Development of a Methodology for the Synthesis of Biorefineries Based on Incremental Economic and Exergetic Return on Investment
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ABSTRACT: Colombia is experiencing significant growth in its agricultural areas, its diverse production chains make the country an excellent candidate in the development of biorefineries, and as a result, there is an increasing need to take full advantage of biomass and obtain high value-added by-products from waste. In this sense, biorefineries are presented as a great alternative for the use of biomass; however, the methodologies of biorefinery synthesis lack a parameter that limits the growth of production lines under incremental exergetic and economic returns. This research develops a biorefinery synthesis methodology using an African palm biorefinery as a case study; a novel approach is developed to facilitate a stop criterion for biorefinery expansion through a combined consideration of economic incremental returns (IROI) and exergetic returns of investment (ExROI), avoiding unnecessary plant expansions or new processes that are not profitable or adequate in terms of useful energy. The development of this methodology required simulations in Aspen Plus software and technical-economic and exergetic evaluation with an incremental approach of four scenarios in Excel. The base case is palm oil production from African palm clusters. The second case includes the production of palm kernel oil and palm cake from residues. The third case implements the production of hydrogen based on other residues from the base case. The last case study incorporates the preceding case and the addition of biodiesel and glycerin production from palm oil. Case 3 exhibits a higher economic performance with an IROI of 42.98%; in terms of exergy, case 2 exhibits considerable improvements over the base case, with an ExROI of 158%. A parameter called the exergo-economic weighted incremental return on investment (IExWROI) was obtained, evidencing a 75% improvement in case 2 compared to the base case. The new indicator aims to provide a more comprehensive approach to biorefinery design by optimization of economic and exergetic returns, contributing a new alternative for decision-making in regard to plant design, plant expansion projects, and implementation of subprocesses.

1. INTRODUCTION

Colombia enjoys a strategic location and reliefs that provide the country with important agro-climatic variations, making it a territory suitable for the production of a great diversity of food and agricultural products. According to the United Nations Food and Agriculture Organization (FAO), the country can become the world’s largest food producer as it is one of the seven countries in Latin America with the highest potential for the development of cultivable areas.1 Its growth during the past few years in the agricultural production evidences such panorama, where coffee, banana, sugar, flowers, palm oil, fresh fruits, and more are the protagonists.

However, the current economy presents an evident dependence on oil and its derivatives; satisfying energy needs with the use of nonrenewable resources results in an unsustainable practice, a situation that is worsening with the increase in world energy consumption. Special attention has been given to the study of biofuels to meet the demand.5 These products are biodegradable, renewable, nontoxic, and more ecological.3 In this sense, biofuels have established themselves as an integral alternative to enhance energy generation and pollution mitigation; a positive future is expected for biofuels as they can reduce dependence on fossil fuels, along with reduction of environmental impacts and emissions of polluting chemicals.4 On the other hand, the biorefinery concept incorporates a wide range of technologies capable of separating biomass into its basic components and converting them by integrating processes and equipment for conversion into value-added products, biofuels, and chemicals.5 Then, under this concept, it is possible to obtain environmentally friendly fuels, take advantage of residues to manufacture by-products with a high
added value, in turn generate economic and energy stability, and reduce negative effects on the environment and health; in other words, biorefinery implementation for biomass valorization provides several benefits due to the diversification of raw materials and products while dealing with sustainability issues.\(^7\)

In this study, a methodology for biorefinery synthesis was developed, considering technical, economic, and exergetic factors, to determine the convenience of additional investments. The methodology was applied to a biorefinery based on African palm as a case study, biomass found in 124 municipalities in Colombia,\(^6\) and was gaining great importance in different industries. Companies are choosing to use the waste obtained from their main production process (palm oil); to manufacture by-products with a high added value, palm kernel oil and palm cake have been presented in recent times as suitable alternatives.

The palm rachis is also waste with a great potential to be exploited. Through a gasification process, this biomass will be converted into hydrogen, a fuel with a high added value as a very attractive and feasible project.\(^7\) Gasification is viewed as a potentially beneficial technology for the use of biomass, which converts biomass into combustible gases, biochar, and useful chemicals.\(^10\) It is important to note that the interest in the study of biomass to produce hydrogen is not recent; its advantage as a clean fuel for power generation was a reason for different authors to propose strategies for obtaining it.\(^11,12\) Hydrogen is considered a novel fuel for the 21st century due to its advantages compared to fossil fuels; studies related to this fuel focus on aspects of efficiency and economy.\(^15\) Our study was conducted with an incremental approach to the economic and exergetic returns of each incorporated process to avoid stages that are not energy-efficient and economically profitable.

2. PROPOSED METHODOLOGY

This methodology has the purpose of obtaining a new parameter as a dimensioning criterion in the synthesis of biorefineries through incremental economic and exergetic returns of the investment. It is necessary to make economic and exergetic evaluations of the case studies. These evaluations are described as follows.

2.1. Economic Evaluation. Economic evaluation is an important criterion for analyzing the quality of a biorefinery’s systems.\(^14\) This assessment permits one to identify promising processes, evaluate investment projects, and assure funding.\(^15\) The design of a process or the improvement of an existing one requires different criteria, including technical and economic considerations for decision-making and project development. It is essential to examine the economic viability, profitability, and performance, establish solid objectives, compare different alternatives, and determine positive factors in terms of safety, quality, and profitability. The mathematical method implemented was proposed by El-Halwagi;\(^16\) the indicators and parameters to be calculated for the development of economic evaluations are specified below.

The economic evaluation was conducted using U.S. dollars and a plant life of 15 years as a reference. According to eq 1, the total capital investment (TCI) is calculated, considering the fixed capital investment (FCI), the working capital investment (WCI), and the start-up cost (SUC). Operating costs (OC) (eq 2) take into account direct production costs (CPD), fixed charges (FCH), overhead POH, and general expenses (GE). The total annualized process costs (TAC) (eq 3) are subject to annualized operating costs (AOC) and fixed costs (AFC) (eq 4). FCI\(_0\) is the initial value of the depreciable fixed capital investment, and ECI is the salvage value of the FCI, which corresponds to the value of the FCI at the end of the recovery period (N years).\(^17\)

Equations 5–11 are indicators of profitability, where DGP is the devaluation of assets, PAT is profitability after taxes, CCF is the accumulated cash flow, PB is the payback period, %ROI is the percentage of return on investment, NPV is the net present value, and IROI is the incremental economic return on investment. This last parameter is established to identify whether adding stages and obtaining new products improve the performance of a linear production chain or base case; the IROI is represented in eq 11 where it relates the annual incremental net benefit of the complementary project (AATP) with the incremental TCI of the complementary project.\(^18\)

\[
TCI = FCI + WCI + SUC
\]
\[
OC = DPC + FCH + POH + GE
\]
\[
TAC = AFC + AOC
\]
\[
AFC = \frac{FCI_0 - FCI}{N}
\]
\[
DGP = \sum_i m_i C_i^D - TAC
\]
\[
PAT = DGP \left(1 - \frac{1}{itr}\right)
\]
\[
CCF = \sum_i m_i C_i^D - AOC
\]
\[
TCI
\]
\[
PBP = \frac{FCI}{PAT}
\]
\[
%ROI = \frac{PAT}{TCI} \times 100\%
\]
\[
NPV = \sum_n AOC \left(1 + i\right)^{-n}
\]
\[
IROI \text{ on project B} = \frac{AATP \text{ of } B - AATP \text{ of } A}{TCI \text{ of } B - TCI \text{ of } A}
\]
thermodynamics presented in eq 13, the second law of thermodynamics presented in eq 14, and the global exergetic equilibrium presented in eq 15. The exergy for heat is determined by Carnot’s efficiency, which is the portion of energy transferred from a heat source $Q_i$ and it is transformed into work of a temperature $T$ given at a reference temperature $T_0$ (eq 16). The exergy for work is equal to the work itself as long as there are no changes in volume in the system (eq 17). The exergy of mass is defined in eq 18.

Physical exergy is associated with pressure, temperature, enthalpy, and entropy, and it is defined as the work achievable by subjecting a substance to reversible physical processes from an initial temperature and pressure to the state determined by the pressure and temperature of the environment (eq 19). This exergy can vary according to the state or behavior of the stream. For a stream that behaves as an ideal gas with constant $C_p$, eq 20 must be considered, and for a stream in a solid or liquid state with constant $C_p$, eq 21 must be considered. Chemical exergy, on the other hand, connects the chemical
exergy of each compound, its composition, and the free energy of Gibb's; this exergy is defined in eq 22. For a mixture, it is required to use eq 23. Nevertheless, it is necessary to identify the total exergy inputs in a system or a step, eq 24 is applied for this purpose, and it is defined based on the exergy of the incoming streams or flows and the energetic contributions of the industrial utilities. The total exergy output considers product flows and residue flows (eq 25). The exergy destroyed is defined as the potential of the system to produce work that is unused; exergetic losses are irreversibilities provided in eq 26 and are calculated, subtracting the exergeries of the product flows from the total input exergies of a system. Equations 27 and 28 allow obtaining the exergetic efficiencies and the percentage of exergy destroyed for a stage regarding the remaining part of the process, respectively.

The exergetic return on investment (ExROI) is defined as the relationship between the exergy generated by the system and the exergy required to develop the system or process. Based on this definition, the equation for the exergetic return of investment is established, eq 29. The ExROI permits one to identify the exergetic return of a punctual process; as a comparative criterion of the study cases, the incremental exergetic return of investment (IExROI) is implemented, and this is a parameter used to determine whether the addition of stages and obtaining new products improve the exergetic return of a linear production chain or base case. It is represented in eq 30 and correlates the exergy generated by the complementary system with the exergy required to build or develop the complementary system; this indicator is analogous to the IROI (incremental return on investment).

\[
\sum_i (\hat{m}_i)_{\text{in}} = \sum_i (\hat{m}_i)_{\text{out}}
\]

\[
\sum_i (\hat{m}_i \times h_i)_{\text{in}} = \sum_i (\hat{m}_i \times h_i)_{\text{out}} + Q - W = 0
\]

\[
\sum_i (\hat{m}_i \times S_i)_{\text{in}} = \sum_i (\hat{m}_i \times S_i)_{\text{out}} + \sum_i \frac{\dot{Q}_i}{T_i} = S_{\text{gen}}
\]

\[
E_{x,\text{mass,in}} - E_{x,\text{mass,out}} + E_{x,\text{heat}} - E_{x,\text{work}} = E_{x,\text{destroyed}}
\]

\[
E_{x,\text{heat}} = \sum \left(1 - \frac{T_0}{T}\right)Q_i
\]

\[
E_{x,\text{work}} = W
\]

\[
E_{x,\text{mass}} = E_{x,\text{phy}} + E_{x,\text{ch}} + E_{x,\text{pur}} + E_{x,\text{kin}}
\]

\[
E_{x,\text{phy}} = (H - H_0) - T_0(S - S_0)
\]

\[
E_{x,\text{ch}} = C_p(T - T_0) - T_0 \left(C_p \ln \frac{T}{T_0} - R \ln \frac{P}{P_0}\right)
\]

\[
E_{x,\text{ch}} = T_0 \ln \frac{T}{T_0} - \nu_m(P - P_0)
\]

\[
E_{x,\text{ch,mixture}} = \sum_i y_i \times E_{x,\text{ch}_{i-1}} + RT_0 \sum_i y_i \times \ln(\gamma_i)
\]

\[
E_{\text{total,in}} = \sum E_{x,\text{mass,in}} - \sum E_{x,\text{utilities,in}}
\]

\[
E_{\text{total,out}} = \sum E_{x,\text{products,out}} - \sum E_{x,\text{wastes,out}}
\]

\[
E_{\text{destroyed}} = \sum E_{x,\text{products,in}} - \sum E_{x,\text{products,out}}
\]

\[
\eta_{\text{energy}} = 1 - \left( \frac{E_{\text{destroyed}}}{E_{\text{total,in}}} \right)
\]

\[
% E_{\text{destroyed}} = \left( \frac{E_{\text{destroyed},j}}{E_{\text{total,destroyed}}} \right) \times 100\%
\]

\[
E_{\text{ROI}} (%) = \frac{\sum E_{x,\text{product}}}{\sum E_{x,\text{required}}} \times 100\%
\]

\[
I\text{ExROI} (%) = \frac{\sum E_{x,\text{product}_{2}} - \sum E_{x,\text{product}_{1}}}{\sum E_{x,\text{required}_{2}} - \sum E_{x,\text{required}_{1}}} \times 100\%
\]

2.3. Methodological Structure. Figure 1 illustrates the proposed methodology structure for the biorefinery synthesis through economic and exergetic incremental returns of the investment. As an initial step, a detailed bibliographic review is done to establish the main production process (linear chain) and various extensions to consider, and the data collection provides options for possible additions of a base case and the necessary information such as operating conditions, required equipment, specifications, input flow, raw material, and its properties, among other data of significant relevance for subsequent evaluations.

After defining the case studies and creating the block diagrams, the proposed expansions are simulated. Computer-assisted simulation is used to establish the thermal requirements of the process flows and the equipment involved to produce the mass and energy balances, as well as to obtain data on the physical exergy.

Following the development of base case mass and energy balances, the economic evaluation and exergetic analysis of this first case are performed. At this point in the methodology, the economic indicators of the process, price of raw materials, ROI, and recovery period are already available. From the exergetic perspective, it is possible to establish the critical stages and identify the irreversibilities, as well as data on product exergy, input exergy, residue exergy, and industrial utility exergy, in addition to the overall efficiency of the process.

Now, the proposed case study mass and energy balances are made, following the economic evaluations and exergetic analysis on an incremental basis for each case. A comparative study on the behavior of the parameters concerning the suggested additions is undertaken. Then, it is feasible to specify the inefficient stages and to gain a broader view of the viability of the additions. To estimate the hybrid indicator of biorefinery sizing, it is necessary to calculate the incremental economic return on investment (IROI) and the incremental exergetic return on investment (IExROI). The results of the hybrid indicator determine the viability or percentage of improvement of a process concerning a previous one.

2.4. Description of Case Studies. The case under study consists of a biorefinery based on African palm, the growth, and importance of this palm in the country and is supported by
numerous reports to assess the efficiency, viability, and particularly, the use of waste from its main process (production of palm oil) to achieve high value-added by-products. This project's case studies are specified as follows, where the block diagram presents the main stages and the input and output flow of the products, by-products, and residues (Figure 2).

- Base case: Plant with linear production chain for African palm oil.
- Case 2: Biorefinery based on African palm for the production of palm oil, palm kernel oil, and palm cake.
- Case 3: Biorefinery producing palm oil, palm kernel oil, palm cake, and hydrogen from African palm rachis.
- Case 4: Biorefinery producing palm kernel oil, palm cake, hydrogen, biodiesel, and glycerin from African palm oil.

The base case, in blue, includes a plant with a linear production chain for African palm oil. Case study 2, in red, consists of an African palm-based biorefinery for the production of palm oil, palm kernel oil, and palm cake. Case 3, in green, incorporates the production of hydrogen using the African palm rachis, which was previously considered as a waste. Finally, case 4 compiles all the stages of the previous cases and additionally uses palm oil for the production of biodiesel and glycerin.

Table 1 presents information to consider when calculating the technical-economic indicators of the case studies. In terms of location considerations, the discount rate, tax rate, wage costs, product costs, raw material costs, and other market factors have been applied under Colombian conditions.

3. RESULTS AND DISCUSSION

3.1. Economic Evaluation of Case Studies. Table 2 specifies the individual costs that were considered for the TCI calculation in the base case. The most significant cost in the total capital investment consists of the purchase of the
equipment; therefore, the FOB (free on board) price of the units involved in the production of palm oil was estimated according to the production capacity and process specifications. The cost of the equipment acquired is a sum of the FOB price estimated plus the transport price. The latter was assumed as 20% of the FOB price; this fraction is variable and depends on local taxes and geographical difficulties, among others. Installation costs represent 12% of the value of the equipment purchased.

Economic indicators resulting from the analysis of the processes under study are presented in Table 3. These results permit us to compare each case and obtain a clearer vision in making final investment decisions. The progressive increase in profits is remarkable as more units are aggregated, especially when adding the stages for hydrogen production in case 3; hydrogen is the highest value product.

In addition, it is crucial to analyze other indicators such as return on investment (ROI) and years of return on investment; these do not exhibit the same progressive behavior as the other indicators. Results indicate that they decrease in the last case, leading to a lower return on investment at the end of the 15 years in case 4. Special care must be given to the return on investment (ROI) since this parameter analyzes each case in a specific manner, not in a progressive manner, i.e., the ROI does not consider the expansion from one plant to another; therefore, the values obtained do not provide a perspective of improvement compared to a previous project. In this sense, the incremental return of investment (IROI) is implemented, a parameter that accounts for both the TCI of the projects under

| Table 1. Technical-Economic Considerations for Case Studies |
|-----------------------------------------------------------|
| **base case** | **case 2** | **case 3** | **case 4** |
| **processing capacity (t/year)** | 240,000 | | | |
| **main product flow (t/year)** | palm oil | palm oil | palm oil | biodiesel |
| | 40,560 | 40,560 | 40,560 | 40,000 |
| **raw material cost ($/t)** | 77.18 | | | |
| **final product cost ($/kg)** | palm oil | palm kernel oil | palm kernel cake | hydrogen | glycerol | biodiesel |
| | 0.83 | 1.74 | 0.15 | 6.00 | 0.65 | 0.94 |
| **plant life (years)** | 15 | | | |
| **salvage value** | | | 10% of FCI | |
| **construction time of the plant (years)** | 3 years | | | |
| **tax rate** | 39% | | | |
| **discount rate** | 8% | | | |
| **capacity operated** | 50% the first year, 75% the second year, 100% the third year | | | |
| **subsidies ($/year)** | 0 | | | |
| **type of process** | proven processes | | new and unproven processes |
| **process control** | digital | | | |
| **project type** | plant on undeveloped land | | | |
| **soil type** | soft clay | | | |
| **percentage of contingency (%)** | 20 | | | |

| Table 2. Total Capital Investment for Biorefinery |
|------------------------------------------------|
| **headings** | **base case (USD)** | **case 2 (USD)** | **case 3 (USD)** | **case 4 (USD)** |
| **delivered purchased equipment cost** | 2,245,852 | 3,496,273 | 8,607,394 | 9,974,648 |
| **purchased equipment (installation)** | 673,755 | 1,048,882 | 2,582,218 | 2,992,394 |
| **instrumentation (installed)** | 269,502 | 419,553 | 1,032,887 | 1,196,958 |
| **piping (installed)** | 673,755 | 1,048,882 | 2,582,218 | 2,992,394 |
| **electrical (installed)** | 426,712 | 664,292 | 1,635,405 | 1,895,183 |
| **buildings (including services)** | 1,122,926 | 1,748,137 | 4,303,697 | 4,987,324 |
| **services facilities (installed)** | 898,341 | 1,398,509 | 3,442,958 | 3,989,859 |
| **total DFCI** | 6,310,843 | 9,824,528 | 24,186,777 | 28,028,760 |
| **land** | 224,585 | 349,627 | 860,739 | 997,465 |
| **yard improvements** | 898,341 | 1,398,509 | 3,442,958 | 3,989,859 |
| **engineering and supervision** | 1,167,843 | 1,818,062 | 4,475,845 | 5,186,817 |
| **equipment (R + D)** | 224,585 | 349,627 | 860,739 | 997,465 |
| **construction expenses** | 763,590 | 1,188,733 | 2,926,514 | 3,391,380 |
| **legal expenses** | 22,459 | 34,963 | 86,074 | 99,746 |
| **contractors’ fee** | 441,759 | 687,717 | 1,693,074 | 1,962,013 |
| **contingency** | 1,347,511 | 2,097,764 | 5,164,436 | 5,984,789 |
| **total FCI** | 5,090,672 | 7,925,002 | 19,510,380 | 22,609,534 |
| **fixed capital investment (FCI)** | 11,401,515 | 17,749,530 | 43,697,157 | 50,638,293 |
| **working capital (WC)** | 9,121,212 | 14,199,624 | 34,957,726 | 40,510,635 |
| **start-up (SU)** | 1,140,151 | 1,774,953 | 4,369,716 | 5,063,829 |
| **total capital investment (TCI)** | 21,662,878 | 33,724,107 | 83,024,598 | 96,212,757 |
study and the addition of new units. Equation 11 was fundamental to obtain the IROI of the expansions studied.

It is observed that as the residues are valorized, the incidence in the IROI is favorable. In case 2, when using the press cake to transform it into palm kernel oil and palm cake, the improvement is 37.47%. Similar behavior is experienced in case 3 using another waste (rachis) from the base case in the production of hydrogen; at this point, three by-products have been achieved from two wastes and it is reflected in the progressive increase in IROI. Case 4 implementation compared to case 3 demonstrates a less favorable behavior in IROI, with a percentage of improvement of 18.19%, since this

### Table 3. Results of Economic Indicators for Biorefinery

| indicators                        | base case   | case 2       | case 3       | case 4       |
|-----------------------------------|-------------|--------------|--------------|--------------|
| gross profit (GP)                 | 5,309,033   | 13,183,779   | 47,473,822   | 51,140,611   |
| gross profit (depreciation) (DGP) | 4,623,445   | 12,362,957   | 44,846,254   | 48,095,663   |
| profit after taxes (PAT)          | 3,505,890   | 8,149,404    | 29,983,783   | 32,383,302   |
| products (revenues)               | 33,664,800  | 43,524,941   | 100,644,941  | 108,318,941  |
| economic potential ($/year) 1     | 15,131,106  | 24,991,247   | 82,111,247   | 89,785,247   |
| economic potential ($/year) 2     | 14,157,016  | 23,795,510   | 70,908,653   | 78,020,968   |
| economic potential ($/year) 3     | 5,309,033   | 12,474,630   | 47,473,822   | 51,140,611   |
| cumulative cash flow (CCF) (1/year) | 0.25       | 0.37         | 0.57         | 0.53         |
| depreciation payback period (DPBP) (years) | 6.69 | 5.36         | 3.75         | 2.91         |
| %ROI                              | 16.18%      | 23.80%       | 36.11%       | 33.66%       |
| NPV (MMS)                         | 8.03        | 27.89        | 148.83       | 153.95       |
| annual cost/revenue               | 0.58        | 3.26         | 17.39        | 17.99        |
| IROI                              | 37.47%      | 42.98%       | 18.19%       |

Figure 3. Cash flow diagram for the four case studies

Figure 4. Overall results of the case studies.

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expansion does not suggest the use of another waste. Although the production of biodiesel and glycerin has palm oil as a raw material (product in the previous cases) and the commercial value of biodiesel is higher than palm oil, the IROI under the considerations made in this work does not justify this investment.

In support of the current literature, it is important to note that "any project that requires additional capital expenditure beyond a base case must be justified by a supplementary profit that meets the company’s ROI". 16 Now, the IROI is the most important parameter to analyze the relevance of adding stages or processes to a base case from an economic perspective; also, from this indicator, it is possible to determine a stopping criterion for progressive projects.

Figure 3 depicts the behavior of cash flow during the construction and operation time of the biorefineries studied. Cases 3 and 4 reach a positive net present value (NPV) from the fifth year of operation of the plant, i.e., the investor recovers the investment at the end of year 4; in this period, it has already paid all expenses and discounted the annual rate of 8%.

3.2. Exergetic Evaluation of the Case Studies. Figure 4 illustrates, in addition to the total irreversibilities of the case studies, the exergy of utilities and exergy of waste.

The total exergy destroyed from the base case is 139,813 MJ/h, while case 2 presents a slight reduction of 6631 MJ/h. Now, it is evident that cases 3 and 4 exhibit high data of irreversibilities compared to the first two plants under study; 1,552,763 and 2, 838,404 MJ/h are the values, respectively. These values of unused useful energy are closely related to the exergetic losses due to residues in the different expansions, which increase in the final cases.

A highly favorable alternative, however, would be to recover selexol for commercial or reuse purposes. The exergetic requirements for industrial utilities are also increasing especially for the process of hydrogen, biodiesel, and glycerin production. The gasification stage contributes significantly to this increase due to their high requirements in terms of heat and work exergy. Therefore, it is not appropriate at this time to establish a criterion to determine the application or viability of the cases under study. Each of the proposals has been evaluated individually and it has been possible to determine the critical stages to suggest potential improvements.

Figure 5 represents the contribution in percentages of the major stages to the total irreversibilities for the proposed case studies. In case 1, the stages that report the greatest exergy destruction are sterilization, threshing, and pressing. These three stages together represent 96.26% of exergy destruction,
and by implementing proposal 2 for waste use in the pressing unit, this stage goes from an exergy efficiency of 90.42% to 99.53%, demonstrating its low contribution to the total exergy destroyed in case 2.

It is also remarkable that peel separation, centrifugation, threshing, and esterification present the highest percentages of irreversibilities in the second case study. These stages contain outputs not used (waste), which justifies their contribution to total irreversibilities. The last three stages mentioned present a greater contribution in terms of percentage. It is pertinent to clarify that the data on irreversibilities in these stages remain the same, but the percentages increase since 100% of total exergy destroyed in case 2 has decreased compared to case 1, and the contribution of pressing is less due to the recovery of its waste and the added stages are very efficient (all above 95% except for shell separation, which is 75.76%).

Hydrogen production from the rachis is the focus of the third case study. Using this residue, the fruiting stage goes from 82,587.97 MJ/h of exergy destroyed to 68,381.04 MJ/h; its contribution to the irreversibilities of case 3 is relatively low, although the exergy of the input used is slightly higher. This low contribution is mostly due to the implementation of two very inefficient exergetic stages that generally affect case 3: indirect gasification and hydrogen purification, with exergetic efficiencies of 42.25 and 18.59%, respectively; the first is inefficient due to its complexity in operating conditions and requirements of additional industrial utilities and the second is inefficient due to the output stream that does not contain a product and represents a higher flow compared to the hydrogen output stream. The inefficient stages of case 3 contribute considerably to the total irreversibilities of proposal 4, where a heating stage and transesterification provide for total exergetic destruction.

Figure 6 illustrates the overall exergetic efficiency of each case study. The overall exergetic efficiencies present a behavior that is not expected, and the implementation of new stages for residue utilization should decrease the exergetic losses by residues and therefore increase the overall exergetic efficiency of the process as it occurs when case 2 is implemented through the production of palm kernel oil and palm cake from palm kernel cake (residue of the base case); however, a completely different panorama is emerging when implementing cases 3 and 4.

Case 3 suggests the use of the rachis by adding the necessary units for hydrogen production; these stages include gasifiers, HTS and LTS reactors, an adsorption column for hydrogen purificaiton, and a desorption column for selexol recovery, among other equipment. The overall exergetic efficiency tends to decrease, a result that can be attributed to the number of waste streams where the exergetic potential of biomass and the necessary industrial utilities are not exploited. The criterion of incremental exergetic return of the investment (IExROI) is now developed to analyze the viability or pertinence of adding stages to a base case in terms of energy.

Table 4 contains information of interest for the IExROI calculations of each case study. The product exergy is constituted by the sum of mass exergies of the product streams, while the required exergy is composed of the raw material stream exergies, the overall process inputs, and the industrial service exergy required for each stage in the suggested extensions.

Implementing case 2 to the linear production chain provides significant improvements. The additional exergy required to apply this case is 12,571.82 MJ/h, while in the products, it goes from using 202,216 MJ/h to 222,053 MJ/h. The total products of case 2 increase by 19,836.96 MJ/h in comparison with palm oil (the only product in the base case), and then the percentage of improvement of case 2 concerning the base case is 158%, a considerably high value, although it is justified since it increases to a greater extent the exergetic use of products with no need to add a larger amount of exergy required; in other words, the numerator (exergetic difference of products) is greater than the difference in the denominator, which allows an improvement that exceeds 100%.25

Case 3 application is 8% higher than case 2. The additional exergetic requirements of proposal 3 exceed the use of exergy reflected in the products, i.e., to increase 123,106.52 MJ/h in the products, it is necessary to add 1,539,032.64 MJ/h (exergy required). Taking into account the fact that the hydrogen production process involves large amounts of exergy in terms of industrial profits, global input flows, and considerable waste outputs, these factors make the process critical as a proposal for improvement of case 2. However, the IExROI should not be, by itself, a criterion to determine the application of the case; it is very important to consider other factors such as economic factor, for example, to establish its feasibility from different aspects of interest.

A particular case is proposal 4 to enhance case 3: the results are not favorable from the exergetic point of view. In this case, biodiesel and glycerin obtained from palm oil (the product in the previous cases) are not being used. The total exergy of these two new products is 119,785.92 MJ/h and does not exceed the exergy of palm oil (202,216.20 MJ/h), which implies that there is no increase in exergy of the products when implementing this new case despite the addition of 1,099,498.98 MJ/h for the production and purification processes of biodiesel and glycerin. The application of case 4 is not viable as a prospect for the utilization of useful energy.

3.3. Implementation of Exergonomic Weighted Incremental Return on Investment as a Stopgap Criterion for Biorefinery Synthesis. The hybrid parameter as a dimensioning criterion for biorefineries with economic and exergetic incremental investment indicators (final objective of this project) is based on the approach presented by El-Halwagi.16 The mathematical approach is described below, where ExWROI is the exergo-economic weighted incremental return of the investment

\[
\text{IExWROI} = \frac{(\text{PAT}_2 - \text{PAT}_1) \times (1 + w\beta)}{\text{TCI}_2 - \text{TCI}_1}
\]

Subindex 2 corresponds to the proposed extension and subindex 1 to the previous case.

\[
\text{PAT}_2 - \text{PAT}_1
\]

is the difference between the annualized after-tax profits of the evaluated cases.

\[
\text{TCI}_2 - \text{TCI}_1
\]

is the total invested capital of the proposed expansion subtracted from the total invested capital of the preceding case.

\[
w\beta
\]

is a weighted factor that indicates the relative importance of the parameter incorporated; for this project, it will be

| Case        | Product Exergy (MJ/h) | Exergy Required (MJ/h) | IExROI |
|-------------|-----------------------|------------------------|--------|
| Base Case   | 202,216               | 342,434                | 345,160|
| Case 2      | 222,053               | 355,006                | 1,894,039|
| Case 3      | 262,729               | 2,993,538              |        |

Table 4. IExROI Data for the Case Studies
assumed as 1, maintaining equality of importance between the economic and exergetic criteria. This value can be defined by the company.\textsuperscript{26}

$I_{E x R O I}$ is the exergetic incremental return of proposal $P$ over the previous case.

$I_{E x R O I}$ is the objective incremental exergetic return of the project; it can be established as the highest $I_{E x R O I}$ of the suggested proposals or it can be established by the company as a target.

\[
\frac{I_{E x R O I}}{I_{R O I}}\quad \text{represents the fractional contribution of the incremental exergetic return in the design, which will be represented with } \beta.
\]

To obtain a formulation of the $ExWROI$ as a function of $I_{E x R O I}$ and $I_{R O I}$, eq 32 is developed.

\[
I_{E x W R O I} = I_{R O I} + \frac{(P_{T_2} - P_{T_1}) \times w \beta}{TC_{I_2} - TC_{I_1}}
\]

Finally, the equation will be set as follows

\[
I_{E x W R O I} = I_{R O I} + w_i \times I_{E x R O I} \times \beta
\]

It is important to highlight the following:

- The $I_{E x W R O I}$ is a parameter that integrates the conventional $I_{R O I}$ calculations, generating a value of easy interpretation in the decision-making.
- In case the fractional contribution of the incremental exergetic return becomes zero, the $I_{E x W R O I}$ will be equal to the economic $I_{R O I}$.
- The $I_{E x R O I}$ does not necessarily have to be a positive value since project $P$ is an improvement project and is not always driven by favorable values. The exergetic indicator can generate a positive, negative, or zero impact on the $I_{R O I}$; in this sense, the $I_{E x R O I}$ can be greater, less, or equal to the $I_{R O I}$.
- If the $I_{E x W R O I}$ is lower than the $I_{R O I}$, then the company can exclude the project based on the fact that the exergetic indicator affects the $I_{R O I}$. Conversely, if the $I_{E x W R O I}$ is higher than the $I_{R O I}$, indicating a positive impact, then the project can be approved.

Since the incremental exergetic return of case 2 is the highest (158%), it was established as the objective $I_{E x R O I}$ indicator for the project. According to the results presented in Table 5, it is possible to identify first the behavior of the exer-go-economic weighted incremental return of the investment for case 2, an extension that represents an improvement of 75% compared to case 1. In this initial value, the positive effect of the incremental exergetic criterion on the incremental economic return is notorious; the extension proposed in case 2 should be approved as it exceeds the $I_{R O I}$ of the project.

The $I_{E x W R O I}$ for case 3 against proposal 2 contributes to a 45% improvement. In this case, the positive effect of the exergetic criterion was not pronounced and is reasonable since, from a merely exergetic perspective, case 3 contributes only 8% over case 2; this project can be approved as it is superior to the $I_{R O I}$ of extension 3. Case 4 presents a particular condition: the $I_{E x R O I}$ is negative. From an exergetic point of view, it is not convenient to approve the extension. Now, the $I_{E x W R O I}$ gives an idea of the contribution of this exergetic criterion regarding the $I_{R O I}$ of the last case. The new parameter is lower than the $I_{R O I}$, which confirms its negative effect and the punctual reason to avoid extension 4. The $I_{E x W R O I}$ is an appropriate indicator to evaluate, in a comparative manner, the performance of a proposed extension, becoming a useful tool for perspectives of improvement and process development.\textsuperscript{26} It also allows the assessment and articulation of energy and economic efficiency indicators, two aspects that are currently indispensable to determine the viability of a project. $I_{E x W R O I}$ provides details of synthesis and selection of design alternatives, cost–benefit analysis, and exergetic use of extensions proposed under the concept of biorefineries.

\section*{4. Conclusions}

This work is focused on the development of a methodology that provides a new parameter for the stopping criteria against the proposal of extensions in a biorefinery; this parameter is based on the return of incremental economic and exergetic returns on the investment and also allows one to determine the viability of the studied proposal. For this project, an African palm biorefinery is taken as a base. Four study proposals were established: a base case or a palm oil-producing plant and three proposals for extensions defined under aspects of waste use and increased value added to products. The production of palm kernel oil, palm cake, and hydrogen allows the exploration of residues with great economic and energy potential; the units necessary for the production of biodiesel and glycerin provide an added value to palm oil as evidenced in the proposed expansion 4.

Economic analyses show improvements in the value of their products as the waste is valued, with an $I_{R O I}$ of 42.98%. Case 3 is shown as the best expansion in economic terms, while with 18.19%, case 4 is the expansion with the least contribution to economic performance; under the conditions of the project, the expansion of the plant from an already established product is not justified as in case 4. In exergy aspects, case 2 with an $I_{E x R O I}$ of 158% is presented as the best alternative with more efficient stages and sustainability, while case 4 with an incremental return of $-7\%$ shows its low contribution to exergy use compared to the case studies. Exergy evaluations are strongly affected by the destruction of exergy by residues and inefficiencies in the stages. Case 4 is unfavorable for both parameters because the expansion does not propose an improvement on waste; it is also evident that waste losses have a considerable influence on the overall efficiency of the processes.

The implementation of the $I_{E x W R O I}$ yields improvements for cases 2 and 3 concerning the $I_{R O I}$ of 38 and 2%, respectively, and case 2 represents the best topology with a maximum percentage of 75%, the impact of the $I_{E x R O I}$ in case 4. Due to the low exergetic efficiency, it leads to a negative contribution, where the $I_{E x W R O I}$ is lower than the $I_{R O I}$, with this being the stopping criterion in the synthesis of the biorefinery studied. The applied methodology allows obtaining a stopping criterion by integrating exercise and economic incremental parameters. The $I_{E x W R O I}$ provides logical results, is easy to interpret, and is comparable with the $I_{R O I}$ to
determine its feasibility. Then, the parameter allows us to determine the best topology of different proposals of extensions to a case of linear production.\textsuperscript{27}

To improve the rigor and precision of this methodology in the synthesis of biorefineries, future research is recommended where this method is evaluated with other case studies, for example, biorefineries based on sugar cane or corn and/or application of new adjustments and considerations. In addition, more indicators can be included in this parameter such as environmental or safety indicators. We study in detail the production of hydrogen and propose improvements in the tentative resulting process because it is a good alternative economically. Finally, the order in which the extensions or proposals are raised can be studied, determining whether it affects the hydride indicator IExWROI.

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\section*{Notes}
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