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Biofixation of CO_2 emissions from natural gas combined cycle power plant

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Abstract

The growing impacts of climate change mainly due to the increasing emissions of GHG, especially carbon dioxide, has led to the development and implementation of specific strategies and policies to reduce them. Carbon capture and utilization (CCU) is currently seen as a good option, as it contributes to reduce the net carbon emissions and fulfil the goals of the Paris Agreement. This work analyses the economic potential of CO_2 biofixation by microalgae from the exhaust gas of a Portuguese Natural Gas Combined Cycle (NGCC) power plant. Literature and real operational data are used, collected from reports of Portuguese power generation companies. A preliminary design and economic analysis of the carbon biofixation system was done. Results show that, although requiring a very large investment, the process is economically viable. In further studies a more in depth approach and detailed project combined with a sensitivity analysis, and a comparison with the chemical based CO_2 fixation will be done.

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Keywords: Biological fixation; Microalgae; CO_2 emissions; Natural gas combined cycle power plant

1. Introduction

Fossil fuels are the source of most of the primary energy consumed in the world [1]. Despite the technological evolution and the development of renewable energy sources, it is expected that the fossil fuels will remain significant in the next decades. Fossil fuels utilization, mainly by combustion processes, is considered to be the most important source of greenhouse gases (GHG) emissions, especially carbon dioxide (CO_2), in particular from industrial sources and transportation. In the Portuguese context the energy sector has the largest share of GHG

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Nomenclature

CO_2	Carbon dioxide
GHG	Greenhouse gas
NGCC	Natural Gas Combined Cycle power plant
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
SO_2	Sulphur dioxide
NO_x	Nitrogen oxides
PBR	Photobioreactor
O_2	Oxygen
vvm	Vessel volumes per minute
NPV	Net Present Value
IRR	Internal Rate of Return

emissions, accounting for around 70% of total emissions. Within this share, electricity and heat production represent the largest contribution, over 25% [2]. Although the renewable energy quota in the Portuguese electricity mix is already significant and increasing, around 45 to 60% depending on the climatic conditions [3], the country is still dependent on fossil fuels to respond to energy needs.

In order to curtail climate change and the negative impacts on the environment, CO_2 emissions have to be constrained. Adequate strategies for GHG mitigation must take into account the full life cycle of energy generation and utilization, considering explicitly the goals of the various stakeholders, and be properly evaluated in terms of their environmental, economic and social sustainability [1,4]. Several potential solutions are available and being implemented to reduce the CO_2 emissions, among which the most relevant are: increasing renewable energy generation and/or utilization efficiency, Carbon Capture and Storage (CCS), and Carbon Capture and Utilization (CCU). Their applicability depends on how emissions are generated, characteristics of emissions streams, and their relative contribution to global emissions. From a cost benefit perspective, a focus should be given to large stationary sources, either heavy industry or energy generation units, as they have the largest potential for minimizing the GHG emissions.

Among the fossil powered plants, natural gas power plants operating in Combined Cycle-NGCC represent the second installed capacity (4.7 GW) for electricity production in Portugal, accounting for more than 26% of the total capacity [5]. During the last decade, all Portuguese NGCC power plants have been operated in a non-continuous mode, working only as backup to fulfil the electricity demand not satisfied by renewable electricity generation. According to data collected from Portuguese NGCC company reports, between 2011 and 2017 (latest data available) the load factor of national NGCC power plants ranged between 6 and 64% of their full capacity [6].

Although CCS is still regarded as one of the most promising ways to reduce CO_2 emissions from large industrial sources, it has several drawbacks, in particular the need for considerable investment and high maintenance costs of sequestration facilities, and the negative public opinion. Currently, CCU technologies and its application to industrial processes are increasingly seen as a more adequate option, as they contribute directly for a more circular economy, and can reduce the net GHG emissions thus contributing to fulfil the goals of Paris Agreement [7]. Furthermore, CCU may allow companies to get some additional revenue to balance carbon capture costs.

Broadly speaking, CCU can be divided in two categories, depending on the fundamental physical–chemical nature of the technology: chemical and biological. The first is based in the physical and chemical processing of CO_2, for example carbon capture by amines and posterior conversion of the captured CO_2 to methane by methanation. The second form consists on the direct capture of CO_2 by incorporating it into organic matter through photosynthesis performed by living organisms, as for example microalgae, and further processing of the biomass [8]. CO_2 biofixation mimics carbon removal by natural sinks (oceans, forests, etc.) into the carbon natural biological cycle [9].

Biological CCU has several advantages when compared to chemical CCU. From an operational point of view, it is simpler and easier to operate under ambient conditions. As demand for captured CO_2 is still difficult to predict [10] due to ongoing changes in the CO_2 utilization markets, being cheaper and more flexible is a key advantage to biological CCU. In addition, capturing CO_2 from flue gases of NGCC power plants is an energy intensive process because CO_2 concentration in exhaust gases is much diluted (4%–8%). This CO_2 concentration range suits microalgae cultivation requirements, allowing the direct use of the exhaust gases without a CO_2 previous capturing step. *Chlorella* and *Scenedesmus* are the most well documented microalgae genera, able to grow at considerable high rates even when exposed to high CO_2 concentrations [11]. Additionally, high purity CO_2 is not required, thus flue gases containing SO_2 and NO_X can be fed to microalgae cultures [12,13]. Carbohydrates and lipids extracted from biomass can be converted to biofuels, or other high value products can be extracted, improving the process economics [14,15]. Despite the advantages, a comprehensive analysis of the associated economic and environmental impacts is still necessary to validate its viability and identify what are the best process options.

In this study the carbon capture by microalgae from the flue gas generated in a Portuguese NGCC power plant is examined from a technical and economic perspective, aiming to reduce the carbon net emissions. Portugal is quite privileged as the average global solar radiation is 152–161 W/m^2 [16]. This irradiance value is higher than the value of 135 W/m^2 corresponding to the maximum light regime intensity of 531 µmol photon m^{-2} s^{-1} [17] reported in the literature. This study results contribute to identify conditions in which carbon biofixation is viable, and the main bottlenecks that need to be tackled first.

2. Materials and methods

The implementation of a biological CCU unit in a Portuguese NGCC power plant has to consider the various process and their integration with each other. In this study it is assumed that, instead of being released to the atmosphere, flue gases will be collected from the stack, transported by a gas duct and directly injected into the nearby microalgae cultivation system. To this purpose, the microalgae production unit has to be installed at the power plant location in order to avoid the transportation of the flue gas by distances beyond a few tens of metres. The alternative strategy for this process integration would require the installation of a CO_2 capture unit by chemical absorption from flue gases because flue gas transport at distances greater than 50 to 100 m would become unfeasible due to the amount of flue gases flow involved [18].

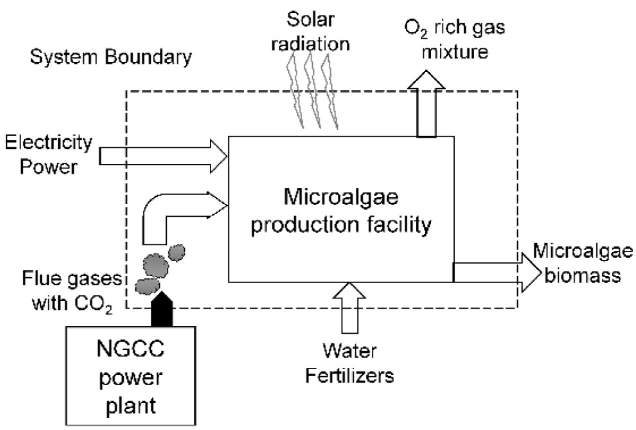

Fig. 1. System boundary of the study.

Fig. 1 presents the system boundary for the study including the following process steps: connection between the flue gas exhaustion and the microalgae production facility, a flue gas distribution system, photobioreactors (PBRs) for microalgae growth, and a microalgae harvesting and processing system to obtain a paste that will be further processed to obtain various biomass fractions.

Also included in the figure are the main process inputs, in particular: electricity, water, fertilizers, and solar radiation; and outputs: O_2 rich mixture, and microalgae processed biomass, that corresponds to the stream that will generate revenue to the company.

To cultivate microalgae, closed Plexiglas PBRs with an internal diameter of 0.30 m, length of 40 m and a wall thickness of 0.01 m were selected, as they can be easily bought from suppliers. A mixing tank is associated with each PBR, in which the flue gas and nutrients are fed, and the gas is cooled down. As expected due to the large volume of total flue gas emissions, a large volume of water will be necessary to grow the microalgae. Thus, a horizontal arrangement of tubes was chosen because it will simplify the construction of the supporting structure and render it more stable. Enough bends, joints and connectors are used to link PBRs with the CO_2 supplying system and the harvesting unit. The PBRs are supported by specially designed and projected concrete and metallic structures, with dimension 10 × 0.1 × 0.1 m, in which the Plexiglas tubes, pipes and other equipment are encased.

PBRs operate in batch mode with an average residence time of microalgae cultures of 10 days until reaching the stationary growth phase at an average biomass concentration of around 2% (w/v) [11]. For each PBR, operation starts by filling it with previously filtered culture medium and a microalgae inoculum. Then, the feeding of the CO_2 enriched stream starts directly from the NGCC exhaust system, with an aeration ratio of 1.0 vvm (vessel volumes per minute), higher than reported literature values for laboratorial scale [19] in order to handle the large flow of flue gases from the NGCC unit. A higher aeration rate is also favourable to improve mixing in long tube vessels and to promote gas-liquid exchange of CO_2 input.

The energy needed to operate the system is taken into account, in particular to inject the CO_2 into PBRs and to move the culture media around PBRs. When the microalgae cultures reach the stationary growth phase, the flue gas flow admission is stopped and the PBR is drained to harvest the cells. The harvesting is done using a spiral plate type centrifuge. For large processing volumes of culture this separation method is proved to be the most efficient and cost effective [20,21]. Harvesting the cultures using this separation technology provides a microalgae thick paste with around 30% of solids on a dry basis, suitable for further dewatering and components extraction (biorefination). The empty PBR is then cleaned and sanitized, in order to initialize another batch. The PBR operation schedule is done in such a way that 90% of them will be operating at any given time.

The main characteristics of the NGCC power plant emissions are presented in Table 1. The data presented was obtained from the Portuguese power plants environmental assessment reports [6] and the National Inventories Report [2]. The values represent an average of the natural gas consumption and emissions of the past 6 years for the NGCC power plants in Portugal, since there are wide variations between years as the power plant output depends on the climatic conditions. Furthermore, as renewable electricity generation capacity installed in Portugal will increase in the near term [3], the probability of not capturing all the emitted carbon by the biological CCU will be smaller.

Table 1. General operational characteristics of the hypothetical case-study NGCC power plant.

Operational item	Characterization/Dimension
Fuel	Natural gas
Specific natural gas consumption	179 (171–190) Nm^3 NG/MWh
Specific CO_2 emissions by electricity production	385 (367–407) kg CO_2/MWh
Specific flue gases flow	3485 ± 935 Nm^3/MWh
Specific flue gases flow per natural gas consumption flow	19.4 ± 4.9 Nm^3 flue gases/Nm^3 NG
Average flue gases flow per stack	$1.50 \times 10^6 \pm 4.0 \times 10^5$ Nm^3/h
CO_2 concentration in flue gases stack flow	0.119 (0.09–0.20) kg CO_2/Nm^3 stack flow
Average CO_2 flow per stack	147 (128–178) ton CO_2/h
Average temperature of flue gases at the stack	80 °C

This study considers the microalgae *Chlorella vulgaris* because it is a very well-studied species, high-tolerant to variable growth conditions and totally adaptable to Portuguese climate conditions. Large variations in the carbon fixation rate can be found in the literature, ranging from 0.2 to 30 kg/m^3 per day, depending on flue gases characteristics [11,17,19,22,23]. A value of 2.9 kg/m^3 per day was considered as less favourable case scenario to account for difficulties in carbon uptake in the system. As it is expected that the cultivation expertise will improve in the future, largest values of carbon fixation rates will be viable in the future.

The economic calculations consider two types of costs, investment and operational costs; and expected revenues. The investment costs correspond to PBRs materials acquisition, support units' construction and implementation. The operational costs correspond to culture media, energy, water and other costs such as labour. Three potential revenues streams were identified: biomass, the O_2 enriched stream exiting the PBRs, and the avoided CO_2 emissions. Although the latter is not really a revenue stream, from an accounting point of view it will reduce the CO_2 emission costs, thus it is equivalent to a revenue. The lifetime of the biological CCU unit is assumed to be 15 years, and a discount rate of 10% is considered to calculate the Net Present Value at the end of the unit lifetime, NPV, the Internal Rate of Return, IRR, and payback time, in order to assess the economic potential.

3. Results and discussion

Calculations were done per stack, using the data presented in Table 1. Since the amount of CO_2 emissions is very large, the microalgae cultivation system will also be very large. Based on the data presented in Table 1, the designed cultivation system main characteristics are shown in Table 2. A total PBR volume of 18 400 m^3 is estimated to be necessary to capture the total amount of flue gases. The total cultivation volume was divided by 145 independent units to ensure that the system can be implemented, allowing a greater operational flexibility since smaller units are easier to build, operate and clean, and a continuous carbon capture is possible. Each PBR has a volume of 127 m^3 and a length of 1640 m, corresponding to 20 tubes of 40 m length connected by the necessary elbows and other connections. Tubes are stacked horizontally to occupy less space as the total tube length is 260 km. Mixing tanks associated with each PBR have a volume of 11 m^3 each, corresponding to Plexiglas tubes of length of 6.5 m and diameter of 1.35 m. The entire production unit occupies a total area of 23 000 m^2, however it can be safely assumed that there is space available to install the biological CCU with no extra cost at the NGCC power plant. This is because in these facilities, it is normal to have large spaces of unoccupied land acting as buffer zones.

Table 2. Main system characteristics.

Microalgae production facility characteristics	Dimension
Total volume of culture	18 400 m^3
PBR individual volume	127 m^3
Number of PBR units	145
Diameter of PBR tube vessel (cylindrical shape)	$\phi = 0.30$ m
Mixing tank volume included in each PBR (cylindrical shape)	11 m^3 (L = 6.5 m, $\phi = 1.35$ m)
Length of tube vessel for each PBR	1640 m
PBR installation in horizontal parallel assemblages	20 tubes of 40 m length
Total length of tube vessels	260 km
Total implantation area of the microalgae culture farm	23 000 m^2

The investments costs are shown in Table 3. The overall investment cost is very large, around 51 million €, justifiable by the large amount of CO_2 that needs to be captured. The main cost term corresponds to the PBRs, 81%, followed by the storage vessels and the supporting infrastructure. Thus, it is clear that a reduction in investment costs must be based on a reduction in the PBRs cost, using for example a cheaper and more durable transparent material.

Table 3. Investment costs for microalgae production facility for the system components.

Microalgae production facility components	Estimated investment cost (euro)
Infrastructure of concrete pillars to support PBR tube vessels	3 400 000 €
Plexiglas tube vessels for tubular PBR	41 526 030 €
Combined probes for oxygen and temperature control system in PBR	171 216 €
Storage vessels for water and culture medium recycling	5 800 000 €
Activated microfiltration/sanitizing system for fresh water and culture medium	175 275 €
Centrifuge for harvesting microalgae biomass	135 300 €

Table 4 presents operating costs in an annual basis, aggregating labour costs, maintenance, management and other costs. The main cost term is the culture medium corresponding to 77% of the overall costs. The utilization of waste streams to supply nutrients may reduce the costs significantly, or an effective recycling of the culture medium between batches. Energy costs correspond to electricity, which can be reduced generating renewable electricity onsite or nearby.

In Table 5 the main revenue streams in a yearly basis are given, together with the market prices at the time of writing this article. As stated above, the CO_2 avoided does not really represent a revenue, because as it reduces

Table 4. Operational costs of the microalgae production facility (€ per year).

Operational items on microalgae production facility	Annual cost (€ per year)
Culture medium (70 €/m^3 assuming 70% of recycling)	12 503 785 €
Electricity and power	761 651 €
General operational costs	2 994 696 €
TOTAL	16 260 131 €

Table 5. Potential revenues streams from microalgae production facility (€ per year).

Microalgae production facility outputs	Annual value (€ per year)
CO_2 emissions avoided (9.6×10^8 kg/year); market price 21 €/ton (source: [24])	20 065 500 €
Microalgae biomass produced (5.0×10^6 kg/year); price 2340 €/ton	11 679 312 €
TOTAL	38 091 905 €

the overall costs of operating the power plant, its accounting effect is akin to a revenue. That represents the main revenue term, and it alone justifies the construction of the biological CCU unit, as it generates more revenue than the annual operation costs. Although the biologic CCU unit may look interesting from an economic perspective, as the revenues are larger than operational costs, an objective evaluation of its potential must take into account the investment and potential interest costs. Based on the results presented in Tables 3 to 5 the values of NPV, IRR, and the payback period are respectively of 18 197 565 €, 14% and 10 years, proving that this is a good investment according to the hypotheses assumed in this work.

4. Conclusions

CO_2 biofixation by microalgae is an end-of-pipe process that does not affect the NGCC energy efficiency. The adaptability of microalgae cultures to changing environmental conditions, such as changes in the CO_2 input charge due to flue gases concentration and flow fluctuations, without a considerable efficiency penalty of the process, is an advantage that does not exist in any physical–chemical processes for CO_2 capturing. Even though the biological CCU unit is very large and a very large investment is necessary, the calculated values of the economic indicators show it is viable. This study will be further extended by performing a more complete economic analysis combined with a sensitivity analysis, including the biomass processing to obtain various products, a life cycle assessment will be performed, and a comparison with chemical CCU will be done.

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