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# Optimal biorefinery design and supply chain for the production of sugarcane bagasse pellets, electricity and bioethanol in Colombia

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**ABSTRACT**

Biofuels are considered an alternative to sustainable energy production due to their potential to reduce greenhouse gas emissions. This paper presents a mixed integer linear programming (MILP) model to evaluate the optimal configuration of a supply chain for the production of bioethanol, electricity and bagasse pellets from sugarcane potential in Colombia. The results show that gasoline demand in Colombia is met through bioethanol production, and the demand for coal used in thermoelectric plants can be met through the production of bagasse pellets from 17 biorefineries located in 13 study regions. The avoided emissions represent 25.17% of the target proposed by the Colombian government, and transport emissions represent only 2.62% of the emissions generated by the model. Despite the promising results obtained in the optimization of the supply chain for bioethanol and bagasse pellet production in Colombia, there are challenges and limitations that must be considered. One of the main challenges lies in the uncertainty associated with the variability in biomass, bioethanol, and carbon credit prices, which can affect the long-term economic viability of the project. The sustainability of land use for sugarcane production must be assessed with a more detailed approach to avoid conflicts with food production and ecosystem conservation. These aspects represent key opportunities for future research and improvements in strategic planning for the bioenergy sector. Finally, the sensitivity analysis shows that the ±20% variation in the price of sugarcane and the price of bioethanol have a high impact on the payback period with respect to the base case.

***Keywords***

Superstructure;
Biomass and Biofuels;
Methodological approach;
Facility location;
Sustainability;
Logistics network;
Mixed-integer linear programming.

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## 1. Introduction

Demand for energy has increased over the last few decades. Between 1971 and 2015, energy consumption increased by 150%, with fossil fuels accounting for 80% of consumption [1], and by 2040, energy demand is expected to increase by 28% [2]. However, energy security, dwindling fossil fuel reserves, geopolitical instability and environmental concerns remain the main consequences that have led to a focus on renewable energy exploration [3]. Renewable energy alternatives (wind, solar, hydro, geothermal and biofuels) can provide an alternative energy supply [4] and in recent years, they have gained recognition as a potential alternative to fossil fuel-based energy systems [5,6].

Biomass energy, also known as bioenergy, is central to the development of sustainable strategies to reduce the use of fossil fuels and combat climate change [7]. Biomass is defined as any organic matter derived from the biodegradable components of agricultural waste, including plant and animal materials [8]. This resource is considered to be one of the most abundant in the world and has a high potential (it is the fourth largest energy source, following coal, oil, and natural gas) and is a primary resource that can be transformed into fuel for the

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*List of Abbreviations*

| | |
|---|---|
| *MILP* | *Mixed Integer Linear Programming* |
| *NPV* | *Net Present Value* |
| *COD* | *Chemical Oxygen Demand* |
| *NDC* | *Nationally Determined Contributions* |

chemical and transportation sectors [9–12]. Its use has increased exponentially because it is an inexhaustible, low-cost source [13], is carbon neutral [14] and can be considered a key pillar in decarbonisation [15]. As a result, renewable biomass, such as agricultural residues, has gained attention in academic research and the global industry for the production of biofuels [16].

Biofuel production contributes to sustainability and can help meet energy demand in the transport sector [17]. These biofuels are produced by converting biomass through chemical, biochemical, and thermal processes [18]. By 2050, biofuel production is expected to account for 25% of total energy consumption [19]. In Colombia, the production of biofuels is expected to replace fossil fuels in the transport sector [20], and in 2021, final energy consumption in the transport sector represented 39.5% of total energy consumption, with most of the energy demand for the transport sector being met by petroleum derivatives: gasoline (49%) and diesel (41%), while biofuels represented 6.2% (biodiesel 74% and bioethanol 26%) [21].

Several biomass studies have investigated process routes for the production of biofuels and products under the biorefinery concept [22], which is becoming increasingly important in terms of sustainability [23]. Biorefineries are a network of facilities where conversion processes for biofuels and bioproducts are integrated and have been analysed using mathematical modelling concepts, process integration and waste stream minimisation [24]. The optimisation approach to biorefinery design creates a superstructure where multiple process routes are involved [25].

Colombia has a large potential for biomass from agro-industrial waste (about 72 Mt produced annually) [26], which comes from crops such as coffee, sugarcane and rice. These residues can be used to produce energy and/or biofuels. For example, the sugarcane process produces a by-product such as bagasse, which can be used to meet the energy needs of power plants, although it can also be used for other purposes due to its high yield. In addition, the fermentation process produces a liquid residue called vinasse, which can be used for biogas production and as a culture medium for microalgae growth [27]. The use of waste represents an opportunity to create marketable products from biorefinery processes [28]. For this, it is important to evaluate the economic, energy and environmental performance through process configuration including localisation and supply chains [29].

Mathematical models are important for optimising biofuel supply chains, although modelling a supply chain is complex due to the different variables and parameters involved [22]real costs, and storage conditions of the raw material to guarantee an accurate feasibility analysis and a standardized production process. Calendula (Calendula Officinalis. Several studies have been carried out to develop mathematical programming models to optimise supply chains. The objective function of most optimization models seeks to minimize planning costs, which encompass both investment and operating costs, while evaluating criteria such as maximizing total profit, minimizing environmental impact, and reducing energy consumption [30,31]. Mixed Integer Linear Programming (MILP) is the most widely used modelling technique for designing supply chains using biomass as a feedstock for energy production [32]. In this type of modelling, the constraints and objective function are linear, while the decision variables are restricted to integer values in order to find an optimal solution. Table 1 shows different studies for biofuel production using mixed linear programming.

Many studies have evaluated the supply chain. Ren et al [41], developed a model to design the supply chain for bioethanol production taking into account multiple modes of transport, multiple feedstocks, different conversion processes and aiming to minimise the environmental footprint. Infante et al [42] presented a MILP formulation to evaluate a sugarcane-microalgae biorefinery considering the production of different biofuels in Colombia. The results showed that microalgae liquefaction was the most viable route among the different routes studied, while bagasse was used as process fuel and pellet production. Ng and Maravelias [43], presented a mixed-integer linear programming model for the bioethanol supply chain, evaluating different time periods. The authors model biomass selection and allocation decisions, technology selection and capacity planning. Gumte and Mitra [14], developed a mixed integer linear

Table 1: Studies for biofuel production using MILP.

| Country | Raw material | End-products | Logistic model | Conclusion | Reference |
|---|---|---|---|---|---|
| Colombia | Coffee Cut-Stems (CCS) | Ethanol, electricity | Yes | Five case studies were carried out. The demand for ethanol in Colombian territory can be replaced by 40% when the biorefinery does not consider existing ethanol plants. Although only 0.43% of the electricity demand can be replaced through the feedstock (CCS). | [33] |
| Colombia | Pulp, mucilage and coffee residue | Ethanol | Yes | The applicability of the logistic model depends mainly on the availability of raw materials in the regions. Coffee stems have higher yields in ethanol production than other by-products (pulp and mucilage). | [34] |
| Colombia | Coffee Cut-Stems (CCS) | Ethanol | Yes | The cost of producing bioethanol from Coffee Cut-Stems (CCS) ranges from 0.794-0.759 USD/L. The raw material is insufficient to replace the domestic market demand. Only 2 cities (Ibague and Armenia) are able to fully meet the demand for bioethanol. | [35] |
| North Dakota (United States) | Switch grass | Ethanol | Yes | The supply chain is highly influenced by carbon emissions and energy consumption penalties. | [36] |
| Iran | Jatropha oil<br>Used cooking oil<br>Microalgae | Biodiesel | Yes | The authors demonstrate supply chain behavior, but the results do not indicate or perform important analyses. The authors evaluate how the objective function varies depending on transportation and production costs. | [30] |
| Illinois (United States) | Corn stubble and urban wood | Ethanol | Yes | Mais custos podem ser poupados quando as biorrefinarias estão localizadas mais perto dos locais de aquisição de biomassa e não da área com elevada demanda de biocombustíveis. | [37] |
| India | Second generation biomass | Ethanol | Yes | Production costs are the highest, followed by import, transportation, infrastructure and stock costs. | [14] |
| Colombia | Eucalyptus<br>Pine | Biofuels | Yes | The distances between the different locations of the supply chain strongly affect the design. The location of biorefineries close to the largest consumer centers in the country is presented as the best alternative for job management and GEE reduction. Profits do not decrease drastically with lower levels of GEE emissions. | [38] |
| Iran | Corn<br>Sorghum<br>Barley | Ethanol | Yes | The production of second-generation bioethanol for the case study has the potential to meet three percent of the demand for fuel for transportation in the country. | [39] |
| Indonesia | Palm oil | Electricity<br>Biodiesel<br>Ethanol | Yes | 7.6 billion liters of ethanol, 17.1 billion liters of biodiesel and 2.25 GW of electricity can be produced from palm oil | [29] |
| N/A | Microalgae | Biodiesel<br>Biochar<br>Biomethane | Not | When profit maximization is prioritized, environmental impact increases.<br>Lower process unit efficiency results in decreased profits and impact due to lower product output. | [40] |
| Colombia | Sugarcane | Ethanol<br>Electricity<br>Bagasse pellets | Yes | Bioethanol production meets the demand for gasoline in Colombia, while bagasse pellet production meets the demand for coal in thermoelectric plants. | This study |

N/A: not available

programming (MILP) model for a multi-period supply chain for the production of second generation bioethanol with the objective of maximising net present value (NPV) taking into account production, import, transport and storage decisions. Carvajal et al. [44], proposed a supply chain planning model to assess the feasibility of a new sugarcane bioethanol production plant in Colombia. The model aims to maximise the net present value (NPV) subject to planting, cultivation and harvesting constraints. Garcia et al. [45] presented a mixed integer linear programming-based superstructure model to identify a biorefinery configuration considering heat integration, selection, and process scaling.

In this article, we propose to apply a Mixed Integer Linear Programming (MILP) model for the supply chain through a biorefinery process from sugarcane, using conversion processes for the production of bioethanol, electricity and pellets, analysing the model from an economic and environmental point of view and the impact of the value of carbon credits in the final optimal configuration.

## 2. Methodology

The system to be optimised is the supply chain for a biorefinery using sugarcane as a feedstock for the production of bioethanol, electricity and bagasse pellets. A Mixed Integer Linear Programming (MILP) model based on superstructure optimisation is developed to support strategic decision making by evaluating an economic objective function. The MILP model was processed in the LINGO software [46] using a database library of process models.

The methodological approach is based on three main steps: 1) theoretical analysis, collection of literature data and estimated data to be used in the model, 2) formulation of the mathematical model using the data collected in the first step and 3) optimisation process. Figure 1 shows the superstructure of the sugarcane biorefinery process flow evaluated in this study. The superstructure includes different processing units, which are explained below.

### 2.1 Distillery

Figure 1 shows that the biorefinery superstructure starts with the production of bioethanol through a stand-alone distillery. Resource consumption and production ratios have been calculated based on a model of a first-generation bioethanol distillery without CHP published by Pina et al. [47].

### 2.2 Vinasse biodigestion

The vinasse produced in the distillation process can be used for fertigation and/or anaerobic biodigestion of vinasse to produce biogas used for electricity and heat production. The main parameters for this unit are: typical COD value for vinasse = 33.25 kg/$m^3$ [48]; UASB reactor efficiency = 62.5% [48,49]; percentage of $CH_4$ in biogas = 60%; biogas production factor per mass of COD removed = 0.234 $m^3$/kg (in terms of $CH_4$) [49]. Table 2 summarises the main parameters used in all biorefinery units.

### 2.3 Dry torrefaction and pelletisation

The bagasse generated at the distillery is processed into pellets using a torrefaction process from sugarcane bagasse. Torrefaction is a heat treatment process that converts waste biomass into a more efficient solid fuel.

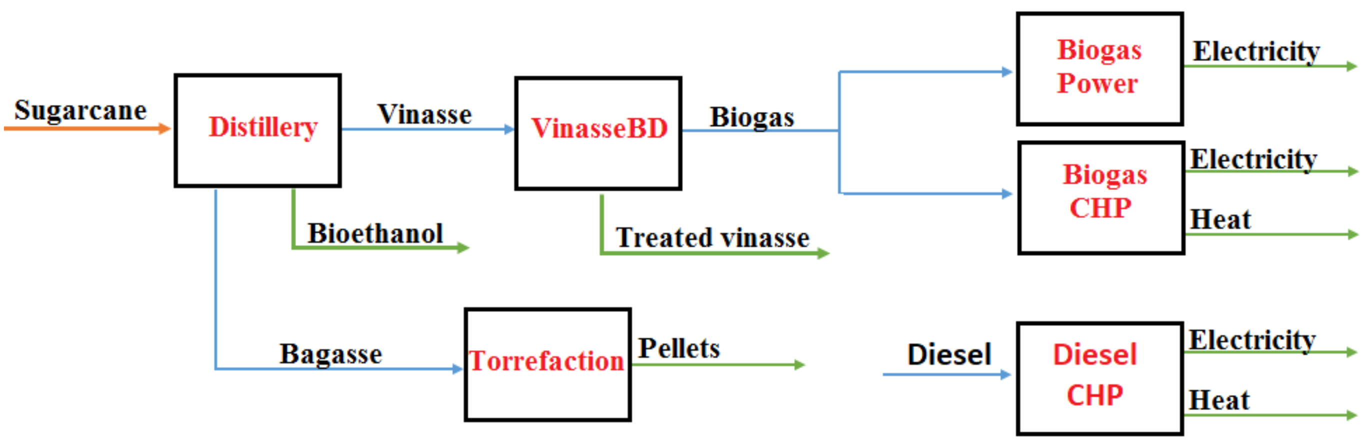


Figure 1: Sugarcane biorefinery process flow.

Table 2: Key data used in the biorefinery.

| Units | Notes |
|---|---|
| Distillery | Anhydrous ethanol production = 0.0648 anhydrous bioethanol t/t sugarcane [47]. |
| | Bagasse production = 0.27648 t bagasse/t of sugarcane [47]. |
| | Vinasse production = 0.89568 t vinasse/t of sugarcane [47]. |
| | Electricity consumption = 0.028 MWh/t of sugarcane [47]. |
| | Water requirement = 0.875 t water/t of sugarcane [47]. |
| | Heat consumed = 0.1704 MWh/t of sugarcane [47]. |
| Vinasse biodigester | COD of vinasse = 33.25 kg/m$^3$ [48]. |
| | COD Removal efficiency = 62.5% [48,49]. |
| | CODr conversion to $CH_4$ = 0.234 Nm$^3$/kg of removed COD [49]. |
| | Biogas $CH_4$ content = 60% (%v/v) [51]. |
| | Biogas density = 1.19 kg/Nm$^3$ (Calculated) |
| | Vinasse density = 1143 kg/m$^3$ |
| Dry torrefaction and pelletisation | Bagasse pellets production = 0.335 t bagasse pellets/t of sugarcane bagasse [50] |
| | Electricity consumption = 0.1465 MWh/t bagasse pellets produced [50] |
| | Heat consumption = 1.2853 MWh/t bagasse pellets produced [50] |

For the model, the bagasse goes through a drying process to evaporate the moisture, then the bagasse goes through a grinding and screening process. It is then pretreated by the dry roasting process and finally pressed into fuel pellets. The modelled consumption rates in this process were calculated from a study developed by Jarunglumlert et al [50].

## 2.4 Combined Heat and Power - CHP

The CHP unit is used to produce heat and electricity. This unit can be fuelled by different sources such as fossil diesel and biogas. The efficiency of the CHP unit is assumed to be 90%, with 30% for electrical energy conversion and 60% for thermal energy conversion.

## 2.5 Biogas power

Another possibility to produce electricity for the integrated biorefinery and/or for sale was the use of biogas. In this study, this unit was assumed to have an efficiency of 35% (HHV basis).

# 3. Structure, formulation and data of the model

The objective is to minimize costs. In the model, profit is defined as the difference between the biorefinery's total cost and its revenue. The total revenue depends not only on the Sales Cost (SC) of bioethanol, electricity and bagasse pellets but also on the generated green credits (CC). The costs depend on Investment Cost (IC), Material Costs (MC) and Transportation Costs (TC) from a production region to a consumption region. Equation (1) shows the objective function addressed in the study.

$$Min\ Cost = IC + MC + TC - SC - GC \quad (1)$$

To calculate the Investment Cost (IC), Equation 2 was used, where AF, MC, OC and LC represent the annualization factor, maintenance cost, operational cost and labour cost, respectively. The values of AF, MC, OC and LC are shown in Table 6.

$$\mathrm{IC} = \sum_{\mathrm{re,cl,u}} \mathrm{UC}_{\mathrm{re,cl,u}} \cdot \left(\mathrm{AF} \cdot \left(1 + \mathrm{MC} + \mathrm{OC} + \mathrm{LC}\right)\right) \quad (2)$$

The following Equations 3 – 6 are used to calculate the Material Cost (MC), Transportation Costs (TC), Sales Cost (SC) and Green Credits (GC) respectively.

$$\mathrm{MC} = \sum_{\mathrm{re,cl,r,s}} (\mathrm{RC_r} \cdot \mathrm{rp}_{\mathrm{re,cl,r,}} \cdot \mathrm{OR}_{\mathrm{r,s}}) \quad (3)$$

$$\mathrm{TC} = \sum_{re,cl,c,s,p} (sic_{re,cl,c,s,p} \cdot DIS_{re,c} \cdot \mathrm{MoC}_s) \quad (4)$$

$$SC = \sum_{re,cl,se,s} (SC_{se} \cdot \mathrm{sp}_{re,cl,se} \cdot \mathrm{IS}_{se,s}) \quad (5)$$

$$GC = \left( \sum_{re,cl,r,s} (\mathrm{EE}_r \cdot rp_{re,cl,r,y} \cdot \mathrm{OR}_{r,s} \right) + \sum_{s} (\mathrm{ET}_s) - \sum_{re,cl,se,s} (\mathrm{EA}_{se} \cdot \mathrm{sp}_{re,cl,se} \cdot \mathrm{IS}_{se,s})) \cdot CC \quad (6)$$

To calculate the Emissions generated by Transport (ET), Equation 7 was used.

$$ET_s = \sum_{re,cl,c,p} \mathrm{sic}_{re,cl,c,s,p} \cdot \mathrm{DIS}_{re,c} \cdot \mathrm{FET}_s \quad (7)$$

Equations in question 8 – 10 are responsible for the transport in the model.

$$\mathrm{sep}_{re,cl,s,p} \cdot \mathrm{T}_s = \sum_{c} \mathrm{sic}_{re,cl,c,s,p} \cdot \mathrm{T}_s \quad (8)$$

$$\sum_{re,cl,p} \mathrm{sic}_{re,cl,c,s,p} \cdot \mathrm{T}_s \leq DC_{s,y,c} \quad (9)$$

$$\sum_{re,cl} \mathrm{sic}_{re,cl,c,s,p} \cdot \mathrm{T}_s = \mathrm{tsc}_{p,c,s} \cdot \mathrm{T}_s \quad (10)$$

The mass balance is presented in Equation 11. The model constraint regarding the demand for consumer streams is shown in equation (12), the total quantity of each stream produced in the biorefinery must be greater than or equal to the consumer demand for each stream.

$$\sum_{u,l} \mathrm{upp}_{re,cl,u,l,p} \cdot \mathrm{OU}_{u,s} + \sum_{r} \mathrm{rpp}_{re,cl,r,p} \cdot \mathrm{OR}_{r,s} \cdot \mathrm{RAC}_{re,cl,r,p} = \sum_{u,l} \mathrm{upp}_{re,cl,u,l,p} \cdot \mathrm{IU}_{u,s} + \sum_{se} \mathrm{spp}_{re,cl,se,p} \cdot \mathrm{IS}_{se,s} \quad (11)$$

$$\sum_{re,cl,se} sp_{re,cl,se} \cdot \mathrm{IS}_{se,s} \cdot T_s \leq \sum_{c} DC_{s,c} \quad (12)$$

Equations 13 – 14 indicate the restrictions on the amount of resources

$$\sum_{re,cl} \mathrm{rqc}_{re,cl,r} \leq \mathrm{RQ}_{re,r} \quad (13)$$

$$\mathrm{rp}_{re,cl,r} \cdot \mathrm{OR}_{r,s} \leq \mathrm{rqc}_{re,cl,r} \quad (14)$$

Equations 15 – 16 indicate the resource quantity balance constraints.

$$\mathrm{rp}_{re,cl,r} \cdot \mathrm{OR}_{r,s} = \sum_{p} \mathrm{rp}_{re,cl,r} \cdot \mathrm{OR}_{r,s} \cdot \mathrm{RAC}_{re,cl,r,p} \quad (15)$$

$$\mathrm{yrp}_s = \sum_{re,cl,p,r} \mathrm{rp}_{re,cl,r} \cdot \mathrm{OR}_{r,s} \quad (16)$$

Equations 17 – 19 indicate the restrictions of the balance of services produced.

$$sp_{re,cl,se} \cdot \mathrm{IS}_{se,s} = \sum_{p} \mathrm{spp}_{re,cl,se,p} \cdot \mathrm{IS}_{se,s} \quad (17)$$

$$ysp_{s,y} = \sum_{re,cl,p,se} \mathrm{spp}_{re,cl,se,p} \cdot \mathrm{IS}_{se,s} \quad (18)$$

$$\sum_{se} sp_{re,cl,se} \cdot \mathrm{IS}_{se,s} \cdot T_s = \sum_{p} \mathrm{sep}_{re,cl,c,s,p} \cdot T_s \quad (19)$$

Equations 20 – 23 are constraints used in the model for the units.

$$\mathrm{uu}_{re,cl,u} = \sum_{u,l} \mathrm{uul}_{re,cl,u,l} \quad (20)$$

$$\mathrm{MAXC}_{u,l} \cdot \mathrm{uul}_{re,cl,u,l} \geq \mathrm{uml}_{re,cl,u,l} \quad (21)$$

$$\mathrm{MINC}_{u,l} \cdot \mathrm{uul}_{re,cl,u,l} \leq \mathrm{uml}_{re,cl,u,l} \quad (22)$$

$$\mathrm{uc}_{re,cl,u} = \sum_{l} \mathrm{uml}_{re,cl,u,l} \cdot CE_{u,l} + \mathrm{uml}_{re,cl,u,l} \cdot FC_{u,l} \quad (23)$$

The sets addressed in the model are shown in the Table 3 and the parameters and variables are shown in the Table 4.

## 4 Case study

The model considered the sugarcane potential in the departments of Colombia. Colombia is divided into 33 political departments: 32 departments and the capital Bogotá. In order to evaluate the performance of the proposed optimisation modelling strategy, a case study applied in Colombia was selected due to the country's high potential for sugarcane cultivation. The Rural Agricultural Planning Information System (SIPRA) indicates that Colombia has 12,604,519 hectares of sugarcane, including high, medium and low suitability, with productivity of approximately 120, 90 and 65 t/ha, respectively [52]. For this study, 21 regions of Colombia were selected for their high suitability and productivity (120 t/ha) of sugarcane biomass. Table 5 summarises the data described above. A maximum of 10% of the territory was considered for sugarcane cultivation to avoid environmental concerns about monoculture and the effects of land use change.

Table 3: List of sets.

| Name | Description | Index |
|---|---|---|
| CLUSTER | Limits of a biorefinery that can exist within a region. | cl |
| CONSUMER | Set of consumers studied for the case study. | c |
| LEVEL | Set of levels for the biorefinery. | l |
| MODAL | Set of transportation modes. | m |
| PERIOD | Set of periods. | p |
| REGION | Set of regions studied for the case study. | re |
| RESOURCE | Set of resources available for the biorefinery. | r |
| SERVICE | Set of services (biofuels, value-added products) produced by the biorefinery. | se |
| STREAM | Set of streams that enter or leave a unit for subsequent conversion. | s |
| UNIT | Set of units that carry out the conversion process. | u |

Input parameters and decision variables

### 4.1 Demand

The following assumptions were used to select the consumer regions 1) bioethanol demand would replace gasoline consumption in the entire Colombian territory, except for the departments of Amazonas, Guainía and Vaupés (These 3 departments were not considered because no route information was found); 2) electricity demand for the cities capitals of the departments where potential biorefineries will be installed, electricity transmission losses were assumed to be 7%; and 3) bagasse pellet demand replaces all coal consumption in coal-fired power plants in Colombia and coal exports to Europe. The value of gasoline demand was reported by [53]. The values used for March 2023 and it was assumed that the value would be the same for all months of the year. The value of electricity demand was calculated using the per capita consumption in Colombia, which has a value of 1,492.5 kWh (value reported for the year 2021) [54]. The value of coal demand in thermoelectric power plants for the year 2022 was reported by [55] and the value of exported coal for the year 2022 was reported by [56]. Once the demand for gasoline and coal was obtained, the demand for bioethanol and bagasse pellets was calculated using the gross calorific value.

### 4.2 Emissions

Table 6 shows the amounts of carbon dioxide equivalent avoided per amount of products produced and the amounts of carbon dioxide equivalent emitted per amount of resource used. Due to the characteristics of transport in Colombia, the transport by road of two goods was considered for the demand for biodiesel and pellets, which has an approximate emissions value of 0.000123 t $CO_2$ eq/t-km according to the studies of [57]. For the calculation of emissions from electricity distribution, it was assumed that for transmission systems with a voltage line of ±800 kV, losses are around 7% per 1000 km for an alternating current line [58], therefore the emissions generated by electricity transmission correspond to 0.00001421 t $CO_2$ eq/MWh-km. For the transport of bagasse pellets and bioethanol exported from the ports of Colombia to the port of Rotterdam in the Netherlands (This port was chosen because it is one of the main destinations for Colombian coal in Europe due to its infrastructure and logistical capacity), transport by ship was considered, which has a value of 0.000007 $CO_2$ eq/t-km [57].

### 4.3 Transport costs

To calculate the costs of road transport of bioethanol and bagasse, a simulation was carried out based on data from the Colombian Ministry of Transport [63], taking into account different variables (vehicle configuration, transport unit, waiting time for loading and unloading, origin and destination of the load). The result of the simulation was a cost of 0.076 US$/t-km. DeSantis et al [64] reported the cost of electricity transmission to be 0.0415 US$/MWh-mile. Wan and Liu [65], reported that the cost of transport by ship was 0.015 US$/t-km. The economic data for raw materials, reagents, solvents, products, utilities, labour costs, maintenance costs, modal costs and other costs are presented in Table 7.

### 4.4 Distance

To calculate the distance from the location of the potential biorefinery in the producing region to a consuming department, the distance between the capital city of the

Table 4: List of parameters and variables.

| Parameters | Description |
|---|---|
| $UC_{re,cl,u}$ | Cost of the unit. |
| $RC_r$ | Cost of the resource. |
| $SC_{se}$ | Market price of the service. |
| $DIS_{re,c}$ | Distance from a region to a consumer. |
| $CE_{u,l}$ | Equipment cost per unit of capacity. |
| $FC_{u,l}$ | Fixed cost per unit of capacity. |
| CC | Carbon Footprint Selling Price. |
| $FET_s$ | Transport emission factor. |
| $EA_{se}$ | Quantity of carbon dioxide avoided by service. |
| $EE_r$ | Quantity of carbon dioxide emitted by resource. |
| $IS_{se,s}$ | Flow entering the service. |
| $IU_{u,s}$ | Flow entering the unit. |
| $OU_{u,s}$ | Flow leaving the unit. |
| $OR_{r,s}$ | Flow leaving the resource. |
| $DC_{s,c}$ | Total demand of a flow for a consumer. |
| $MAXC_{u,l}$ | Maximum capacity of a unit depending on the level |
| $MINC_{u,l}$ | Minimum capacity of a unit depending on the level |
| $RQ_{re,r}$ | Quantity of resource available in the regions |
| $MoC_s$ | Cost of modal |
| $T_s$ | Indicates whether a flow can be transported. |
| $RAC_{re,cl,r,p}$ | Availability of resources in the regions. |
| **Variables** | **Description** |
| $ET_s$ | Emissions generated by transport |
| $yrp_s$ | Total resource consumption by all regions |
| $ysp_s$ | Total production of the service by all regions |
| $rp_{re,cl,r}$ | Total consumption of the resource in one year |
| $sic_{re,cl,c,s,p}$ | Quantity of a resource transported by a modal m from a location re to c. |
| $sp_{re,cl,se}$ | Total production of the service. |
| $sep_{re,cl,s,p}$ | Flow exported during a period. |
| $tsc_{p,c,s}$ | Flow exported by consumers. |
| $upp_{re,cl,u,l,p}$ | Quantity produced during a period. |
| $rpp_{re,cl,r,p}$ | Total consumption of the resource in a year. |
| $uu_{re,cl,u}$ | Binary variables. |
| $uul_{re,cl,u,l}$ | Binary variables. |
| $uul_{re,cl,u,l}$ | Amount of input and output in the unit in a level. |
| $spp_{re,cl,se,p}$ | Total production of the service in a year. |
| $rqc_{re,cl,r}$ | Amount of resource depending on the units that are per region. |

Table 5: Sugarcane production potential.

| Regions | Aptitude (ha) | Sugarcane ($10^6$ t) |
|---|---|---|
| Antioquia (P1) | 706,789 | 76.33 |
| Cauca (P2) | 321,270 | 35.17 |
| Santander (P3) | 270,723 | 32.5 |
| Valle del Cauca (P4) | 263,523 | 26.63 |
| Cundinamarca (P5) | 209,907 | 25.19 |
| Tolima (P6) | 197,025 | 23.64 |
| Huila (P7) | 126,848 | 15.22 |
| Caldas (P8) | 235,298 | 9.50 |
| Córdoba (P9) | 70,455 | 8.45 |
| Boyacá (P10) | 63,413 | 7.6 |
| Nariño (P11) | 60,883 | 7.31 |
| Risaralda (P12) | 115,864 | 4.97 |
| Norte de Santander (P13) | 36,062 | 4.33 |
| Quindío (P14) | 73,348 | 2.21 |
| Magdalena (P15) | 14,758 | 1.77 |
| Cesar (P16) | 12,971 | 1.56 |
| Caquetá (P17) | 8,952 | 1.10 |
| Casanare (P18) | 3,926 | 0.47 |
| Bolívar (P19) | 3,413 | 0.40 |
| Meta (P20) | 1,957 | 0.23 |
| La Guajira (P21) | 1,570 | 0.19 |

producing region and the capital of the potential consuming department was calculated using Google Maps [66] and the half radius of the consuming department and the producing region was added. The radius value was calculated using Equation (24).

$$r = \frac{\sqrt[2]{\frac{A}{\pi}}}{2} \tag{24}$$

Where,

A: is the area of the producing region. The calculated value of r was added to the distances obtained by google maps. To calculate the distance from where the possible biorefinery was going to be installed in the producing region to a consuming department, the distance between the capital city of the producing region and the capital city of the possible consuming department was calculated and half the radius of the consuming department and the producing region was added.

Table 6: Amount of $CO_{2eq}$ avoided by products and amount of $CO_{2eq}$ emitted by resources.

| **Products** | **Value (t $CO2_{eq}$/t products)** | **Reference** |
|---|---|---|
| Bioethanol[a] | 2.47 | [59] |
| Electricity[b] | 0.203[c] | [60] |
| Bagasse pellets[d] | 1.87[e] | Calculated |
| Bioethanol export | 2.41[f] | Calculated |
| Bagasse pellets export | 1.81[g] | Calculated |
| **Resources** | **Value (t $CO_{2eq}$/t resource)** | |
| Sugarcane | 0.01 | [61] |
| Electricity | 0.203[c] | [60] |
| Water | 0.00003 | [62] |

[a] Anhydrous bioethanol replaces fossil gasoline fuel.

[b] Electricity replaces the Colombian electrical matrix.

[c] T $CO_2$ eq/MWh.

[d] Bagasse pellets and biochar replaces mineral coal in energy basis.

[e] Calculated on the energy basis of mineral coal.

[f] Value of bioethanol minus the emissions emitted from transporting the bioethanol by ship to Rotterdam.

[g] Value of the bagasse pellets minus the emissions emitted from transporting the bioethanol by ship to Rotterdam.

Table 7: Cost used in the economic analysis.

| **Item** | **Price** | **Reference** |
|---|---|---|
| Sugarcane | 35 US$/t | [67] |
| Electricity | 65 US$/MWh | [68] |
| Water | 1.23 US$/t | [67] |
| Diesel | 403 US$/t | [69] |
| Bioethanol[a] | 534 US$/t | Calculated |
| Bagasse pellet[b] | 172 US$/t | Calculated |
| Coal | 268 US$/t | [69] |
| Bioethanol export[c] | 407 US$/t | Calculated |
| Bagasse pellet export[d] | 45 US$/t | Calculated |
| Transport cost of bioethanol | 0.076 US$/t-km | Calculated |
| Transport cost of electricity | 0.026 US$/MWh-km | [64] |
| Transport cost of bagasse pellet | 0.076 US$/t-km | Calculated |
| Transport cost of bagasse pellet export | 0.015 US$/t-km | [65] |
| Transport cost of bioethanol export | 0.015 US$/t-km | [65] |
| Labour Cost | 10% cost production | |
| Maintenance Cost | 6% cost of capital | [70] |
| Other Cost[e] | 8.6% cost of capital | [71] |
| Annualisation Factor | 7% | |

[a] The bioethanol price was quoted based on the opportunity cost of the energy-based price of gasoline and considering the cost of the producer.

[b] Since there is a market for bagasse pellets as a fuel, the opportunity price is based on the energy-based price of coal.

[c] The bioethanol export price was quoted based on the opportunity cost of the energy-based price of gasoline and considering the cost of the producer minus the cost of transporting it by ship from the port of Colombia to Rotterdam.

[d] Since there is a market for bagasse pellets as a fuel, the opportunity price is based on the energy-based price of coal minus the cost of transporting it by ship from the port of Colombia to Rotterdam.

[e] Administration costs, operating supplies, plant overhead costs, local taxes and insurance.

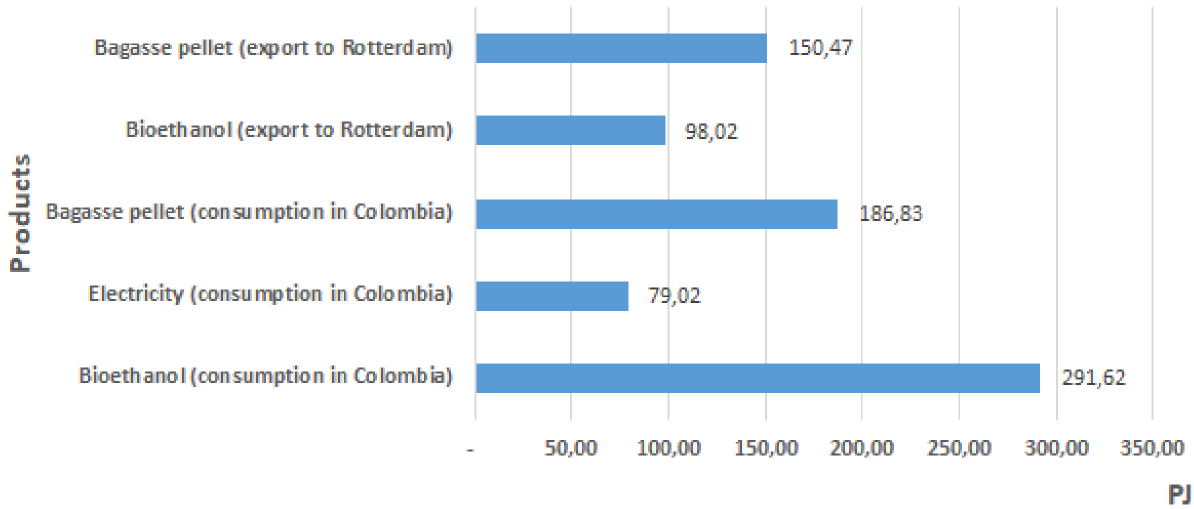


Figure 2: Energy in the products obtained for consumption in Colombia and for export to Rotterdam.

## 5 Results

The model was developed using LINGO version 20.0 on a computer with Intel(R) Core(TM) i7-13700 processor, 64 GB RAM and CPU@ 2.10GHz. The optimisation of the model provided complete information about the biorefinery according to the parameters set, so an analysis of the operations involved was carried out. The biorefinery was evaluated using a carbon credit price of US$100/t $CO_2$ eq. For the 21 selected Colombian producing regions, the results show that 17 biorefineries are installed: 3 in Antioquia, 2 in Santander, 2 in Cundinamarca, 1 in Valle del Cauca, 1 in Cauca, 1 in Caldas, 1 in Tolima, 1 in Huila, 1 in Córdoba, 1 in Boyacá, 1 in Nariño, 1 in Magdalena and 1 in Cesar. 212.770 MT of sugarcane are used to produce 13.787 MT of bioethanol, 30.785 TWh of electricity and 19.701 MT of bagasse pellets. 71.3% of the electricity produced is sold and the remainder is used to meet the electricity needs of the distilleries and torrefaction units. The electricity produced in the biorefineries is carried out by the biogas and diesel cogeneration units, which produce 8% and 92%, respectively. All biogas produced from the biodigestion of the vinasse is used to produce electricity and heat in the biogas CHP unit. The results show that the production of bioethanol can substitute the consumption of gasoline in the whole of Colombia and the production of bagasse pellets can substitute the consumption of coal in coal-fired power plants in Colombia. In terms of electricity demand, Cali, Bogotá, Santa Marta, Valledupar and Cartagena cover 86%, 47%, 21%, 18% and 3% of electricity demand respectively. Villavicencio, Riohacha and Yopal have no electricity and the remaining capitals covered by the study have 100% coverage. In addition, 25.16% and 44.61% of the bioethanol and pellets produced are exported to Rotterdam, respectively. Figure 2 shows the amount of energy in the products obtained for consumption in Colombia and for export to Rotterdam.

### 5.1 Economic analysis

The result of the economic analysis carried out for the biorefinery is shown in Table 8. The objective function gives a solution with a negative value, i.e. the biorefinery is profitable at the processing scale evaluated. For the configuration evaluated, the benefits depend on the total revenue and costs involved. In addition, the payback period was calculated to determine the time

Table 8: Economic results of supply chain.

| Item | Value |
|---|---|
| Investment cost (MUS$/y) | 7,767.56 |
| Operation cost (MUS$/y) | 133.76 |
| Transportation cost (MUS$/y) | 553.40 |
| Resource cost (MUS$/y) | 11,653.41 |
| Products revenue (MUS$/y) | 10,810.19 |
| Carbon credit revenue (MUS$/y) | 4,438.55 |
| Objective function (MUS$/y) | 2,908.17 |
| Net present value (MUS$) | 20,785.28 |
| Cash flow (MUS$/y) | 2,908.17 |
| Internal Rate of Return (%) | 37 |
| Payback (years) | 2.67 |

Table 9: Techno-economic assessment of biorefineries.

| Biomass type | NPV (MUS$) | Payback (years) | TIR | Reference |
|---|---|---|---|---|
| Corn stover | 65.6 | 5.4 | N/A | [72] |
| Sugarcane bagasse | 59.4 | 6 | N/A | [72] |
| Calendula (Officinalis) | 2.4 | 1.17 | N/A | [73] |
| Residues | 21.35 | 6.14 | 17.58 | [74] |
| Microalgae | 174.02 | N/A | N/A | [75] |

”N/A” (Not Available)

Table 10: Quantity of emissions.

| Emissions | Value (t $CO_2$ eq) |
|---|---|
| Avoided* | 74,617,316 |
| Emitted by Resource | 29,440,693 |
| Emitted by Transport | 791,115 |
| Balance | 44,385,508 |

*Avoided when anhydrous bioethanol replaces fossil gasoline fuel, electricity replaces the Colombian electrical matrix, bagasse pellets replaces mineral coal in energy basis.

required to recoup the total cost of the investment. The payback period can be calculated from Equation (25):

$$Payback\ period = \frac{Investment\ cost}{Profit} \tag{25}$$

The results of the economic analysis demonstrate the financial viability of the evaluated project, thanks to its high profitability: an IRR of 37% (significantly higher profitability); a payback period of 2.67 years (demonstrating an accelerated return on invested capital); and a positive net present value (NPV) of MUS$20,785.28 (indicating significant value generation over time). With an investment of MUS$7,767.56 and total operating costs of MUS$12,340.57/year, the project generates combined revenues of MUS$15,248.74/year, considering both product sales and carbon credits. From an economic and environmental perspective, the diversification of revenue sources, including carbon credits, strengthens the project's financial stability and fosters sustainability. Table 9 shows the results of economic analyses from different studies for the production of biofuels and/or value-added products using different raw materials.

Resource costs are the largest contributor to total costs at 90.4%, followed by transport and capital costs at around 4% each. Operating costs account for 1.0% of total costs. In addition, the sale of products accounts for 71% of revenues.

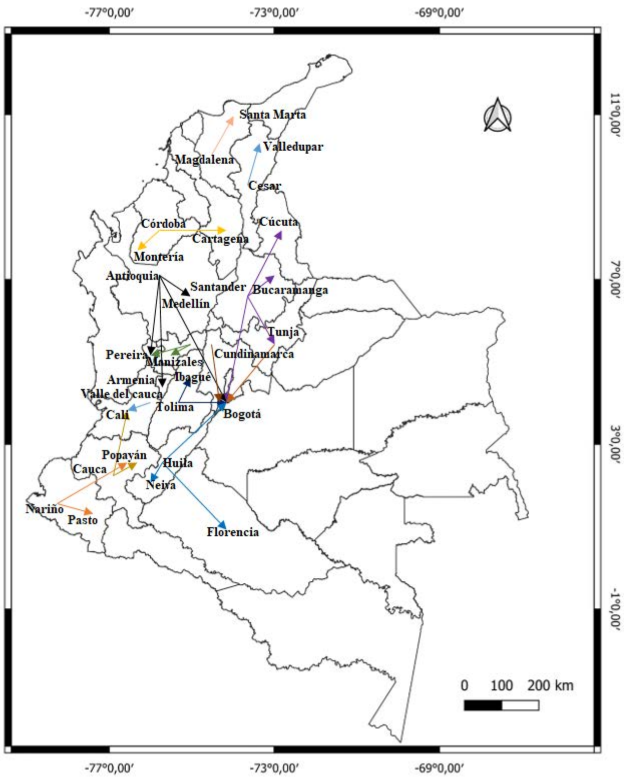


Figure 3: Supply chain of electricity.

## 5.2 Emissions

The value of avoided carbon dioxide emissions, resource emissions and transport emissions for the assessed configuration is shown in Table 10. The transport emissions of the products represent 2.62% of the emissions produced.

Equation (26) shows how the actual emission reduction can be calculated:

$$Actual\ emission\ reduction = \frac{Avoided - emitted\ by\ resource - emitted\ by\ transpor}{Avoided} \tag{26}$$

The actual reduction in avoided emissions is 59.5%. Colombia in its Nationally Determined Contributions (NDC) set its target to reduce greenhouse gas emissions

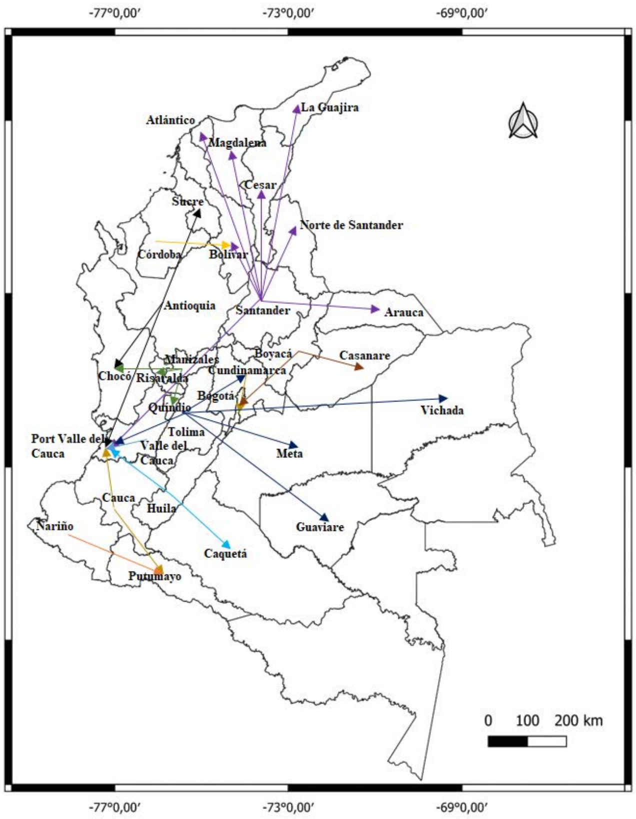


Figure 4: Supply chain of bioethanol.

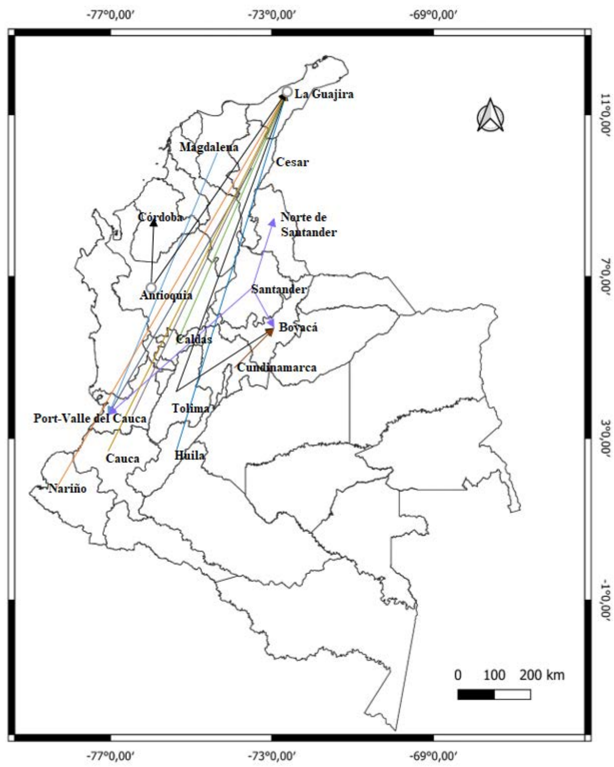


Figure 5: Supply chain of bagasse pellet.

Table 11: Supply chain of electricity (GWh/y).

| | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 | P10 | P11 | P15 | P16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CP1 | 501.6 | | | | | | | | | | | | |
| CP2 | 125.1 | | 795.6 | | 2,598.5 | 909.6 | 692.2 | | | 784.0 | | | |
| CP3 | | | 993.3 | | | | | | | | | | |
| CP4 | | 1.375.1 | | 1,782.6 | | | | | | | | | |
| CP5 | | | | | | | | | 48.4 | | | | |
| CP6 | | | 1.271.0 | | | | | | | | | | |
| CP7 | | | | | | | 283.6 | | | | | | |
| CP8 | | | | | | 873.0 | | | | | | | |
| CP9 | | | | | | | | 728.7 | | | | | |
| CP10 | 4,193.4 | | | | | | | | | | | | |
| CP11 | | | | | | | | | 823.3 | | | | |
| CP12 | | | | | | | 594.3 | | | | | | |
| CP13 | | | | | | | | | | | 630.7 | | |
| CP14 | 527.7 | | | | | | | 251.3 | | | | | |
| CP15 | | 407.4 | | | | | | | | | 123.4 | | |
| CP16 | | | | | | | | | | | | 182.6 | |
| CP17 | | | 291.6 | | | | | | | | | | |
| CP18 | | | | | | | | | | | | | 160.9 |

CP1= Armenia, CP2= Bogotá, CP3= Bucaramanga, CP4= Cali, CP5= Cartagena, CP6= Cúcuta, CP7= Florencia, CP8= Ibagué, CP9= Manizales, CP10= Medellín, CP11= Montería, CP12= Neiva, CP13= Pasto, CP14= Pereira, CP15= Popayán, CP16= Santa Marta, CP17= Tunja, CP18=Valledupar.

Table 12: Supply chain of bioethanol (MT/y).

| | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 | P10 | P11 | P15 | P16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C1 | 1.45 | | | | | | | | | | | | |
| C2 | | | 0.07 | | | | | | | | | | |
| C3 | | | 0.43 | | | | | | | | | | |
| C4 | | | | | 1.34 | | | | | 0.10 | | | |
| C5 | | | 0.10 | | | | | | 0.28 | | | | |
| C6 | | | | | | | | | | 0.28 | | | |
| C7 | | | | | | | | 0.18 | | | | | |
| C8 | | | | | | | 0.10 | | | | | | |
| C9 | | | | | | | | | | 0.11 | | | |
| C10 | | 0.27 | | | | | | | | | | | |
| C11 | | | 0.30 | | | | | | | | | | 0.10 |
| C12 | 0.03 | | | | | | | 0.06 | | | | | |
| C13 | | | | | | | | | 0.27 | | | | |
| C14 | | | | | 0.29 | 0.42 | | | | | | | |
| C15 | | | | | | 0.02 | | | | | | | |
| C16 | | | | | | | 0.26 | | | | | | |
| C17 | | | 0.18 | | | | | | | | | | |
| C18 | | | 0.05 | | | | | | | | | 0.11 | |
| C19 | | | | | | 0.25 | | | | | | | |
| C20 | | | | | | | | | | | 0.38 | | |
| C21 | | | 0.39 | | | | | | | | | | |
| C22 | | 0.01 | | | | | | | | | 0.10 | | |
| C23 | | | | | | | | 0.13 | | | | | |
| C24 | | | | | | | | 0.24 | | | | | |
| C25 | | | 0.49 | | | | | | | | | | |
| C26 | 0.14 | | | | | | | | | | | | |
| C27 | | | | | | 0.29 | | | | | | | |
| C28 | | | | 1.06 | | | | | | | | | |
| C29 | | | | | | 0.02 | | | | | | | |
| C30 | 1.73 | 0.84 | 0.08 | 0.05 | | 0.12 | 0.64 | | | | | | |

C1 = Antioquia, C2 = Arauca, C3 = Atlántico, C4 = Bogotá, C5 = Bolívar, C6 = Boyacá, C7 = Caldas, C8 = Caquetá, C9 = Casanare, C10 = Cauca, C11 = Cesar, C12 = Chocó, C13 = Córdoba, C14 = Cundinamarca, C15 = Guaviare, C16 = Huila, C17 = La Guajira, C18 = Magdalena, C19 = Meta, C20 = Nariño, C21 = Norte de Santander, C22 = Putumayo, C23 = Quindío, C24 = Risaralda, C25 = Santander, C26 = Sucre, C27 = Tolima, C28 = Valle del Cauca, C29 = Vichada, C30 = Port - Valle del Cauca.

by 51% by 2030 and achieve carbon neutrality by 2050 [76]. The results of the study show that carbon dioxide emissions avoided are 44.39 million t, which represents 25.17 % of the target proposed by the Colombian government for 2030.

### 5.3 Supply chain

It is clear that in the supply chain all products produced are destined for the consuming region closest to the producing region. The supply chain of electricity, bioethanol and bagasse pellets are shown in figures 3–5 respectively.

Table 13: Supply chain of bagasse pellet (MT/y).

| | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 | P10 | P11 | P15 | P16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C6 | | | 0.20 | | 1.04 | 0.11 | | | | 0.70 | | | |
| C13 | 3.66 | | | | | | | | 0.78 | | | | |
| C14 | | | | | 1.28 | | | | | | | | |
| C17 | 1.13 | 1.60 | | 1.60 | | 1.49 | 1.40 | 0.88 | | | 0.67 | | |
| C21 | | | 1.48 | | | | | | | | | | |
| C30 | | | 1.31 | | | | | | | | | 0.16 | 0.14 |

C6= Boyacá, C13= Córdoba, C14= Cundinamarca, C17= La Guajira, C21= Norte de Santander, C30= Port - Valle del Cauca.

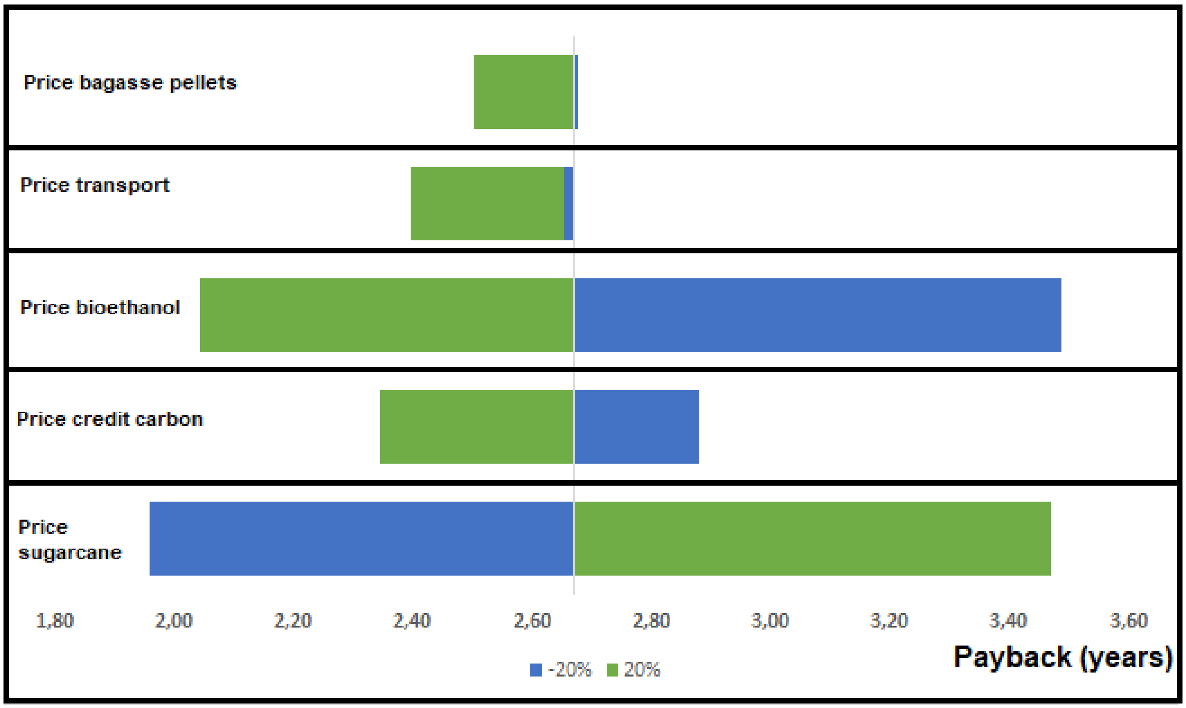


Figure 6: Sensitivity analysis on payback period.

The quantities of electricity, bioethanol and bagasse pellets destined from a producing region to a consuming region are shown in Tables 8, 9 and 10 respectively.

### 5.4 Sensitivity analysis

A sensitivity analysis is performed to investigate and assess the impact of the model parameters on the payback period. The parameters evaluated include the price of bioethanol, sugarcane, bagasse pellets, transport costs and carbon credits. Each parameter is varied by ± 20% and the optimisation problem is re-solved. The results of the sensitivity analysis are shown in Figure 6.

As can be seen in Figure 3, the ± 20% variation in the sugarcane price and the bioethanol price have a large impact on the model. The payback period increases to 3.47 years, i.e. 30%, when the sugarcane price increases by 20%, because the profits are 50% lower than in the base case. If the price of bioethanol decreases by 20%, the payback period is 3.49 years, in which case profits are 44% lower than in the base case. It can be said that of all the parameters, changes in the cost of bagasse pellets have the least impact on the payback period. For the different parameter variations, resource costs contribute the most to the total costs (89 - 91%), while the sale of products accounts for 66 - 74% of the revenue.

In addition to the influence on the payback period, the effect of parameter variation on the production of products was also analysed. For all parameters evaluated, the demand for internal coal consumption for thermoelectric power plants is satisfied by pellet production. The demand for gasoline is satisfied in most cases, except when the price of sugarcane increases by 20% and the price of bioethanol decreases by 20%, in which case the demand is satisfied by 85% and 95% respectively. If the price of sugarcane decreases by 20% and the price of bioethanol increases by 20%, the amount of bioethanol and bagasse pellets exported is 6.423 Mt and 13.011 Mt respectively (equivalent to 56% of coal exports to Rotterdam). In addition, bagasse pellets are always exported and their demand can be satisfied by 7-56% when the parameters are varied. When transport prices increase by 20%, there are no bioethanol exports and, in addition, bagasse pellet exports decrease by 57%.

## 6. Policy implications

This study has strong implications for energy policy-making (it shows that bioethanol production can replace gasoline consumption in Colombia, suggesting that the government could strengthen biofuel blending policies in transportation; in addition, bagasse pellet production allows for a reduction in coal consumption in thermo-electric plants, supporting an energy transition towards more sustainable sources), environmental (the reduction in $CO_2$ emissions achieved in the model indicates that promoting biorefineries could be an effective mechanism for meeting the country's commitments in the Paris Agreement), economic (investment and operating costs are high, but the model is profitable with a payback period of 2.67 years), and infrastructure (the export of bioethanol and pellets to Europe could boost trade agreements and international treaties in the bioenergy sector), and could guide strategic decisions of the Colombian government in its transition towards a more sustainable energy system.

## 7. Conclusions

This paper develops a MILP model of a biorefinery based on the potential of sugarcane for the production of bioethanol, electricity and bagasse pellets in Colombia. The objective function of the model was to minimise the cost of the plant. The main constraints of the model are: transportation constraints, raw material availability and demand for services. The uncertainties addressed in the model are: raw material availability (the study takes sugar cane potential as a reference), market demand and service sales price, uncertainty in logistics and distribution (problems in the supply chain: delays and transportation costs). The optimisation results showed that the production of bioethanol, electricity and bagasse pellets is an economic alternative with a payback period of 2.67 years. The production of bioethanol and bagasse pellets can replace 100% of the consumption of gasoline and coal in thermal power plants, and a surplus of bagasse pellets can be exported to Europe. Emissions from the transport of the energy produced represent 2.62% of the emissions produced, while emissions from the resources used represent 97.38%. The avoided emissions amount to 44.385 Mt of $CO_2$ eq per year, which represents 25.17% of the Colombian government's proposal for 2030. Sensitivity analysis showed that variations of ±20% in the price of sugarcane and the price of bioethanol have a large impact on the payback. Finally, changes in the cost of bagasse pellets have the least impact on the payback period.

## Acknowledgment

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