THERMAL DESIGN and OPTIMIZATION

Academic Year 2018-2019 – P. Leone, A. Lanzini, V. Verda

PRACTICE 1

DESIGN AND OPTIMIZATION OF A COMPRESSED AIR ENERGY STORAGE PLANT

Team composition:

BAROTTO Luca

BRUNO Lorenzo

DI FRANCESCO Luisa

GIGLIOTTI Sara

Contents

1. Introduction

After the energy crisis in the Seventies many methods have been developed in order to store electrical or thermal energy. The various methods considered take into account different technological options:

- Pump storage covers the largest amount of electricity stored
- Batteries consist of new applications. These are quite costly and must be dimensioned for grid-scale
- Hydrogen conversion is still under research: through the chemical conversion, electrical or thermal energy can be stored

The Huntorf power plant is situated in the north of Germany and has been the first Compressed Air Energy Storage plant around the world. The goal of the plant is to store electricity when the demand on the grid is low, and to release electricity when there is a high demand. The system is composed by a charge and discharge cycle, where air is compressed into a cavern. The CAES technology is classified under large scale or bulk storage: power stored can reach value between 50 and 1.000 MW. The daily application concerns timing of 4-8 hours for peak shaving and 15-60 min for grid integration.

The plant operates following two phases: charging and discharging mode. The Figure 1 shows the plant model provided by Aspen, where we considered the two phases in the same cycle, assuming a mass flow rate of about 108 kg/s for both the charging and discharging.

In that way our plant differs from the real Huntorf one, where 108 kg/s is the mass flow rate for charging and the one for discharging is a higher value, around 407 kg/s, so what we obtain is a lower power produced by the two turbines, due to the reduced mass flow rate during discharging.

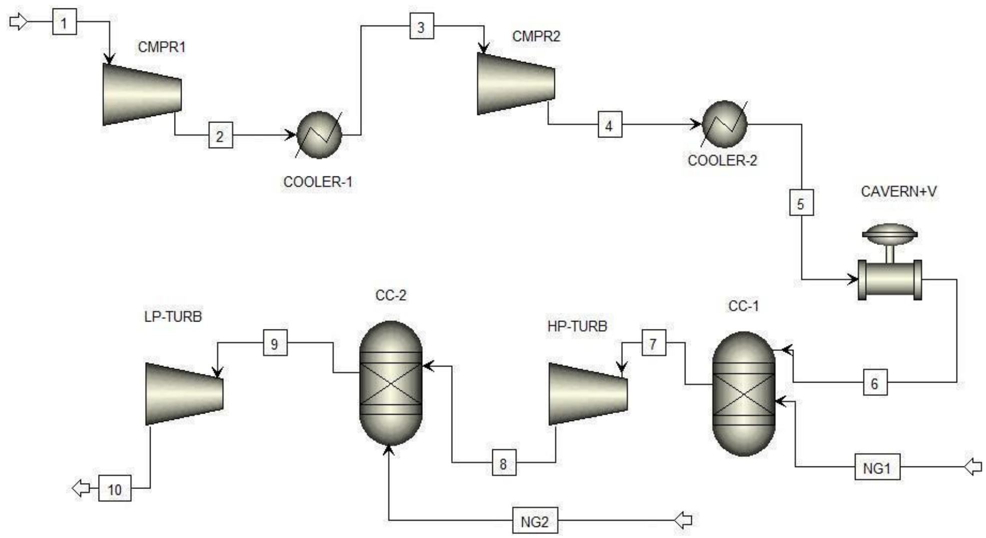

Figure 1 - Plant Model by Aspen program

During the charging phase the surplus of electricity of the grid is converted in the form of mechanical energy and compressed air. For the plant solution two compressors are chosen in series and separated by an intercooler, in order to reduce the temperature at the inlet of the second compressor and improve the efficiency. Air is stored underground in the cavern; for the Aspen simulation we model the cavern as a second intercooler, evaluating the heat exchange between hot air at the outlet of the second compressor and ducts. Other technologies consider limestone cavern, salt deposition or underground volume system (offshore balloons).

The discharging mode allows the plant to export electricity on the grid. The air exits the cavern and feeds the burner: the combustion product will expand in the turbines producing electricity. The air is pressurised but at low temperature: a throttling valve considers the drop pressure; the air is heated by a burner fed by natural gas as fuel. There are two stages of the energy production: HP turbine and LP turbine. After the first expansion, the mixture is heated again by a burner to enter the LP turbine. Exhausts exiting the second turbine are discharged in the external environment.

We decided to dimension the plant considering the TERNA analysis for the year 2050 in South Italy, taking into account an average day balance. TERNA is in an Italian company responsible for electricity dispatch in Italy.

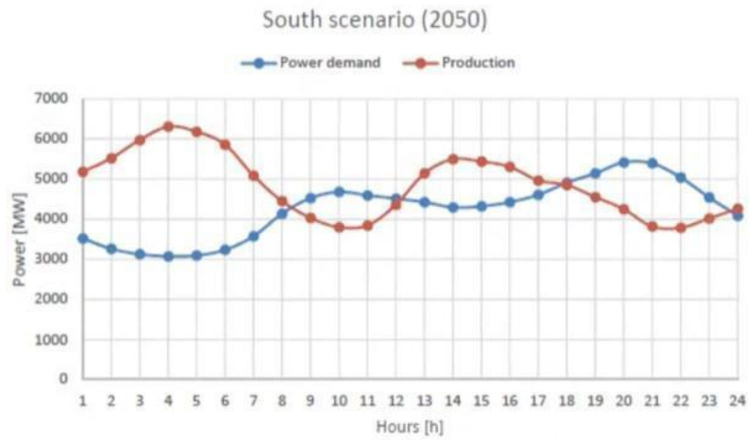

Figure 2 - Data Elaboration for 2050 in South Italy by TERNA

In general the profile shows a surplus of electricity during the night hours (1am-6am): we use the electricity from the grid to compress the air into the cavern, slower than in discharging phase, because of the lower demand. During the day we expand the air compressed in our cavern by sending it to the two turbines. In this case the mass flow rate is bigger with respect to the one used in the charging, in order to perform a better peak shaving.

In our plant scheme we will consider the two phases one after another, without separating them.

2. Plant description

Physical structure

Considering the system under investigation we have first to define its physical structure, which consists in a mathematical representation of how the system interacts with the external environment and how its components interact with each other, in terms of streams of energy and matter.

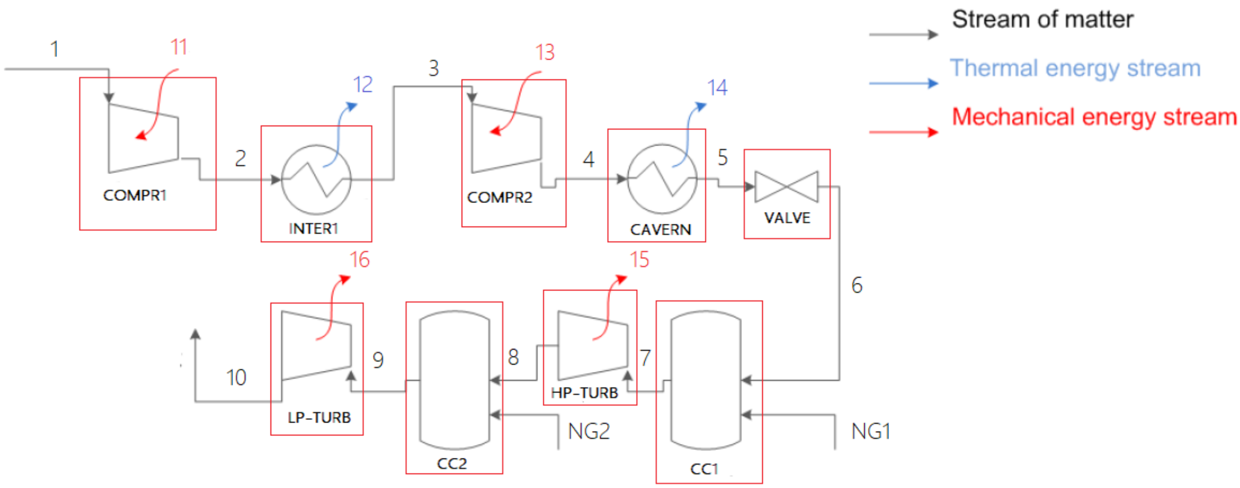

Figure 3 - Physical Structure of the System

The disaggregation level required is the one that includes a control volume for each component, in order to achieve information about all the streams produced in our system (considering two components in the same control volume, for example, would mean to lose the information about the streams exchanged between them).
The relationship between the flows and the different subsystems is reported in the incidence matrix A (N x M).

Productive structure

Defining the productive structure of the system is very important because in this way we can highlight the productive purpose of each component, determining its needs in terms of fuel (F), so the resources we will have to spend, its Products (P) namely what we can obtain from it and the eventual Discharges (D) or Losses (L) in the environment.

Table 1 - Productive Structure

Flow	Process Unit	Fuel	Product	Losses
1	COMPR1	E11	E2-E1	-
2	INTER-1	E2	E3	Q1

3	COMPR2	E13	E4-E3	-
4	CAVERN	E4	E5	Q2
5	VALVE	E5	E6	-
6	CC-1	NG1	E7-E6	-
7	HP-TURB	E7-E8	E15	-
8	CC-2	NG2	E9-E8	-
9	LP-TURB	E9-E10	E16	-
Total Plant		E13+E2+E15+E4+E5+NG1+(E7-E8)-NG2+(E9-E10)	(E2-E1)+E3+(E4-E3)+E5+E6+(E7-E6)+E15+(E9-E8)+E16	Q1+Q2

Thermodynamic analysis

The first analysis is done to determine the properties of each stage and also to calculate the energy and mass flows. It is also useful to know the inlet and outlet parameters of each component and the enthalpies and the entropies of the flows. The system is considered in steady state.

At the inlet the fluid operates in standard conditions, so T1=25 °C and p1=1 bar, the mass flow rate during the charging phase is G = 108 kg/s. During the night when we charge the cavern, the demand of the users is at the minimum, so we have a surplus of electricity and the cavern is charged slowly. During the day the power demand is high but for a short period, so we need to discharge faster the cavern to compensate the peak demand.

The specific work of the two compressors is:

$$l_{comp,1} = R \cdot T_1 \cdot \frac{\gamma}{\gamma - 1} \cdot \left[\frac{P_2}{P_1}^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

$$l_{comp,2} = R \cdot T_3 \cdot \frac{\gamma}{\gamma - 1} \cdot \left[\frac{P_4}{P_3}^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

The intercooler cools the fluid down before the second compression and due to the fact that after the intercooling the thermodynamic conditions are T1=T3 and p2=p3, the work is:

$$I_c = I_{comp,1} + I_{comp,2} = R \cdot T_1 \cdot \frac{\gamma}{\gamma - 1}\left[\frac{P_2}{P_1}^{\frac{\gamma-1}{\gamma}} + \frac{P_4}{P_2}^{\frac{\gamma-1}{\gamma}} - 2\right]$$

The energy lost to the environment is:

$$\Phi_{cool,1} = G \cdot (h_3 - h_2)$$

The isentropic compression efficiency is $\eta_{is,CMPR} = 0{,}90$ for the two compressors and the outlet pressure of the second compressor is $P_4 = 72bar$.

Then there is the cavern as the second cooler and here the fluid is at $T_5 = 40°C$ and $\Delta p = 0bar$.

The valve is an adiabatic component with constant discharge pressure $P_6 = 42bar$.

The first and the second combustion chamber are adiabatic with small pressure drops that can be neglected.

The inlet temperature of the first turbine HP is $TITT1 = 550°C$and pressure $P_7 = 42bar$ and the inlet temperature of second turbine LP is $TITT2 = 825°C$and pressure $P_8 = 11bar$, so we can compute the fuel flows rate G7 and G10, as a consequence.

The isentropic expansion efficiency of the turbines is $\eta_{is,TURB} = 0{,}85$, with discharge pressures $P_9 = 11bar$ and $P_{10} = 1bar$.

In the end it is possible to define the efficiency as:

$$\eta = \frac{W_T}{W_c + \Phi \cdot \eta_{fuel}}$$

At the numerator we have the useful output of the turbine and at the denominator we put what we supply to the plant, so there is the power for the compressor and the chemical power for the burners.η_{fuel} is 0,55 and is the nominal efficiency of a combined cycle that converts natural gas into electricity.

Table 2 - Mass Flows, Temperature and Pressure

	Mass Flows [kg/s]	Temperature [°C]	Pressure [bar]
1	108	25	1,01325
2	108	298,413	8,59743
3	108	30	8,59743
4	108	309,085	72,94920
5	108	40	72,94920
6	108	34,081	42
7	109,243	549,841	42
8	109,243	343,412	11
9	110,530	824,892	11
10	110,530	407,623	1
NG1	1,243	25	50
NG2	1,287	25	50

Table 3 - Enthalpy and Entropy

	Molar Enthalpy [J/kmol]	Mass Enthalpy [J/kg]	Molar Entropy [J/kmol/K]	Mass Entropy [J/kg/K]	Enthalpy, mixture (T=25(C) P=1(atm)) [J/mol]	Entropy, mixture (T=25(C) P=1(atm)) [J/mol/K]
1	-8146,41494	-282,37	4250,4	147,325	-8146,41	4250,40
2	8,09E+06	280538,55	5702,01	197,641	-8146,41	4250,40

3	79775,29417	2765,14	-13204,5	-457,687	-8146,41	4250,40
4	8,38E+06	290571,27	-11744,6	-407,088	-8146,41	4250,40
5	-33150,83589	-1149,06	-31181,6	-1080,8	-8146,41	4250,40
6	-33150,54091	-1149,05	-26655,5	-923,921	-8146,41	4250,40
7	-1,56E+06	-54646,16	4152,9	145,254	-1,78E+07	4088,80
8	-8,19E+06	-286422,17	6109,65	213,694	-1,78E+07	4088,80
9	-9,57E+06	-337828,88	24727	872,741	-3,55E+07	3128,36
10	-2,37E+07	-835033,47	28604,6	1009,6	-3,55E+07	3128,36
NG1	-7,54E+07	-4,70E+06	-115185	-7179,89	-7,45E+07	-80639,83
NG2	-7,54E+07	-4,70E+06	-115185	-7179,89	-7,45E+07	-80639,83

Table 4 - Energy Streams

	ϕ [W]	W [W]	MW [W]
COMPR1	-	30947612,9	30,9
INTER-1	-29999530,1	-	-
COMPR2	-	31717414,3	31,7
CC-1	-	-	-
CAVERN	-31505799,2	-	-
HP-TURB	-	-24813569,5	-24,8
CC-2	-	-	-

LP-TURB	-	-53856961,2	-53,9

3. Exergy analysis

The term "exergy" points out a measure of disequilibrium between a thermodynamic system and the environment that surrounds it. In particular the exergy tells us the maximum work that we can achieve bringing our thermodynamic system from its state to the state of equilibrium with the environment, for this reason it has the physical dimension of an energy.

Since the exergy is referred to a stream, our exergy analysis will be carried out separately for each stream in the system and our reference environment will be the biosphere (T=25°C, p=1 atm).

The exergy can also be divided into two contributions:

• Physical exergy, due to the physical transformations of the stream, it can be calculated as:

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

Where: h is the molar enthalpy of the flow [J/kmol], h_0 is the molar enthalpy of the biosphere [J/kmol], T is the temperature of the flow [K], s is the molar entropy of the flow [J/kmol/K], s_0 s the molar entropy of the biosphere [J/kmol/K] and $m^{\cdot}$ is the mole flows [kmol/s], as a consequence E_{ph} will be computed in MW.

• Chemical exergy, due to the chemical reactions in the plant, it can be calculated as:

$$E_{ch} = \left[\sum b^0_{ch,i} \cdot y_{k,i} + R \cdot T_0 \cdot \sum y_{k,i} \cdot ln(y_i)\right] \cdot m^{\cdot}$$

Where: $b^0_{ch,i}$ is the standard chemical exergy of the i-th compound [J/kmol], $y_{k,i}$ is the molar fraction of the i-th compound [-], R is the constant of the ideal gas equal to 8,314462 [J/mol/K], T_0 is the temperature of the biosphere [K] and $m^{\cdot}$ is the mole flows [kmol/s], therefore E_{ch} will be computed in MW.

Table 5 - Exergies

Flow	Physical Exergy [MW]	Chemical Exergy [MW]	Total Exergy [MW]
1	0,00	5,25	5,25
2	28,71	5,25	33,96
3	19,81	5,25	25,06
4	49,26	5,25	54,51
5	39,45	5,25	44,7
6	34,40	5,25	39,65
7	62,01	7,64	69,65
8	34,46	7,64	42,1
9	76,30	10,12	86,42
10	16,83	10,12	26,95
NG-1	0,73	64,45	65,18
NG-2	0,75	66,71	67,46

As expected, the physical exergy in point 1 is zero, in fact the inlet conditions we put on Aspen ($T1=25°C$, $p1=1{,}01325$ bar) coincides with the conditions of the biosphere and for this kind of flow the physical exergy is always zero. For the other flows the physical exergy increases as much as their conditions are far from the biosphere ones.

Regarding the calculation of the energy destroyed in the various components, it has been obtained multiplying the incidence matrix A with the vector E:

- A is a NxM matrix called "Incidence Matrix" where N is the number of components and M the number of streams, it is obtained putting 1 for a stream entering a component, -1 for the stream exiting a component and 0 if the steam and the component do not directly interact.

Table 6 - Incidence Matrix

STREAMS	1	2	3	4	5	6	7	8	9	10	NG 1	NG 2	11	12	13	14	15	16
COMPR1	1	-1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
INTER-1	0	1	-1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0
COMPR2	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
INTER-2	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
CC-1	0	0	0	0	0	1	-1	0	0	0	1	0	0	0	0	0	0	0
HP-TURB	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	-1	0
CC-2	0	0	0	0	0	0	0	1	-1	0	0	1	0	0	0	0	0	0
LP-TURB	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	-1

- E is the vector of the exergy flows, calculated previously, its dimensions are M x 1.

$$[A] \cdot [E] = [I]$$

Table 7 - Irreversibilities

Component	Irreversibilities [MW]	% Irreversibility
COMPR1	2,24	2,36
INTER-1	8,90	9,37
COMPR2	2,26	2,38
CAVERN	9,81	10,34
VALVE	5,05	5,32
CC-1	35,18	37,05
HP-TURB	2,74	2,89
CC-2	23,14	24,38
LP-TURB	5,61	5,91

Total	**94,94**	**100**

4. Exergy cost analysis

The exergy analysis allows us to find the components where we have the higher irreversibilities, and so maximum exergy destruction, providing the information aggregated at the component level.
As next step the exergy cost analysis permits to disaggregate these information, allowing us to understand how the exergy destroyed in different components is actually destroyed to produce each specific stream in our plant.
In summary exergy balances allow the localization of losses, but not the way through which they originate, while the exergy cost allows to understand what is the cost of the resources that has to be paid in order to produce a specific stream.
The exergy cost analysis is based on the concept of exergy cost (E*), which represents a quantity that can be associated to each stream, corresponding to the sum of the amount of exergy and all the irreversibilities required to obtain a certain product.
A suitable technique to identify the cost formation process is the exergy accounting method, that provides an objective cost allocation to the products of our system.
The exergy cost is a conservative property, so for each component the sum of the exergy cost of the inlet flows is equal to the sum of the exergy cost of the outlet flows.
In that way the exergy cost can be obtained through many balance equations, one for each component, expressed in the matrix form A×E*=0.
The incidence matrix A, as said before, has M columns (number of streams) and N rows (number of components), so in our case, having 18 streams and only 9 components, it means to have only 9 equations with 18 unknowns.
In order to compute the exergy cost of all the streams we need to add 9 additional equations, defining a control volume for our plant that includes all the components. These equations are called auxiliary equations, and they represent a mathematical indication in order to give a criteria for disaggregation losses within each individual stream.
There are four propositions (rules) in order to obtain these auxiliary equations:

P1: regarding exergy cost of resource flows, which sets that in absence of specific external assessment the exergy cost of flows entering the plant equals their exergy;
P2: regarding the exergy cost of a discharged flow, which sets that in absence of external assessment the exergy cost of a waste stream to the environment is assumed to be zero;
P3: it sets that if an output flow of a unit is a part of the fuel this unit (non-exhausted fuel), the unit exergy cost is the same as that of the input flow from which the output flow comes from;

$$\left(the\ unit\ exergy\ cost\ is\ defined\ as\ k^* = \frac{E^*}{E}\right)$$

P4: it sets that if a component has a product composed of several flows with the same thermodynamic quality, then the same unit exergy cost will be assigned to all of them.

In our case we can derive 5 equations from P1 (there are 5 input streams), 3 equations from P2 (there are 3 losses) and then the remaining equation from P3:

P1: $E_1{}^* = E_1$
P1: $E_{NG1}{}^* = E_{NG1}$
P1: $E_{NG2}{}^* = E_{NG2}$
P1: $E_{11}{}^* = E_{11}$
P1: $E_{13}{}^* = E_{13}$
P2: $E_{12}{}^* = E_{12}$
P2: $E_{14}{}^* = E_{14}$
P2: $E_{10}{}^* = E_{10}$
P3: $k_7{}^* = k_8{}^*$ and so $\frac{E_7{}^*}{E_7} = \frac{E_8{}^*}{E_8}$

By adding these new equations to the incidence matrix we can write the full matrix, that is called cost matrix [Ac], MxM, where M is again the number of streams.

Table 8 - Cost Matrix (Ac)

STREAMS	1	2	3	4	5	6	7	8	9	10	NG1	NG2	11	12	13	14	15	16
COMPR1	1	-1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
INTER-1	0	1	-1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0
COMPR2	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
INTER-2	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
CC-1	0	0	0	0	0	1	-1	0	0	0	1	0	0	0	0	0	0	0
HP-TURB	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	-1	0
CC-2	0	0	0	0	0	0	0	1	-1	0	0	1	0	0	0	0	0	0
LP-TURB	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	-1
P1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
P1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
P1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
P1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
P2	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
P2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
P2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
P3	0	0	0	0	0	0	(-E8/E7)	1	0	0	0	0	0	0	0	0	0	0

After the expansion of the incidence matrix the system of equations, in matrix form becomes:

$$\begin{bmatrix} A \\ \alpha_e \\ \alpha_x \end{bmatrix} * \boldsymbol{E}^* = \begin{bmatrix} 0 \\ \varpi \\ 0 \end{bmatrix}$$

that can be written also in compact form as:

$$[A_c] \cdot E^* = Y_e$$

Looking at the two forms there are some new terms that have been introduced:

α_e is a matrix with number of rows equal to the number of flows incoming into the plant and flowing out from the plant, it contains the set of equations that can be built by introducing propositions P1 and P2;
ω is a vector that, for P1 preposition, accounts for the evaluation of the exergy cost of the streams from the external environment (includes the values of exergy assigned to those flows), while for P2 preposition it is equal to zero.
α_x is a matrix with number of rows equal to n-m-F-L (where F stays for resources and L stays for losses), it contains the set of equations that can be built by introducing propositions P3 and P4;
Y_g is the vector of external assessment.

Looking at the first extended form of the system we can summarize propositions P1 and P2 as:

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

While propositions P3 and P4 can be written as:

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

What we are interested in is the exergy cost vector, which can be obtained from the compact form:

$$E^* = [A_c]^{-1} \cdot Y_e$$

Table 9 - Inverted Cost Matrix (Ac^{-1})

STREAMS	1	2	3	4	5	6	7	8	9	10	NG1	NG2	11	12	13	14	15	16
COMPR1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
INTER-1	-1	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
COMPR2	-1	-1	0	0	0	0	0	0	0	1	0	0	1	0	0	-1	0	0
INTER-2	-1	-1	-1	0	0	0	0	0	0	1	0	0	1	1	0	-1	0	0
VALVE	-1	-1	-1	-1	0	0	0	0	0	1	0	0	1	1	0	-1	-1	0
CC-1	-1	-1	-1	-1	-1	0	0	0	0	1	0	0	1	1	0	-1	-1	0
HP-TURB	-1	-1	-1	-1	-1	-1	0	0	0	1	1	0	1	1	0	-1	-1	0
CC-2	-0,6	-0,6	-0,6	-0,6	-0,6	-0,6	0	0	0	0,6	0,6	0	0,6	0,6	0	-0,6	-0,6	1
LP-TURB	-0,6	-0,6	-0,6	-0,6	-0,6	-0,6	0	-1	0	0,6	0,6	1	0,6	0,6	0	-0,6	-0,6	1
P1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
P1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
P1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
P1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
P1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
P2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
P2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
P2	-0,4	-0,4	-0,4	-0,4	-0,4	-0,4	-1	0	0	0,4	0,4	0	0,4	0,4	0	-0,4	-0,4	-1
P3	-0,6	-0,6	-0,6	-0,6	-0,6	-0,6	0	-1	-1	0,6	0,6	1	0,6	0,6	-1	-0,6	-0,6	1

	Yg		E*		k*
0	0	1	5,25	1	1,001
0	0	2	36,25	2	1,068
0	0	3	36,25	3	1,447
0	0	4	67,95	4	1,247
0	0	5	67,95	5	1,520
0	0	6	67,95	6	1,714
0	0	7	122,15	7	1,754
0	0	8	73,29	8	1,741
0	0	9	140,79	9	1,629
E_1	5,25	10	0,00	10	0,000
E_{NG1}	54,2	NG1	54,20	NG1	0,832
E_{NG2}	67,5	NG2	67,50	NG2	1,001
E_{11}	31	11	31,00	11	1,002
E_{13}	31,7	12	0,00	12	1,000
0	0	13	31,70	13	0,999
0	0	14	0,00	14	1,000
0	0	15	48,86	15	1,969
0	0	16	140,79	16	2,614

Table 10 - Vector of External Assessment (Y_g), Vector of Exergy Costs (E*) and Vector of Unit Exergy Cost (k*)

5. Cost of the CAES system

The purpose of our analysis will be that of determining the exergoeconomic cost of the products, in particular we are interested in the monetary cost of the streams production in our system.

The cost formation is determined by two contributions:

-the monetary cost of the exergy;

-the cost generated in the productive process.

We calculate the cost formation of each component using the following equation: The cost balance equation.

$$\sum_{i=1}^{nin} cin, i * Ein, i + Z = \sum_{I=1}^{nout} cout, i * Eout, i$$

Z in the cost rate of the component[euro/s], the first term is the cost of inlet flows and the last is the cost of outlet flows.

In matrix form we get:

$$A \cdot C = -Z$$

A is the incidence matrix calculated in the exergy cost analysis. C is the vector of exergoeconomic cost of the different flows and Z is the vector accounting for the cost rate of the different components.

It is necessary to introduce a certain number of auxiliary equations to compute the exergoeconomic costs of the flows. This equation can be formulated using the P1, P2, P3 and P4 rules.

$$[A_c] \cdot C = Z_e \quad \text{this is equal to} \quad [A\ \alpha_e\ \alpha_x\ ] \cdot C = [-Z\ C_e\ 0\ ]$$

C_e is similar to the vector ω introduced in the calculation of exergy costs and accounts for information gathered from P1 and P2 rules.

We can evaluate the price of flows coming into the plant in the column vector C_e. The NG2 and NG1 flows are methane and its price is estimated as 18 $/MWh or 0.005 $/MJ. Taking into account the exergy flows of the two streams, the cost rate of the methane is 1,635 $/s for flow NG2 and 1,58 $/s for flow NG1. The cost of the first flow is zero because it is air taken from the environment. Streams 11 and 13 are low cost electricity with price estimated at 36$/MWh therefore the cost rate estimate of the two streams including their exergy is 0.8 $/s for flow CLP and 0.8 $/s for flow CHP. Now it is possible to define the vector column Ce.

To define the cost of each component we use the information given by the cost estimation methodology of NETL, the National Energy Technology Laboratory of the U.S. department of Energy.

There are five levels:

- BEC - The Bare Erected Cost comprises the cost of process equipment, on-site facilities and infrastructure that support the plant (e.g., shops, offices, labs, road), and the direct and indirect labor required for its construction and/or installation. It is an overnight cost expressed in constant currency;
- EPCC - Engineering, Procurement and Construction Cost comprises the BEC plus the cost of services provided by the engineering, procurement and construction (EPC) contractor. EPC services include detailed design, contractor permitting and project/construction management costs. It is an overnight cost expressed in constant currency;
- TPC - The Total Plant Cost comprises the EPCC plus project and process contingencies. It is an overnight cost expressed in constant currency.
- TOC - Total Overnight Capital comprises the TPC plus all the other overnight costs, including owner's cost. It is an overnight cost expressed in constant currency.
- TASC - Total As Spent Capital is the sum of all the capital expenditures, it also includes interest during construction.

What we done at that point is to calculate the capital cost of each component within our plant:

COMPRESSOR 1

For a compressor, the cost referred to base conditions can be written as:

$$C_p^0 = 10^{K_1 + K_2 \cdot log_{10}A + K_3 \cdot (log_{10}A)^2}$$

From appendix A of Turton the coefficients K1, K2 and K3 for a centrifugal, axial and reciprocating compressor can be written as:
K1=2.2897
K2=1.3604
K3=-0.1027
Regarding A, a size parameter, as a reference for this device it is used A=3 MW but since our compressor is rated 30.9 MW we will have to scale the result.
So we obtain:

$C_p^0 = 2{,}432{,}186.44$ $

From this value we can compute the Bare Erected Cost (BEC) as:

$$c_{BEC} = C_p^0 \cdot F_m \cdot F_p$$

Where FM and FP are the material and pressure factors, they are higher than 1 when operating far from base conditions, in this case:
FM=2.8
FP=1

$c_{BEC}(2001) = 6{,}810{,}122.03$ \$

Updating the value we obtain:

$c_{BEC}(2019) = 10{,}500{,}378.51$ \$

INTERCOOLER 1

For the the first intercooler, that can be considered as a flat plate heat exchanger:

$$C_p^0 = 10^{K_1 + K_2 \cdot log_{10}A + K_3 \cdot (log_{10}A)^2}$$

From appendix A of Turton the coefficients K1, K2 and K3 for a flat plate heat exchanger can be written as:
K1=4.6656
K2=-0.1557
K3=0.1547
Regarding A, in this case the area of the heat exchanger, we can compute the cost at the bare case with A=1000 m^2 and then buy as many heat exchangers as we need considering our heat exchange area:

$C_p^0 = 389{,}762.45$ \$

Knowing the heat flux exchanged (equal to 29.999530 MW) and using the global heat transfer coefficient U=100 $W/m^2/K$, we can say that the heat exchanger is rated 3846 m^2 so we need to buy four of the previous heath exchangers with A=1000 m^2, obtaining:

$C_p^0 = 1{,}559{,}049.81$ \$

The BEC is:

$$c_{BEC} = C_p^0 \cdot (B_1 + B_2 \cdot F_m \cdot F_p)$$

Where:
FM=1 for carbonaceous steel
FP=1
B1=0.96
B2=1.21

So:

$$c_{BEC}(2001) = 3{,}383{,}138.09\ \$$$

$$c_{BEC}(2019) = 5{,}216{,}386.78\ \$$$

COMPRESSOR 2

The only thing that changes between the two compressors is the work, for the compressor 2 we have 31.7 MW instead of 30.9 MW, so the result has to be scaled differently and we obtain:

$$C_p^0 = 2{,}469{,}774.67\ \$$$

$$c_{BEC}(2001) = 6{,}915{,}369.08\ \$$$

$$c_{BEC}(2019) = 10{,}662{,}656.64\ \$$$

VALVE

Looking at the valve we have assumed that $C_{BEC} = 0$, because its cost is negligible with respect to the total cost of the plant.
In that way this component can be considered just a system to control the pressure rather than a valve.

HP TURBINE

$$W_{HP-TURB} = 24{,}8\ MW$$
$$T_{TIT} = 550°C$$
$$p_{TIT} = 42\ bar$$

$$C_p° = 10^{[k1+k2log_{10}(A)+k3(log_{10}(A))^2]}$$

Which is the same expression used for the compressors, from this value we can compute similarly the Base Erected Cost (BEC) as:

$$C_{BEC} = C_p{}^\circ \cdot F_M \cdot F_P$$

The values of the parameters presented above are derived from Appendix A of Turton cost function, considering an axial turbine:
k1 = 2,7051
k2 = 1,4398
k3 = -0,1776
The size parameter for the turbine is the fluid power, with a range of validity equal to 100-4000 [kW].
Our HP turbine produces a power of 24,8 MW that is out of this range, but we can compute $C_p{}^\circ$ for the upper limit value of the range and then scale this cost to our value:
$C_p{}^\circ(4000\ kW) = 386380{,}4\ \$$

$\frac{C_P{}^\circ(24813\ kW)}{C_p{}^\circ(4000\ kW)} = \left(\frac{24813}{4000}\right)^n$ using the six-tenths-rule (n=0,6)

So $C_p{}^\circ(24{,}8\ MW) = 1155012\ \$$

From this value we can compute the Base Erected Cost, finding on the tables that for an axial turbine $F_p = 1$ and $F_M = 5{,}9$ (considering stainless steel as reference material)

$$C_{BEC}(2001) = C_p{}^\circ \cdot F_M \cdot F_P = 6814570\ \$$$

$$C_{BEC}(2019) = C_{BEC}(2001) \cdot \frac{CEPCI(2019)}{CEPCI(2001)} = 10507237\ \$$$

Considering CEPCI(2001)=394, and CEPCI(2019)=607,5

LP TURBINE

$$W_{LP-TURB} = 53{,}9\ MW$$

$$T_{TIT} = 825°C$$

$$p_{TIT} = 11\ bar$$

The equations are the same used for turbine 1:
k1 = 2,7051
k2 = 1,4398
k3 = -0,177

$$C_p{}^\circ(4000\ kW) = 386380{,}4\ \$$$

Our power is again out of the range of validity, so we proceed as done before, scaling the cost to 53,9 MW

$$C_p°(53{,}9\ MW) = 1838757\ €$$

We consider again $F_p = 1$ and $F_M = 5{,}9$

$$C_{BEC}(2001) = C_p° \cdot F_M \cdot F_P = 10848666\ \$$$

$$C_{BEC}(2019) = 16727321\ \$$$

CAVERN

For the cavern, differently from the other components, we have not a cost function but we have to give a look at the scientific literature.
Two possibilities consist in considering the cost as a function of the kW produced during the discharging phase, or as a function of the volume of the cavern.
Choosing to consider the first option we can assume the cost of the cavern as 75$/kW (cost of 2009), so $C_{BEC}(2009) = 75 \cdot (24813 + 53857) = 5900250\ \$$

$$C_{BEC}(2019) = 6879850\ \$$$

Considering CEPCI(2009) = 521

COMBUSTION CHAMBER 1

The combustion Chamber can be modeled as a horizontal process vessel. The cost at base case is evaluated by the formula

$$C_p^0 = 10\text{^}(K_1 + K_2 * A\ + K_3 * (A\ )^2)$$

Where K1=3.5565, K2=0.3776, K3=0.0905. A stands for the characteristic volume: the range of validity is 0.1-628 m^3.

For the volume we will consider stream 6, NG1 and 7

$$G_{inlet} = G_6 + G_{NG1} = 2.29\ m^3/s$$

$$G_{outlet} = G_7 = 6.30\ m^3/s$$

$$G_{ave} = \frac{(G_{inlet} + G_{outlet})}{2} = 4.30\ m^3/s$$

Resident Time is the time needed for chemical conversion: $\tau = 0.5\ s$: the volume $V = 2.15\ m^3$.

Assuming the volume $V = \frac{\pi D^2}{4} L$ and $L = 1\ m$ the diameter is $D = 1.65\ m$.

$$C_p^0 = 4920.74\ \$$$

The Bare Erected Cost is $C_{BEC} = C_p^0 * (B_1 + B_2 * F_M * F_P)$

B1=1.45, B2=1.52; for the pressure factor we use the formula by the ASME Technical code for $thickness\ t > 0.0063\ m$ for an operating pressure of $p = 42\ bar$

$$F_{p,vessel} = \frac{\left(\frac{(p+1) * D}{2 * [850 - 0.6 * (p+1)]} + 0.00315\right)}{0.0063} = 7.33$$

$$F_{M,ss} = 3.1$$

$$C_{BEC} = 177139.2\ \$$$

$$C_{BEC\_2019} = 273127\ \$$$

COMBUSTION CHAMBER 2

The combustion Chamber can be modeled as a horizontal process vessel. The cost at base case is evaluated by the formula

$$C_p^0 = 10\text{^}(K_1 + K_2 * A\ + K_3 * (A\ )^2)$$

Where K1=3.5565, K2=0.3776, K3=0.0905. A stands for the characteristic volume: the range of validity is 0.1-628 m^3.

For the volume we will consider stream 8, NG2 and 9

Resident Time is the time needed for chemical conversion: $\tau = 0.5\ s$: the $G_{inlet} = G_8 + G_{NG2} = 17.9\ m^3/s$

$$G_{outlet} = G_9 = 32.46\ m^3/s$$

$$G_{ave} = \frac{(G_{inlet} + G_{outlet})}{2} = 25.18\ m^3/s$$

volume $V = 12.6\ m^3$.

Assuming the volume $V = \frac{\pi D^2}{4} L$ and $L = 1\ m$ the diameter is $D = 4\ m$.

$$C_p^0 = 12066.4\ \$$$

The Bare Erected Cost is $C_{BEC} = C_p^0 * (B_1 + B_2 * F_M * F_P)$

B1=1.45, B2=1.52; for the pressure factor we use the formula by the ASME Technical code for $thickness\ t > 0.0063\ m$ for an operating pressure of $p = 11\ bar$

$$F_{p,vessel} = \frac{\left(\frac{(p+1)*D}{2*[850-0.6*(p+1)]} + 0.00315\right)}{0.0063} = 5.02$$

$$F_{M,ss} = 3.1$$

$$C_{BEC} = 302923.1\ \$$$

$$C_{BEC\_2019} = 467070.5\ \$$$

Starting from C Bec referred to the year 2019 it is possible to calculate the TOC using 8%for the EPCC, 20% for TPC and 20,2% for TOC.

The CAPEX of our plant is equal to 95.389.878,06 $

Then we calculate the Annuity, which is such a virtual payment we do every year in terms of Capex. This Capex is paid at the “year zero”, but because the plant will work for thirty years, it is like if each year we are paying a certain amount of money, which is discounted in order to consider the time effect.

$$Annuity = \ CAPEX\ * \frac{i*(1+i)^n}{(1+i)^n - 1}$$

Where *n* is the number of years to extinguish the payment and is equal to 30, then there is *i* that is the discount rate, assumed equal to 3.4%

Table 11 - Cost of Components, TOC and Annuity

	C,bec,2001 [$] Cavern,2009	C,bec,2019 [$]	TOC,2019 [$]	Annuity,2019 [$/year]
Compressor 1	6810122,03	10500378,51	16357405,64	878266,03
Intercooler 1	3383138,09	5216386,78	8126045,59	436305,73
Compressor 2	6915369,08	10662656,64	16610201,21	891839,20

Combustion Chamber 1	177139,20	273127,00	425475,06	22844,72
Turbine 1	6814570,00	10507237,00	16368089,74	878839,68
Combustion Chamber 2	302923,10	467070,50	727598,69	39066,42
Turbine 2	10848666,00	16727321,00	26057686,84	1399096,02
Cavern	5900250,00	6879850,00	10717375,29	575440,07
Valve	0,00	0,00	0,00	0,00
Total			95389878,06	5121697,87

We can calculate the cost in a year of electricity and of gas by multiplying the term of exergy and the cost.

$$c_{el} = 36\ \$/MWh \qquad c_{gas} = 18\ \$/MWh$$

$$Eel = (E_{11} + E_{13}) * 8760 * 0{,}4 = 219595{,}68\ MWh/year$$

$$Egas = (E_{NG1} + E_{NG2}) * 8760 * 0{,}4 = 464770{,}56\ MWh/year$$

We have chosen the availability 0,4 due to the fact that we have analyzed one phase at a time, in order to have a total availability for the two phases 0,8.

$$C_{el} = E_{el} * c_{el} = 7905444{,}48\ \$/year$$

$$C_{gas} = E_{gas} * c_{gas} = 8365870{,}08\ \$/year$$

$$Copex = C_{el} + C_{gas} = 16271314{,}56\ \$/year$$

$$C_y = Copex + Annuity = 21393012{,}43\ \$/year$$

Production of energy

$$E_{prod} = (E_{15} + E_{16}) * 8760 * 0{,}4 = 275659{,}68\ MWh/year$$

$$C_{el} = \frac{C_y}{E_{prod}} = 77{,}6066\ \$/MWh$$

This value obtained for the unit cost of the electricity produced will be almost the same we will find at the end of the next step, that is the Exergo-economic analysis.

6. Exergo Economic Analysis

From the relation:

$$[A_c] \cdot C = [Z_e]$$

we need to find C which represents the cost of inlet flows and can be written as:

$$C_{in} = c_{in} \cdot E_{in} \left[\frac{\$}{s}\right]$$

this is done in order to obtain c_{el} that is the cost of the electricity produced, measured in dollars per MWh.

Returning to the first relation, A_c is the cost matrix which includes the incidence matrix that represents the components and the equations derived from the propositions P1, P2, P3 and P4 that are the auxiliary equations, this matrix is known from the exergy cost analysis and Z_e is a vector composed of:

$$[Z_e] = [-Z\ C_i\ 0\ ]$$

Where:

- $-Z$ represents the cost rate of the system in dollars per second and is composed by N-rows, one for each component. It can be calculated as:

$$Z_j = \frac{annuity_j}{h \cdot 0.4 \cdot 3600}$$

- C_i comes from the properties P1 and P2 and stands for the cost of the inlet flows, so it has to be calculated for the flow 1 of air, the flows 11 and 13 for electricity and the flows NG1 and NG2 of natural gas:

$$C_i = c_i \cdot E_i$$

Where c_i is 0 \$/MWh for air, 36 \$/MWh for electricity and 18 \$/MWh for natural gas and E_i are known from the exergy analysis.

- The zeros instead come from the properties P3 and P4.

So the vector Z_e is:

Table 12 - Vector Ze

STREAMS	Annuity,2019 [$/year]	Ze [$/s]
COMPR1	878266.03	-0.06962408279
INTER-1	436305.73	-0.03458790985
COMPR2	891839.20	-0.07070008879
CAVERN	575440.07	-0.0456177123
VALVE	0.00	0
CC-1	22844.72	-0.001811003298
HP-TURB	878839.68	-0.0696695586
CC-2	39066.42	-0.003096970129
LP-TURB	1399096.02	-0.1109126094
P1-Flow 1	-	0
P1-Flow 11-C_el	-	0.309476129
P1-Flow 13-C_el	-	0.317174143
P1-Flow NG1-C_gas	-	0.3258968675
P1-Flow NG2-C_gas	-	0.3373228963
P2	-	0

P2	-	0
P2	-	0
P3	-	0

Now we can calculate C:

$$C = [A_c]^{-1} \cdot [Z_e]$$

Since C will be in dollar per second, is useful for us to convert it dollar per megawatt hour:

Table 13 - C and c

STREAMS	C [$/s]	c [$/MWh]
1	0,000	0
2	0,396	41,93552131
3	0,430	61,7970526
4	0,838	55,35285229
5	0,884	71,17789269
6	0,884	80,24728251
7	1,195	61,76888692
8	0,717	61,31345434
9	1,037	43,21052492
10	0,000	0
NG1	0,309	17,09304654
NG2	0,317	16,92483563
11	0,326	37,91015245
12	0,000	0
13	0,337	38,28693018
14	0,000	0
15	0,548	79,45907356

16	1,148	76,75035054

Converting also the exergies of the two turbines from megawatt to megawatt hour it is possible to finally obtain the cost of the electricity produced:

$$c_{el} = \frac{c_{15} \cdot E_{15} + c_{16} \cdot E_{16}}{E_{15} + E_{16}} = 77.605 \left[\frac{\$}{MWh}\right]$$

As expected we obtain, using both the procedures, the same result for the unit cost of the electricity produced, equal to 77,6 $/MWh.

7. Investment analysis of the base plant

Once we obtain the total overnight cost of our plant and the unit cost of the electricity that it is able to produce, the following step is represented by the computation of the net present value (NET), in order to obtain a first estimate of the investment in monetary terms.

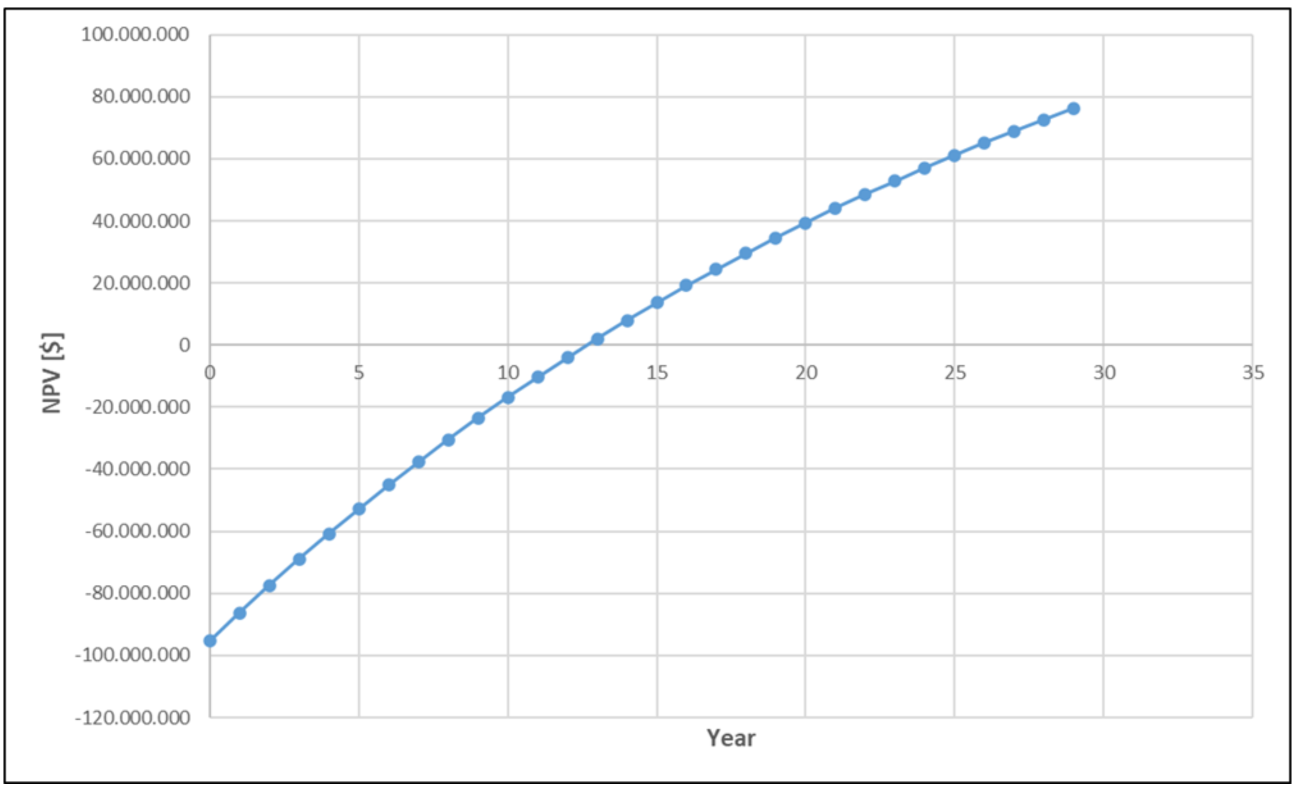

Figure 4 - NPV vs Year

Table 14 - NPV vs Year

Copex [$/year]	Eprod [MWh/year]	cel [$/MWh]	cel retail [$/MWh] (+20%)	NPV year 29 [$]
16.271.315	275.660	77,6	93,1	76.199.942

Assuming for the plant an availability of 40%, what we obtained is a unit cost of electricity produced around 77,6 $/MWh.

This cost is not so competitive if we think about competitors in the market, for example if we take as reference “Prezzo unico nazionale” (PUN) for Italy, which is the reference price of electricity recorded on the italian stock market, the last ten years statistics shows:

Table 15 - PUN Average

year	PUN average [€/MWh]	PUN average [$/MWh]	PUN average 2010-2019 [$/MWh]
2010	64,12	76,71	70,53
2011	72,23	86,41	
2012	75,48	90,30	
2013	62,99	75,36	
2014	52,08	62,31	
2015	52,31	62,58	
2016	42,78	51,18	
2017	53,95	64,54	
2018	61,31	73,35	
2019	52,32	62,59	

We can see from the table above that, considering the last years, our production price is quite higher, considering also that in order to obtain some revenues it has to be increased up to a certain retail price.

The configuration we have considered for our plant, assuming the same flow for both charging and discharging phase, and so a lower power output, allows to reduce the capital cost of the plant and gain something in terms of a better exploitation, but anyway it seems however not so convenient for the moment, if compared with the other competitors.

Coming back to our results, we chose to increase the unit cost of the sold electricity of about 20%, with respect to its unit cost of production, so the selling price is 93,1 $/MWh.

Table 16 - Discount Ratio, BCR, IIR, PBT

Discount rate	Benefit cost ratio (BCR)	Internal rate of return (IIR)	Payback time (PBT)
3,40%	0,80	9,00%	13 years

In that way we are able to recover our investment in about 13 years, which could be quite good in the energy field, always thinking that this assumption is quite subjective and related to the investor.

At the end of the twenty-ninth year (considering the investment in the year zero) we’ll have in our bank account about 76.199.942 $, corresponding to the final NPV value.

In the table above have been reported also the Internal rate of return, the value of the discount rate that makes the net present value of all cash flows almost equal to zero (final NPV), and the benefit cost ratio, which describes the average profitability of an investment per unit of invested capital.
This last one in particular is introduced to make possible comparisons with other projects, even if they present a different initial investment (we should choose the project with the higher BCR).

Table 17 - Sensitivity analysis

Range [%]		NPV [$]
	Retail electricity [$/MWh]	
-10%	83,79	73.712.607
0%	93,10	76.199.942
10%	102,41	78.676.614
	Natural gas [$/MWh]	
-10%	16,20	77.003.688
0%	18,00	76.199.942
10%	19,80	75.385.532
	Availability [%]	
-10%	36%	75.286.235
0%	40%	76.199.942
10%	44%	77.102.985
	Purchased electricity [$/MWh]	
-10%	32	77.044.110
0%	36	76.199.942
10%	40	75.345.110

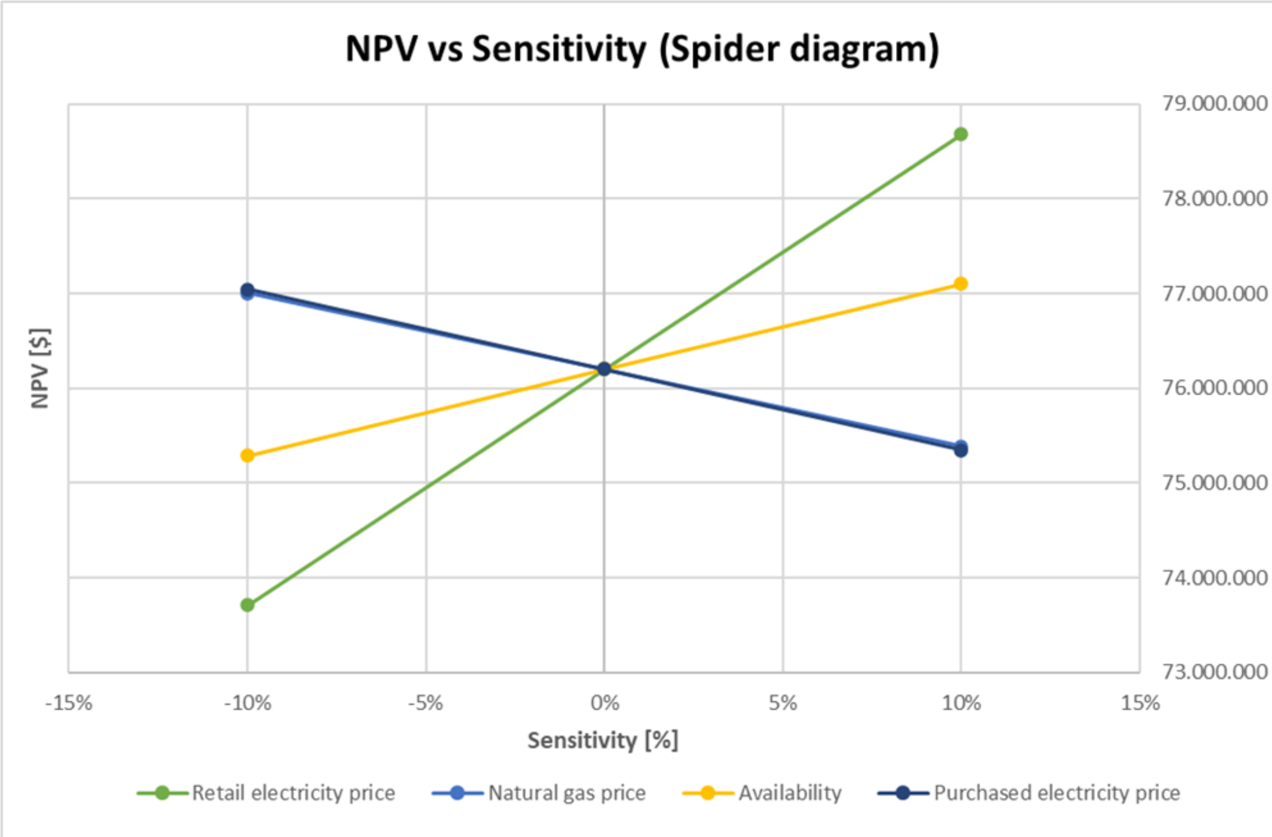

Figure 5 - Sensitivity Analysis

Regarding the Sensitivity analysis we chose to vary some parameters, observing how this variation affects the final NPV.
Varying those parameters in a range between -10% and +10%, respect their initial value, is possible to see from the previous plot that the most influencing parameter from the point of view of NPV is the retail price of electricity.
The line related to this parameter is steeper, presenting a bigger impact on the final revenues.
The other lines present a smaller slope, which is almost comparable between them, in particular we can see that the variation of both the purchasing natural gas price and the purchasing electricity price is quite similar, this last one is only a bit more effective.
The variation of the last parameter considered, the availability, is also quite flat if compared to the retail electricity price, presenting an effect similar to purchased gas and electricity.

8. Design improvement

The two first CAES plants were built in 1978 in Huntorf (DE) and in 1991 Alabama (USA). The design improvements are reasonable suggestions to increase the efficiency of these cases.

- Increase the number of intercooled compressor stages

- Add a recuperator to recover heat from the low pressure turbine exhaust after the second expansion. Fresh air from the cavern can be preheated before entering the turbine.
- Recover heat from the intercooler or the cavern. It is useful to raise some steam in the later injection in the LP turbine to increase the power output
- Adiabatic CAES

McIntosh plant adopts 4 intercoolers and a recuperator using exhaust gasses. Less fuel is required for the plant.

Heat recovering is possible from the recuperators. After the compressor we have the recuperatore. Intercoolers will bring down the temperature in order to produce steam by feeding water in an evaporator. Steam is then accumulated into a storage system (charging phase).

The second option is to recuperate heat by the turbine exhausts throw an evaporator. This option concerns the discharge phase.

Steam stored is injected in the LP turbine with hot exhausted gas where it can expand. It is critical to allow condensation because water droplets can damage the blades. There is no need for Natural Gas because the enthalpy of steam is enough.

The adiabatic CAES doesn't need external fuel or heat source for the plant. We have an adiabatic compression but three additional compression. Enthalpy of the hot compressed air is storage in a heat storage system: the research is for Phase Change Material (PCM). Compressed air will exchange heat before entering the cavern. The heat stored will be used during the discharge phase

The futuristic concept is to increase the energy density of the storage system instead of compressing: air is liquified and stored in liquid phase. The critical points are high pressure and low temperature that must be reached.

Case Study Improvements

The design improvements come from the analysis of reduction of the price of product. In order to be more competitive on the market we have to consider all the costs of products: we consider the cost of resources and products for all the components.

The estimation is based on the following rules :

- If the resources or product stream consists of a physical stream, we consider the cost of the physical stream
- If the resources stream consists of the difference of two physical streams, we consider the cost of one of the physical stream (and are equal due to rule P3)
- If the product stream consists of the sum of two physical streams, we consider the cost of one of the physical stream (and are equal due to rule P4)
- If a resource consists of the sum of two physical streams, for example E1+E2, we consider:

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

- If a product consists of the sum of two physical streams, for example E1+E2, we consider:

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

Once we have these costs, we can evaluate two important factors.

Relative cost difference

For a given component, the relative cost difference concerns the difference between the unit exergo-economic cost of product and of the resource divided by the unit exergo-economic cost of the resource

$$r_i = \frac{c_{P,i} - c_{F,i}}{c_{F,i}}$$

The factor r represents the potential of the improvement: high values of r mean higher relative cost increase of the products we have in a certain component, so high potential for improvement.

Exergo-economic factor

It takes into account the contribution of the investment cost Z of a certain component and the increase of the unit cost occurring because of the cost rate of exergy destruction:

$$f_i = \frac{Z_i}{Z_i + c_{F,i} * I_i} = \frac{Z_i}{Z_i + C_D}$$

C_d represents the cost associated with the exergy destroyed in a component. The denominator $Z + C_d$ represents the absolute level of monetary waste in a component. High values of global factor f stand for high incidence of the investment cost, while low f value stands for high incidence of thermodynamic efficiency in the cost increase of the products.

The following tables report the values for r and f.

Table 18 and 19 - Relative Cost Difference r and Exergo Economic Factor f

streams	cF	cF [$/MWh]	cP	cP [$/MWh]	r
COMPR1	c11	37.91	=(c2*E2-c1*E1)/(E2-E1)	49.60	0.308
INTER-1	c2	41.94	c3	61.80	0.474
COMPR2	c13	38.29	=(c4*E4-c3*E3)/(E4-E3)	49.87	0.303
CAVERN	c4	55.35	c5	71.18	0.286
VALVE	c5	71.18	c6	80.25	0.127
CC-1	cNG1	17.09	=(c7*E7-c6*E6)/(E7-E6)	37.35	1.185
HP-TURB	c7	61.77	c15	79.46	0.286
CC-2	cNG2	16.92	=(c9*E9-c8*E8)/(E9-E8)	26.01	0.537
LP-TURB	c9	43.21	c16	76.75	0.776

streams	Z [$/s]	I [MW]	CD [$/s]	Z+CD [$/s]	f
COMPR1	0.035	2.24	0.024	0.058	0.596
INTER-1	0.017	8.9	0.104	0.121	0.143
COMPR2	0.035	2.26	0.024	0.059	0.595
CAVERN	0.023	9.81	0.151	0.174	0.131
VALVE	0.000	5.05	0.100	0.100	0.000
CC-1	0.001	35.18	0.167	0.168	0.005
HP-TURB	0.035	2.74	0.047	0.082	0.426
CC-2	0.002	23.14	0.109	0.110	0.014
LP-TURB	0.055	5.61	0.067	0.123	0.452

The f factor presents low values for the intercoolers, the combustion chambers and the cavern. It is evident that the level of irreversibilities in the combustion chamber is high but instead of operating directly on them, we can consider the idea of installing a regenerator in order to recover heat from the LP turbine exhausted, so with this method also irreversibilities at the combustion chambers will be reduced.

As we can notice, the Z+CD values for the two compressors are the lowest, so they do not need more improvement, while the two combustion chambers and the low pressure turbine present a high potential for increasing efficiency (both high Z+CD and r). The multiple-stage compression is not so interesting because the stages of the compression contribute to Z+Cd for less than 10%, so even adding different stages what we obtain is more an increment in the Capex than a real improvement in terms of performance.

So looking at the tables reported above we start considering some of the components that present the highest value of Z+CD, representing the ones from which we could get highest benefits from an improvement, in absolute terms.

In particular we decided to perform the optimization part of the project considering the two combustion chambers and the LP turbine, presenting both high Z+CD and f values.
As just suggested, the very low value of f for the two combustion chambers suggest that there is something that does not work from the thermodynamic point of view, which means that the prevailing cost for these components is coming from inefficiencies, while for the LP turbine the higher value of f can be linked also to a problem in terms of Capex, that could be too high respect the Opex.

9. Regeneration

Table 20 - Recuperator Results (assuming U=100 W/m2K as gas-to-gas global heat transfer coefficient)

ΔT(hot side)	Area [m^2]	Eff [%]	Capex [$]	Opex [$/y]	Eprod [MWh/y]	cel [$/MWh]	Savings (30y) [$]	Capex (HX) [$]
50	193,6	42,98%	96.628.423	15.830.503	274.924	76,5	13.224.334	1.238.545
100	458,3	44,45%	97.484.729	15.393.145	274.118	75,2	26.345.079	2.094.851
150	840,7	46,03%	98.609.482	14.977.367	273.662	74,1	38.818.436	3.219.604
200	1459,8	47,69%	100.000.164	14.562.739	273.032	73,0	51.257.259	4.610.286
250	2592,8	49,45%	101.897.245	14.156.207	272.401	72,1	63.453.232	6.507.367
300	**5488,5**	**51,33%**	105.594.896	13.732.111	271.875	**71,4**	76.176.102	10.205.018
325	9525,3	52,31%	109.595.832	13.545.973	270.088	71,9	81.760.240	14.205.954

The first modification to the base plant scheme consists in the introduction of a recuperator (a flat plate heat exchanger, in stainless steel) which allows us to recover a part of the heat remaining in the exhausted gas, that otherwise would have been wasted once released into the environment.
The first goal of this implementation is that of reducing the irreversibility generated in the two combustion chambers, which in the base case represent the major contributions.
In particular we can see from the table below that this modification affects strongly the irreversibility generated by the first combustion chamber, moving from 35,18 MW to 9,10 MW in the case with regeneration, also for the second combustion chamber the irreversibility slightly decreases, even if its incidence in percentage increases a bit.
We can also see that the total level of irreversibility decreases from 94,94 MW to 71,67 MW.

Table 21 - Regeneration vs Base Case

	Regeneration		Base case	
	IRR	% IRR	IRR	% IRR
COMPR1	2,24	3,13	2,24	2,36
INTER-1	8,90	12,42	8,9	9,37
COMPR2	2,27	3,16	2,26	2,38
INTER-2	9,81	13,69	9,81	10,34
VALVE	5,05	7,05	5,05	5,32
HX	3,25	4,53		
CC-1	9,10	12,70	35,18	37,05
HP-TURB	2,69	3,75	2,74	2,89
CC-2	22,87	31,91	23,14	24,38
LP-TURB	5,50	7,67	5,61	5,91
Total	**71,67**	100	**94,94**	100

Focusing on the approach we follow in this section, we started from the temperature of the exhaust gases in the base scheme, around 407°C, and then we tried to identify the heat exchanger which better suits our needs, both in terms of efficiency and cost.
In particular we consider two main parameters, the efficiency of the plant and the unit cost of the electricity produced: the first one shows us that the regeneration was the right way to improve the plant from a thermodynamic point of view, because the efficiency always approaches to higher values when the amount of heat exchanged in the recuperator increases.
On the other hand we saw that from an economical point of view, thinking to the unit cost of the electricity generated, increasing the heat exchanger too much is not a good idea, because while the amount of heat exchanged increases, the logarithmic mean temperature difference (LMTD) decreases more and more.
What happens is that the added exchange surface is not fully exploited, making the installation of a too big heat exchanger seams not a good idea, because this additional area costs too much compared to the fuel savings obtained.
Looking at the minimum reached in the unit cost of the electricity produced (cel), what we found is an optimal area of almost 5488,5 m^2 for the heat exchanger, corresponding to a reduction of almost 300°C of the temperature of the exhausted gas.
In that way we achieve the second goal of this first optimization process, consisting in a reduction of the natural gas consumption: the amount of natural gas required by the plant strongly reduces from almost 1,24 kg/s to 0,45 kg/s for the first combustion chamber, and also from 1,29 kg/s to 1,26 kg/s for the second one.
We can also see that the capital cost of this new component is lower than the savings in Opex (over the 30 years), so its installation could represent a suitable option.

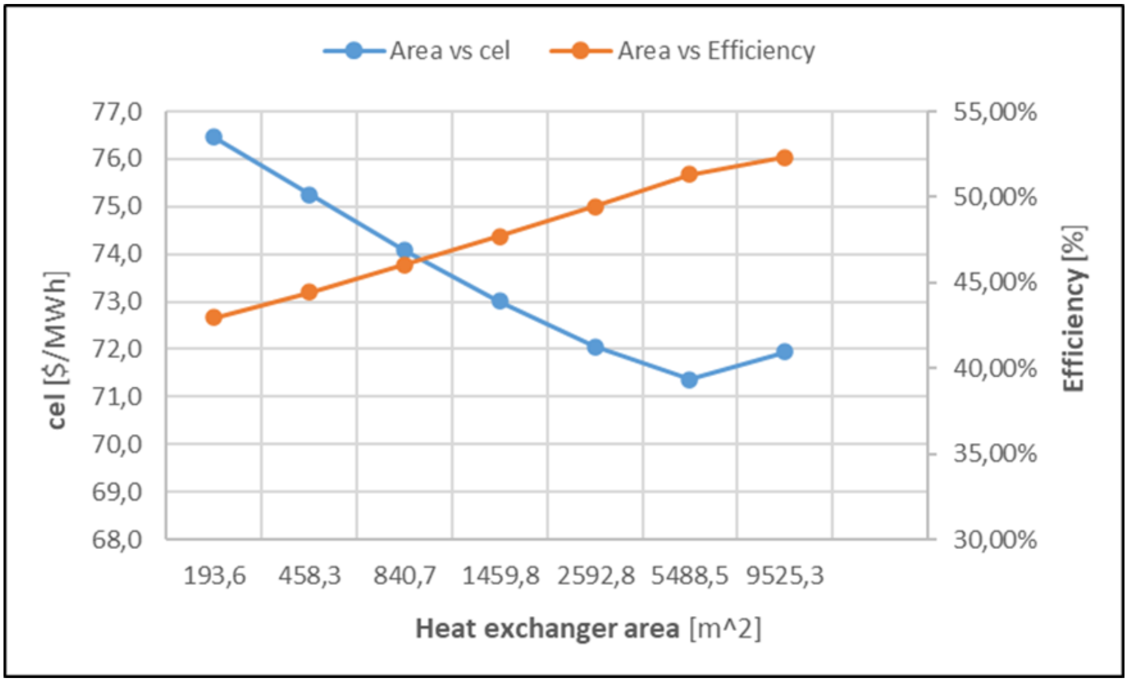

Figure 6 - Heat Exchanger, Area vs cel and Area vs Efficiency

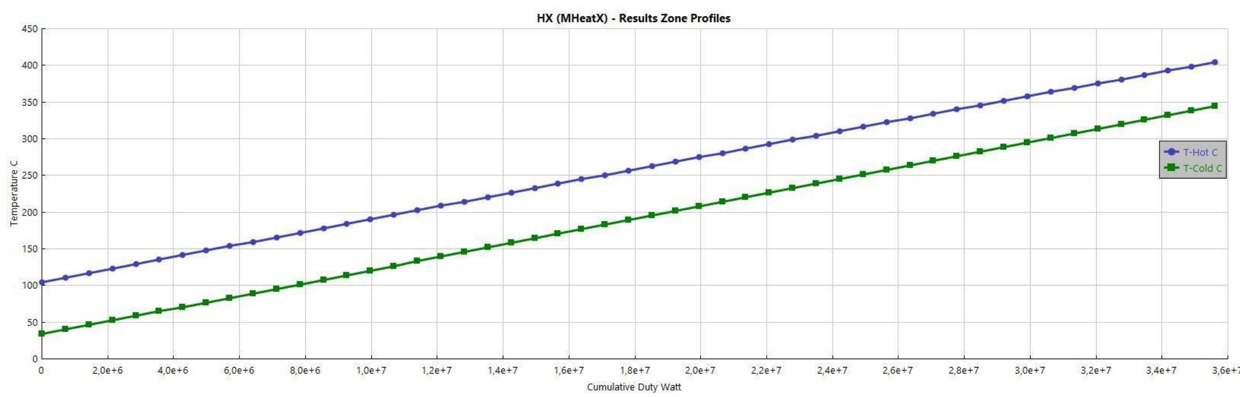

Figure 7 - Recuperator Heat Curves

In the figure above is represented the trend of the two streams within the heat exchanger (the optimal one we considered at the end this step), in particular we have the exhausted gas in blue (hot side) and the compressed air from the cavern in green (cold side).

10. Optimal pressure and final configuration

After the implementation of the regeneration process, we decided to give a deeper look at the LP turbine, thinking about what could be the optimal inlet pressure level in order to optimize the unit cost of production of the electricity.
The starting value is the one of the base case, 11 bar, then we try to substitute different values in order to see what happens.
Performing this process we try to keep constant the temperature of the exhausted gas at the outlet of the heat exchanger (hot side), in order to obtain almost the same thermodynamic conditions at the outlet of the regeneration case, for all the new cases analysed.
In that way the optimal size for the heat exchanger obtained before is modified a bit, together with the Opex and the Capex in that portion of the plant.
The main purpose of this optimization step is to reduce a bit more the unit cost of the electricity produced, even if the impact will be much lower than the previous case.

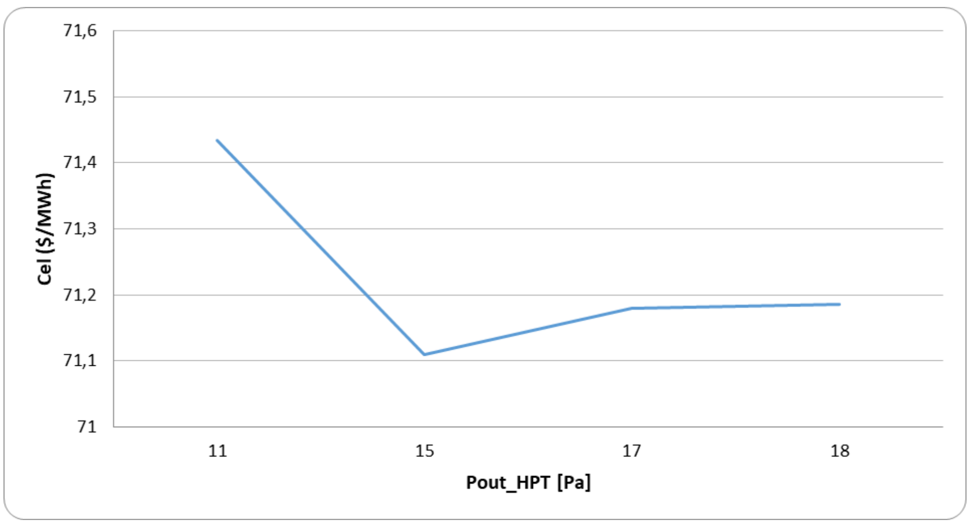

Figure 8 - Outlet pressure of the HP turbine vs cel

As we can see from the picture above the impact of this pressure regulation on the unit cost of the electricity produced is quite small, anyway it allows us to reach the final value of **71,1 $/MWh**, considering a pressure level of 15 bar (instead of the 11 bar of the base case).

Table 22 - Regeneration Only vs Final Case

	Regeneration		Final case	
	IRR	% IRR	IRR	% IRR
COMPR1	2,24	3,13	2,25	3,07
INTER-1	8,90	12,42	8,89	12,13
COMPR2	2,27	3,16	2,27	3,1
INTER-2	9,81	13,69	9,81	13,39
VALVE	5,05	7,05	5,05	6,89
HX	3,25	4,53	3,03	4,13
CC-1	9,10	12,70	13,12	17,9
HP-TURB	2,69	3,75	2,04	2,78
CC-2	22,87	31,91	20,42	27,86
LP-TURB	5,50	7,67	6,41	8,75
Total	**71,67**	100	**73,29**	100

From the point of view of the irreversibility, the total value increases a bit from the previous case, and the bigger changes generally involve the portion of the plant which follows the heat exchanger (the previous one remains unchanged respect the previous case).
In particular there is a reduction for the second combustion chamber, because of the modification of the pressure at the inlet and the reduction of the natural gas flow injected (what we change on Aspen is the pressure at the outlet the HP turbine), while for the first combustion chamber the value increases a bit because of the higher amount of natural gas required, related to a reduction of the heat exchanger size (now equal to 4678,51 m^2).
At the end what we obtain anyway is a slightly reduction of the unit cost of electricity produced, achieving our goal.
For this part, what we did at the components level is to recalculate the new Capex of the heat exchanger (smaller than the previous “optimal one” found before), and also scaling the cost of the two turbines, because of the variation of the power produced with respect to the previous cases.
So finally the Capex and Opex values change from the base case, allowing to reach a higher final NPV.

11. Investment analysis of the optimized plant

Coming back to the investment analysis of the plant, but considering now the final configuration, deriving from the implementation of both the regeneration and the optimal pressure at the LP turbine inlet, what we obtain is:

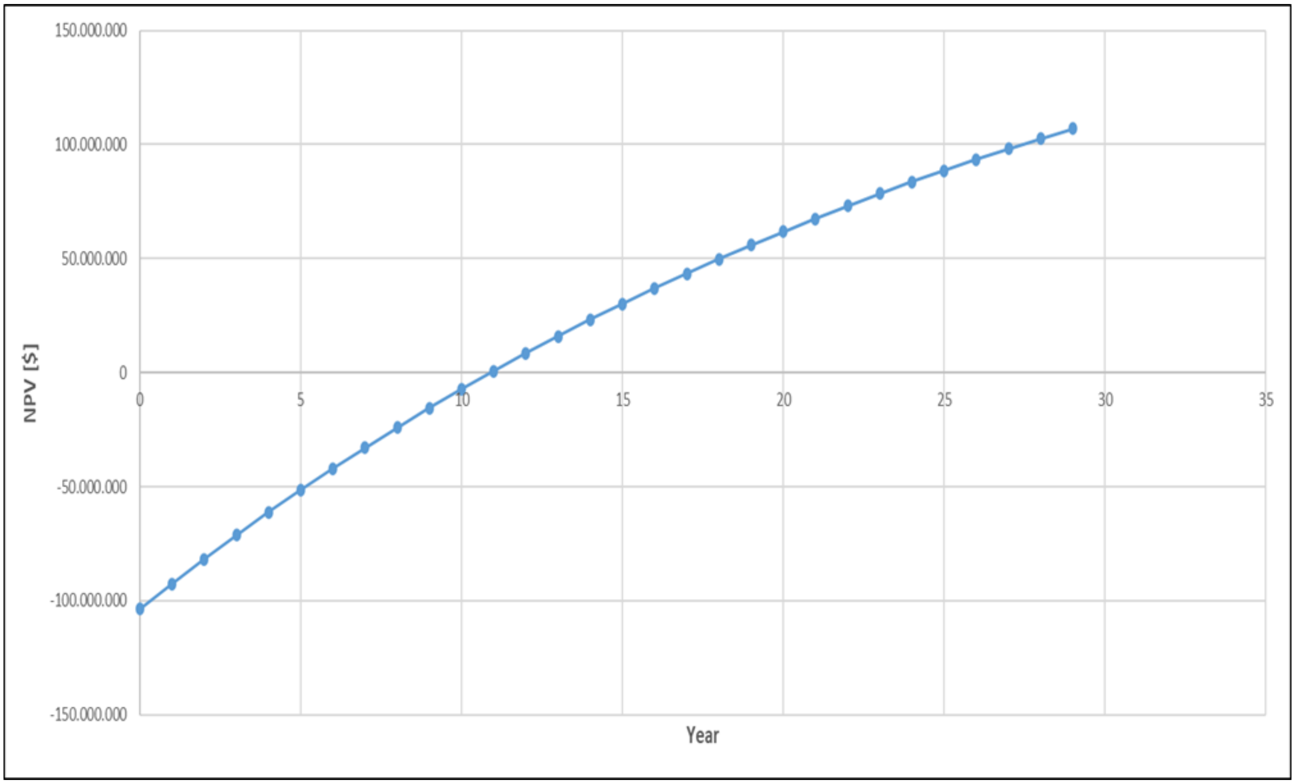

Figure 9 - NPV vs Year

Table 23 - NPV vs Year

Copex [$/year]	Eprod [MWh/year]	cel [$/MWh]	cel retail [$/MWh] (+20%)	NPV year 29 [$]
13.740.721	271.501	71,1	93,1	107.063.748

In order to make a comparison between the base and the optimized configuration we considered to sell the electricity produced at the same price that we assumed previously for the base case (93,1 $/MWh).

As we can see in the table above the optimization process allows us to reach a higher value of the final NPV, passing from almost 76 million to 107 million dollars.

Table 24 - Discount Ratio, BCR, IIR, PBT

Discount rate	Benefit cost ratio (BCR)	Internal rate of return (IIR)	Payback time (PBT)
3,40%	1,03	10,50%	11 years

In that way the Payback time of the investment goes from 13 years to 11 years for the optimized scheme, while both the BCR and the IIR increase, making the plant more competitive.

Table 25 - Savings

Opex old	Opex new	Savings (30y)
16.271.315	13.740.721	**75.917.798**

As we can see from the table above, adopting this final configuration we obtain, over the 30 years, savings of about 76 million dollars on the Opex.

In order to summarize our results, we obtained:

Table 26 - Summary

	Base plant	Final plant
Copex [$/year]	16.271.315	13.740.721
Capex [$]	95.389.878	103.658.500
Cel [$/MWh]	77,6	71,1
NPV year 29 [$]	76.199.942	107.063.748
PBT [years]	13	11
IIR [%]	9	10,5
BCR [%]	0,8	1,03

12. Bibliography

Data Elaboration for 2050 in South Italy by TERNA: https://www.terna.it/it/sistema-elettrico/statistiche/pubblicazioni-statistiche

Cost Equations and Curves for the CAPCOST Program:

Appendix a Cost Equations and Curves for the CAPCOST Program