Applied Energy 378 (2025) 124821

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Technological, economic, and emission analysis of the oxy-combustion process

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HIGHLIGHTS

- Oxy-combustion system technological and economic assessment.
- Emissions evaluation of a case study of a cogeneration system for an educational university campus.
- Retscreen energy and financial evaluation of a case study.

ARTICLE INFO

Keywords:
Oxycombustion
Carbon capture sequestration
Efficiency
Economic analysis
Retscreen
Exergy analysis

Abstract: The high concentration of polluting emissions, and in particular of CO_2 in the atmosphere, determines the greenhouse effect, therefore it is necessary to reduce its quantity as much as possible. For this reason, a strong commitment is underway to obtain effective technological improvements and to study adequate operational measures. One measure among these may be the oxy-combustion process.

Many researchers have studied this process, its characteristics, and operating conditions but what is not known in the literature is the economic feasibility of a plant employing this technology and its environmental impact. There are few plants powered by oxy-combustion and many of these are still pilot plants, for this reason using Retscreen it was possible to evaluate and optimize the technical and financial feasibility of an oxy-fuel cogeneration plant for a university campus in such a way as to demonstrate the cost-effectiveness and lower environmental impact that an oxy-fuel system causes compared to a traditional system. It was evaluated the return on investment for the cogeneration plant as the economic parameters varied: in almost all cases analyzed the investment turned out to be convenient and the minimum calculated payback time was 2.5 years.

With this software, it was also possible to determine the environmental impact of this technology which corresponds to a reduction of approximately 3700 tons/year of carbon dioxide compared to a traditional type of system. This work will encourage the investors and corporate sector to embrace this alternative technology for decreasing polluting emissions from the process.

1. Introduction

Global warming and the recent rise in average world temperature are the results of an increase in the greenhouse effect, generated by human activities and CO_2 emissions, with fossil fuel power plants emitting the majority of this gas. With the aim of preventing climate change, the European Union has set ambitious goals to reduce its greenhouse gas emissions. The EU aims to achieve climate neutrality by 2050 and this goal is set out in European climate law, together with the intermediate target of reducing CO_2 emissions by 55 % by 2030. Although the technological and scientific worlds have been developing a variety of clean energies, fossil fuels, such as coal, are still the primary energy source in the world, consequently, the capture and storage of CO_2 has become a high-priority demand.

There are different strategies to reduce CO_2 emissions, such as the use of renewable energies, the regulations on CO_2 emissions [1], using CO_2 as a raw material [2] or through Carbon Capture Sequestration (CCS) [3].

There are various strategies to reduce CO_2 emissions into the atmosphere both of industrial origin and of other types such as forestry. In fact, sequestering carbon dioxide through forest harvesting is a promising method to partially offset the anthropogenic greenhouse gas

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https://doi.org/10.1016/j.apenergy.2024.124821
Received 9 March 2024; Received in revised form 4 October 2024; Accepted 28 October 2024
Available online 6 November 2024

emissions that drive climate change. The growth of algae naturally removes carbon dioxide from the atmosphere, imagining it to be biomass. The fact that forests have a large potential to sequester carbon dioxide globally- removing 1.1–1.6 billion tons of carbon dioxide annually- is becoming more widely acknowledged [4]. Kasim and Ghassan [5] have studied differential models that better describe and optimize the long-term forestry process in order to capture the greatest amount of CO_2 emitted into the atmosphere. Fernandez et al. [6] have also studied a mathematical model for CO_2 capture in forest plantations. Their model highlights optimal strategies to obtain maximum biomass yield and at the same time maximum carbon capture by adopting a management method and forestry operations such as fertilization and prevention.

Instead among the industrial techniques for sequestering and capturing the CO_2 emitted into the atmosphere, three methodologies are worth mentioning in particular: post-carbonization system, pre-carbonization system, and oxy-combustion process. Oxy-combustion is a technique of burning fuel using pure oxygen, resulting in higher temperatures, lower fuel use, and higher CO_2 concentration. It is particularly promising, given the possibility of integrating this technology with other systems mentioned above. In fact, it increases the convective and radiative heat transfer, produces a highly concentrated CO_2 stream, and a low NOx production [7] with a 7–11 % of efficiency penalty [8,9].

The Oxycombustion technology was introduced in 1982 [10]. It uses a combination of 95 % pure oxygen and recycled flue gas (as an oxidizer) and, in this way, it generates an exhaust gas with CO_2 and water, while conventional combustion reaction uses air, in which the nitrogen dilutes the CO_2 concentration in the flue gas. After impurities are removed, the primary combustion products are CO_2 and H_2O, which may be easily separated by condensation. These will be in significantly higher concentrations than in a conventional power plant due to the lack of nitrogen dilution, which causes more serious corrosion issues, but also makes the process of separating the contaminants themselves easier. This technology is appropriate for mixed or steam cycles due to the purity requirements for carbon dioxide storage and the necessity of optimizing humidity reduction by lowering the temperature of the expelled gases.

All of the emissions from the plant are controlled by sending the produced carbon dioxide, possibly compressed, to storage, even when using particularly filthy fuels like coal.

Buhre et al. [10], in their experimental studies, found the differences between air combustion and oxycombustion process, including reduced flame temperature, delayed flame ignition, and reduced NO_x and SO_x emissions. Replacing nitrogen with carbon dioxide CO_2 has significant effects on the combustion characteristics of the whole process: for example, CO_2 has a higher heat transfer, diffusivity, and molecular weight than N_2 and because of this latter characteristic, the density of unburned gases in the oxyfuel process is greater than in the other processes.

A substantial difference between the two processes is in the amount of oxygen required for the reaction: the combustion process requires an excess of O_2 compared to the stoichiometric ratio, but to obtain a similar fraction of exhaust gas between the two reactions, oxyfuel requires a higher percentage. This value of oxygen depends also on the purity of the elements used in the reaction. The high-purity O_2, as an oxidizer instead of air, can affect the economics of oxyfuel combustion, in fact, depending on the degree of purity of the oxygen, the energy cost to obtain a given degree of purity will also vary. In 2006, Shah [6] studied the cost of electricity which rose from 72.1 to 73.9 $/MWh, as oxygen purity increased from 90 % to 99.5 %.

The oxy-combustion process brings many advantages compared to traditional combustion in several aspects:

- **Recycles Ratio**: Gas recirculation is a useful approach for the combustion process. However, because SO_3 and vapour are present in the exhaust gases, corrosion problems can occur at both low and high temperatures. This can be prevented by keeping all recirculation ducts over the output temperature. Tan et al. [10] examined coal combustion in a blend of pure oxygen and recycled flue gas in a vertical combustor laboratory to study the properties of combustion comprising multiple distinct coals. They demonstrated this by changing the oxygen content and gas that was recirculated during combustion, the latter might accomplish the same results similar to traditional burning but producing fewer emissions.
- **Flame propagation**: In combustion, replacing air with pure oxygen results in different temperature distributions and radiation fluxes within the combustion chamber, due to the different chemical properties of N_2 and CO_2. Because the triatomic molecule of CO_2 differs from nitrogen in several significant physical and chemical ways, there are changes in thermodynamic parameters that account for the variances in flame morphologies between air-fired and oxyfuel-fired flames. By using numerical analysis, Choi et al. [11,12] examined the structure of a CH_4-O_2 edge flame and compared it with the CH_4-air edge, observing a noticeable difference between the two. Because the chemical composition of exhaust gases varies in the oxyfuel process compared to normal combustion, there is a difference in heat transfer.
- **Heat transfer**: Because the chemical composition of exhaust gases varies in the oxyfuel process, compared to air combustion, there is a difference in heat transfer. Triatomic gases (CO_2 and H_2O) are byproducts of burning oxyfuel, and unlike diatomic gases (N_2), they are less transparent to radiation. Furthermore, their extremely high partial pressure raises the exhaust gases' emissivity and absorption. After studying the laminar flame, Chen et al. [13] observed that in an O_2/CO_2 environment, the flame propagation speed and adiabatic flame temperature are less than

  values measured in an atmosphere of air. They also observed that these values rise, with rising CO_2; specifically, the latter's temperature peak drops by roughly 200 K [14].

In the past, oxy-fuel combustion was not regarded as a cost-effective process, due to the high costs of oxygen production. Several recent studies indicate that this process could be more energy-efficient and cost-efficient than carbon capture technology [15,16], but the existing literature is not enough to promote the application of oxy-fuel combustion in industry.

Huang et al. [17] simulated an oxy-fuel system with the ASPEN PLUS software. Their system involved the separation of exhaust gases (CO_2 and H_2O) through an absorption process using an ionic liquid. In their study, they also compared the energy consumption of the process with oxyfuel and post-combustion carbon dioxide capture. The high-purity oxygen, required for oxy-fuel combustion, is provided by an energy-consuming air separation system, but overall, this process saves about 81.42 % of energy consumption, compared to post-combustion CO_2 capture, because there is no need for filtering and capture systems downstream of oxycombustion.

In 2005, Gupta et al. [18] studied oxyfuel combustion with and without CO_2 capture and concluded that the oxyfuel process without carbon capture, compared with conventional air-fired coal, was very competitive in terms of costs and integrated control of air pollutants, while they observed that the oxyfuel process with carbon capture was a very competitive technology option.

This is because downstream of the process the exhaust gases have a higher content of CO_2 and H_2O and, consequently, the exhaust gases have higher emissivity, compared to those in combustion with air and, therefore, higher adiabatic flame temperature (AFT) is also reached in oxycombustion for oxygen percentages below 30 %.

Another important aspect to consider is the environmental impact that an oxy-fuel plant has. In the past, the high energy costs have been the main driver of energy efficiency improvements in the industry sector, now laws, limiting the environmental impact and emissions of industrial processes, drive towards improved operating conditions and performance of the entire system.

There are many studies on the Environmental Assessment (EA) [19] to analyze the potential environmental, cultural, and social impact of oxycombustion to improve the performance, efficiency, and cost of using a coal-fueled system to generate electricity. Some argue that oxyfuel combustion could be the new frontier in waste circulation, because being a "flameless" reaction due to the saturated environment at 5–6 bar pressure and elevated temperatures, around 1400–1500 °C, it allows for complete oxidation of the material, thus reducing the risk of pollutants production. Becidan et al. [20] have studied municipal solid waste oxyfuel combustion and noticed that it offers great potential for the treatment of waste, the production of heat/power, and carbon-capture-storage technology with low CO_2 emissions. In addition, its ashes are considered as secondary materials and therefore directly recyclable, thus guaranteeing the closure of the low environmental impact waste recovery cycle.

Each of these technology applications is considered an important option for fighting the rise of carbon dioxide in the atmosphere and is a key measure to fight climate change. Therefore low-carbon solutions must be implemented in energy-intensive industrial applications, for example in the heat and power sector to significantly reduce CO_2 emissions, in order to meet global climate change goals [21].

All these need new equipment and advanced processes that are cost-effective and all of them need a great amount of capital investment as well as advanced technologies. The IEA GHG report of 2005 estimated that, for a plant with 500MWe power output, the oxyfuel case would have a cost of electricity of 7.28 $/kWh compared with 4.9$/kWh for the base case [22].

One of the aims of this study is to assess the efficiency and economic feasibility of a large-scale oxyfuel plant.

The present paper focuses on the energy efficiency and environmental impact of the oxyfuel process. These two factors are strongly linked because energy efficiency reduces energy consumption and industrial greenhouse gas emissions and also increases the competitiveness and productivity of the industries.

However, a non-negligible problem is understanding the considerations of the environmental and economic sustainability of an industrial process because the technical language is different for example from the economic and socio-political one. In this context, in fact, the main tool adopted to provide information and obtain evaluations is represented by indicators such as the GDP, while in the technical field, a fundamental indicator is, for example, the process efficiency or the performance coefficient of a machine. To overcome this problem, a general indicator was introduced, which allows the introduction of an engineering approach to sustainability by providing an evaluation in terms of costs through exergy analysis, obtaining a relationship between the technological level and the economic value.

This work aims to raise awareness among the scientific community to consider oxy-combustion as a valid process for obtaining electricity from fossil sources and, at the same time, reducing polluting and CO_2 emissions into the atmosphere by using the Retscreen simulation software, which provides an overview of energy efficiency and economic and environmental aspects of the proposed technology.

This study is unique in its kind, it provides an overview of the economic and environmental aspects of an investment in a cogeneration plant that will help to advance towards decarbonization and get closer to the Net-Zero condition, i.e. an impact world of CO_2 equal to zero.

2. Exergy analysis

To evaluate the performance of a system, it is important to highlight many aspects of the process, including the efficiency of electricity production, the energy expenditure incurred to reach the target, and the SPECCA coefficient (Specific Primary Energy Consumption of CO_2). To assess the efficiency of a cogeneration system, the concept that in thermodynamics is called EXERGY, i.e., the maximum fraction of energy that can be converted into mechanical work, is used.

The exergy concept was introduced as a tool for process analysis in the 1950s by Keenan and Rant [1,23]. Exergy analysis is a technique for identifying the potential for improvement in a process. In designing energy systems and in the thermodynamics process in general, it has been extensively applied together with economic analysis to help improving environmental impact mitigation and sustainability.

Exergy analysis has also been applied to such fields as biology and ecology, management of industrial systems, and economics because it is a measure of usefulness and potential to cause change.

The basic exergy expression [24], in relation to the thermomechanical reference conditions, is defined by Eq. 1:

$$E_x = (H - H_0) - T_0(S - S_0) \tag{1}$$

A more common method of determining the exergy content is provided by Kotas [25], but Hinderink et al. [24] divide the exergy content into three distinct components, according to Eq. 1:

$$E_x = E_{x_{chem}} + E_{x_{phys}} + \Delta_{mix} E_x \tag{2}$$

where:

- $E_{x_{chem}}$ is the chemical exergy of a multicomponent material stream, calculated according to the Eq. 2, evaluated at reference conditions [26] and the environment components in their concentration:

$$E_{x_{chem}} = L_0 \sum_{i=1}^{n} x_{0,i} E_{x^{0,i}{}_{chem,i}} + V_0 \sum_{i=1}^{n} y_{0,i} E_{x^{0,v}{}_{chem,i}} \tag{3}$$

In particular, $E_{x^{0,i}{}_{chem,i}}$ denotes the standard chemical exergy of any species i. The method for calculating standard chemical exergies is indicated by the Eq. 3:

$$E_{x^{0,i}{}_{chem,i}} = \Delta_f G^0{}_i - \sum_j \nu_j E_{x^{0,i}{}_{chem,j}} \tag{4}$$

- $E_{x_{phys}}$ determines the composition of the mixture and the pure component enthalpy and entropy according to Eq. 4:

$$\begin{aligned} E_{x_{phys}} = &\Delta_{actual \to 0} \left[L \left(\sum_{i=1}^{n} x_i H^i{}_i - T_0 \sum_{i=1}^{n} x_i S^i{}_i \right) \right. \\ &\left. + V \left(\sum_{i=1}^{n} y_i H^v{}_i - T_0 \sum_{i=1}^{n} y_i S^v{}_i \right) \right] \end{aligned} \tag{5}$$

- $E_{x_{mix}}$ represents the exergy of mixing [27] [28] according to Eq. 5:

$$E_{x_{mix}} = F\left\{ L\left[h^i - \left(\sum x_i h^i{}_i\right)\right] - T_0\left[S^i - \left(\sum x_i S^i{}_i\right)\right] + V\left[h^v - \left(\sum y_i h^v{}_i\right)\right] - T_0\left[S^i - \left(\sum x_i S^i{}_i\right)\right]\right\}_{T,P} \tag{6}$$

where: F represents the total stream molar flow, T_0 represents the stream temperature in Kelvin, L represents the stream liquid fraction, V the stream vapour fraction, h represents the combined stream enthalpy in the liquid and vapour phase [J], y represents the component mole fraction in liquid and vapour phase.

Previous works studied the efficiency penalties associated with an oxy-combustion power plant. Khesa et al. [29] used ASPEN Plus V8.4 to model air- and oxy-combustion plants to study the thermal efficiency penalty associated with retrofits. They compared the results of the primary exergy analysis from the literature [30,31] and their results, but they assumed that the exergy of the ash was zero, and the exergy of the limestone slurry was calculated as the exergy of components, according to the literature, and ignored the physical exergy of the coal feed. In their studies, Khesa et al. considered the ambient air with noble gases and inorganic substances like He or Ne according to Kotas's method [26].

The comparison shows that the exergy input for the air separation is higher in Khesa's process than in the previous works, but the situation of coal exergy input is the opposite, and the coal exergy level is lower than in previous work, and also the efficiency penalty associated with oxy-combustion was found to be 9.25 %, when it was 9.4 % in the literature [32,33].

3. Software

The analysis of investment requires knowledge of the cash flows generated by the project and not only by economic parameters such as costs, revenues and profit. Discounting cash flows is the technique through which comparability is obtained between cash flows available at different times. There are different methodologies for evaluating an investment:

- Payback method;
- Internal rate of return (IRR).

The term payback period refers to the amount of time it takes to recover the cost of an investment. Shorter paybacks mean more attractive investments, while longer payback periods are less desirable. The payback period is calculated by dividing the amount of the investment by the annual cash flow. One of the downsides of the payback period is that it disregards the time value of money.

The internal rate of return is a metric used in financial analysis to estimate the profitability of potential investments. The ultimate goal of IRR is to identify the rate of discount, which makes the present value of the sum of annual nominal cash inflows equal to the initial net cash outlay for the investment. IRR is ideal for analyzing capital budgeting projects to understand and compare potential rates of annual return over time. In addition to being used by companies to determine which capital projects to use, IRR can help investors to determine the investment return of various assets. The formula used to determine IRR is as follows:

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0$$

where: *Ct* is the Net cash inflow during the period t, *C*0 is the total initial investment costs, and *t* is the number of time periods.

Since this is an economic feasibility study, carried out before the installation of the actual cogeneration plant, it will have to be based on the economic analysis carried out on software, assuming investment costs, raw material costs and maintenance costs.

There are many softwares to evaluate energy production, energy project costs, and saving costs and to model or design renewable energy systems: two of them are PHAST and RETScreen.

PHAST was developed by the U.S. Department of Energy. This tool is used to estimate savings from recovering waste heat and to identify the energy losses and energy efficiency potential according to different scenarios [32].

Minxing [33] estimated oxy-fuel combustion costs with PHAST software, according to oxygen stoichiometric combustion, and obtained that the energy savings was 195,430 GJ/yr and it also resulted that the oxyfuel technologies reduced heating time while increasing the productivity by about 50 %.

Retscreen was developed in 1996 by Natural Resources Canada [34,35]. It is used to analyze the energy scenarios of different energy systems and to provide detailed financial analysis and emissions analysis. It can be used to evaluate energy production and savings, costs, emissions reduction, financial viability, and risk for various types of Renewable energy and Energy-efficient Technologies (RETs). With Retscreen, it can be assessed energy production and performed a life cycle analysis to reduce emissions of several kinds of gases, that contribute to global warming solutions to increase the energy efficiency of renewable energy sources. The applications include a database with the climate parameters required to calculate energy output, together with technical data and the costs of available technologies. The modules that are available cover photovoltaic and wind power, mini-hydroelectric power, cogeneration, biomass heating, solar collectors, passive building heating, heat pumps that exchange heat with the earth, and refrigeration systems.

This software has been chosen because it provides a detailed analysis of the relationships between the construction and operating costs of the new plant, with the obtained revenues, and provides a global indication of the economic and financial convenience of the investment. To carry out a feasibility assessment of the intervention, the software compares the performance, consumption, and revenues of the pilot plant compared to the basic plant. Typically, the proposed plant employs a green energy technology, while the baseline scenario employs a traditional energy source technology.

Fig. 1. Geographical position of university campus.

3.1. Case study

The proposed project is a comparison between a traditional cogeneration plant and a cogeneration oxy-combustion plant. It has been assumed that the plant is located in Italy, specifically in the city of Lecce, in Puglia. The plant generates electricity and supplies the heat for heating different buildings in a university campus at the University of Salento, Lecce. Its geographical position is shown in Fig. 1.

It was decided to apply the study of the cogeneration plant with oxy-combustion to the University Campus because it is a preliminary feasibility study on the construction of a real cogeneration pilot plant to be installed within the Campus. In this way, with the creation of the cogeneration plant powered by oxy-combustion within the Campus it will be possible to validate the proposed model. Of course, this is just one example of the applicability of the proposed system; once validated, it can easily be scaled up to an industrial level in such a way as to satisfy the thermal and electrical demand of an entire community or it could be used in different industrial sectors.

Fig. 2 shows a panoramic view of the campus, and the Fig. 3 shows the campus scheme.

As shown in Fig. 3, there are numerous and heterogeneous buildings that require heat and electricity. Many of these are laboratories and classroom buildings. In the center of the campus, there is the cogeneration system which will power the entire campus through the main pipes. Each building is connected to the cogeneration plant with a delivery and return pipe. The smallest and more distant buildings will be powered through secondary pipes in such a way as to guarantee the same pressure losses along the district heating path. The sports center requires much more heat and electricity, due to the presence of a gym and changing rooms as well.

The campus consists of about 40 buildings. It is divided into a student residence, a sports center, school buildings, a library, laboratory buildings, and an administrative office block. The number, heat load and seasonal efficiency of each building are represented in Table 2. Data relating to the seasonal efficiency of the building and the required thermal load derive from previous studies carried out on the individual buildings that make up the entire university campus. Thermal loads and seasonal efficiency were estimated with the TRNSYS dynamic simulation software [36,37, 39–41].

Many of the buildings shown in Table 1 are not used exclusively as classrooms or laboratories or administrative offices, but each building is made up of floors, whose functionality is heterogeneous, therefore an attempt was made to standardize the categories, as shown in the table. For each category, depending on the intended use of the rooms, an average thermal load and a seasonal efficiency expressed in percentage terms were assumed.

As shown in Fig. 3, it was thought to place the cogeneration plant in the middle of the campus. This position is a strategic configuration to be able to uniformly supply all the buildings of the campus. Furthermore, this location has been chosen because of the available land, able to allocate it for this purpose.

The heat load of district heating was divided into 4 sections, as shown in Fig. 3. The orange and purple routes are approximately 75 m long. This district heating network powers the student residence (ISUFI), the Sports Center, many laboratories such as the National Research Center (C.N.R.), the High-Tech Technological District (DHITECH), and many school buildings, in particular the Engineering and Law departments. The green and blue routes are 150 m long because they are further away from the cogeneration plant. These provide heat to many more buildings than the previous ones: Mathematics and Physics department, Biology and Economics departments, other buildings of the Engineering department, the canteen, the museum, the library, and many laboratories.

To develop a complete analysis of the potential of the energy production system, 4 steps were followed:

1. Describe the demand and base scenario energy system.
2. Define the case energy study validity with initial costs, annual costs, extra funding, service expenditures etc.
3. Do a greenhouse gas assessment to see if the designed system reduces emissions more than the base case.
4. See a financial overview analysis if the project is financially viable.

Step 1: Currently, the thermal energy of the entire campus is provided by heat pump systems, which means that it has a significant consumption of electricity throughout the year, both for heating and cooling. The proposed solution could have significant energy savings, but the change in plant technology increases the initial costs compared to conventional technology.

Step 2: To make the oxy-combustion technology more viable, the capital cost needs to be minimized. For this purpose, it was estimated the cost of the system utilizing the literature database [35] and engineering data. Table 3 reports the estimated costs that have been compared to other recent research pilot plants.

As reported in Table 2, the main cost for replacing the cogeneration plant is related to the procurement of equipment (30 %) and the labor

Fig. 2. Panoramic view of the campus [36].

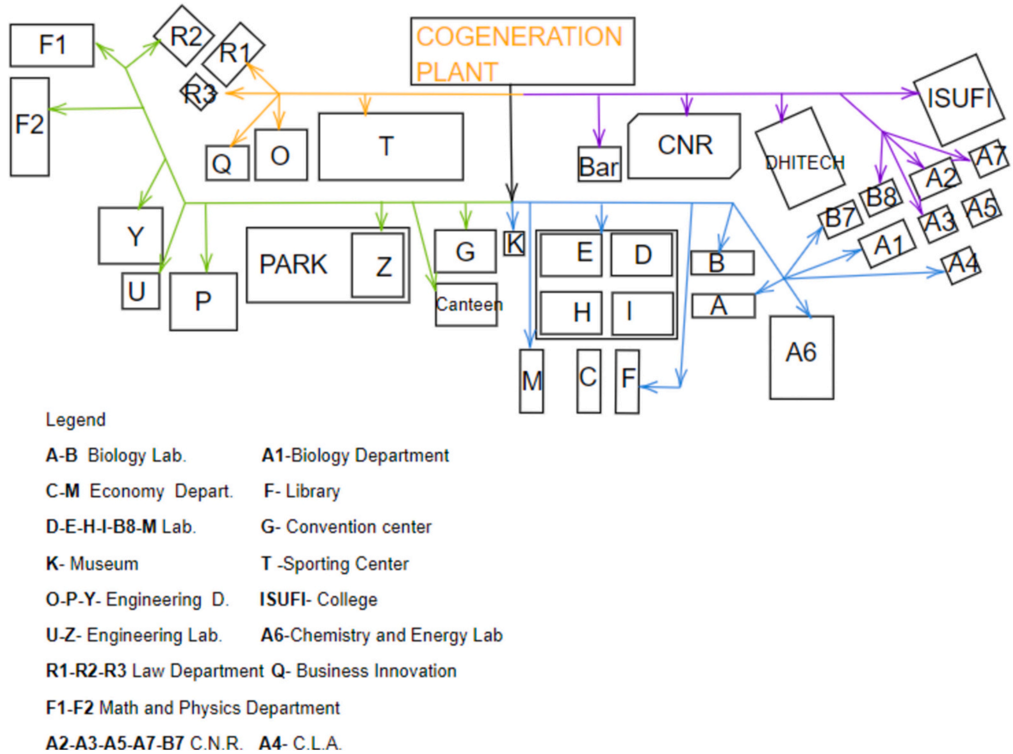

Fig. 3. Outline of the University Campus.

Table 2
University campus composition.

Building	n. Buildings	Heating load [W/m^2]	Seasonal Efficiency [%]
Student residence "ISUFI"	1	80	80
Recreation center (Bar and Canteen)	4	50	65
School building	8	90	60
Laboratories	20	50	75
Administrative offices	6	50	65
Library	1	50	65
Sports center	1	80	65
Museum	1	50	65
University Language Center C.L.A.	1	50	65

Table 1
Estimation of costs for the 25 MWth Pilot Plant [35].

	Capital costs [€]	Factor [%]
Initial costs	3,928,808	49.8
Equipment	301,750	3.7
Materials	50,290	0.7
Labor & construction	201,170	2.50
Engineering	90,530	1.1
Total connection cost	1,164,467	14.5
Fuel	2,308,982	28.7

Table 3
Estimation of fixed operating and maintenance costs for the 25 MWth Pilot Plant [35].

	Unit	Value
Labor rate	€/yr	157,668
Maintenance material	€/yr	145,355
Maintenance labor	€/yr	96,286

Table 4
Entropy values for combustion elements.

Element	Enthalpy $h^0{}_F$ [kJ/kmol]	Entropy s^0 [kJ/kmolK]
CH_4	−74.595	186.360
O_2	0	205.137
CO_2	−393.486	213.774
$H_2O(liq)$	−285.813	69.938
$H_2O(vap)$	−241.811	188.818

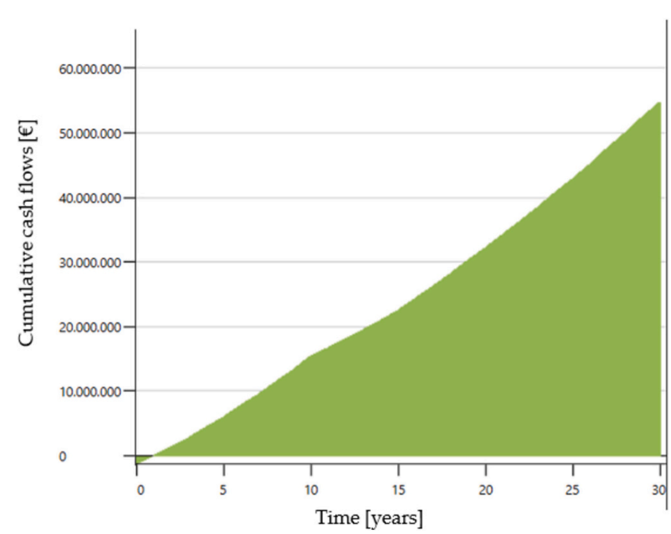

Fig. 4. Cumulative Cash Flow.

and construction of the plant (28 %). Engineering and materials constitute a marginal cost compared to the total investment.

The costs related to the management and annual maintenance of the system have also been estimated and are shown in Table 4. The data set are average values of the costs to be incurred for maintenance in terms of materials and maintenance [35].

By adding the costs reported in Fig. 3 and Fig. 4 it can be stated that the initial cost of the investment is equal to 4.5 million euros.

Step 3: When renewable energy sources are used to produce energy, instead of conventional energy sources like natural gas, coal, oil etc., greenhouse gas emissions are reduced. A basic cogeneration system powered by fossil fuel and air is compared with a system of the same type and equal demand for electrical and thermal energy with natural gas in an oxygen atmosphere.

Naturally, the different nature of the fuel could vary the efficiency of the proposed technology obtained in the software but given that a comparison of technologies takes place with the same heat and electrical energy supplied to the user, then the variation in fuel does not influence the result obtained.

Step 4: The spreadsheets of the Retscreen program were used to get an overview of the financeability of the proposed project, considering the current financial parameters of the economic state of the country.

The software also calculates how the fuel used in the cogenerator's combustion process converts the change in chemical potential energy of the reaction into thermal energy. In a reference time interval, the thermal energy released by the process in the combustion chamber is considered to come from a thermal source and part of it is supplied to the cogeneration plant to produce electricity and the remaining part is supplied to the user which in this case are the various buildings of the campus.

In this way, given that the chemical potential energy of the fuel is used in the cogeneration plant at high temperatures to produce electrical energy and in the oxy-combustion regime, higher combustion temperatures are obtained compared to traditional combustion in air, from the exergetic point of view, oxy-combustion cogeneration will be more convenient and efficient than traditional cogeneration.

3.2. Exergetic efficiency

In this case, of a cogeneration plant with an oxy-combustion boiler, the usable energy of the fuels must be taken into consideration. The latter is of chemical type as it derives from the destruction of the existing atomic bonds between the reagents accompanied by the formation of new bonds of the combustion products.

It is necessary to determine the usable energy of the fuels or the exergetic power, the mechanical work that can be obtained from combustion by interacting only with the environment. To define the exergy power, in addition to the first law of thermodynamics, the second principle must also be considered and consequently, it must be estimated the entropy differences between fuel, oxidizer and fumes.

For the evaluation of the exergetic power of the fuel, the reference is a combustion process with some of the following hypotheses:

- Steady-state at constant pressure;
- Variations in kinetics and potential energy are negligible;
- Exchanges of technical work with the outside world.

Furthermore, when determining the exergy power, it is necessary to consider that the concentrations of the combustion products are brought into equilibrium with the concentrations of the gases in the atmosphere.

Based on all these hypotheses, it is possible to calculate the exergetic power of methane in the gaseous state with reference to a temperature of 25 °C and a pressure of 1 bar.

For the stoichiometric combustion process, eq. (7) is used:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{7}$$

Consequently, the exergetic power associated with the combustion reaction will be:

$$\overline{e}^0{}_{CH_4} = \overline{H}^0{}_s - T_a\left[\overline{s}^0{}_{CH_4} + 2\overline{s}_{O_2} - 1\overline{s}_{CO_2} - 2\overline{s}^0{}_{H_2O}(liq)\right] \tag{8}$$

With $\overline{s}^0$ absolute entropy at a temperature T_0 of 25 °C and a pressure P_0 of 1 atm. If there is a different pressure from P_0 then $\overline{s}$ will be calculated according to the following equation:

$$\overline{s}(t_0;p) = \overline{s}^0(t_0,p_0) - \overline{R}ln\frac{p}{p_0} \tag{9}$$

Since it concerns the combustion of methane, reference can be made to the known entropy values reported in the following Table 4.

Considering the higher calorific value of methane $\overline{H}^0{}_s$ equal to 890.517 kJ/kmol, the exergetic power of methane ($\overline{e}^0{}_{CH_4}$) is equal to 830.444 kJ/kmol (51.773 kJ/kg).

For combustion processes serving thermal systems (as in this case) the first law conversion efficiencies can be defined according to:

$$\eta_I = \frac{energy\ obtained}{energy\ supplied} = \frac{|q_u^-|}{\dot{m}_c H_i(t_a) + |P_v^-|} = \frac{\dot{m}_w(h_{wu} - h_{we})}{\dot{m}_c H_i(t_a) + |P_v^-|}$$
$$= 1 - \frac{|q_a^-| + |q_{fa}^-|}{\dot{m}_c H_i(t_a) + |P_v^-|} \tag{10}$$

where: $|P_v^-|$ is the mechanical power of the auxiliaries [W]; H_i is the lower calorific value (LHV) of the fuel [J/g]; $|q_u^-|$ is the energy obtained [J].

The efficiency of the second law, which considers the exergetic power of the fuel and the degradation of energy due to irreversibility, must be added to this efficiency.

This efficiency is defined as follows:

$$\eta_{II} = \frac{energy\ obtained}{energy\ supplied} = \frac{\dot{m}_w(e_{wu} - e_{we})}{\dot{m}_c e_c + |P_v^-|} \tag{11}$$

Where $(e_{wu} - e_{we})$ is the difference between the exergetic power of the process of water and it is calculated by:

$$(e_{wu} - e_{we}) = c_w\left[(t_{wu} - t_{we}) - T_a ln\frac{T_{wu}}{T_{we}}\right] \tag{12}$$

In the combustion chamber, and therefore also in the oxy-combustion chamber, the useful effect is given by the supply of energy to the same fluid that participates in the combustion, because the work is obtained by expanding the fumes exiting the combustion chamber into the turbine. In light of this, the balance of the first law is:

$$q_a^- + \dot{m}_a h_{ae} + \dot{m}_c h_c = \dot{m}_{fu} h_{fu} \tag{13}$$

Where: h_{ae} and h_{fu} are the enthalpy [J] of inlet air and combustion gases respectively.

The resulting equation is:

$$|q_a^-| + \left[\dot{m}_{fu}cp_{fu}\ (t_f - t_0) - \dot{m}_a cp_a\ (t_{ae} - t_0) - \dot{m}_c cp_c\ (t_c - t_0)\right] = \dot{m}_c H_i^0 \tag{14}$$

Where $|q_a^-|$ is the heat flow dispersed towards the environment by radiation and convection, while $\left[\dot{m}_{fu}cp_{fu}\ (t_f - t_0) - \dot{m}_a cp_a\ (t_{ae} - t_0) - \dot{m}_c cp_c\ (t_c - t_0)\right]$ corresponds to $|q_u^-|$ that is the useful heat flow.

In practice, however, the combustion chamber is often considered adiabatic, therefore q_a^- is neglected, making the combustion efficiency close to unity.

But, in order to determine the actual efficiency of the combustion process, the efficiency based on the second principle of thermodynamics as a function of exergy will be needed.

From eq. (11) it is obtained the following equation:

$$\eta_{II} = \frac{\dot{m}_{fu}(e_{fu} - e_{fu}^0) - \dot{m}_a(e_{ae} - e_a^0) - \dot{m}_c(e_c - e_c^0)}{\dot{m}_c e_c^0} \tag{15}$$

With $\dot{m}_{fu} = \dot{m}_a + 1$ and the other terms are calculated by:

$$e_{fu} - e_{fu}{}^{0} = cp_{u}\,(t_{f} - t_{0}) - cp_{u}T_{a}\left[ln\left(\frac{T_{f}}{T_{0}}\right) - \frac{k-1}{k}ln\left(\frac{p_{f}}{p_{0}}\right)\right] \tag{16}$$

$$e_{ae} - e_{a}{}^{0} = cp_{a}\,(t_{ae} - t_{0}) - cp_{a}T_{a}\left[ln\left(\frac{T_{ae}}{T_{0}}\right) - \frac{k-1}{k}ln\left(\frac{p_{f}}{p_{0}}\right)\right] \tag{17}$$

Replacing all the terms with the parameters provided the calculations determine an exergetic efficiency of approximately 67 % compared to a combustion efficiency according to the first law of approximately 48.3 %.

The exergy efficiency obtained depends on the type of fuel considered. In the case in question, we chose to use methane but naturally in the cogeneration plant different types of fuel can be used such as coal, biofuels and other substances [42]. Naturally, as the type of fuel varies, the percentage of exergy efficiency calculated will vary because it strictly depends on the nature of the fuel but in general, however, the exergy efficiency of the cogeneration process remains high enough to make the cogeneration plant economically convenient.

3.3. System efficiency

The efficiency of the combustion process and the resulting emissions are influenced by several factors:

- Type and quality of fuel;
- Atmospheric pressure, humidity and temperature of the comburent;
- Gradual deterioration of the various components of the burner.

To obtain an efficient system, in terms of consumption and emissions, it is essential to have a combustion control system that allows adjusting the reaction parameters in real-time, the correct excess of comburent in relation to the quantity of fuel that is burned. All of this could be implemented using an Artificial Intelligence-based system.

This kind of system uses algorithms capable of transforming data into other algorithms [38], providing a new and creative interpretation of the data and predicting future trends of the system. With such a control system, one could continuously monitor the excess oxygen required by the system and also the amount of recirculating gases to keep the reaction under control and monitor the exhaust gases in terms of pressure, temperature and pollutants.

Gaska et al. [43] have studied in their work artificial intelligence methods for the analysis and optimization of cogeneration units based on landfill biogas. In their study, they applied AI-based predictive diagnostic tools to support the decision-making process that controls the process. To maximize the efficiency of the cogeneration plant they used Model Predictive Control which generates optimal sequences of control decisions, i.e. systems that regulate gas flows according to the signals received from the process itself. Thanks to this system, their plant had an increase in the efficiency of the cogeneration cycle with an electrical efficiency of 42 % and thermal efficiency of 50 %.

Other studies have highlighted how big data analysis, and the use of clustering methods can help in the design of cogeneration systems, capable of more efficiently satisfying energy demand profiles. Noro and Vialetto [44], in their study, recognized how cogeneration is one of the most effective methods for increasing energy efficiency. In their study, they proposed an approach based on unsupervised machine learning to define and improve the efficiency of polygeneration systems. The cogeneration plant was sized based on the cumulative operating hours curve, regardless of the type of energy, and did not analyze the relationship between them. The authors proposed the clustering method to improve the methodology with which a cogeneration system is chosen, by dividing the data obtained into data sets grouped by similarities, such as according to the energy demand, or the necessary energy ratio.

Cerri et al. [45] have, instead, adopted an artificial intelligence system with a neural network for the management of heat cogeneration systems. Their study was born from the need to manage and optimize the cogeneration process in different operating conditions. In general, although, the plant is equipped with a distributed control system, which provides a significant number of measurement data to form a neural network, all the data refer to certain operating conditions, which change from time to time depending on environmental conditions and different maintenance interventions, different energy demands at different times.

For this reason, Cerri et al. [45] developed a methodology for setting up neural tools to perform optimal load allocations on cogeneration plants. This method was applied to a cogeneration plant in the Italian city of Turin. Optimal load allocation occurs through the minimization of an objective cost function of fuel and consumables.

However, the monitoring system based on artificial intelligence is a management system of the plant, therefore, in the study covered by this paper it is not considered how the monitoring and control system of the system works, but everything was sized according to the optimal conditions of the plant at full workload. The Retscreen software analyzes the efficiency and emissions of only the cogeneration system without considering any kind of additional management system, whose purpose is to further increase efficiency.

4. Results

Retscreen provides an analysis of the economic feasibility of the investment. Considering a useful life of the plant of around 30 years, an initial investment cost of around 4.5 million euros, and an inflation rate of 5 % (value reported by ISTAT [46]). In these conditions, the return on investment will occur in approximately 2.5 years, with a reduction cost per tonnes of CO_2 of 329€ and with a Net Present Value (VAN) of about 107,751,067€.

As shown in Fig. 4, it can be seen that the increasing trend of cash flows throughout the life cycle of the plant follow two different lines: for the first ten years of operation of the system, there are revenues from the reduction of greenhouse gases, which amount to around 1,007,700€ (in ten years) to which the revenues obtained from the sale of electricity must be added.

Currently, the market price of electricity has undergone a significant increase. In current conditions, therefore, the advantage of choosing an investment of this type would also bring a greater advantage in economic as well as environmental terms.

As shown in Fig. 4, from the 10th year onwards, the incentive obtained for the reduction of carbon dioxide is no longer paid, therefore annual revenues vary and consequently the slope of the cash flow line.

The previously analyzed monetary flow arose by considering a series of economic parameters which are reported in the following Table 5. These financial parameters derive from a pre-feasibility study of an oxy-combustion plant of equal power to the one proposed in this study therefore, it was decided to use these financial parameters.

Table 5 contains the most important financial parameters that Retscreen software takes into consideration in its analysis. Fundamental parameters are the percentage of debt and the debt interest rate. In the analysis, the debt ratio, inflation, and reinvestment rate parameters were chosen in accordance with the current market as reported on the website of the Bank of Italy [47] and the Ministry [48]. It has been assumed that the system will last approximately 30 years. It was preferred not to include any incentives for the construction of the plant

Table 5
Financial parameters.

Parameters	Unit	Value
Fuel cost escalation rate	%	2
Inflation rate	%	5
Reinvestment rate	%	9
Debit ratio	%	70
Debt interest rate	%	30
Project life	Year	30
Incentives and grants	€	//

because the incentives may undergo variations over the years and in this way, the economic feasibility study will not be affected by them.

Naturally, the input data used for the economic analysis such as the costs of raw materials, engineering costs, maintenance costs, fuel prices are the result of estimates, deriving from studies of similar plants. Even if a single cost changes, such as an increase in fuel or maintenance costs, the payback time will also change.

Even the cost of the initial invested capital or even the percentage of incentive obtained for the reduction of CO_2 influences the NPV. The case in question, as previously mentioned, does not take into consideration any incentives therefore, if it were considered the incentives obtained for the reduction of CO_2 in the financial analysis, the return on investment would be reduced.

As the initial costs of the plant increase, the initial debt will increase and all other costs and financial parameters being equal, such as at the base case, the payback time will increase. In the following graph, the initial cost of the investment has been evaluated as influencing the proposed financial analysis. It was hypothesized to increase the initial cost of the base case investment by 50 % (grey color in the graph) and even double the initial cost (orange color in the graph).

As can be seen from the graph, as the initial investment costs increase, all other parameters being equal, it significantly influences the case study. We can notice a variation in the slope of the cumulative line of the monetary flow and naturally the monetary flows vary. Higher initial investment costs lead to lower cash flow over the entire useful life of the plant.

Then, it moved on to evaluate how changes in financial parameters influence the proposed economic analysis. As these parameters in Table 5 vary, the return on investment may vary, maintaining a constant debt ratio of 70 %, not considering any incentive or subsidy for the new technology, but only varying the fuel cost indexation rate and the repurchase rate, the cash flow changes as can be seen from the following Fig. 5.

Fig. 5 represents the trend of the investment return flow as the inflation rate, fuel cost escalation rate and discount rate vary.

In these conditions, the return on investment will occur in approximately 2.4 years, with a reduction cost per tonnes of CO_2 of 288€, with a Net Present Value (NPV) of about 14,309,074.3€. In both cases, despite varying economic parameters significantly, the NPV remains always high. The return on investment also remains almost unchanged, but what changes is the cost per ton of CO_2. If for the first case (base case with the economic parameters reported in Table 4) there was a cost of 329€/tons of CO_2 by varying the percentage of the fuel cost and keeping the other economic parameters unchanged, the cost of carbon dioxide drops to 288€/tons. This decrease involves a decrease in revenues and a slight variation in return times, because the annual revenues will consequently be lower than in case one.

By further varying the economic parameters, it is possible to define

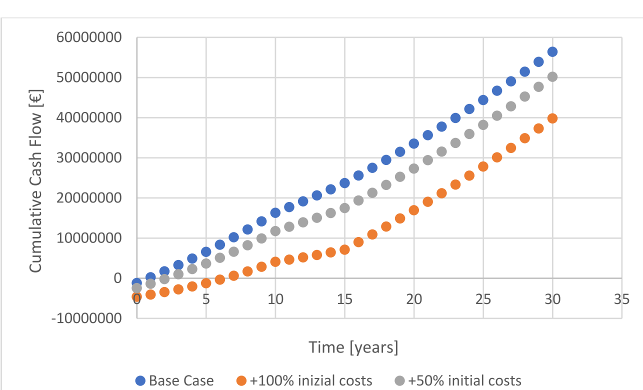

Fig. 5. Comparison of cash flow as initial investment costs increase.

Table 6
Case studies.

	Fuel cost escalation rate	Inflation rate	Debt interest rate	Reinvestment rate
CASE1-REFERENCE	2 %	2 %	7 %	9 %
CASE2	10 %	2 %	7 %	9 %
CASE3	15 %	2 %	7 %	9 %
CASE4	2 %	10 %	7 %	9 %
CASE5	2 %	15 %	7 %	9 %
CASE6	2 %	2 %	5 %	9 %
CASE7	2 %	2 %	15 %	9 %
CASE8	2 %	2 %	7 %	5 %
CASE9	2 %	2 %	7 %	15 %

the investment trend. As shown in Fig. 5, as interest rates and inflation rates increase, the NPV of the investment decreases, this means that the investment is positive and with high profitability and added value higher than its initial cost and therefore can be considered profitable.

Different economic scenarios were analyzed. Four fundamental financial parameters for investments were taken into consideration:

- fuel cost;
- Inflation rate;
- Debt interest rate;
- Reinvestment rate.

The different case studies are reported in Table 6. It was decided to vary these parameters arbitrarily and individually to determine their influence on the economic feasibility of the proposed cogeneration plant.

The analysis showed that there is no change in cash flows if the debt and reinvestment vary. The only variations occur when the inflation rate varies, and the cost of fuel varies. In light of what emerged from the analysis, the cash flow of the first four cases is reported below in Table 7.

Fig. 6 shows the change in cash flows in the different cases. As can be seen from Fig. 7, the increase in the cost of fuel causes the cash flow of the investment to decrease over the years. In particular, case 3 is the worst. Significantly increasing the percentage of fuel cost (up to 15 %) will imply a negative NPV of the investment and, therefore, the investment may not be profitable.

Although the increasing inflation rate (case 4 and case 5), with low fuel cost, presents an overall decreasing cash flow over the years. In the first ten years, it can be seen that the cash flow values are slightly higher compared to the first three cases. Even if this increase was a few percentage points, overall, the investment can be considered less convenient than in the reference case (case 1).

In general, it can be said that high inflation percentages or fuel costs make the investment no longer convenient.

The software highlighted that with the proposed system it will be possible to obtain a reduction of about 3.578 tons/year of CO_2, corresponding to 30 % annual reduction (Fig. 8). Considering the entire useful life of the cogeneration plant, the total reduction of greenhouse gas emissions over 30 years would be approximately 96,700 t of carbon dioxide with a credit of approximately 70€/tCO_2 and a duration of the credit for greenhouse gas reduction of about 10 years, the revenue will be of about 2.504.600€.

The gross annual reduction in greenhouse gas emissions obtained in the simulation corresponds to approximately 1255 tons of recycled waste or better yet, it would correspond to 1,563,294 l of unconsumed fuel.

The reference case was a cogeneration plant that uses methane gas as fuel. If a comparison were made with a cogeneration reference system whose fuel was coal, then the emissions of burnt gases in the proposed case would decrease considerably until obtaining an annual reduction of approximately 70 %.

Table 7
Cash Flows trend in different cases.

CASH FLOW [€]					
Year	**CASE1**	**CASE2**	**CASE3**	**CASE4**	**CASE5**
0	−1,197,955	−1,197,955	−1,197,955	−1,197,955	−1,197,955
1	224,860	231,607	187,742	1,472,935	1,458,659
2	1,708,203	1,727,773	1,590,540	3,167,045	3,120,648
3	3,255,878	3,293,511	3,006,972	4,896,881	4,796,271
4	4,872,025	4,931,932	4,432,799	6,663,246	6,481,290
5	6,561,152	6,646,300	5,862,881	8,466,968	8,170,562
6	8,328,169	8,440,040	7,291,015	10,308,903	9,857,888
7	10,178,431	10,316,746	8,709,763	12,189,932	11,535,827
8	12,117,781	12,280,190	10,110,233	14,110,968	13,195,489
9	14,152,594	14,334,331	11,481,846	16,072,955	14,826,293
10	16,289,833	16,483,327	12,812,047	18,076,868	16,415,685
11	17,696,276	17,890,714	13,245,150	19,282,890	17,107,980
12	19,136,987	19,317,822	13,520,369	20,448,818	17,642,390
13	20,612,650	20,761,061	13,608,642	21,567,332	17,989,854
14	22,123,964	22,216,240	13,476,442	22,630,315	18,116,845
15	23,671,642	23,678,503	13,085,103	23,628,771	17,984,698
16	25,563,313	25,449,147	12,696,949	24,600,445	17,596,544
17	27,492,818	27,214,835	11,953,701	25,486,596	16,853,295
18	29,460,912	28,968,201	10,796,156	26,275,019	15,695,751
19	31,468,369	30,700,845	9,156,114	26,952,213	14,055,709
20	33,515,974	32,403,213	6,955,023	27,911,649	11,854,618
21	35,604,532	34,064,469	4,102,425	28,159,179	9,002,020
22	37,734,861	35,672,348	494,168	28,159,179	5,393,763
23	39,907,796	37,213,002	−3,989,654	28,225,723	909,941
24	42,124,190	38,670,819	−9,487,061	28,089,068	−4,587,467
25	44,384,912	40,028,235	−16,156,912	27,724,696	−11,257,317
26	46,690,849	41,265,513	−24,182,030	27,105,556	−19,282,435
27	49,042,904	42,360,514	−33,772,800	26,201,803	−28,873,205
28	51,442,000	43,288,428	−45,171,308	24,980,523	−40,271,713
29	53,889,078	44,021,493	−58,656,097	23,405,420	−53,756,503
30	56,385,098	44,528,670	−74,547,640	21,436,476	−69,648,045
VAN	16,765,985	15,506,233	−1,479,180	13,560,457	1,621,806

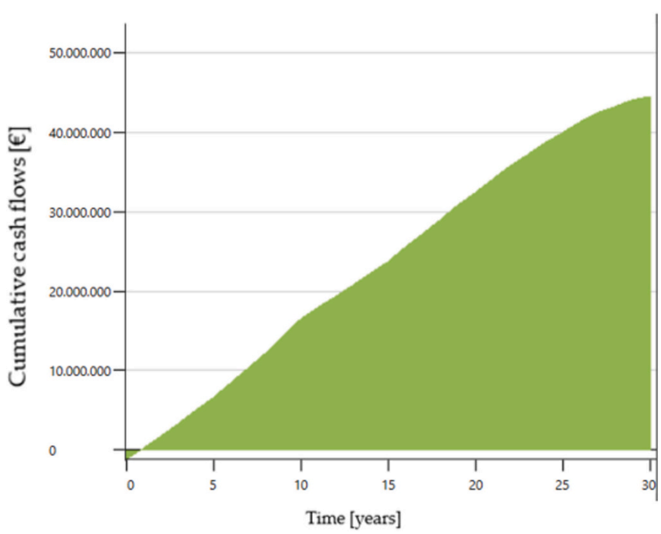

Fig. 6. Cumulative cash flow with different indexes.

Naturally, all the data obtained and the percentages of reduction in polluting emissions are simulations carried out on the software. If in light of this pre-feasibility study, it was decided to build the plant under study then the data on the reduction of polluting emissions would be validated and the economic efficiency of the system would increase because there are subsidized incentives to encourage the reduction of carbon dioxide produced.

With these reductions in carbon dioxide emissions, the replacement of the cogeneration plant with oxy-combustion would be the optimal choice to fall within the European policy to reduce CO_2 emissions by 55 % by 2030 in exchange for a small investment for the technological variation of the plant.

5. Conclusion

In general, combustion systems still present problems closely linked to conversion efficiency or energy losses that occur in the combustion chamber or with the auxiliaries. This study analyzes and compares the performance of an oxy-combustion cogeneration plant. Compared to conventional air-fired power plants with carbon dioxide capture, oxy-fuel systems require more capital investment, justified by the construction of air separation units. At the same time, this system is considered simpler than the traditional ones because it does not require carbon dioxide purification processes, because the oxy-combustion plant has a high concentration of carbon dioxide and condensable water in the gases and with the condensation process it is possible to obtain the separation of water from the exhaust gas.

Furthermore, as previously reported, the proposed system is more efficient from the point of view of exergy power, obtaining an exergy efficiency of approximately 67 % compared to the 48.3 % efficiency of all systems.

This phenomenon of increased system efficiency derives from the chemical energy of the fuel that is, the energy associated with the destruction of the existing atomic bonds between the reactants and the formation of new bonds between the products.

Furthermore, the oxy-combustion reaction considered in the case study will be exergetically more efficient and favorable also due to the high combustion temperatures that characterize the transformation, and which therefore favor the increase in the exergetic power of the reaction.

This study highlights the economic feasibility of building a cogeneration plant with an oxycombustion process and its environmental impact. Various scenarios of more or less achievable economic conditions were analyzed. They all highlighted that despite having a moderate increase in the cost of fuel and the purchase rate, up to around 10 %, the investment is always convenient. Naturally, only when faced with a high increase in the financing rate or the cost of fuel does the proposed case

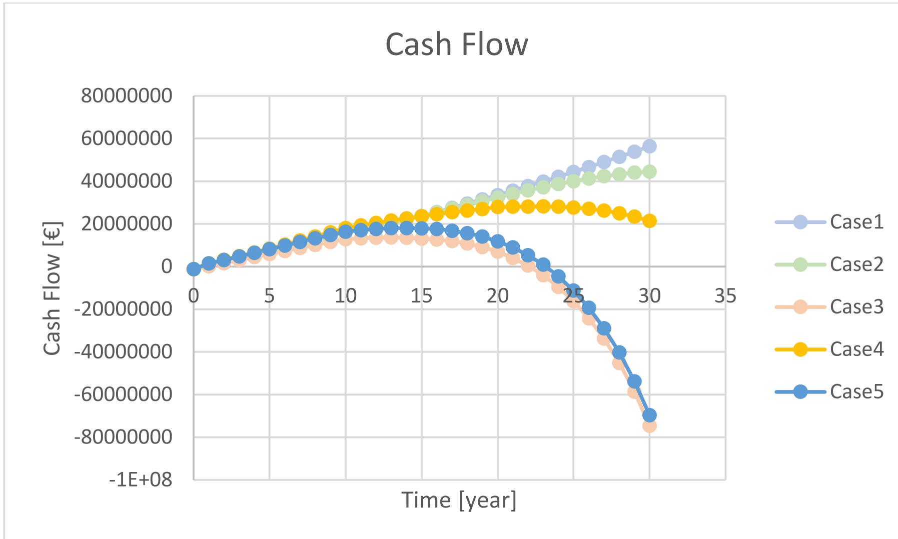

Fig. 7. Trend of Cash Flow as economic parameters.

GHG emission		
Base case	tCO_2	11.670
Proposed case	tCO_2	8.032
Gross annual GHG emission reduction	tCO_2	3.638

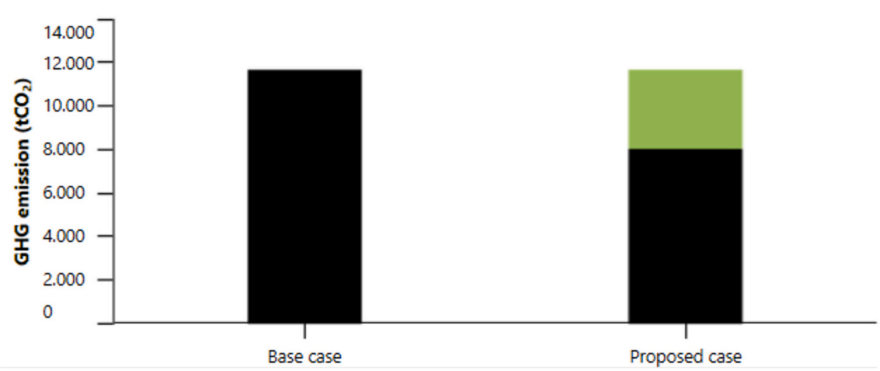

Fig. 8. Comparison of GHG emissions in the base case and proposed case.

appears to have a decreasing trend in cash flow, so the investment does not present the average percentage of convenience as the previous cases.

The study also highlighted that compared to a high initial cost of 3.5 million euros for the change of plant technology, the investment could be recovered in about 7 years. This short payback time is benefited by the contribution of incentives that the oxy-combustion cogeneration plant would obtain from the reduction of CO_2 emissions.

The results obtained from this study are very encouraging, they show that this technology is economically advantageous and therefore could motivate large industries to focus on the oxy-combustion process for example, all existing coal power plants in Italy and Europe could be modified in such a way as to obtain a significant reduction in polluting emissions compared to the current ones.

In the future it is planning to create the cogeneration system with oxy-combustion and compare the theoretical data obtained with this study with the experimental ones. Scaling the case study for power plants would help to understand the advantages and contributions that a plant of this kind can provide to achieve carbon dioxide neutrality. A study with a broader spectrum will help in popularizing the technology at an industrial level. Other future developments could involve the application of artificial intelligence in the system to better optimize the process.

Nomenclature

AFT	Adiabatic Flame Temperature [K]
C_t	Net cash inflow during the period t
C_0	total initial investment costs
CCS	Carbon Capture Sequestration
CFD	Computational Fluid Dynamic
C.L.A.	University Language Center
C.N.R.	National Research Center
DHITECH	High-Tech Technological District
E_(x_chem)	Chemical exergy of a multicomponent material stream [J]
E_(x_phys)	Chemical exergy that depends on the composition of the mixture [J]
E_(x_mix)	Exergy of mixing [J]
$\bar{e}^0{}_c$	Exergetic power of generic element c [kJ/kmol] e_{fu}
EA	Environmental Assessment
EU	European Union
F	Total stream molar flow
G	Gibbs free energy
GHG	Green House Gases
H	Enthalpy [J]
h	Combined stream enthalpy in the liquid and vapour phase [J]

H_i	lower calorific value of the fuel [J/kg]
IEA	International Energy Agency
IRR	Internal Rate of return
ISTAT	National Institute of Statistics
L	Stream liquid fraction
LHV	lower calorific value of the fuel [J/kg]
$\dot{m}_a$	mass flow rate of air [kg/s]
$\dot{m}_{fu}$	mass flow rate of fuel [kg/s]
NPV	Net Present Value
P	Pressure [bar]
P_v^-	mechanical power of the auxiliaries [W]
q_a^-	heat flow dispersed towards the environment by radiation and convection [J]
RETs	Renewable energy and Energy efficient Technologies
S	Entropy [J/K]
SPECCA	Specific Primary Energy Consumption of CO_2
t	number of time periods in IRR
T	Temperature [K]
T_0	Steam temperature [K]
V	Stream vapour fraction
NPV	Net Present Value
y	Component mole fraction in liquid and vapour phase
η_I	First law conversion efficiency
η_{II}	Second law conversion efficiency

CRediT authorship contribution statement

Brenda Raho: Writing – original draft, Software, Investigation, Formal analysis, Data curation. **Marcello Giangreco:** Software, Formal analysis, Data curation. **Gianpiero Colangelo:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marco Milanese:** Supervision, Investigation, Data curation, Conceptualization. **Arturo de Risi:** Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Thanks to the National Energy Technology District (Di.T.N.E.) 72100 Brindisi (Italy) for the technical support received and for the data provided for the analysis.

Data availability

Data will be made available on request.

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