forests

MDPI

Article

The Impact of Wood Moisture Content on the Productivity and Costs of Forest Energy Supply Chains in Southeast Brazil

Elaine Cristina Leonello [1], Mauricio Acuna [2], Mark Brown [3], Maura Seiko Tsutsui Esperancini [1], Adriano Wagner Ballarin [1], Saulo Philipe Sebastião Guerra [1] and Humberto de Jesus Eufrade-Junior [4,*]

1 School of Agriculture, São Paulo State University, Botucatu 18610-034, Brazil; leonelloec@gmail.com (E.C.L.); maura.seiko@unesp.br (M.S.T.E.); adriano.ballarin@unesp.br (A.W.B.); saulo.guerra@unesp.br (S.P.S.G.)
2 Natural Resources Institute Finland (Luke), Yliopistokatu 6B, 80100 Joensuu, Finland; mauricio.acuna@luke.fi
3 Forest Research Institute, University of the Sunshine Coast, Sippy Downs, QLD 4556, Australia; mbrown2@usc.edu.au
4 Luiz de Queiroz College of Agriculture, University of São Paulo, Piracicaba 13418-900, Brazil
* Correspondence: h.eufrade@usp.br

Abstract: Using wood for power generation necessitates a more efficient production chain in the various steps: harvesting, forwarding, storage, chipping, transport, and conversion systems. In this context, the moisture content (MC) of wood can impact the harvesting operation, the volume to be chipped, the transportation of raw materials, the storage time, and other factors, thereby influencing the economic aspects of the chain. The primary objective of this study is to investigate the influence of wood moisture content on the yield and costs of different forest operation chains for power generation in São Paulo State, Brazil. Our findings reveal that harvesting and forest transport are the primary cost components (over 80%) in the supply chains under study. We observed a difference of up to 17.6% in the unit cost of the energy generated among the studied supply chains. In economic and sustainable terms, our results suggest that logs should be stored in the field for three to four months and the transport distance to the power plant should not exceed 100 km.

Keywords: forest operations; biomass power plant; storage time; operational cost; transport

Citation: Leonello, E.C.; Acuna, M.; Brown, M.; Esperancini, M.S.T.; Ballarin, A.W.; Guerra, S.P.S.; Eufrade-Junior, H.d.J. The Impact of Wood Moisture Content on the Productivity and Costs of Forest Energy Supply Chains in Southeast Brazil. *Forests* **2024**, *15*, 139. https://doi.org/10.3390/f15010139

Academic Editor: Bruno Esteves

Received: 29 November 2023
Revised: 23 December 2023
Accepted: 5 January 2024
Published: 9 January 2024

1. Introduction

Renewable energy sources, ranked in order of importance by hydropower, solar and wind power, bioenergy, and geothermal power, accounted for approximately 30% of global electricity production in 2022 [1]. Despite significant solar and wind power increases over the past decade, the demand for critical minerals essential to battery storage and electricity networks, such as copper, nickel, cobalt, and others, is projected to rise two- to four-fold by 2030 [2]. In this context, biomass, derived from organic materials of agriculture residues and forestry plantations, appears as a versatile feedstock for generating bioenergy and represents a crucial step toward sustainable and renewable energy solutions [3]. Consequently, as society increasingly focuses on transitioning to cleaner energy alternatives, adopting biomass as a renewable energy source becomes pivotal in fostering a greener and more resilient energy landscape to reduce GHG emissions and mitigate global warming [4,5]. Furthermore, lignocellulosic biomass is crucial to the circular economy, as are new conversion technologies for climate-neutral energy production and value-added products, including biomaterials and biochemicals [6–10].

Due to their low soil quality requirements, non-competitiveness with food crops, and higher biomass production per hectare than annual plantations, wood and residues from forest plantations have become significant sources of lignocellulosic biomass. In South America, for example, *Eucalyptus* plantations are widely used as the primary source of supply for the forestry industry, including pulp and paper products, wood panels, charcoal, and roundwood. These crops have been consolidated over the last decades due to short rotations (less than seven years) and high productivity (about 40 m^3 per hectare per year) [11–13].

The drastic changes in water and temperature regimes faced in the last decade [14], combined with concerns about maintaining the productivity of eucalypt plantations [15–18] and significant investments in the sector (wood demand), have considerably increased their market price [19]. Even with this situation, the use of wood for bioenergy is increasing, and private initiatives are making efforts to expand wood power plants, which already account for more than 120 thermoelectric plants, corresponding to 25% (or 4.4 GW) of the supervised capacity of thermal energy generation in Brazil [20]. Thus, wood is an alternative mainly to replace the lower capacity of hydroelectric plants during drought months, serving as an alternative fuel for fossil thermoelectric plants.

Biomass from eucalypt forest plantations has properties suitable for direct burning; in particular, greater attention should be paid to moisture content as it has a direct effect on wood density and calorific value. Wood residues have a higher calorific value ranging from 17 MJ kg^{-1} to 22.2 MJ kg^{-1}, including leaf fractions, bark, and stumps [21]. However, fresh biomass has its calorific value reduced by half or more immediately after harvesting due to its moisture content [22]. The wood moisture content (MC) can vary depending on the storage period and final use, with values of 53% and 30% common for freshly harvested and air-dried wood, respectively. In tropical conditions, the drying period for *Eucalyptus* logs can extend up to 180 days during the rainy season, directly affecting the energy content [23]. This affects the weight of the wood, which is related to the determination of its basic density (ratio of dry mass to saturated volume) and apparent density (ratio of mass to volume at a given MC). In addition, wood is often used as chips to minimize handling, storage, and transport issues in power plants, enhancing energy conversion by reducing particle size and homogenizing composition to generate electricity [24].

All of these wood characteristics have operational and economic implications; cheaper fuelwood requires an optimized forest operations chain, including harvesting and forwarding, storage, chipping, and transporting biomass to the power plant [25]. Among these operations, transporting raw materials is a significant biomass-use cost component [26–29]. Generally, road transport is suitable for short distances (less than 100 km), rail transport is suitable for greater distances, and waterways are suitable for distances exceeding 800 km [30]. In Brazil, wood transportation is predominantly performed by logging trucks on the available road system [31], whose viability is conditioned by the distance between the forest and the thermoelectric plant. Another costly activity is the chipping process, which, in some situations, significantly contributes to the cost of the forestry chain, this cost can vary depending on the MC of the wood, whether it is damp wood (freshly cut) or dry wood (after storage) [25], and also due to the models of forestry chippers [32].

Over the years, pursuing more efficient and cost-effective chains has led to their optimization based on critical parameters, such as MC. After harvesting, fresh *Eucalyptus* wood logs have high MC (>50% wet basis), affecting the entire logistical planning of the supply chain, including the harvest season, woodchip demand, the number of trucks needed for raw material transport, the field storage time, and the energy content, among other factors [28,33]. Therefore, this study aims to investigate the effect of wood moisture content on operating costs and the volume demand of wood to supply a thermoelectric plant through different supply chains and their respective conditions, such as the storage time and the distance from the forest to the thermoelectric plant (transport operation). As a complementary objective, the price of energy generated from wood is compared to hydroelectric power in the same year as the study.

2. Materials and Methods

2.1. Forestry Operations Chains

The forest energy supply chains used in this study are exemplified in Figure 1. They reveal the main stages that comprise the transformation of wood into woodchips for energy generation: Supply Chain I—chipping of fresh logs immediately after harvesting followed by woodchip transportation and storage at the biomass power plant; Supply Chain II—log storage after harvesting operations followed by the transportation and chipping of logs; and Supply Chain III—storage of logs after the harvesting operation followed by chipping and woodchip transportation to the conversion biomass power plant.

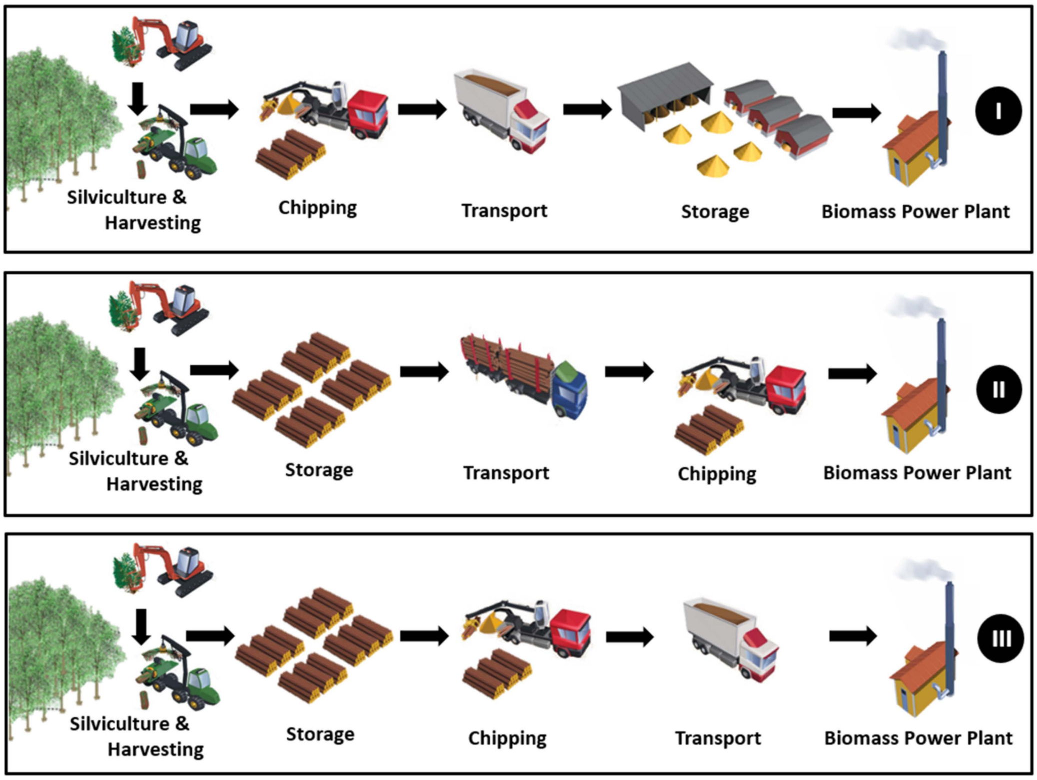

Figure 1. Supply chains (**I**), (**II**), and (**III**) for the use of woodchips for energy generation. Source: Forest Energy Portal [34], modified by the authors.

Simulations with various transport distances and storage periods were conducted to identify the supply chain that ensures the minimum wood volume to meet the thermoelectric plant's monthly energy demand. The simulation considered raw materials from the clonal eucalypt plantation described in Table 1.

Table 1. Clonal *Eucalyptus* forest characteristics and wood properties.

Characteristics	Unity	
Specie	-	*Eucalyptus urophylla* S.T. Blake
Clone	-	AEC 0144
Age	years	7
Planting Density	trees ha^{-1}	1667
Average Height	m	21.7
Average DBH	cm	16.9
Mean Annual Increment	m^3 ha^{-1} year^{-1}	42.4
Wood Basic Density	kg m^{-3}	460
Higher Heating Value (HHV)	MJ kg^{-1}	19.00

2.2. Demand for Solid Wood to Supply the Biomass Power Plant

To conduct the study, we simulated the supply of a biomass power plant located in the central region of the State of São Paulo, Brazil, with an installed capacity of 20 MW and a constant monthly energy demand throughout the year.

The monthly quantity of woodchips required to supply the thermoelectric plant was calculated based on the amount of steam, the enthalpy of steam and water, the net heating value (NHV), and the boiler yield to determine the biomass needed for the thermal process (Equation (1)). It is important to note that the NHV is the primary property studied to understand the impact of wood MC on the volume demanded by the thermoelectric plant. In operational terms, the usable or net heating value (NHV) is used; this represents the energy effectively available per unit of fuel mass after deducting losses due to moisture content [22]. Additionally, to produce 17.78 MWh, a flow of 80,000 kg of steam per hour is required, and it was estimated that a total of 680 productive hours result in a monthly demand of 13,600 MWh [35–40].

$$Qc = [Qv\ (hv - ha)]/[\eta\ (NHV)] \quad (1)$$

where:

Qc—amount of fuel, kg
Qv—amount of steam, kg
hv—enthalpy of steam as a function of pressure and temperature, MJ kg^{-1}
ha—enthalpy of water as a function of temperature, MJ kg^{-1}
η—boiler yield, decimal
NHV—net heating value, MJ kg^{-1}.

The NHV was calculated based on CEN/TS 14918:2005 [41]. Subsequently, mass-to-volume conversions were performed based on experimental relationships in materials similar to the one proposed in this work. The accuracy of the results relies solely on this empirical relationship (Equations (2) and (3)) [42]. From the value of apparent density and the amount of fuel consumed (Qc), the demand for the solid volume of wood (m^3) and the specific wood consumption (m^3 MWh^{-1}) of a thermoelectric plant of 20 MW were obtained (Equations (4) and (5)).

$$da = wd\ [0.01\ (100\ U/100 - U) + 1]\ [1 - 0.28wd/(1 + 0.028wd)]\ 1000 \quad (2)$$

where:

da—apparent wood density at a specific moisture content, kg m^{-3}
wd—wood density at 0% moisture content, g cm^{-3}
U—moisture content (wet basis), %

$$wd = bd/(1 + 0.28bd) \quad (3)$$

where:

wd—wood density at 0% moisture content, g cm^{-3}
bd—basic density, g cm^{-3}

$$v = Qc/da \quad (4)$$

where:

v—solid wood volume demanded by the power plant, m^3
Qc—amount of fuel, kg
da—apparent wood density at a specific moisture content, kg m^{-3}

$$C = v/HP \quad (5)$$

where:

C—specific wood consumption, m^3 MWh^{-1}
v—solid wood volume demanded by the power plant, m^3
H—productive hours in a certain period of time, hours
P—thermoelectric power, MW

2.3. Estimated Forest Operation Costs

Yields documented in the literature and data from established Brazilian companies in the sector were utilized to ascertain the operational costs of forestry operations in a commercial *Eucalyptus* plantation. The operational cost of biomass delivered to the thermoelectric plant was determined based on the solid volume of wood (USD m^{-3}) to establish a standard unit in forestry operations. Each forestry operation (harvesting, transporting, chipping, and storage) cost was determined by the sum of fixed costs (depreciation, interest, administration costs, and insurance) and variable costs (labor, fuel, lubrication, repairs, and maintenance) following the ASAE D472-3 [43] proposal.

For the silviculture and harvesting operation, the total cost was USD 11.48 m^{-3}—a value consistent with that practiced by forestry companies in South America. The harvesting system comprised a feller-buncher, skidder, and grapple saws (bucking logs with a length of up to 6 m) [44]. The silviculture system encompassed a conventional approach used in Brazil, with clonal eucalypt plantations grown using the coppice method.

A cargo vehicle composition (CVC) with a capacity of 100 m^3 was considered for wood transport operations. However, it is worth noting that the Brazilian Traffic Law stipulates rules based on the total shared gross weight (PBTC) as a limitation (tractor plus trailer plus load weight). For woodchips, a tractor–truck plus a self-unloading trailer (walking floor) system with six axles (PBTC max of 48.5 tons) was considered. A tractor–truck plus a double logging trailer with seven axles (bi-train) and a PBTC max of 57 tons was considered for log transportation. The estimated tare was 21.5 tonnes in the woodchip transport system and 22.0 tonnes in the log wood transport system, resulting in a net load of 27 and 35 tonnes, respectively. These CVCs are relatively efficient due to their unrestricted traffic certification on the entire national road network [45].

Transport costs can vary significantly with the MC of the material to be transported, as the load can reach its weight limit before occupying the entire trailer space [46]. Thus, the number of trips required to supply the thermoelectric plant was estimated considering the monthly demand for raw materials and the load composition limits (by volume or weight).

Various transport distances from the forest to the power plant were simulated: 0, 50, 100, 150, 200, 250, and 300 km. Commercial prices obtained through a survey of freight costs in the regional market in February 2019, as indicated in Table 2, were used for the transport costs.

Table 2. Transport cost (USD km^{-1}) for different distances in Sao Paulo State, Brazil.

Distance (km)	Wood LOG Transport Cost	WoodCHIP Transport Cost
1–50	3.22	2.79
51–100	2.53	2.46
101–150	2.30	2.19
151–200	2.18	1.97
201–250	2.07	1.76
251–300	2.03	1.59

The cost of the transport operations was calculated according to Equation (6).

$$CT = (Ck \times d \times n)/V \tag{6}$$

where:

CT—transport cost, USD m^{-3}
Ck—cost per distance travelled, USD km^{-1}
d—distance travelled, km
n—number of trips per month
V—monthly wood demand, m^3.

The storage cost was calculated as the opportunity cost of the land (Equation (7)), considering the area used for storing wood, the price of land for use in silviculture in the State of São Paulo—USD 5468.96 ha^{-1} practiced in January 2019 [47]—the storage time, and an interest rate of 0.5% per month (reference rate of the Special Settlement and Custody System—Selic) practiced in February 2019.

$$CO = (Vi \times r \times A)/V \quad (7)$$

where:

CO—opportunity cost of the land, USD m^{-3}
Vi—initial value of the land, USD ha^{-1}
r—interest rate, % $month^{-1}$
A—total area used for storing wood, ha.
V—monthly solid wood demand, m^3.

For the total area (Equation (8)) used for wood storage, a maximum height of 3.0 m was considered for log piles and 6.0 m was considered for woodchip piles. A correction factor (=3.0) was applied to account for the spaces between the piles in the yard or field, including maneuvering areas for loading and handling. The stacking factor (Fe), which converts the solid volume into a stacked volume, was also factored into the calculation. Additionally, a safety stock of two months was assumed to guarantee a wood stock in case of a shortage in wood supply.

$$A = \{[(V \times Fe/h) \times 3]/10{,}000\} \times e \quad (8)$$

where:

A—total area used for wood storage, ha
V—monthly solid wood volume demanded by the power plant, m^3
Fe—stacking factor for logs (Fet) or woodchips (Fec)
h—pile height, m
e—storage time, month

In addition, chipping operation costs were calculated based on the MC of the raw materials (Table 3) as detailed by Acuna et al. [25]. Drier wood increases the frequency with which chipper knives have to be changed, as well as requiring more resistance to be converted into woodchips, which leads to higher fuel consumption costs and higher prices.

Table 3. Chipping cost per m^3 of wood during storage for a range of MCs.

Moisture Content—MC (Wet Basis)	Operational Cost USD m^{-3})
≤35%	3.53
36%–50%	2.27
≥50%	1.86

Table 4 presents other parameters and factors used in the different calculations performed.

Finally, the monthly operational cost of the wood delivered to the thermoelectric plant was determined by considering the amount of biomass needed to meet the unit's energy demand. With this quantity, estimating the cost per MWh using Equation (9) was possible.

$$CEn = \{(V \times (CCo + CT + CCa + [(CO \times A)/V]\}/(P \times hm) \quad (9)$$

where:

CEn—operational cost of electric power generation, USD MWh^{-1}
V—monthly solid wood volume to attend the power plant unit, m^3
CCo—harvesting operation cost, USD m^{-3}
CT—wood transport operation cost, USD m^{-3}

CCa—chipping operation cost, USD m^{-3}
CO—opportunity cost of the land, USD ha^{-1}
A—total area used for storing wood, ha
P—thermoelectric power, MW
hm—monthly productive hours, hours

Table 4. Conversion parameters and factors used.

Conversion Parameters and Factors	Abbreviation/Symbol	Value
	Thermoelectric Plant Related Data	
Thermoelectric power	P	20 MW
Amount of steam	Qv	80,000 kg h^{-1}
Enthalpy of steam *	hv	3394 MJ kg^{-1}
Enthalpy of water *	ha	0.439 MJ kg^{-1}
Boiler yield	η	89%
	Wood Pile-Related Data	
Logs stacking factor	Fet	1.79
Woodchip stacking factor	Fec	2.43

* These values can vary depending on the working pressure and temperature of the boiler.

2.4. Wood Moisture Content during Storage

Daily drying rates during the spring–summer period for the wood stored in logs and woodchips were previously monitored in other studies, which thoroughly describe the methodological details of continuous MC monitoring and are presented in Table 5. The drying of wood is characterized by two outflows of water (capillary and diffusion movement), which occur simultaneously during the process. As discussed in the literature [48,49], initially, moisture is reduced predominantly by capillary movement (free or capillary water) up to the fiber saturation point (FSP) and, subsequently, hygroscopic or impregnation water (adsorbed to the cell walls) is released by diffusion movement. Thus, the moisture loss in chip piles is lower than in logs in tropical conditions, since there is a lack of ventilation inside the piles to maintain capillary movement for longer, which also favors a greater MC gradient from the interior to the edge of the pile.

Table 5. MC variation (arithmetic mean and standard deviation) during the storage of logs and woodchip piles in southeast Brazil.

Storage Time (Months)	Logs Pile	Woodchip Pile
0	52.4 ± 0.9	52.4 ± 5.0
1	48.9 ± 1.1	51.5 ± 3.2
2	45.4 ± 1.3	50.7 ± 3.2
3	42.0 ± 1.3	49.8 ± 7.9
4	38.5 ± 1.4	49.0 ± 3.2
5	35.0 ± 1.6	48.1 ± 3.2
6	31.5 ± 1.4	47.2 ± 3.1

MC wet basis, %. Source: Adapted from Eufrade et al. [48] and Eufrade et al. [49].

2.5. Data Analysis

Statistical analysis was performed using R free software version 4.3.1 (R Foundation for Statistical Computing, Vienna, Austria). The Shapiro–Wilk and Bartlett tests were used to evaluate the data distribution and the homogeneity of variances, respectively. Analysis of variance (ANOVA) complemented by Tukey's test was used to evaluate the effects of supply chains (SCs) and storage time (ST) on the volume of wood demand and consumption per energy to supply a thermoelectric plant. The results were analyzed with $p < 0.05$ representing statistical significance.

As the costs were estimated based on the variation in wood MC, it was assumed that the same pattern of statistical behavior between the variation factors reported for wood volume demand would apply, so a thorough analysis of the values generated in the simulations is presented including the transport distances from the forest to the power plant.

3. Results

3.1. Wood Volume Demand

The supply chains and storage time had a significative double interaction in the volume demand of wood to supply a 20 MW thermoelectric plant, as shown by *p*-values of the ANOVA (Table 6).

Table 6. The *p*-values of the analysis of variance (ANOVA) for the volume demand of wood to supply a thermoelectric plant through different supply chains and storage times.

Factors	Volume Wood Demand m^3		Wood Consumption per Energy m^3 MWh^{-1}	
	F	*p*-Value	F	*p*-Value
Supply chain (SC)	288.77	0.00 *	282.97	0.00 *
Storage time (ST)	177.00	0.00 *	1026.75	0.00 *
SC × ST	13.14	0.00 *	73.71	0.00 *

$p < 0.05$ (*) significant according to test F.

Table 7 shows the volume of solid wood required to fuel a 20 MW thermoelectric plant, generating 13,600 MWh of electrical energy per month. The calculation takes into account the arithmetic daily drying process during the spring–summer season shown in Table 5.

Table 7. Arithmetic means of the monthly wood demand to supply a thermoelectric plant through different supply chains and storage times.

Storage Time (Months)	Supply Chain		
	I	II	III
Volume wood demand ($10^3 \times m^3$)			
0	33.58	33.58	33.58
1	33.37	32.78	32.78
2	33.17	32.12	32.12
3	32.98	31.57	31.57
4	32.79	31.09	31.09
5	32.62	30.67	30.67
6	32.45	30.30	30.30
Arithmetic mean	32.99 a	31.73 b	31.73 b
Wood consumption per energy (m^3 MWh^{-1})			
0	2.47	2.47	2.47
1	2.45	2.41	2.41
2	2.44	2.36	2.36
3	2.42	2.32	2.32
4	2.41	2.29	2.29
5	2.40	2.25	2.25
6	2.39	2.23	2.23
Arithmetic mean	2.43 a	2.33 b	2.33 b

Note: Mean values marked by different letters were shown to be significantly different according to Tukey's test ($p < 0.05$). Lowercase letters represent differences between values in the same line (supply chain effect).

As supply chains II and III incorporate wood (log) storage, the MC exhibited consistent variation. Consequently, the demand for biomass remains unchanged. The monthly volumetric demand for wood, in the form of woodchips stored for up to six months, decreased by 3.3%. Similarly, the demand for wood stored in log form decreased by 9.8% over the same period. This reduction is attributed to the higher daily drying that occurs from log storage [23], requiring a smaller amount of wood per unit of generated energy (m^3 MWh^{-1}).

In fact, the use of drier wood increases efficiency in energy generation; this behavior can be verified when considering the variation in the net heating value (NHV) during storage. The greater the loss of MC (log wood storage), the greater the increase in the NHV (Figure 2).

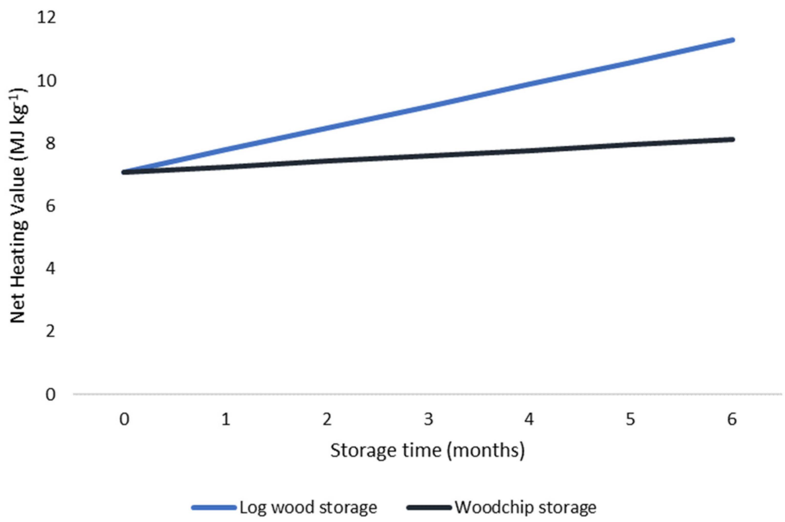

Figure 2. Net heating value (NHV) versus storage time for logs and woodchips.

3.2. Forest Operational Costs

For an initial analysis, the operating cost of wood delivered to the thermal power plant was estimated considering a fixed distance of 100 km. The unit volume cost by supply chains and storage time to meet the monthly demand of the 20 MW power plant considering distances up to 100 km between the forest and the thermoelectric plant are presented in Table 8.

Table 8. Arithmetic means of the monthly wood demand to supply a thermoelectric plant through different supply chains and storage times considering a fixed distance of 100 km.

Storage Time (Months)	Supply Chain		
	I	II	III
Costs per wood volume (USD m^{-3})			
0	20.33	18.92	20.36
1	20.21	18.96	20.30
2	20.09	18.63	19.89
3	20.42	18.42	19.88
4	20.34	18.47	19.93
5	20.27	19.78	21.23
6	20.20	19.83	21.28
Arithmetic mean	20.27 a	19.00 b	20.41 a
Costs per month (mi USD)			
0	0.68	0.64	0.68
1	0.67	0.62	0.67
2	0.67	0.60	0.64
3	0.67	0.58	0.63
4	0.67	0.57	0.62
5	0.66	0.61	0.65
6	0.66	0.60	0.64
Arithmetic mean	0.67 a	0.60 b	0.65 a
Costs per energy (USD MWh^{-1})			
0	35.18	31.72	35.26
1	34.66	31.05	34.27
2	34.16	29.65	32.60
3	34.76	28.66	32.03
4	48.81	42.02	45.33
5	34.02	30.88	34.16
6	33.68	30.62	33.85
Arithmetic mean	36.47 a	32.09 b	35.36 a

Note: Mean values marked by different letters in the same line were shown to be significantly different according to Tukey's test ($p < 0.05$).

One meaningful relationship is observed between the decrease in wood demand and the increase in operational unit cost, reflected in the monthly total cost of the delivered wood. This interaction suggests an optimal in-field wood storage period between 3 to 4 months.

In the case of Supply Chain I, there was a 1.5% reduction in the total delivered wood cost up to the third month of storage. By the sixth month, this reduction increased to 2.9%. The MC of the woodchips continued to decrease until the sixth month of storage, and as a result, the total delivered wood cost also decreased.

Supply chains II and III had an optimal storage time that ranged between three and four months, coinciding with the period of the lowest operation cost for delivered wood. During this same period, both supply chains exhibited significant cost reductions, with supply chains II and III showing reductions of 10.9% and 8.8%, respectively, after four months of wood storage.

The lowest cost of electricity was observed in Supply Chain II after four months of storage, followed by Supply Chain III and, finally, Supply Chain I. When comparing the unit cost of production per MWh between the supply chains, 7.2% and 13.9% reductions in cost were found between supply chains I and III and between supply chains I and II, respectively.

The operational cost per m^3 of wood is associated mainly with silviculture, harvesting and forest transport activities. Figure 3 shows the cost breakdown by operational activity: storage, chipping, transport, and silviculture and harvesting operations for different distances between the forest and the thermoelectric plant, considering a fixed storage time of three months.

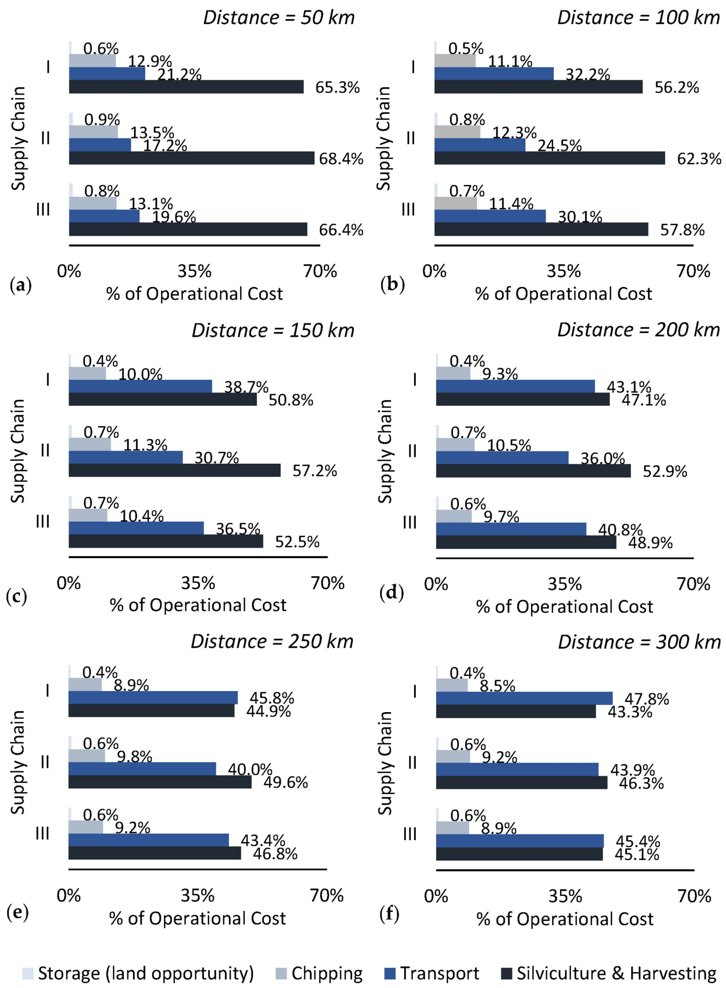

Figure 3. Operational cost (%) by operational activity considering different wood transport distances: (**a**) 50 km; (**b**) 100 km; (**c**) 150 km; (**d**) 200 km; (**e**) 250 km; (**f**) 300 km, and 90 days of storage.

Overall, up to a distance of 50 km, there is a greater influence on the cost of the silviculture and harvesting operations. The greater the distance between the origin of the forest and the power plant, the greater the cost and the proportional significance of transport. Transport reaches a maximum level of 47.8% of the total cost of biomass delivery in Supply Chain I, which is 300 km away from the forest plantation. Even in the ideal storage period, the cost of electricity increases considerably with the distance of transportation, as illustrated in Figure 4.

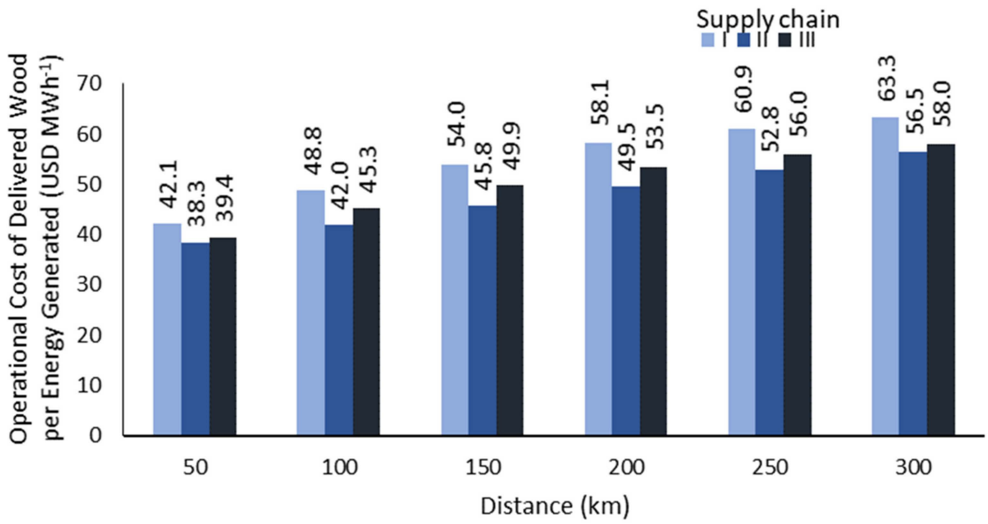

Figure 4. Monthly operational cost per MWh of delivered wood by supply chain and storage time.

Although the costs obtained may increase with the transport distance and MC, the use of wood to generate electricity is conditioned by the price of energy sold on the Brazilian market. As an indication, Table 6 shows historical data on the settlement price of differences (SPD) for energy sold on the Brazilian free market in 2018, the same year as this research study (Table 9). The SPD calculation considers the differences between the energy contracted and the amounts actually generated or consumed [50].

Table 9. Monthly average of the settlement price of differences (SPD) in USD MWh^{-1} and precipitation (mm) for the Brazilian southeast submarket in 2018.

Month	SPD (USD MWh^{-1})	Mean Precipitation (mm)
Jan	49.24	256.8
Feb	51.62	104.2
Mar	59.95	229.6
Apr	30.00	27.6
May	89.00	11.6
Jun	129.31	14.8
Jul	138.14	23.2
Aug	138.14	48.6
Sep	129.27	72.8
Oct	74.33	120.4
Nov	33.89	105.8
Dec	21.59	192.0

Source: [48].

4. Discussion

4.1. Wood Volume Demand

The MC of the wood is the factor with the greatest impact on the volume of wood demanded by the thermoelectric plant. Supply Chain I, which stores wood as woodchip piles, presents lower daily drying rates (0.029% day^{-1}). This necessitates a longer storage time for biomass to reach lower and more desirable MC levels, making it the period of greatest demand for wood storage areas. Furthermore, temperature plays a crucial role in the storage of fresh forest biomass, in which elevated temperatures correspond to the accelerated biological degradation rate of wood chips, making them more susceptible to rapid decay [51]. This has important implications for the operation of the power plant since a bigger volume of raw material is required to sustain its operation. On the contrary, in-forest drying of logs (0.116% day^{-1}) in supply chains II and III allows for greater MC losses due to storage, substantially reducing the volume of wood required by the power plant for its operation in the same storage period (Table 7). This demand for wood tends to stabilize as the biomass is stored in the field and reaches MC stabilization [23].

In terms of electricity generation, the specific consumption of wood chips estimated in this study (2.23 to 2.47 m^3 MWh^{-1}) was compatible with the performance of a wood chip-powered cogeneration plant in a fluidized bed steam boiler in other studies [52,53]. The lowest consumption occurred when using wood with a lower moisture content (after six months of storage), since the energy effectively available per unit mass of fuel less losses from water losses in the wood, or the NHV, increased considerably [22,54].

The results suggest that using wood with lower MC or a longer storage time directly reflects on the forest area to be harvested to supply the power plant. In addition, it affects the area to be planted for the next rotation, highlighting the importance of wood quality and its effects on the entire forest value chain [25,33,55]. These implications are important aspects to be considered by forest planners and decision-makers when comparing different supply chains and moisture control strategies. Thus, more studies could use biomass properties as target parameters in supply chain optimization.

4.2. Forest Operational Costs

The cost per m^3 was consistently lower in Supply Chain II, regardless of the storage time considered. This indicates that log transport is more cost-effective than chipwood transport when considering a transport system with the same cargo capacity (100 m^3) due to the lower stacking factor.

After four months of storage, there was a reduction in MC in supply chains II and III. This resulted in higher chipping operational costs, revealing the importance of conducting the chipping operation before the wood loses too much MC. In addition, the study confirms that the cost of the chipping operation can be reduced if the activity is carried out in the plant yard using stationary chippers rather than chipping in the forest using mobile chippers [56].

Considering the regional market dynamics, MC levels, and chipping operations, Supply Chain II—with storage and transportation of wood as logs—emerged as the most economical chain to supply wood-based industries. The results show that supplying the thermoelectric plant is more expensive in Supply Chain I, which is explained by the higher demand for biomass due to its high MC regardless of the storage time in the field. Some studies have suggested that one way to reduce this cost is to store and protect the wood chips using some form of cover [48].

The cost of the transport operations surpasses harvesting operations, especially over long distances of wood transportation. Long transport distances are not the norm in the region; therefore, this is one of the crucial factors to consider when identifying a viable location for installing the plant. The combined operation of transport and harvesting represents more than 80% of the operational cost for delivering raw materials. In Brazil, wood transportation alone can account for up to 60% of logistical costs for distances exceeding 150 km [26].

On the other hand, the stocking operation had the lowest operating cost among the evaluated chains, close to 0.9%. This behavior aligns with findings by Acuna et al. [25], who reported similar values for wood storage for up to two years in Finland.

The relation between the decreasing demand for wood and the increasing operational unit suggests 3–4 months as the optimal in-field storing time for logs (Supply Chain II).

The values obtained in this study indicate that longer transport distances from the forest to the power plant require longer storage periods to control transport costs, confirmed by previous studies [28]. Furthermore, storage directly influences the reduction in trips required for factory supply, particularly in Brazil, where legal weight limits exist. The drier the wood, the lower its weight, leading to a greater tendency to increase the volume loaded per trip. This is consistent with previous studies; for example, Zanuncio et al. [55] reported a 27.8% reduction in the number of trips needed to supply a pulp and paper factory after 90 days of *Eucalyptus urophylla* wood drying in logs.

Considering the historical data of SPD for energy sold on the free market (Table 9), with the year 2018 serving as an example of the trend in Brazil and taking into account the operational costs presented in this study, the forest operation chains proved to be feasible for delivering biomass during the dry season, spanning from May to September. This trend reinforces the potential of biomass as a complementary renewable energy source to hydroelectric power plants and an important strategy to avert energy crises in developing tropical countries.

During the rainy season (October to March), the use of biomass can become impractical, even over short distances. Implementing public policies becomes essential to secure investments in this energy source during such periods. Silva et al. [31], in their study on the costs of different wood transport vehicles, reported a maximum distance radius of 100 km for reforestation wood. Another European study revealed that transporting wood in logs remains viable up to a distance of 170 km, with viability decreasing as MC increases and with the adoption of wood formats with lower apparent density (such as chips and residues) [57].

This study has demonstrated that the energy price of biomass can be highly favorable in South America despite the consistent variability in the climate and irregular patterns in monthly precipitation. This becomes particularly critical during periods of low precipitation that lead to reductions in power generation by hydroelectric plants.

5. Conclusions

The forest operations which comprised in-field storage, transporting wood as logs, and chipping at the power plant's yard, resulted in the least expensive supply chain. The results of the study suggest that for the more efficient and sustainable use of wood for energy generation throughout the year in Southeast Brazil, logs must be stored in the forest for 3 to 4 months. Under the conditions of this study, drying logs in the forest for up to six months, with the consequent reduction in MC, resulted in a 9.8% reduction in the amount of wood required to satisfy the power plant's demand for wood.

New studies should be designed to optimize the logistics of operations, taking into account other biomass characteristics, such as the wood density, stacking factor, and calorific value of different species. We believe that pursuing more cost-effective forestry supply chains will further encourage and foster the use of wood for power generation, thereby contributing to a cleaner and more renewable energy matrix in South America.

Author Contributions: Conceptualization, H.d.J.E.-J., A.W.B., and S.P.S.G.; methodology, H.d.J.E.-J., M.S.T.E., and M.A.; validation, H.d.J.E.-J. and E.C.L.; formal analysis, H.d.J.E.-J. and E.C.L.; investigation, H.d.J.E.-J.; resources, H.d.J.E.-J. and S.P.S.G.; data curation, H.d.J.E.-J.; writing—original draft preparation, H.d.J.E.-J. and E.C.L.; writing—review and editing, M.A. and M.B.; supervision, S.G and A.W.B.; project administration, H.d.J.E.-J. and S.P.S.G.; funding acquisition, H.d.J.E.-J. and S.P.S.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Brazilian National Council for Scientific and Technological Development (CNPq), grant number 140145/2017-6.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: In memoriam of our friend and researcher Elaine Cristina Leonello.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. REN21. Renewables 2023 Global Status Report Collection, Renewables in Energy Demand. 2023. 126p. Available online: https://www.ren21.net/gsr-2023 (accessed on 16 November 2023).
2. IEA. *World Energy Outlook 2022*; IEA: Paris, France, 2022; 522p. Available online: https://www.iea.org/reports/world-energy-outlook-2022 (accessed on 16 November 2023).
3. Perišić, M.; Barceló, E.; Dimic-Misic, K.; Imani, M.; Brkić, V.S. The Role of Bioeconomy in the Future Energy Scenario: A State-of-the-Art Review. *Sustainability* **2022**, *14*, 560. [CrossRef]
4. Antar, M.; Lyu, D.; Nazari, M.; Shah, A.; Zhou, X.; Smith, D.L. Biomass for a sustainable bioeconomy: An overview of world biomass production and utilization. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110691. [CrossRef]
5. Velvizhi, G.; Goswami, C.; Shetti, N.P.; Ahmad, E.; Pant, K.K.; Aminabhavi, T.M. Valorisation of lignocellulosic biomass to value-added products: Paving the pathway towards low-carbon footprint. *Fuel* **2022**, *313*, 122678. [CrossRef]
6. Gil, L.; Bernardo, J. An approach to energy and climate issues aiming at carbon neutrality. *Renew. Energy Focus* **2020**, *33*, 37–42. [CrossRef]
7. Stafford, W.; De Lange, W.; Nahman, A.; Chunilall, V.; Lekha, P.; Andrew, J.; Johakimu, J.; Sithole, B.; Trotter, D. Forestry biorefineries. *Renew. Energy* **2020**, *154*, 461–475. [CrossRef]
8. Nahak, B.K.; Preetam, S.; Sharma, D.; Shukla, S.K.; Syväjärvi, M.; Toncu, D.C.; Tiwari, A. Advancements in net-zero pertinency of lignocellulosic biomass for climate neutral energy production. *Renew. Sustain. Energy Rev.* **2022**, *161*, 112393. [CrossRef]
9. Mujtaba, M.; Fraceto, L.F.; Fazeli, M.; Mukherjee, S.; Savassa, S.M.; Medeiros, G.A.; Pereira, A.E.S.; Mancini, S.D.; Lipponen, J.; Vilaplana, F. Lignocellulosic biomass from agricultural waste to the circular economy: A review with focus on biofuels, biocomposites and bioplastics. *J. Clean. Prod.* **2023**, *402*, 136815. [CrossRef]
10. Saravanakumar, A.; Vijayakumar, P.; Hoang, A.T.; Kwon, E.E.; Chen, W.H. Thermochemical conversion of large-size woody biomass for carbon neutrality: Principles, applications, and issues. *Bioresour. Technol.* **2023**, *370*, 128562. [CrossRef]
11. Hakamada, R.E.; Hubbard, R.M.; Stape, J.L.; Lima, W.P.; Moreira, G.G.; Ferraz, S.F.B. Stocking effects on seasonal tree transpiration and ecosystem water balance in a fast-growing Eucalyptus plantation in Brazil. *For. Ecol. Manag.* **2020**, *466*, 118149. [CrossRef]
12. Resquin, F.; Navarro-Cerrillo, R.M.; Carrasco-Letelier, L.; Casnati, C.R.; Bentancor, L. Evaluation of the nutrient content in biomass of *Eucalyptus* species from short rotation plantations in Uruguay. *Biomass Bioenergy* **2020**, *134*, 105502. [CrossRef]
13. Binkley, D.; Campo, O.C.; Alvares, C.; Carneiro, R.L.; Cegatta, I.; Stape, J.L. The interactions of climate, spacing and genetics on clonal *Eucalyptus* plantations across Brazil and Uruguay. *For. Ecol. Manag.* **2017**, *405*, 271–283. [CrossRef]
14. IPCC. *2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, A.P., Pirani, S.L., Connors, C., Péan, S., Berger, N., Caud, Y., Chen, L., Goldfarb, M.I., Gomis, M., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2021. [CrossRef]
15. Elli, E.F.; Sentelhas, P.C.; Bender, F.D. Impacts and uncertainties of climate change projections on *Eucalyptus* plantations productivity across Brazil. *For. Ecol. Manag.* **2020**, *474*, 118365. [CrossRef]
16. Ryan, M.G.; Stape, J.L.; Binkley, D.; Alvares, C.A. Cross-site patterns in the response of *Eucalyptus* plantations to irrigation, climate and intra-annual weather variation. *For. Ecol. Manag.* **2020**, *475*, 118444. [CrossRef]
17. Almeida, M.N.F.; Vidaurre, G.B.; Pezzopane, J.E.M.; Louzada, J.L.P.C.; Silva, M.E.C.M.; Câmara, A.P.; Rocha, S.M.G.; Oliveira, J.C.L.; Campoe, O.C.; Carneiro, R.L.; et al. Heartwood variation of *Eucalyptus urophylla* is influenced by climatic conditions. *For. Ecol. Manag.* **2020**, *458*, 117743. [CrossRef]
18. Almeida, M.N.F.; Vidaurre, G.B.; Louzada, J.L.P.C.; Pezzopane, J.E.M.; Rocha, S.M.G.; Câmara, A.P.; Oliveira, J.C.L.; Alvares, C.A.; Campoe, O.C. Wood density variations of E. urophylla clone among growth sites are related to climate. *Can. J. For. Res.* **2023**, *53*, 343–353. [CrossRef]
19. Souza, A.G.O.; Barbosa, F.S.; Esperancini, M.S.T.; Guerra, S.P.S. Economic Feasibility of Electrical Power Cogeneration from Forestry Biomass in an Engineered Wood Panel Industrial Facility. *Croat. J. For. Eng.* **2021**, *42*, 313–320. [CrossRef]
20. Brazilian Electricity Regulatory Agency (ANEEL). Number of Thermoelectric Plants by Type. SIGA—ANEEL Generation Information System. 2023. Available online: https://dadosabertos.aneel.gov.br/dataset/usinas-termeletricas-por-tipo (accessed on 10 November 2023).
21. Mitchell, E.J.S.; Gudka, B.; Whittaker, C.; Shield, I.; Price-Allison, A.; Maxwell, D.; Jones, J.M.; Williams, A. The use of agricultural residues, wood briquettes and logs for small-scale domestic heating. *Fuel Process. Technol.* **2020**, *210*, 106552. [CrossRef]
22. Telmo, C.; Louzada, J.L.P.C. Heating values of wood pellets from different species. *Biomass Bioenergy* **2011**, *35*, 2634–2639. [CrossRef]
23. Eufrade-Junior, H.J.; Spadim, E.R.; Rodrigues, S.A.; Dal Pai, E.; Ballarin, A.W.; Guerra, S.P.S. Impact of rainy and dry seasons on eucalypt fuelwood quality logs stored in piles: A case study in Brazil. *Croat. J. For. Eng.* **2021**, *42*, 291–300. [CrossRef]
24. Canto, J.L.; Machado, C.C.; Seixas, F.; Souza, A.P.; Santanna, C.M. Evaluation of a wood chipping system for *Eucalyptus* tops for energy. *Braz. J. For. Sci.* **2011**, *35*, 1327–1334. [CrossRef]

25. Acuna, M.; Anttila, P.; Sikanen, L.; Prinz, R.; Suvinen, A. Predicting and controlling moisture content to optimise forest biomass logistics. *Croat. J. For. Eng.* **2012**, *33*, 225–238.
26. Alves, R.T.; Fiedler, N.C.; Silva, E.N.; Lopes, E.S.; Carmo, F.C.A. Análise técnica e de custos do transporte de madeira com diferentes composições veiculares. *Rev. Árvore* **2013**, *37*, 897–904. [CrossRef]
27. Searcy, E.; Flynn, P.; Ghafoori, E.; Kumar, A. The relative cost of biomass energy transport. *Appl. Biochem. Biotechnol.* **2007**, *137*, 639–652. [CrossRef] [PubMed]
28. Acuna, M.; Sánchez-García, S.; Canga, E. An Optimization Approach to Assess the Impact of Drying and Dry Matter Losses of *Eucalyptus globulus* Roundwood and Biomass on Supply Chains Costs and GHG Emissions. *Forests* **2022**, *13*, 701. [CrossRef]
29. Lo, S.L.Y.; How, B.S.; Leong, W.D.; Teng, S.Y.; Rhamdhani, M.A.; Sunarso, J. Techno-economic analysis for biomass supply chain: A state-of-the-art review. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110164. [CrossRef]
30. Hamelinck, C.; Suurs, R.; Faaij, A. International bioenergy transport costs and energy balance. *Biomass Bioenergy* **2005**, *29*, 114–134. [CrossRef]
31. Silva, M.L.; Oliveira, R.J.; Valverde, S.R.; Machado, C.C.; Pires, V.A.V. Análise do custo e do raio econômico de transporte de madeira de reflorestamentos para diferentes tipos de veículos. *Rev. Árvore* **2007**, *31*, 1073–1079. [CrossRef]
32. Spinelli, R.; Eliasson, L.; Magagnotti, N. Determining the repair and maintenance cost of wood chippers. *Biomass Bioenergy* **2019**, *122*, 202–210. [CrossRef]
33. Silva, J.F.; Ramos, A. Analysis of the truck transportation of eucalyptus logging residues to Portuguese power plants. *Int. J. For. Eng.* **2019**, *30*, 35–44. [CrossRef]
34. Forest Energy Portal Illustrations for Your Presentations and Publications. Available online: https://www.renewablebusiness.eu/en/publications/images/:gallery/null (accessed on 9 February 2021).
35. Perea, L.A. *Technical and Economic Evaluation of the Cogeneration Process in a Sugar-Alcohol Industry*; São Paulo State University (UNESP): Botucatu, São Paulo, Brazil, 2005; 124p. (In Portuguese)
36. Vallios, I.; Tsoutsos, T.; Papadakis, G. Design of biomass district heating systems. *Biomass Bioenergy* **2009**, *33*, 659–678. [CrossRef]
37. Hugot, E. *Manual da Engenharia Açucareira*; Editora Mestre Jou: São Paulo, Brazil, 1977; 78p. (In Portuguese)
38. Nascimento, M.D.; Biaggioni, M.A.M. Avaliação energética do uso de lenha e cavaco de madeira para produção de energia em agroindústria seropédica. *Rev. Energ. Agric.* **2010**, *25*, 104–117. (In Portuguese)
39. Miranda, M.A.S.; Ribeiro, G.B.D.; Valverde, S.R.; Isbaex, C. *Eucalyptus* sp. woodchip potential for industrial thermal energy production. *Rev. Árvore* **2017**, *41*, e410604. [CrossRef]
40. Ribeiro, G.B.D. *Technical and Economic Analysis of Thermoelectric Energy Production from Forest Biomass*; Viçosa Federal University (UFV): Viçosa, Minas Gerais State, Brazil, 2018; 106p. (In Portuguese)
41. *CEN/TS 14918:2005*; Solid Biofuels—Determination of Calorific Value. CEN. European Committee for Standardisation: Brussels, Belgium, 2009; pp. 1–140.
42. Rezende, M.A.; Escobedo, J.F.; Ferraz, E.S.B. Retratibilidade volumétrica e densidade aparente da madeira em função da umidade. *Sci. For.* **1988**, *39*, 33–40.
43. *ASAE D472-3 Standards 2001*; Machinery, Equipment, and Buildings: Operating Costs. ASABE. American Society of Agricultural Engineers: Ames, IA, USA, 2001; p. 226.
44. Miyajima, R.H. *Influence of Relief and Experience of Operators in Yield and Costs of Eucalyptus Wood Harvesting*; Sao Paulo State University (UNESP): Botucatu, São Paulo, Brazil, 2015; 70p. (In Portuguese)
45. Widmer, J.A. Compatibilidade de tráfego de bitrens de 25 m com a infra-estrutura viária brasileira. In Proceedings of the II Colóquio Internacional de Suspensões and I Colóqui de Implementos Rodoviários, Caxias do Sul, Rio Grande do Sul State, Brazil, 16–17 May; 2002; p. 10. (In Portuguese).
46. Acuna, M.; Sessions, J.; Zamora, R.; Boston, K.; Brown, M.; Ghaffariyan, M. Methods to manage and optimise forest biomass supply chains. *Curr. For. Rep.* **2019**, *5*, 124–141. [CrossRef]
47. IEA. Instituto de Economia Agrícola. Valor de Terra Nua. Available online: http://ciagri.iea.sp.gov.br/nia1/precor_SEFAZ.aspx?cod_tipo=1&cod_sis=8 (accessed on 10 February 2021). (In Portuguese)
48. Eufrade-Junior, H.J.E.; Oguri, G.; Melo, R.X.; Ballarin, A.W.; Guerra, S.P.S. Storage of whole-tree chips from high-density energy plantations of *Eucalyptus* in Brazil. *Biomass Bioenergy* **2016**, *93*, 279–283. [CrossRef]
49. Eufrade-Junior, H.J.; Rodrigues, S.A.; Spadim, E.R.; Guerra, S.P.S.; Ballarin, A.W. Predicting moisture content of long length log piles of *Eucalyptus urophylla* under outdoor storage. *Sci. For.* **2021**, *49*, e3461. [CrossRef]
50. CCEE. Chamber of Electric Energy Commercialization. Settlement Price of Differences (SPD): Monthly Average. Available online: https://www.ccee.org.br/dados-e-analises/dados-pld (accessed on 15 November 2023).
51. Barontini, M.; Scarfone, A.; Spinelli, R.; Gallucci, F.; Santangelo, E.; Acampora, A.; Jirjis, R.; Civitarese, V.; Pari, L. Storage dynamics and fuel quality of poplar chips. *Biomass Bioenergy* **2014**, *93*, 17–225. [CrossRef]
52. Cimdina, G.; Blumberga, D.; Veidenbergs, I. Analysis of wood fuel CHP operational experience. *Energy Procedia* **2015**, *72*, 263–269. [CrossRef]
53. Cimdina, G.; Veidenbergs, I.; Kamenders, A.; Ziemele, J.; Blumberga, A.; Blumberga, D. Modelling of biomass cogeneration plant efficiency. *Agron. Res.* **2014**, *12*, 455–468.
54. Brito, J.O. Expressão da produção florestal em unidades energéticas. In Proceedings of the 7th Brazilian Forestry Congress, SBS/SBEF, Curitiba, Paraná State, Brazil, 19–24 September; 1993; pp. 280–282. (In Portuguese)

55. Zanuncio, A.J.V.; Carvalho, A.G.; Silva, M.G.; Lima, J.T. Importance of wood drying to the forest transport and pulp mill supply. *Cerne* **2017**, *23*, 147–152. [CrossRef]
56. Diego, R.; Giorgio, M.; Giuseppe, L.; Alessandro, D.R. Wood energy plants and biomass supply chain in Southern Italy. *Procedia-Soc. Behav. Sci.* **2016**, *223*, 849–856. [CrossRef]
57. Kühmaier, M.; Stampfer, K. Development of a multi-criteria decision support tool for energy wood supply management. *Croat. J. For. Eng.* **2012**, *33*, 181–198.