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Harnessing Residual Biomass as a Renewable Energy Source in Colombia: A Potential Gasification Scenario

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Abstract: Currently, developing new or more efficient ways of producing bioenergy has caused governments from around the world to formulate compromises. These compromises translate, on a national scale, into government policies and strategies that aim to decarbonize the energy matrix of each country. The first step for efficient development is the quantification and energy-potential characterization of the available biomass. Using this framework, this study establishes the energy potential of the residual biomass produced by agricultural, agro-industrial, and forestry processes in Colombia, with gasification being the selected transformation technology. For this purpose, data from primary and secondary sources were analyzed. Next, some biomasses were prioritized according to their availability and physicochemical properties. Then, the theoretical energy potential of the total biomass produced in these productive sectors was estimated by using its physicochemical properties. The technical biomass–energy potential of the country (204.8–235.3 PJ) was estimated by considering the current level of unused biomass and evaluating the logistics and conditioning requirements of the gasification process, while accounting for the peaks and off-peaks of production in the country. Thus, if all the biomasses were processed in a gasification plant (22.2–24.0% efficiency), as proposed in this study, then the installed capacity—if the plant-use factor was 85%—would range between 1696.7–2111.3 MW. The results of the present research were validated by representatives of unions, companies, and government entities.

Keywords: biomass; potential; renewable energy; gasification

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1. Introduction

Due to its renewable nature and potential as a substitute for fossil fuels, biomass has attracted, and continues to attract, the attention of researchers and companies looking for valuable sources of energy [1]. Moreover, these efforts are aligned with the seventh sustainable development goal (SDG) proposed by the UN: "Ensure access to affordable, reliable, sustainable, and modern energy for all" [2]. Indeed, the use of biomass as a renewable energy source has reduced the CO_2 emissions in most countries that have adopted it [3]. According to the reports of the International Energy Agency, by 2019, renewable energies represented 23.2% of the global electricity generation, whereas for carbon-generated energy, this value was 37.8%. Thus, bioenergy is the fourth most important energy source worldwide, after oil, coal, and natural gas [4]. In the case of Latin America, 85,014 GWh of bioenergy were generated in 2020, making it the second most important energy source in the continent, after oil. It is worth noting that bioenergy is being used at a higher rate in developing countries, even if the majority of it currently comes from developed countries [5].

One of the barriers to adopting biomass as a source of renewable energy is the logistic costs associated with its collection, storage, and transport; however, densification technologies have been studied as a viable solution to reduce these costs [6]. Indeed, the development of these technologies, coupled with the strategies that are currently being implemented by governments, such as carbon taxes and bonds, is promoting the use of biomass [7].

Nowadays, we have plenty of information regarding the energy potential of different regions across the globe. For instance, a bioenergy study in Turkey estimates that there are 73 MW potentially available from this source in the country. It is worth mentioning that in Turkey, most of the biomass produced comes from forestry and crop pruning residues, which makes combustion and cogeneration the most relevant transformation technologies in that context [8]. Similarly, the energy potential of solid biomass—agro-industrial and field residues—in Croatia ranges from 12.18 to 51.14 PJ [9]. On the other hand, in the Sabah region in Malaysia, the yearly bioenergy potential of oil palm (and other minor biomass sources) was 267.18 PJ. According to the author of the study, if this energy potential was actually converted, at 25% efficiency, it would be enough to supply 3.8 times the demands of the region [10]. Finally, a study carried out in Brazil found that 9947.12 GWh/year could be produced through biogas in the area of Paraná, where the byproducts of crops such as sugar cane, soy, corn, and cassava represent 79.7% of the energy potential, and livestock-generated biomass represents 14.8% of this potential [11].

In the case of Colombia, which is blessed with a privileged geography and location, the production of large-scale crops such as sugar cane and oil palm, as well as the multiple harvesting seasons of different crops during the year, generate a constant flow of biomass that could be harnessed for energy production. For instance, in 2019, the total agricultural production of the country was 63.2 million tons, which was divided thusly: sugar cane, 23 million tons; panela cane, 11 million tons; oil palm fruit bunches, 6.6 million tons; plantain, 4.1 million tons; bananas, 2.1 million tons; rice, 1.9 million tons; among other crops that were not so widely represented [12]. Furthermore, it is worth noting that small-scale agriculture, from farms of 5 ha or less, makes up 60% of the total production of the country [12]. Colombia's bioenergy potential, 400–750 PJ per year, has been calculated by using the biggest crops, animal waste, forestry residues, and urban residues as the main biomass sources by considering cogeneration and bio-digestion as the transformation technologies [13–16]. More specifically, a study on biogas potential showed a total of 150.8 PJ of available energy in Colombia [17]. The energy potential for agricultural biomasses in particular, has been estimated at 331.65 PJ/year [13]. To put this data into perspective, Colombia consumes around 1336 PJ/year, which is distributed among the transport (41.2%), industrial (22.5%), residential (19.3%), and public sectors (17%) [18]. Its electricity generation, which equals 16,994 GWh (230.4 PJ), is currently supplied mostly by hydraulic (71.9%) and thermal (26.7%) generation [19].

Gasification, an efficient thermochemical conversion process used to transform different materials into a fuel gas (syngas), may be used to take advantage of the aforementioned bioenergy potential and to diversify the energy sources of the country. Indeed, through a combination of overlapping processes such as pyrolysis, drying, and partial oxidation, gasification is much more efficient than current energy conversion processes, such as the direct combustion of agricultural waste, which the country uses on a small scale [20,21]. The main product obtained from gasification is syngas, which, in turn, can be used as a biofuel to generate heat or electricity [21]. Moreover, when air is the gasifying agent, syngas has an average low heating value (LHV) that is much smaller than that of natural gas (approximately one sixth of it) [22], but it can still be used in internal combustion engines.

Nowadays, woody biomass is one of the most studied materials for bioenergy conversion, given its chemical composition and low moisture content, which provides good gasification efficiency [23–25]. For Colombia, this is no different. Indeed, when studying the bioenergy potential of the country, we identified a subtype of woody biomass that ought to be studied further: gorse (*Ulex Europeaus*). Gorse is a bushy plant species introduced from Europe which is currently classified as invasive. In addition to being a threat to endemic species, this plant is highly flammable and spreads very easily to its surrounding areas [26,27]. In 2019, an area of 386,931 ha was affected by gorse, and an area of 1,717,815 ha in the Cundinamarca and Boyacá regions was found to be at risk of being affected in the future [26,28]. Hence, taking advantage of this plant as an energy source would simultaneously aid in the disposal of these biomasses while generating bioenergy.

The present study calculates the gasification energy potential of gorse and other biomasses in Colombia. This study focuses on utilizing field and industry biomass generated as residues, alongside an analysis of the production of the main agro-industrial and forestry products in the country; the fluctuations in the amount of product produced per year was accounted for by considering peak and off-peak values during a five-year period. The biomass materials selected for this study were chosen by considering their availability and whether they could be efficiently gasified. Gasification was chosen as a suitable technology to efficiently convert the biomass into a fuel gas, because it is easy to handle and can be used to produce electricity if a conventional internal combustion engine is coupled with an electric generator. The results of this study show that the energy potential calculated for Colombian biomasses could satisfy a large part of the country's electricity demand by using biomasses such as oil palm trunks, oil palm fronds, coffee wood, and gorse, which are often undervalued resources.

2. Materials and Methods

The present study has three main purposes: (1) to evaluate the potential of biomasses that either have no current defined use, or whose value for energy-production processes has been overlooked; (2) to offer reliable results that can be validated by conversations with representatives of unions, companies, and government agencies that are related to the biomass generating processes; and (3), to frame the chosen biomasses as value sources, specifically when they are transformed via gasification.

The first step for estimating the energy potential in this area required studying the most common biomasses generated in Colombia (i.e., focusing on the biggest agricultural products of the country (palm oil, sugar cane, plantain, and banana)). Afterwards, properties such as the moisture content (MC) and LHV of each biomass were weighed in order to exclude those outside of the usable range recommended for gasification [19]. Crops that yield particularly valuable products and have a high residue-to-final-product ratio, such as coffee and cocoa, were also studied. Additionally, we considered forestry residues as a possible biomass source. It is worth noting, however, that we focused exclusively on industrial roundwood processed in sawmills, which only represents 27% of the biomass generated by the forestry industry [29]. The reason for this choice was, as well as being much more difficult and costly to collect, the remaining forestry biomass cannot be gasified as efficiently as roundwood biomass. Finally, we evaluated the energy potential of gorse, an invasive species with a rapid expansion rate that is currently threatening local biodiversity [26].

Upon identifying the relevant biomasses for this study, the methodology presented in Figure 1 was applied. First of all, we had to find more information on the chosen biomasses. The production and yield data we used were taken from national databases [12]. In order to account for possible production fluctuations over time, we analyzed production data spanning 5 years (see Appendix A). We chose to work with data from the 2015–2019 period because, in Colombia, since 2014, an increasing amount of accurate data in this area started being collected after the third national agricultural census took place; thus, by analyzing data across a significant timeframe, we were able to estimate the minimum and maximum energy potential for each biomass, which, in turn, allowed us to propose different possible scenarios for the implementation of gasification.

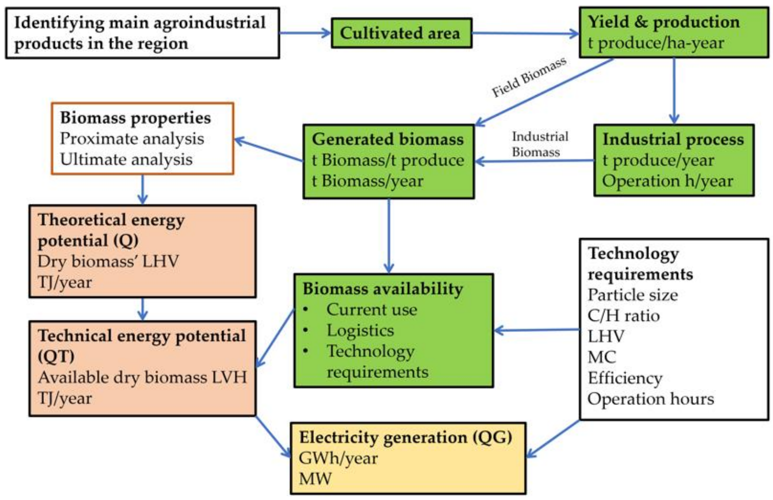

Figure 1. Biomass energy potential methodology.

The information on the residue-to-final-product ratio of each biomass came from a review of government statistics and the official union reports for each product. The current uses, logistics, and spatial dispersion of each biomass came from official union reports, and national and international research papers. The physicochemical properties of each biomass were taken from local sources when available, and from international research when necessary. Finally, we measured the LHV and MC of oil-palm trunks and leaves by following the ASTM D3172 and ASTM D5142. All of the collected data were discussed with Colombian representatives from biomass-generating production chains, who confirmed their validity for each biomass. Afterwards, we estimated the energy potential of each one, which required us to determine their current uses and disposal practices. This was achieved through further literature reviews, interviews with union leaders and product experts, and field work; thus, the availability of each biomass was estimated, which allowed us to provide both a theoretical and a technical energy potential for them.

Finally, in order to estimate the potential amount of electricity that could be generated through gasification in Colombia, a hypothetical gasification plant with a use factor of 85% (7446 h per year) was proposed. The gasification efficiency factor used in this calculation was based on the amount of syngas generated by each biomass, as well as its LHV; thus, the average efficiency of converting biomass to energy was set between 60–65% [30], following previous gasification studies. The efficiency of converting syngas into electricity was, in turn, determined to be 37% (if an internal combustion engine is used in the process) [31].

Mathematical Calculations

In the following section, the equations used to calculate the theoretical and technical energy potential, as well as the gasification energy potential of each biomass, are presented.

In order to calculate the quantity of produced biomass (B) of a region, its annual main biomass production (P) and its residue-to-final-product ratio (R) must be taken into account (Equation (1)). The sub index i represents the reference product, and j represents the type of biomass generated in its production.

$$B_{ij} = P_i \cdot R_j \quad (1)$$

For the specific case of gorse, the affected areas (a) reported by the CAR comprised the starting point. Then, its output factor (F) was estimated (as recommended by the public entities in charge of managing the territories affected by this species) as the amount of above-ground biomass per unit of area. Additionally, a renewal period (RP) (i.e., the time needed for the plants to reach an average height of 1.5–2 m) was accounted for (Equation (2)).

$$B_{gorse} = \frac{a \cdot F}{RP} \quad (2)$$

To calculate the theoretical energy potential (Q) of each biomass, both B and their particular physicochemical properties were taken into consideration. It is worth noting, however, that only dry matter is relevant for energy-potential calculations, which is why LHV and (MC) had to be included in Equation (3).

$$Q_{ij} = B_{ij} \cdot \left(1 - MC_j\right) \cdot LHV_j \quad (3)$$

In order to estimate the technical energy potential (QT) of a given biomass, its availability factor (A) is crucial (Equation (4)). Most of the field-generated biomasses have an A of 0.5, since it is recommended that at least half of the biomass residue of a crop is left on the field in order to protect soil quality, and to preserve its moisture and organic matter levels.

$$QT_{ij} = Q_{ij} \cdot A \quad (4)$$

Next, its gasification potential (QG) was calculated based on the yearly hours of operation of the generation plant (H), the gasification efficiency (E), and the motor-generator efficiency (n) (Equation (5)).

$$QG_{ij} = QT_{ij} \cdot H \cdot E \cdot n \quad (5)$$

Finally, to calculate the total energy potential of a particular region, all of the aforementioned energy potentials must be added (Equation (6)).

$$\overline{Q} = \sum Q_{ij}\ ;\ \overline{QT} = \sum QT_{ij}\ ;\ \overline{QG} = \sum QG_{ij} \quad (6)$$

3. Results

Table 1 relates each biomass to the industry that produces it and/or the product that generates it. Additionally, the residue-to-final product ratio, and the maximum and minimum production of each reference product, are presented.

Table 1. Reference product quantities and residue-to-final product ratios of each generated biomass.

Industry	Reference Product	P (kt/Year)	Biomass	R (t br/t Product)
Oil palm [a]	Fresh fruit bunches	5612.3–7172.8	Empty fruit bunch	0.23
			Oil palm kernel	0.06
			Mesocarp fiber	0.12
			Oil palm trunks	0.51
			Oil palm fronds	1.08
Sugar cane [b]	Raw sugar	2118.5–2371.2	Tops and leaves	2.4
			Sugar cane bagasse	2.5
Sugar cane (p) [c]	Panela	1098.2–1183.4	Tops and leaves (p)	3.7
			Sugar cane bagasse (p)	2.5
Coffee [d]	Green coffee	813.4–885.1	Coffee husks	0.38
			Coffee wood	0.34
Rice [e]	Green paddy rice	1988.2–2591.7	Rice husks	0.23
			Rice straw	1.43
Cocoa [f]	Dry cocoa beans	54.8–60.5	Cocoa pods	8
			Cocoa husks	0.12

Table 1. *Cont.*

Industry	Reference Product	P (kt/Year)	Biomass	R (t br/t Product)
Banana [g]	Fresh banana	1997.4–2238.3	Banana rachis Banana pseudostem	1 5
Plantain [g]	Fresh plantain	3542.4–4805.6	Plantain rachis Plantain pseudostem	1 5
Coconut [h]	Fresh Coconut	122.8–153.8	Coconut exocarp Coconut endocarp Coconut fiber	0.18 012 0.12
Forestry [i]	Sawmill roundwood	536.5–883.7	Forestry residues Sawmill residues	0.38 0.34
Invasive species [j]	Gorse	4546.4	Gorse biomass	1

[a] The production data for oil palm was taken from the statistical yearbook [32]; the biomasses residue-to-reference-product-ratios were taken from the local literature [33,34]. [b] The production data for sugar cane was taken from [35]; its residue-to-reference-product ratios were obtained directly from Cenicaña. A 10% sugar-to-sugar-cane ratio was considered. [c] The production data for panela was taken from [36]; its residue-to-reference-product ratios and availability were obtained directly from FedePanela, based on a previous study [13]. [d] The production data for coffee was taken from [37]; its residue-to-reference-product ratios were taken from studies published by Cenicafe [24,38]. [e] The production data for rice was taken from [12]; its residue-to-reference-product ratios were taken from [39,40]. [f] The production data for cocoa was taken from [41]; its residue-to-reference-product ratios were obtained from [42]. [g] The production data for banana and plantain was taken from the banana producers' organization reports [41,43]; their residue-to-reference-product ratios were obtained from [13,16]. [h] The production data for coconut was taken from [41]; its residue-to-reference-product ratios were obtained from [44,45]. [i] The production data for sawmill roundwood was taken from [29]; its residue-to-reference-product ratios were obtained from [13,17], as recommended by a MADR representative. [j] The area affected by gorse was determined to be 386,931 ha [26,27]. The gorse biomass that may be obtained per hectare was determined to be 23.48 t, following the final disposal certification reports from WELTNEU. The renewal period for gorse (i.e., how long it takes for it to reach a height of 2 m) was estimated to be 2 years.

The physicochemical properties of each biomass, which were then used to calculate their energy potential, are presented in Table 2.

Table 2. Physicochemical properties and availability factors of different biomasses.

Biomass	MC [%]	LHV [MJ/kg]	A [Available t/t]
Empty fruit bunch [a]	66	15.7	0.83
Palm kernel shell [a]	12	19.1	0.05
Mesocarp fiber [a]	38	17.42	0.12
Oil palm trunks [a]	50	12.33	0.5
Oil palm fronds [a]	45	20.09	0.5
Tops and leaves [b]	30	16.9	0.5
Sugar cane bagasse [b]	50	17.93	0
Tops and leaves (p) [b]	30	16.9	0.5
Sugar cane bagasse (p) [b]	50	17.93	0
Forestry residues [c]	40	19.3	0.2
Sawmill residues [c]	13	19	0.2
Gorse [d]	45	19.04	1
Coffee husks [e]	10	18.3	0
Coffee wood [e]	13	17.4	0.5
Rice husks [f]	13.1	18.4	0
Rice straw [f]	11.7	14.9	0.5
Cocoa pods [g]	85	15.5	1
Cocoa husks [g]	6.7	17.3	1
Banana rachis [h]	91	7.6	0.5

Table 2. *Cont.*

Biomass	MC [%]	LHV [MJ/kg]	A [Available t/t]
Banana pseudostem [h]	93	9.91	0.5
Plantain rachis [h]	91	7.57	0.5
Plantain pseudostem [h]	93	8.5	0.5
Coconut exocarp [i]	85	14.7	0.5
Coconut endocarp [i]	10.5	19.1	1
Coconut fiber [i]	13.5	16.7	0

[a] The physicochemical properties of these industrial residues were taken from [33]; the authors of this study measured the LHV and MC of oil palm trunks and leaves. The availability factor of oil palm biomasses were taken from [46]. [b] The physicochemical properties of these industrial residues were taken from [47,48]. Their availability factor was obtained directly from union representatives and organizations (Cenicaña and FedePanela). [c] The physicochemical properties of these industrial residues were taken from [16,17,49]. Their availability factor was obtained from union and company representatives, and it was further confirmed in the field (Fedemadera, Colombian Ministry of Environment and Sustainable Development). [d] The physicochemical properties of gorse were taken from [27,50]. Its availability factor is equal to 1 due to the nature of the biomass and the manner in which it is disposed. [e] The physicochemical properties of these industrial residues were taken from [24,38]. Their availability factor was estimated in accordance with the recommendations made by representatives of Cenicafe. [f] The physicochemical properties of these industrial residues were taken from [40,51]. Their availability factor was estimated in accordance with the recommendations made by industry representatives. [g] The physicochemical properties of these industrial residues were taken from [42,52]. [h] The physicochemical properties of these industrial residues were taken from [13]. Their availability factor was estimated in accordance with the recommendations made by industry representatives. [i] The physicochemical properties of these industrial residues were taken from [44,45].

The theoretical potential of each biomass was calculated using Equations (1)–(3). The technical potential of each biomass was calculated using Equation (4) (i.e., by multiplying each biomass' theoretical potential by its availability factor). The gasification potential of each biomass was calculated through Equation (5) (i.e., by including the hours of operation of the gasification plant and the efficiency of the gasification process). The total energy potential of Colombia was calculated using Equation (6). The results of these calculations are presented in Table 3. Additionally, the amount of available biomass (AB), which was obtained by multiplying Equation (1) by A, are presented in order to relate the energy-potential data of each biomass with its yearly production and availability. It is worth noting that the data are presented as ranges, given that we decided to account for fluctuations in biomass production by considering peak and off-peak production seasons. Moreover, in order to account for possible variations during the gasification process, we calculated the gasification energy potential of each biomass with a 60–65% efficiency range. In Table 3, QG presents a gasification-potential range for each biomass. The lower end of the range indicates the potential energy that could be produced in a situation where the available biomass was at its lowest and the gasification efficiency was also at its lowest; the higher end of the range presents the same energy-potential range in a situation where the available biomass was at its highest and the gasification efficiency was also at its highest.

Table 3. Total amount of biomass produced, its available quantity, and its energy potential.

Biomass	PB [kt/Year]	AB [kt/Year]	Q [TJ/Year]	QT [TJ/Year]	QG [MW]
Empty fruit bunch	1290.8–1649.7	1071.4–1369.3	6890.4–8806.3	5719.0–7309.2	47.4–65.6
Palm kernel shell	336.7–430.4	16.8–21.5	5659.9–7233.6	283.0–361.7	2.3–3.2
Mesocarp fiber	673.5–860.7	80.8–103.3	7273.8–9296.3	872.9–1115.6	7.2–10.0
Oil palm trunks	2862.3–3658.1	1431.1–1829.1	17,645.8–22,552.3	8822.9–11,276.1	73.1–101.2
Oil palm fronds	6061.2–7746.6	3030.6–3873.3	66,973.8–85,595.9	33,486.9–42,798.0	277.3–384.0
Tops and leaves	5084.4–5690.9	2542.2–2845.4	60,149.0–67,323.0	30,074.5–33,661.5	249.1–302.0
Sugar cane bagasse	5296.3–5928.0	0.0	47,481.3–53,144.5	0.0	0.0
Tops and leaves (p)	4063.4–4378.5	2031.7–2189.2	48,069.6–51,797.4	24,034.8–25,898.7	199.1–232.4
Sugar cane bagasse (p)	2745.5–2958.4	0.0	24,613.5–26,522.3	0.0	0.0
Forestry residues	203.9–335.8	40.8–67.2	2361.0–3888.5	472.2–777.7	3.9–7.0
Sawmill residues	182.4–300.4	36.5–60.1	3015.5–4966.4	603.1–993.3	5.0–8.9

Table 3. *Cont.*

Biomass	PB [kt/Year]	AB [kt/Year]	Q [TJ/Year]	QT [TJ/Year]	QG [MW]
Gorse	4546.4	4546.4	47,610.3	47,610.3	394.3–427.2
Coffee husks	187.1–203.6	0.0	3081.3–3352.9	0.0	0.0
Coffee wood	2928.3–3186.4	1464.2–1593.2	44,328.8–48,236.2	22,164.4–24,118.1	183.6–216.4
Rice husks	357.9–466.5	0.0	5722.2–7459.1	0.0	0.0
Rice straw	2843.1–3706.1	1421.6–1853.0	37,405.9–48,759.6	18,702.9–24,379.8	154.9–218.7
Cocoa pods	438.4–484.3	438.4–484.3	1019.2–1126.0	1019.2–1126.0	8.4–10.1
Cocoa husks	6.6–7.3	6.6–7.3	106.1–117.3	106.1–117.3	0.9–1.1
Banana rachis	1997.4–2238.3	998.7–1119.2	1366.2–1531.0	683.1–765.5	5.7–6.9
Banana pseudostem	9987.0–11,191.6	4993.5–5595.8	6927.9–7763.6	3464.0–3881.8	28.7–34.8
Plantain rachis	3542.4–4805.6	1771.2–2402.8	2413.4–3274.1	1206.7–1637.0	10.0–14.7
Plantain pseudostem	17,711.8–24,028.1	8855.9–12,014.1	10,538.5–14,296.7	5269.2–7148.4	43.6–64.1
Coconut exocarp	22.1–27.7	11.0–13.8	48.7–61.1	24.4–30.5	0.2–0.3
Coconut endocarp	14.7–18.5	14.7–18.5	251.8–315.6	251.8–315.6	2.1–2.8
Coconut fiber	14.7–18.5	0.0	212.8–266.7	0.0	0.0
Total	73,398.2–88,866.4	34,804.1–42,006.7	451,166.8–525,296.4	204,871.5–235,321.9	1696.7–2111.3

In the first scenario (i.e., low production and low efficiency), the calculated technical energy potential was 451.2 PJ/year, its total technical energy potential was 204.8 PJ/year, and finally, its total gasification potential was 1696.7 MW of electricity. In the second scenario (i.e., high production and high efficiency), the calculated energy potential was 525.3 PJ/year, its total technical energy potential was 235.3 PJ/year, and finally, its total gasification potential was 2111.3 MW of electricity. Additionally, in a low-production and high-efficiency scenario, the total gasification potential would be 1948.9 MW, whereas in a high-production and low-efficiency scenario, this potential would be 1831.1 MW. In what follows, however, we will mostly focus on the first two scenarios, since they allow us to establish the widest possible energy-potential range for the evaluated biomasses.

The notable difference between the theoretical and technical energy potential in both scenarios is attributed to the availability factor of each biomass. Working with strict availability factors guarantees that there will be no conflicting uses for each produced biomass (e.g., the residues needed to protect and enrich the soil of a field will not be used for energy production). Figure 2 presents an overview of the technical energy potential estimated for the country.

Thus, overall, gorse turned out to have the highest technical energy potential in both scenarios (20.23–23.23%), followed by oil-palm leaves (16.34–18.18%), sugar cane tops and leaves (14.30–14.67%), sugar cane (p) tops and leaves (11.00–11.73%), coffee wood (10.25–10.85%), and oil-palm trunks (4.30–4.79%). It is worth stating that those biomasses with an energy potential equal to 0, such as sugar cane bagasse and coffee husks, also had an availability factor of 0. This is due to the fact that they are already being transformed into energy, though not in gasification plants. Since Colombia's energy consumption sits at around 1336 PJ/year and the total technical energy potential of the country was estimated to be 204.9–235.3 PJ/year, 15.3–17.6% of this energy demand could be supplied by biomasses if there was a transformation technique whose efficiency was 100%. On the other hand, if gasification were to be chosen as the transformation technique to convert all available biomasses into energy, 3.69–4.24% of the total energy demand of the country could be supplied, since the total gasification potential of these biomasses is 1696.7–2111.3 MW (49.3–56.6 PJ/year). It is worth noting that gorse alone would be able to supply 3.6% of the national energy demand if it could be converted to energy with a 100% efficiency. Realistically, however, if gasification was the chosen transformation technique, this invasive species would be able to supply 0.88% of that demand, given that its gasification potential is 427.2 MW (11.5 PJ/year). Furthermore, the total gasification energy potential calculated in this study for each scenario, which was 12,633.7–15,720.8 GWh (1696.7–2111.3 MW), could supply 74.34–92.51% of the 16,994 GWh of the electricity consumed in the country.

The gasification energy potential of gorse alone could supply 17.28–18.72% of the national electricity demand, since it equals 2935.97–3180.63 GWh (394.3–427.2 MW).

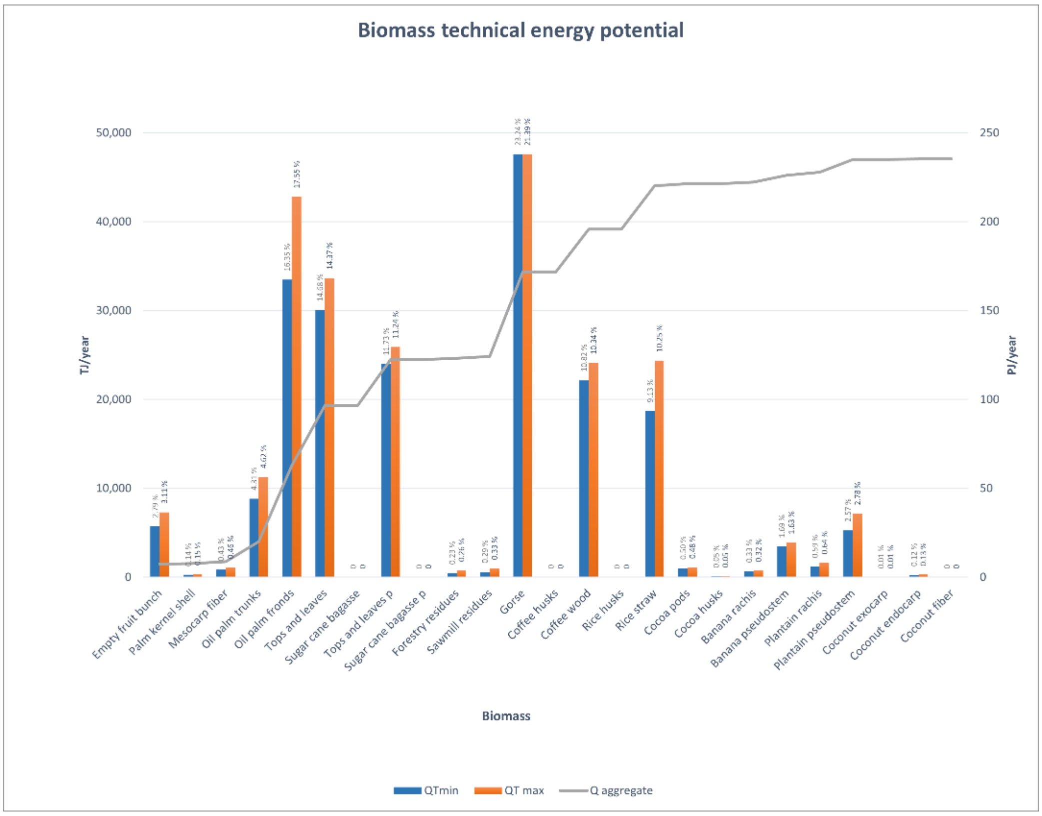

Figure 2. Maximum (orange) and minimum (blue) Colombian biomass technical energy potential and technical energy potential aggregate value (grey).

Thus, overall, gorse turned out to have the highest technical energy potential in both scenarios (20.23–23.23%), followed by oil-palm leaves (16.34–18.18%), sugar cane tops and leaves (14.30–14.67%), sugar cane (p) tops and leaves (11.00–11.73%), coffee wood (10.25–10.85%), and oil-palm trunks (4.30–4.79%). It is worth stating that those biomasses with an energy potential equal to 0, such as sugar cane bagasse and coffee husks, also had an availability factor of 0. This is due to the fact that they are already being transformed into energy, though not in gasification plants. Since Colombia's energy consumption sits at around 1336 PJ/year and the total technical energy potential of the country was estimated to be 204.9–235.3 PJ/year, 15.3–17.6% of this energy demand could be supplied by biomasses if there was a transformation technique whose efficiency was 100%. On the other hand, if gasification were to be chosen as the transformation technique to convert all available biomasses into energy, 3.69–4.24% of the total energy demand of the country could be supplied, since the total gasification potential of these biomasses is 1696.7–2111.3 MW (49.3–56.6 PJ/year). It is worth noting that gorse alone would be able to supply 3.6% of the national energy demand if it could be converted to energy with a 100% efficiency. Realistically, however, if gasification was the chosen transformation technique, this invasive species would be able to supply 0.88% of that demand, given that its gasification potential is 427.2 MW (11.5 PJ/year). Furthermore, the total gasification energy potential calculated in this study for each scenario, which was 12,633.7–15,720.8 GWh (1696.7–2111.3 MW), could supply 74.34–92.51% of the 16,994 GWh of the electricity consumed in the country. The gasification energy potential of gorse alone could supply 17.28–18.72% of the national electricity demand, since it equals 2935.97–3180.63 GWh (394.3–427.2 MW).

The theoretical energy potential estimated for most of the agricultural biomasses is similar to the values reported in previous studies [13–15]; however, in the case of sugarcane, coffee, rice, bananas, and plantains, there were some slight variations, which we attribute to the different MC and LHV values used in the present study. Furthermore, in addition to the aforementioned changes in physicochemical properties, we included a new variable in our estimation of the palm-oil-industry's energy potential. We considered the energy potential of field residues (i.e., oil palm trunks and oil palm fronds); this caused significant variations between the final energy potential values obtained for this industry, which, when compared with previous studies, focused mostly on biomasses that could be obtained from industrial processing. The forestry energy potential estimated in this study also turned out to be different to that reported in previous works [13,16], most likely as a consequence of the boundaries we applied to the study, which focus on roundwood processed in sawmills.

4. Discussion

This study presented the energy potential of Colombian biomasses while accounting for possible variations in agricultural and forestry production, which directly affects biomass availability. Moreover, we considered the possible efficiency variations in the gasification process. We would like to note that we established the scenarios by focusing on the values of properties which are the most susceptible to fluctuations. Biomass production and gasification efficiency may vary for many reasons, whereas the physicochemical properties and the residue-to-final-product ratios of each biomass remain quite stable as time goes on.

Colombia is a country with great potential for generating energy from biomass, due to the high production of the latter in several industries. Moreover, due to their woody nature, high LHV, and centralized production, some of these biomasses are particularly apt for conversion into energy through gasification. Indeed, the residues from these industries may be used to supply their own energy demands or to produce electricity to be sold in the market. Even in industries where other transformation methods, such as combustion in the sugar cane industry, are already comprehensively in place, research on gasification could still be fruitful. Certainly, the tops and leaves of sugar cane are conventionally not used as a viable energy resource; thus, presenting a more efficient technology as an alternative, such as gasification, can increase its value and the industry's interest.

On the other hand, the energy potential estimated for biomasses produced at a smaller scale, such as cocoa pods, is comparable with the potential of residues generated at much greater scales, such as those generated in the sugar cane and palm oil industries; therefore, harnessing the energy potential of small-scale residues may allow farmers to supply their own energy needs. They may also be a driving force for the replacement of fossil fuels. Taking this into account, and considering the relatively high costs associated with setting up and operating gasification plants, it is crucial to find ways of guaranteeing the profitability of this practice in order to make it more accessible. Indeed, implementing strategies such as setting up agricultural-producers' associations, installing regional plants, and tax incentives put in place by the government may help gasification to find its place as a sustainable energy-generation technology in Colombia.

Similarly, the energy potential estimated for gorse is comparable to that of some of the biomasses generated in the large-scale agroindustry. Hence, this material might be revalorized and turned into a temporary or permanent source of bioenergy. It is clear that partially reframing an invasive species as a source of biomass for energy generation could interfere with its ultimate eradication; however, taking advantage of the energy potential of such species requires, at the very least, regulating its spread, which would tackle some of the ecological problems that gorse is currently causing, even if it does not lead to a complete solution. Moreover, the exact outcome of a combination of economic incentives and the need to solve ecological problems is not always straightforward. Indeed, there are various conceivable scenarios that could take place if the gasification of gorse was implemented.

With this in mind, we present two possibilities, one that privileges economic sustainability and another one that privileges ecological concerns. The first one requires collecting the total available gorse biomass in the affected regions and subsequently transforming it into energy. These areas could then be carefully monitored to guarantee the complete eradication of the invasive species. In this case, the profits of selling the produced energy would be limited, since the biomass supply would not be constantly regenerating. This would perhaps mean that the sale of bioenergy would not be enough to recover the initial investments; however, the gasification plants set up for this purpose could be repurposed to convert other types of biomasses once gorse is eradicated. Moreover, the ecological benefit that this would produce is invaluable. The second scenario involves regularly collecting a portion of the available gorse biomass in order to turn it into energy; thus, the spread of the invasive species would be controlled, while guaranteeing a steady supply of biomass and economic sustainability in the long run. Additionally, despite the damage that it causes, gorse has proven to be able to provide some ecosystem services, such as erosion prevention and soil-moisture retention. Indeed, despite the aforementioned services often being less significant than the ones provided by native biomes, working with a limited amount of gorse may be very useful in some ecosystems where water is scarce and the soil is low in nutrients [26]. In controlled settings, these services could be properly harnessed, while keeping damages to a minimum.

Furthermore, field-generated biomasses have the highest energy potential when their availability and the scale at which they are produced are considered; however, taking full advantage of this potential has some challenges associated with the transport, collection, and storage of the relevant biomasses. Nevertheless, as this study shows, their energy potentials may make it worth facing such challenges and coming up with solutions, such as densification; such technologies would increase the profitability of gasifying them. Moreover, this potential may be further increased in the future due to optimization of the gasification efficiency, or an increase in biomass production. The availability factor of field-generated biomasses was established at 50%, since the soil requires a portion of that biomass to be mulch in order to remain healthy; however, this number comes from unsystematic observations from farmers, and could perhaps be made more precise for each biomass in each particular case. By verifying the soil requirements of each farm and crop, only the absolutely necessary amount of biomass could be left in the soil, which would increase its availability factor for gasification and would allow farmers to extract more value from it.

Moreover, the results of this study may be used by unions and research centers as a stepping-stone to take advantage of the potential of often-overlooked materials. Developing plans and studies that promote the implementation of biomass-transformation technologies, may prove to be worthwhile in the near future. Even though this study focused on gasification as a viable energy production technology, here, the technical potential found for each of the evaluated biomasses can be harnessed through the use of other technologies to produce electricity or heat.

The worldwide climate crisis, which will most likely intensify in the coming years, also makes research on gasification and other biomass-transformation methods a necessity. Even if hydroelectric plants are, in the long run, a low-cost alternative for producing renewable energy, they are vulnerable to events such as droughts. Nowadays, Colombia's electricity generation relies almost entirely on hydroelectric power, so it would be wise to start diversifying energy sources in order to mitigate the negative effects of future climate phenomena. Although bioenergy is also vulnerable to droughts, it is not vulnerable to the same extent, nor in the same way as hydroelectric power. This means that bioenergy production would not necessarily collapse or be significantly affected if the same were to happen to the hydroelectric plants of a region (the opposite, of course, is also true). Furthermore, large-scale crops, such as sugar cane, show peaks of production during dry periods in the country [53]. The energy supplied would most likely be insufficient to offset the shortages that a failing hydroelectrical plant would produce; nevertheless, it is sensible to diversify energy sources to reduce the impact that such events may cause with regard to energy availability.

Finally, it is worth mentioning that the accuracy of the gathered data on biomass-production and biomass physicochemical properties attests to the fruitful results of academic researchers, union representatives, and government agencies collaborating with each other. Overcoming the disjointed relationships between academia, the government, and the various productive industries of a country will be crucial for the development and actual implementation of technologies that may contribute to the current efforts to combat climate change while also increasing the efficiency of industrial production. Similar methodologies can be applied to any region to help it move towards a more sovereign and sustainable energy supply.

5. Conclusions

The gasification energy potential of several currently unused biomasses in Colombia is significant. Indeed, the data show that 92.51% of the electricity demands of the country could be satisfied—as well as up to 17.6% of its overall energy demands—through gasification. As diversifying the energy-production strategies of a country makes it more resilient against the negative effects of climate change, implementing gasification is also advisable. Moreover, implementing this technology requires using materials that would otherwise be discarded, which may help to reduce CO_2 emissions. Thus, an environmentally conscious implementation of gasification could help countries fulfill their SDG compromises. For these reasons, analyzing the suitability of implementing gasification in different regions across the globe, and optimizing its operational and logistical conditions, seems to be a sensible path for future bioenergy research.

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Appendix A. Agricultural and Forestry Production Data (kt)

Reference Product	2015	2016	2017	2018	2019	μ	σ	Min	Max	cv
Oil palm	6291.2	5612.3	6646.9	7007.3	7172.8	6546.1	623.0	5612.3	7172.8	0.10
Sugar cane	2371.2	2118.5	2233.8	2335.4	2204.0	2252.6	102.0	2118.5	2371.2	0.05
Sugar cane (p)	1168.3	1101.3	1166.6	1183.4	1098.2	1143.6	40.5	1098.2	1183.4	0.04
Forestry	569.2 *	575.5	536.5	883.7	751.1	663.2	149.1	536.5	883.7	0.22
Coffee	850.5	823.9	851.6	813.4	885.1	844.9	28.0	813.4	885.1	0.03
Rice	1988.2	2526.2	2591.7	2486.7	2536.9	2425.9	247.6	1988.2	2591.7	0.10
Cocoa	54.8	56.8	60.5	56.9	59.7	57.7	2.4	54.8	60.5	0.04
Banana	1997.4	2001.5	2120.7	2125.2	2238.3	2096.6	100.5	1997.4	2238.3	0.05
Plantain	3542.4	3909.0	4111.7	4430.2	4805.6	4159.8	483.9	3542.4	4805.6	0.12
Coconut	130.0	122.8	127.2	145.3	153.8	135.8	13.2	122.8	153.8	0.10

* Data from 2020.

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