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Sustainable Renewable Energy by Means of Using Residual Forest Biomass

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Abstract: The substitution of energy based on fossil fuel by bioenergy could be an effective solution to reduce external energy dependency, thereby promoting sustainable development. This article details a study of the use of biomass residues produced in the forestry sector as a consequence of field operations of the two predominant forest species (*Pinus radiata* D. Don and *Ecualyptus globulus* Labill) of Biscay (Spain). The potential of forest residues is estimated to be 66,600 dry Mg year^{-1}. These residues would provide 1307 TJ year^{-1}. Energy parameters, ultimate and proximate analyses, and the level of emissions of the forest residues are performed in order to estimate their characteristics as fuel. The research done has shown very similar values in terms of the net calorific value of the residues of *P. radiata* (19.45 MJ kg^{-1}) and *E. globulus* (19.48 MJ kg^{-1}). The determined emission factors indicate a reduction in gas emissions: CO (23–25%), CO_2 (22–25%), SO_2 (87–91%) and dust (11–38%) and an increase of 11–37% in NO_x compared to hard coal. Estimation of the emission factors of the residual biomass allows the environmental impacts, that are potentially produced by biofuel, to be estimated.

Keywords: aboveground biomass; forest biomass residue; bioenergy potential; emission factors

1. Introduction

In recent times, there has been an increase in the interest in bioenergy due to the growing awareness of the problems of climate change. The increase in global energy demand together with the high cost of fossil fuels and their associated environmental problems has caused the need for increased research into renewable energy sources, including biomass [1–3]. Among the renewable energies, biomass plays a very important role in the new energy framework, as forest and agricultural residues are produced in relatively great quantities all over the world, and its high energy content is managed, out of the inconveniences that other renewable sources have, such as the sun and/or the wind, which are subjected to temporary availability for exploitation. According to several reports [4], biomass contributes about 11% to the global amount of primary energy and is the fourth biggest resource exploited in the world [5]. In the Autonomous Community of the Basque Country (ACBC, Spain), biomass is the most commonly used renewable source of energy [6]. For example, in 2015, the renewable energy consumption was 5.06 million MWh of which 85% was biomass [7]. Nowadays, bioenergy only provides 4.9% of electricity and heat generation in the ACBC. However, the energy exploitation of biomass could reduce the Basque external energy dependence, which is currently 93.1%, higher than that of any of the European Union countries, except Luxembourg.

Projections suggest increasing the participation of cogeneration and renewable energies for electric generation will increase bioenergy from 20% in 2015 to 31% in 2025. With this increment, it will be possible to contribute to the reduction of 1.6 Mt of CO_2, with biomass being one of the most relevant renewable energy sources (Energy Strategy 3E-2025 [8]). Several studies suggest that the use of forest biomass is an available strategy to help compensate for greenhouse gas emissions (GGE) [9–14]. If biomass comes from agricultural or forest residues, the reduction in the emissions of CO_2 exceeds 80% in comparison to fossil fuel [15]. The energy use of the residues generated by forest mass is, at the very least, an interesting alternative, especially in Biscay, a province belonging to the ACBC, where more than 60% of the surface is forest. This province has the highest relative quantity of wood volume in Spain, with an average standing timber stock of 177 m^3/ha [16]. These data suggest that the forest biomass residues could be an abundant fuel source for bioenergy projects, replacing a portion of the fossil fuel in energy facilities.

The forestry management of the forests of Biscay, which are mainly private, is essential for the ecological sustainability and the supply of wood products. Sustainable management of the woods plays an essential role in environmental protection. However, little is known about the biomass reserves that are now available in the woods of this area, which could sustain the bioenergy industry. Its quantification is essential to determine the structure, functioning, and dynamics of these ecosystems, as well as to determine the carbon sequestration in the vegetation and evaluate its use as an energy resource [17,18]. One of the main problems faced by researchers when dealing with bioenergy is the difficulty in accurately estimating the available resources. The inability to completely address the capacity of indigenous biomass resources and their probable contributions to energy continues to be a severe constraint to the complete realization of the bioenergy potential. Traditional forest inventories have provided a great quantity of data about biomass estimation and the growth of trees. Therefore, they have been widely used by different authors [19,20].

The object of this research project is to develop a methodology for the evaluation of the forest biomass used in energy production and the cartography of the resources by means of the Geographic Information Systems (GIS) in Biscay (Spain). To this end, it involves determining the quantity of forest biomass residue (FBR) that is available and usable as an energy source coming from the forestry treatments of the main local forest species. As a rule, logging operations only eliminate the marketable part of timber. The rest of the biomass is normally left to rot in the reaping or unloading site, but its energy use could reduce the risk of wildfire [21]. Although industrial by-products, such as sawdust and woodchips, are available and can be alternative fuel sources, they are not taken into account for their use as biofuel in this research as they are currently widely used in the area by birch plywood and wood fibreboard industries. Only the availability of primary residues is taken into consideration in the calculations, and its assessment considers the different stages through which the full rotation of the forest species is developed and the forest biomass generated in each stage.

In this research, we consider environmental protection and sustainable development; thus, the estimation of residual biomass usable for energy purposes is analysed, not only in terms of economical aspects (land inclination) but also environmental ones, considering the reduction of greenhouse gas emissions (GGE) in the biomass combustion with respect to fossil fuels. However, biomass combustion provokes gas emissions and particles (PM) which can severely affect the atmosphere and human health [3,22,23], and it is therefore essential to carry out estimations so as to determine the emissions of pollutant gases produced in energy assessment.

Today, the main problem regarding the use of forest residues as energy sources arises from the lack of available information about the traceability of the biomass to be used in the installation of energy exploitation. This obliges them to have an analytical infrastructure, sometimes complex, to determine the quality of the biofuel. Because of this, in this research, as a second objective, we aimed to estimate the levels of gas emissions (CO, CO_2, CH_4, NO_x and SO_2) and dust in the use of forest residues as fuel, using the methodology of emission factors [24]. To obtain this information, it was necessary to obtain information about the properties of FBR as a fuel by determining its chemical and fuel properties.

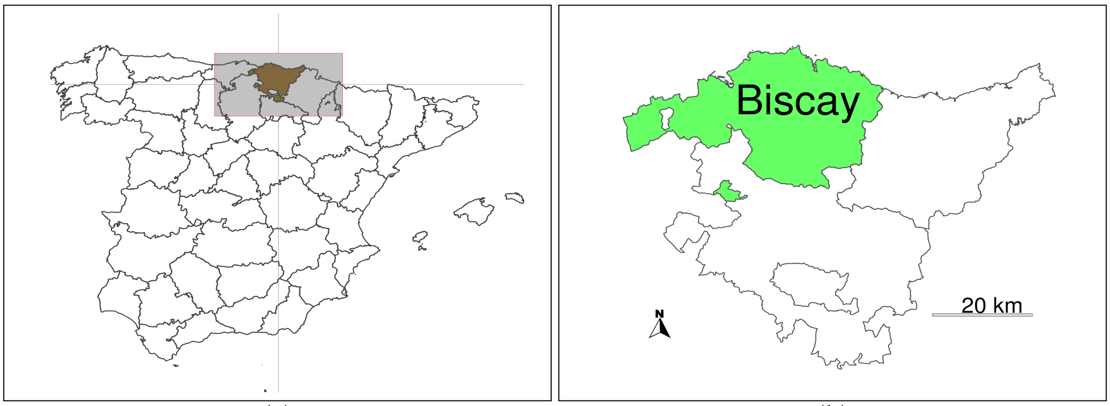
2. Methodology

2.1. Study Area

The study area is located in Biscay, a Spanish province situated in the north part of Spain (43″46′–42″92′ N, 03″45′–02″40′ W) (Figure 1). Most of the courses of rivers in Biscay belong to the Atlantic slope and their gradient is very marked. As a result of this, erosion in these stretches is considerable. The average annual temperature is 12–14 °C. In Biscay, forests cover approximately 132,000 ha [16] and represent 60% of its surface (221,232 ha). The main tree species of Biscay are *Pinus radiata* D. Don which covers 74,720 ha and *Eucalyptus globulus* Labill with coverage of 10,123 ha according to the Fourth National Forest Inventory [16]. The majority of these plantations are on slopes of more than 7% gradient; thus, almost 50% of the plantations are covered with slopes between 30% and 50%. In this research, we considered these two species because 93% of the annual loggings in Biscay are of *P. radiata*, 5% are *E. globulus*, and the rest are native species (Table 1). In this research, we did not consider the thicket areas, because apart from covering a very discreet surface in the area (8.6%), its low productivity and broad spread as well as the logistic problems involved in its collection, suggest that it should not be considered.

Table 1. Loggings carried out in the forests of Biscay between 2011 and 2016 (Basque government). V_{ob}—wood volume over bark (m^3).

Year Cuttings	2011 V_{ob}	2012 V_{ob}	2013 V_{ob}	2014 V_{ob}	2015 V_{ob}	2016 V_{ob}	Total
Pinus sylvestris					35	64	99
Pinus laricius	16,124	21,802		2533	1258	970	42,687
Pinus pinaster	11,723	18,532		26,658	30,248	24,125	111,286
Pinus halapensis						30	30
Pinus radiata	72,463	573,586	536,071	641,389	607,602	705,940	3,137,051
Spruce	450	1567		90	370	226	2703
Other Conifers	16,175	9400	42,984	11,413	19,003	33,116	132,091
Total Conifers	116,935	624,887	579,055	682,083	658,514	764,472	3,425,946
Walnut				2		1	3
Poplar				35	329	10	374
Birch				7		30	37
Alder						7	7
Beech				1798	32	213	2043
Chestnut				49	204	1	254
Quercus petraea						3	3
Quercus robur		359		107	39		505
Other Quercus	2106	1821		302	563	566	5358
Eucalyptus globulus	129,157	164,038	141,180	173,155	66,890	204,292	878,712
Elm				11	31	62	104
Other Broadleaves	9216	1270		1202	1514	1780	14,982
Total Broadleaves	140,479	167,488	141,180	176,668	69,601	206,965	902,381
TOTAL	257,414	792,375	720,235	858,751	728,115	971,437	4,328,327



(**a**) (**b**)

Figure 1. Map of the province of Biscay (Spain). (**a**) Spain; (**b**) Biscay.

2.2. Estimation of Production of Aboveground Biomass and Forest Residues

The estimations of the different aboveground biomass fractions were done considering the Fourth National Forest Inventory (NFI4) and followed an indirect methodology. Originally, all the plots from the NFI4 whose areas were occupied by the two predominant species in Biscay according to the forest map of ACBC were selected [25]. The estimation of forest biomass was carried out using the methodology of Esteban et al. [26] (Figure 2) by applying allometric equations:

$$W_{ij} = \beta_0\,(DBH_{ij})^{\beta_1} \tag{1}$$

where W_{ij} is the biomass of each of the biomass fractions (timber, branches, needles, . . .) of the species i and the tree j, expressed in kg of dry matter, DBH is the diameter at breast height, β_0 is the intercept (allometric factor), and β_1 is the slope (allometric exponent). To eliminate the bias introduced in the logarithmic transformation, the final result must be multiplied by a correction factor (CF) calculated from the standard error of estimate (SEE) [27]. Previous research has proven the suitability of this type of equation in the forests of Biscay [28], as it has been used by several researchers in order to get a suitable level of precision [29–32]. In each selected plot, we used Montero's [29] allometric equations to calculate the biomass fractions (Table 2).

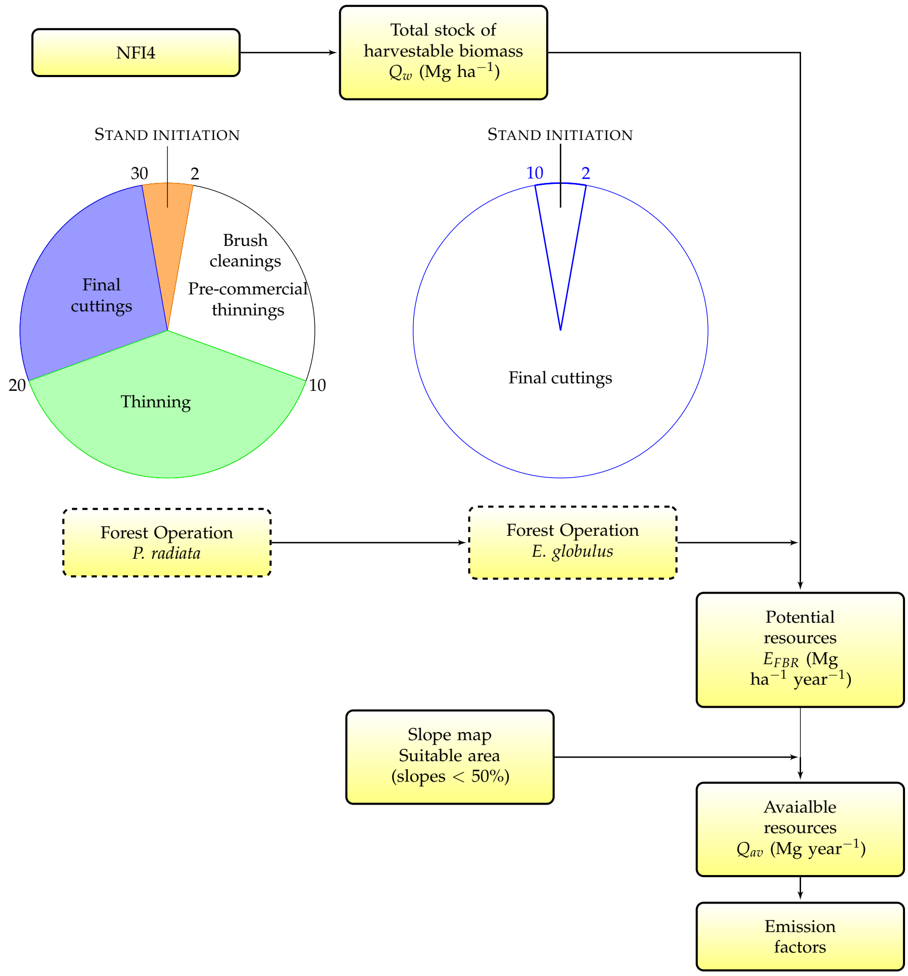


Figure 2. Methodological diagram for determining the forestry residue and emission factors.

Table 2. Biomass fraction equations [29]. *AB* = aboveground biomass; *SW* = stem wood biomass; B_7 = branches > 7 cm; B_{2-7}= branches 2–7 cm; B_2 = branches < 2 cm minimum top diameter; B_r = root biomass.

Species	**Parameters**		R^2_{adj}	**SEE**
	β_0	β_1		
P. radiata				
AB	–2.611	2.487	0.977	0.193
SW	–3.029	2.564	0.976	0.200
B_7	–10.569	3.649	0.710	0.525
B_{2-7}	–4.125	2.117	0.746	0.615
B_2	–3.535	1.759	0.669	0.616
Needles	–5.035	2.058	0.739	0.610
E. globulus				
AB	–1.330	2.194	0.980	0.158
SW + B_r	–2.204	2.382	0.974	0.197
B_{2-7}	–2.676	1.872	0.822	0.442
B_2	–2.648	1.614	0.858	0.333
Leaves	–2.059	1.618	0.859	0.333

The plots of NFI4 are of variable radius, so this circumstance necessitated the use of expansion factors ($EXP_{factors}$) in order to reduce the data to the hectare level. The biomass of each tree was weighted by the expansion factor of NFI4 according to its diametric range:

$$EXP_{factors_j} = \frac{10{,}000\ \mathrm{m}^2\ \mathrm{ha}^{-1}}{S_j} \tag{2}$$

where S_j is the area of each plot with size j measured in m^2. The stock of the different fractions of aboveground biomass Q_{w_i} (Mg ha^{-1}) in dry matter were obtained according to the equation:

$$Q_{w_i} = \sum_{i}^{n} EXP_{factors_j} \cdot \frac{W_{ij}}{1000}. \tag{3}$$

The annual growth of biomass (ΔW_i, kg year^{-1}) was estimated by means of the introduction of diametrical growth into the models:

$$\Delta W_i = f(D_n + \Delta I_n) - f(D_n) \tag{4}$$

where D_n is the normal diameter (cm) and ΔI_n is the annual diameter growth (cm year^{-1}). In order to estimate the net growth of the forests, data from cuttings of *P. radiata* and *E. globulus* in the province of Biscay during the period 2011–2016 were collected. Data of use were provided by the Biscay Provincial Council [33] (see Table 1).

In the forest mass, the biomass suitable for use in the generation of energy was the residual biomass (non-timber) left in the mount (branches, twigs, and leaves) after the forest treatments which were implemented along the complete rotation of a forest stand in distinct phases. The most important forest treatments in each forestry species were identified using the local management programs [34]. In this research, we took into account the loggings of *P. radiata* over 30 years in which a forest treatment was applied every 10 years involving the removal of one-third of the trees. With respect to *E. globulus*, the forest treatment was limited to the final logging every 10 years (see Table 3).

Table 3. By-products obtained in the forest treatments along the rotation of *P. radiata* and *E. globulus*.

Species	Age (Year)	Activity	By-Products	Equation	Source
P. radiata	10	Brush cleanings	Small trees *DBH* < 7.5 cm	$W = e^{\frac{0.19327^2}{2}} e^{-2.61093}$	[29]
		Pre-commercial & pruning	Branches and needles	$\ln(W) = -2.47 + 1.95\ln(D_n)$	[30]
	20	Thinning	Branches and needles	$\ln(W) = -2.47 + 1.95\ln(D_n)$	[30]
	30	Final cuttings	Branches and leaves		
E. globulus	10	Final cuttings	Branches and leaves	$W = \frac{0.1785\, D_n^{1.756}}{2.110}$	[35]

The estimation of the amount of annual forest biomass residue in dry matter E_{FBR} (Mg ha^{-1} year^{-1}) was obtained as

$$E_{FBR} = \frac{\sum_{T_1}^{T_2} N \cdot Q_{w_i}}{1000 \cdot T} \tag{5}$$

where N is the number of trees cut in the time period $T_2 - T_1$ elapsed between two forest operations. In the management of the forest mass, there are some environmental and technical restrictions that prevent the total use of the obtained residual biomass. For this reason, in this research, the usable biomass was estimated taking into account the constraints from the slope of the field. The removal of biomass was only considered for slopes less than 50%, as, apart from not being suitable economically, steeper slopes could lead to problems of erosion and soil loss. Moreover, the steeper the slope is, the more expensive the removal is [19,36,37]. We used the slope map which had to be previously digitalised for its use by GIS [38]. In order to determine the area suitable for collecting residual forest biomass, the area of the province was reclassified using its slope layers in the GIS, giving a value of "1" to those areas with a slope less than 50% and a value of "0" to those areas with a slope greater than the value from topographic data, creating a new layer which included the areas usable for energy use [19]. The annual available quantities of residual forest biomass expressed in dry basis (Mg year^{-1}) were obtained as

$$Q_{av} = \sum_{n} A_n \cdot E_{FBR} \quad (6)$$

where A_n represents the available surface (ha) for the collection of forest residue taking into account the economical and sustainability criteria (slopes less than 50%).

2.3. Experimental

The fieldwork focused on the collection of samples of residual forest biomass after the forest treatments of *P. radiata* and *E. globulus* in Biscay. Stratified random sampling was done. The samples were collected between the months of April and June in 2015. The forest biomass samples collected—about 2 kg per sample—consisted of branches of variable diameter between 7 cm and 1 cm, and leaves and needles. The forest residue samples were prepared and conditioned for analysis in the laboratory. Measurements included an estimated elemental analysis of each sample (% C, H, N and S), moisture content, a proximate analysis (ash, volatile matter and fixed carbon), and gross calorific values (GCV). All determinations were carried out in triplicate.

2.3.1. Proximate Analysis

The proximate analysis was carried out in a muffled furnace (Select-Horn-TFT) to determine the average percentage moisture in air-dried residual biomass samples to determine the weight fractions of moisture, volatile matter (VM), ash, and fixed carbon (FC) according to standard analysis methods [39–41]. The moisture content (wet basis) was estimated by the convection oven dry method [39]. The ash content (A) (in dry matter) was analyzed according to the European Standard [40]. The volatile matter content (dry matter) was established according to [41]. The fixed carbon content (%) is the difference between the sum of moisture (M, %), volatile matter (%) and ash contents (%) from 100. The fuel ratio (FBR, %) was calculated as the ratio of FC to volatile matter (VM).

2.3.2. Ultimate Analysis

An elemental composition of residual biomass was carried out according to European Standard methods [42,43] to determine the carbon (C), hydrogen (H), nitrogen (N) [42], and [43] sulfur (S) content. Ultimate analyses were carried out using a LECO CHN-2000 for C, H, and N and a LECO SC-144DR for sulfur determination. The oxygen content was measured by subtracting the sum of (C, H, N, S, and ash) contents from 100%.

2.3.3. Calorific Value

The gross calorific value (GCV) of residual biomass samples was evaluated according to European Standard methods [44] using a adiabatic bomb calorimeter (IKA C 5012). The net calorific value (NCV) was calculated as

$$GCV = NCV - 2.442\,\frac{W}{100} - 2.442\,\frac{9\,H}{100} \tag{7}$$

where H is the percentage by weight of hydrogen in the dry simple, W is the percentage by weight of moisture which the sample has, and 2.442 MJ kg^{-1} is the latent heat of water vaporization, and 9 is the coefficient conversion of H content in the water. As Equation (7) shows, the difference between GCV and NCV only depends on the energy consumed in the vaporization of the water obtained through the hydrogen that the fuel contains.

2.4. Emission Factors

Emission factors are defined as the amount of pollutant emitted per Mg of burned biomass (E_i, kg Mg^{-1} fuel). The main emissions that may be released from biomass combustion are nitrogen oxides (NO_x), sulphur oxides (SO_x), carbon oxides (CO_x), and dust. In this research, we considered NO_x (NO, NO_2) and SO_x (SO_2, SO_3) as NO_2 and SO_2 respectively because they are the products from the main reactions [45]. The potential emissions produced during the FBR combustion can be theoretically calculated based on the balance principle of mass conservation, that is to say

$$x(\text{C,N,S})_{FBR} \longrightarrow x(\text{CO}_2, \text{NO}_2, \text{SO}_2)_{emission}$$

where s is the quantity of FBR consumed in the combustion of dry matter or FBR gas emission. In this study, the level of gas emissions and FBR dust were estimated taking into account the factor emission method [24]. The emission of particles E_{dust} kg was calculated by means of the following formula:

$$E_{dust} = \frac{Q \cdot EF \cdot A \cdot 100}{100 - k} \tag{8}$$

where Q is the consumption of fuel (Mg), E is the dust emission factor, A is the percentage of ash in the biomass, and k is the content of fuel components in dust (5% in biomass). Gas emission levels (CO_x, SO_x, NO_x) and dust were calculated by following this methodology [24] (see supplementary article).

3. Results

3.1. Estimation of Aboveground Forest Biomass (Timber and Non-Timber Forests)

Table 4 shows the results of the biomass estimations obtained in the forests of Biscay. The total stock of aboveground forest biomass (AB) in 2011 was estimated to be 10,352.23 Gg (dry matter), of which 8334.36 Gg was timber aboveground biomass that is susceptible to commercial exploitation (7223.34 Gg *P. radiata* and 1111.02 Gg *E. globulus*), and 2017.87 Gg was non-timber aboveground biomass, with an annual gross growth of 602.5 Gg $year^{-1}$. The distribution of the biomass fractions obtained based on the diametric classes is shown in Figure 3. Data about loggings in Biscay Table 1 show that the total volume of timber removed (in dry matter) in the period 2011–2016 was 4.328 million m^3, with the average annual removal of timber biomass being 336.89 Gg $year^{-1}$. By deducting the extractions from the gross growth, we obtained a net annual growth of 265.61 Gg $year^{-1}$. With these values, the total aboveground biomass in Biscay in 2016 was estimated to be 11,680.28 Gg.

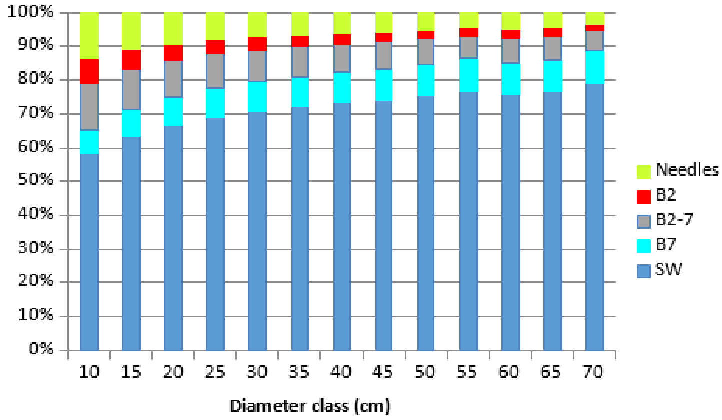


Figure 3. Graphic of aboveground biomass fractions.

Table 4. Aboveground biomass (dry matter, Gg) and its annual growth (Gg year^{-1}) in Biscay.

	Aboveground Biomass (AB)		
	Timber Biomass	**Non-Timber Biomass**	**Total AB**
Biomass (2011)	8334.36	2017.87	10,352.23
Annual growth	489.53	112.97	602.50
Annual extraction	270.73	66.16	336.89
Biomass (2016)	9428.36	2251.92	11,680.28

The average quantity of residue E_{FBR} in dry matter estimated in *P. radiata* and *E. globulus* was 1.102 Mg ha^{-1} year^{-1} (dry basis) and 1.024 Mg ha^{-1} year^{-1} (dry basis), respectively. The available quantity of forest residue suitable for energy assessment was 66,600 Mg year^{-1} dry mass, of which 56,610 (85%) was from *P. radiata* (Table 5).

Table 5. Average values of annual forest biomass residue (dry matter) (E_{FBR_i}, Mg ha^{-1} year^{-1}). Annual available residual forest biomass as dry mass (Q_{av}, Mg year^{-1}).

Forests Species	E_{FBR}			Q_{av}
	Minimum	**Mean**	**Maximum**	
P.radiata	0.312	1.02	1.165	56,610
E. globulus	0.784	1.024	1.243	9990
Total				66,600

3.2. Results of the Energy Evaluation

3.2.1. Proximate Analysis

The proximate analysis results are shown in Table 6. The samples obtained in the present study had moisture levels of 8.10 and 9.2%. Ash and volatile matter (VM) contents ranged from 2.92 to 4.12% and 70.43 to 71.76% for the residues of *P. radiata* and *E. globulus*, respectively. The average fixed carbon (FC) obtained was slightly higher in the residues of *P. radiata* (18.55%) than in *E. globulus* (14.92%); thus, the percentage of fuel ratio (FBR) in *P. radiata* (0.26) was higher than that in *E. globulus* (0.21).

Table 6. Properties of raw biomasses.

	P. radiata	***E. globulus***	**Large Needles** [24]	**Pine Raw** [46]	***P. pinaster* Bark** [47]	**Pine Shells** [48]	**Wood without Bark** [49]	***P. radiata* Wood** [50]	***E. globulus* Wood** [50]	**Coal** [48]	**WH *** [51]
Proximate Analysis (wt (%))											
Moisture	8.10	9.2	14.41	7.51	7.001	13.9	6.82	7.12		1.7	5.02
Ash	2.92	4.12	0.54	0.13	0.272	1.3	0.4–0.5	0.30	0.18	2.3	13.38
Volatile matters (VM)	70.43	71.76	71.72	86.71	79.552	58.9		77.71	76.50	44.6	30.52
Fixed carbon (FC)	18.55	14.92	13.34	5.68	13.243	25.9		15.17	16.20	51.4	51.08
FC/VM (FR ‡)	0.26	0.21	0.19	0.07		0.44		0.20	0.21	1.15	1.67
Ultimate Analysis (wt (%), dry basis)											
C	51.56	50.12	45.73	51.2	46.978	47.8	48–52	48.94	48.72	79.3	72.1
H	5.83	6.64	5.81	6.77	6.277	5.6	6.2–6.4	6.91	6.70	5.9	4.62
N	1.67	1.34	0.91	0.034		0.3	0.1–0.5	0.12	0.02	1.9	1.55
S	0.36	0.23	0.09	0.01		0.0	<0.05			0.5	0.26
O †	40.58	41.67	47.46	41.99		46.3		44.03	44.56	12.4	7.38
GCV (GJ/Mg)	20.75	20.96	16.83	19.2	19.093	18.82		18.89	17.45	35.04	27.31
NCV (GJ/Mg)	19.45	19.48	15.32				18.5–20.0				25.16

* Australian bituminous coal (whitehaven); † By difference; ‡ Fuel ratio (%).

3.2.2. Ultimate Analysis

The results obtained in Table 6 show that the forest residues of *P. radiata* and *E. globulus* had average carbon (C) percentages of 51.56 and 50.12%, respectively. The elementary hydrogen (H) weight contents achieved were 5.83% and 6.64% for the *FBR* of *P. radiata* and *E. globulus* respectively. The percentages of nitrogen (N), sulphur (S), and oxygen (O) in the residue of *P. radiata* were 1.67%, 0.36%, 40.58%, and those of *E. globulus* were 1.34%, 0.23%, and 41.67%.

3.2.3. Calorific Value

The results of the energy evaluation for the *FBR* values of *P. radiata* and *E. globulus* are shown in Table 6. The residues of both tree species showed little variability in the calorific value, with mean values of 20.75, 19.45 and 20.96, 19.48 GJ Mg^{-1} for the gross and net calorific values (*GCV* and *NCV*) of *P. radiata* and *E. globulus*, respectively.

3.3. Emission Factors

The emission factors E_i (kg Mg^{-1}) of the main gaseous pollutants (CO, CO_2, NO_x, SO_2) and dust obtained from the residues of *P. radiata* and *E. globulus* are shown in Table 7. The emission factors E_i of CO, CH_4 and CO_2 in the residues of *P. radiata* and *E. globulus* were very similar, with average values of around 60 kg Mg^{-1}, 3 kg Mg^{-1} and 1500 kg Mg^{-1}, respectively. Due to this, the emissions factors of CO, CH_4 and CO_2 per unit of energy (*EF*, kg GJ^{-1}) were very similar in the residual biomass of *P. radiata* and *E. globulus*, with approximate average values of 3.2, 0.15, and 70 kg GJ^{-1} for E_{CO}, CH_4 and CO_2, respectively (Table 8). On the contrary, the emissions of NO_x and SO_2 of the residue of *P. radiata* were estimated to be 5.63 kg Mg^{-1} and 0.72 kg Mg^{-1}, 19.71% and 36.11% higher than those obtained in *E. globulus* (Table 7). Logically, the *EF* of NO_x and SO_x were 5.03% and 50% higher in the *FBR* of *P. radiata* (Table 8), due to its higher content of N and S (Table 6). We obtained an average dust *E* value of 3.69 kg Mg^{-1} in *P. radiata* samples, 29% lower than the *E* of the residues of *E. globulus* (5.20 kg Mg^{-1}). The dust emission per unit of energy (*EF*, kg GJ^{-1}) was higher in the *FBR* of *E. globulus*—42.1% in relation to *P. radiata* (see Table 8).

Table 7. Dust and gas emission factors (*E*, kg Mg^{-1} fuel).

Material	CO	CH_4	CO_2	NO_x	SO_2	Dust
P. radiata (BFR)	63.52	3.02	1527.79	5.63	0.72	3.69
E. globulus (BFR)	61.75	2.94	1484.34	4.52	0.46	5.20
P. radiata wood [52]	49.85		1947.52	0.41	0.48	
E. globulus wood [52]	38.98		1701.62	0.58	0.37	
Larch needles [24]	56.34		1351.90	3.07	0.18	0.68
Hard coal [53]	82.01		1969.00	4.09	5.2	23.57

Table 8. Dust and gas emission factors per unit of energy (*EF*, kg GJ^{-1} fuel).

Material	CO	CH_4	CO_2	NO_x	SO_2	Dust
P. radiata (BFR)	3.27	0.16	78.56	0.29	0.04	0.19
E. globulus (BFR)	3.18	0.15	76.20	0.23	0.02	0.27
Larch needles [24]	3.20		68.38	0.18	0.01	0.04
Hard coal [53]	3.83		70.87	0.04 *	0.28	1.14

* NO_x formed from the nitrogen present in the fuel should be added to this value.

4. Discussion

The precise estimation of the availability of forest residues for bioenergy is very important for the sustainability of biomass supply in energy installations. The use of forest biomass is considered renewable if the extraction rate does not exceed the rate of its natural regeneration, as indicated by the results obtained in the study. We estimated that the total annual growth of timber biomass of *P. radiata* and *E. gobulus* in Biscay is 489.53 Gg year^{-1} (dry matter), and the extraction of timber resources of these species is 270.73 Gg year^{-1}. These data show that only 55.3% of the total annual growth of forest biomass is used, as it is in most of the countries in the European Union, whose reports show that only between 60 and 70% of the annual forest resources are used [54]. Estimations of *P. radiata* residue (E_{FBR}) ranged from 0.312 to 1.165 Mg ha^{-1} year^{-1} and 0.784 to 1.243 Mg ha^{-1} year^{-1} (dry mass), respectively. Previous research on the residues of different forest species has shown very similar results. Dominguez et al. [55] estimated 0.91 Mg ha^{-1} year^{-1} (dry matter) in the residue of *P. radiata* in Navarra (Spain), and Zabalo [56] found values of E_{FBR} between 0.71 and 1.47 Mg ha^{-1} year^{-1} (dry matter) in *E. globulus* plantations in Huelva (Spain).

The results of the proximate analysis of the *FBR* (Table 6) showed reduced moisture values below 10%, which is considered optimal for combustion processes [47]. The *FBR* samples had average ash contents of around 3 and 4 %. These values are higher than the ash content of timber biomass (0.4–0.5) [49]. Arteaga et al. [50] measured ash contents of 0.3 and 0.18% in timber samples of *P. radiata* and *E. globulus*, respectively. These results show that the ash content is higher in the branches fraction than in the biomass from the timber stage [57,58] which decreases its quality as a fuel residue compared to wood. However, the ash content of the samples analyzed is much lower than that presented by some coals [51].

High percentages (>70%) of VM were obtained from the analyzed forest residues. Such high values show the potential of these percentages in gasification processes, which is much higher than the content in coal volatile matters (30.52 and 44%) [48,51]. The fixed content ranged from 14.92 to 18.55% for the *FBR* of *E. globulus* and *P. radiata*, respectively. Thus, the percentage of fuel ratio (FR) was higher in *P. radiata* (0.26) than in *E. globulus* (0.21). These results show that the residue of *E. globulus* is a fuel with easier ignition [59]. In Filipe dos Santos et al. [60], values of around 18% of FC were obtained for the branches and needles of maritime pine. In relation to the timber fraction, Arteaga-Pérez et al. [50] found values of 15.26 and 16.20% for the FC of timber of *P. radiata* and *E. globulus*, respectively.

Carbon (C) and oxygen (O) are the main components of solid fuels. In the ultimate analysis (Table 6), percentages of C higher than 50% were obtained in the residues of *P. radiata* and *E. globulus*, slightly higher to those found by Arteaga-Pérez in the timber of these species (48.84 and 48.72%). Another reference [50] gave the C weight percentages as 51.0 and 44.8% for stems and 52.0 and 45.5% for branches of *P. radiata* and *E. globulus*, respectively. The percentage of oxygen in both types of residual forest biomass analyzed was very similar, about 41%, slightly lower than the timber fraction [50]. In comparison, for coal, the content of C is much higher than the biomass fractions, and the content of oxygen is much lower. As an average, the percentage in C is higher than 70% and the oxygen is lower than 13% [48]. For the elementary analysis, hydrogen (H) values of around 6% were obtained for the residues of the two species. Other authors found similar results with percentages of H in the range of 5.6–6.9% in the different fractions of forest biomass (see Table 6). The nitrogen (N) and sulphur (S) content of fuels affects the emission of atmospheric pollutants (NO_x and SO_x). The percentages of nitrogen and sulphur in the residues of *P. radiata* and *E. globulus* were 1.67%, 0.36% and 1.34%, 0.23%, respectively (Table 6). These values are higher than those found by other authors in different biomasses [24,46–48,50]. Some studies have shown that the leaves of the species studied have the highest percentages of nitrogen and sulphur in relation to the biomass fraction [30,60]. Another reference [51] gave the N weight percentage as 1.55%, and in [48], the N amount was shown to be 1.9% in different types of coal. In [51], the sulphur content was around 0.26% in Australian bituminous coal (WH), while in [48], a value of 0.5% was reported for coal.

The *GCV* analysed for the *FBR* of *P. radiata* and *E. globulus* resulted in very similar values of 20.75 and 20.96 (MJ kg^{-1}) respectively (Table 6). Similar *GCV* values were presented in Filipe dos Santos et al. [60] in different fractions of maritime pine. Likewise, we obtained very similar values for the net calorific value (*NCV*), 19.45 MJ kg^{-1} and 19.48 MJ kg^{-1}, for *P. radiata* and *E. globulus* respectively. In this respect, Kollmann [61] claimed that the calorific value of dry timber varies so little that it can be considered to have an average value of 4500 cal kg^{-1}. Nevertheless, other studies have shown that the calorific value of the chips of the forest residues is slightly higher than that of the chips from the tree and the trunk [47,50,62]. Compared to forest biomass, coal has a much higher GCV, more than 27 MJ kg^{-1}.

Broadly speaking, the E_i (kg Mg^{-1} fuel) of FBR of *P. radiata* and *E. globulus* was higher than that obtained in the timber biomass of these species [24] or the residues from other species, but lower than the E_i of hard coal [53], except for NO_x. The results show that the FBR of *P. radiata* is fuel with a higher E of pollutant gases (CO, CH_4, CO_2, NO_x, and SO_2) in relation to the FBR of *E. globulus*. However, its dust emission is lower (see Table 7). These results are consistent with studies undertaken in the timber biomass of these two species [52]. The E of CO, CH_4, and CO_2 in the residues have average values of around 60 kg Mg^{-1}, 3 kg Mg^{-1}, and 1500 kg Mg^{-1}, respectively, with the EF of *P. radiata* (2.8%, 2.7%, 2.6%) being slightly higher than those of *E. globulus*.

5. Conclusions

The main conclusion reached in the study is that the analysis of biomass properties can generate information that can be used to optimize the management and use of biomass to generate energy. The results obtained in this study indicate that the FBR of both *P. radiata* and *E. globulus* has good energetic properties. The high calorific value of FBR (20.75 to 20.96 MJ kg^{-1}) reveals the considerable potential of this residue to be utilized as an important source of energy.

The elemental analysis indicated that a high carbon content (50.12 to 51.56%) is stored in the FBR of *E. globulus* and *P. radiata*. This shows the importance of this species in the global cycle of carbon. Despite the fact that the bioenergy based on these residues is not emission-free, its use can help to mitigate climate change. If the forest residues are burnt in order to obtain energy, their carbon content is immediately released. On the contrary, if the forest residues are not burnt, they decompose and emit carbon gradually, so that their emission is not avoided. On the other hand, unless fossil fuels are burnt, carbon remains stocked in the ground and it is not released [63], which is an advantage of the use of biomass fuel in relation to fossil fuels. It also adds value to waste materials [64]. The determined emission factors indicate a reduction in gas emissions, namely CO (23–25%), CO_2 (22–25%), SO_2 (87–91%), and dust (11–38%), and an increase in NO_x by 11–37% compared to hard coal.

Finally, despite its small extension, the study area contains a large percentage of forest land, similar to that of Northern European countries. The study was carried out only on the two predominant species (*P. radiata* and *E. globulus*) because they represent more than 90% of the short species with possible energy use. This study could be generalized to other European countries (e.g., Finland, Austria, Sweden) with a strong presence of fast forest species. The use of forest residue as a renewable energy source is an excellent solution for the socio-economic development of disadvantaged areas, rural or peripheral, which, in most cases, contain most of the forest areas. This would also reduce the risk of fire.

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