

Environmental assessment of the integrated bio-combustion process: A life cycle energy balance**Avaliação ambiental do processo integrado de bio-combustão: balanço energético do ciclo de vida**

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ABSTRACT

The aim of the present study was to evaluate the life cycle energy balance of the integrated bio-combustion process. The life cycle analysis tool was applied to assess the environmental performance of the system. The experiments were performed in a bubble column photobioreactor with a volume of 2L, photon flux density of 150 $\mu\text{mol}/\text{m}^2/\text{s}$, continuous aeration of 1VVM, and injection air-enriched with 15% of CO_2 . The photobioreactor exhaust gases were integrated into the bio-combustion furnace, which was designed on a lab-scale. The operational conditions were: initial coke mass of 1g, total combustion reaction time of 20 min, and airflow rate of 1 L/min. The energy balance was determined by equating of the energy produced by the required energy, followed by the net energy ratio. The results obtained showed a net energy ratio for the integrated process of 0.69, indicating an energy efficiency improvement close to 70%. Thus, the system has the potential to boost the sustainability of industrial facilities.

Keywords: microalgae, photobioreactor, combustion, process integration, life cycle assessment.

RESUMO

O objetivo do presente estudo foi avaliar o balanço energético do ciclo de vida do processo integrado de bio-combustão. A ferramenta de análise de ciclo de vida foi aplicada para avaliar o desempenho ambiental do sistema. Os experimentos foram realizados em um fotobiorreator de coluna de bolhas com volume de 2L, intensidade luminosa de 150 $\mu\text{mol}/\text{m}^2/\text{s}$, aeração contínua de 1VVM e injeção de ar enriquecido com 15% de CO_2 . Os gases de exaustão do fotobiorreator foram integrados no forno de bio-combustão, projetado em escala laboratorial. As condições operacionais foram: massa inicial de coque de 1g, tempo total da reação de combustão de 20 min e fluxo de ar de 1 L/min. O balanço energético foi determinado pelo equacionamento da energia produzida pela energia requerida, seguido da razão de energia líquida. Os resultados obtidos mostraram uma relação de energia para o processo integrado de 0,69, indicando melhoria na eficiência energética próxima a 70%. Assim, o sistema tem potencial para promover a sustentabilidade das instalações industriais.

Palavras-Chave: microalga, fotobiorreator, combustão, integração de processo, análise de ciclo de vida.

1. INTRODUCTION

The use of fossil inputs is a vicious cycle. Since many decades ago, emissions related to non-renewable energy use have grown exponentially, and the trend is that this phenomenon will continue at the same pace (Jiang et al., 2019). According to the International Energy Agency, in the year 2014, carbon dioxide (CO₂) emissions were approximately 32 Gt/yr, and the forecast to minimize them is 8 Gt in the coming years (IEA, 2019). However, the race towards to resolve this critical issue seems endless.

Therefore, looming and currently environmental crises – including mainly climate change and resource scarcity – are increasingly inspiring sustainability ideas, led by innovation alliances between research and development (R&D) sectors. Current engineering approaches suggest carbon capture and storage (CCS) or utilization (CCU) technologies in combustion systems (Yan and Zhang, 2019). Nevertheless, they have many technical, economic, and environmental bottlenecks that an industrial process requires (Cuéllar-Franca and Azapagic, 2015).

Recently, carbon capture and biological utilization (BCCU) has been developed and has been considered as a promising technological route to improve energy-intense industrial processes (Jacob-Lopes et al., 2017; Severo et al., 2018a). This bioprocess is mediated by microalgae-based systems, which are cultivated in photobioreactors, considered the centerpiece for CO₂ capture and conversion into commercial interest products (Severo et al., 2019). Photobioreactors must be designed to withstand high workloads, precisely to meet the demands of large-scale production (Verma and Srivastava, 2018).

In this way, in the study conducted by Severo et al. (2018b), the BCCU technique applied to an integrated bio-combustion process was demonstrated. The technology integrates photobioreactor exhaust gases containing O₂, volatile organic compounds (VOCs), and unconverted CO₂ into a combustion furnace, which are reused as oxidizer, biofuels and nitrogen diluent, respectively. This enabled a potential increase in thermal efficiency by approximately 30%. Nevertheless, it is crucial to evaluate the system from an environmental performance perspective.

Thus, the need arises to address energy issues to improve the sustainability of industrial production facilities. For this, life cycle assessment (LCA), a powerful tool that helps to verify the environmental impacts of a "cradle-to-grave" product or process can be adopted. It defines energy flows, mass, emissions, water, among other aspects, making it possible to evaluate resource use and provide opportunities for upgrading (Xu et al., 2019). In this sense, the

objective of this work was to establish the life cycle energy balance of the integrated bio-combustion process through the LCA.

2. MATERIAL AND METHODS

This study applies the LCA tool to evaluate the environmental performance of the integrated bio-combustion process. The LCA identifies and quantifies the potential environmental impacts of a system considering its entire life cycle following the guidelines established by the International Organization for Standardization (ISO) 14000 series. For this, our sequential steps are considered: (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation of results (ISO, 2006).

2.1 GOAL AND SCOPE DEFINITION

The goal of the LCA here was to investigate the integrated process, whose laboratory scale experimental data were previously obtained from Severo et al. (2018b). Assuming that microalgae-based processes all data were standardized for a functional unit of 1 kg of mass and 1 MJ of energy for comparison with a future industrial scale. Figure 1 demonstrates the scope of the process.

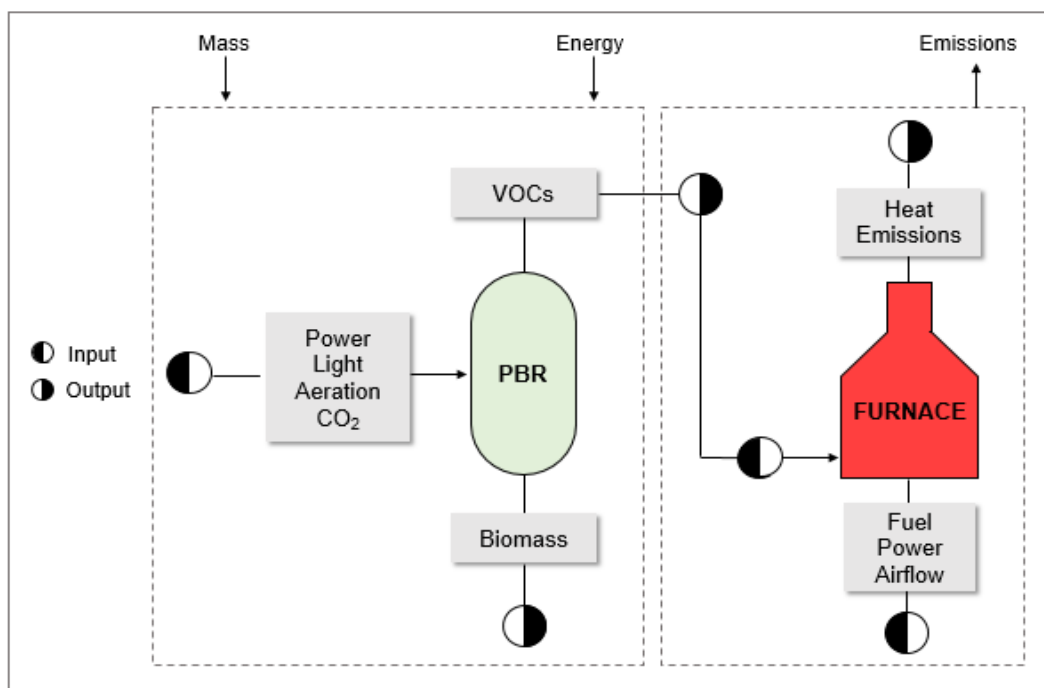


Figure 1. Scope of the integrated bio-combustion process.

2.2 PROCESS DESCRIPTION

The integrated bio-combustion process developed was based on the biological CO₂ capture and utilization (BCCU) technique, which was performed in a bubble column photobioreactor, considered the core of the process. The photobioreactor served as cultivation system for the *Scenedesmus obliquus* microalgae, obtained from the Canadian Phycological Culture Centre. Stock cultures were propagated and maintained in synthetic BG-11 medium (Rippka et al., 1979) and pH 7.6. The incubation conditions are as follows: temperature of 30°C, the photon flux density of 15 μmol/m²/s and a photoperiod of 12h. The experiments were conducted in the photobioreactor operating under intermittent regime, fed with 2L of culture medium, initial cell concentration of 100 mg/L, temperature of 26°C, the photon flux density of 150 μmol/m²/s, continuous aeration of 1VVM (volume of air per volume of culture per minute), and injection air-enriched with 15% of CO₂. The microalgae photosynthetic metabolism reactions enable the CO₂ bioconversion in gaseous products such as O₂, VOCs, and CO₂ (corresponding to the injected percentage that is not converted). These bioproducts were then recovered and integrated into the bio-combustion furnace as the oxidizer, fuels, and nitrogen diluent, respectively.

The furnace was manufactured in lab-scale, consisting of a thermal energy generation system, composed of refractory material, equipped with electrical resistors (600W), and with a central combustion chamber of the primary fuel, the petroleum coke. Simultaneously, the furnace was fed with gaseous products from the photobioreactor, which were considered as improvers of combustion performance. The experimental conditions were as follows: initial coke mass of 1g, a total combustion reaction time of 20 min, and airflow rate of 1 L/min. Further specifications of the integrated process are described in patent WO2017/112984A1 (Jacob-Lopes et al., 2017) and Severo et al. (2018b).

2.3 INVENTORY ANALYSIS

Table 1 shows the main inventory data used, which were based on the input and output flows of the integrated process.

Table 1. Input and output flows of the integrated bio-combustion process.

Process step	Flow	Consumable	Amount
Photobioreactor	Input	Power	15,840 kWh
		Light	82 kWh
		Aeration	103 kWh

	Output	VOCs	805 MJ
		Biomass	58,990 MJ
		Fuel	35 MJ
Furnace	Input	Power	7,130 kWh
		Airflow	240 kWh
	Output	Heat	0.65 MJ

2.4 IMPACT ASSESSMENT

Impact assessment aims to understand and assess the potential environmental impacts caused by the resources identified during the life cycle inventory. Thus, the category considered refers to the Net Energy Balance (NEB) and Net Energy Ratio (NER).

2.5 NET ENERGY BALANCE AND NET ENERGY RATIO

The NEB was calculated from the difference of total input energy and total output energy, through Eq. 1 (Jorquera et al., 2010):

$$NEB = \sum E_{out} - \sum E_{in} \quad (1)$$

where E_{out} is the output energy and E_{in} is the input energy, expressed in terms of mega joules (MJ).

Already the NEB of the bio-combustion furnace was defined by the Second Law of Thermodynamics, calculated from Eq. 2:

$$Q = m_F c_p (T_{out} - T_{in}) \quad (2)$$

where Q is the amount of heat lost in the exhaust gases (MJ), m_F is the fuel mass, C_p is the average specific heat of fuel, and T_{out} and T_{in} are the exhaust gases and pre-combustion temperatures, respectively.

The NER, which is defined as the ratio of total energy produced and required for operations was calculated according to Eq. 3:

$$NER = \frac{\sum_{out}}{\sum_{in}} \quad (3)$$

where E_{out} is the sum of the total energy produced and E_{in} is the sum of the total energy required (dimensionless).

3. RESULTS AND DISCUSSION

Table 2 lists the net energy balance and net energy ratio values according to the input and output operations flows for the photobioreactor, furnace, followed by process integration. Values were based on inventory and assumptions described in Section 2.3.

Table 2. Net energy balance and net energy ratio of the process life cycle steps.

Step	Input energy (MJ)	Output energy (MJ)	NEB (MJ)	NER
Photobioreactor	57,690.00	59,795.00	2,228.00	1.00
Furnace	26,567.00	0.65	-26,566.00	0.000024
Process integration	84,257.00	59,795.65	-24,461.35	0.69

According to Table 2, it is first observed that when considering the processes independently, a positive balance was obtained for the photobioreactor (NEB = 2,228.00 MJ), resulting in a NER of 1.00. This means that the amount of output energy, represented by biomass and VOCs, can be considered as a renewable energy source since it is higher than the input energy. This, in turn, is related to the fossil energy consumed throughout the process. Studies show that energetics assessments should have $NER > 1$, which justifies an environmental performance favorable to the implementation of microalgae-based processes (Jorquera et al., 2010; Slade and Bauen 2013; Tredici et al., 2015).

On the other hand, when considering the bio-combustion furnace, the energy balance was extremely negative, resulting in a value of NEB -26,566.00 MJ and NER 0.000024. These data support the fact that combustion systems are very inefficient in terms of energy efficiency, generally characterized by exothermic reactions, where combustion products accumulate less amount of heat than the reactants (Glassman et al., 2015).

In order to improve combustion systems, the photobioreactor integration into the furnace was evaluated, which even with a negative NEB (-24,461.35 MJ) and NER of 0.69, an energy efficiency improvement of approximately 70% was achieved. This is due to the integration of the photobioreactor exhaust gases, which have considerable energy content (Severo et al., 2018b). The process integration strategy has been widely claimed in patents and pilot-scale plants (Ahrens et al., 2012; Bliss, 2013; Gonzalez et al., 2014; Tredici et al., 2015; Nurdiawati et al., 2019). This limitation persists in the high cost and energy expenditures in other steps of the process.

4. CONCLUSION

Based on the results obtained, the microalgal photobioreactor has the potential to be integrated as retrofit equipment in industrial combustion facilities to increase thermal

efficiency. The overall energy balance of the integrated process can, therefore, achieve even better environmental performance if other generated surpluses are adequately exploited. Finally, further investigations should be conducted in an attempt to optimize microalgae-based processes toward commercial viability.

REFERENCES

- Ahrens, T.D., Kitchner, S.R., Haley, J.W., 2012. Systems, apparatuses and methods of cultivating organisms and mitigation of gases. Patent US 20120252105 A1, 2012.
- Bliss, C., 2013. Method for establishing synergism between renewable energy production and fossil energy production. Patent US 2013/0224841 A1, 2013.
- Cuéllar-Franca, R. M.; Azapagic, A., 2015. Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. *Journal of CO₂ Utilization*, 9, 82-102.
- Gonzalez, J.A., Kolesnik, M., Martin, S.C., Sajewycz, M., 2014. Recovering off- gas from photobioreactor. Patent WO 2014063233, 2014.
- Glassman, I., Yetter, R. A., Glumac, N. G., 2015. *Combustion*. 5th edition, Academic Press, Elsevier, 774p.
- IEA. International Energy Agency. Available at: <https://www.iea.org/>. Accessed in: 08.30.2019.
- IHEA. *Improving Process Heating System Performance: A Sourcebook for Industry*, 2015. 3rd edition, Prepared for the United States Department of Energy Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office.
- ISO. International Standardization Organization. Environmental management–life cycle assessment-principles and framework, ISO 14040, 2006. Available at: http://www.iso.org/iso/catalogue_detail?csnumber=37456.
- Jacob-Lopes, E., Severo, I.A., Bizello, R.S., Barin, J.S., Menezes, C.R.D., Cichoski, A.J. et al., 2017. Process and system for re-using carbon dioxide transformed by photosynthesis into oxygen and hydrocarbons used in an integrated manner to increase the thermal efficiency of combustion systems. Patent WO2017/112984 A1, 2017.
- Jiang, J., Ye, B., Liu, J., 2019. Research on the peak of CO₂ emissions in the developing world: Current progress and future prospect. *Applied Energy*, 235, 186-203.
- Jorquera, O., Kiperstok, A., Sales, E. A., Embiruçu, M., Ghirardi, M. L. 2010. Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors. *Bioresource Technology* 101, 1406-1413.
- Nurdiawati, A., Zaini, I. N., Aziz, M., 2019. Dual-stage chemical looping of microalgae for methanol production with negative-carbon emission. *Energy Procedia*, 158, 842-847.
- Rippka, R., Deruelles, J., Waterbury, J.B., Herdman, M., Stanier, R.Y., 1979. Generic assignments strain histories and properties of pure cultures of cyanobacteria. *Journal of General Microbiology*, 111, 1-61.

- Severo, I. A., Barin, J. S., Wagner, R., Zepka, L. Q., Jacob-Lopes, E., 2018a. Biofuels from Microalgae: Photobioreactor Exhaust Gases in Oxycombustion Systems. In: Jacob-Lopes E., Zepka L. Q., Queiroz M. I. (eds) *Energy from Microalgae*. Green Energy and Technology. Springer, pp 271-290.
- Severo, I.A., Deprá, M.C., Barin, J.S., Wagner, R., Menezes, C.R.de., Zepka, L.Q., Jacob-Lopes, E., 2018b. Bio-combustion of petroleum coke: The process integration with photobioreactors. *Chemical Engineering Science*, 177, 422-430.
- Severo, I. A., Siqueira, S. F., Deprá, M. C., Maroneze, M. M., Zepka, L. Q., Jacob-Lopes, E., 2019. Biodiesel facilities: What can we address to make biorefineries commercially competitive? *Renewable and Sustainable Energy Reviews*, 112, 686-705.
- Tredici, M. R., Bassi, N., Prussi, M., Biondi, N., Rodolfi, L., Chini Zittelli, G. et al., 2015. Energy balance of algal biomass production in a 1-ha “Green Wall Panel” plant: How to produce algal biomass in a closed reactor achieving a high Net Energy Ratio. *Applied Energy*, 154, 1103–1111.
- Slade, R., Bauen, A., 2013. Micro-algae cultivation for biofuels: Cost, energy balance, environmental impacts and future prospects. *Biomass and Bioenergy*, 53, 29-38.
- Verma, R., Srivastava, A., 2018. Carbon dioxide sequestration and its enhanced utilization by photoautotroph microalgae. *Environmental Development*, 27, 95-106.
- Yan, J., Zhang, Z., 2019. Carbon Capture, Utilization and Storage (CCUS). *Applied Energy*, 235, 1289-1299.
- Xu, X., Gu., X., Wang, Z., Shatner, W., Wang, Z., 2019. Progress, challenges and solutions of research on photosynthetic carbon sequestration efficiency of microalgae. *Renewable and Sustainable Energy Reviews*, 110, 65-82.