POLITECNICO DI TORINO

Corso di Laurea Magistrale

in

Renewable energy systems

Group project report

DESIGN AND OPTIMIZATION OF A COMPRESSED AIR ENERGY STORAGE PLANT

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1. Introduction

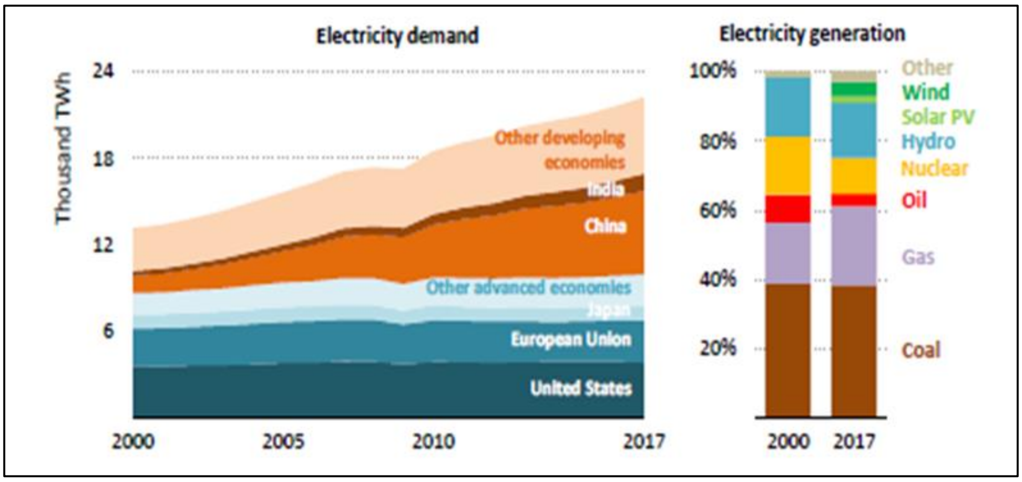

Figure 1 *- Generation and demand of electricity*

The energy sector is still evolving, but not fast as the demand of energy, specifically for electricity. Global Electricity demand has increased slightly over 70% from 2000 to 2017 and this trend looks set to continue and it is true to consider electricity as the "fuel of the future", according to the electrification of end-use. Although electricity generation is still dominated by fossil fuel, but the production by renewable sources still increases and will be essential in the future energy system because of environmental policies and sustainability paths.

It is possible to have a general view of future electricity demand, viewing different scenarios that touch different aspects. Thanks to the projections done by IEA (International Energy Agency) it is possible to identify three kind of scenarios:

- *New Policies Scenarios (NPS)* based on energy context with new policies and national energy plans that has already announced
- *Future is Electric* with a jump in use of electricity in many sectors
- *Sustainable Development Scenario (SDS)* based on policies that will allow to not exceed 2 °C of global mean temperature. For this reason, it will be high penetration of renewables, especially for photovoltaic systems and wind generators, and it will be markedly reduced

the generation part by fuel-based plant.

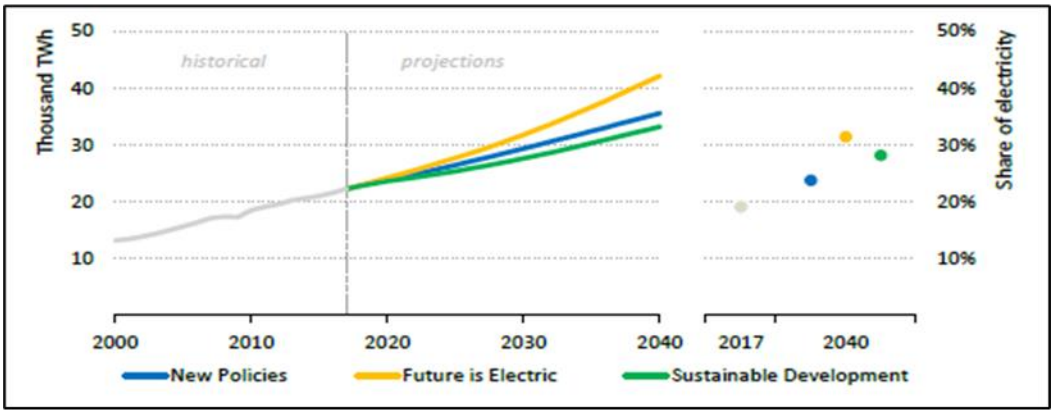

Figure 2 *- Projection of electricity consumption*

It is shown that electricity continues to rise whatever scenario selected.

1.1 Energy storage system

The stability of a grid must be guaranteed to have a secure connection among generation and consumption. Energy Storage Systems (ESS) cover this role.

Energy storage systems are essential to manage as well as possible the variation of the load curve and to minimize the effect of fluctuations in the energy production due to the intermittent behavior of renewable sources.

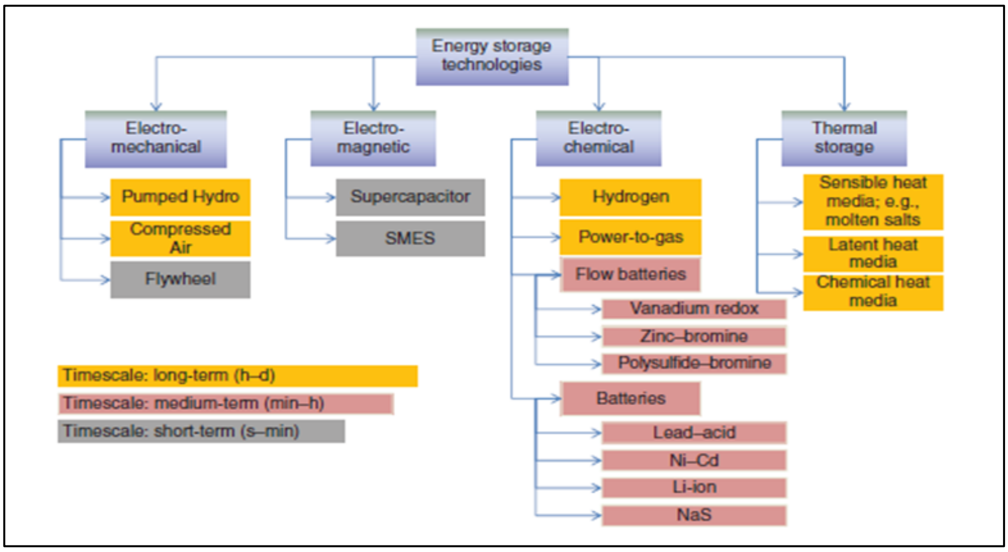

Figure 3 *- Main energy storage technologies*

It is also useful to frame the energy storage systems by the capacity to store energy (energy rating) and power rating, that allocate different kinds of systems at different discharge time.

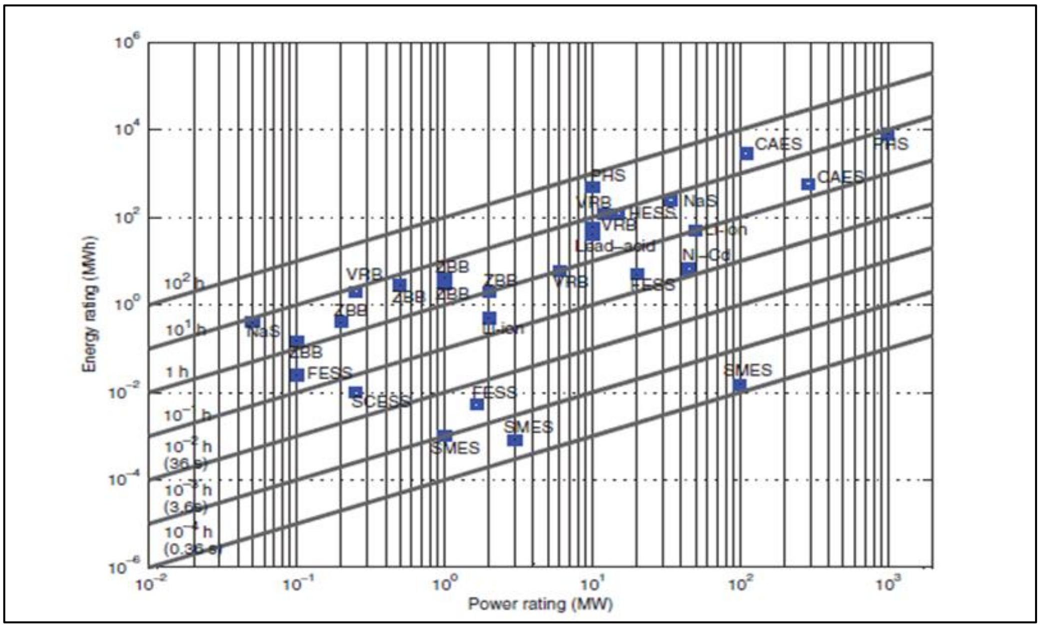

Figure 4 - *Power and energy rating for ESSs*

Allowing to have a transition of the energy systems, it is needed to consider storage systems as one of the main keys to this transition.

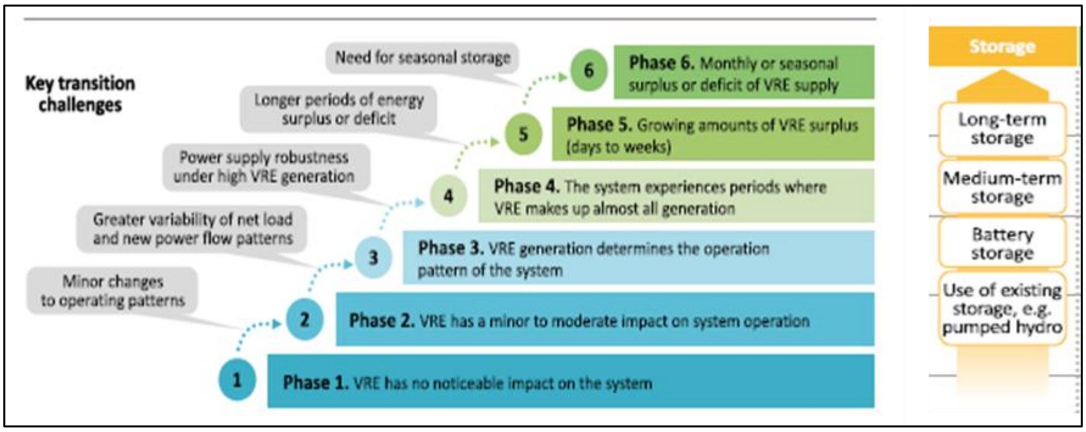

Figure 5 - *Steps for the transition*

Demand patterns have always changed hourly, daily, weekly, and seasonally, therefore it is useful considerate also long-term storage system as a solution to balance demand when it is not possible to cover and will be higher flexibility needs, higher become the support of storage system at different time scale.

1.2 Compressed air storage system (CAES)

As it is said before, the need of storage at different time scale will become more important in future perspective.

CAES operate as a long-term storage system that provides the possibility to store the surplus of energy when low demand occurs. The principle of operation is to take electricity from the grid and transform it as compressed air into a cavern. This kind of systems are generally attached with a gas power plant which takes compressed air from the cavern and use it for combustion process. Most important CAES systems are located one in McIntosh (Alabama, USA), with its cavern volume of 560.000 m^3 and power output of 110 MW (60 Hz), and one in Huntorf[1] (Germany) constituted by 2 caverns with a total volume of 310.000 m^3 and power output of 290 MW (50 Hz).

1.2.1 CAES project: location and availability

The location selected to install gas plant based on CAES system is Italy as a region with varied energy mix and possible cavern design in the future.

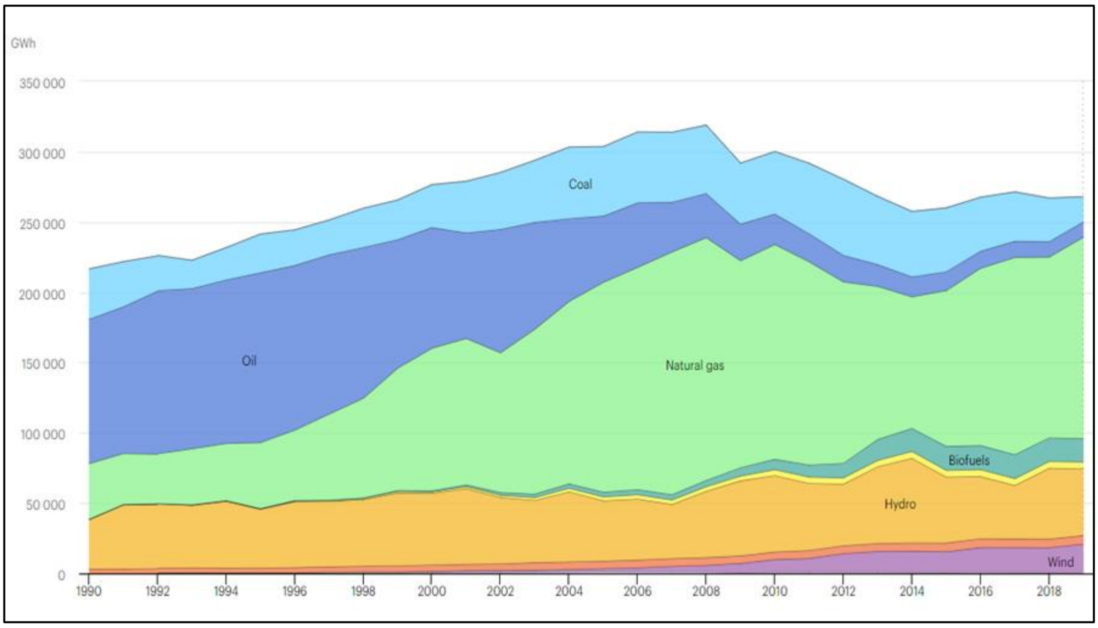

Figure 6 *- Energy mix of Italy*

As we can see from the figure, Italy still covers its energy production using plant based on fossil fuel, principally natural gas. Decarbonization path has reduced the consumption of oil and coal over years, promoting renewables technologies based on wind and solar radiation. The 16 December 2019 is selected to highlight the operating hours of our power plant. The gas power plant, that works coupled with CAES, must operate when there will be critical situations by the power generation system to satisfy the load. The availability of the plant is calculated as the summation of charging time and the discharging time of the cavern. For a practical point of view, this power plant must produce only when peaks occur and not every time it is found a gap between generation and load also to make a better estimation of the availability and more realistic work condition of plant. Moreover, for an economical point of view it cannot satisfy both peaks, but only one of them.

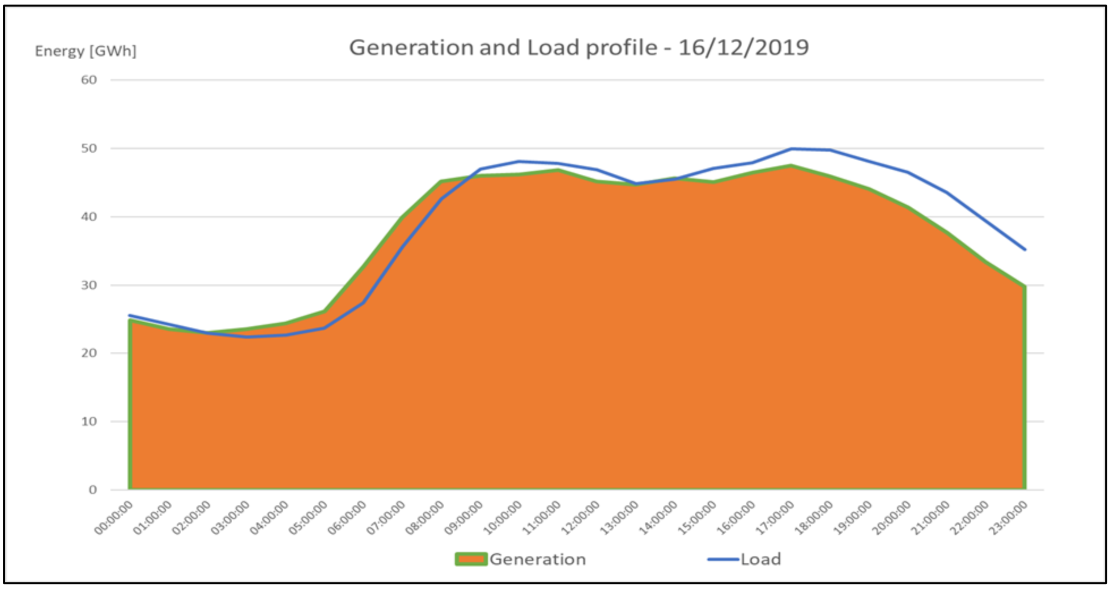

***Figure** 7 - Load and Generation curve on 16/12/2019*

Following the load curve and overlapping the generation one, it can be seen the time range when the production is higher than the demand and this corresponds to the charging phase of the cavern. During the day, the load curve presents generally two peaks, one in the morning and one in the afternoon. In this way it is possible to recover surplus of energy in form of compressed air into the cavern and use it when peaks occur. This allows:

- Satisfying the peak demand in economic way due to a lower cost of energy, in form of compressed air, compared to take it from grid without storage
- Minimizing the effect of peaks during the day (peak shaving)
- Actuating a levelling of load curve

The charging phase started at 02:00 a.m. and finished around 09:00 a.m. therefore it is 7 hours in total. For discharging phase, it is selected the second load peak, related to the afternoon hours and it corresponds to 3 hours in total, from 16:00 p.m. to 19:00 p.m.

The summation of charging and discharging phases is equal to operating hours of CAES system coupled with gas plant and it is equal to 10 hours per day.

Following the Sustainable Development Scenario, it is possible to estimate generation curve in the future. The scenario considers different changes in the energy mix, but to do a good approximation and a comparison between load and generation, it is assumed also changes in the load curve. Talking about generation, it will have a considerable increase in generation from renewable sources principally by solar photovoltaic systems and wind power generation**.**

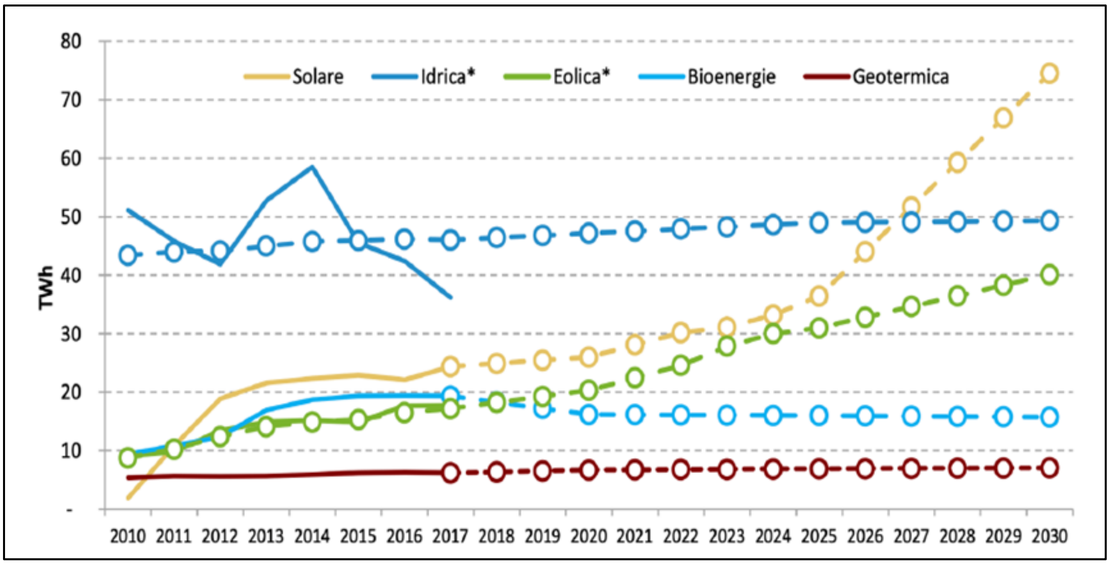

Figure 8 *- Projection of renewables until 2030*

We assume a fourfold generation by solar PV systems and an increase of wind production by a factor of two, following gain factors calculated in the projection made by ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development).

Regarding traditional plant, it is assumed an increase of 50% compared to the generation mix of our case studied. On the other hand, it will be an upward trend in demand of energy due to the rise of dispositive, services and good that require energy. Also, efficiency should increase, but it is not considered the evolution of it, because of the difficulty in finding a good forecast of efficiency evolution in the future, therefore it is considered a rise of 30% of total load that it is almost equal to the electricity future sharing in 2030, accordingly with Sustainable Development Scenario.

SDS projection		
Time	Load	Gen.
00:00:00	33,16	32,25
01:00:00	31,48	30,71
02:00:00	29,87	30,13
03:00:00	29,15	30,85
04:00:00	29,43	31,98
05:00:00	30,84	34,30
06:00:00	35,65	42,44
07:00:00	46,25	50,91
08:00:00	55,46	57,86
09:00:00	61,06	60,61
10:00:00	62,54	62,59
11:00:00	62,15	64,82
12:00:00	60,96	65,20
13:00:00	58,29	63,60
14:00:00	59,12	63,22
15:00:00	61,16	59,56
16:00:00	62,29	59,30
17:00:00	64,99	60,04
18:00:00	64,76	58,27
19:00:00	62,51	56,52
20:00:00	60,43	53,87
21:00:00	56,57	49,78
22:00:00	51,17	44,73
23:00:00	45,74	40,18

SDS projection by ENEA (2019)		
Solar (PV)	Wind	Thermal
4	2	1,5

SDS elec. Sharing
Load factor
1,3

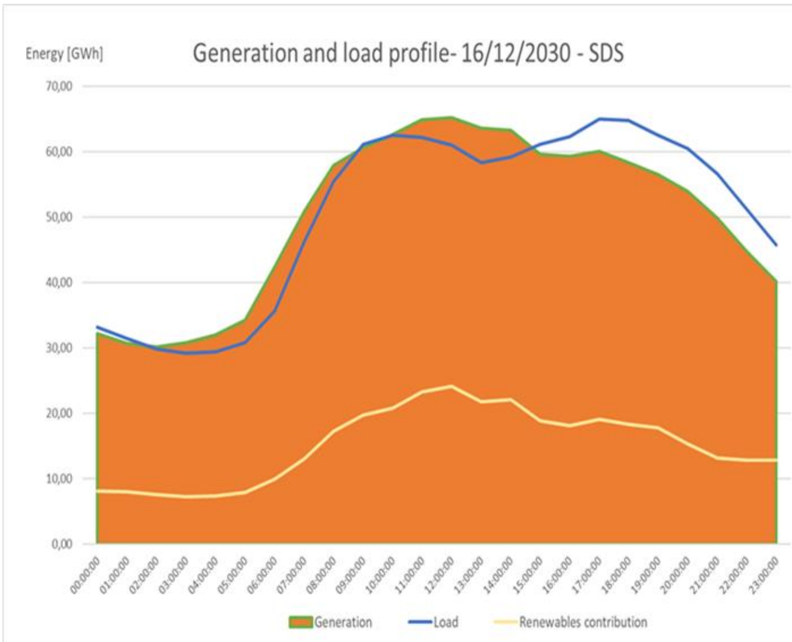

***Figure 9**- Load and Generation curve on 16/12/2030*

Following these curves and assuming the CAES system in this condition, the charging phase could be done in two different time-range: from 02:00 to 09:00 and from 10:00 to 15:00, while discharge phase will cover afternoon/evening gap between load and generation. In this case, the operating hours of this plant will increase and reach around 18 hours, considering 6 hours of discharge phase.

For this specific project we have assumed an average value between 2019 and 2030 conditions: 14 hours of operation for an estimated availability of 60%.

1.2.3 Plant, components and streams description

It is possible to see the general configuration and main components of the power plant in Figure 3. After discussion, we think it is necessary to separate cavern from the second intercooler. Therefore, we separated them in Aspen Plus and the simulation diagram is as follows:

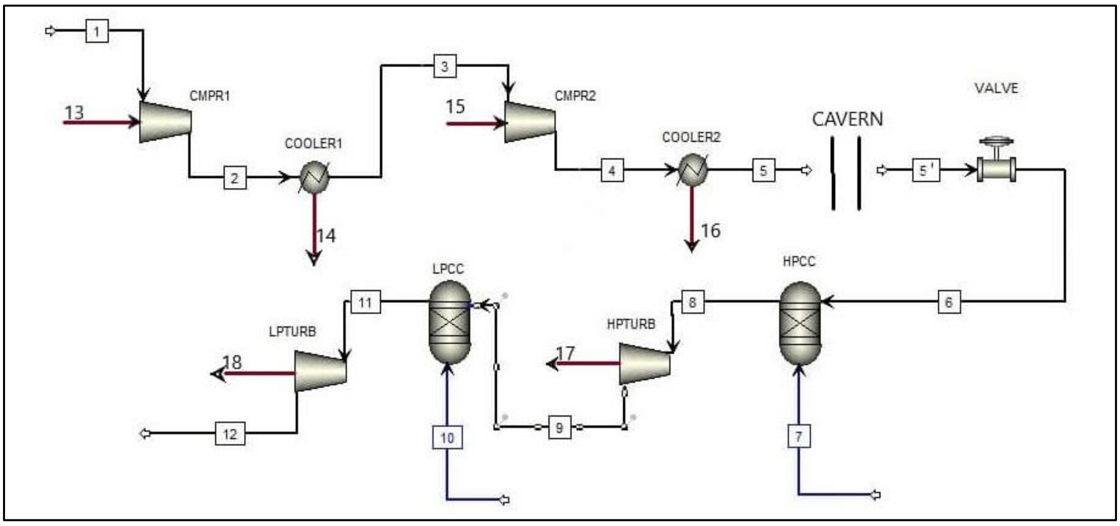

Figure 10 *- Simulation of a compressed air storage system in Aspen plus*

In the Figure, some comments can be done concerning the functionality of different components:

No1, Air Compressor, CMPR1;

No2, Intercooler, COOLER1;

No3, Air Compressor, CMPR2;

No4, Intercooler, COOLER2;

No5, Cavern;

No6, Valve;

No7, Combustion chamber, HPCC;

No8, High Pressure Gas Turbine, HPTURB;

No9, Combustion chamber, LPCC;

No10, Low Pressure Gas Turbine, LPTURB;

The specific process is as follows:

The power plant is firstly composed by two compressors (*CMPR1* and *CMPR*2) with an intercooling stage between them (*COOLER1*). After taking air from the environment at ambient condition, compressors must increase air pressure from ambient to a specific value, while the intercooler have the role to improve compression phases. The cooling process of the air at the outlet of the first compressor allows to a considerable decrease of the specific volume of air that will enter in the second compressor. As a result of this, the second compressor will require less power to increase air pressure compared to a compression phases without intercooling.

Thanks to the cavern, it is possible to store compressed air and use it when needed. In this configuration, the cavern is sandwiched between the second intercooling phase (COOLER2), where the heat transfer is taken into account, and the throttling valve (VALVE) that is responsible of keeping constant the pressure at the inlet of the turbine during the discharging phase. In this configuration, the cavern is modeled as an ideal pressure tank without any irreversibility generation. The second intercooler comes before with the goal of cooling the air coming from the second compressor's outlet to the safe temperature of 40°C to guarantee the stability of the cavern.

When air leaves the cavern, it flows in a combustion chamber (*HPCC*). In the combustion chamber, the air and natural gas, which is chosen as a fuel in this analysis, start a combustion reaction until all fuel is consumed and high temperature and pressure mixture is produced. This combustion products reaches the first high-pressure expansion stage in a gas turbine (*HPTURB*) that will produce the first power output of the plant.

After the expansion process, another combustion in a second chamber (*LPCC*) occurs. The flue gases burn into *LPCC* with natural gas and then the combustion products reach the second gas turbine (*LPTURB*) that will allow to completely expand the working fluid back to the atmospheric pressure.

At the end, the exhausted products leave the system toward the ambient at the ambient pressure but still at high temperature.

2. Thermodynamic analysis

2.1 Thermodynamic states definition

As first, a thermodynamic analysis of the system can be carried out with the aim to find the main thermodynamic properties and mass or energy flows. The thermodynamic model allows to calculate firstly the thermodynamic conditions at the inlet and outlet of each component and for the whole plant and then the enthalpies and entropies of the related flows. The system is simulated in an assuming steady state condition.

Furthermore, all the components are supposed to be adiabatic if not properly specified. The first and second law of thermodynamic have been used in the control volume form, neglecting potential and kinetic contribution.

Considering the canonical form of the I law for open system, it is possible to apply it to the different components along with the mass balance equation:

$$\Phi_n - W_n = \left(\frac{dE_t}{dt}\right)_{\mathrm{cv}} + G_{Hn}$$

Subsystems No1, CMPR1 and No3, CMPR2:

In the proposed case study, as already seen, the fluid compression takes place in two-stages. At the inlet of the I stage, the thermodynamic conditions are T_1=25°C and $P_1 = 1\ bar$, the mass flow rate is G=108 kg/s according to specifications from Huntfort plant[1]. The technical specific work for the two compressors is given by:

$$l_{t\mathrm{I}} = R^* \cdot T_1 \cdot \frac{\gamma}{\gamma - 1} \cdot \left[\frac{p_2}{p_1}^{\frac{\gamma-1}{\gamma}} - 1\right] < 0$$

$$l_{t\mathrm{II}} = R^* \cdot T_3 \cdot \frac{\gamma}{\gamma - 1} \cdot \left[\frac{p_4}{p_3}^{\frac{\gamma-1}{\gamma}} - 1\right] < 0$$

After the first intercooling, the thermodynamic conditions are $T_3 = 30°\mathrm{C},\ P_2 =$

p_3, therefore,

$$l_t = l_{t\,\mathrm{I}} + l_{t\,\mathrm{II}} = R^* \cdot T_1 \cdot \frac{\gamma}{\gamma - 1} \cdot \left[\frac{p_2}{p_1}^{\frac{\gamma-1}{\gamma}} + \frac{p_4}{p_3}^{\frac{\gamma-1}{\gamma}} - 2 \right] < 0$$

For a total $\Delta P = P_4 - P_1$, it is possible to optimize the intermediate pressure P_2. And we know $P = 72\ bar$ from the beginning because is the pressure at which air is stored in the cavern, therefore the optimized compression ratio:

$$\beta = \sqrt{\frac{p_4}{p_1}} = 8.485 bar$$

Moreover, it is known that the isentropic compression efficiency is $\eta_{\mathrm{IC}} = 0.9$ for both compressors while the mechanical efficiency is $\eta_m = 0.98$.

The *Subsystem No2, Intercooler Cooler1*, has the aim to cool down the fluid before the second compression stage. The removed thermal energy is lost to the external environment, no pressure drop:

$$\Phi_{14} = G \cdot (h_3 - h_2)$$

The Subsystem No4, Intercooler Cooler2, is modeled as a cooler, where the fluid is at the thermal equilibrium with the cavern wall temperature (40-50 °C):

$$\Delta \mathrm{P} = 0 bar \text{ and } T_5 = 40°\mathrm{C}$$

The Subsystem No5, Cavern, the cavern is modeled as an ideal pressure tank without any irreversibility generation. Thus, we don't need to discuss it too much in this section.

The Subsystem No5, Throttling valve, is an adiabatic component with fixed discharge pressure. The value of discharge pressure is known and corresponds to the design turbine inlet pressure:

$$P_6 = 42\ bar$$

The Subsystem No6, combustion chamber HPCC, is adiabatic, with negligible pressure drop. Since the air flow is fixed from CAES operation, the fuel flow rate, G_7 is computed to achieve a turbine inlet temperature equal to:

$$TIT_{T1} = 550℃$$

The *Subsystem No8, combustion chamber LPCC*, is adiabatic, with negligible pressure drop. In this case, the fuel flow rate, $G10$ is computed to achieve a turbine inlet temperature of:

$$TIT_{T2} = 825℃$$

The *Subsystem No7, gas turbine, HPTURB*, has isentropic expansion efficiency of η_{IE} = 0.85. The discharge pressure $P_9 = 11\ bar$.

The *Subsystem No9, gas turbine LBRURB*, has isentropic expansion efficiency of η_{IE} = 0.85. The discharge pressure $P_{12} = 1 bar$.

Inputting all the above data to ASPEN PLUS, the simulation results are summarized below.

Table 1 *- Simulation results for reference plant*

Stream Name	Temperature	Pressure	Mass Flows	Mass Enthalpy	Mass Entropy
Units	**K**	**bar**	**kg/sec**	**kJ/kg**	**kJ/kg-K**
1	298.15	1.00	108.00	-0.279	0.151
2	571.56	8.49	108.00	280.229	0.201
3	303.15	8.49	108.00	2.799	-0.453
4	582.22	72.00	108.00	290.242	-0.403
5	313.15	72.00	108.00	-0.914	-1.075
6	307.40	42.00	108.00	-0.914	-0.923
7	298.15	50.00	1.24	-4692.782	-7.068
8	823.15	42.00	109.24	-54.300	0.146
9	616.69	11.00	109.24	-286.135	0.214
10	298.15	50.00	1.29	-4701.834	-7.180
11	1098.15	11.00	110.53	-337.544	0.873
12	680.85	1.00	110.53	-834.814	1.010

2.2 Physical structure (incidence matrix)

The incidence matrix A[n×m] allows to correlate all the flows with the corresponding subsystems of the plant. This matrix has as many rows n as the number of the components and as many columns m as the number of flows exchanged between the components and the external environment.

In this case, the number of components n is equal to 9, while the number of mass or energy flows m is equal to 18 including the mechanical power absorbed by the air compressors CMPR1 and CMPR2, the generated mechanical power from the turbine HT and LT, and the heat released from two intercoolers (COOLER1 and COOLER2).

It is defined that if the j^{-th} stream is entering in the i^{-th} component, then the $a_{i,j}$ value will be +1 and vice versa. (If the stream is flowing out it will be -1.) If a stream does not interact with the component, then the value will be 0. The obtained incident matrix is shown in the Table 2.

Table 2 *- Incident Matrix*

A	Mass Stream												Energy System					
	1	2	3	4	5	6	7	8	9	10	11	12	w_{C1}	ϕ_{IC1}	w_{C2}	ϕ_{IC2}	w_{HT}	w_{LT}
CMPR1	1	-1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
COOLER1	0	1	-1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0
CMPR2	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
COOLER2	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	-1	0	0
VALVE	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0
HPCC	0	0	0	0	0	1	1	-1	0	0	0	0	0	0	0	0	0	0
HPTURB	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	-1	0
LPCC	0	0	0	0	0	0	0	0	1	1	-1	0	0	0	0	0	0	0
LPTURB	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	-1

2.3 Exergy states definition

The opportunity to obtain useful work exists whenever two systems at different states are placed in communication, in principle, work can be developed as the two are allowed to come into equilibrium. Exergy is the maximum theoretical useful work obtainable as the systems interact to equilibrium with biosphere. Alternatively, exergy is the minimum theoretical useful work required to form a quantity of matter from substances present in the environment and to bring the matter to a specified state.

It is therefore an attribute of the system and environment together. Once the environment is specified, a value can be assigned to exergy in terms of property values for the system, so the exergy can be regarded as an extensive property.

The aim of the exergy analysis is to compute the exergy balance for each subsystem of the whole plant. The analysis has the aim to calculate the exergy destruction rate in each component.

2.4 Dead states

When the pressure, temperature, composition, velocity, or elevation of a system is different from the environment, we have seen that there is an opportunity to develop work. As the system changes state toward that of the environment, the opportunity diminishes, ceasing to exist when the two, at rest relative to one another, are in equilibrium. This state of the system is called the dead state. At the dead state, the conditions of mechanical, thermal, and chemical equilibrium between the system and the environment are satisfied: the pressure, temperature, and chemical potentials of the system are equals to those of the environment. In addition, the system has zero velocity and zero elevation relative to coordinates in the environment. Under these conditions, there is no possibility of occurring a spontaneous change within the system or the environment, and an interaction between them.

To define the entropy and enthalpy at the dead states we should create a new thermodynamic property in PROP-SETS in Aspen plus at first. Then, in the tab 'Qualifiers' specify the thermodynamic state (set up $T_0 = 288.15K, p_0 = 1bar$) at which the requested physical property should be evaluated and repeat that procedure to create the specific entropy (s_0) at the given dead state.

The result is obtained from the stream results table, which is shown in table 3:

Table 3- *Dead state*

	H_0	**S_0**
Units	**kJ/kg**	**kJ/kg-K**
1	-0.27868	0.151129
2	-0.27868	0.151129
3	-0.27868	0.151129
4	-0.27868	0.151129
5	-0.27868	0.151129
6	-0.27868	0.151129
7	-4646.21	-5.0197
8	-622.605	0.146852
9	-622.605	0.146852
10	-4646.21	-5.0197
11	-1252.01	0.114293
12	-1252.01	0.114293

2.5 Exergy analysis

Exergy has physical dimensions of power and, as we have already discussed, it expresses the maximum work that could be obtained with a reversible process that brings the system into equilibrium with a reference environment, usually the biosphere.

To compute the total exergy of each stream we will split it in two contributions, physical and chemical exergy.

Physical exergy can be computed using the definition below:

$$E_{ph} = [h - h_0 - T \cdot (s - s_0)] \times G$$

Where h [kJ/kg] is the specific enthalpy of the flow, h_0 [kJ/kg] is the specific enthalpy of the reference environment is the specific enthalpy of the stream at dead state, T [K] is the temperature, s [kJ/(K·kg)] is the specific entropy, s_0 [kJ/(K·kg)] is the specific entropy at the reference environment and G [kg/s] is the mass flow rate.

The chemical exergy of the air, considering all the fluid as ideal gases, is:

$$E_{ch} = \sum[y_i \cdot \tilde{e}_i + R \cdot T_0 \cdot y_i \cdot \ln(y_i)] \times G$$

where n is the number of chemical elements of the flow, yi is the molar fraction of the i-th component, $\tilde{e}i$ is the reference chemical exergy of the i-th element, R is the universal gas constant [kJ/(kmol·K)], T_0 is the temperature at the dead state and G is the total molar flow, expressed in [kmol/s].

Total exergy can be calculated by:

$$E = E_{ph} + E_{ch}$$

Table 4 - *Exergy*

Stream Name	physical exergy	chemical exergy	total exergy
Unit	MW	MW	MW
1	2.38E-06	0.480741	0.480744
2	28.67568	0.480741	29.15642
3	19.79478	0.480741	20.27552
4	49.21048	0.480741	49.69122
5	39.42284	0.480741	39.90358
6	34.52361	0.480741	35.00435
7	0.701079	64.43822	65.1393
8	62.12612	0.971261	63.09738
9	34.57071	0.971261	35.54197
10	0.757233	66.70954	67.46677
11	76.07632	2.408968	78.48528
12	16.60309	2.408968	19.01206

2.6 Mass, energy and exergy (irreversibility) balance

Once the exergies of the streams have been calculated, the exergy balance of each component can be investigated to evaluate the exergy destruction rate in these components. Assuming that the system is in steady state, the exergy destruction rate can be obtained by the function, called 'equation of usable energy':

$$\Sigma_{i=1}^{n} \Phi_i \times \left(1 - \frac{T_0}{T_i}\right) - w = \left(\frac{dA}{dt}\right)_{Cv} + E + \psi$$

Where n is the number of heat fluxes exchanged by the system, Φ_i is the i-th heat flux exchanged at temperature T_i, T_0 is the reference temperature, and W is the net-work exchanged by the system, (dA/dt) cv is the time rate variation of the total internal energy in the control volume, E is the exergy related to the mass flows, while Ψ is the exergy destroyed in the system.

In this case, the related results can be obtained by using the incidence matrix which had been introduced before of the system with the formula:

$$A \times E = I$$

Where A[n×m] is the incidence matrix, E[m×l] (showed in the Tab.) is the vector of the exergy flows with the number of rows is equal to the number of streams m identified in the physical structure and the result I [n×1] is the vector of irreversibility generated into the specific component.

Table5 *- Exergy Vector Matrix*

E (WM)	
1	0.481
2	29.156
3	20.276
4	49.691
5	39.904
6	35.004
7	65.139
8	63.097
9	35.542
10	67.467
11	78.485
12	19.012
13	30.9742
14	0
15	31.6779
16	0
17	24.8191
18	53.8631

The exergy of point 14 and 16 is zero, since they are heat fluxes exchanged with environment in the process, as discharged streams.

The irreversibility can be calculated as below:

Table 6 - Irreversibility For Each Component

I	Irreversibility (WM)	Percent
CMPR1	2.299	2.34 %
INTER-COOL1	8.881	9.06 %
CMPR2	2.262	2.31 %
INTER-COOL2	9.788	9.98 %
VALVE	4.899	5.00 %
HPCC	37.046	37.79 %
HP-TURB	2.736	2.79 %
LPCC	24.523	25.01 %
LP-TURB	5.610	5.72 %
TOTAL	98.045	100.00 %

These data are plotted as pie chart, which can be obtained in Figure 11.

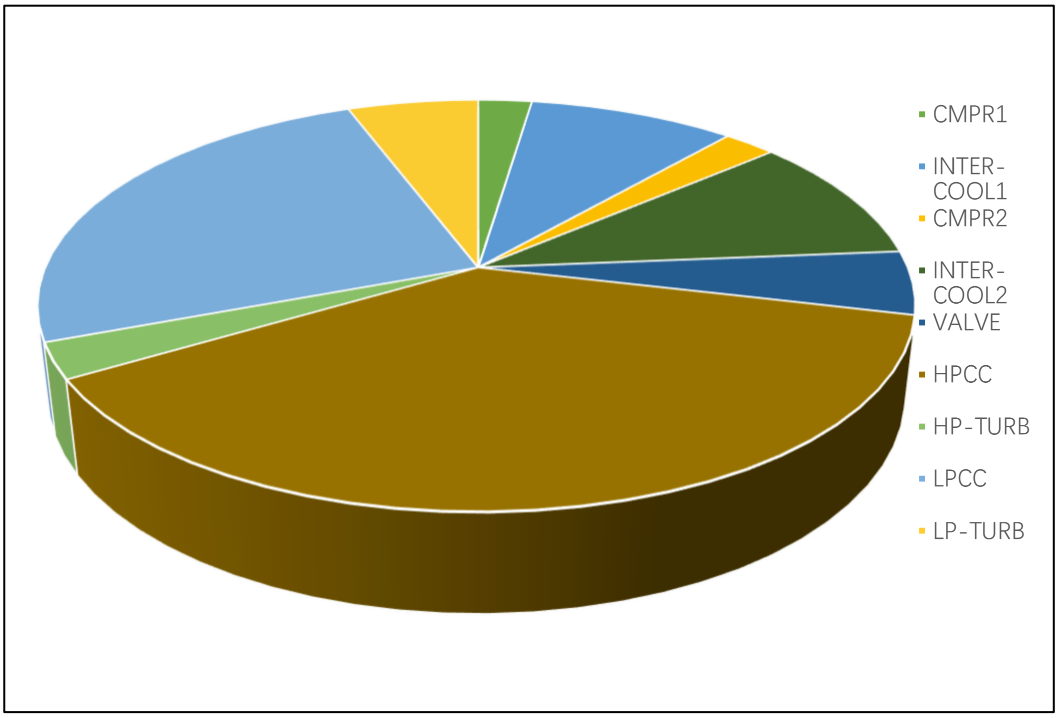

***Figure 11** - Pie Chart of Irreversibility*

To sum up, it is clear that the HPCC (High Pressure Combustion Chamber) has the largest part of the irreversibility, which is up to 37.79% of the total, while the Low Pressure Combustion Chamber captures 25.01%.

3. Exergy-cost analysis

Having seen the thermodynamic state definition of each stream which takes part in the CAES reference plant, we can start developing the exergy cost analysis with the aim to investigate irreversibility production (or exergy destruction) related to the components but then spread on the streams themself. The purpose of this analysis is to define the resources (in terms of energy/matter streams) that are needed to produce a certain product in our system (monetary costs are not considered yet).

3.1 Productive structure of a system

As a first step the productive structure of the system is defined, so for each component of the plant resources (or fuel F), products (P) and eventually, losses or discharged flows (L or D) are identified. The productive structure of a system can be developed in multiple ways according to the way, the different streams are considered. In order to better understand this particular point, it's useful to start creating the productive structure by analyzing each component one by one.

For the identification of the streams number the same legend of Chapter 1 will be used.

CMPR 1 and CMPR 2

As a first components we consider the compressors. Their job is to bring the air from a certain pressure to a higher value.

For the compressor, the fuel will be the extra-electrical power coming from the grid during the charging phase, when the energy demand is low. The product P will be the total exergy variation experienced by the working fuel, so the exergy difference equals to E2-E1.

Considering the compressor adiabatic, we don't identify any losses or discharged streams.

For the second compressor the process is the same: as a fuel we consider the energy stream number 16, so the energy from the electric grid. And as a product we will consider the exergy jump between stream 4 and 3. Also for the second compressor no losses or discharged streams are considered.

COOLER1 and COOLER2

Let's consider now the two heat exchangers that are present after each compression stage to perform the cooling of the working fluid to better follow the ideal isothermal expansion. The definition of resources, products and discharged flows is the same, with only difference in the specific numbers of each stream.

For the first inter-cooler the fuel is the exergy of the stream 2, while the product is be the exergy of stream number 3. Obviously, since in the reference plant heat recovery is not performed, the large amount of heat extracted will be discharged in the external ambient, so the heat flux 14 is the discharged one.

For inter-cooler 2 we can summarize saying that the fuel is E4, the product is E5 and the loss is E16, where E indicates the exergy content or the heat flux, since the exergy of heat discharged into the environment is zero.

VALVE

The regulation valve has the particular aim to decrease the pressure from 72 bar to 42, that is the design pressure at the inlet of the first turbine. For the valve we can define the fuel as E5(or E5') and the product as E6. No discharged streams or losses.

HPCC and LPCC

For the two combustion chambers the productive structure is a little bit more complex since we have the convergence of more than two mass streams.

Considering the first combustion chamber the fuel will be the natural gas with its total exergy E7. The product will be considered as the exergy variation between the inlet air and the flue gasses at the outlet, so E8-E6 having done the hypothesis of a completely adiabatic component, we do not have any losses.

For the combustion chamber operating at a lower pressure the fuel will be the exergy of the natural gas stream E10 and the product will be defined as E11-E9. No losses too.

HPTURB and LPTURB

By doing the productive structure of the two turbines we can appreciate the different ways that can be followed.

Considering the first turbine, in the scheme, we can define the fuel as the exergy variation experienced by the working fluid during its expansion, which is equals to E8-E9, and the product as the electric power generated E17. No discharged flow.

For the second turbine instead, we want to underline the fact that the stream 12 is actually discharged into the environment, so the productive structure will see E11 as a fuel, E18 as a product and finally E12 as a discharged flow.

So, at the end we can summarize all the previous information inside a table 7, where for each component are presented resources, products, and losses.

***Table** 7 - Productive structure*

COMPONENT	Resources F	Products P	Losses/discharged L-D
CMPR 1	E13	E2-E1	//
COOLER 1	E2	E3	E14
CMPR 2	E15	E4-E3	//
COOLER 2	E4	E5	E16
VALVE	E5	E6	//
HPCC	E7	E8-E6	//
HP-TURB	E8-E9	E17	//
LPCC	E10	E11-E9	//
LP-TURB	E12	E18	E12

3.2 Cost allocation

Once the productive structure of the system has been defined, we can proceed with the cost allocation phase. The purpose of this step is to finally define the exergy cost E^* of each stream in order to understand the resources that are needed to produce them.

In other words, the exergy cost is the sum of the exergy of a particular flow plus all the irreversibilities that have been accumulated to get a certain product.

The first thing that must be taken into account is the fact that the exergy cost is a **conservative property,** so for each component we can write the exergy cost balance between the inlet streams and the outlet streams:

$$\sum E_{in}^* = \sum E_{out}^*$$

It's clear from this point that we will be able to write 9 different exergy cost balance equations since the components in the CAES plant are 9.

These 9 equations can be joined together in a matrix form using the previously introduced incidence matrix:

$$[A] \cdot E^* = 0$$

But that is not enough since the exergy cost is a stream property and in the system, we have 18 streams (12 mass streams and 6 energy streams).

If we want to close the linear system, we have to add 9 more equations, called auxiliary equations, in order to have 18 equations in 18 variables. These auxiliary equations are written considering 4 general rules, that can be quickly summarized here:

Rule 1: "The exergy cost of resources is equal to their exergy"

We are disconnecting our system with other possible systems by not considering how the resources were actually produced: we are interrupting the causal-effect chain considering our plant as a brand-new start. Considering how the productive structure was built, we can write up to five rule 1-type equations:

$$E1^*=E1$$

$$E7^*=E7$$

$$E10^*=E10$$

$$E13^*=E13$$

$$E15^*=E15$$

Rule 2:"The exergy cost of discharged flows into the environment is assumed to be null"

With that specific preposition we're allocating all the exergy cost inside our plant, redistributing the cost of discharged flows in other streams of the system. Again, considering the productive structure we have 3 discharged streams and so three will be the number of rule 2-type equations:

$$E12^*=0$$

$$E14^*=0$$

$$E16^*=0$$

Rules 1 and 2 equations can be also summarized in the matrix form, and from now they will be called α_e equations.

$$[\alpha_e] \cdot E^* = \omega$$

Rule 3: "The unit exergy cost ($k_i=E_i\times/E_i$) of an output stream which is part of the fuel is the same of the inlet stream from which it comes from"

This is the example of the high-pressure turbine, since the output mass flow derives from the inlet mass flow.

For the CAES system we can write only one rule 3-type equation, since with it, we reach the number of 18 equations:

$$k_8^* = k_9^*$$

$$\frac{E_8{}^*}{E_8} = \frac{E_9{}^*}{E_9}$$

$$-\frac{E_9}{E_8}E_8^* + E_9^* = 0$$

We could write a rule 3-type equation also for the second turbine, but it wouldn't be linear independent from the other.

The last rule, **rule 4**, has not been used in this specific example, but it states that **"two or more products of a component with the same thermodynamic quality have the same unit exergy cost".**

Rule 3 and rule 4 equations can also be coupled together and written in a matrix form, calling them α_x.

$$[\alpha_x] \cdot E^* = 0$$

At the end, our linear system will have this particular shape:

$$\begin{bmatrix} A \\ \alpha_e \\ \alpha_x \end{bmatrix} \cdot E^* = \begin{pmatrix} 0 \\ \omega \\ 0 \end{pmatrix}$$

That in a more compact way is presented as:

$$[Ac] \cdot E^* = Ye$$

Where the matrix [Ac] is called cost matrix and vector Ye is called vector of external assessment.

Being a linear system, it can be easily solved and the exergy cost vector defined. Here are reported both the exergy cost vector and the unit exergy cost vector in Table 8.

Table 8 *- Exergy cost*

Stream	Exergy cost vector (MW)	Unit exergy cost vector
1	5.085	1
2	3.603	1.07
3	3.603	1.45
4	6.775	1.25
5	6.775	1.53
6	6.775	1.72
7	6.497	1
8	132.72	1.91
9	80.03	1.91
10	67.59	1
11	147.62	1.71
12	0	0
13	30.95	1
14	0	0
15	31.71	1
16	0	0
17	526.89	2.12
18	147.62	2.74

3.3 Exergo-economic analysis

The next step of the process is called exergo-economic analysis and has the purpose to define the monetary cost of the streams in the CAES plant. In fact with this analysis the economic resources are pointed out and for each stream is defined the money flow in $/sec.

The final goal of this process is to understand what is the cost of products for the owner of the plant, in order to properly fix the product price in the market.

Like the exergy cost analysis, also the exergo-economic analysis is performed starting from cost balance equation for every component in the plant. In particular, the cost balance will include different terms like the cost of inlet flows, the cost rate of the specific component and the cost of outlet flows.

Here the balance is presented in a mathematic form:

$$\sum_{i=1}^{n,in} c_{i,in} \cdot E_{i,in} + Z = \sum_{i=1}^{n,out} c_{i,out} \cdot E_{i,out}$$

Where:

$c_{i,in}$, $c_{i,out}$ are the unit exergo-economic cost [$/MWh]

$E_{i,in}$, $E_{i,out}$ are the exergy of inlet and outlet streams [MW]

Z is the cost rate of the component, the annuity computed considering the availability of the plant.

As for the exergy-cost analysis again we have 18 streams but the cost balance will only guarantee a number of equations equal to the number of components. Auxiliary equation will be written.

3.3.1 Cost rate of component

The aim of this specific section is to define the cost rate of each component starting from the **bare erected cost**, computed with the help of cost functions.

According to Turton's paper, the bare erected cost of technical equipment can be evaluated generally in two different ways:

$$C_{bec} = Cp° \cdot F_m \cdot F_p$$

$$C_{bec} = Cp° \cdot (B_1 + B_2 \cdot F_p \cdot F_m)$$

Where Cp° is the purchasing cost of equipment referred to base operating condition and Fp and Fm are factors that respectively take into account the real operating pressure and the real operating temperature (and so the proper material choice).

Talking specifically to the purchasing cost Cp°, it is defined using regression constant k_1, k_2, k_3 that considers the type of the component and the size parameter A, which changes according to the specific component. For instance, in a turbine the size parameter is the power output, in a combustion chamber instead the size parameter may refer to the combustion chamber volume.

From the Turton’s paper:

$$\log_{10} Cp° = k1 + k2 \cdot \log_{10} A + k3 \cdot (\log_{10} A)^2$$

Analog definitions can be written for the two correcting factors, for Fp:

$$\log_{10} F_p = C1 + C2 \cdot \log_{10} P + C3 \cdot (\log_{10} P)^2$$

Where C1, C2, C3 are constants for data fitting and P is the working pressure of the real component inside the CAES plant.

For the material factor specific tables are available, and according to the equipment type and to the constitutive material, they can make the Cp° ten or even eleven times higher.

Unfortunately, the cost functions are valid inside specific range of the size parameter, so when the real size of the component exceeds this range, the **effect of scale** on purchased equipment cost must be introduced.

In particular, it is fundamental to say that the cost of a component does not vary linearly with the size, but instead, it follows an exponential function ruled by the cost exponent n.

Specifically, adopting the “six-tenths rule” the cost exponent is fixed to be equal to 0.6, so the scale effect can be written:

$$\frac{C_{bec,real\ size}}{C_{bec,reference\ size}} = \left(\frac{A_{real}}{A_{ref}}\right)^{0.6}$$

During the definition of the costs rate of components is also needed to consider the **effect of time** on purchased equipment cost. In fact, in Turton tables alle the prices are referred to 2001$, so in order to take into account inflation we have to consider cost indices like MSECI or CECPI.

With the introduction of cost indices the bare erected cost is modified:

$$\frac{C_{bec,present}}{C_{bec,past}} = \frac{I_{present}}{I_{past}}$$

Where I is the MSECI or CEPCI index.

With all of that being said, is it possible to compute Cbec for every component inside the plant.

CMPR1 AND CMPR2

Both the compressors are centrifugal, and they are made of CS since the temperature of the working fluid (air) doesn't exceed 310°C.

In the table 9 below the essential values are reported:

Table 9 *- CMPR1 and CMPR2*

Component	Type	Cp° (2001$)	Fp	Fm	CEPCI (2001)	CEPCI (2019)	Cbec (2019$)
CMPR 1	Centrifugal	2434415	1	2.7	394	607.5	10134644
CMPR 2	Centrifugal	2470401	1	2.7	394	607.5	10284456

COOLER1 AND COOLER2

Concerning the intercoolers we refer to heat exchangers where this time the size parameter is the surface area of the heat exchanger itself.

In order to compute the size of each intercooler we supposed that a mass flow rate of water (500t/h) was available at an inlet temperature of 15°C, with a global thermal heat exchanger coefficient $U=100W/m^2$.

Scale effect is then applied to the purchased cost referred to the base configuration

Again, the maximum temperatures are not so high (less than 310°C) so carbon steel will be fine.

In the table below results are reported, the cost indices will be the same as before, so they're not reported. Integrating the data into table 10.

__Table 10__ - Cooler1 and Cooler2

Component	Type	Size(m^2)	Cp°(2001$)	Fp	Fm	Cbec(2019$)
Cooler 1	Floating head	3700	311340	1.01	1	485309
Cooler 2	Floating head	3300	287296	1.29	1	572952

VALVE

For the valve it is a little bit more difficult since they are not present in Turton's paper tables. Having done some research online, considering throttle valves used in gas pipeline network, the price is generally negligible with the ones of other components.

Anyway, we decide to consider a value higher than the average found on internet, in order to be as conservative as possible.

__Table 11__ - Valve

Component	Typer	Cbec(2019$)
Valve	Thermal expansion	462563

CAVERN

The bare erected cost of the cavern is surely the most difficult one to define, since there are lots of secondary aspect that must be taken into account, also because the purchasing of an underground limestone cave is not so common.

According to the literature the cost of the cavern can be function of the power produced during the discharging phase or function of the volume of the cavern (they are related by the discharging time and the mass flow rate during the discharging time).

From the thermodynamic analysis of the reference plant the power produced by the HP and LP turbines, considering a symmetric configuration of the plant ($\dot{m_{charge}} = \dot{m_{discharge}} = 108\ kg/s$), is around 80MW.

From literature we find the cost of the cavern to be 60 $2001/kW of discharged power. Again, in the table results are summarized:

Table 12 *- Carven*

Component	Specific cost ($/kW)	Output power (MW)	Cbec(2019$)
Cavern	60	78.7	7279002

HPCC AND LPCC

In the components presented in the Turton's paper the combustion chamber are specifically not reported.

In order to compute the Cbec of the two components we start from process vessels costs.

The size parameter this time is the volume of the combustion chamber, and in order to compute this value, we need to take into account the volumetric flows rate that each vessel deal with and the residence time τ, a very important parameter that is defined starting from the analysis of the chemical reactions that take place during the combustion process.

Having computed that for both the process vessels, we have to remember that the cost functions for process vessels is different from the one used previously, and also the formulation of the pressure factor Fp is different.

This time, because of typical high temperatures related to combustion process, the material for both the vessels will be stainless steel.

In the table 13 all the important results are summarized:

Table 13 *- HPCC and LPCC*

Component	Type	Volume(m^3)	Cp°(2001$)	Fp	Fm	Cbec(2019$)
HPCC	Process vessel	2.15	11705	6.7	3.1	597602
LPCC	Process vessel	12.6	33841	3.3	3.1	895276

HPTURB AND LPTURB

The last components taken into account for the investment costs definition are the two turbines, fundamental piece of equipment related to power production.

The role of the two turbines is to convert the high exergy content of hot streams into mechanical work and then into electricity thanks to alternators.

During the definitions of the investment costs the material factor plays an important role, since both the turbines have to deal with fluids at a quite high temperature and stainless steel is preferable.

Again, it is necessary to apply the size effect (on the output power) and the time effect (because of inflation).

Here in the table 14 the most relevant results are reported:

Table 14 *- HPCC and LPCC*

Component	Type	Size(kW)	Cp°(2001$)	Fp	Fm	Cbec(2019$)
HPTURB	Axial gas turbine	24819	1650810	1	6.1	15526624
LPTURB	Axial gas turbine	53863	2627870	1	6.1	24716321

Once all the investment costs are defined considering the proper size, the working pressure, the temperature and the effect of time on the currency value, it's possible to make a step forward in the cost estimation methodology introduced by NETL ("National energy technology laboratory").

The next step in fact consists in the specification of additional expenditures that must be taken into account during the definition of the capital cost.

Firstly, all the expenditures related to detailed designs, contractors permitting and management costs are considered in the **EPCC**, that stands for "Engineering, procurement and construction cost". In this particular analysis they're estimated to be 10% of the bare erected cost.

Then the "Total plant cost" **TPC** is defined, it includes all the extra expenditures related to project and process contingencies. Process contingencies are related to the maturity level, technology readiness level TRL, of the different technologies. In a CAES plant all the component and the process can be considered to be well consolidated, so process contingencies are neglected.

In this particular analysis the TPC has been defined as the 20% of the EPCC.

Then finally the **TOC,** that stands for "Total overnight cost", is defined to be 20% of the TOC. It includes the cost of royalties, of land and of the different tests needed to ensure the reliability of the plant.

As any other levels before, it is defined in constant currency.

The summary of the cost estimation methodology can be presented in the following table 15:

Table 15 *- Summary*

Level	Definition	Estimation
BEC	Cost of equipment	Defined considering different equipment cost functions
EPCC	Detailed design, management costs and contractors permitting	10% of BEC in addition
TPC	Extra-expenditures related to process and project contingencies	20% of EPCC in addition
TOC	Cost of royalties, operating tests	20% of TPC in addition

At the end we can state that for the CAES plant at issue:

$$TOC = BEC \cdot 1.1 \cdot 1.2 \cdot 1.2 = 1.584 \cdot BEC$$

Once the total overnight cost is defined, is it necessary to compute the annuity ($/year) for each component according to:

-Life time of the plant

-Financial structure

-WACC

For the lifetime of the plant, considering an availability of 60% as seen previously in the intro, we used as reference other existing plant related to energy production from fossil fuels, not necessary CAES ones, since the lifetime of equipment like compressors, turbines and combustion chamber is well defined. So the CAES plant will be designed to operate for 35 years, then maybe its life will be extended thanks to equipment upgrade ecc.

The financial structure takes into account the type of developer/owner and the risk profile of the plant.

In general, without knowing or having further information, it is used to put 50%

of equity and 50% of debts as a general ratio.

Then to proceed in the WACC definition ("Weighed average cost of capital") we need to know more info about other parameters.

The definition of WACC is reported here:

$$WACC = K_e \cdot \frac{E}{D+E} + K_d \cdot \frac{D}{D+E}$$

So in order to compute the WACC, that will be used as real discount rate c (another fundamental parameter for the definition of the annuity), we need to know the financial structure (E,D) and the cost of equity (Ke) and finally the cost of debt (Kd).

Let's start with the definition of the cost of equity.

As a general definition, the cost of equity must include two different component, that are **the systemic risk $\mathbf{R_f}$** and **the specific risk**, also defined ***premium***.

$$K_e = R_f + Premium$$

The cost of equity will be at least equal to the systemic risk if no premium are considered.

This is not the case and so also premium contribution must be taken into account and that is done considering this general expression:

$$Premium = R_S + \beta \cdot (R_m - R_f)$$

Where:

Rs is a "personal risk" related to the fact that maybe the investor is using a significant amount of his savings, in this particular case the personal risk will be set to be equal to zero, no small investors.

β is a parameter that will be set equal to one in absence of further info, it takes into account the particular sub-sector of a market, in this case the energy market.

(Rm-Rf) is also defined as the EMRP "equity market risk premium", in this particular situation it will be defined considering:

$$R_m = 8.25\% \, ; R_f = 2.25\%$$

For the cost of debts, K_d, the definition is different and takes into account different parameters:

$$K_d = (IRS + SPREAD)$$

Where IRS stands for "interest rate swap" and the spread is referred to the interest rate depending on the ability of the investor to return the capital.

The values of these two parameters are assumed to be equal, respectively, to 0.80% and 1%.

With all the parameters defined it is possible to compute the WACC, and as said before, this value will be important since the real discount rate can be chosen to be equal to the WACC in a constant currency economic analysis.

$$c = WACC = 5.025\%$$

The annuity of each component will be the present value of the TOC cost as an uniform series spread over the entire life time of the plant, so the capex split in a uniform way.

The way to compute that is given by the formula:

$$annuity_i = TOC_i \cdot \frac{c \cdot (1+c)^n}{(1+c)^n - 1}$$

Where n is the life time of the plant expressed in year.

Then the annuity ($/year) must be converted into the actual cost rate ($/s) of the component considering the availability of the system (working hours in a year).

Here below the cost rates of the different component are summarized in Table 16:

Table 16 - Cost rate

Component	Cost rate ($/s)
CMPR1	0.051977
COOLER1	0.002489
CMPR2	0.052746
COOLER2	0.002938
CAVERN	0.037332
VALVE	0.002372
HPCC	0.003065
HP-TURB	0.079631
LPCC	0.004592
LP-TRUB	0.126762

As specified before, auxiliary equations are needed to close the linear system, since we only have at disposal 9 equations for 19 streams.

The methodology to write these equations is very similar to the one seen for the exergy-cost analysis, four different rules that let define the extra info needed:

Rule 1: "In absence of further info the exergo-economic cost of inlet flows in the plant is equal to zero".

In this case we can put the exergo-economic cost of the inlet air equal to zero, since we don't pay air.

For the electricity taken from the grid for the compressors (streams 13,15) this way of thinking is no longer valid, since we have to include the electricity price. Same story for the incoming inlet flows of natural gas (streams 7 and 10), where the actual price of natural gas must be considered.

Since the plant is located in Italy, info for electricity and natural gas cost can be easily found in EUROSTAT[3] website:

Table 17 *- Cost of natural gas and electricity*

Resource	Price ($/MWh)
Nat. gas	30.845
Electricity	101.86

To be more conservative as possible the two costs will not be modified, even though in a real scenario these one could be defined in different ways, in particular, they can be decreased according to special agreements and deals. Thus, 5 auxiliary equations can be written:

C1 = 0

C7 = c7×E7

C10 = c10×E10 *where c10 and c7 are the natural gas price*

C13=c13×E13

C15=c15×E15 *where c13 and c15 are the electricity price*

Rule 2: "The exergo-economic cost of discharged flows is equal to zero"

That again it's true in absence of other particular info or restrictions (like taxes for pollutants emission).

Thanks to rule number two we're able to write three more auxiliary equations:

C12=0 *since c12=0*

C14=0 *since c14=0 but also E14=0*

C16=0 *since both c16 and E16 are null*

Rule 3: "The unit exergo-economic cost of output flows which are part of the fuel will be the same of the fuel itself"

That particular rule can be applied for the first turbine, always keeping in mind the productive structure, so we can write:

$$-(E9/E8+)C8 + C9 = 0$$

The fourth rule, which states that the unit exergo-economic cost of products with the same thermodynamic quality is the same, and is not useful since we're already reached the exact number of independent equations needed to close the system.

3.3.2 Exergo-economic cost C and unit exergo-economic cost c

Once all the exergo-economic balance and the auxiliary equations are written, we can think to condensate them into a matrix formulation with the aim to find the exergo-economic cost ($/s) of each stream.

From the previous consideration, we can summarize the exergo economic balance for the different components into:

$$[A] \cdot C = -Z$$

Where A is the incidence matrix and -Z is the vector of cost rates for different component, with the sign changed.

From auxiliary equations type 1 and 2 we have written 8 auxiliary equations, the can also be summarized into a matrix form:

$$[\alpha_e] \cdot C = C_e$$

Where Ce is a vector including the constant term of each equations.

Finally type 3 and 4 equations (in our case only type 3) can be written as:

$$[\alpha_x] \cdot C = C$$

Putting together all this information we can finally write:

$$\begin{bmatrix} A \\ \alpha_e \\ \alpha_x \end{bmatrix} \cdot C = Z_e$$

Where the matrix $\begin{bmatrix} A \\ \alpha_e \\ \alpha_x \end{bmatrix}$ is again the cost matrix Ac.

By doing the inverse of the matrix we can find the value of the exergo-economic cost for all the streams in the CAES, in the table below all the results are reported.

In the table also the unit exergo-economic costs are reported, in particular, they are defined in this way:

$$c\left(\frac{\$}{MWh}\right) = \frac{C(\$/s)}{E(MW)}$$

Where E is the exergy content of the specific stream.

Finally, we get table 18 of exergo-economic cost.

Table 18 - Exergo-economic cost

Stream	$C(\$/s)$	$c(\$/MWh)$
1	0	0
2	0.928	114.89
3	0.930	166.013
4	1.880	136.413
5	1.883	170.277
5’	1.920	173.652
6	1.923	176.161
7	0.557	30.845
8	2.483	141.953
9	1.497	152.206
10	0.579	30.845
11	2.081	95.230
12	0	0
13	0.876	101.864
14	0	0
15	0.897	101.864
16	0	0
17	1.065	154.518
18	2.207	147.542

Looking at the results we can instantly check some of them having in mind all the previous steps:

-As expected, the exergo-economic cost of heat streams (14-16) is null since they are discharged flows and according to rule 2 their unit exergo-economic cost is zero.

-The unit-exergo economic cost of gas streams (7-10) must be equal to the price found on the market, the same for electricity streams incoming in the plant (13-15). That’s quite obvious but it’s just a way to be sure that no errors have been done during the developing of the process.

Therefore, looking at the results we can also appreciate the power of the exergo-economic analysis since we are finally able to define which is the real price of **every streams** inside the plant with particular attention towards the real cost, for the owner of the plant, of the energy streams that are produced and that will be sold again in the market.

The retail price will be chosen according those values and then an economic analysis will be performed to understand the revenues and other fundamentals parameters like the payback time PBT and the internal rate of return IRR needed to evaluate the investment.

From the exergo-economic analysis we got a unit exergo-economic cost of 154.5 $/MWh for the power stream produced by HPTURB, and 147.5 $/MWh for the power produced by LPTURB, with an average unit exergo-economic cost of electricity (weighted on electricity production of each turbine):

$$c_{el,average} = 149.7 \frac{\$}{MWh}$$

It's interesting to see that this result can be also obtained by means of a simple economic evaluation considering opex (gas and electricity consumption), yearly cost of the plant and annual electricity production:

$$opex = \sum_i Exergy_i \cdot availability_i \cdot 8760 \cdot resource\ price_i = 55038650.38\ \$$$

$$c_{tot,yearly} = opex + annuity = 61924309.81\ \$$$

$$El_{yearly} = \sum_i Exergy_i \cdot availability_i \cdot 8760 = 413542.08\ MWh$$

$$c_{el,average} = \frac{c_{tot,yearly}}{El_{yearly}} = \frac{61924309}{413542.08} = 149.7\ \$$$

4. Improvement

4.1 Introduction

The purpose of this and next chapters is to analyze and change the initial configuration of the plant to improve the system and obtain an optimized layout of the plant. It has been firstly found the irreversibility associated to each component, then modifications have been carried out considering which component generates much irreversibility. The design improvement steps follow the relationship between the investment cost of components and the irreversibility associated to:

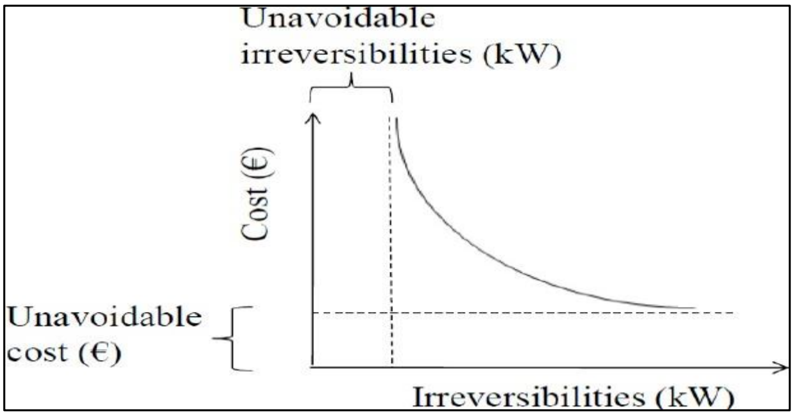

Figure 12 - *Cost and irreversibilities*

Generally, components with high efficiency are characterized by higher cost, while components with lower efficiency are associated with lower cost. The optimum is found when compromise between these two quantities occurs. In addition, the system can be also improved by changing thermodynamic parameters of the cycle, using in a better way already existing device.

The power plant is crossed by physical flows, but it is not mandatory that they are similar or equal to unit cost of resources or products. For this reason, it is useful to do some considerations for design improvement method and consider different cases to define unit cost of each stream. Starting from the physical flows, it has been calculated the cost of fuel flows (c_F) and of products (c_p) according to specific rules:

Resource corresponding to a physical flow

$$c_F = c_i$$

Product corresponding to a physical flow

$$c_P = c_i$$

Resource defined as a summation between two physical flows

$$c_F = \frac{c_1 E_1 + c_2 E_2}{E_1 + E_2}$$

Resource defined as a difference between two physical flows

$$c_F = c_1 = c_2$$

Product defined as a difference of physical flows

$$c_P = \frac{c_1 E_1 - c_2 E_2}{E_1 - E_2}$$

Resource defined as a summation of physical flows

$$c_P = c_1 = c_2$$

In this way, it has been given a structure and defined main characters to the method. However, it is not sufficient to compare and decide which component has much weight in terms of cost and irreversibility produced, therefore it is necessary to find other two thermo-economic factors, that allows to see which component needs improvement and decide if it is better to decrease the cost of the component itself or to reduce the irreversibility generated from it.

Thanks to the knowledge of exergo-economic cost of resources and products, it can be found:

-The relative cost difference that represents the relative increment of the average cost between resources and products of a specific component per unit of exergy:

$$r = \frac{c_P - c_F}{c_F}$$

-The exergo-economic factor that is defined as the ratio between investment cost of a certain component (Z) and the increase of unit cost due to the exergy destruction (C_D):

$$f = \frac{Z}{Z + c_F \cdot I} = \frac{Z}{Z + C_D} \quad ; \quad 0 < f < 1$$

The choice to improve a component is based on specific steps:

Calculate the sum of investment cost (Z) and cost of destroyed exergy (C_D). Then results must be ordered from the highest to the lowest value and components related to an higher value of this sum have high potential of improvement. In addition, this potential is reliable if components account for a high relative cost difference.

Seeing exergo-economic factor associated with a component, it confirms which is the main cause of rising in cost. Particularly, higher will be the value higher is the weight of investment cost for the component, while a low value indicates a high incidence of thermodynamic efficiency.

The goal is to find a solution that permit to select a cheaper component or increase the investment cost and use a component with a higher efficiency, obviously when it is necessary.

In this project, after finding cost rate of components and cost of exergy destruction and, thanks to the knowledge of exergo-economic cost of resources and products, there will be represented results for each component in table 19 that also contains the cost of exergy destroyed. $(C_D = c_F \cdot I)$

Table 19 - *Cost of exergy destroyed*

Components	Unit cost of resources C_F (\$/MWh)	Unit cost of products C_P(\$/MWh)	Cost rate of component Z(\$/s)	Irreversibilities I (MW)	Cost of exergy destroyed C_D(\$/s)
CMPR1	101.864	116.82366	0.051977419	2.361174531	0.066810745
INTER-COOL 1	114.890419	166.0127198	0.002488998	8.896993	0.283938682
CMPR2	101.864	116.1406683	0.052745757	2.2634367	0.064045199
INTER-COOL 2	136.4131707	170.2772746	0.002938492	9.806118	0.371578791
CAV	170.2772746	173.6528343	0.037331726	0	0
VALVE	173.6528343	198.4480134	0.002372343	4.931531	0.23788176
HPCC	30.8448	71.76806024	0.003064916	36.8951281	0.316117458
HP-TURB	141.9530765	154.5182759	0.079631194	2.7348291	0.107838168
LPCC	30.84479998	48.58694219	0.004591591	24.34236523	0.208565385
LP-TURB	95.23027912	147.5420547	0.126762278	5.6093033	0.148382089

According to the table 20 and the previous definition of these factors, components need improvements under both economic and thermodynamic point of view.

Following the step 1, the first combustion chamber (HPCC) and low-pressure turbine (LPCC) could need economic improvements due to the high values of cost of exergy destroyed $(Cd + Z)$ and calculated relative cost difference (r). Particularly, this last coefficient for the combustion chamber is markedly high due to the high cost of product.

Table20- *r in different components*

Components	Cd+z (\$/s)	r
INTER-COOL 2	0.374517283	0.248246586
HPCC	0.319182373	1.326747466
INTER-COOL 1	0.286427679	0.140154209
LP-TURB	0.275144367	0.549318726
VALVE	0.240254103	0.142785917
LPCC	0.213156976	0.08851657
HP-TURB	0.187469362	0.575206914
MCPR1	0.118788164	0.146859146
MCPR2	0.116790955	0.444965744

The exergo-economic factor represents which components is the most subjected by irreversibility. Components highlighted in red have a higher potential of improvement from a thermodynamic point of view. Critical values are related to two combustion chambers that are working in the generation phase of the system.

Table 21 *- f in different components*

Components	Exergo-economic factor f
CMPR1	0.437563957
INTER-COOL 1	0.008689795
CMPR2	0.451625354
INTER-COOL 2	0.007846078
CAV	1
VALVE	0.009874309
HPCC	0.009602397
HP-TURB	0.42476911
LPCC	0.02154089
LP-TURB	0.460711879

Once it is found a general frame of the operating conditions of components and how they are working, they must be selected candidates for an eventual improvement following also factors that it have been calculated.

The idea of the project for improvement part was to work on the layout of the system, adding or removing components and changing working conditions of fluid in specific part of the plant.

For improving the power plant, it has been chosen to remove the combustion chambers, that are a high source of irreversibility, and go towards the adiabatic configuration of CAES system. Adiabatic CAES system (A-CAES) permits to leave fossil fuel for power production and improve the system avoiding combustion chambers which are components that generate irreversibility and increase the cost of product. For this reason, the unique path to recover heat without combustion process is represented by compression stages of air that allows to achieve a twofold purpose:

1-Heat for working fluid to generation phase

2-Cooling of air at the inlet of compressor reducing the specific work required *by the compression*

External circuit coupled with a thermal storage is needed to provide heat exchanging in specific point of the plant and to split charging and discharging phases in time.

It can be extracted other aspects from ‘f’ table, like the value associated to the Cavern. The cost of the cavern is mainly attributed to the initial investment because there is no irreversibility production of this component, but of course, as already mentioned before, it’s because we model it as an ideal device.

However, before studying the adiabatic configuration, we wanted to understand the possibility to add more compression stages to investigate the effect that this particularly decision would have had on plant’s performances and efficiency

4.2 Three-stage compression

In order to further improve the efficiency and increase the economy, we tried to add an extra compressor at first, and the simulation process is shown in Figure 6. In this design, we don't add the cavern which can be regarded as the ideal component because of only thermodynamic analysis is carried out.

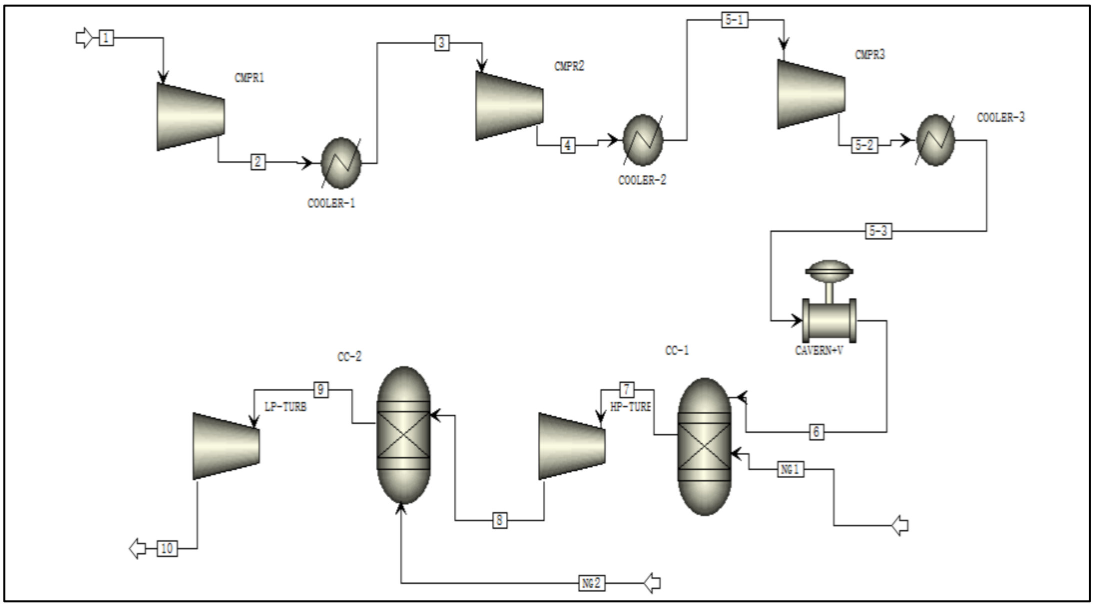

Figure 13 *- Simulation about 3-stage compression*

4.2.1 thermodynamic analysis

Through the simulation, we can see the following data in Table 22:

Table 22 *- 3-stage compression simulation results*

Stream Name	Temperature	Pressure	Mass Flows	Mass Enthalpy	Mass Entropy
Units	**K**	**bar**	**kg/sec**	**kJ/kg**	**kJ/kg-K**
1	298.15	1	108	-0.27868	0.151129
2	462.9994	4.16	108	167.5336	0.188026
3	303.15	4.16	108	3.940676	-0.24519
4	470.9748	17.3056	108	174.7146	-0.20829
5--1	308.15	17.3056	108	5.714252	-0.64859
5--2	479.6306	71.9913	108	180.2722	-0.61157
5--3	313.15	71.9913	108	-0.96243	-1.07645
6	307.4034	42	108	-0.96242	-0.92331
7	298.15	50	1.243263	-4701.83	-7.17989
8	823.1505	42	109.2433	-54.4616	0.145477
9	616.6874	11	109.2433	-286.284	0.213917
10	298.15	50	1.286854	-4701.83	-7.17989
11	1098.151	11	110.5301	-337.692	0.872864
12	680.8471	1	110.5301	-834.949	1.009723

Through the calculation, exergy and irreversibilities for each component can be obtained as shown in table 23 and table 24, respectively.

Table 23 *- Exergy*

Stream Name	physical exergy	chemical exergy	total exergy
Units	**MW**	**MW**	**MW**
1	0.00	0.481	0.481
2	16.936	0.481	17.416
3	13.217	0.481	13.698
4	30.473	0.481	30.953
5-1	26.398	0.481	26.879
5-2	44.058	0.481	44.539
5-3	39.454	0.481	39.935
6	34.523	0.481	35.004
7	0.732	64.450	65.182
8	62.111	0.971	63.082
9	34.556	0.971	35.528
10	0.757	66.710	67.467
11	21.795	2.409	78.470
12	21.795	2.409	18.998

__Table 24__ - Irreversibility for Each Component

	I (WM)	Percent
CMPR1	1.558	1.69%
COOLER1	3.718	4.04%
CMPR2	1.565	1.70%
COOLER2	4.074	4.43%
CMPR3	1.577	1.71%
COOLER3	4.604	5.00%
VALVE	4.931	5.36%
HPCC	37.104	40.33%
HPTURB	2.736	2.97%
LPCC	24.524	26.66%
LPTURB	5.609	6.10%
total	92.001	100.000%

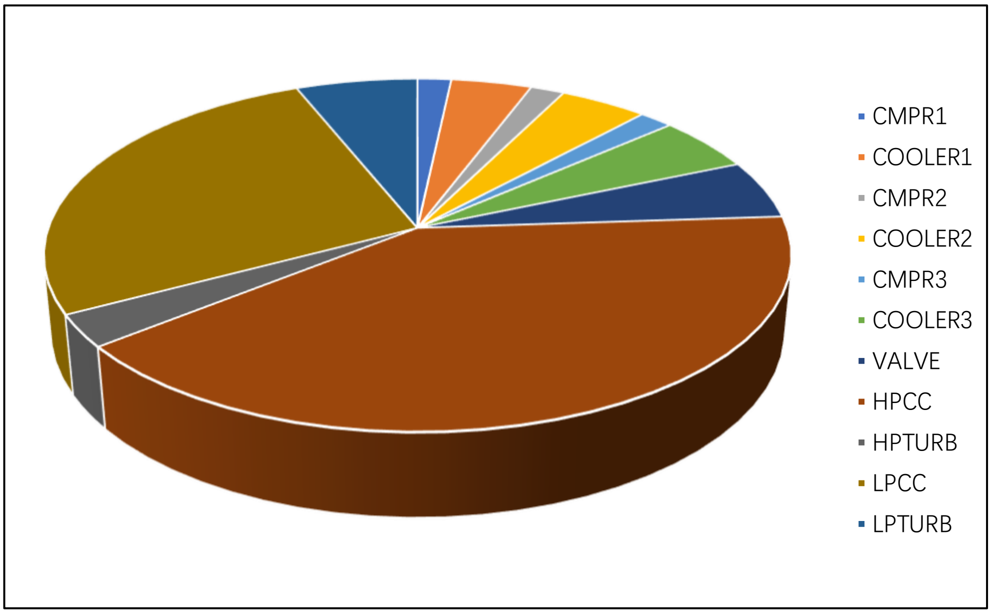

__Figure 14__ - Pie Chart of Irreversibility for Three-stage compression

By comparison, the irreversibilities has decreased, but the decrease is not significant, with a new round trip efficiency of 42.85% (reference 42.6%). Therefore, we will discuss the adiabatic scheme in the next chapter, with the same number of compression stages of the reference plant.

4.3 Adiabatic

The aim of this section is to completely redesign the CAES in an adiabatic configuration.

The purpose of an adiabatic configuration is to totally avoid the use of natural gas (or other possible fossil fuels) and more in general to hinder combustion processes (and thus pollutants emissions).

Imaging an adiabatic CAES is not easy though, since without external fuel all the energy must be recovered from the compression stages. It is also evident that, since the charging phase and the discharging one are de-coupled in time, it is needed to install a TES (thermal energy storage) to properly match the two processes.

In order to verify the feasibility of the plant, in a thermodynamic point of view, pinch analysis will be applied.

4.3.1 Pinch analysis starting from design data

In this section the goal is to identify which are the minimum heating and cooling demand of the plant if we consider exactly the temperatures found in the first section of the report with pure air as a working fluid (we know that in the real plant we will have flue-gasses with different thermodynamic properties). That's the starting point to properly understand which will be **limits** and **compromises** related to an adiabatic CAES configuration.

For sake of simplicity, at this level we consider the charging and discharging phases to be performed in parallel at the same time, which means that, in a symmetric configuration, the hot streams coming from compression stages are ideally used to heat up the cold streams from the cavern in order to reach high temperatures at HP and LP turbines.

No TES or/and diathermic oil modeling at this level.

We also include the air coming out from the second turbine as an important source of heat since they’re still at high temperature (from previous simulation $\approx 407°C$).

Here are reported all the summary tables and schemes used to develop the pinch analysis in an analytical way, where we consider pure air:

$$G = 108\ kg/s\ ;$$

$$c = 1047\ \frac{kJ}{kg \cdot K}\ \text{, constant;}$$

$$\Delta T_{min} = 20°C\ ;$$

Table 25 *- Properties of five streams*

STREAM	TYPE	Gc (kW/K)	Tin(°C)	Tout(°C)	T*in(°C)	T*out(°C)
1	hot	113.076	298.41	30	288.41	20
2	hot	113.076	309.07	40	299.07	30
3	cold	113.076	34.25	550	44.25	560
4	cold	113.076	343.54	825	353.54	835
5	hot	113.076	407	30	397	20

Stream 1: hot air coming out from the first compression stage

Stream 2: hot air coming out from the second compression stage

Stream 3: cold air from the cavern after the lamination by a throttling valve

Stream 4: hot air after the first expansion that need to be re-heated

Stream 5: hot air after the second expansion

Here is reported the pinch analysis process and the results:

Pinch analysis										
Range	T*	1	2	3	4	5	$\sum G \cdot c ; \left[\frac{kW}{k}\right]$	$\phi_{av}[kW]$	$\phi_{cm}[kW]$	$\phi_{cm}[kW]$
	835,00								0	72872,959
1	560,00						-113,076	-31095,900	-31095,900	41777,059
2	397,00						-226,152	-36862,776	-67958,676	4914,283
3	353.54						-113,076	-4914,283	-72872,959	0,000
4	299.07						0,000	0,000	-72872,959	0,000
5	288.41						113,076	1205,390	-71667,569	1205,390
7	44.25						226,152	55217,270	-16450,299	56422,660
8	30,00						339,228	4834,000	-11616,299	61256,660
9	20,00						226,152	2261,520	-9354,779	63518,180

Figure 15 *- Pinch analysis*

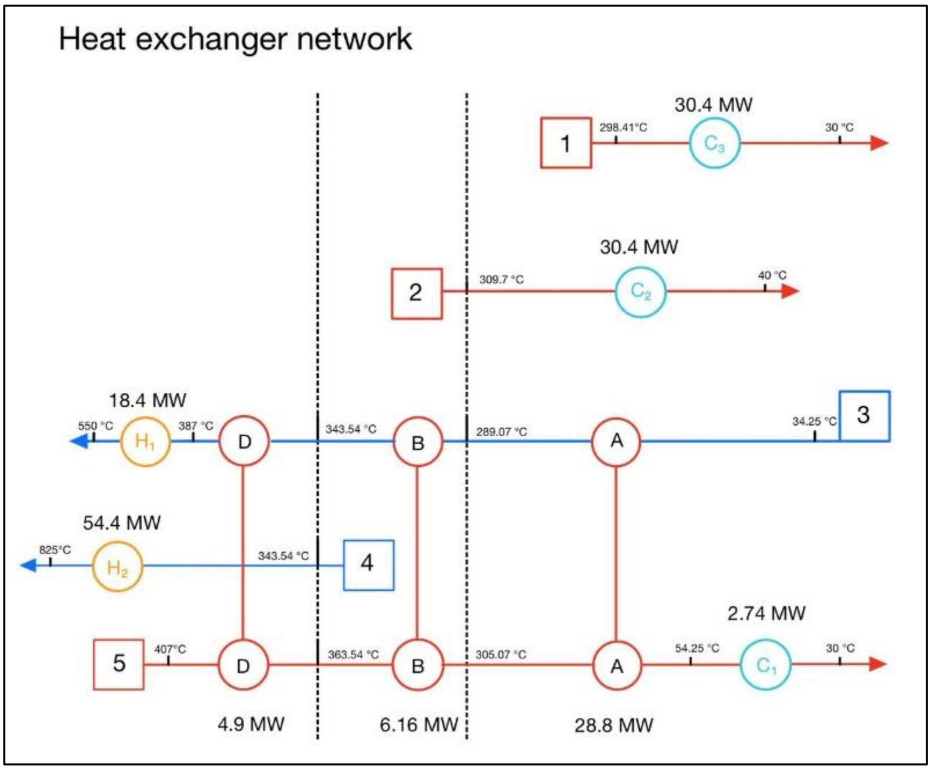

Figure 16 *- Pinch analysis in heat exchanger network*

At the end of this process we can see that, considering the design temperatures of the first part of the report, the minimum heating and cooling demand are relevant:

$$\Phi_{hd} \approx 72.9\ MW$$

$$\Phi_{cd} \approx 63.5\ MW$$

And from that analysis we have seen that only the stream number 5 and 3 can be coupled together in order to achieve the complete heating of cold streams below the pinch point and the complete cooling of hot streams above the PP.

In a design point of view that is equivalent to the installation of a **recuperator** after the second turbine.

With the recuperator we are almost able to reach the first design TIT of 550°C (the fluid exiting the heat exchanger reaches 387°C) and thus to reduce the mass flow rate of natural gas in the first combustion chamber.

For the re-heating of stream number 4, the second law of thermodynamic doesn't leave space for improvement, since no thermal coupling is possible and thus all the NG mass flow rate in the LPCC found in the first simulation is needed.

Finally, all the heat available from the compression stages is discharged into the environment, since its temperature is not high enough to participate in the heat recovery.

In conclusion, with that results we're far away from the goals that we have established at the beginning of the design improvement section, because we've only reduced the amount of fuel needed without totally avoiding the combustion processes.

In the following pages we will study a possible configuration for the adiabatic CAES plant with limited performances with respect to the reference CAES.

4.3.2 Scheme of the adiabatic plant

From pinch analysis we have found that in order to recover the heat from the intercoolers of the compression stages the maximum temperatures of the cycle must be lowered.

Obviously that will dramatically reduce the specific power output of the plant, since for the same mass flow rate we will have less than an half of the power produced with respect to the previous case with two combustion chambers.

But the goal of this section is only to apply the exergy analysis on a different configuration of CAES plant in which no combustion processes are needed, since all the heat for the discharging phase is recovered from the charging one.

Here below it is presented the new configuration:

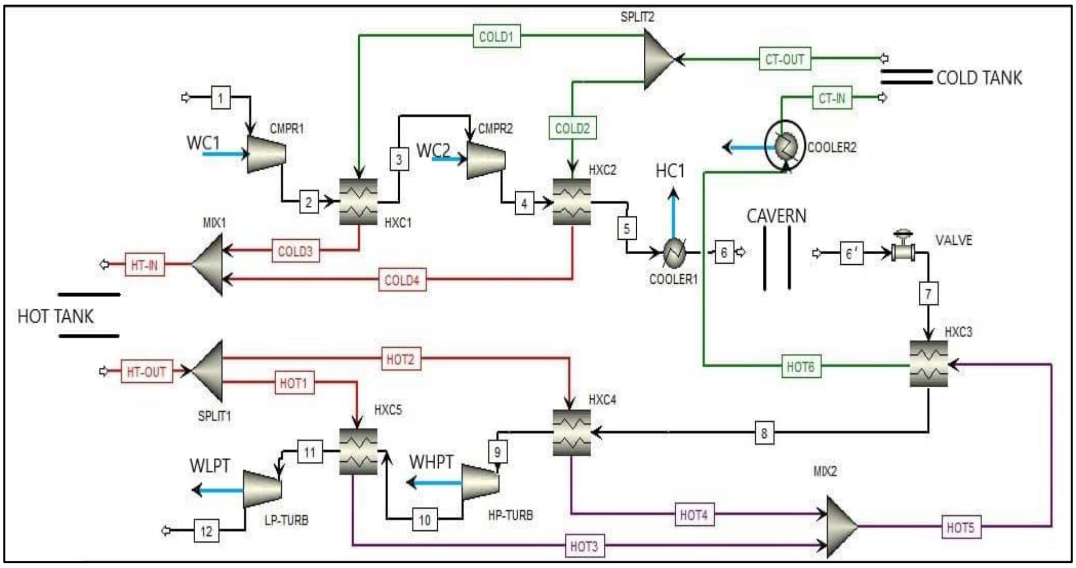

Figure 17*- Scheme of the adiabatic plant*

As can be seen, in order to couple together the discharging phase with the charging one, a TES (thermal energy storage) is needed.

For sake of simplicity, the TES has been modeled with pressurized water at 50 bar in an ideal circuit with no pressure drops (and so no turbo-pumps needed).

The high pressure of the water will partially hinder the phase-transition of the water into steam (from saturation table of water T_{sat}=263.92°C @50 bar).

In real application the working fluid may be replaced with diathermic oil.

In the scheme above the TES circuit is closed as it will be in real life, the second cooler is only a fictitious component (in the real plant the cooling process will be performed by the biosphere itself).

The role of the first cooler instead is to lower the temperature of the pressurized air coming out the compression stages at 40°C, which is the maximum temperature allowed at the cavern inlet for safety reasons.

The plant is also equipped with mixers and splitters whose investment costs will be considered negligible.

Splitters, mixers, cavern and cold/hot tanks are also modeled as ideal devices where no exergy destruction takes place.

A	MATERIAL STREAMS (AIR)													MATERIAL STREAMS (WATER)														ENERGY STREAMS					
	1	2	3	4	5	6	6'	7	8	9	10	11	12	COLD1	COLD2	COLD3	COLD4	HT-IN	HT-OUT	HOT1	HOT2	HOT3	HOT4	HOT5	HOT6	CT-IN	CT-OUT	WC1	WC2	HC1	WHPT	WLPT	HC2
CMPR1	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
HXC1	0	1	-1	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CMPR2	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
HXC2	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
COOLER 1	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0
CAVERN	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VALVE	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HXC3	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0
HXC4	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0
HP-TURB	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0
HXC5	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0
LP-TURB	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
MIX1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HOT TANK	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SPLIT1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0
MIX2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	-1	0	0	0	0	0	0	0	0	0
COOLER2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	-1
COLD TANK	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0
SPLIT2	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0

***Figure 18** -Incidence Matrix*

4.3.3 Thermodynamic Analysis

Through software simulation and calculation, we get the properties of each stream as shown in table 26. The calculated total exergy is also attached here:

Table 26 *- Streams' results*

	Temperature	**Pressure**	**Mass Flows**	**Mass Enthalpy**	**Mass Entropy**	**Total Exergy**
Units	**C**	**bar**	**kg/sec**	**kJ/kg**	**kJ/kg-K**	**MW**
1	25	1	108	-0.27868	0.151129	0.481012
2	298.4103	8.485	108	280.5386	0.201444	29.18913
3	45	8.485	108	18.19067	-0.40424	20.35873
4	336.4415	71.99523	108	320.1656	-0.35353	51.33925
5	45	71.99523	108	4.656118	-1.05867	39.96962
6 and 6'	40	71.99523	108	-0.9632	-1.07647	39.93599
7	34.25274	42	108	-0.9632	-0.92332	35.00446
8	50	42	108	16.04323	-0.86936	35.10382
9	220	42	108	196.3488	-0.42078	40.13249
10	87.25958	11	108	61.09	-0.35233	23.32025
11	238	11	108	217.0361	0.009004	28.52747
12	24.00503	1	108	-1.28662	0.147743	0.481194
COLD1	25	50	25	-15967.4	-9.3277	1.394072
COLD2	25	50	30	-15967.4	-9.3277	1.672887
COLD3	257.757	50	25	-14834.1	-6.54969	9.02752
COLD4	258.1769	50	30	-14831.6	-6.545	10.86583
COLDTANK	25	50	55	-15967.4	-9.3277	3.066959
HOT1	257.9861	50	27.5	-14832.7	-6.54713	9.946673
HOT2	257.9861	50	27.5	-14832.7	-6.54713	9.946673
HOT3	139.1807	50	27.5	-15445.2	-7.84631	3.751304
HOT4	118.7125	50	27.5	-15540.8	-8.08426	3.07092
HOT5	128.9868	50	55	-15493	-7.96377	6.797371
HOT6	121.8218	50	55	-15526.4	-8.04756	6.334302
HOT-TANK	257.9861	50	55	-14832.7	-6.54713	19.89335

By comparison with the reference plant(the table and the pie chart is in the next page), we know that adiabatic plant is better regarding both the irreversibility and the efficiency (58%).

In terms of the productive structure, exergy cost and exergo-economic cost, we will use the same method introduced before, based on the physical structure we built in Aspen Plus and the data generated which has been mentioned above.

***Table** 27 - Irreversibility associated to each Component*

	I(MW)	Percent
CMPR1	**2.239092**	**0.083617**
HXC1	1.196954	0.044699
CMPR2	2.298359	0.08583
HXC2	2.176678	0.081286
COOLER 1	0.033632	0.001256
CAVERN	0	0
VALVE	4.931531	0.184164
HXC3	0.363706	0.013582
HXC4	1.847085	0.068978
HP-TURB	2.496448	0.093228
HXC5	0.988149	0.036902
LP-TURB	4.938993	0.184442
MIX1	0	0
HOT TANK	0	0
SPLIT1	0	0
MIX2	0	0
COOLER2	3.267342	0.122016
COLD TANK	0	0
SPLIT2	0	0
Total	26.77797	1

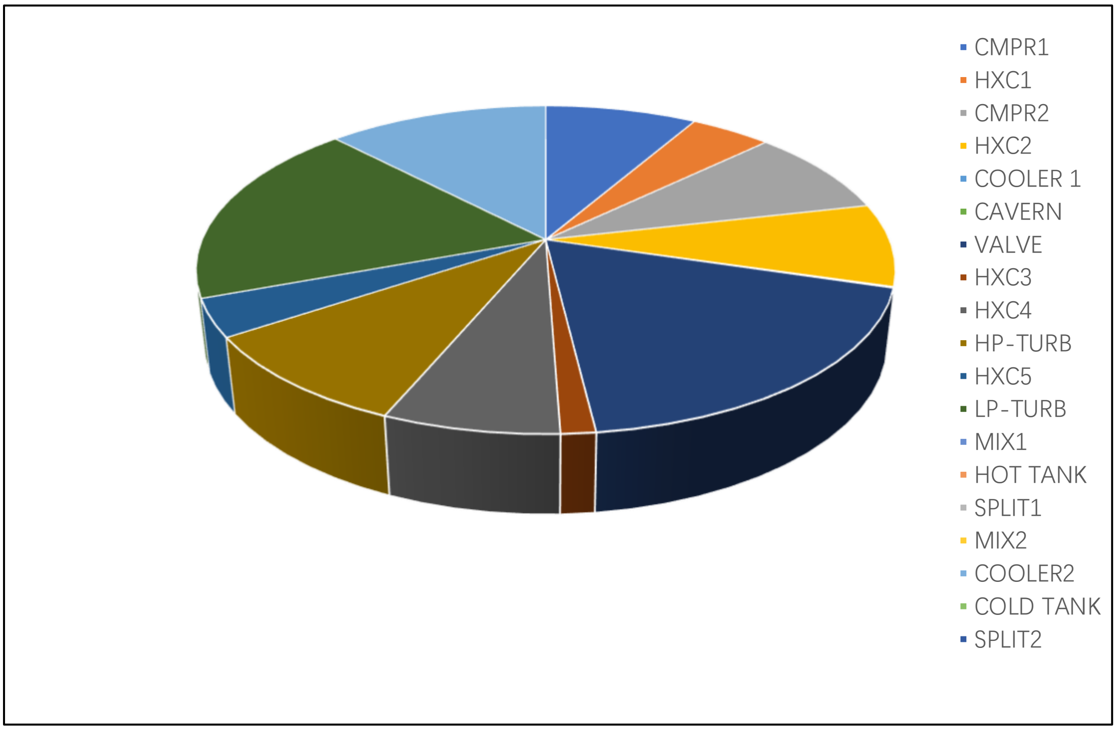

***Figure 19**- Pie Chart of Irreversibility for Adiabatic plant*

To get the Productive structure table, we need to identify the resources (or fuel F), products (P) and losses or discharged flows (L or D) of each component in the plant. And it is shown as below:

Table 28 *- Productive structure for adiabatic plant*

Component	Resources F	Products P	Losses/discharged LorD
CMPR1	WC1	E2-E1	//
HXC1	E2-E3	COLD3-COLD1	//
CMPR2	WC2	E4-E3	//
HXC2	E4-E5	COLD4-COLD2	//
COOLER 1	E5	E6	HC1
CAVERN	E6	E6'	//
VALVE	E6'	E7	//
HXC3	HOT5-HOT6	E8-E7	//
HXC4	HOT4-HOT2	E9-E8	//
HP-TURB	E9-E10	WHPT	//
HXC5	HOT1-HOT3	E11-E10	//
LP-TURB	E11	WLPT	E12
MIX1	COLD3+COLD4	HT-IN	//
HOT TANK	HT-IN	HT-OUT	//
SPLIT1	HT-OUT	HOT1+HOT2	//
MIX2	HOT3+HOT4	HOT5	//
COOLER2	HOT6	CT-IN	HC2
COLD TANK	CT-IN	CT-OUT	//
SPLIT2	CT-OUT	COLD1+COLD2	//

After the productive structure of the system has been defined, we can proceed with the exergy cost E* definition of each stream. Same rules will be followed for the definitions of auxiliary equations:

Rule 1: “The exergy cost of resources is equal to their exergy.”

Rule 2:“The exergy cost of discharged flows into the environment is assumed to be null.”

Rule 3:”The unit exergy cost ($k_i=E_i^*/E_i$) of an output stream which is part of the fuel is the same of the inlet stream from which it comes from.”

Rule 4, “Two or more products of a component with the same thermodynamic quality have the same unit exergy cost.”.

By applying these 4 rules and incidence matrix to get the cost matrix A_C, and then follow the matrix equation $[Ac] \cdot E^{*} = Ye$, it's not difficult to get the data of exergy cost for each stream.

Table 29 *- Exergy cost for adiabatic plant*

Stream	Exergy cost E*(MW)	Unit exergy cost k*
1	0.481012231	1
2	31.42822323	1.076709772
3	21.92044356	1.076709772
4	55.19931856	1.075187565
5	42.97483883	1.075187565
6	42.97483883	1.076093022
6'	42.97483883	1.076093022
7	42.97483883	1.227696167
8	43.72102828	1.24547777
9	54.76025204	1.364486798
10	31.82016846	1.364486798
11	41.76701466	1.464098269
12	0	0
COLD1	4.639586999	3.328081585
COLD2	5.567504398	3.328081585
COLD3	14.14736667	1.567137643
COLD4	17.79198413	1.637424603
HT-IN	31.9393508	1.605529293
HT-OUT	31.9393508	1.605529293
HOT1	15.9696754	1.605529293
HOT2	15.9696754	1.605529293
HOT3	6.022829203	1.605529294
HOT4	4.930451648	1.605529291
HOT5	10.95328085	1.611399627
HOT6	10.2070914	1.611399628
CT-IN	10.2070914	3.328081585
CT-OUT	10.2070914	3.328081585
WC1	30.947211	1
WC2	33.278875	1
HC1	0	0
WHPT	22.94008357	1.60243169
WLPT	41.76701466	1.807526306
HC2	0	0

After that, we are going to do the exergo-economic analysis for adiabatic CAES plant by the methodology introduced by NETL. At first, the bare erected cost of technical equipment should be calculated, and the process is similar with that of reference plant that has been introduced before. By considering the real operating pressure and the real operating temperature (the proper material choice), the effect of scale and the effect of time, we will get a BEC value in 2019$ of each technical equipment. Secondary, use the equation of TOC based on BEC for adiabatic CAES plant, which is the same with the reference plant:

$$TOC = BEC \cdot 1.1 \cdot 1.2 \cdot 1.2 = 1.584 \cdot BEC$$

Regarding the WACC, at this time, we use the same properties with those of the reference plant, which equals to 5.025%. Then it's possible to calculate the valve of annuity of each component from TOC (in 2019$). Finally, we can compute annuity ($/year) converted into the actual cost rate ($/s) of the component by considering the availability of the system, so the working hours in a year.

Here below the cost rates of the different components are summarized in table:

Table 30 *- Cost rates of the different components for adiabatic plant*

Component	z($/s)
CMPR1	0.051977419
HXC1	0.005256093
CMPR2	0.054292893
HCX2	0.005579179
COOLER1	0.000585762
CAVERN	0.037331726
VALVE	0.002372343
HXC3	0.00054212
HXC4	0.002969061
HP-TURB	0.033781552
HXC5	0.003539617
LP-TRUB	0.045023536
MIX1	0
HOT-TANK	0.005483141
SPLIT1	0
MIX2	0
COOLER2	0
COLD TANK	0.005483141
SPLIT2	0

After obtained the cost matrix A_C and the related vector of cost rates, by applying the equation $\begin{bmatrix} A \\ \alpha_e \\ \alpha_x \end{bmatrix} \cdot C = Z_e$, we can find the value of the exergo-economic cost for all the streams after doing the inverse of the matrix, which is shown in table 31. Meanwhile, the unit exergo-economic costs can be defined in this way:

$$c\left(\frac{\$}{MWh}\right) = \frac{C(\$/s)}{E(MW)}$$

Where E is the exergy content of the specific stream.

Table 31 *- Exergo economic cost and Unit exergo-economic cost for adiabatic plant*

	Exergo economic cost C($/s)	**Unit exergo-economic cost c($/MWh)**
1	0	0
2	0.927645947	114.4098925
3	0.647011143	114.4098925
4	1.642948292	115.2064813
5	1.279099813	115.2064813
6	1.279685575	115.3563042
6'	1.317017301	118.7215449
7	1.319389644	135.6913661
8	1.342809032	137.7090135
9	1.684227366	151.0800501
10	0.978673335	151.0800501
11	1.287171249	162.433508
12	0	0
COLD1	0.144736473	373.7619852
COLD2	0.173683768	373.7619852
COLD3	0.43062737	171.7258456
COLD4	0.543111425	179.9402705
HT-IN	0.973738796	176.2126668
HT-OUT	0.979221937	177.2049235
HOT1	0.489610968	177.2049235
HOT2	0.489610968	177.2049235
HOT3	0.184652672	177.2049236
HOT4	0.151161695	177.2049233
HOT5	0.335814368	177.852842
HOT6	0.3129371	177.8528421
CT-IN	0.3129371	367.325869
CT-OUT	0.318420241	373.7619852
WC1	0.875668528	101.864
WC2	0.941644256	101.864
HC1	0	0
WHPT	0.739335582	185.921082
WLPT	1.332194785	207.5493711

It can be seen that the average unit exergo-economic cost of electricity has increased with respect to the reference plant:

$$\boldsymbol{c_{el,average} = 199.28 \frac{\$}{MWh}}$$

4.4.4 Economic Analysis

After the technical analysis shown above, an economic analysis should be performed to evaluate the feasibility and the stability of investing an adiabatic CAES system.

Concerning the economic analysis, it has been analyzed firstly the reference CAES system then our optimized CAES system. And the assessment parameters are:

1. Net Present Value *(NPV)*

It is the algebraic sum of the investment cost (I) with the net cash flows (B_t) over the whole life-time (n) of the project that are discounted at a certain nominal rate (i).

$$NPV = -I + \sum_{t=1}^{n} \frac{B_t}{(1+i)^t}$$

2. Benefit-Cost Ratio (BCR)

It describes the average profitability of an investment per unit of invested capital.

$$BCR = \frac{\sum_{t=1}^{n} \frac{B_t}{(1+i)^t}}{I}$$

3. Internal Rate of Return (IRR)

It is a metric used in financial analysis to estimate the profitability of potential investments. The internal rate of return is a discount rate that makes the net present value (NPV) of all cash flows equal to zero in a discounted cash flow analysis.

$$-I + \sum_{t=1}^{n} \frac{B_t}{(1+i)^t} = 0$$

4. Pay Back Time (PBT)

It describes the opportunity to choose the investment with the shortest period of return of the invested capital.

$$-I + \sum_{t=1}^{\tau} \frac{B_t}{(1+i)^t} = 0$$

Before the calculation, we need to define some parameters of the CAES system and economic parameters:

Table.32 *- Parameters of CAES system and economic parameters*

	Reference CAES System	**Adiabatic CAES System**
Availability of the plant [%]	60	60
Life time of the plant [years]	35	35
Annual Electricity consumed [MWh]	329,344.1977	337,572.308
Annual Natural Gas consumed [kg]	47,871,648	/
Annual Electricity produced [MWh]	413,547.993	196,695.6769
Electricity price in Italy [$/MWh]	101.86	101.86
Average Electricity Cost [$/MWh]	149.7	199.28
Retail Price for Electricity [$/MWh] (+15% with respect to adiabatic case)	229	229
Total Gas Price with IVA [$/MWh]	Variable Number	/
WACC	5.025%	5.025%

As can be seen, in our analysis, the retail price of electricity is set to be 15% higher than the average electricity cost of the adiabatic CAES, which is assumed as a reference, since is it a constant value over the time ($199.28 \times 1.15 = 229\ \$/MWh$).

In the first few years, the retail price for the reference CAES system would be much more than 15% higher, since the average cost of electricity for this plant starts from an absolute low value (149.7$/MWh). With the years passing by, because of a variable carbon tax penalization, the cost of electricity for the reference system increases and the retail price will be fixed at 229 $/MWh finally, appearing to be only 1.9% higher than the average cost of electricity itself.

To include the effect of taxation on natural gas, we must modify some parameters inside the exergo-economic analysis. There are two possible way to do that: we can include the gas tax in the specific cost of natural gas (stream 7 and 10 of the reference plant) and replace the auxiliary equation where we put the unit exergo-economic cost of discharged flow 12 equal to zero, with the unit-exergo economic cost weighted on the amount of CO_2 present in the stream, or we can condensate both the carbon tax and the gas tax directly in the unit exergo-economic cost of streams 7 and 10. By following the second option, a simple conversion is needed since the carbon tax is expressed as cost per unit ton of CO_2 emitted, while unit cost in the exergo-economic analysis must be expressed in $/MWh.

From the combustion of methane:

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

We will notice that from 1 molar of burned methane, 1 molar of CO_2 can be obtained.

From the total consumption of methane per year, considering the molar mass $\bar{M}_{CH4} = 16\frac{kg}{kmol}$. we can find the molar consumption, and this value multiplied by the molar mass of carbon dioxide ($\bar{M}_{CO2} = 44\frac{kg}{kmol}$) will give the ton of CO2 emitted by the plant in one year.

The production ton of CO_2 per year is then multiplied by the carbon tax. Put the results ($/year of CO2) be divided by the total consumption of natural gas, and in this way, we can get the cost of CO2 per unit mass of CH4. At last, by dividing this value for the lower heating value of CH4 (MWh/kg), the additional price for the natural gas can be obtained.

In the table below, it is presented that the effect of the carbon tax on the average electricity price, in order to define the break-even value that will make the average cost of electricity for the reference plant equal to the average cost for the adiabatic CAES, explore different values of the carbon tax should be done.

Table. 33 *- The effect of the carbon tax on the average electricity price*

Carbon tax ($/tonCO2e)	**New Gas price ($/MWh)**	**New Electricity price ($/MWh)**
13	33.327	152.46
26	35.81	156.75
52	40.775	165.33
104	50.706	182.5
117	53.188	186.79
130	55.671	191.08
143	58.154	195.37
150	59.491	197.69
155	60.445	199.34

Considering the break-even value and the strong possibility that, in the future, the carbon tax will grow, we can make a hypothesis of a time variable value with a linear evolution.

In other words, during the 35 years of the plant's life time, we suppose that the carbon tax increases linearly from the actual value (13$/ton CO_2 e) to the break-even value (155 $/ton CO_2 e), as presented in the figure below:

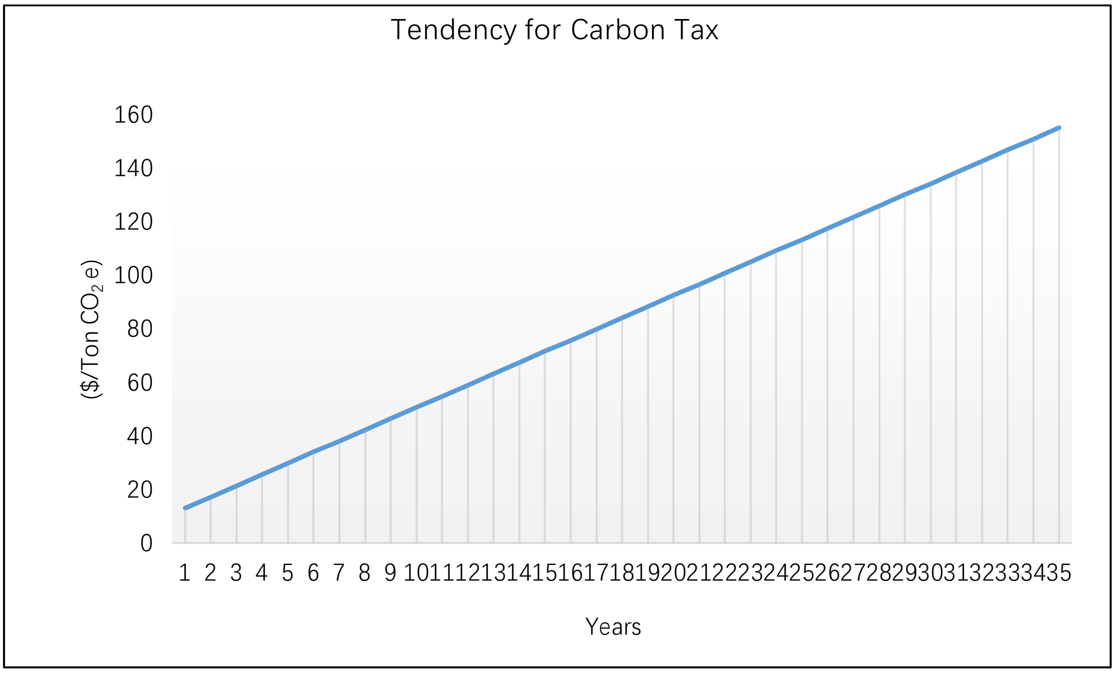

Figure 20 *- Tendency for Carbon Tax*

In addition to the carbon tax, has said before, we added some other additional costs related to the natural gas consumption in Italy. It is the Total Gas Price with IVA that four elements included in as below: natural gas price, gas tax, carbon tax, and IVA, which is computed over the total gas price (base cost + taxes). Regarding the natural gas price and IVA, they are real number (30.8448 [$/MWh] and 22% respectively). Regarding the gas taxes instead, we consider two constant contributions over the time, as it shown below:

Table. 34 *- The gas tax for Total Gas Price with IVA*

Accisa [$/MWh]	0.7927448
Imposta regionale [$/MWh]	0.549636394
Gas tax(accisa + imposta regionale) [$/MWh]	1.342381194

At the end, we can summarize all the previous information in the table below, where the total price of natural gas and the average cost of electricity are reported for the different years of operation:

Table. 35 *- Natural gas price & Average electricity cost with years*

Year	Natural Gas Price [$/MWh]	Average Electricity Cost [$/MWh]
1	42.2971805	169.0382516
2	43.27106245	170.6791078
3	44.24494439	172.319964
4	45.21882633	173.9608202
5	46.19270828	175.6016764
6	47.16659022	177.2425326
7	48.14047217	178.8833888
8	49.11435411	180.524245
9	50.08823606	182.1651012
10	51.062118	183.8059574
11	52.03599995	185.4468137
12	53.00988189	187.0876699
13	53.98376383	188.7285261
14	54.95764578	190.3693823
15	55.93152772	192.0102385
16	56.90540967	193.6510947
17	57.87929161	195.2919509
18	58.85317356	196.9328071
18	59.8270555	198.5736633
20	60.80093745	200.2145195
21	61.77481939	201.8553757
22	62.74870133	203.4962319
23	63.72258328	205.1370881
24	64.69646522	206.7779444
25	65.67034717	208.4188006
26	66.64422911	210.0596568
27	67.61811106	211.700513
28	68.591993	213.3413692
29	69.56587495	214.9822254
30	70.53975689	216.6230816
31	71.51363883	218.2639378
32	72.48752078	219.904794
33	73.46140272	221.5456502
34	74.43528467	223.1865064
35	75.40916661	224.8273626

Taking into account the exergo-economic part and the data introduced above, it has been possible to calculate the assessment parameters for the two plant's configuration.

The results are shown below:

Table. 36 *- The result for assessment parameters*

	Reference CAES System	**Adiabatic CAES System**
NPV	269,307,558.4 [$]	95,969,125.41 [$]
BCR	3.40	2.22
IRR	25.85%	13.45%
PBT	5 years	10 years

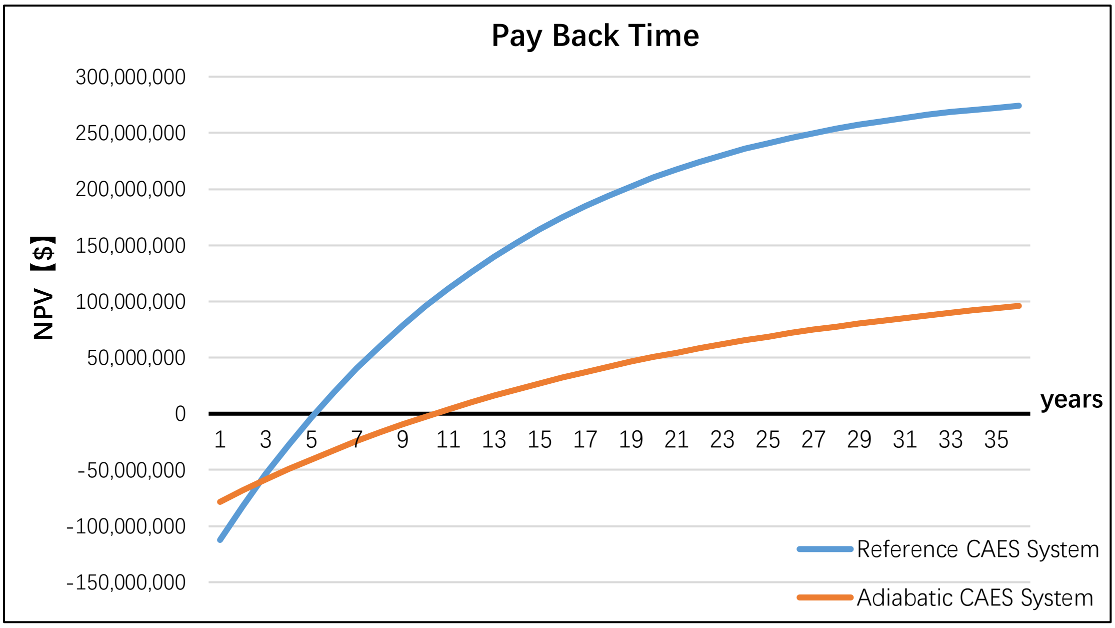

Figure 21 *- Pay Back Time*

5. Conclusions and perspective

In the previous pages, we've presented the thermo-economic analysis of two possible configurations of a CAES plant: in the reference layout the use of fossil fuels (methane) provides the possibility to better exploit the cavern with higher power output during the discharging phase, in the adiabatic plant instead we've demonstrated the feasibility (under both thermodynamic and economic point of view) of a fossil fuel-free configuration, with lower investment cost, higher efficiency but lower power density (MWe/$m^3$of cavern).

But it's time now for some deeper considerations.

It's fundamental to keep in mind all the hypothesis that have been made so far, all the simplifications that let us obtain the results shown above, and to give them a look in a critic way.

The adiabatic configuration plant, which has been called "珍惜". In the Chinese context, it means treat something like jewelry, treasure, lover, whatever you name it. Cherish is not only including the value of every energy, but also to cherish our environment, science and technology. What's more important, cherish our group's friendship which built in the course design. The plant has the potential to be completely sustainable and independent from fuel. The layout that has been presented it's not optimized though and there are lots of further analysis/improvements that should be carried out, for instance:

-more detailed model of the thermal energy storage, with the possibility to exploit different technologies (phase change material, liquid air…)

-optimization analysis to find the working point characterized by the maximum plant efficiency with respect to water mass flow rate, water pressure, cold and hot tanks' temperature, split ratio, inlet and outlet temperature of streams in the heat exchangers

-possibility to produce hot water for district heating or thermal users with very specific thermal demand (it has to match with the discharging phase) in order to completely exploit the energy still present in the water before the cold tank

-transient analysis of the cavern during both charging and discharging phase

All these possible solutions aim to better estimate (and hopefully reduce) the final cost of products, because this is the Achille's heel of the adiabatic configuration: it is not competitive with respect to the reference configuration yet.

It can be appreciated in the economic assessment of the two plants by means of economic indicators like NPV, IRR and BCR.

Looking at the NPV for example, they are both very high (and so not completely realistic, but it's a consequence of a very high electricity selling price of 229$/MWh) but the reference one, even if subjected to taxes and penalties, completely obscures the adiabatic one, sending away like a scarecrow the wallets of the investors that are completely blinded by its monumental economic potential.

That's the important conclusion of this report: even if the adiabatic configuration hits the top-efficiency, it will be still very hard to compete with a substance (methane) which is characterized by high specific chemical exergy, able to produce high energy for low price, even though it is converted in the worst, reactionary and less efficient way possible by means of combustion.

At the end we think that it's primary to still work and put effort in order to optimize as much as possible all the technologies that represent the pilasters of our society, but it's also high time to re-think about the **real price**, that we pay indirectly, of some resources. Not only the purchasing price.

6. Bibliography

[1] F.Crotogino, Huntorf CAES: More than 20 Years of successful operation. Proceeding from Spring 2001, Meeting Orlando, Florida, USA, 2001.
[2] Adrian Bejan, George Tsatsaronis, Thermal Design & Optimization [M]1996:115-116.
[3] EUROSTAT statistics explained, info:https://ec.europa.eu/eurostat/tgm/refreshTableAction.do?tab=table&plugin=1&pcode=ten00117&language=en; https://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=ten00118&plugin=1.
[4] IEA (2018), World Energy Outlook 2018, IEA, Paris, https://doi.org/10.1787/weo-2018-en
[5] Sparber, W. & Manzolini, Giampaolo & Moser, David & Prina, Matteo & Vaccaro, Roberto. (2019). Energy system model Italy 2030. 10.13140/RG.2.2.30178.89280.