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Computer-Aided Environmental Evaluation of Bio-Hydrogen Production from Residual Biomass of Palm Cultivation

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Abstract

The environmental assessment of a process allows detection of improvement areas from this point of view, serving as a tool for making decision and quantification of environmental benefits for a raw material transformation into a final product. In this work, a bio-hydrogen production process was evaluated using WAR algorithm. The process was carried out via gasification from 40.84 t/h of palm rachis and analyzed under 8 impact categories that can be classified into two groups: local toxicological impacts on humans (HTPI, HTPE) and ecological (ATP, TTP), and global (GWP, ODP) and regional (AP, PCOP) atmospheric impacts. In addition, it was performed a comparative assessment to know the environmental impact of coal, oil and gas as energy source in the process. Results show that the total PEI generated is negative for cases where it was only considered the product streams, showing that in general terms, the process is environmentally beneficial. In addition, when coal is used as fuel, the PEI output is higher due to changes caused by the ozone concentration wake of volatile organic compounds emissions that can contribute to the generation of acid rain; while using gas as energy source can lead to less impact for all cases studied. The process generates 4 tons of CO_2 per ton of rachis, therefore, values for PEI output for atmospheric environmental impacts categories could decrease considerably if are carried out energy improvements by changing the type of fuel or using the heat of gases emitted into the atmosphere through an energy integration.

Keywords: WAR algorithm, Impact Categories, Palm Rachis, Bio-Hydrogen

1. Introduction

The current world energy demand mostly depends on the utilization of fossil fuels, and the huge consumption of these over the years has caused various detrimental effects on environment such as global warming, air pollution and severe climate changes. Renewable energy is an important instrument for world energy demand satisfaction, it has been estimated that percentage of renewable sources in total world power generation will reach about 33% in 2040, starting from 12% of 2012[1]. However, hydrogen is anticipated as the key alternative to existing fossil fuel for internal combustion engines due to it does not emit greenhouse gases but just water when combusted [2], and exhibits a high calorific value (122 kJ/g) which is about three times higher than gasoline. Therefore, it is important to generate hydrogen by clean technologies using renewable sources such as biomass, wind power or hydraulic and solar energy in order to dwindle environmental pollution and production costs. [3]. Biomass is an important contributor to the world economy. Agriculture and forest products industries provide food, feed, fiber, and a wide range of necessary products like shelter, packaging, clothing, and communications. However, biomass is also a source of a large variety of chemicals and materials, and of electricity and fuels. About 60% of the needed process energy in pulp, paper, and forest products is provided by biomass combustion. The biomass industry can produce additional ethanol by fermenting some by-product sugar streams. Lignocellulosic biomass is a potential source for ethanol that is not directly linked to food production. Also, through gasification biomass can lead to methanol, mixed alcohols, and Fischer-Tropsch liquids [4]. Palm is one of the potential sources of biomass, which has become a major financially viable culture, able to become the backbone of the economy [5]. A tropical palm "*Elaeis Guineensis*", a crop that produces 3 to 8 times more oil from a particular given area than any other temperate or tropical oil land crop. In 2010, Colombia was the first Latin American country producer of palm oil and the fifth in the world after Indonesia, Malaysia, Thailand and Nigeria, with domestic production of 753,000 tons [6]. In addition, in Colombia there are plans to increase production to six times by 2020, which would require 3 million hectares for plantations [7]. This process generates a large amount of residual wastes or biomass such as oil palm fiber and empty fruit bunches that contain lignin, cellulose, hemicellulose, a little number of other extractives and a high moisture content, which allows it to be appropriate for thermal conversion process. An alternative for hydrogen production is the gasification of palm rachis produced. Despite the great advantages from the economic and environmental point of view that exhibits this process related to diminishing the greenhouse gas emissions and using agroindustrial wastes, which are a source of environmental problems derived from its incorrect disposal in rural areas, this technology is under research and development to project it into an industrial scale due to related costs that have to be assumed to carry out the plant design and operation [8]. In this sense, one of the evaluations apply in research is the environmental assessment, that provides an orderly, replicable and multidisciplinary analysis of possible environmental impacts that a process can have on the ecosystem, either causing an ecological imbalance or exceeding the limits and conditions set forth in the applicable provisions to protect, preserve and restore the environment. Some of the methodologies and tools used to develop an analysis are the Waste Reduction (WAR) Algorithm [9], and Life-Cycle Assessment [10] [11]. Regarding WAR algorithm, this is useful because allows quantifying the generation of potential environmental impacts based upon several different impact categories [12]. In this work, it was performed an environmental assessment of a bio-hydrogen production process from palm rachis using the software WARGUI, which is based on WAR algorithm, in order to quantify eight impact categories that can lead to possible optimization thereof.

2. Material and Methods

2.1. Process description

Several experiments on gasification of biomass with air, by means of downdraft gasifier, have been performed and different kind of vegetable biomasses have been used, such as wood sawdust and sunflower seeds, rice husk, empty fruit bunches from palm-oil production, corn cobs, vine pruning Pyro-gasification of hazelnut pruning using a downdraft gasifier [1]. The process of bio-hydrogen production from rachis via gasification is presented in Figure 1. In the pre-treatment stage, palm rachis (40.84 t/h) is milled in order to reduce the particle size increasing the heat transfer area and syngas production efficiency, then is dried from a wet base of 55.6 % at 101 °C. In the gasification stage enters coal and pure liquid oxygen at 80 K, product of an air separation unit (ASU). Air enrichment with oxygen is used as gasificant due its lower cost and the less complex engineering necessary to provide the stream following the gasification reaction requirements; but this practice is most effective in process where a high purity syngas (~ 99.9% H_2) is not necessary, as Integrated Gasification Combined Cycle (IGCC)[13]. After this stage, the biogas enters to a cooling step in a heat exchanger and then to an electric cooling to decrease the temperature from 1173.15 K to 283.15 K. In order to increase hydrogen concentration in the syngas, the methane is converted into CO_2 and H_2 in a water gas shift reactor. Low CO_2 content and saturated in water syngas is heated to reach the high temperature shift (HTS). The efficiency in the reactor is affected mainly by temperature, therefore, the reactor first operates at 283.15 K and HTS to 643.15 K. Then, syngas pass through a cooling until a temperature of 553.15 K. The synthesis gas flow has a high content of water, so, it is carried out a separation step. The syngas stream is mixed with selexol to dissolve the undesired components such as CH_4, CO and CO_2 and, finally, the syngas-selexol mix is subjected to a flash separation process where H_2 is obtained [14].

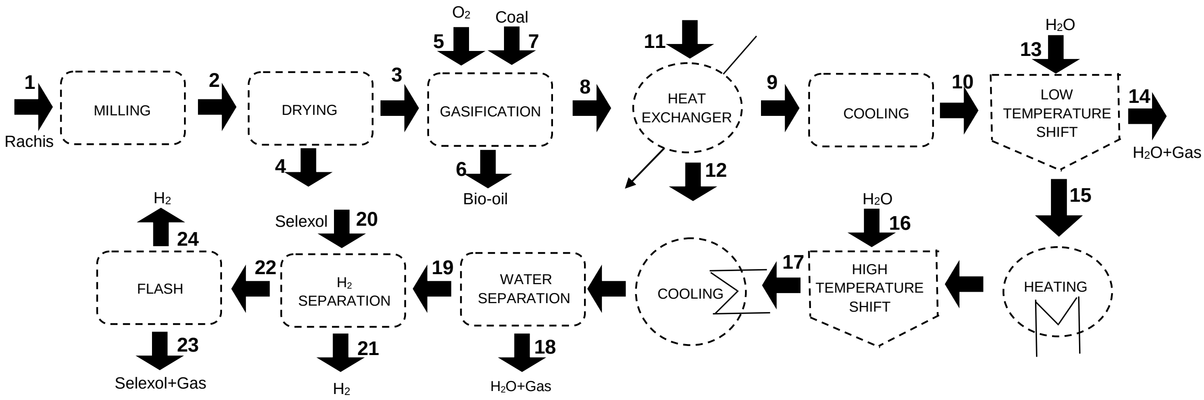

Figure 1. Process diagram of bio-hydrogen production process from palm rachis.

2.2 Environmental assessment using WAR Algorithm

Environmental assessment of a hydrogen production process from palm rachis was carried out using software WARGUI, based on six cases. In case 1, were not considerate product and energy impacts; for case 2, hydrogen was considered as the only product and it was taken into account product impacts without considering energy source. In case 3, hydrogen was considered as the only product and were considered energy impacts without product impacts; for case 4, hydrogen is the only product and were considered product and energy impacts. In case 5, hydrogen and bio-oil from gasification stage were considered as products, taking into account both product impacts without considering energy impacts. Finally, for case 6, hydrogen and bio-oil from gasification stage were considered as products taking into account both product impacts and energy impacts. The WAR algorithm introduces the concept of balance Potential Environmental Impact (PEI), which involves the flow of an environmental impact throughout system boundaries, due to the mass or energy that crosses these limits. This index is considered from two points of view, PEI output and PEI generated. The first measures the PEI impact emitted by the process around, and its main use consists in solving questions about the external environmental efficiency of the process, i.e., the ability of the process to obtain final products to a minimum potential environmental impact discharge. As regards the second, it measures the generation of PEI within the limits of the process and its importance lies in find out the internal environmental efficiency of the process, i.e., how much environmental impact potential is consumed in the process. The smaller is the value of these indexes, the process is more environmentally efficient. In addition, the WAR algorithm considers eight categories where it is evaluated the PEI of chemicals and process.

These categories can be classified into two major groups: local toxicological impacts on humans (HTPI, HTPE) and ecological (ATP y TTP), and global (GWP y ODP) and regional (AP y PCOP) atmospheric impacts [15].

3. Results and Discussion

3.1. Composition of the main process streams

Total hydrogen flowrate was estimated in 1.45 t/h from a palm rachis flow rate of 40.84 t/h. In Table 1, flow rates for mainly gases present in syngas are registered. Oxygen flow rate required to gasify the biomass was 7.89 t/h.

Component	Gasifier	LT Shift	HT Shift	Water separation
H_2	9.4445	6.3751	8.9125	8.9982
CH_4	2.2222	1.3923	1.4382	1.4397
CO_2	12.5001	2.7421	5.1644	5.1172
CO	3.6111	2.3618	0.0959	0.0266

Table 1. Syngas composition in the outlet stream of mainly systems of the process (t/h).

Regarding operating conditions presented in Table 2, temperature was measure in a range of 80.0 and 1173.2 K and pressure between 1 and 60 bar.

Stream	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
T (K)	298.0	298.0	374.2	374.2	80.0	1173.2	-	1173.2	333.3	283.2	298.2	416.8
P (bar)	1.0	1.0	1.0	1.0	1.5	60.0	-	60.0	60.0	60.0	4.0	4.0
ṁ (t/h)	40.8	40.8	18.1	22.7	7.9	20.3	22.1	27.8	27.8	37.8	15.2	15.2
Stream	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
T (K)	283.2	286.5	285.0	643.2	643.2	308.0	308.0	283.2	283.2	284.7	284.5	284.5
P (bar)	60.0	60.0	60.0	60.0	58.0	36.2	36.2	36.3	36.1	36.1	6.9	6.9
ṁ (t/h)	390.6	405.5	12.9	30.7	43.6	38.5	15.6	979.9	1.6	982.2	480.9	1.3

Table 2. Current operation condition of the bio-hydrogen production process

3.2. Total potential environmental impacts of the process: Generated and output

As it is observed in Figure 2, according to the impacts output from energy usage, the values for cases 3, 4 and 6 are greater (range of 1.2 x 10^7 PEI/h) than the one including only the product streams (1.33 x 10^6 PEI/h), which means that energy has a strong influence on the process. In addition, PEI output per hour is higher in the same 3 last cases (range of 1.2 x 10^7 PEI/h), because of energy used in the process. This same trend is presented for the case of PEI output per kilogram of product (range of 5 x 10^6 PEI/Kg), due to hydrogen can have effects on human health. The fact that PEI generated values were negative for cases 1, 2 and 5 (-3.5x10^5, -3.9x10^{-1} and -4.4x10^4 PEI/h, respectively) indicates that the process within it, has a good environmental performance due to quality products. For cases 3, 4 and 6, the PEI values are similar and higher (1.03x10^7, 1.06x10^7 PEI/h and 1.06x10^7 PEI/h, respectively), leading to the conclusion that the amount of product does not represent a significant influence on the value thereof but energy used. Finally, this same trend is observed in PEI generated per kilogram of product but in smaller proportions. From an environmental point of view the process is not aggressive, however, an alternative to improve it, it is reducing energy requirements using the waste generated.

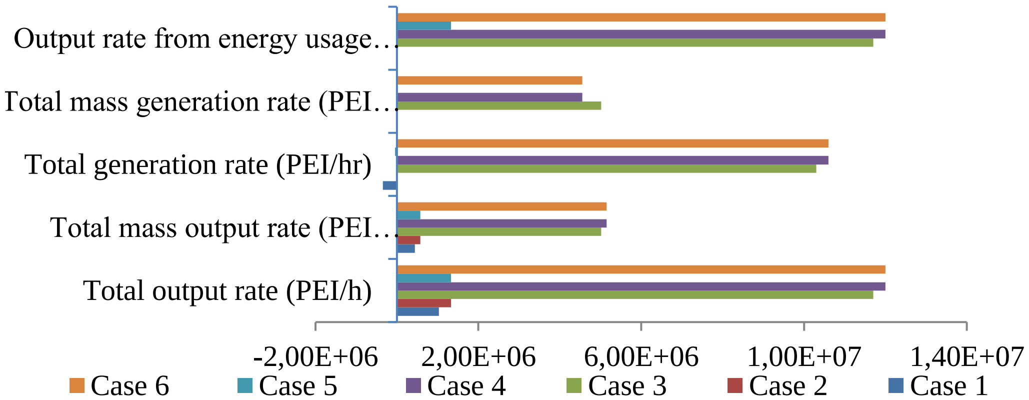

Figure 2. Total PEI generated and output of the system for hydrogen production process

3.3. Local toxicological impacts of the process

Figure 3 shows the local toxicological impacts output of the process, which includes humans (HTPI y HTPE) and ecological (ATP y TTP) impacts. For HTPE impact category, the contribution is minimal (range of 3x10^4 for cases 1, 2 and 5; and 5x10^4 for the other cases) under situations studied and considerably minor compared to TTP, HTPI and ATP categories, indicating that the impacts generated by this process on humans are low. In addition, it is observed that for all categories the impacts values in cases that included energy (cases 3, 4 and 6) were higher compared to those did not use it; for these last cases, the values were the same (2.22x10^5 for HTPI and TTP, 3.51x10^4 for HTPE and 6.66 PEI/h for ATP), which indicates that product streams do not represent a great influence on them. Finally, for ATP category, these impacts are less polluting in cases that include product stream compared to those that include energy (4.27x10^5 PEI/h).

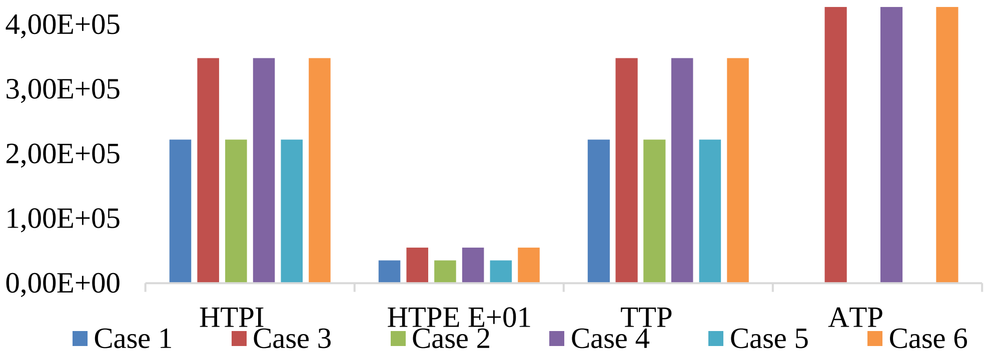

Figure 3. Local toxicological impacts output for bio-hydrogen production process

On the other hand, Figure 4 shows that PEI generated for the 4 impact categories is lower that PEI output, especially for cases 1, 2 and 5, suggesting that the process have in the product streams, less toxic chemicals with tolerance values limits (TVL) lower than those fed to the system. However, this value only increases (HTPI) if it is considered energy requirement due to its possible impact on the environment. For HTPE category, this generates negative impacts on all cases, however these values are greater (-3.12×10^4 PEI/h) when the product stream is included that by including energy (-1.16×10^4 PEI/h).

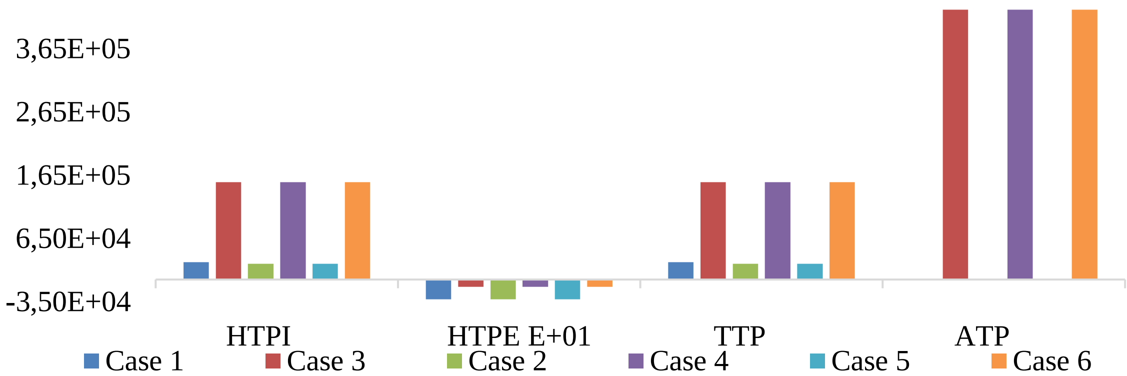

Figure 4. Local toxicological impacts generated for bio-hydrogen production process

3.4. Atmospheric impacts of the process

Figure 5 show that atmospheric impacts are composed for global (GWP y ODP) and regional (AP y PCOP) ones. For this particular process, it is observed that values for ODP and AP impact categories in cases 1, 2 and 5 are zero, which leads to the conclusion that this process is environmentally neutral under these categories, so the only contribution to PEI out for atmospheric categories comes from the use of fuels in the process as energy sources.

The fact that the PEI generated (Figure 6) and output values are the same for all categories, except for PCOP (-9.56×10^5 PEI/h for cases 3, 4 and 6; and -9.57×10^5 PEI/h for the other cases), is because of the process generates chemicals products with reduced ability to degrade themselves in the environment as a result of gasification stage.

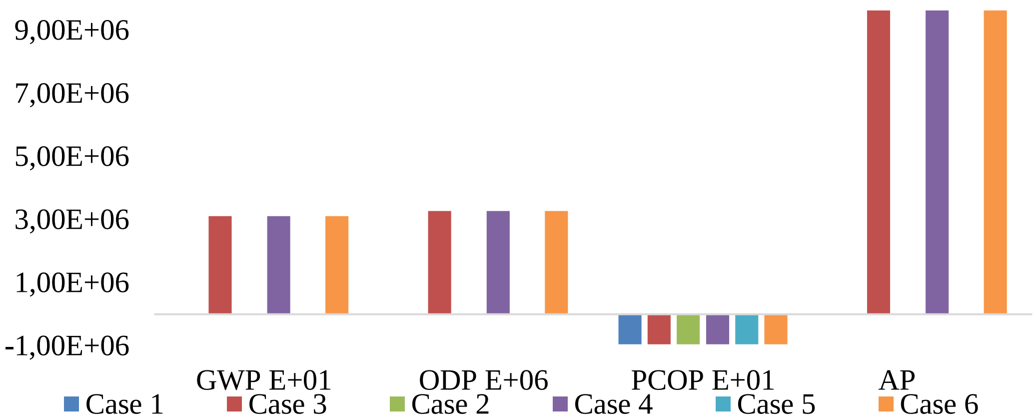

Figure 5. Atmospheric impacts generated for bio-hydrogen production process

3.5. Effect of energy source in hydrogen production process

Under this scenario, three types of fuel were evaluated for PEI output for all six study cases. Figure 6 shows the change in PEI output based on the type of fuel used. It is observed that there are cases under which is more convenient to use oil derivate and others where is more convenient to use coal. In this process, coal is used as fuel, which has the higher impact on cases 3, 4 and 6 (1.20×10^7 PEI/h), due to changes caused by the concentration of ozone wake of VOC emissions. In the other hand, using gas as energy source can lead to less impact for all cases studied. Finally, it is observed that when it is not considered the energy source into environmental assessment (cases 1, 2 and 5), the impact generated for coal, gas and oil is the same (1.33×10^6 PEI/h).

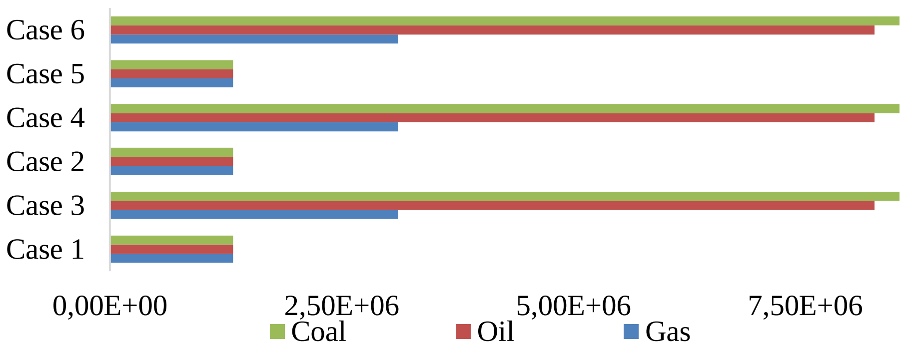

Figure 6. Effect of energy source in bio-hydrogen production process

3.6. Effect of energy source on PEI output rate in hydrogen production process

Figure 7 shows the change in the different impact categories in case 6, based on the type of fuel used. It is observed that AP category represents the higher impact when coal ($9.63x10^6$ PEI/h) is used in the process due to are emitted VOC that can contribute to the generation of acid rain. PCOP produces the same impact despite the energy source used ($8.83x10^5$ PEI/h). In the case of ODP and GWP categories, the effect for using gas and oil as energy source is reduced, except, when it is used coal (3.27 and $3.11x10^6$ PEI/h, respectively). Regarding, categories of toxicological impacts, for TTP, HTPI and HTPE, this value is higher when using oil in the process ($3.69x10^6$, $3.69x10^6$ and $1.56x10^6$ PEI/h, respectively) instead of coal or gas. For all categories, gas is the energy source that generates less environmental impact in the process.

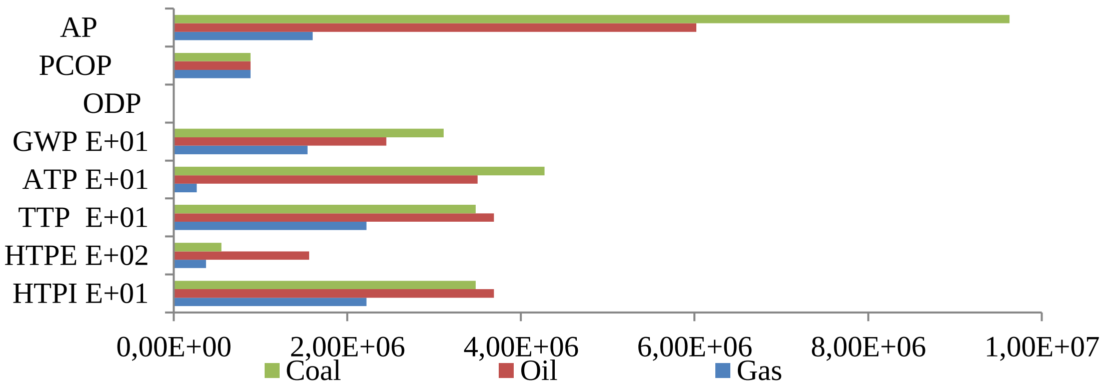

Figure 7. Effect of energy source on PEI output rate in bio-hydrogen production process

Conclusions

In this work, 8 categories of environmental impact were evaluated in the hydrogen production process. In general, it can be said that the process is beneficial in environmental terms, which is reflected in a total PEI generated negative in cases where it was only considered the product stream. Moreover, emissions of greenhouse gases are present due to the use of coal as fuel, so atmospheric impact categories are affected (GWP, ODP and AP). Finally, the different output environmental impacts of the process are influenced in greater or lesser proportion by the type of fuel used in the gasifier. When it is used coal as fuel, the process generates 4 tons of CO_2 per ton of rachis, therefore, PEI output values for atmospheric environmental impacts categories could decrease if are carried out energy improvements by changing the type of fuel or using the heat of gases emitted into the atmosphere. Considering the results obtained, it is recommended for future researches, apply energy integration to hydrogen production process from palm rachis, including the crude palm oil extraction.

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