CAES Compressed Air Energy System: Dynamic Simulation & Optimization

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Abstract: A CAES (Compressed Air Energy System) plant can be considered as a storage system. The purpose is to store air under pressure and then use it, when required, to generate energy. The system is composed of a series of compressors and heat exchangers and the architecture of the plant aims to reduce compression work and improve storage efficiency. The storage tank can be different depending on the case and the final use, so a cave, a combustion chamber or an expander. Currently the plants that have been built are in Germany (plant built in 1978 with a rated power of 290 MW) and in the USA (built in 1991 with a rated power of 110 MW). In both configurations, the plants use saline caves as reservoirs. Lately, different types of plant are being studied, but they are still in the design phase.–

The objective of the present work is, through a steady-state and then a dynamic simulation, to analyze the positive aspects of this technology and its criticalities, trying to optimize its layout. In addition, through a comparison with the few data available on existing plants, create a database of great interest for researchers and experts in the field. Finally, evaluate, based on the data obtained, the possible developments of technology in the context of the "low carbon transition" through the possible use of renewable sources, such as solar photovoltaic, wind and so on.

Keywords: CAES plant, Data analysis, Dynamic simulation, Plant optimization.

INTRODUCTION

In the system of energy generation and transport, with the necessary optimization of the vectorization of electricity, accumulation systems are becoming increasingly important. In the case of very complex and integrated grids, these systems must be characterized by a storage capacity depending on the energy generated, depending on the size of the system itself. Current technologies (in the field of storage) allow to respond satisfactorily to the demand of users and possibly to buy energy at a favorable price and sell it at an increased cost. This entrepreneurial philosophy allows a very fast recovery of the investment to build the storage facility. Finally, these systems will become vital, within the electricity system, as the drift towards the use of renewable sources, characterized by a marked "randomness", makes their use indispensable. With the percentage increase of renewable energy sources, the system will always require more flexibility. In fact, wind energy is uncertain and not constant in time, and PV-generated electricity follows a daily curve that is also affected by non-negligible oscillations that cannot be completely foreseen. The various systems and subsystems must be able to manage numerous sources within a large geographical distribution. Their storage capacity will allow them to be available both in the event of a peak in demand and in the time, the slots characterized by lower demand. Storage systems thus become essential to ensure the reliability and flexibility of the network [1, 2]. These systems are designed according to the power required to meet both the transients and the total energy needed to combine "green (*i.e.* from renewable sources)" production with loads over time. Installing batteries, super capacitors or any type of flywheel, allows to mitigate time fluctuations. These technologies can provide short duration services related to power quality and stabilization but are not cast effective options far load shifting and wind generation support; besides, they are limited to relatively small installations. Thermal energy storage may be useful for storing solar energy generated at midday to meet evening demands. Currently, the two main technologies capable of delivering several hours of output at a plant-level output scale with attractive system costs are limited to Pumped Hydro Electric Systems (PHES) and Compressed Air Energy System (CAES). Storage, specifically via PHES and CAES, can address ramping rates problems and help correlate generation and loads. Although PHES is not fossil-fuel based and enjoys a larger number of field implementations than CAES, it is economically viable [3-5] only at sites where reservoirs at differential elevations are available or can be constructed at a manageable cast. Furthermore, the environmental impacts of large-scale PHES facilities are becoming more relevant, as the sites where PHES facilities can be built are becoming increasingly rare. In contrast, CAES can use a broad range of reservoirs for air storage and has a more modest surface footprint, giving it a greater siting flexibility relative to PHES.

1. REVIEW OF EXISTING CAES POWER PLANTS

CAES technology can be considered a low-cost technology, despite the ability to store a large amount of electrical energy, in the form of pressurized energy. It can work for long periods, and its size can vary from a few hundred watts to the megawatt. The air can be

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stored in surface tanks, but for large plants it is preferred to use underground quarries, abandoned mines or saline aquifers. In addition, the capital cost to expand the storage capacity is proportionally low, a CAES plant can provide energy for a long time and to respond to base-load energy demand. [6-8]. In a wind farm, CAES systems can store the surplus generated by the plant in the event of an energy demand reduction, and to compensate, by providing electricity, for periods of plant downtime. Also, in the field of wind energy, CAES plants can quickly follow the cut-off transient and operate at partial load with good efficiency. The system is therefore suitable for counterbalancing the characteristic fluctuations of wind energy. Finally, from an environmental point of view, the emissions of this storage system can balance the characteristic CO_2 footprint of the wind farm.

The operation of the CAES plant is like that of gas turbines [9-12]. The difference lies in the fact that the compression and expansion transformations take place separately and independently of each other. since the compressor is powered separately, it is possible to exploit the entire power available to the turbine to generate electricity. During storage operations, the compressors draw energy from the power grid.

The most important existing CAES plants at industrial scale are two, one in Huntorf near Bremen, Germany and another in McIntosh, Alabama, USA. The successful operation of these two plants has demonstrated the technical viability of CAES technology in load management, spinning reserve, load following and power generation. Even though these two plants have been a technical and commercial success, no additional CAES power plants have been built in recent years. The most likely explanation is that CAES concepts are very rigid for what operating flow rates and pressures are concerned, and this affects the storage depth and volume. These restrictions make it difficult to adjust the plant specification to meet the needs of specific renewable plant capacities, operating modes and sites. An interesting possibility is related to compression transformations. In fact, it is possible to recover the compression heat in thermal energy storage systems (TES). This heat recovery can take place in each of the various compression phases. In this way it is possible to pre-heat the air taken from the tank, without using the fuel, partially or eliminating the use of the fuel. The ADELE project (Germany) is the most important Advanced Adiabatic CAES power plant that will implement this process. The *Huntorf CAES* [4, 5] supplies a nameplate power of about 290 MW and the following figure (Figure **1**) shows the layout of the plant. The Huntorf plant was designed to ensure a storage volume capable of covering, in the case of its use, a period of 2 hours. It was then modified to bring this capacity to 3 hours, always with a view to compensating for production from wind power (at that time rapidly growing in Germany). The storage system consists of two salt caves with a total capacity of 310,000 m3, operating at between 48 and 66 bar.-The compression and expansion sections draw 108 and 417 kg/s of air respectively, and each one consists of two sub-sections. The first turbine expands air from 46 bars to 11 bars. To ensure a correct operational mode and to control NOx emissions, the input temperature to the HP turbine is set at 550°C. This temperature - not excessive - at the input to the turbine facilitates daily ignitions. In addition, for the plant there is also the possibility of operating with a lower heat rate, equipping

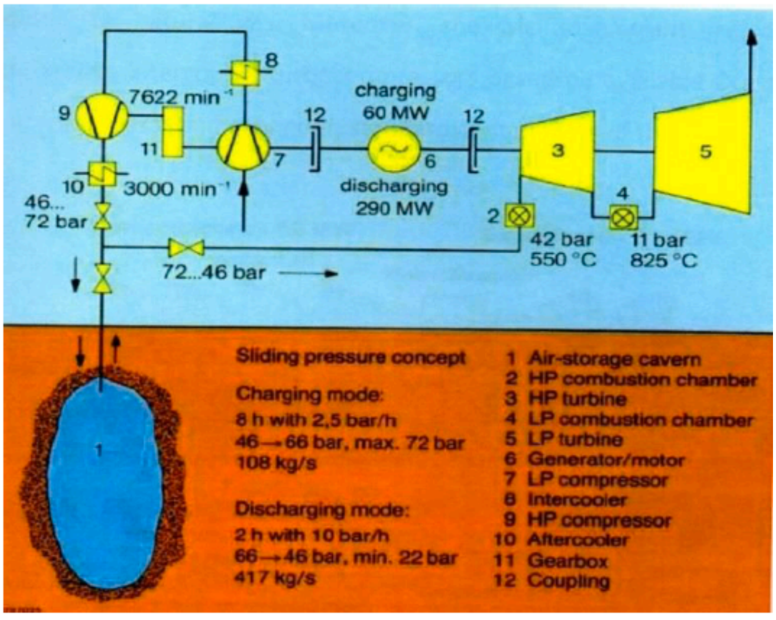


Figure 1: Huntorf CAES plant layout.

it with regenerators, but in this case this option has not been considered to simplify start-up operations.

The 110 MW *McIntosh plant* [7, 9] was built by the Alabama Electric Cooperative on the McIntosh salt dome in south western Alabama and has been operational since 1991. It was designed for 26 hours of generation at full power and uses a single salt cavern (560,000 m^3) designed to operate between 45 and 74 bar. The operating specifications (pressures, temperatures, fluid flow rate, etc.) are quite like the Huntorf ones. However, the McIntosh system provides a heat regenerator that allows a reduction in fuel consumption of about 22% at full load. In addition, the combustion chamber (a dual-fuel combustor) can burn both natural gas and fuel oil. Finally, this system has recuperative intercooled turbo compressors.

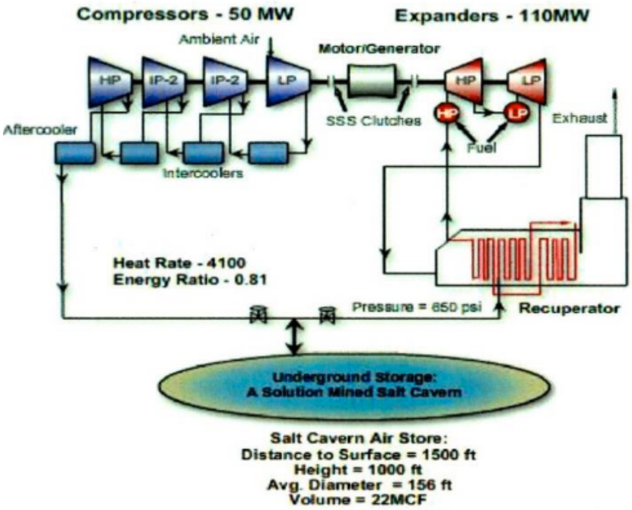


Figure 2: McIntosh CAES plant layout.

The construction of an Advanced Adiabatic Compressed Air Energy System (AA-CAES) project named ADELE (Adiabatic Compressed air Energy System for Electricity Supply) will begin in 2013 in Starβfurt, Germany [7,10]. The aim of the project is to erect a first demonstration plant after 2013 with a storage capacity of one billion watt-hours (GWh) and an electric output of up to 360 MW. This enables ADELE to provide substitute capacity at extremely short notice and replace 50 ultra-modem wind turbines for a period of five hours. ADELE will help provide peak-load electricity from renewable energies, completely without $C0_2$ emissions. Other CAES plants are under development: in Norton, Ohio, into a storage reservoir for an 800 MW CAES facility with provisional plans to generate up to 2,700 MW (9 x 300 MW). In Dallas Centre of 268 MW CAES plant that will be directly coupled to a wind farm of a total 100 MW of wind capacity. In Texas, to install a 540 MW (4 x 135 MW) system in Matagorda County based on the McIntosh design and utilizing a previously developed brine cavern, and in the Shanghai area, a project has been launched for a 300 MW CAES plant.

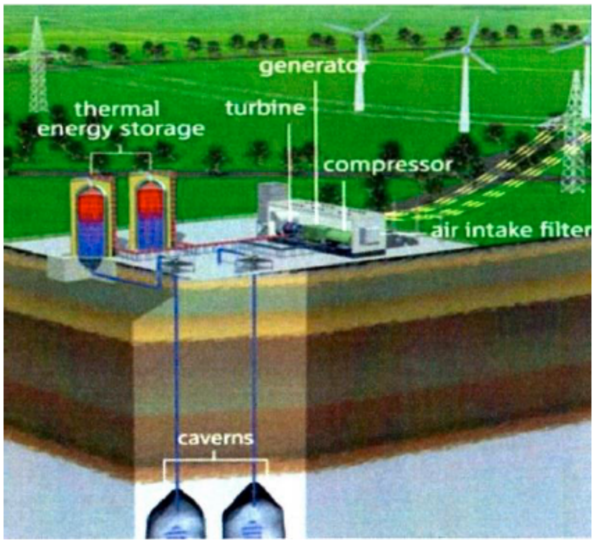


Figure 3: ADELE CAES plant.

2. THE PLANTS SIMULATIONS

The work of this paper consists on the analysis of some different ideal CAES power plants. Different schemes have been analyzed and then, to find the "optimal" solution, efficiency index (related to generation mode, storage mode and a global efficiency) have been computed for each scheme. First, CAES systems can be divided in two different categories:

- Adiabatic
- Other

The Adiabatic CAES [12-15] system is designed to compress air when there is a high availability of electricity, to accumulate the compression heat in a temporary TES and to pump the air into the underground caves. In the event of an increase in demand, the air stored can be sent to the turbines to generate energy. During this operation, the TES releases its energetic contents to the air, so that it is not necessary to burn fuel to heat the fluid. This adiabatic process allows to achieve high efficiency plant since the input of fossil fuels is avoided and differs from existing CAES facilities, above all when it comes to the much higher efficiencies (approx. 70%). Furthermore, this technology permits the CO_2 neutral provision of peak-load electricity from renewable energy. The critical component of the plant is the heat storage tank that could be performed with containers with beds of stones or ceramic molded bricks through which the hot air flows, or with a heat recovery which uses diathermic oil. The other CAES plants are based on the use of a fuel source of energy. The fuel is used as in the conventional GT plants and the exhaust gas are used to heat the compressed air. In general, this CAES category has the advantage to be able to produce electricity even when compressed air is no available. This advantage is paid with lower global efficiencies due to the Carnot limit of thermodynamic energy conversion. In these simulations, it has been started from available schemes that the research group on CAES produced. The same rated power, flow rates, pressures and temperature has been used, to generate a realistic database, in relationship to the technological limit of the facilities. In this work, three concept plant sketches have been carried out:

- Adiabatic CAES;
- CAES-AI-BCE concept with the Air Injection Bottoming Cycle Air Expander;
- CAES-BCE-IC concept with the Bottoming Cycle Air Expander and Inlet Chilling.

2.1. Adiabatic CAES

Cooling of the compressed air and heating of the stored air for power generation are achieved with thermal energy storage. During storage operations, oil

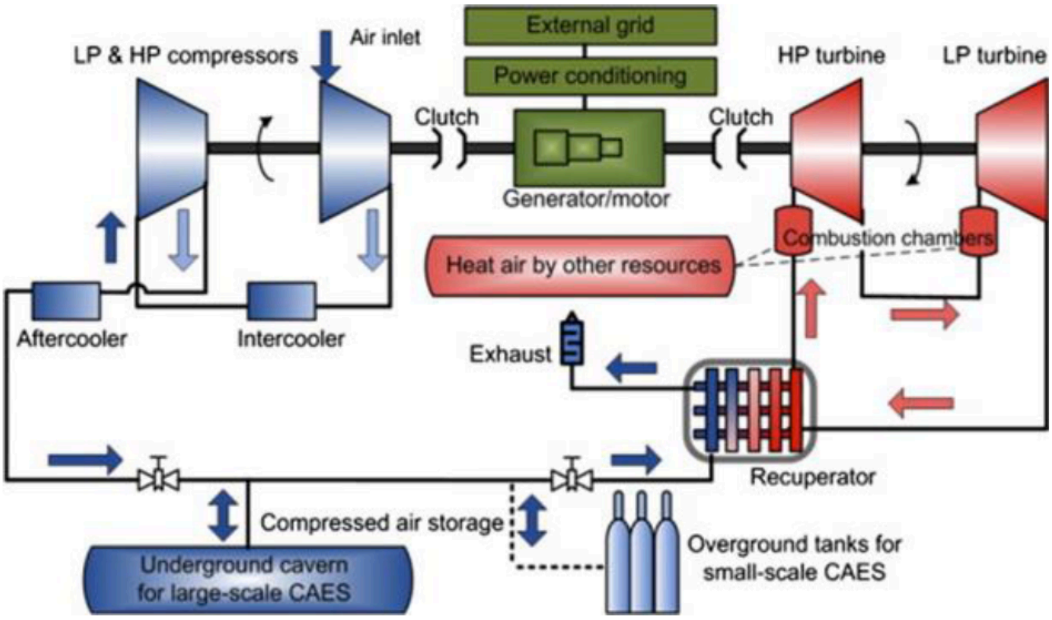


Figure 4: Adiabatic CAES plant layout.

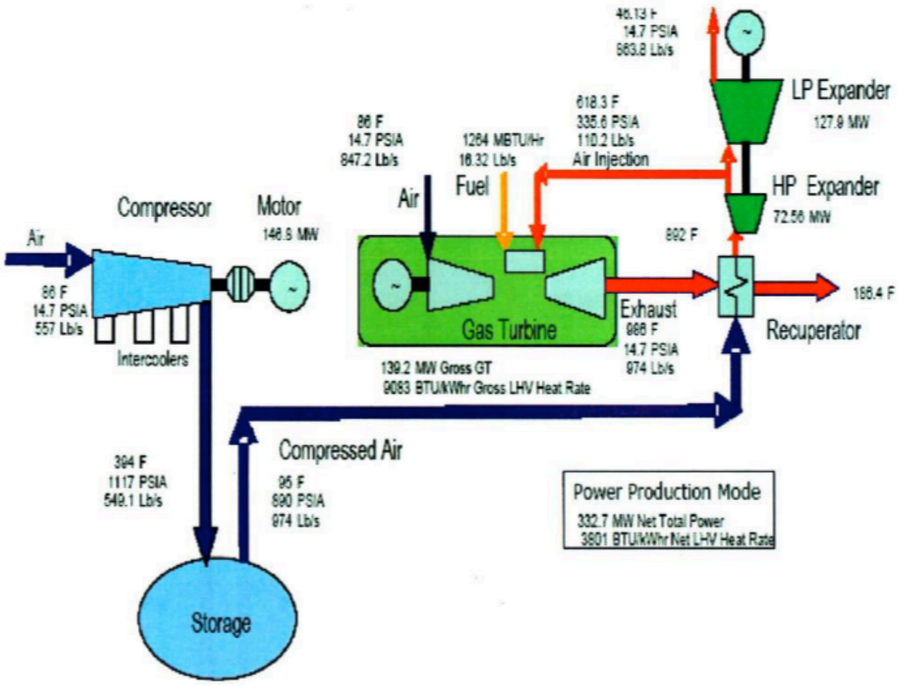


Figure 5: CAES-AI-BCE plant layout.

is used to cool the compressed air and then to heat the stored air. Overall conversion efficiency from off-peak electricity to on-peak electricity is similar to pumped hydroelectric plants (75 to 85%). The key components are the compressors, the thermal oil, the heat exchanger, and air expanders for driving electric generators. In the simulated plant, the air is stored at 90 bars. Both inlet and outlet mass flow rate are 150 kg/s. The nameplate power production is 72 MW.

2.2. CAES-AI-BCE

This plant could be divided in two different parts: the first part is composed by an intercooled compressor driven by an electric motor and the second part is composed by a standard fossil fuel GT with a heat recovery and two expanders. The connection between these two parts is represented by the cavern. During low-demand hours motor extracts power from the net to drive the compressor to inject 250 kg/s of compressed air into the cavern at a pressure of 75 bars. Intercoolers are necessary to increase compression efficiency and to store air at low temperature. During high-demand hours the air is extracted from the cavern with a higher mass flow rate (440 kg/s), heated-up with GT exhaust gases and then is expanded in two stages expanders: after the high-pressure expander a portion of the flow rate goes into combustion chamber to increase turbine flow rate, and so increase the power produced. The other portion of the air from the cavern expands into a low-pressure expander stage and then it is expelled in the atmosphere. During generation mode a surplus power output comes both from the GT and from the two stages expanders, but fuel is needed to heat-up air from the cavern. The net total power of the generation mode is about 333 MW.

2.3. Caes-BCE-IC

This scheme is very similar to the CAES-AI-BCE. In fact, storage mode operates in the same way and in our simulation with the same pressure, mass flow rate and power. The difference consists in the generation mode: air is heated-up by exhaust gases coming from the GT, then there is only one stage expander. Air exits at atmospheric pressure directly into compressor inlet, which increases GT flow rate and the power produced. However, the GT power increase due to inlet temperature that is lower than ambient temperature (less compression work). In relation to the previous scheme, in this case, more fuel is needed to heat-up the air coming from the cavern because there is not hot air injection in the combustor chamber.

3. STEADY STATE SIMULATIONS

For having a comparison with the dynamic simulation, first the steady state simulation for every CAES plant scheme has been carried out [14-16]. To simulate the Adiabatic CAES plant, a specific type of heat recovery was required, so a diathermic oil device has been considered, thanks to its efficiency and practicality. In industrial applications, the diathermic mineral oils are widespread because they have, regarding the use of steam or chemicals, several advantages like wide temperature operational range and possibility of operating at atmospheric pressure. So, there are not required expensive installations. Moreover, the diathermic oil has an excellent lubricity which ensures low wear of pumps and valves and its protective capacity ensures the absence of rust on metal surfaces. The following characteristics are required to the diathermic oils:

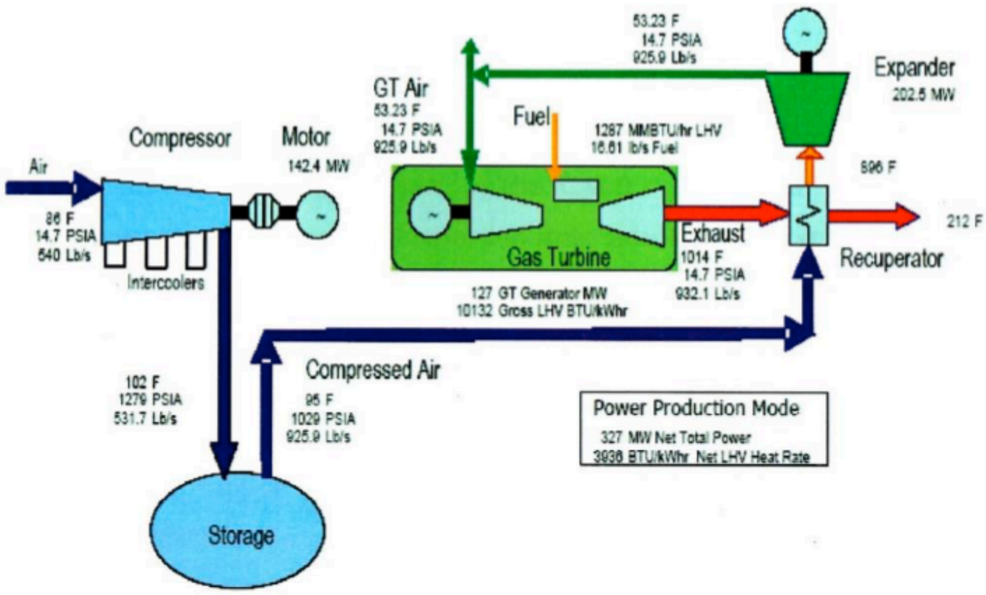


Figure 6: CAES-BCE-IC layout.

- Transfer the heat using small mass flow rates, that means density high enough, good thermal conductivity and a high value of the specific heat;

- Low vapor pressure to avoid the risk of cavitation;

- Low viscosity in operation to limit the head losses.

The oil selected and used in these simulations is a commercial oils series. These are obtained from paraffinic mineral base severely solvent refined of very high-quality level for subsequent filling of diathermic plants either "closed" or "open" system. These diathermic oils are available in different shades to allow users to select the one that best suits their operational needs. The oil characteristics are reported in Table **1**.

Table 1: Diathermic oil Specifications for Simulations

Viscosity at 40°C	16 ÷ 96.3
Viscosity at 100°C	3.3 ÷ 10.9
Viscosity index	105 ÷ 97
Flash point [°C]	194 ÷ 230
Pour point [°C]	-12 ÷ -9
Neutralization Value [mg KOH/g]	≤ 0.03
Conradson carbon residue CCR [%p]	0.01 ÷ 0.097
Copper corrosion (3h at 150°C)	1
Cubic Thermal Expansion coefficient [m^3/°C]	0.00067 ÷ 0.00064
Density [kg/m^3]	856 ÷ 889

As first step, the static simulations have been carried out using a costumer code and successively a commercial one, in such a way to produce a database on which do some considerations and optimization. Static simulation consists in a simulation in a steady-state condition where the dynamic behavior of some component (in this case the "tank") is not consider. Therefore, the inlet air pressure is lower than the inlet tank pressure of a suitable percentage. The performance for CAES systems is a little bit more complicated comparing to a conventional fossil fuel power plant, due to the presence of several different energy inputs: the shaft power delivered to the compressors motor (P_{CM}), the turbine power generated (P_{GT}), the compressor motor required power delivered to the (P_{GC}), the power of the compressed air (P_{air}), the thermal power in the fuel (P_{fuel}) in the BCE configurations and the thermal power in the diathermic oil (P_{oil}) in the adiabatic configuration. These following parameters are so defined:

$$P_{air} = \int \dot{m} \cdot v dp = \dot{m} \cdot R \cdot T_m \cdot \ln(p_{out}/p_{in}) \quad (1)$$

$$P_{fuel} = \dot{m} \cdot LHV \quad (2)$$

$$P_{oil} = \dot{m} \cdot \Delta h \quad (3)$$

SO, it is not so easy to describe CAES efficiency using a single index, because the efficiency index depends on the specific application for CAES. So, a *storage efficiency* η_{stor}, a *generation efficie*ncy η_{gen} and the *global efficiency* η for each kind of CAES, adiabatic and non-adiabatic, have been considered. In the analysis of the efficiencies authors adopted the *specific power* P_{sp} of each component instead of the nominal power, due to in some components flows different mass flow rate:

$$P_{sp} = \frac{P}{\dot{m}} \quad (4)$$

3.1. Adiabatic CAES. Black Box Analysis

To define efficiency, the plant as a black box have been analyzed, for identifying the energy streams into the system. From the black box analysis, it is obtained the fluxes reported in Figure **7**.

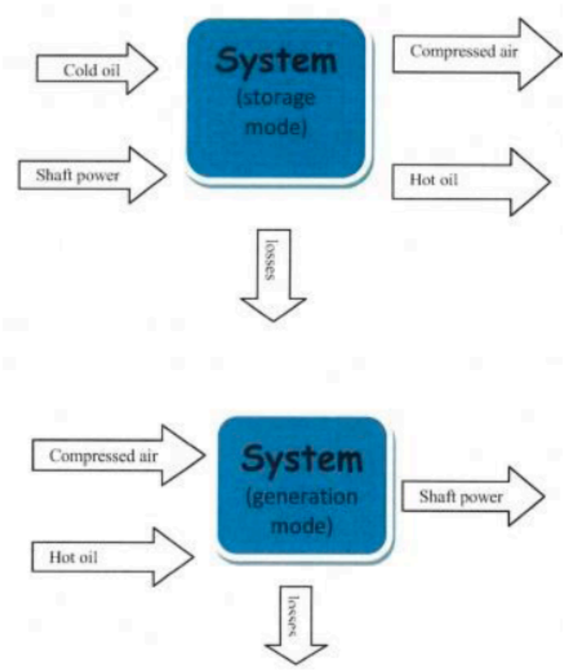


Figure 7: Adiabatic CAES Black Box.

So, it is possible to write:

- Energetic storage mode efficiency:

$$\eta_{sto} = \frac{P_{sp,air}+P_{sp,oil}}{P_{sp,CM}+P_{sp,oil\_in}} \quad (5)$$

- Energetic generation mode efficiency:

$$\eta_{gen} = \frac{P_{sp,GT}}{P_{sp,air}+P_{sp,oil}} \quad (6)$$

These indexes are used in the steady steady simulations, in two different operational mode: storage and generation. The results are summarized in Table **2** and **3** respectively.

Table 2: Storage Operational Mode

Out	Compressed air power [kW]	60165
	Thermal Power [kW]	108152
In	Shaft power 1 [kW]	55379
	Shaft power 2[kW]	47361
	Thermal Power [kW]	77034
η_{sto}	0.928	

Table 3: Generation Operational Mode

Out	Shaft power 1 [kW]	37211
	Shaft power 2 [kW]	33501
In	Compressed air power [kW]	57275
	Thermal Power [kW]	84600
η_{gen}	0.498	

3.2. CAES BCE. Black Box Analysis

As the previous case it starts from a black box analysis to define the different kind of efficiency index: in this case there are only air streams and shaft power

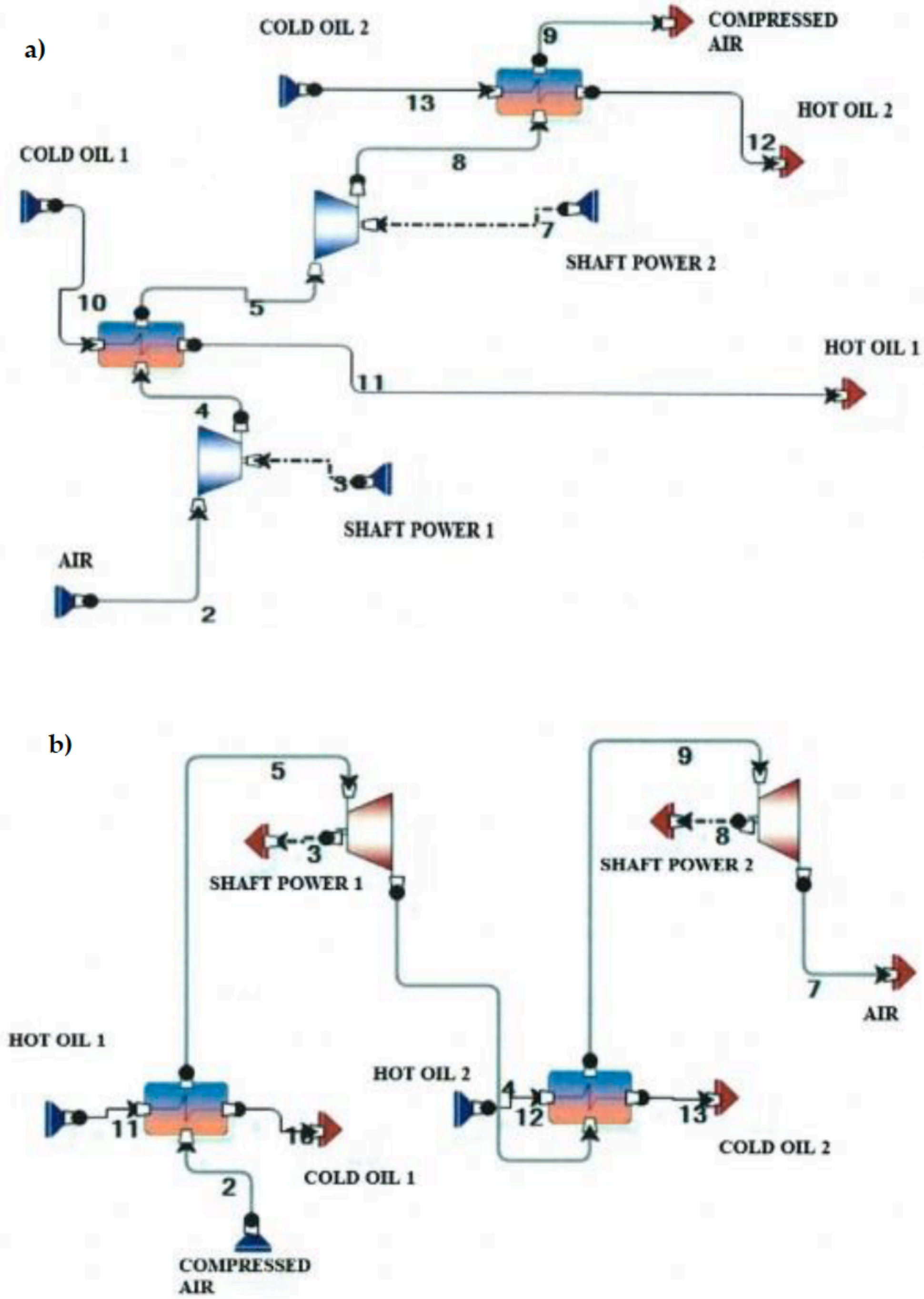


Figure 8: Adiabatic CAES. **a**) Storage Mode; **b**) Generation Mode.

"streams". In fact, such a plant does not use hot air coming from intercoolers.

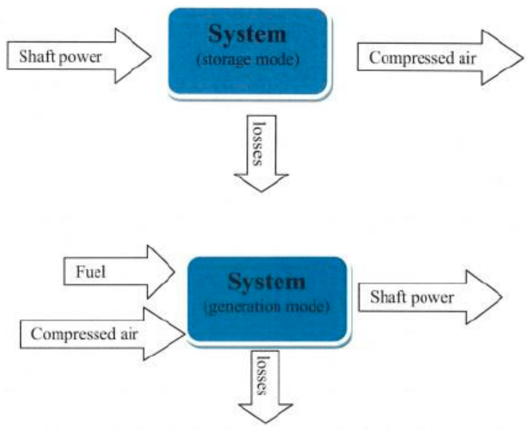


Figure 9: CAES BCE black box analysis.

As previously define:

- Energetic storage mode efficiency:

$$\eta_{sto} = \frac{P_{sp,air}}{P_{sp,CM}} \qquad (5)$$

- Energetic generation mode efficiency:

$$\eta_{gen} = \frac{P_{sp,net}}{P_{sp,fuel} + P_{sp,air}} \qquad (6)$$

3.2.1. CAES AI-BCE

The storage phase (Figure **10a**) consists in air compression with two intercoolers and one aftercooler. The air from intercooler is disposed in the atmosphere. In generation phase (Figure **10b**) there is shaft power production by three expanders and a portion of mass flow rate from one of them is sent to the combustion chamber. The simulations results are reported in Table **4** and **5** respectively.

Table 4: Storage Operational Mode

Out	Compressed air power [kW]	94805
In	Shaft power 1 [kW]	45682
	Shaft power 2 [kW]	48037
	Shaft power 3 [kW]	48296
η_{sto}	0.667	

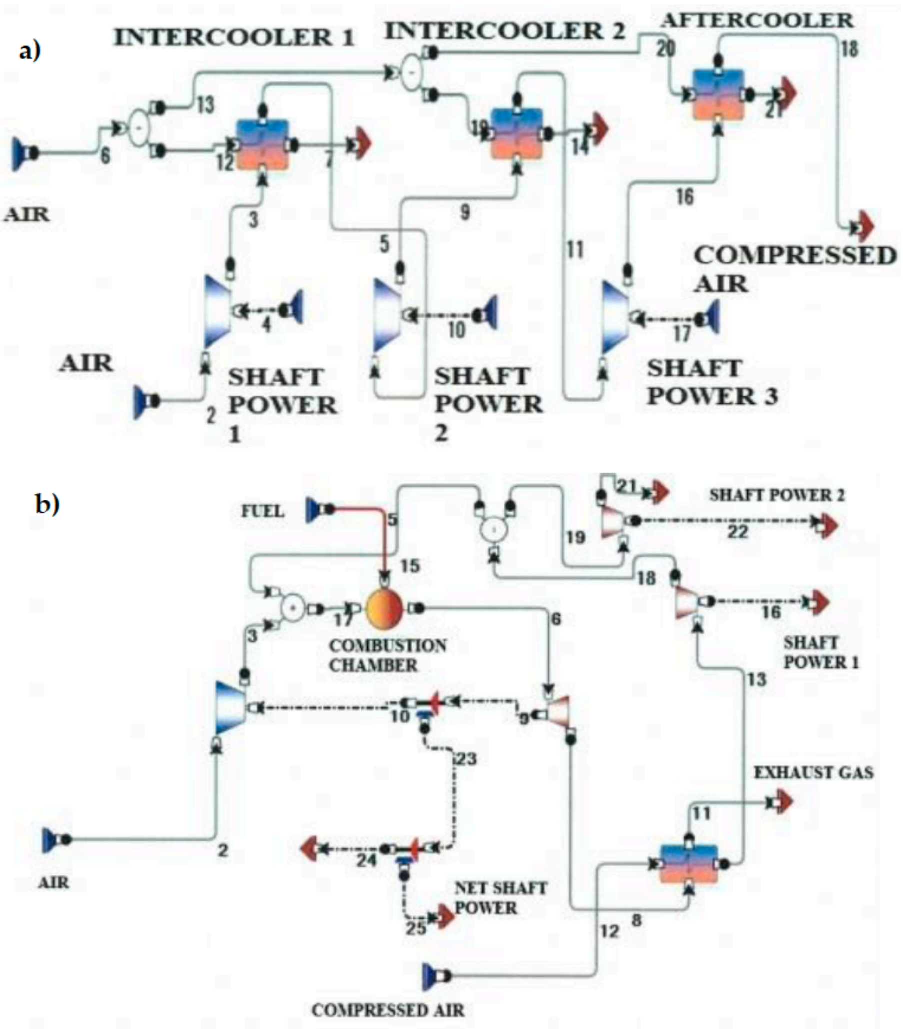


Figure 10: CAES AI-BCE. **a**) Storage Mode; **b**) Generation Mode.

Table 4: Storage Operational Mode

Out	Shaft power net [kW]	106402
	Shaft power 1 [kW]	84999
	Shaft power 2 [kW]	57100
In	Fuel Power [kW]	308998
	Compressed air power [kW]	154511
η_{gen}	0.517	

3.2.2. CAES BCE-IC

The storage mode is the same of the CAES AI-BCE. The difference between AI -BCE and BCE-IC is in the generation mode. In fact, the air at the exit of the cavern, after the heating process, flows through only one expander and after the expansion it goes into the inlet of the compressor. Figure **11** shows the plant layout and Table **6** reports the results.

Table 6: Generation Operational Mode

Out	Shaft power net [kW]	217889
	Shaft power 1 [kW]	154172
In	Fuel power [kW]	671852
	Compressed air Power [kW]	154511
η_{gen}	0.529	

This first phase of simulations suggests some improvements on the BCE plants, to increase the efficiencies.

3.2.2.1. AI-BCE optimization

In this case, through the analysis of the results and the various simulations carried out, it was seen that the parameter to be optimized is the expansion ratio $\beta = p_{in}/p_{out}$ of the first expander, in such a way the outlet pressure (12.27 bar) is almost the same than the pressure of the combustion chamber inlet (12.15 bar) while, in the standard AI -BCE, outlet pressure of the first expander is 20.45 bar and the pressure of the combustion chamber is 12.15 bar (as in the optimized plant). So, it is possible to increase generation mode efficiency by reducing the pressure drop. In Table **7** the results after this optimization.

Table 7: Optimized AI-BCE: Generation Mode

Out	Shaft power net [kW]	106471
	Shaft power 1 [kW]	78803
	Shaft power 2 [kW]	65808
In	Fuel power [kW]	308998
	Compressed air Power [kW]	154511
η_{gen}	0.524 (0.517)*	

* in parentheses the previous value.

3.2.2.2. BCE-IC optimization

As previously case, all simulations indicate that to increase the plant generation efficiency is needed to adopt two expanders instead of the single expander (Figure **12**). After the first expansion a portion of the high-pressure air flow rate goes into combustion chamber at the same pressure of the combustion chamber (11.93 bar), the other portion goes into the second expander and, here, it expands to atmospheric pressure. Then it goes into the compressor to be re-elaborated. Table **8** represents the simulations results.

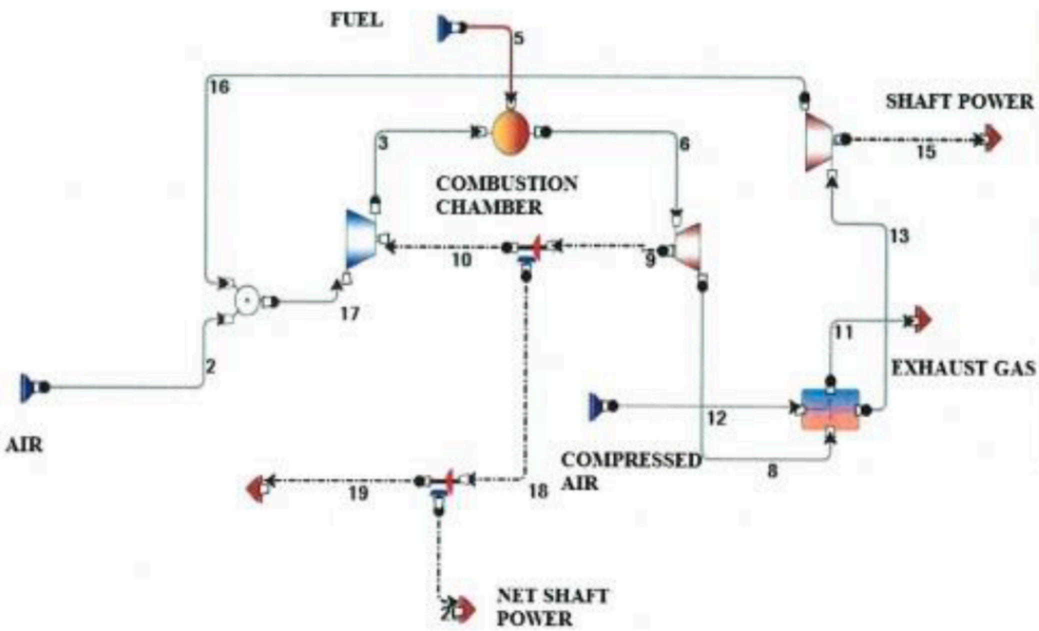


Figure 11: CAES BCE-IC. Generation Mode.

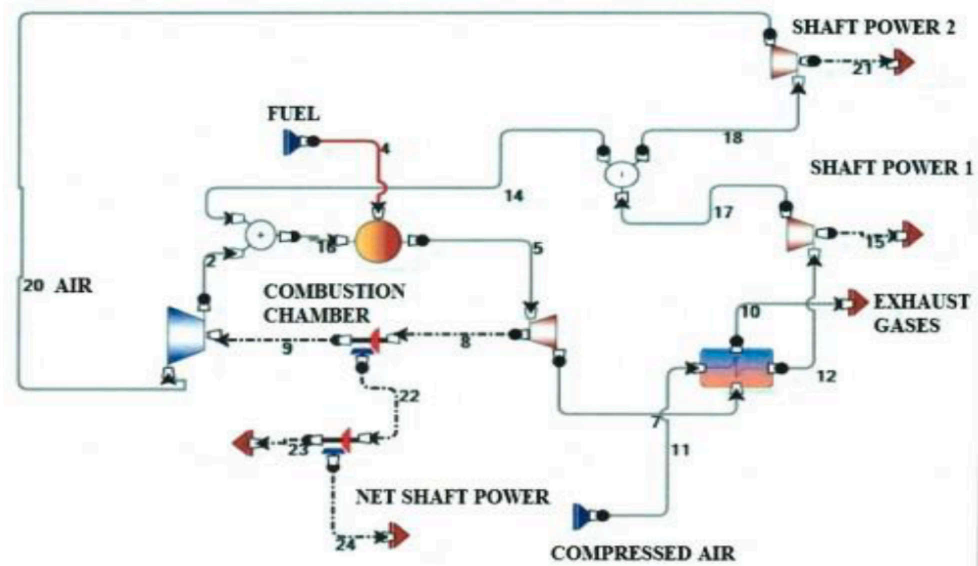


Figure 12: Optimized CAES BCE-IC plant layout.

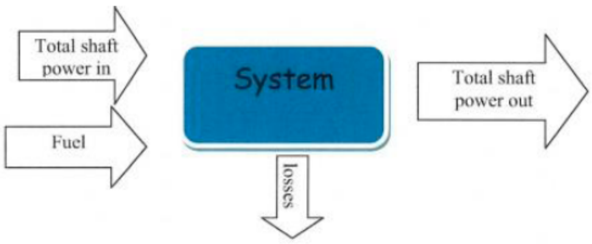
Table 8: Optimized BCE-IC: Generation Mode

Out	Shaft power net [kW]	159838
	Shaft power 1 [kW]	79046
	Shaft power 2 [kW]	66015
In	Fuel Power [kW]	417036
	Compressed air power [kW]	154511
η_{gen}	0.531 (0.529)*	

* in parentheses the previous value.

3.3. Global Efficiency and Steady-State Simulations Final Remarks

Final step of the steady-state simulations is the introduction of a global efficiency index, valid for every kind of CAES, and defined as the ratio of the total shaft power out to the total shaft power in. The black box analysis is represented in Figure **13**, while the collection of all simulations data is described by Figure **14**.



$$\eta = \frac{\text{Net shaft power out}}{\text{Total shaft power in} + \text{Fuel}}$$

Figure 13: Black Box analysis.

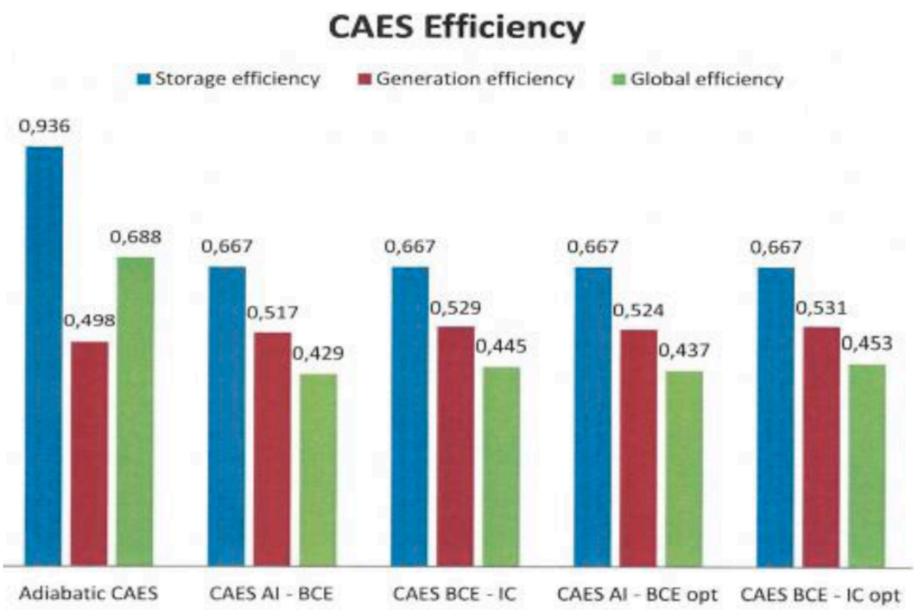


Figure 14: CAES plants efficiency comparison.

In conclusion, it is evident that Adiabatic CAES has the higher global efficiency. In fact, adiabatic means additional use of compression heat to increase efficiency. During compression (storage mode) the heat is not wasted, but it is stored with consequent high storage efficiency (η_{sto} = 0.936). During generation mode the heat-storage device exchange its energy with the compressed air, so no exhaust gas to heat the compressed air is needed. On the other hand, it suffers from several! technological problems because it needs an efficient heat-storage facility and the generation efficiency is lower because the turbine inlet temperature is lower than a common GT. Both nonadiabatic CAES (AI - BCE and BCE - IC) have similar efficiencies. This CAES plant needs exhaust gas to heat up compressed air. The global efficiency is lower than Adiabatic CAES because there is not heat storage, evident considering the storage efficiencies (η_{sto} = 0.667). On the other hand, they do not suffer technological problem because they are composed by standard facilities and components, as well as expanders, compressors, heat-exchanger, and so on. Moreover, for the same nameplate the AI - BCE will be more flexible than the others, but it is reflecting in a more expensive cost of investment.

4. DYNAMIC SIMULATIONS

A complete dynamic simulation of each plant configuration is performed, starting from the steady-state operations under steady rotational velocity of the compressors and the turbines. The goal of the simulation is to compute, in a time lapse, the energy produced by the turbines, the energy absorbed by the compressors, the thermal energy of refrigerants, the amount of fuel used and the efficiency of the plants [17,18]. An essential aspect of any simulation is the analysis of the "characteristic response time" of each component. This response time introduces a delay in the response of a component to a variation of one or more of its boundary conditions, and it depends on several physical parameters:

1. Mechanical inertia:

$$\tau_{mech} = \frac{I \cdot \omega^2}{W_{ref}} \tag{7}$$

Defined as the ratio of the angular acceleration to a reference power. “I” is the equivalent moment inertia of the rotating parts.

2. Thermal inertia:

$$\tau_{th} = \frac{c \cdot M_{sto}}{c \cdot M} \tag{8}$$

as the ratio between the sensible heat stored in the component and the inlet thermal energy rate.

3. Fluid inertia:

$$\tau_{flu} = \frac{M_{con\_com}}{\dot{m}_{in}} \tag{9}$$

the ratio between the mass "contained" in the component and the inlet mass flow rate or rather the inertia associated to the compressibility of the fluid masses in each controlled volume at each instant in time. The inertial terms influence the response times of all the components, then the steps of numerical integration should be selected smaller than the smallest "characteristic response time" of each component. In the dynamic simulation of CAES plants, the compressors and the turbines are assumed to be adiabatic and the heat exchangers are characterized by a constant volume capacity. Since the simulation has been run under steady rotational velocity and constant mass flow rate, the tank is the only component which is necessary to calculate the "characteristic response time" $\boldsymbol{\tau_{flu}}$. At present, in the costumer code, is not possible to run a dynamic simulation with variable integration steps. Since the storage and generation mode operate for hours, to simulate this phase, both considering the characteristic response time and to reduce the computational time required, every mode has been divided into three parts of different length; that because the initial part of the storage and the final part of the generation are those with the most rapid variation of the basic parameters.

Each of these parts must be integrated with an integration step smaller than the smallest characteristic time of the part itself. In order to reduce the computational time of the simulations, an integration step at most one order of magnitude smaller than the maximum characteristic time of the part has been chosen. The corresponding basic parameters are:

t is the simulation time;

M is the mass of air in the tank;

$\dot{m}$ is the air mass flow rate in/out of the tank;

Δt is the lasting time of each section.

4.1. Adiabatic CAES Simulations Results

The storage mode lasts 10 hours and the generation mode lasts 9 hours and 59 minutes. The Tables **9** shows, according with the previous consideration, the basic parameters of each part.

The generation mode lasts 9 hours and 59 minutes. Table **10** shows the results.

Table 9: Adiabatic Storage Mode

	Part I (0 ÷ 10 min.)		Part II (10 min.÷ 1 h)		Part III (1 ÷ 10 h.)	
t [s]	0	600	600	3600	3600	36000
M [kg]	9539	99539	99539	549539	549539	5409539
$\dot{m}$ [kg/s]	150	150	150	150	150	150
τ_{flu} [s]	64	664	664	3664	3664	36064
Δt [s]	600		3000		32400	

Table 10: Adiabatic Generation Mode

	Part I (0 ÷ 9h.)		Part II (9h.÷ 9h 50 min.)		Part III (9h 50 min.÷ 9h 59 min.)	
t [s]	0	32400	32400	35400	35400	35940
M [kg]	5400960	540960	540960	90960	90960	9960
$\dot{m}$ [kg/s]	150	150	150	150	150	150
τ_{flu} [s]	36006	3606	3606	606	606	66
Δt [s]	32400		3000		540	

4.2. BCE-AI and BCE-IC Simulations Results

The storage mode is the same in the two configurations and it lasts 10 hours. The Table **11** shows the basic parameters.

The generation mode of the two configuration lasts 5 hours and 40 minutes; results are shown in Table **12**.

4.3. Discussion on the Simulation Results

The analysis of the energy performance far CAES in the dynamic simulations starts, as in the steady state simulations, by defining a storage efficiency η_{sto}, a generation efficiency η_{gen} and the plant efficiency η. However, it was necessary to consider the energy instead of power. The compressors motor required energy (E_M), the turbines generated energy (E_T), the energy delivered to the compressor motor (E_{CM}), the energy of the compressed air (E_{air}), the fuel thermal energy (E_{fuel}) in the BCE configurations, and the thermal energy of the diathermic oil (E_{oil}) in the Adiabatic configuration.

Table 11: BCE Storage Mode

	Part I (0 ÷ 15 min.)		Part II (15 min.÷ 55 min.)		Part III (55 min ÷ 10 h.)	
t [s]	0	300	300	3300	3300	36000
M [kg]	7787	82787	82787	832787	832787	9007787
$\dot{m}$[kg/s]	250	250	250	250	250	250
τ_{flu} [s]	31	331	331	3331	331	3631
Δt [s]	300		3000		32700	

Table 12: BCE Generation Mode

	Part I (0 ÷ 5h.)		Part II (5h.÷ 5h 35 min.)		Part III (5h 35 min.÷ 5h 40 min.)	
t [s]	0	18000	18000	20100	20100	20400
M [kg]	9006383	1086383	1086383	159088	159088	27087
$\dot{m}$ [kg/s]	440	440	440	440	400	440
τ_{flu} [s]	20469	2469	2469	361	361	61
Δt [s]			2100		300	

These terms are derived from the power previously defined multiplied for the lasting time of each part that forms the operating mode of the CAES. Then for evaluating the efficiencies it was referred to the specific values:

$$E_{sp} = \frac{E}{\dot{m}} \tag{10}$$

The Compressed-air energy storage is similar in its principle to the pumped-storage power plant, then the efficiency of each CAES configuration must be compared to the efficiency of these systems (that is between 75% and 85%).

4.3.1. Adiabatic

The efficiency of the adiabatic configuration is defined as:

$$\eta_{sto} = \frac{E_{sp,air}+E_{sp,oil}}{E_{sp,M}+E_{sp,oil\_in}} \tag{11}$$

$$\eta_{gen} = \frac{E_{sp,T}}{E_{sp,air}+E_{sp,oil}} \tag{12}$$

$$\eta = \frac{E_{sp,T}}{E_{sp,M}} \tag{13}$$

The Table **13** shows the values of the energy terms and the storage, generation, and global efficiency.

The purpose of the Adiabatic Project ("ADELE") is to reach an efficiency around 70%. The results of our simulation are consistent with this. These results have been achieved thanks to the use of the heat storage device that releases the compression heat into the compressed air. Furthermore, the input of fossil fuel is avoided since no gas combustion to heat the compressed air is needed.

4.3.2. BCE

In the Black-Box analysis the efficiency has the same expression for the two configurations IC and AI:

$$\eta_{sto} = \frac{E_{sp,air}}{E_{sp,M}} \tag{14}$$

$$\eta_{gen} = \frac{E_{sp,T} - E_{sp,CM}}{E_{sp,air}+E_{sp,fuel}} \tag{15}$$

$$\eta = \frac{E_{sp,net}}{E_{sp,M}+E_{sp,fuel}} \tag{16}$$

The Tables **14** and **15**. Show the values of the energy terms and the storage, the generation, and the global efficiency for the BCE-IC optimized and AI-BCE optimized configuration.

The results are consistent with the efficiency of existing plants. However, the global efficiency of BCE-IC and AI-BCE is lower than that of the adiabatic one because, here, there is no heat storage from the compression and the compressed air is heated with the exhaust gases of a GT powered by fossil fuels. The results show that the global efficiency of the adiabatic CAES is similar to PHES efficiencies so it could be a good candidate for the large-scale energy storage.

Table 13: Adiabatic Plant Energy Flows

Adiabatic	E_{air} [kWh]	E_{oil} [kWh]	E_M [kWh]	E_T [kWh]	η
Storage	593166	1081527	1027410	0	0.931
Generation	591276	855208	0	701231	0.489
Global efficiency	0.691				

Table 14: Optimized BCE-IC Plant Energy Flows

$BCE\text{-}IC_{opt}$	E_{air} [kWh]	E_{oil} [kWh]	E_M [kWh]	E_T [kWh]	η
Storage	934076	0	1420172	0	0.658
Generation	930326	2348312	0	1749126	0.518
Global efficiency	0.451				

Table 15: Optimized AI-BCE Plant Energy Flows

$AI\text{-}BCE_{opt}$	E_{air} [kWh]	E_{oil} [kWh]	E_M [kWh]	E_T [kWh]	η
Storage	934076	0	1420172	0	0.658
Generation	9304960	1765136	0	1749126	0.251
Global efficiency	0.427				

However, the non-adiabatic CAES are not only storage plants but also fossil fuel power plants. So, their efficiencies should not be compared with those of PHES and are cost effective.

FINAL REMARKS AND CONCLUSIONS

Although the few CAES plants are operational, the technological state is still in the "embryonic phase". This is because existing plants are based on the mature technology of gas and steam turbines. An interesting application could be that of the use of biomass as fuel. This would result in a twofold result: a reduction in emissions and a decoupling of the plant's operation from fluctuations in the market price of the fuel. In addition, it is possible to think of creating a plant that uses fuel produced on site, encouraging the different energy crops in remote areas and, perhaps, rich in wind, reducing the supply of conventional fuel. In the case of an adiabatic plant, this benefit is very limited, since its emissions are already very low. In the possibility of using biofuels, an additional system of storage of the fuel itself would be necessary, which is produced in large plants. Remaining in the field of renewables, a possible modification (or variant) of the CAES plant (in the wind sector) is to replace the electric generator of the nacelle with a compressor. In this way (nothing new anyway, see the American mill) the wind turbine, through the compressor, would directly generate compressed air. In this way two energy conversion processes would be eliminated. In addition, the reduced losses and reduced cost of the turbine should be able to balance the additional cost of the compressors and the piping system needed for storage.

Innovation in the field of turbomachinery can also lead to an efficiency of the system. The input temperature in the turbine could be increased, taking advantage of a greater enthalpy drop, improving efficiency. This is using the same technology used for the blades cooling in the high-performance gas turbines. In addition, humidification and steam injection systems must be improved in the event of an increase in power, thus reducing storage volumes. In a recent project, the proposed CAES plant uses a standard gas turbine to replace the expander. The air, coming from the tanks, is heated using the exhaust gases of the turbine, by means of a recuperator. In this way, once injected into the turbine, it allows an increase in the generated power. Thus, the use of current technology and the elimination of the various combustors would allow a reduction in capital costs for the construction of the plant and provide a low-risk realization. In addition, the AI-BCE plant could include the inclusion of a

NOMENCLATURE

AI	Air Injection		**Greek letter**
BCE	Bottoming Cycle Air Expander	β	Pressure ratio
c	Specific heat [kJ/kg K]	η	efficiency
CAES	Compressed Air Energy Storage	ω	Rotational speed
E	Energy [kWh]		
GT	Gas Turbine		**Subscripts**
h	Enthalpy [kJ/kg]	air	air
HP	High-pressure turbine	CM	Generation compressor motor
I	Inertia Moment [kg/m^2]	fuel	fuel
IC	Inlet Chilling	gen	generation
LHV	Low Heating value [MJ/kg]	GT	Gas turbine
LP	Low-pressure Turbine	in	inlet
$\dot{m}$	Mass flow rate [kg/s]	M	Compressor motor
M	Mass [kg]	net	Net power or energy
p	Pressure [bar]	oil	Diathermic oil
P	Power [kW]	sp	Specific energy or power
PHES	Pumping Hydro Electric Storage	sto	storage
R	Gas Constant [kJ/kg K]	T	turbine
v	Specific volume [m^3/kg]		

bottoming cycle and a TES system to reduce fuel consumption.

Once these guidelines are adopted, it is reasonable to expect that the costs of CAES "new plants" will decrease, allowing for a faster pay-back time.

Until now, CAES systems are used as a "support" to the distribution grid, operating in such a way as to regulate the load and compensate for any deviations. As part of the global policy of "low carbon emission", the solution mentioned above could become a fundamental aspect in electrical management. The wind farm/CAES would be characterized by short response times to follow the fluctuations of the required power by the compressor. The wide availability of "wind-rich" zones indicates CAES technology as the one suitable for making the wind farm as a basic plant, allowing an electrical "penetration" of more than 20%. If these areas are far from the main markets, it is possible to use high-voltage transmission lines at competitive and attractive costs. As a result, net of all the cons, CAES systems present themselves as an important solution for large-scale energy storage, given that from the simulations carried out in this work, such plants present a interesting efficiency. Finally, quantifying the true potential of such plants will require more detailed characterization and more technological development and operational experience from several plants.

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