750 $/kW. It can be seen the obvious NPV improvement due to fuel price reduction. Changing the PHES efficiency, the NPVs after 30 years are similar to those of conventional CAES with fuel prices between 6 and 8 $/mlnBTU.

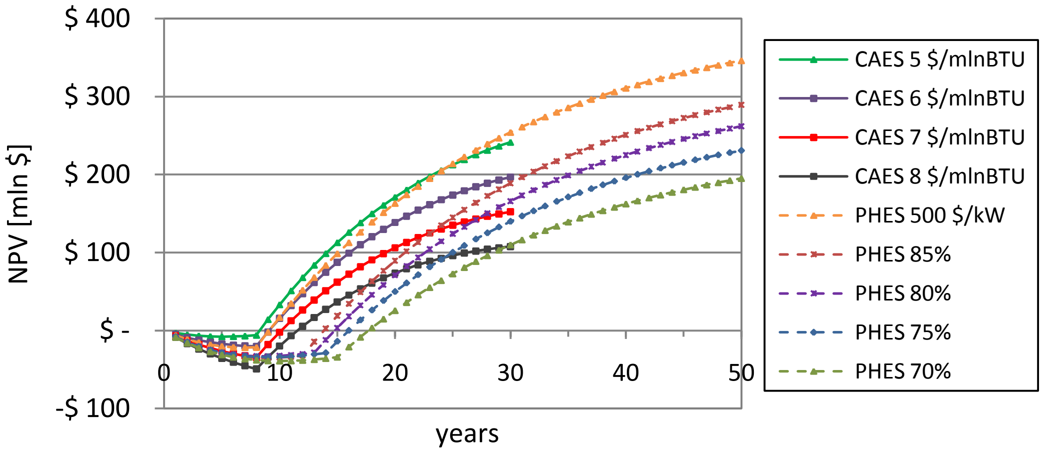

Figure 7-13 NPV comparison for PHES and CAES (fuel price and efficiency effects)

If a scenario with off-peak electricity price of 40 $/MWh, on-peak electricity price of 125 $/MWh, fuel price of 5 $/mlnBTU (escalation rate of 5,5%) is assumed, the NPV trends are those in Figure 7-14. Gas turbine power plant presents a positive NPV, but still worse than Compressed Air Energy Storages.

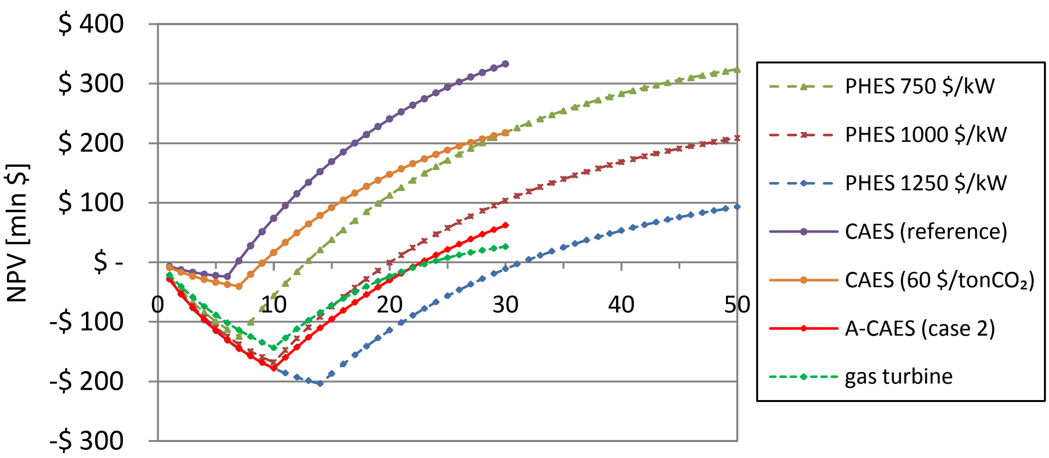

Figure 7-14 Peaking power plants comparison (positive NPVs)

Analysing now smaller plants (225 MW) the results are almost the same. A gas turbine characterized by the parameters presented in Table 7-1 and a mass flow of 560 kg/s is used for generating the power required. The A-CAES is the plant seen in the economic analysis of A-CAES with a DP mass flow of 350 kg/s able to delivery about 1500 MWh. The conventional CAES is instead a plant with compressor train composed of 3 compressors operating at 125 kg/s (65 MW) and generation train at 205 kg/s (225 MW), the air storage is a 210000 m^3 underground cavern. The total investment costs are respectively 200 mln$ for the gas turbine, about 140 mln$ for the CAES, 211 mln$ for A-CAES (case 2) and 248 mln$ for A-CAES (case 1). Assuming 40 $/MWh for off-peak electricity price, 115 $/MWh for on-peak electricity price, 5 $/mlnBTU and an escalation rate of 6%, after 30 years the best plant is the PHES with a specific cost of 500 $/kW, followed by the conventional CAES. Gas turbine power plant is better than A-CAES with higher capital cost (case 1), but as seen before, it creates a significant amount of emissions, therefore if a small CO_2 tax is added, the NPV falls down becoming easily less attractive than A-CAES.

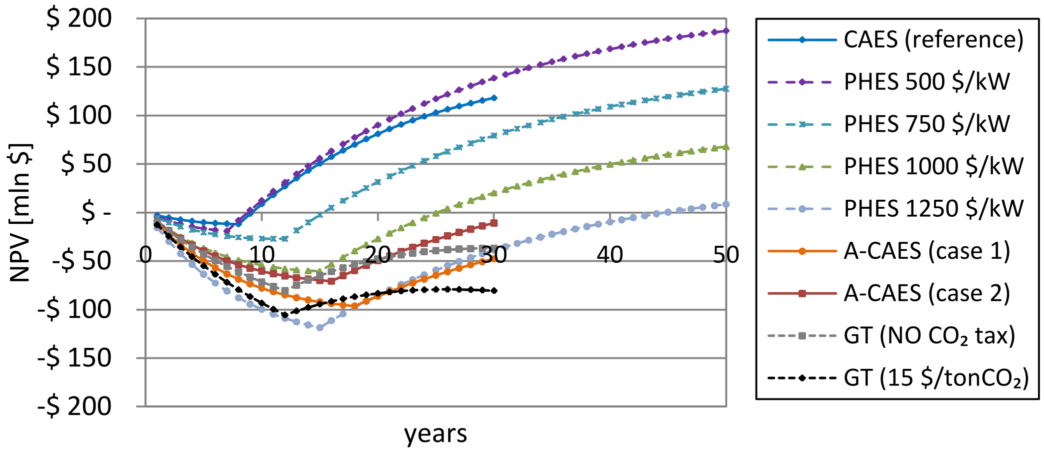

Figure 7-15 225 MW Peaking power plants comparison

If the fuel price is increased to 7 $/mlnBTU, maintaining constant the other parameters, and CO_2 tax is applied, the trends are similar to those seen for the bigger plant, where the NPV of the conventional CAES may reach that one of A-CAESs (Figure 7-16). If instead the fuel price increment introduces electricity price increments the NPV trends assume the behaviours already seen in Figure 7-12.

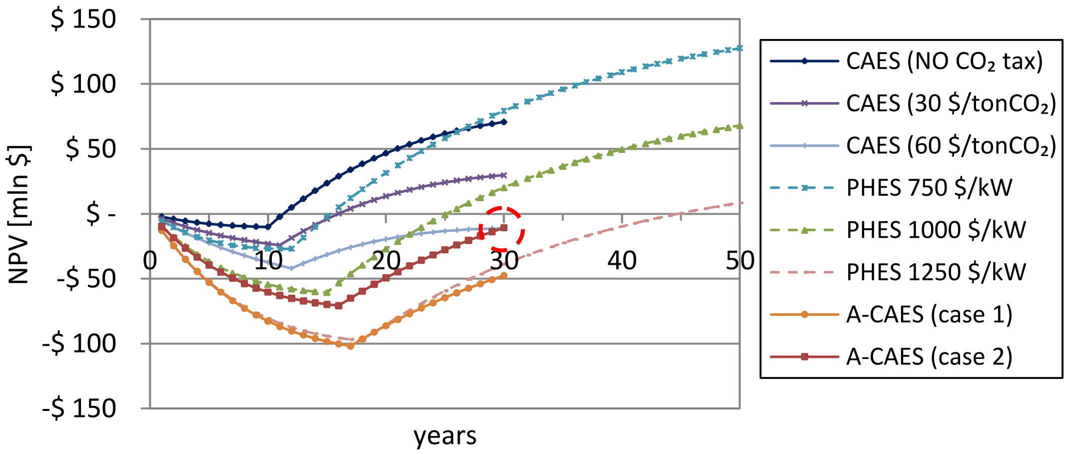

Figure 7-16 225 MW Peaking power plants comparison (CO_2 effects)

Since output power for PHES can be around 1 GW and more [95], big plants of about 995 MW are analysed. For conventional CAES, two units with a generation train composed of three turbines (about 497,5 MW each train) that operate using a total air storage of about 800000 m^3 (with specific cost of 11 \$/kWh) are analysed. The total capital cost is about 490 mln\$. For A-CAES, it is assumed to use 5 units with a total air storage of about 2,7 mln m^3; 4 units with a generation train at 350 kg/s and a small unit with a train of about 170 kg/s. The total investment cost, much higher than conventional, is about 930 mln\$ (case 2). Similarly to the previous results, conventional CAES can compare with PHES with low specific costs, and also thanks to the benefits of a train with three turbines, the NPV after 30 years is higher than PHES with specific cost of 500 \$/kW, when usually it was slightly less. Similar considerations of the previous cases for the A-CAES, which profitability is still inside the range of PHES with costs between 1000 \$/kW and 1250 \$/kW.

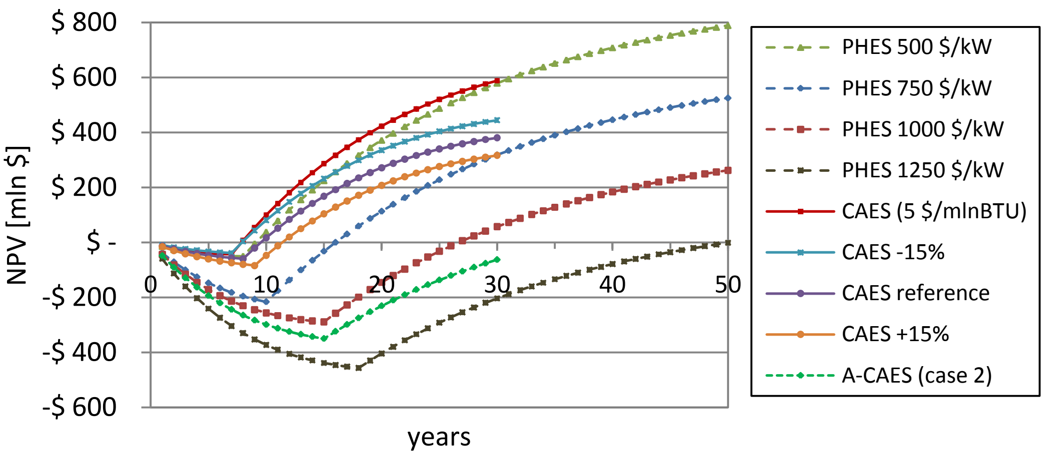

Figure 7-17 1 GW Peaking power plants comparison

7.3.1 Conclusion

The results achieved highlight the high profits of conventional CAESs compared to other energy storage plants, motivating the interest on these for storing the electricity from renewable sources. Conventional CAESs show good profitability after 30 years, only Pumped Hydro Energy Storages with low specific cost (500 \$/kW) can reach higher values. Because of the combustion, conventional CAES has the benefit of high CER (and incomes) achieved, but in the other side, it needs to face the fuel price fluctuations and CO_2 tax that may affect significantly the profits, placing these plants at the same level of more expensive PHES.

The introduction of A-CAES is attractive if significant increment in fuel price and CO_2 tax take place without any electricity price increments. But if these increments, as usually happens in real market, take place, the need of having low off-peak price and a sufficient difference between off-peak and on-peak electricity prices is required for maintaining enough profitability of the A-CAES. If there is not a good energy market, the low CER and the high capital cost, make this plant no very viable and either PHES or conventional CAES are better. Conventional CAES that, in a scenario where CO_2 tax and fuel increase the electricity prices, remain still economically attractive with positive NPV. However, from the results achieved, the A-CAESs have profitability that averages in the same range of PHES with specific costs between 1000 $/kW and 1250 $/kW. This can justify the interest also in this technology, which plant construction may be easier and less geological dependent of PHESs.

It is worthy to say that even if some PHES have been built with very low capital costs (350 $/kW reached for the Guangzhou Pumped Storage), geological characteristics can affect the capital costs defining capital costs of more than 2000 $/kW (Kazunogowa PHES). It is also important to note that the PHESs considered present an efficiency of 75%, if it was lower (70% as Tianhuangping plant), the CAES plants would look more economic attractive than PHES. In the other hand, the TITs chosen for conventional CAES can vary, defining profits variations respect to the trends proposed.

It is obvious that gas turbine power plants are used only for peaking generation. They remain attractive when low fuel prices and high on-peak electricity price permit to pay back the high investment of a machine that operates only few hours a day. In these conditions the gas turbine may be more attractive than A-CAES with expensive cavern and TES. However, if an economical cavern and TES were available, a small fuel price increment or a small CO_2 tax was applied, the A-CAES would become again better than a gas turbine which NPV would fall down, and the investment should be avoided. Although the gas turbine power plants problems of fuel consumption and emissions, the benefit maintained respect to the other peaking power plants is that they have not any geological limitation, making them feasible wherever required.

CONCLUSIONS

8.1 Overall conclusions

The increment of intermittent and renewable energy are requiring systems to store the electricity produced during the off-peak period for selling it when the price and the demand are higher. Aim of this research is a thorough technical and economic investigation of the main types of Compressed Air Energy Storages, conventional with combustion and adiabatic.

The technical analysis highlights for both, significant performances improvements increasing the compressors and turbines efficiencies, that have to be as much as possible constant and high in the entire operative pressure range of the air storage. Beyond the compressor efficiency, in the compressor train of a conventional CAES, the increment of the number of compressors and intercoolers among them, highlights performances improvements with an input energy reduction and an air injection into the storage in less time. For A-CAES instead, the thermal energy produced during the compression is the resource for the generation, so only a small intercooler after the first stages of compression is required just to maintain the maximum compressor train outlet temperature under the technical limits (about 923 K).

In both plants, the different storage characteristics, function of the storage depth and underground formation structure, may affect the operative conditions of the machinery. This is one of the reasons why interest in the aboveground storages, with more definite conditions, is also in progress. However, while the underground storage has the drawback that the characteristics vary on the basis of the formation available, the aboveground storage has limited dimensions (about 11000 m^3), hence small output energy is generated, making this solution not applicable for managing large amounts of renewable energy. Moreover, aboveground storages operate with higher air storage pressure (up to 14 MPa) in order to store more mass in the small volume. Higher air storage pressures may generate higher output powers, but they have the downside of lower Charging Electricity Ratio since more electric energy is spent for compressing air.

In the generation train of a conventional plant, beyond the turbines efficiency, TITs and a sliding pressure generation mode are the elements to improve. It is worth mentioning that, while turbine efficiency increases the output power generated without any fuel increments, all the TITs increments have the disadvantage of the more fuel required. About the sliding pressure generation, in both conventional and adiabatic plants, the air should be released through the generation train without any valve, avoiding energy losses and increasing the output energy generated and the revenues.

The turbines have to operate at the highest TITs in a wide operative pressure range with the highest efficiency possible, maintaining the high availability and reliability of the generation train, essential elements for peaking generation. Benefits in the high TITs are also visible when the conventional generation train with two turbines is modified adding a third turbine. The disadvantage is again the fuel consumption increment (about 2,2%), that in any case does not affect the profits. Profits that instead increase in comparison to a conventional train with two turbines, even when it is added a CO_2 tax.

Even if the Huntorf plant is still without recuperator in order to be fast and following the peaks demand, the technical and economic analyses highlight the need of this component for reducing the fuel consumption and consequently the operating costs. The reduction of fuel consumption calculated is about 30% and more on the basis of the recuperator effectiveness chosen. The significant capital cost reduction of about 7%, avoiding the recuperator, is not sufficient to compensate the fuel costs and possible CO_2 tax; tax that may affect significantly the final Net Present Value of a conventional plant if no electricity prices increments take place.

On the basis of the output energy required and the amount of off-peak electricity that needs to be managed, the storage can have different dimensions that define the total capital cost, which impact could be considerable if an economic formation was not available. In this case, a reduction of the air mass flow withdrawn (producing the same output energy) is necessary; aim that in conventional CAES can be achieved increasing the TITs or using humidification. In adiabatic plants, the problem of the storage is more significant since bigger amount of air is required for generating the same amount of energy of a conventional CAES. In some calculation performed the storage of the A-CAES has arrived to be three times the storage for the conventional, with also consequent problems of finding an economic storage available.

In Adiabatic-CAES, the low TITs create also problems in the last stages of the Low Pressure turbine where the temperatures can reach values much below 273 K if an high expansion ratio is used. A relationship between this temperature and TES dimensions underlines that the problem reduces if a bigger TES is used; it is obvious that this solution increases the capital costs. The possibility to use two turbines in parallel reduces the low temperature problems, but with the drawback of a lower output energy produced. The train produces up to 5% less output energy, that for an A-CAES is a significant loss. Therefore, the generation train with two turbines in series seems the more promising configuration to undertake.

The results define a relationship between the air storage dimensions and the TES dimensions, which produces significant variations in the profits. Smaller storage increases the Net Present Value due to the lower capital cost of the cavern and the TES, but this requires higher number of charge and discharge cycles inside the Thermal Energy Storage. This component still under development, represents challenges to face, and the effects of higher number of cycles are unknown. Critical points are the medium and the container walls that need to resist at very high temperatures and pressures (proposed up to 10 MPa and more).

Because of a possible medium degradation, it has been investigated the TES with different mediums, as pebbles and rocks. The technical analysis underlines good results for A-CAES with these mediums, that exhibit efficiency close to the values for concrete (about 70%), even if a volume increment is registered. The required TES volume varies when the medium characteristics change, with consequent cost variations. The analyses highlight that if the TES with gravel or pebbles (with high density and specific heat capacity) had a specific cost at least 20% less expensive than that with concrete, the profits would be better. TES with mediums having low density and specific heat capacity (for example 1870 kg/m^3 and 0,750 kJ/kgK) has to be avoided since the specific cost should be very low (more than 40%) in order to have a profitability similar to concrete. For this novel adiabatic concept, the direct heat-exchange at high pressures still represent an unknown; stop of the machinery for maintenance might happen reducing the revenues, thereby this drawback should be reduced to the minimum. Therefore, while in conventional CAESs, the main risks of operation interruptions are represented by the underground formations and their environments with possible consequences of wells and generation train degradations, in Adiabatic-CAESs, have to be added the risks introduced by the Thermal Energy Storage.

The results confirm that the A-CAES is technically more efficient than conventional CAES, since operates with an efficiency of about 70% against values of about 60% and less of the conventional. Despite the lower efficiency, the conventional is characterized by high Charging Electricity Ratio, index that is desired to be as high as possible in CAES, since more energy can be sold to the grid increasing the revenues. CER values up to 2,0 have been found for the conventional with high TITs, while for the A-CAES it is about 0,7. Higher CER and lower capital costs, make the conventional plant much more profitable and less dependent to the market conditions than the adiabatic. The adiabatic instead needs to be in a market characterized by sufficient prices difference between off-peak (30 $/MWh) and on-peak electricity (115 $/MWh) for paying back the investment and getting profit.

Analysing the Discounted Payback Periods, it is obvious that the conventional with its higher profitability is characterized by a shorter period than an adiabatic plant. The period is calculated in 18 years (DR equals to 8%) for a conventional CAES that would reduce to 16 years if a generation train with three turbines was introduced. On the basis of the cavern dimensions and market conditions, for the adiabatic, the periods calculated can reach 28 years.

The comparison with Pumped Hydro Energy Storage shows the high profitability of the conventional CAES, that in a market with low fuel price, can be higher than PHES with low specific costs (500 $/kW). Fuel costs and CO_2 tax increments, without any electricity price increments, can have significant impact on the earning capacity, reaching levels comparable to more expensive PHES. There is also the possibility to reach same level of economic A-CAES. In the analysis has been found that, if the electricity prices do not increase, a low cost adiabatic plant could potentially become as attractive as a conventional one in a market characterized by a fuel cost of 7 $/mlnBTU and a CO_2 tax of 60 $/tonCO_2$. If instead, as happens in real markets, the electricity prices increase when the fuel price increases, the profitability of an adiabatic plant may drop down, while for the conventional remains attractive.

For Adiabatic plants, the profits are at levels comparable to PHES with specific costs between 1000 $/kW and 1250 $/kW. However, if an economic underground formation and lower specific costs for the TES (the trend shows a decrement of the cost of TES with concrete during the years) were available, the profits could also improve moving to values higher than PHES with specific capital cost equals to 1000 $/kW. In this way the adiabatic could potentially be more competitive, reducing the differences versus the conventional in a scenario characterized by high fuel price and CO_2 tax. However, in the meanwhile of technical improvements of the adiabatic plant (with consequent economic benefits), the conventional could also improve, maintaining also the gap in the profits.
The gas turbine power plants, used for peaking power generation, burning an high amount of fuel and producing consequently an high amount of greenhouse gases, are very sensitive to fuel prices and CO_2 tax. Therefore, these plants might have problems to operate in markets with high fuel costs and CO_2 tax. If the fuel price is low, their profits reach and overcome the Net Present Value of A-CAES plant. But if a small CO_2 tax is applied without any electricity price increments, the profits of gas turbine decreases significantly, while for the A-CAES they maintain the same value. It follows that simple cycle gas turbine power plant could be substituted in the next future by the more technical and economic efficient energy storages.
The benefits of CAES compared to gas turbines are not only the less Heat Rate and emissions, but also in the independent compression and generation stages. This introduces economic benefits since all the power produced by the generation train is sold to the grid during the peak request. But it is also important since it is possible to optimize the generation train independently of the compression train. Therefore it is possible to optimize the compressor train in order to reduce the energy spent for injecting air inside a certain formation, and on the other hand, the generation can be optimized in order to achieve the highest output energy.
The results of these studies motivate the growing interest toward Compressed Air Energy Storages as solutions to manage the off-peak electric energy increment, both from renewable energies and low Levelized Cost Of Electricity power plants such as nuclear power plants. Satisfied the geological location and the market conditions requirements, the analyses identify, from an economic point of view, the conventional CAES as the most promising technology to undertake. Much less interesting, but still viable, the “green” technical efficient Adiabatic CAES.

8.2 Suggestions for further work

This has been a preliminary study towards understanding the feasibility of CAES plants on which nowadays there is a growing interest.

- Different configurations can be studied starting from the CASH, with the injection of hot water during the generation in order to reduce the mass flow withdrawn, hence decreasing the storage dimensions, the compression and the generation trains. With similar results, the air injection (proposed by ESP) during the generation could be studied. A techno-economic analysis of these two concepts could be carried out, evaluating advantages and downsides.

- Simulink® models of both conventional and adiabatic CAESs could be created; each model could include inside both technical and economic part. A random energy market with peaks requests and periods of off-peak in a day or in a year, could be simulated, thorough both technical and economic aspects of the plant. It could be also used for evaluating the effects of charging a cavern that it has not emptied till the minimum pressure, but it could be charged at 20%, 40%, and so on. The idea is to create a more realistic analysis that permits to understand the potentials and the drawbacks of these technologies. A comparison among the CAESs, PHESs and gas turbine power plants could be realized.
- A more detailed analysis of the compression using compressors maps could be done. The air storage model could be improved assuming variable temperature during the charge process; temperature that affects the storage volume with possible economic drawbacks. Seen the benefits of TITs increments in the generation train of conventional CAES, a technical analysis of the turbines materials, finalized to evaluate the maximum temperatures and pressures achievable maintaining a good reliability could be studied. At this point could be done an economic analysis finalized to see the impact of these high TITs in terms of initial capital costs and later fuel consumption and O&M costs.
- An economic optimization could be realized for studying the effects that each technical parameter has on the investment costs and on the profitability. Monte Carlo method could be implemented to analyse the uncertainty in costs and performances of energy storage plants; it could be also used to take into account a distribution of fuel and electricity prices generating a more realistic energy market.
- Aboveground CAES has not been investigated since the attention has been put on big plants able to store the significant amount of renewable energy. If believed worthwhile, an analysis that compares aboveground CAES with small peaking power plants could be carried out.
- A thorough investigation of the A-CAES with indirect heat-exchange has not been fully undertaken because of the higher environmental risks and also because, doing the literature research, more interest of companies in the A-CAES with direct heat-exchange has been found. However, if believed worthwhile, a techno-economic analysis could be realized in order to see benefits and downsides of this plant.

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APPENDICES

Appendix A: Potential CAES sites in Europe and U.S.

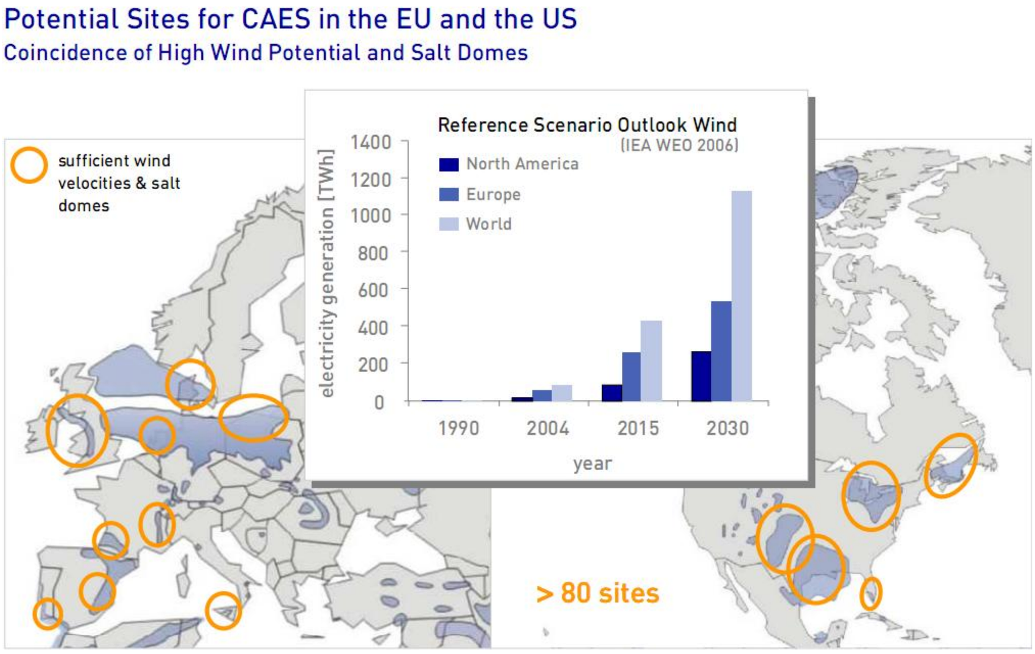

Figure A-1 Potential CAES sites in US and EU [48].

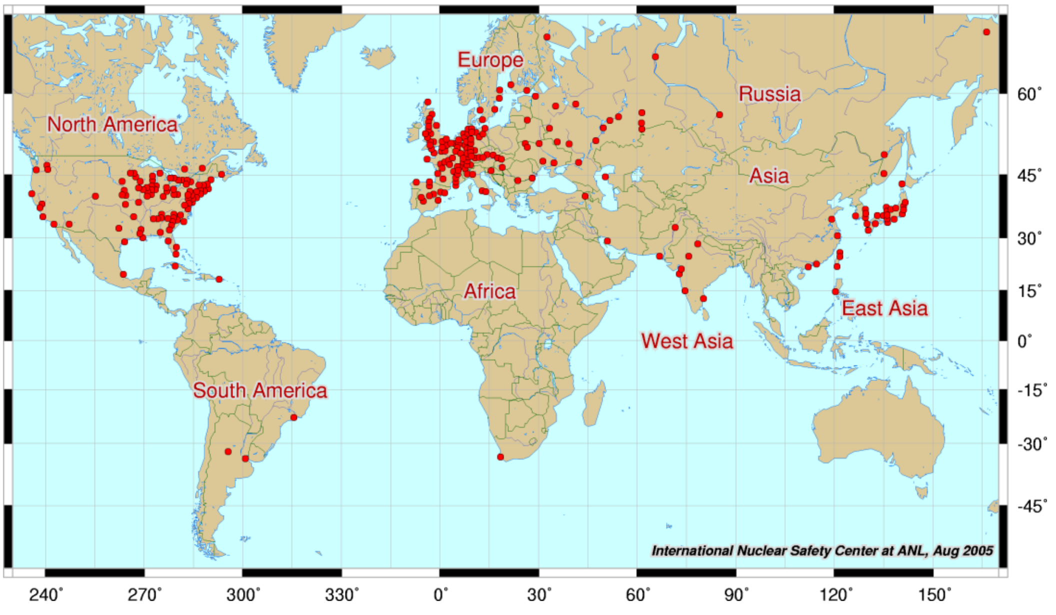

Figure A-2 Nuclear power plants in the world [49].

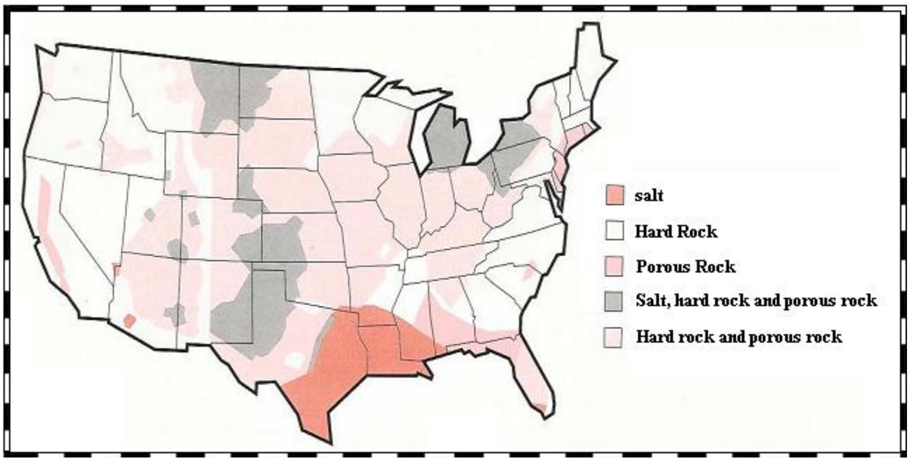

Figure A-3 Underground formation map in USA [7].

Appendix B: Tables, data and graphs for models calculation

Table B-1 Constants used to calculate fluid c_p [26]

	Dry air	O_2	N_2	CO_2	H_2O
A0	0,992313	1,006450	1,075132	0,408089	1,937043
A1	0,236688	-1,047869	-0,252297	2,027201	-0,967916
A2	-1,852148	3,729558	0,341859	-2,405549	3,338905
A3	6,083152	-4,934172	0,523944	2,039166	-3,652122
A4	-8,893933	3,284147	-0,888984	-1,163088	2,332470
A5	7,097112	-1,095203	0,442621	0,381364	-0,819451
A6	-3,234725	0,145737	0,074788	-0,052763	0,118783
A7	0,794571	—	—	—	—
A8	-0,081873	—	—	—	—
A9	0,422178	0,369790	0,443041	0,366740	2,860773
A10	0,001053	0,000491	0,001262	0,001736	-0,000219

Table B-2 Constants used to calculate exhaust gas c_p [26]

combustion products			
B0	-0,718874	B5	3,081778
B1	8,747481	B6	-0,361112
B2	-15,863157	B7	-0,003919
B3	17,254096	B8	0,0555930
B4	-10,233795	B9	-0,0016079

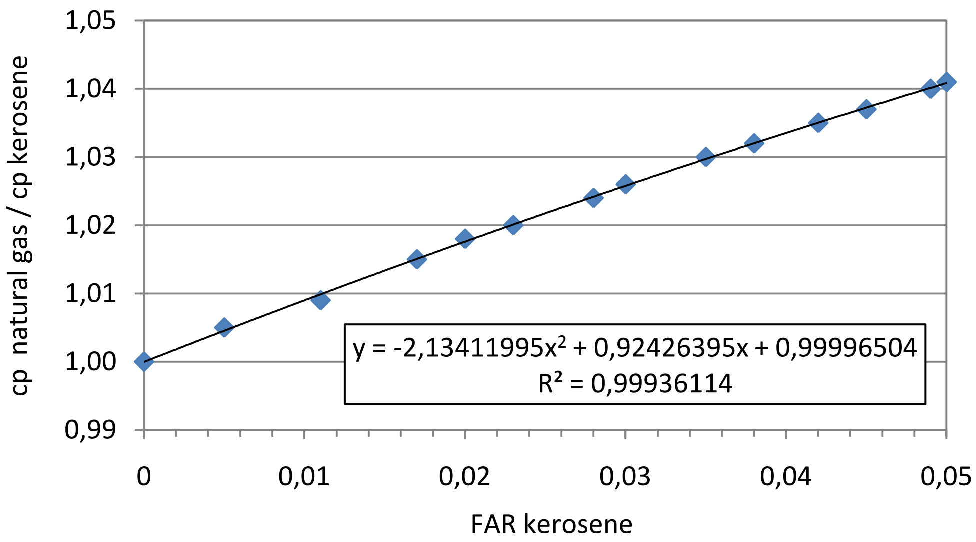

Figure B-1 c_p ratio versus FAR kerosene [26]

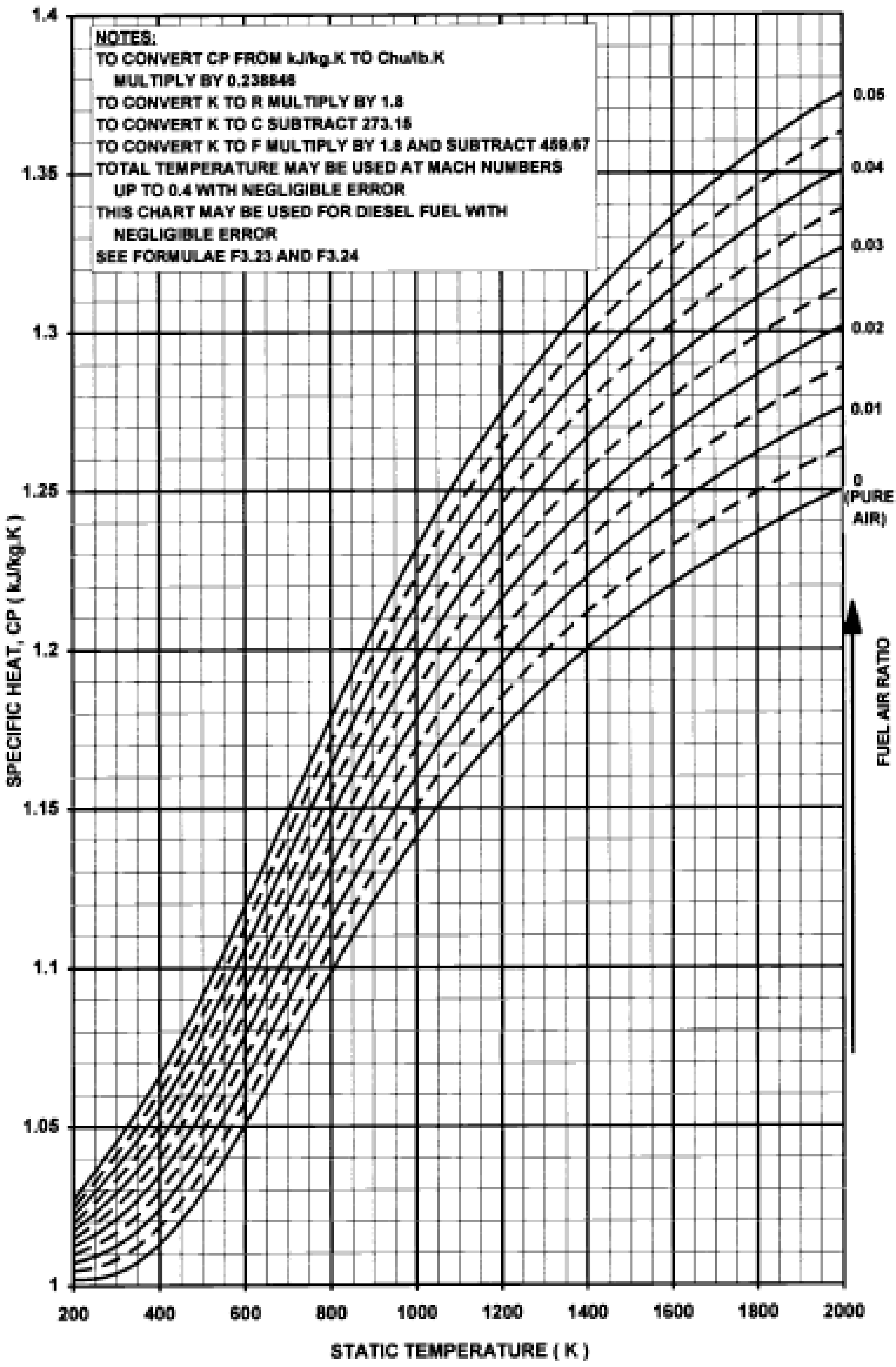

Figure B-2 Specific Heat of combustion products (kerosene) [26]

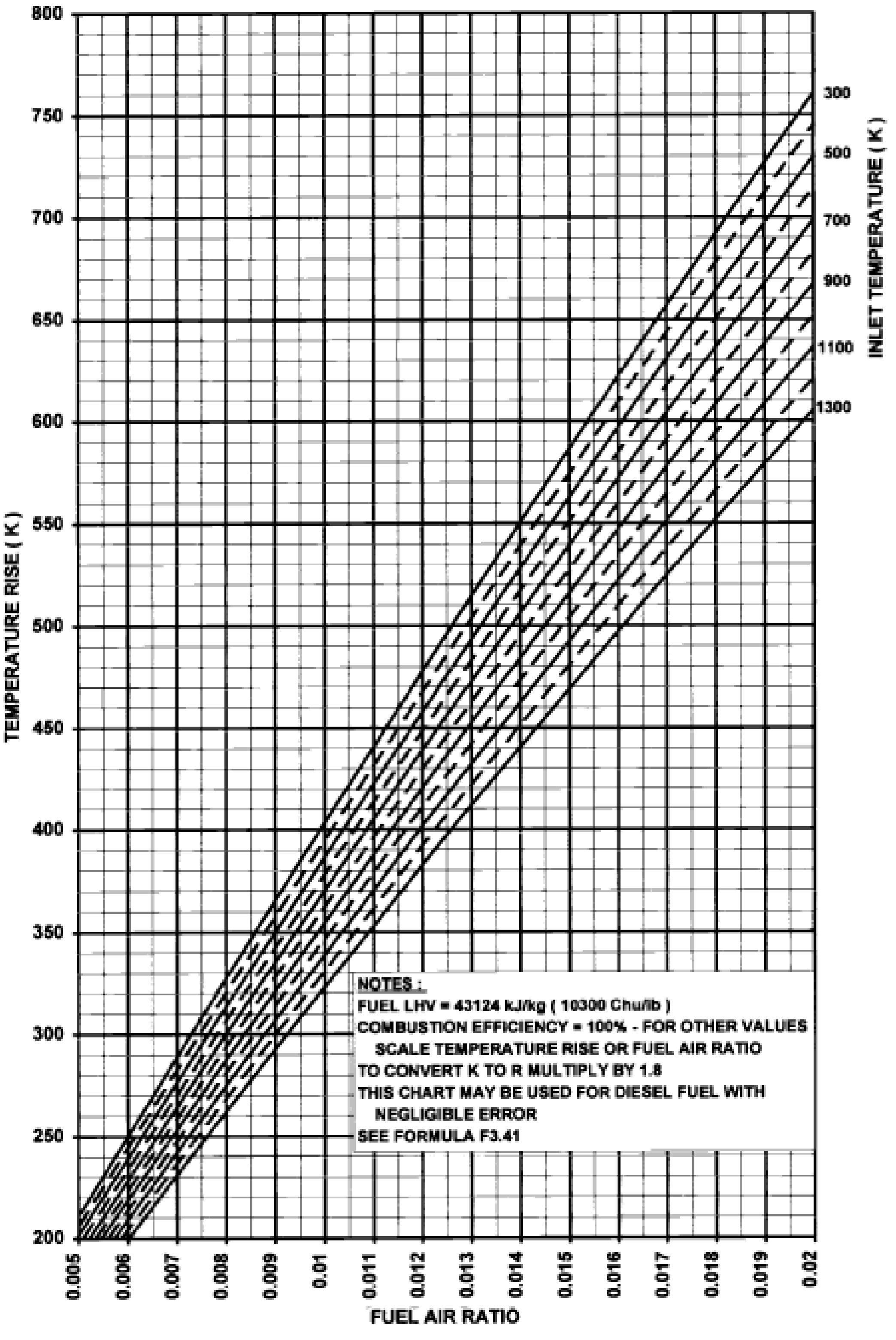

Figure B-3 Fuel to Air Ratio (0,005 – 0,02) (kerosene) [26]

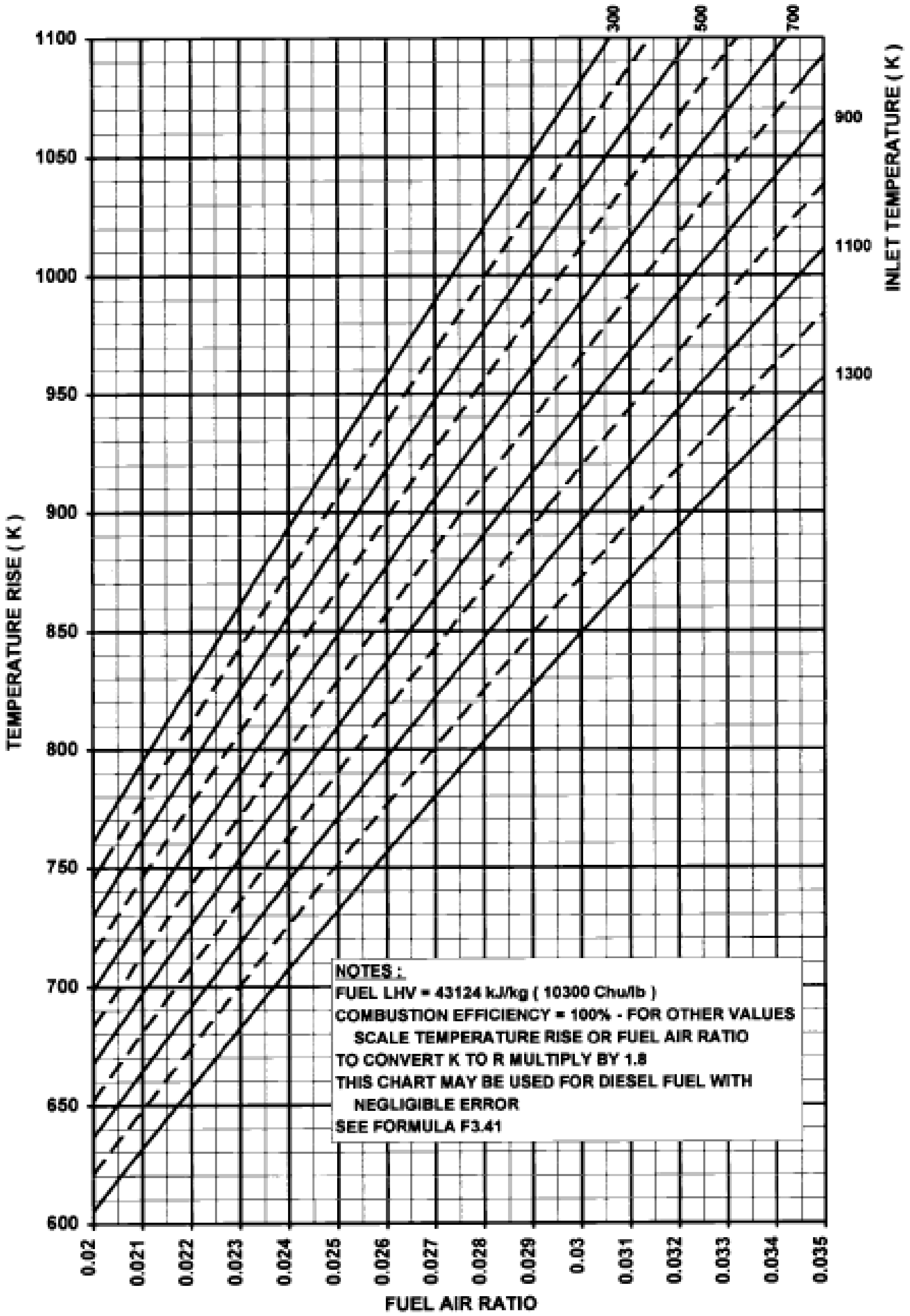

Figure B-4 Fuel to Air Ratio (0,02 – 0,035) (kerosene) [26]

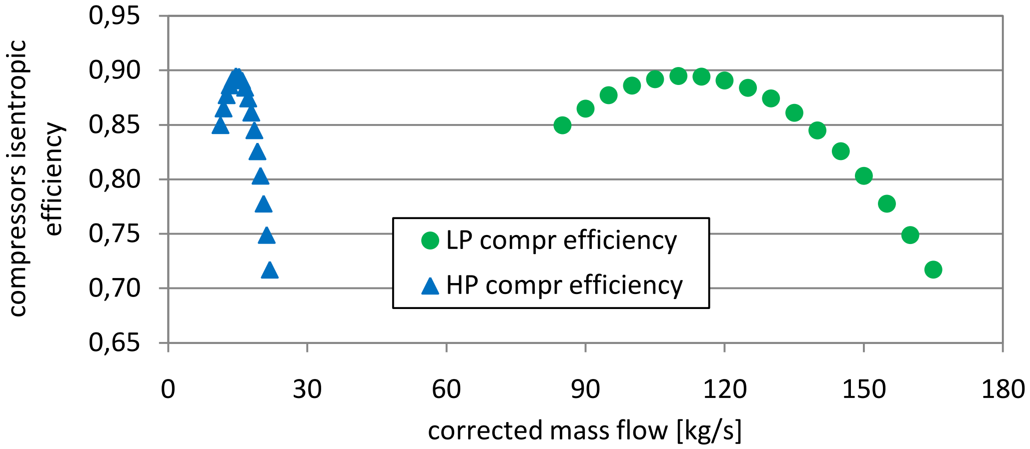

Figure B-5 Compressors efficiencies versus corrected mass flow (two compressors)

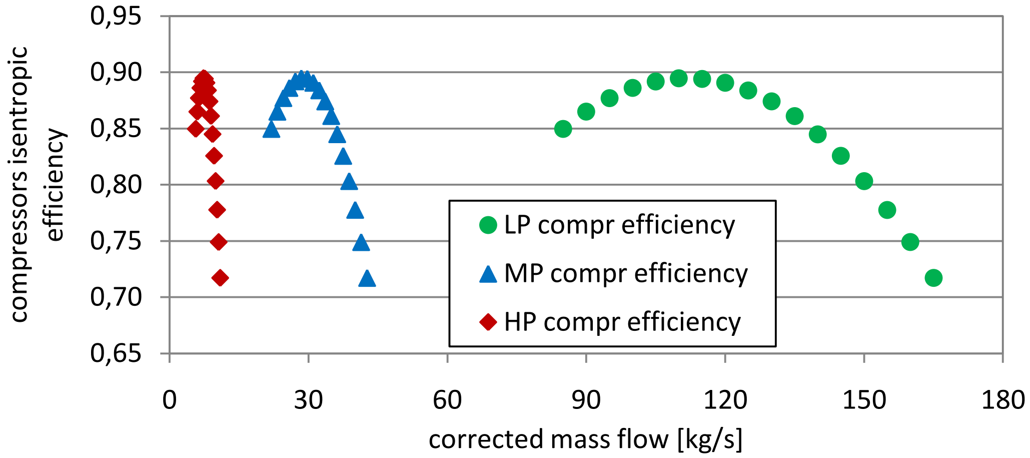

Figure B-6 Compressors efficiencies versus corrected mass flow (three compressors)

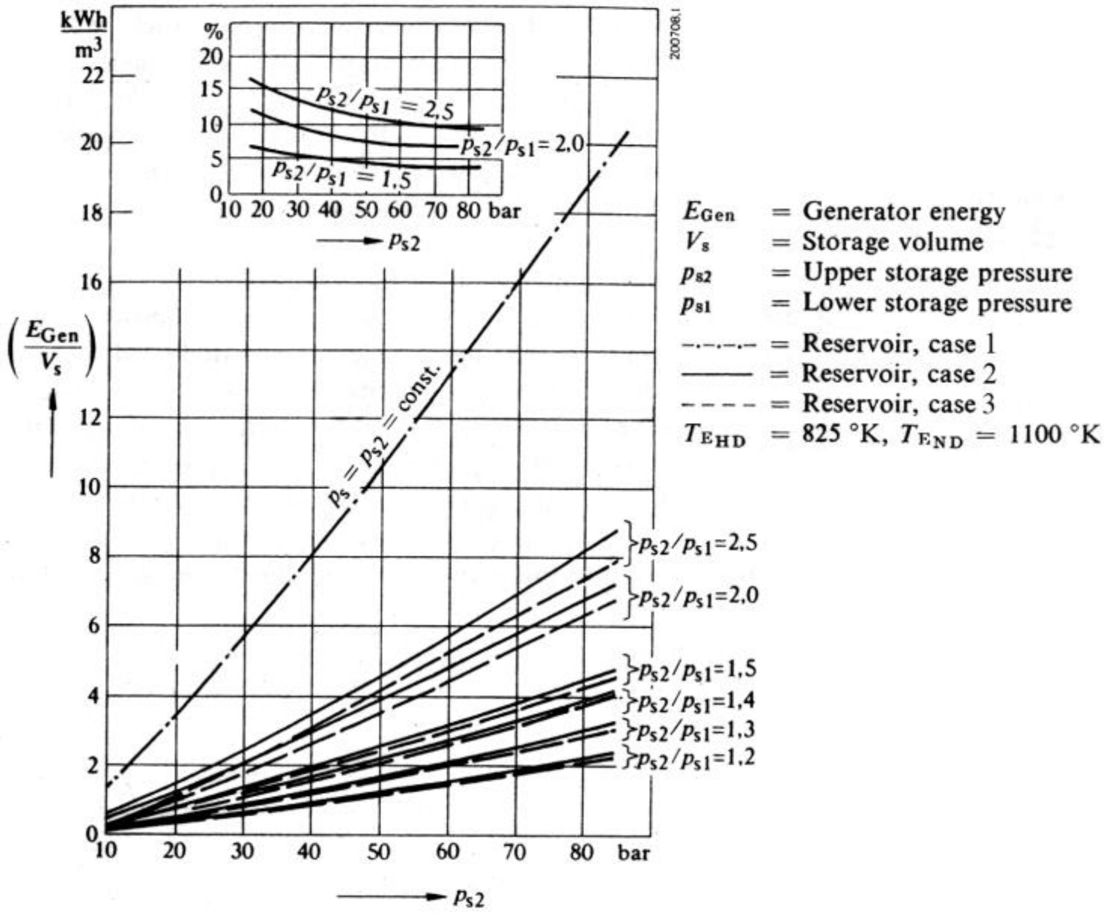

Figure B-7 EVR for different storage configuration [59]

Case 1 proposes the EVR trends for CAES with constant pressure reservoir, case 2 for variable pressure reservoir and case 3 for variable pressure reservoir with constant turbine inlet pressure. The inset represents throttling losses associated with case 3, compared with case 2.

Appendix C: CAES technical information

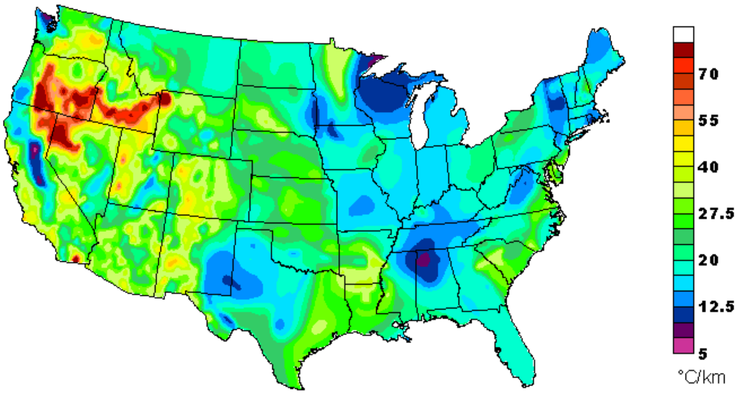

Figure C-1 Geothermal gradient in the U.S. [33]

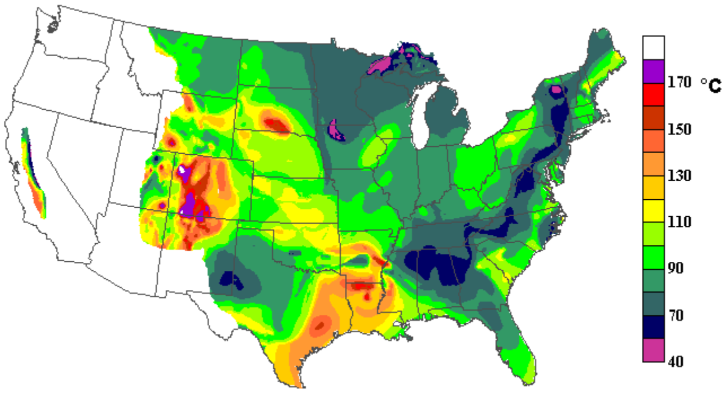

Figure C-2 Estimated Temperature at 4 km depth in the U.S. [33]

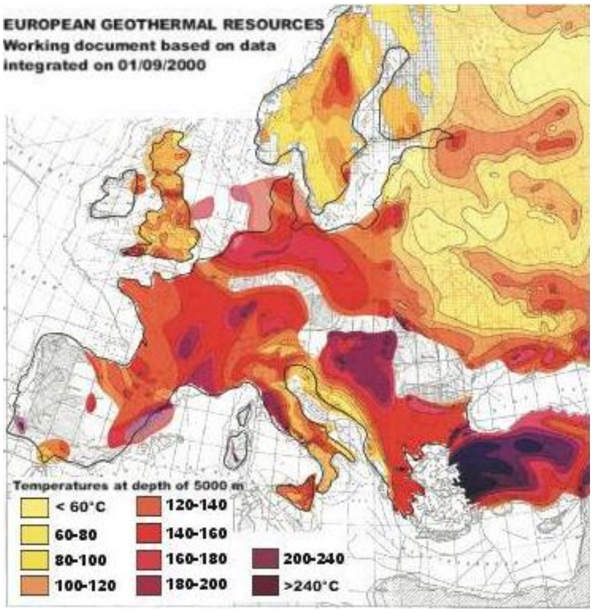

Figure C-3 Estimated Temperature at 5 km depth in Europe [87]

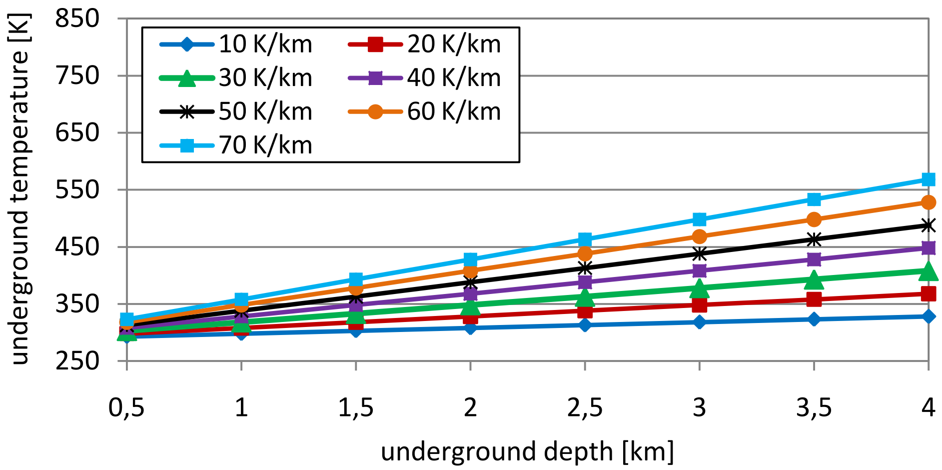

Figure C-4 Underground temperature versus underground depth

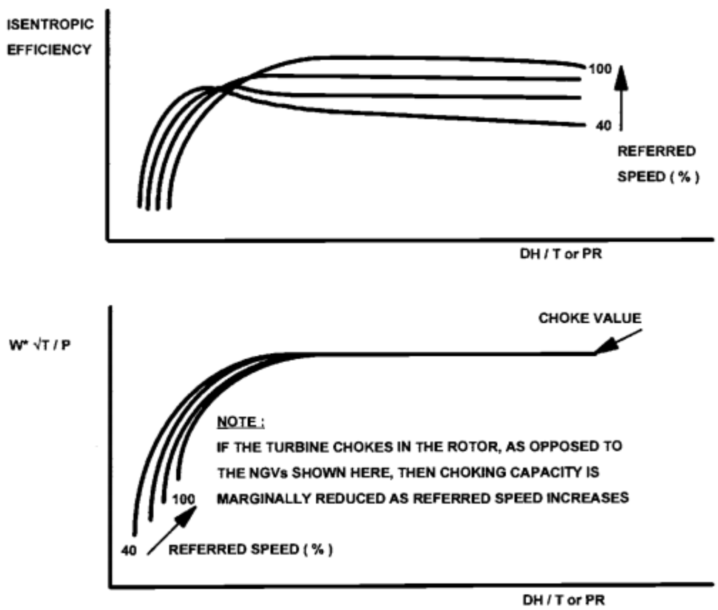

Figure C-5 Turbine Maps [26]

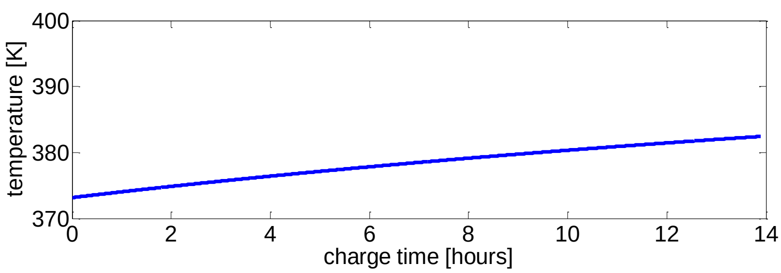

Figure C-6 Water temperature inside the TES (30000 m^3)

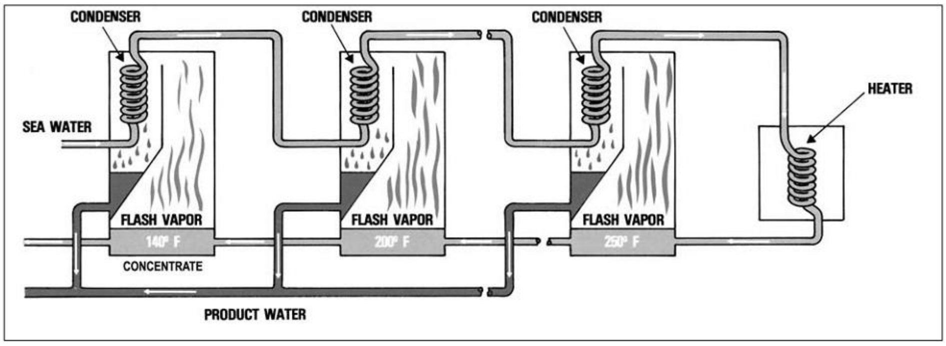

Figure C-7 Multiple Effect Flash [41]

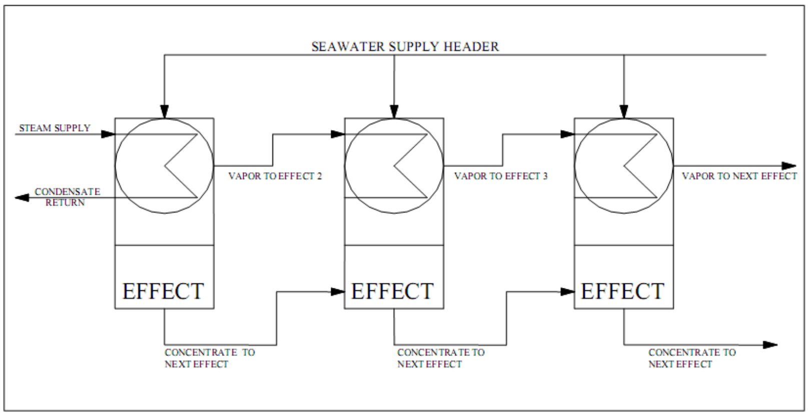

Figure C-8 Multiple Effect Distillation [41]

Appendix D: Verification of the models

Despite the effort to introduce the right values in order to verify the models created, the literature do not propose all the data and sometimes different data for the same parameters of the plant are proposed.

Table D-1 Real and simulated data of McIntosh plant [20]

		real data	simulation data [output]
Rated Generation Capacity (MW)		110	109,6
Generation Hours at 100 MW		26	≈25,5
Generation Hours at 110 MW			≈23,5
Compression hours		41	≈38
Compression hours / Generation hours		1,6	≈1,6
Heat Rate [kJ/kWh, gas LHV] [110 MW]		4330	4299
Compression energy per kWh output		0,69	0,70
2^{nd} Turbine Outlet Temperature [K]		644	675
Recuperator Outlet Temperature [K]		558	583
Cavern Volume [m^3]		538000	
Cavern Temperature, normal [K]		308,15	
Generation train			
	Fuel	natural gas, diesel, oil	natural gas
	Mass Flow at 110 MW [kg/s]	154,40	
	Mass Flow at 100 MW [kg/s]	142,83	
HP Expander			
	Inlet Temperature [K]	810,15	
	Inlet Pressure [bar]	44,81	
LP Expander			
	Inlet Temperature [K]	1144,15	
	Inlet Pressure [bar]	14,68	
Compressor train			
	Compression Power [MW]	49,00	
	Low pressure compressor PR	3,80	
	Intermediate pressure compressor PR	6,24	
	High pressure compressor PR	3,2	

Table D-2 Real and simulated data of Huntorf plant [8]

		real data	simulation data [output]
Rated Generation Capacity (MW)		290	291
Compression hours		12	≈12
Generation Hours at 290 MW [417 kg/s]		3	≈3
Heat Rate during Generation [kJ/kWh, gas LHV]		5860	5890
Compression Energy per kWh Output [input power 60 MW]		0,8	0,77
Fuel Energy per kWh Output [LHV 48120 kJ/kg]		1,60	1,63
Cavern Volume (cubic meter)		310000	
Cavern Temperature, normal [K]		308,15	
Generation train			
	Fuel	natural gas	
	Mass Flow at 290 MW [kg/s]	417	
HP Expander	Inlet Temperature [K]	823,15	
	Inlet Pressure [bar]	46	
LP Expander	Inlet Temperature [K]	1098,15	
	Inlet Pressure [bar]	11	
	Turbine Outlet Temperature [K]	673	680
Compressor train	Compression Power [MW]	60	≈60

Appendix E: Adiabatic-CAES

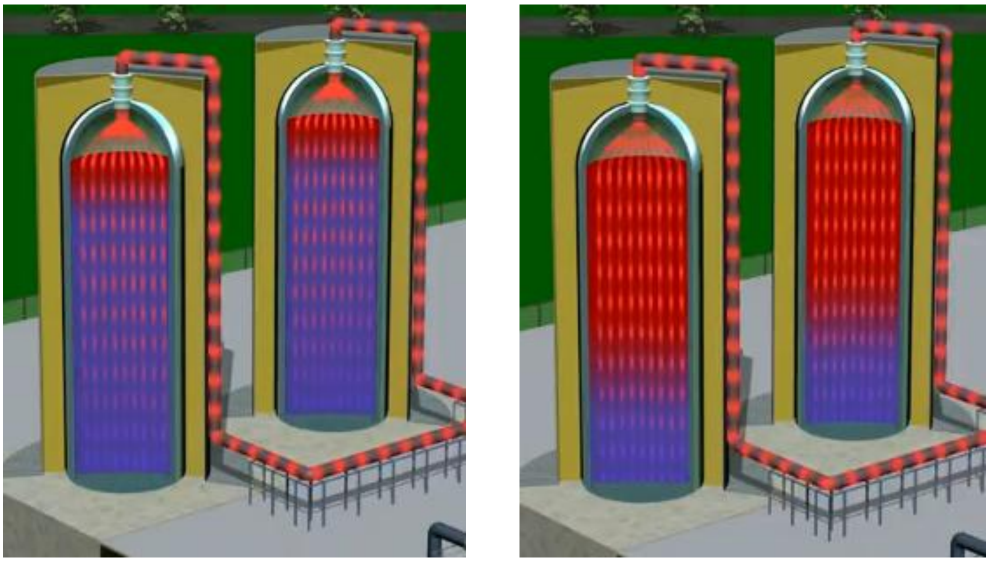

Figure E-1 Thermal Energy Storage [75]

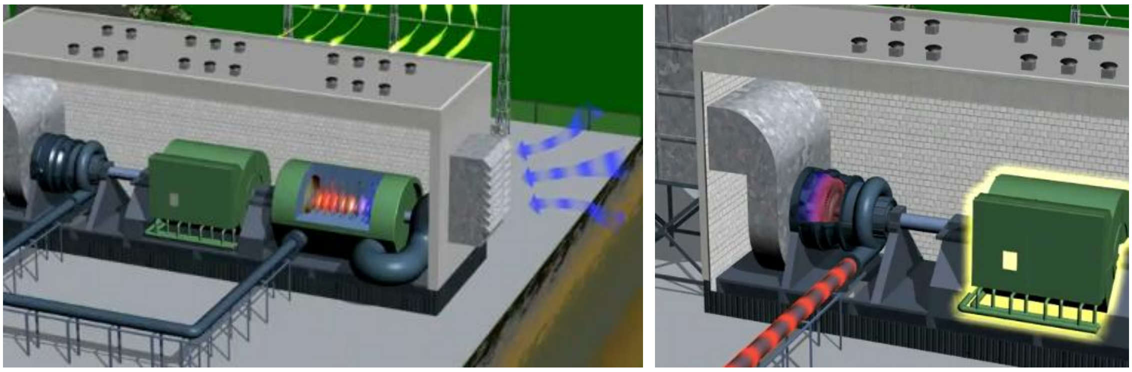

Figure E-2 Compression and Generation in a A-CAES [75]

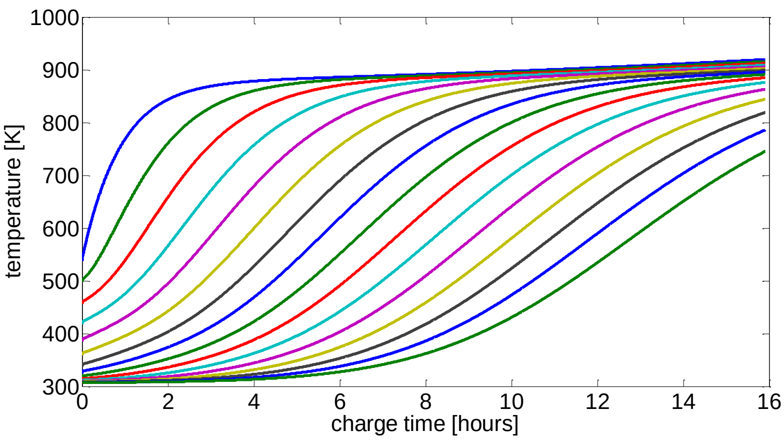

Figure E-3 Charge with TES of 10000 m^3

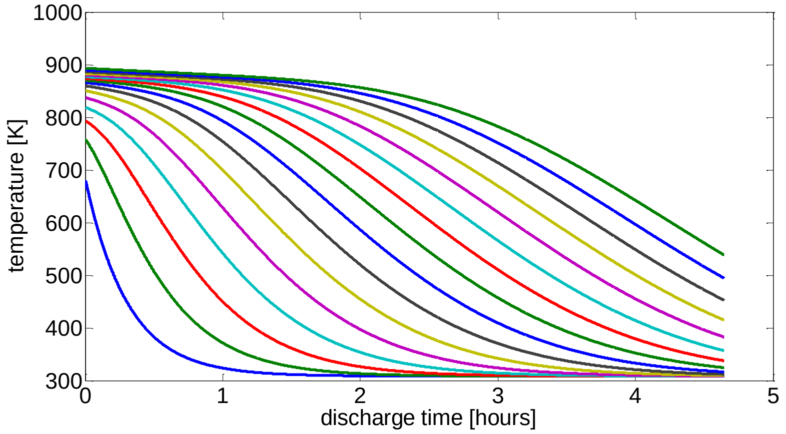

Figure E-4 Discharge with TES of 10000 m^3

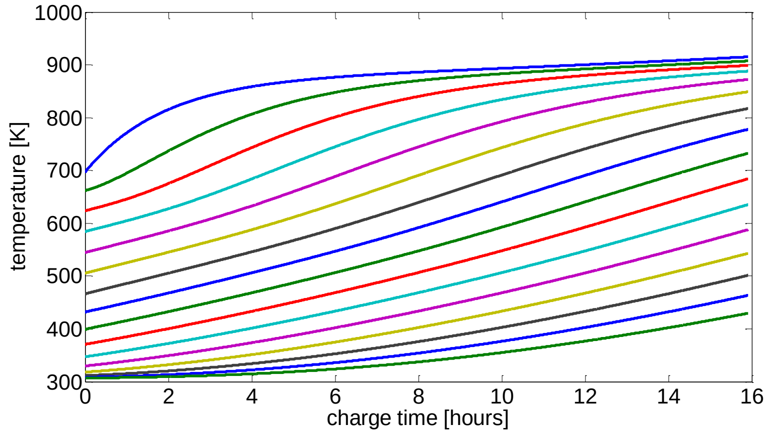

Figure E-5 Charge with TES of 22000 m^3

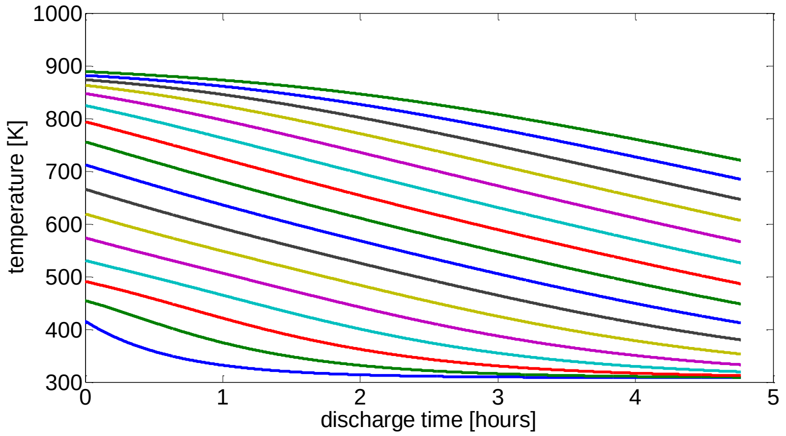

Figure E-6 Discharge with TES of 22000 m^3

Appendix F: Economic analysis of conventional CAES

Table F-1 Annual loan repayment scheme [58]

Year	Interest	Repayment	total payment	Unpaid part of loan at the end of the year
Loan				V_0
1	V_0*i	A_1	V_0*i + A_1	$V_1 = V_0 - A_1$
2	V_1*i	A_2	V_1*i + A_2	$V_2 = V_1 - A_2$
…				
p	V_{P-1}*i	A_P	V_{P-1}*i + A_P	$V_P = V_{P-1} - A_P$
p+1	V_P*i	A_{P+1}	V_P*i + A_{P+1}	$V_{P+1} = V_P - A_{P+1}$
…				
N	V_{N-1}*i	A_N	V_{N-1}*i + A_N	$V_N = V_{N-1} - A_N = 0$

Table F-2 Estimated Well and Reservoir Development Costs for Aquifer CAES [a] [7]

	Site 1: Oneida	Site 2: Rockland County	Site 3: Buffalo
Depth	910	460	610
CAES Well, Each ($)	775,000	480,000	520,000
Well Lateral, Each ($)	100,000	100,000	100,000
Gathering System ($)	2,600,000	2,600,000	2,600,000
Number of Wells	18 - 38	80 – 107	40 - 71
Total Cost ($ per kWh of storage capacity)[b,c]	2.0 – 2.2	5.6 – 7.0	2.7 – 3.4

a. Costs based on a 1994 survey of CAES plant sites in New York State [6] inflation-adjusted to a $2006 basis

b. Wells, laterals and gathering system account for 90% of total cavern development costs. Remaining costs include reservoir characterization activities such as a seismic monitoring array for the candidate site.

c. Storage costs assume a five-to-one ratio of base gas volume to working gas volume. Actual base gas volume ratios will depend on the characteristics of individual sites.

Table F-3 Parameter of the reference case considered

	DP mass flow [kg/s]	DP pressure ratio	efficiency
LP compressor	200	4,1	0,9
MP compressor		4,1	
HP compressor		4,1	
	surface [m^2]		max pressure [MPa]
1st intercooler	4350 [effectiveness 0,8]		0,45
2nd intercooler	4650 [effectiveness 0,8]		1,8
aftercooler	3800 [effectiveness 0,8]		8,5
recuperator	8800 [effectiveness 0,85]		8,5
	DP mass flow [kg/s]	TIT [K]	pressure losses [%]
HP combustor	410	1144	3,5
LP combustor		1473	3,5
	DP mass flow [kg/s]	TIT [K]	DP expansion ratio
HP turbine	410	1144	4,3
LP turbine		1473	11,3

Table F-4 Total Investment Cost of the reference case analysed

MACHINERY	COSTS [$]
HP compressor	$ 1.157.000
MP compressor	$ 1.157.000
LP compressor	$ 1.157.000
1st intercooler	$ 1.421.850
2nd intercooler	$ 2.194.900
aftercooler	$ 2.949.050
recuperator	$ 5.264.100
HP combustor	$ 6.596.000
LP combustor	$ 7.193.450
HP turbine	$ 6.865.400
LP turbine	$ 11.413.100
generator	$ 23.486.700
TOTAL	**$ 70.855.550**

TOTAL INVESTMENT COST	
PIC (plus 5% unlisted)	$ 74.398.300
PSBC	$ 49.811.500
SITE DEVELOPMENT COST	$ 7.122.200
INITIAL SPARE COST	$ 1.116.000
TOTAL DIRECT COST	**$ 132.448.000**
TOTAL INDIRECT	**$ 33.906.700**
CONTINGENCY [15%]	**$ 19.867.200**
TOTAL INVESTMENT COSTS	**$ 186.221.900**
Cost [$/kWe] [436,5 MW]	
426,6	

Table F-5 Total Investment Cost of the reference case analysed without recuperator

MACHINERY	COSTS [$]
HP compressor	$ 1.157.000
MP compressor	$ 1.157.000
LP compressor	$ 1.157.000
1st intercooler	$ 1.421.850
2nd intercooler	$ 2.194.900
aftercooler	$ 2.949.050
recuperator	$ 0
HP combustor	$ 6.596.000
LP combustor	$ 7.193.450
HP turbine	$ 6.865.400
LP turbine	$ 11.413.100
generator	$ 23.921.000
TOTAL	**$ 66.025.750**

TOTAL INVESTMENT COST	
PIC (plus 5% unlisted)	$ 69.327.000
PSBC	$ 46.416.150
SITE DEVELOPMENT COST	$ 6.636.700
INITIAL SPARE COST	$ 1.039.900
TOTAL DIRECT COST	**$ 123.419.750**
TOTAL INDIRECT	**$ 31.595.450**
CONTINGENCY [15%]	**$ 18.512.950**
TOTAL INVESTMENT COSTS	**$ 173.528.150**
Cost [$/kWe] [445 MW]	
390,0	

Table F-6 TIC for a generation train composed of three turbines

MACHINERY	COSTS [$]
HP compressor	$ 1.157.000
MP compressor	$ 1.157.000
LP compressor	$ 1.157.000
1st intercooler	$ 1.421.850
2nd intercooler	$ 2.194.900
aftercooler	$ 2.949.050
recuperator	$ 5.255.850
HP combustor	$ 6.596.000
MP combustor	$ 7.193.450
LP combustor	$ 7.193.450
HP turbine	$ 2.497.550
MP turbine	$ 7.849.600
LP combustor	$ 7.849.600
generator	$ 26.584.300
TOTAL	**$ 81.056.600**

TOTAL INVESTMENT COST	
PIC (plus 5% unlisted)	$ 85.109.300
PSBC	$ 56.982.800
SITE DEVELOPMENT COST	$ 8.147.550
INITIAL SPARE COST	$ 1.276.650
TOTAL DIRECT COST	**$ 151.516.300**
TOTAL INDIRECT	**$ 38.788.200**
CONTINGENCY [15%]	**$ 22.727.450**
TOTAL INVESTMENT COSTS	**$ 213.031.950**
Cost [$/kWe] [497,3 MW]	
428,4	

Table F-7 TIC for different mass flow of the generation train

DP mass flow	325 kg/s	350 kg/s	375 kg/s
Power generated	354,4 MW	381,7 MW	409 MW
Machinery Cost	**$ 59.264.800**	**$ 62.845.800**	**$ 66.459.700**
PIC (plus 5% unlisted)	$ 62.228.000	$ 65.988.100	$ 69.782.650
PSBC	$ 41.663.200	$ 44.180.700	$ 46.721.250
SITE DEVELOPMENT COST	$ 5.957.100	$ 6.317.100	$ 6.680.350
INITIAL SPARE COST	$ 933.400	$ 989.850	$ 1.046.750
TOTAL DIRECT COST	**$ 110.781.700**	**$ 117.475.750**	**$ 124.231.000**
TOTAL INDIRECT	**$ 28.360.100**	**$ 30.073.800**	**$ 31.803.150**
CONTINGENCY [15%]	**$ 16.617.250**	**$ 17.621.350**	**$ 18.634.650**
TOTAL INVESTMENT COSTS	**$ 155.759.050**	**$ 165.170.900**	**$ 174.668.800**
Specific Cost [$/kW$_e$]	**439,5**	**432,7**	**427,1**

Table F-8 CAES with TES of waste heat

MACHINERY	COSTS [$]
compressors	$ 3.471.000
heat exchangers	$ 13.378.550
combustors	$ 13.789.400
turbines	$ 18.278.500
generator	$ 23.486.700
TOTAL	**$ 72.404.150**

TOTAL INVESTMENT COST	
PIC (plus 5% unlisted)	$ 91.774.400
PSBC	$ 61.445.300
SITE DEVELOPMENT COST	$ 8.785.600
INITIAL SPARE COST	$ 1.376.600
TOTAL DIRECT COST	**$ 163.381.900**
TOTAL INDIRECT	**$ 41.825.800**
CONTINGENCY [15%]	**$ 24.507.300**
TOTAL INVESTMENT COSTS	**$ 229.715.200**
Cost [$/kWe] [436,5 MW]	
526,3	

Table F-9 CAES without HP combustor

MACHINERY	COSTS [$]
compressors	$ 3.471.000
intercoolers	$ 6.565.750
recuperator	$ 8.953.000
LP combustor	$ 7.018.000
turbines	$ 18.278.500
generator	$ 22.437.600
TOTAL	**$ 66.723.850**

TOTAL INVESTMENT COST	
PIC (plus 5% unlisted)	$ 70.060.100
PSBC	$ 46.907.000
SITE DEVELOPMENT COST	$ 6.706.900
INITIAL SPARE COST	$ 1.050.900
TOTAL DIRECT COST	**$ 124.724.900**
TOTAL INDIRECT	**$ 31.929.600**
CONTINGENCY [15%]	**$ 18.708.750**
TOTAL INVESTMENT COSTS	**$ 175.363.250**
Cost [$/kWe] [412 MW]	
421,6	

Table F-10 Parameters of the configuration with low TITs

	DP mass flow [kg/s]	DP pressure ratio	efficiency
LP compressor	110	7,8	0,9
HP compressor		7,8	
	surface [m^2] [effectiveness 0,8]		max pressure [MPa]
intercooler	2500		0,84
aftercooler	2250		7
recuperator	5850		7
	DP mass flow [kg/s]	TIT [K]	pressure losses [%]
HP combustor	410	823	3
LP combustor		1098	3
	DP mass flow [kg/s]	TIT [K]	DP expansion ratio
HP turbine	410	823	4,1
LP turbine		1098	10,5

Table F-11 TIC of the configuration with low TITs

	reference	NO recuperator	3 compressors
Power generated	289,5 MW	294,5 MW	289,5 MW
Machinery Cost	**$ 57.197.450**	**$ 53.670.550**	**$ 56.179.450**
PIC (plus 5% unlisted)	$ 60.057.150	$ 56.354.000	$ 58.988.200
PSBC	$ 40.209.750	$ 37.730.400	$ 39.494.050
SITE DEVELOPMENT COST	$ 5.749.300	$ 5.394.800	$ 5.647.000
INITIAL SPARE COST	$ 900.850	$ 845.550	$ 884.850
TOTAL DIRECT COST	**$ 106.917.050**	**$ 100.324.750**	**$ 105.014.100**
TOTAL INDIRECT	**$ 27.370.800**	**$ 25.683.100**	**$ 26.883.600**
CONTINGENCY [15%]	**$ 16.037.550**	**$ 15.048.700**	**$ 15.752.100**
TOTAL INVESTMENT COSTS	**$ 150.325.400**	**$ 141.056.550**	**$ 147.649.800**
Specific Cost [$/kW$_e$]	**519,3**	**479,0**	**510,0**

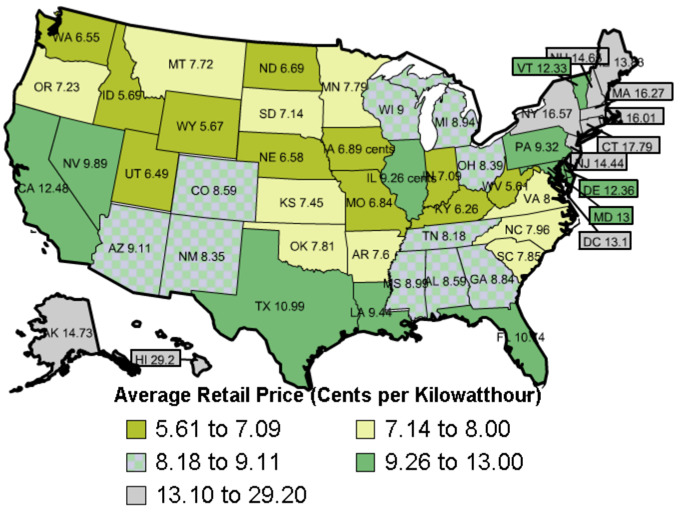

Figure F-1 Average price of electricity in U.S. [76]

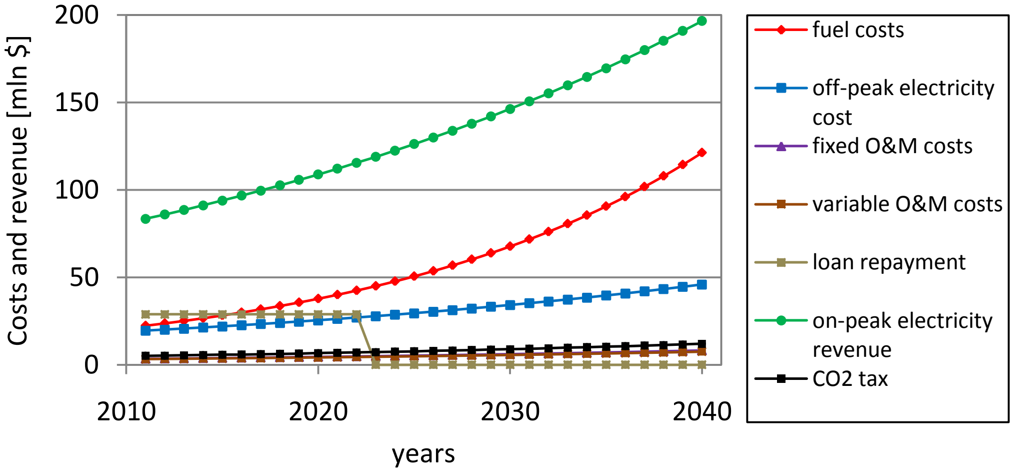

Figure F-2 Costs component trend in the economic analysis

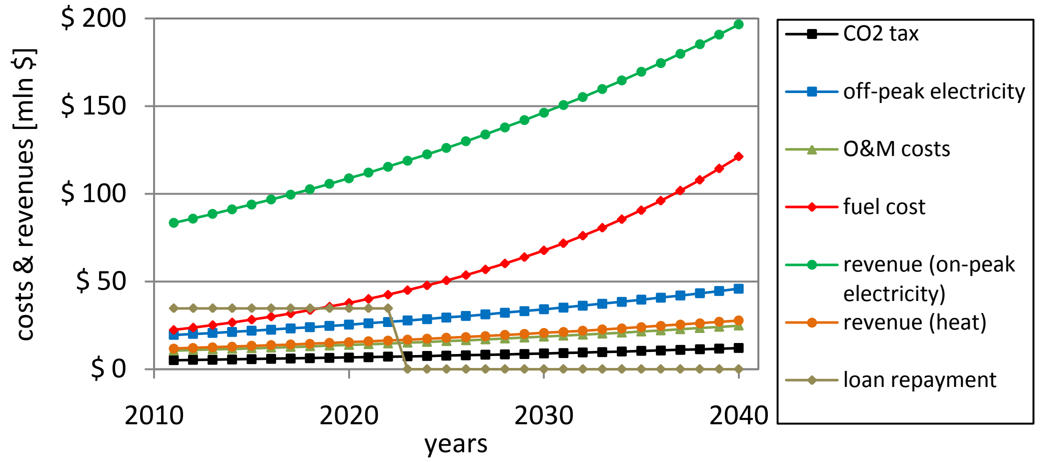

Figure F-3 Costs component trend in the economic analysis

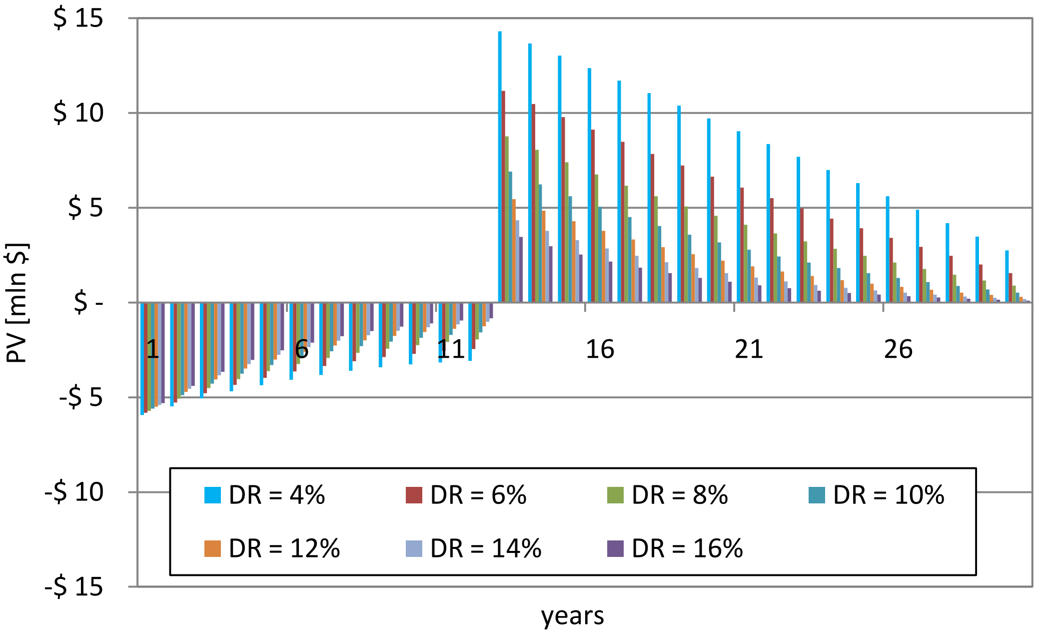

Figure F-4 Discount ANCF for different DR

Appendix G: Economic analysis of Adiabatic CAES

Table G-1 Parameter of the A-CAES analysed

	DP mass flow [kg/s]	DP pressure ratio	Efficiency
LP compressor	200	3,3	0,9
MP compressor		3,3	
HP compressor		6,6	
	surface [m^2]		max pressure [MPa]
intercooler	700		3,5
aftercooler	1350		8
	DP mass flow [kg/s]	TIT [K]	DP expansion ratio
HP turbine	500	853	7,75
LP turbine		500	7,75

Table G-2 TIC calculation for the A-CAES with generation at 500 kg/s

MACHINERY	COSTS [$]
HP compressor	$ 788.000
MP compressor	$ 788.000
LP compressor	$ 2.490.950
intercooler	$ 375.700
aftercooler	$ 1.419.650
HP turbine	$ 11.753.750
LP turbine	$ 11.752.450
generator	$ 16.447.600
TES	$ 42.000.000
TOTAL	**$ 87.816.100**

TOTAL INVESTMENT COST	
PIC (plus 5% unlisted)	$ 92.208.200
PSBC	$ 61.735.750
SITE DEVELOPMENT COST	$ 8.827.150
INITIAL SPARE COST	$ 1.383.100
TOTAL DIRECT COST	**$ 164.154.200**
TOTAL INDIRECT	**$ 42.023.500**
CONTINGENCY [15%]	**$ 24.623.100**
TOTAL INVESTMENT COSTS	**$ 230.800.800**
Cost [$/kWe] [300 MW]	
769,3	

Table G-3 TIC calculation for the A-CAES with generation at 350 kg/s

MACHINERY	COSTS [$]
HP compressor	$ 788.000
MP compressor	$ 788.000
LP compressor	$ 2.490.950
1st intercooler	$ 375.700
aftercooler	$ 1.419.650
HP turbine	$ 8.227.650
LP turbine	$ 8.226.450
generator	$ 12.514.400
TES	$ 42.000.000
TOTAL	**$ 76.830.800**

TOTAL INVESTMENT COST	
PIC (plus 5% unlisted)	$ 80.673.500
PSBC	$ 54.012.900
SITE DEVELOPMENT COST	$ 7.722.900
INITIAL SPARE COST	$ 1.210.000
TOTAL DIRECT COST	**$ 143.619.300**
TOTAL INDIRECT	**$ 36.766.600**
CONTINGENCY [15%]	**$ 21.542.900**
TOTAL INVESTMENT COSTS	**$ 201.928.800**
Cost [$/kWe] [225 MW]	
897,4	

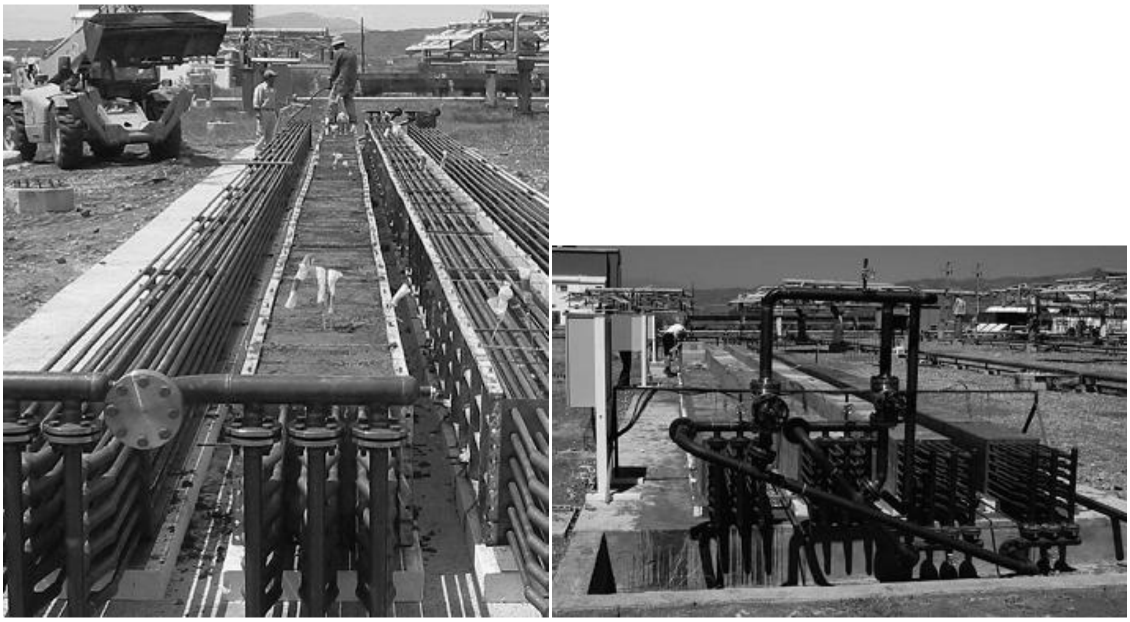

Figure G-1 Building process of thermal energy storage with solid medium [69]

Appendix H: Peaking Power Plants

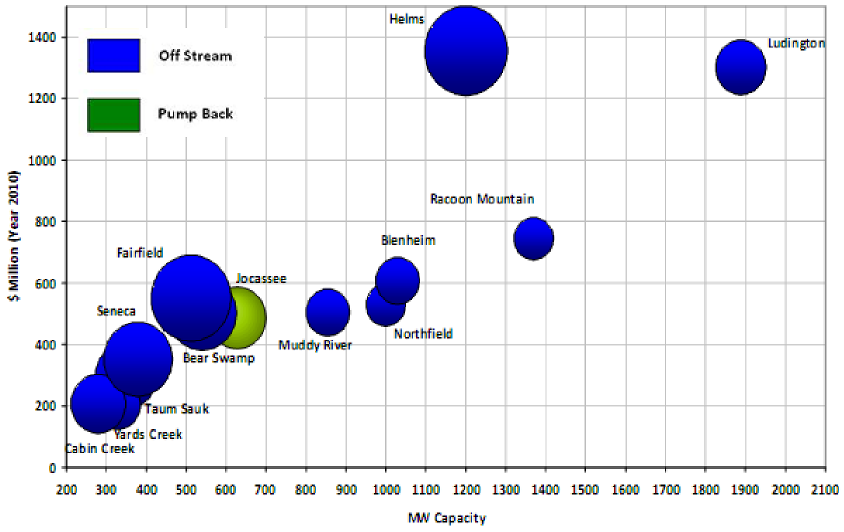

Figure H-1 Proposed Pumped Hydro Energy Storage costs in U.S. [90, 91]

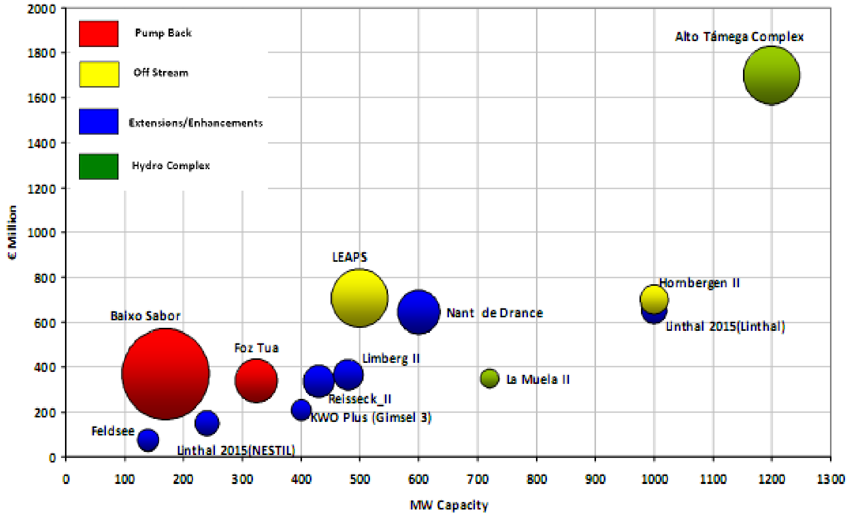

Figure H-2 Proposed PHES costs in Europe [90, 91]

Table H-1 Specific costs for different Pumped Hydro Energy Storage Sizes [92]

	Sizing of Plant	Overnight Cost
Mini	< 1 MW	5,000 $/kW
Small	> 1 MW, < 10 MW	3,500 $/kW
Medium	>10 MW, < 50 MW	2,500 $/kW
Large	>50 MW, <200 MW	1,800 $/kW
Extra Large	>200 MW	1,300 $/kW