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Optimizing Biomass Supply Chains to Power Plants under Ecological and Social Restrictions: Case Study from Poland

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Abstract: The growing demand for social and regulatory forest ecosystem services can significantly modify the availability and cost of biomass for energy purposes. This article presents a model for optimizing biomass supply chains using a linear programming framework integrated with a geographic information system (GIS). Based on a given type of biomass resource, its calorific value, price, distance from the power plant, and transportation costs, the model identifies the optimal source of biomass, allowing it to cover the demand for the required total energy value with the lowest possible costs. The case study includes the Połaniec power plant in southeastern Poland and potential sources of forest biomass and agricultural straw within 100 km of the plant. The impact of constraints on the availability and cost of biomass was analyzed in the following scenarios: (1) all forest and agriculture biomass is available, (2) forest area in Natura 2000 network is excluded, and (3) firewood and forests with dominated ecological and social function are excluded. Unit costs of biomass varied depending on biomass availability and energy demands. The lowest unit costs of biomass (3.19 EUR/MJ) were for energy demand at the level of 1 TJ yearly for all kinds of biomass and the highest (4.91 EUR/MJ) for ecological and social constraints and energy demand 4 TJ. As energy demand increased, unit costs increased, and the ability to meet this demand with just one type of biomass decreased. The energy biomass sector can utilize the model to benefit both biomass producers and their final buyers.

Keywords: biomass; bioenergy; forest residues; renewable energy sources; GIS; linear programming; biomass restrictions

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1. Introduction

Ensuring energy security during climate change has become one of humanity's main challenges. Phasing out fossil fuels and replacing them with renewable energy sources is a central assumption of the EU Energy Policy [1,2]. At the same time, consumers increasingly want clean, renewable, and affordable energy, among others, from biomass sources [3].

In 2020, about 60% of the EU's total renewable energy came from biomass, with forestry biomass accounting for 60% and agricultural biomass and waste accounting for 40% [4]. About half of the woody biomass used for energy production is primary biomass, while the other half is secondary biomass from the timber industry and post-consumer wood. Woody biomass is particularly suitable for energy production due to its high calorific value and relatively low ash content [5]. Wood is the oldest energy source used by humans [6]. More than half of all wood harvested worldwide is used as fuel, supplying about 9% of global primary energy. Over 40% of the world's population relies on solid fuels for space heating and cooking [7,8].

By depleting stocks of aboveground woody biomass, unsustainable harvesting can contribute to forest degradation, deforestation, and climate change. Management of forests following the principles of sustainable development and the afforestation of new areas

has resulted in a steady trend of increasing woody resources in Europe in recent decades. This creates opportunities to use part of the woody biomass from forests for energy but requires proper balancing considering both the needs of the timber industry and ecological requirements [9,10].

The primary source of woody biomass is wood from forests, but the amount of biomass harvested from forests is limited and should be consistent with sustainable forest management. Some of the wood, usually of the lowest quality, is used for energy purposes and is referred to as energy wood. According to Directive 2018/2001 of 11 December 2018 of the European Parliament and the Council of the European Union on the promotion of the use of renewable energy sources [2], energy wood is defined as raw wood material that, due to its qualitative–dimensional and physical–chemical characteristics, has a reduced technical utility value, preventing its industrial use. Logging residues are a significant source of biomass that can be used for energy purposes. The current use of forest residues for commercial and household energy production is small relative to their availability [11].

Assessment of the potential and availability of biomass has been the subject of a relatively large number of studies and scientific publications. Still, for the most part, the results are generalized for large regions, e.g., the world [12] and Europe [13]. They can help shape energy policy while they are of little use to individual biomass users, where transportation distance is a key factor in profitability. Research on the supply and use of woody biomass for energy in the EU has been presented by Panoutsou et al. [14], Bentsen and Felby [15], and Camia et al. [16]. Relatively numerous works show the potential and use of biomass for energy at the national level, including in Sweden [17,18], Germany [19], Czechia [20], and Poland [21,22].

The production of woody biomass and its transport requires some energy input. The energy balance in integrated commercial timber production (saw wood and pulpwood) and energy wood (small dimensions wood and logging residues), considered energy inputs during the whole production cycle and harvesting and transport, was calculated by Routa et al. [23]. The results indicate that the primary energy use incurred during the production cycle is relatively small (less than 3%) compared to the increased potential of energy forest biomass. Winder and Bobar [24] pointed out that the principal use of timber from boreal and temperate forests should be evaluated from a holistic perspective, i.e., it needs to include forest carbon flows related to forest management. They stressed that a scenario where timber is used for 100% energy production is economically unlikely and may create a significant carbon change. In contrast, multiple end-uses are financially feasible and typically achieve far better overall greenhouse gas (GHG) emission reductions. Favero et al. [25,26] discussed wood bioenergy's role in climate mitigation and concluded that the expanded use of wood for bioenergy will result in net carbon benefits. Still, an efficient policy also needs to regulate forest carbon sequestration. The emission benefits of bioenergy compared to the use of fossil fuels are time-dependent [27,28]. All sources of woody bioenergy from sustainably managed forests will produce emission reductions in the long term. Different woody biomass sources have various impacts in the short–medium term. The use of forest residues that are easily decomposable can produce GHG benefits compared to the use of fossil fuels from the beginning of their use. However, the risk of short-to-medium-term negative impacts is high when additional resources are extracted to produce bioenergy [29].

Optimization methods are widely used for modeling the biomass supply chain for energy purposes [30–32]. Methods using geographic information systems (GISs) are used to identify the location of bioenergy plants or accurately assess transport distances [33–36]. Linear programming methods are employed for optimizing the supply chains of biomass by minimizing costs or maximizing profit [37–41].

The paper aims to develop a model to optimize biomass supply chains for energy by employing the linear programming method integrated with a geographic information system (GIS). Based on the distance from a given type of biomass resource, its price, and transportation costs, the model identifies the optimal source of woody biomass, allowing it

to cover the demand for biomass of a certain total energy value with the lowest possible purchase and transportation costs.

2. Materials and Methods

2.1. Data

The study area includes the Połaniec power plant located in southeastern Poland (50°26′10.58″ N 21°20′15.78″ E) and an area with a radius of 100 km around the plant (Figure 1). The Połaniec power plant, consists of seven energy units of 225 to 240 MW, fired by coal with biomass co-firing, and a "Green Unit" of 225 MW, using only biomass in the proportion of 80% wood biomass and 20% from agriculture [42].

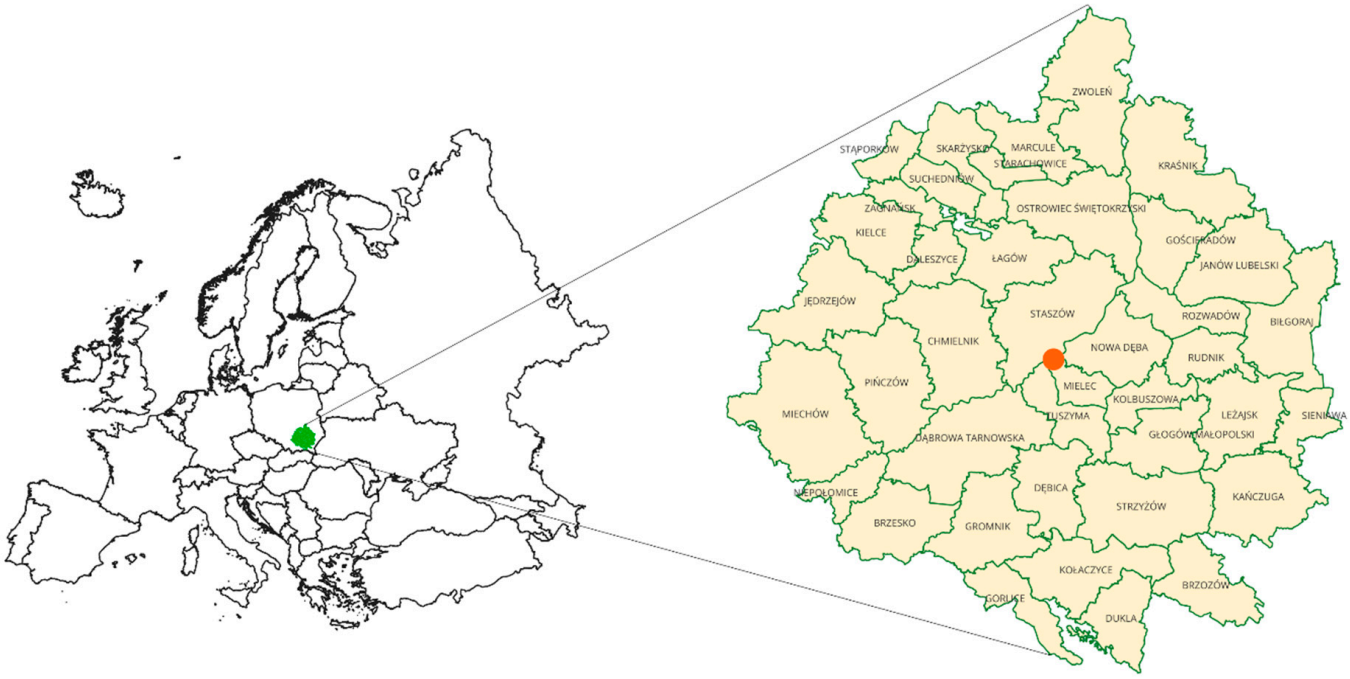


Figure 1. Location of the study area and boundaries of the spatial units. The Połaniec power plant is marked by a red point.

The research material consists of data on the supply, price, and transportation costs of forest biomass and straw from agriculture. Potential sources of biomass were identified within 40 administrative units, coinciding with the boundaries of forest districts, hereafter referred to as spatial units (Table 1). For each spatial unit, a centroid was appointed, and the distance from the centroid point to the power plant was assumed as the mean distance to the power plant. Units with a distance up to 100 km were chosen for study. The average forest cover of the study area is 26%, and the arable area is 43%. Timber harvesting in forest areas varies spatially as 51% are forests with a dominant production function, while social and ecological functions dominate the remaining 49%. About 28% of the forested areas are covered by the Natura 2000 network. The sources of data about biomass availability and prices are listed in Table 2.

Table 1. Characteristics of spatial units.

ID	Spatial Unit	Distance [(a)] (km)	Arable Area (ha 10^3)	Forested Area (ha 10^3)	Natura 2000 [(b)] (ha 10^3)	Social Forests [(c)] (ha 10^3)
1	Mielec	16	14.39	11.51	8.52	8.92
2	Staszow	18	66.17	27.79	3.24	9.95
3	Tuszyma	24	21.40	16.05	4.81	10.65
4	N Deba	30	39.01	27.31	22.45	15.76
5	Chmielnik	33	78.49	20.93	2.07	4.65
6	Dabrawa T	39	73.39	23.48	0.71	12.01
7	Łagow	41	33.7	19.38	5.72	11.33
8	Kolbuszowa	42	16.75	12.98	4.80	8.61
9	Debica	48	30.10	18.81	1.37	8.35
10	Glogow	53	22.23	18.53	6.73	12.56
11	Daleszyce	54	16.64	14.97	3.99	9.92
12	Ostrowiec	55	72.52	29.01	3.43	13.33
13	Pinczow	57	78.18	13.03	5.93	6.98
14	Rozwadow	57	30.58	22.02	5.69	11.81
15	Rudnik	62	19.56	20.54	5.02	7.03
16	Gromnik	65	1.98	22.77	0.69	7.92
17	Goscieradow	66	39.78	23.21	8.77	8.91
18	Strzyżów	67	40.31	29.56	0.82	12.35
19	Starachowice	69	2.24	14.31	1.61	14.18
20	Suchedniow	73	3.75	19.90	12.00	18.02
21	Leżajsk	77	35.45	25.7	2.37	15.82
22	Jedrzejow	78	70.17	23.39	4.12	7.54
23	Zagnansk	78	2.66	11.18	5.11	9.41
24	Janow L	80	56.67	44.39	31.14	20.92
25	Kołaczyce	81	30.33	22.24	6.90	9.68
26	Brzesko	82	26.75	19.62	0.06	5.55
27	Kielce	82	32.86	23.00	5.91	13.03
28	Marcule	82	40.38	16.82	0.28	2.94
29	Krasnik	85	87.35	30.57	2.80	2.94
30	Skarżysko	86	25.35	20.28	3.50	15.47
31	Zwolen	86	69.00	31.74	4.08	4.12
32	Niepolomice	88	15.01	10.70	10.5	10.17
33	Biłgoraj	92	42.48	40.35	8.07	8.04
34	Gorlice	92	1.03	20.64	14.01	15.79
35	Miechow	92	103.4	13.79	0.18	6.67
36	Stąporkow	94	2.77	17.20	2.10	8.56
37	Kańczuga	96	42.83	18.2	5.46	10.24
38	Dukla	99	18.57	19.81	16.84	14.53
39	Brzozów	100	21.82	24.73	6.83	15.51
40	Sieniawa	100	17.99	17.54	6.97	9.93
Total		-	1444.04	857.98	245.60	420.14

[(a)] Mean distance to Połaniec power plan, [(b)] Forested area under the protection of Natura 2000 network, and [(c)] forests with dominant social and ecological functions.

Table 2. Sources of biomass data.

Biomass Source	Potential Availability	Price
Forest biomass	Forest Data Bank [43]	State Forests [44]
Straw from agriculture	Gradziuk et al. [45]	AgroProfil Agricultural Portal [46]

The availability of woody biomass in spatial units usable for energy purposes was calculated based on the projected timber harvest in each spatial unit in 2023–2032 [43]. For energy purposes, low-quality wood, firewood, and forest residues (branches from harvested trees) can be used. Shares of low-quality wood and firewood were calculated as

the volume of these assortments harvested during the last five years (2018–2022) divided by the total volume of industrial timber harvested in this period.

The biomass of forest residues was obtained by multiplying the total volume of industrial timber predicted to be harvested by biomass expansion factors (BEFs) for branches [47]. Stand-level BEFs allowed for converting stem volume directly to the dry weight of biomass components. In this study, we used BEFs for pine, spruce, and birch, developed by Lehtonen et al. [48], and for oak, developed by Krejza et al. [49]. The volume of low-quality wood and firewood in m^3 was converted to dry biomass in tons, multiplying the volume of the assortment by the wood density factor of a given species [50]. Detailed information about the potential annual supply of different kinds of biomass is given in Table 3.

Table 3. The annual potential availability of different kinds of biomass in dry thousand tons yearly.

ID	Low-Quality Wood	Firewood	Forest Residues	Agriculture Straw
1	2.00	2.63	3.48	6.42
2	6.02	9.48	9.44	50.45
3	3.47	4.85	5.89	11.46
4	4.76	6.85	7.99	38.99
5	2.76	3.98	4.60	64.18
6	4.79	7.16	7.87	89.59
7	4.41	7.18	6.72	24.95
8	3.26	5.24	5.11	8.82
9	5.37	9.92	7.36	17.46
10	3.65	5.41	5.98	12.90
11	3.28	4.67	5.50	9.93
12	7.01	10.47	11.38	43.33
13	3.24	5.37	4.88	69.11
14	4.53	6.04	7.91	30.00
15	4.09	5.72	6.95	17.77
16	4.27	7.92	5.84	1.18
17	4.55	6.69	7.46	39.75
18	6.08	11.12	8.40	106.69
19	3.68	5.12	6.22	0.64
20	3.53	5.01	5.92	1.53
21	4.87	7.47	7.77	19.30
22	4.24	6.44	6.83	54.28
23	2.43	3.36	4.11	1.41
24	8.42	11.77	14.37	68.65
25	3.82	6.81	5.41	18.41
26	4.31	7.84	6.02	30.01
27	4.48	6.40	7.47	22.51
28	3.57	4.84	6.10	23.76
29	5.78	10.10	8.50	109.51
30	3.88	5.34	6.62	16.25
31	5.48	7.95	9.11	51.08
32	2.41	3.73	3.82	19.43
33	5.79	7.67	10.11	40.13
34	5.32	9.51	7.46	0.46
35	4.36	8.29	5.83	93.69
36	2.60	3.31	4.60	0.86
37	3.35	6.36	4.47	27.90
38	3.67	6.64	5.09	44.22
39	7.18	13.54	9.56	37.94
40	4.61	7.94	6.80	26.54
Total	175.32	276.14	274.95	1351.49

The supply of straw from agriculture was taken as the excess of production over internal consumption of straw in agriculture according to the methodology presented by

Gradziuk et al. [45]. The price of woody biomass comes from State Forests [44], the price of straw comes from the AgroProfil agricultural portal [46], while average transportation costs come from transport companies operating in the area close to the power plant (information by phone and e-mail). Information about the price and transport costs of biomass is summarized in Table 4.

Table 4. Prices, transport costs, and calorific value of different kind of biomass.

Biomass Assortment	Price (EUR/ton)	Transport Cost (EUR/km/ton)	Calorific Value (GJ/ton)
Low-quality stacked wood	51.80 [(a)]; 70.52 [(b)]; 57.06 [(c)]	0.12	17.5
Firewood	25.20 [(a)]; 35.62 [(b)]; 31.34 [(c)]	0.12	15.7
Forest residues	44.20	0.28	13.0
Straw from agriculture	50.56	0.45	14.0

[(a)] softwood (pine and spruce); [(b)] hardwood I (oak and beech); and [(c)] hardwood II (birch and alder).

The potential availability of biomass was unevenly distributed in the study area and directly depended on the geographic location of spatial units. The supply of forest biomass depends on the share of forests in a given unit, the species composition and age of forest stands, and the intensity of forest management (Figure 2a), while the potential of straw depends on the share of arable land and the dominant agricultural production profile (Figure 2b).

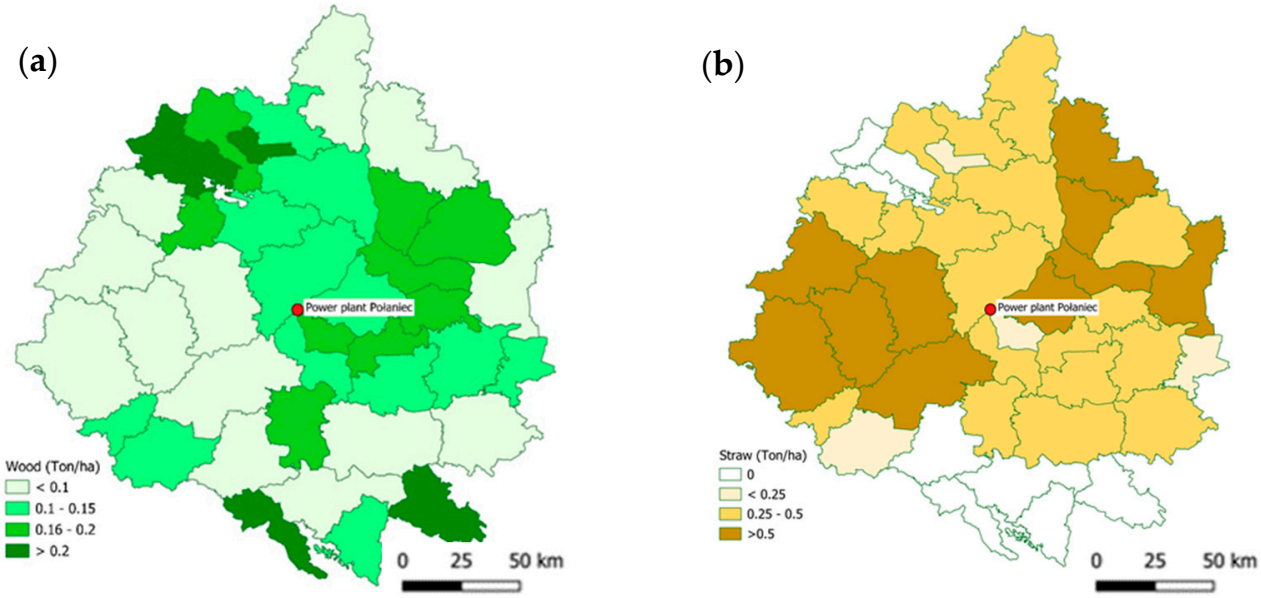


Figure 2. Distribution of the potential availability of forest biomass (**a**) and straw from agriculture (**b**) in spatial units.

2.2. Model Framework

The model concept is presented in the scheme (Figure 3). Data input into the model include information on the sources of all biomass potentially usable by the power plant for technological reasons. Each biomass source is treated separately in the model and is described by specifying the type (forest residues, solid wood, straw, etc.), quantity (in tons), and distance from the power plant. For a given type of biomass, it is also necessary to specify its price (EUR/ton), unit transportation costs (EUR/ton/km), and calorific value (GJ/kg).

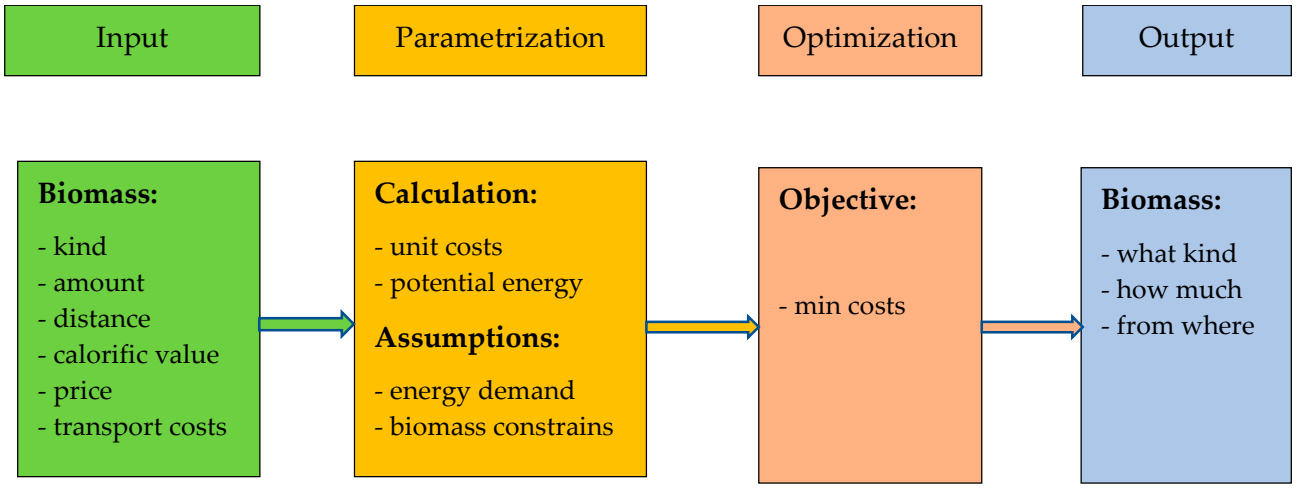


Figure 3. Conceptual diagram of the biomass supply chain optimization model.

At the model parameterization stage, unit costs are determined for each biomass source, taking into account the purchase of biomass on-site, its transportation to the power plant (EUR/ton), and its energy potential (GJ/ton). The power plant's total energy demand of biomass over a given period (1 year) is also given.

The optimization process uses a linear programming method to minimize the costs of biomass purchase for the given constant demand of biomass energy. The aim can be reversed to maximize the biomass energy amount for a given constant biomass purchase budget. The objective function is defined as follows [51].

Minimize:

$$C_k = \sum_{i=1}^{n} \sum_{j=1}^{k} x_{ij} \cdot P_j + x_{ij} \cdot l_i \cdot T_j. \quad (1)$$

Subject to:

$$E_k = \sum_{i=1}^{n} \sum_{j=1}^{k} x_{ij} * \gamma_j. \quad (2)$$

Constrains:

$$x_{ij} \leq V_{ij}; \quad (3)$$

$$\sum_{i=1}^{n} \sum_{j=\text{straw}} x_{ij} * \gamma_j = 0.2 \text{ E}. \quad (4)$$

Unit costs were calculated according to the formula

$$C_{u,k} = C_k / E_k. \quad (5)$$

where

C_k—total cost of biomass under assumptions of scenario k;
i—the spatial unit of the biomass source;
j—kind of biomass;
x_{ij}—quantity x of biomass of type j designated for purchase in unit I;
l_i—distance from unit i to power plan (km);
P_j—price of biomass of kind j (EUR/ton);
T_j—unit transport cost of j kind of biomass (EUR/ton/km);
E_k—power plant energy demand in scenario k;
γ_j—net calorific value of dry biomass of kind j;
V_{ij}—total availability of biomass in spatial unit i of type j.

Inequality No. 3 reflects the restriction that the amount of biomass designated in a unit cannot be greater than the total amount of this type of biomass in that unit. Relationship No.

4 imposes the restriction that the share of straw biomass should be 20% of the total amount of biomass purchased. Constraints, considering the ecological and social limitations are incorporated into the following scenarios of biomass availability for the power plant:

Scenario 1—all kinds and amounts of biomass in spatial units are available;

Scenario 2—all kinds of biomass are available, but the forest area under Natura 2000 protection is excluded from timber harvest;

Scenario 3—firewood is not available for the power plant (this assortment is entirely for local households only) and forests with dominated social and ecological functions are excluded. In each scenario the following variants of power plant energy demand were distinguished: (a) 1 TJ, (b) 5 TJ, and (c) 10 TJ, respectively.

Linear programming model calculations were performed using the Gurobi optimizer computer package, version 9.5.1 [52]. Based on the vector layers in the GIS system, the spatial distribution of the analyzed types of biomass was prepared and then, as part of the geolocation process, vector layers were created in which the amount of a particular kind of biomass was associated (distance determination) with the biomass consumer—the power plant. The source data were integrated into QGis software [53] to generate a layer showing the biomass availability's spatial distribution and the final optimizing process result.

3. Results

Scenario 1. The results of the optimization process for the assumptions: the energy demand is 1 TJ and all kinds of biomass are available, as illustrated in Table 5. It is recommended to purchase all available firewood (2.63 thousand tons) from the nearest unit, Mielec (16 km), with an energy value of 41.42 GJ and a cost of EUR 116.27 thousand. It is also recommended to purchase all straw biomass (6.42 thousand tons) from this unit, which would cost EUR 370.82 thousand and supply 89.88 GJ of energy. Similarly, it is recommended to purchase all firewood from the Staszów unit, but only 7.87 thousand tons of straw is needed (from a total available 50,45 thousand tons) to meet the total demand for agriculture biomass in this scenario (20% of all biomass). To provide 1TJ of energy, it is recommended to purchase 38.68 thousand tons of firewood from the subsequent six closest units. In summary, the optimal solution in scenario Ia is to purchase 50.79 tons of firewood and 14.29 tons of straw (Table 6, Figure 4a). Unit costs in this scenario are the lowest (3.19 EUR/MJ) among all analyzed variants. It is not recommended to purchase residues and low-quality wood due to the less favorable cost-to-energy ratio and low energy demand in this variant.

Table 5. Detailed results of biomass supply chain optimization in scenario Ia *.

Spatial Unit	Biomass (tons 10^3)		Energy (GJ)		Cost (EUR 10^3)	
	Firewood	Straw	Firewood	Straw	Firewood	Straw
Mielec	2.63	6.42	41.42	89.88	116.27	370.82
Staszów	9.48	7.87	149.31	110.12	423	461.65
Tuszyma	4.85	–	76.39	–	219.85	–
Nowa Dęba	6.85	–	107.89	–	316.61	–
Chmielnik	3.98	–	62.69	–	185.19	–
Dąbrowa	7.16	–	112.81	–	339.24	–
Łagów	7.18	–	113.09	–	339.11	–
Kolbuszowa	5.24	–	82.53	–	251.36	–
Dębica	3.42	–	53.87	–	164.91	–
Total	50.79	14.29	800.00	200.00	2355.54	832.47
	65.08		1000		3188.01	

*—all kind of biomass are available and the energy demand is 1TJ.

Table 6. Summarized results of the optimal kind, amount, and costs of biomass in particular scenarios.

Scenario	Biomass Kind	1 TJ	5 TJ	10 TJ	1 TJ	5 TJ	10 TJ
		Biomass (tons 10^3)			Unit Costs (EUR/MJ)		
I	Firewood	50.79	253.97	276.14	3.19	3.41	4.05
	Straw	14.29	71.43	142.86			
	Residues	–	–	217.21			
	Low-quality wood	–	–	47.26			
II	Firewood	50.79	199.14	199.14	3.22	3.61	4.38
	Straw	14.29	71.43	142.86			
	Residues	–	66.43	196.23			
	Low-quality wood	–	–	132.15			
III	Straw	14.29	58.36 [a]	in.	4.37	4.92 [a]	in.
	Residues	61.54	136.47 [a]				
	Low-quality wood	–	85.37 [a]				

[a] The maximum biomass energy available in this scenario is 4085 TJ; in.—insufficient amount of biomass in this variant to meet energy needs.

With an increase in energy demand to 5 TJ, the optimal choice is to purchase 253.97 thousand tons of firewood from 38 units with a distance of up to 99 km and 71.42 thousand tons of straw from four units (up to 30 km) (Figure 4b). In this case, the unit cost of biomass increases to 3.41 EUR/MJ (Table 5) due to the need to transport biomass from further locations.

If the demand is 10 TJ, the optimal choice is to purchase firewood from all units (276.14×10^3 tons), 217.21×10^3 tons of biomass from residues (from a distance up to 86 km), 47.26×10^3 tons of low-quality wood (from a distance up to 57 km), and 142.86×10^3 tons of straw (from a distance up to 33 km) (Figure 4c). The unit cost of biomass in this variant is 4.05 EUR/MJ (Table 5). Its increase is due to both the transport of biomass from further distances and the need to purchase more expensive biomass such as low-quality stacked wood.

Scenario 2: all kinds of biomass are available, but forests under Natura 2000 protection are excluded from harvest. The optimization results for an energy demand of 1TJ are similar to those in scenario 1a in terms of the type and amount of biomass. However, due to the exclusion of some stands from use (under Natura 2000 protection), harvesting 50.79×10^3 tons of firewood requires an increase in the purchase distance to 55 km (Figure 4d), which slightly increases unit costs to 3.22 EUR/MJ. When the energy demand increased to 5 TJ, the optimal choice was to purchase 199.14×10^3 tons of firewood, 66.43×10^3 tons of residues chips, and 71.43×10^3 tons of straw from a distance up to 100 km, 57 km, and 30 km, respectively (Figure 4e). Meeting an energy demand of 10 TJ requires the purchase of all available low-quality wood, firewood, and biomass from residues within 100 km, in amounts of 132.15×10^3 tons, 199.14×10^3 tons, and 196.23×10^3 tons, respectively. Additionally, 196.23×10^3 tons of straw from a distance up to 33 km should be purchased (Figure 4f). The unit costs in this variant increased to 4.38 EUR/MJ due to the need to purchase more expensive biomass and the longer distance of biomass transport.

Scenario 3 excludes firewood from all forests and woody biomass from forests with priority placed on social functions. To cover the energy demand of 1 TJ, 61.54×10^3 tons of residues (from a distance up to 67 km) and 71.43 tons of straw (up to 18 km) should be purchased from the two nearest units (located up to 18 km from the power plant) (Figure 4g). The unit cost of this variant is 4.37 EUR/MJ. The possibilities for meeting the higher energy demand with all the constraints in this scenario are significantly limited. All biomass available within 100 km (136.47×10^3 tons, 85.37×10^3 tons, and 58.36×10^3 tons from low-quality wood, residues, and straw, respectively) meets the energy demand of 4085 TJ. The unit cost of this variant is at the highest level of 4.92 EUR/MJ.

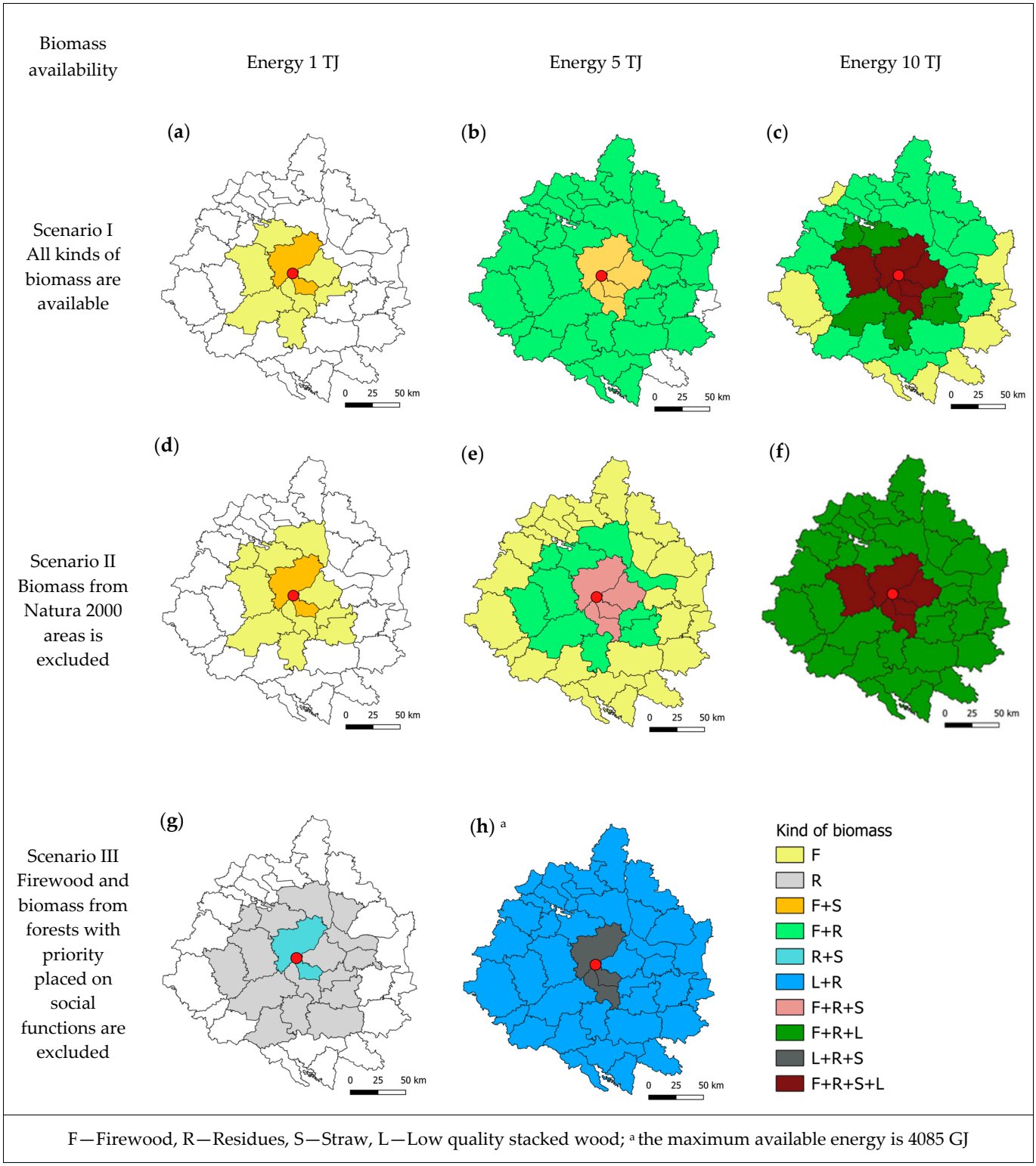


Figure 4. Optimal selection of spatial units for biomass purchase with all kind of biomass available (**a**–**c**), excluded biomass from Natura 2000 areas (**d**–**f**), excluded firewood and biomass from forests with social functions priority (**g**,**h**), and energy demand 1TJ (**a**,**d**,**g**), 5 TJ (**b**,**e**,**h**), and 10 TJ (**c**,**f**).

4. Discussion

In this paper, we developed a model to optimize biomass supply chains for a power plant or any end-users of biomass for energy production. Based on a given type of biomass

resource, its calorific value, price, distance from the power plant, and transportation costs, the model identifies the optimal source of biomass, allowing it to cover the demand for the required total energy value with the lowest possible costs.

The peculiarity of biomass used for energy purposes is characterized by significant geographic variation in supply and price. In our case study, units located to the east of the power plant have a high supply of straw (Lublin province) and are dominated by agricultural areas with high grain production. In contrast, southern and northwestern units have a higher supply of woody biomass (a high proportion of forests) and no surplus straw for energy use. Similar studies in central Polan and upper Silesia were conducted by Zyadin et al. [36]. Authors used GIS applications, secondary data from official sources, and data from a field survey to produce land use and GIS maps for surplus forest and agricultural biomass. Surplus residues from all crops in Upper Silesia and in Kujawsko-Pomorskie were estimated at 0.60 t/ha over a 12-month period. In our research, the surplus of forest and agriculture residues was estimated at the average level of 0.49 t/ha yearly.

Biomass transport costs play an important role due to their significance in relation to the value of energy; therefore, the spatial analysis of biomass source analysis is important [54,55]. Perpiñá et al. [56] analyzed the spatial distribution of agricultural and forest residue biomass to locate a network of bioenergy plants. They assumed spatial units as a grid of rectangles with an area of 1 km^2. Zhao et al. [57] developed a spatially explicit optimization model for agricultural straw-based power plant site selection in China using space units at 1 km $\times$ 1 km intervals. Nordin et al. [58] investigated the cost-effective localization of production facilities for ethanol from agricultural land in Sweden. They used a municipality as a spatial unit. In our study, as spatial units, we used administrative units, overlapping in scope with the boundaries of the forest district. The adoption of such a unit in the spatial analysis was due to the fact that the availability of woody biomass under the analyzed ecological and social constraints is determined at the forest district level.

The developed model simultaneously optimizes biomass's purchase price and transportation costs. In our case study, the cheapest were (without transportation costs) forest residues, and straw, and the most expensive stacked wood. Unit transportation costs were different, depending mainly on the volume occupied by a ton of biomass, and were lowest for stacked wood, followed by chips from forest residues, and highest for straw (0.12, 0.28, and 0.45 EUR/km/tons, respectively). The model first selected forest residues from units closest to the power plant at low demand. As demand increased, straw from the closest units was selected, while at high demand and with the need to reach for biomass much farther away, sacked wood was a more favorable choice than straw.

A study of the effectiveness of small-scale biomass supply chains and different bioenergy production systems utilizing forest residues as biomass sources was conducted by Ahmadi et al. [59]. The authors stated that bioenergy production could be cost-effective in the current carbon credit market. Costs related to the use of wood biomass for energy production on a regional scale were assessed by Furubayashi and Nakata [60]. Our results indicated that unit costs were lowest at low-energy demand and increased as demand increased. The findings confirm the results of other studies that it is better to build local, small heat plants than large ones that require transporting biomass from farther distances, which, in addition to costs, increases the amount of indirect energy spent and CO_2 emissions.

Woody biomass energy potential depends on the available woody biomass resources and the competition between alternative uses [61]. Lauri et al. [62] stated that woody biomass resources are large enough to cover a substantial share of the world's primary energy consumption in 2050. However, these resources have alternative uses, and their accessibility is limited. Hence, the key question regarding woody biomass use for energy is not the amount of resources but rather their price.

The greenhouse gas emission (GHG) performance of different supply chain configurations of lignocellulosic biomass (stem wood, forest residues, sawmill residues, and sugarcane bagasse) was analyzed by Vera et al. [63]. They found that the use of woody biomass yields better GHG emission performance for the conversion system than sugarcane

bagasse or sugar beets as a result of the higher lignin content. The allocation of biomass resources for minimizing energy system greenhouse gas emissions was studied by Bentsen et al. [64]. They stated that electricity production should be based on forest residues and other woody biomass, heat production on forest and agricultural residues, and liquid fuel production should be based on agricultural residues.

The advantage of this work is integrating the spatial availability of different forest and agriculture biomass sources with cost analysis, as well as socio-ecological constraints in the framework of linear programming optimization. On the other hand, the disadvantage of this study is the relatively large area of units used in spatial analysis (forest district range boundaries), which affects the accuracy of the optimization results. The second inconvenience is the lack of a minimum biomass threshold at a given site (e.g., the payload of one truck), below which it would be uneconomical to purchase biomass from that site. Adopting smaller spatial units, e.g., 1 km^2, would make it easier to solve this issue by setting an additional constraint on the model.

5. Conclusions

The developed model allows the identification of optimal biomass supply chains in terms of economic viability and regulation constraints. The input data in the model are the price and spatial availability of each potential kind of biomass.

The unit costs of biomass varied depending on biomass restrictions and energy demand. As energy demand increased, unit costs increased, and the ability to meet this demand with just one type of biomass decreased. The lowest unit costs of biomass (3.19 EUR/MJ) were for energy demand at 1 TJ yearly, when all kinds of biomass were available, and the highest (4.91 EUR/MJ) with ecological and social constraints and energy demand of 4 TJ.

Ecological constraints generally involve the exclusion of forest areas from timber harvesting. In contrast, social constraints affect the limitation of timber harvest in recreational forests and the purpose of firewood is restricted only to local household use, making it unavailable to power plants. The exclusion of 29% of the Natura 2000 forest area from timber harvesting resulted in a 6% increase in the unit cost of energy from biomass. The additional exclusion of 20% of the forest area with social functions and the restriction of firewood sale only to households increased unit costs by 44% and resulted in the inability to fully cover the power plant's energy demand.

The results of this study indicate that it is better to build local, small power/heat plants than large ones that require transporting biomass from farther distances, which, in addition to costs, increases the amount of indirect energy spent and CO_2 emissions.

Integrating supply chains with geographic information systems allows us to trace the legality of biomass sources. The methodology presented here can help efficiently allocate possible renewable energy subsidies and eliminate cases of inappropriate use of quality wood by power plants, such as subsidies directly to reduce the purchase price of better quality wood initially intended for the timber industry. The energy biomass sector can utilize this model to benefit both biomass producers and their final buyers.

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References

1. Moser, C.; Leipold, S. Toward "hardened" accountability? Analyzing the European Union's hybrid transnational governance in timber and biofuel supply chains. *Regul. Gov.* **2021**, *15*, 115–132. [CrossRef]
2. *Directive (EU) 2018/2001 of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Resources*. 2018. Available online: https://www.europeansources.info/record/directive-eu-2018-2001-on-the-promotion-of-the-use-ofenergy-from-renewable-sources/ (accessed on 20 March 2024).
3. Richter, D.D.; Jenkins, D.H.; Karakash, J.T.; Knight, J.; McCreery, L.R.; Nemestothy, K.P. Resource policy. Wood energy in America. *Science* **2009**, *323*, 1432–1433. [CrossRef] [PubMed]
4. Chudy, R.; Szulecki, K.; Siry, J.; Grala, R. Biomasa drzewna jako surowiec dla energetyki. *Academia* **2021**, *65*, 62–65. [CrossRef]
5. McKendry, P. Energy production from biomass (part 1): Overview of biomass. *Bioresour. Technol.* **2002**, *83*, 37–46. [CrossRef] [PubMed]
6. Bailis, R.; Drigo, R.; Ghilardi, A.; Masera, O. The carbon footprint of traditional woodfuels. *Nat. Clim. Chang.* **2015**, *5*, 266–272. [CrossRef]
7. Ahmad, R.; Zhou, Y.; Hua, L.; Zhao, N.; Abbas, A.; Sultan, M.; Raman, P.; Dong, R. Study on biomass-based gasifier cookstovefor domestic application. *Fresenius Environ. Bull.* **2021**, *30*, 4365–4374.
8. Ahmad, R.; Ilyas, H.N.; Li, B.; Sultan, M. Current challenges and future prospect of biomass cooking and heating stoves in Asian Countries. *Front. Energy Res.* **2022**, *10*, 880064. [CrossRef]
9. Verkerk, P.J.; Anttila, P.; Eggers, J.; Lindner, M.; Asikainen, A. The realisable potential supply of woody biomass from forests in the European Union. *For. Ecol. Manag.* **2011**, *261*, 2007–2015. [CrossRef]
10. Banaś, J.; Utnik-Banaś, K. Using Timber as a Renewable Resource for Energy Production in Sustainable Forest Management. *Energies* **2022**, *15*, 2264. [CrossRef]
11. Durocher, C.; Thiffault, E.; Achim, A.; Auty, D.; Barrette, J. Untapped volume of surplus forest growth as feedstock for bioenergy. *Biomass Bioenergy* **2019**, *120*, 376–386. [CrossRef]
12. Smeets, E.M.W.; Faaij, A.P.C. Bioenergy potentials from forestry in 2050. *Clim. Chang.* **2007**, *81*, 353–390. [CrossRef]
13. Karjalainen, T.; Asikainen, A.; Ilavsky, J.; Zamboni, R.; Hotari, K.-E.; Röser, D. *Estimation of Energy Wood Potential in Europe*; Working papers of the Finnish Forest Research Institute; Finnish Forest Research Institute: Helsinki, Finland, 2004; Available online: https://jukuri.luke.fi/handle/10024/535922 (accessed on 20 March 2024).
14. Panoutsou, C.; Eleftheriadis, J.; Nikolaou, A. Biomass supply in EU27 from 2010 to 2030. *Energy Policy* **2009**, *37*, 5675–5686. [CrossRef]
15. Bentsen, N.S.; Felby, C. Biomass for energy in the European Union—A review of bioenery resource assessment. *Biotechnol. Biofuels* **2012**, *5*, 25. [CrossRef] [PubMed]
16. Camia, A.; Giuntoli, J.; Jonsson, R.; Robert, N.; Cazzaniga, N.E.; Jasinevičius, G.; Grassi, G.; Barredo, J.I.; Mubareka, S. *The Use of Woody Biomass for Energy Production in the EU*; JRC science for policy report JRC122719; Publications Office of the European Union: Luxembourg, 2021.
17. Lundmark, R.; Athanassiadis, D.; Wetterlund, E. Supply assessment of forest biomass—A bottom-up approach for Sweden. *Biomass Bioenergy* **2015**, *75*, 213–226. [CrossRef]
18. Kumar, A.; Adamopoulos, S.; Jones, D.; Amiandamhen, S.O. Forest Biomass Availability and Utilization Potential in Sweden: A Review. *Waste Biomass Valor.* **2021**, *12*, 65–80. [CrossRef]
19. Ralf-Uwe, S.; Tran Thuc, H.; Karsten, G.; Suili, X.; Wolfgang, W. Residential Heating Using Woody Biomass in Germany—Supply, Demand, and Spatial Implications. *Land* **2022**, *11*, 1937. [CrossRef]
20. Šafařík, D.; Hlaváčková, P.; Michal, J. Potential of Forest Biomass Resources for Renewable Energy Production in the Czech Republic. *Energies* **2022**, *15*, 47. [CrossRef]
21. Różański, H.; Jabłoński, K. Możliwości pozyskania biomasy leśnej na cele energetyczne w Polsce. *J. Civ. Eng. Environ. Archit.* **2015**, *62*, 351–358.
22. Majchrzak, M.; Szczypa, P.; Adamowicz, K. Supply of Wood Biomass in Poland in Terms of Extraordinary Threat and Energy Transition. *Energies* **2022**, *15*, 5381. [CrossRef]
23. Routa, J.; Kellomäki, S.; Kilpeläinen, A.; Peltola, H.; Strandman, H. Effects of forest management on the carbon dioxide emissions of wood energy in integrated production of timber and energy biomass. *GCB Bioenergy* **2011**, *3*, 483–497. [CrossRef]
24. Winder, G.M.; Bobar, A. Responses to stimulate substitution and cascade use of wood within a wood use system: Experience from Bavaria, Germany. *Appl. Geogr.* **2018**, *90*, 350–359. [CrossRef]
25. Favero, A.; Daigneault, A.; Sohngen, B. Forests: Carbon sequestration, biomass energy, or both? *Sci. Adv.* **2020**, *6*, eaay6792. [CrossRef] [PubMed]
26. Favero, A.; Mendelsohn, R.; Sohngen, B. Using forests for climate mitigation: Sequester carbon or produce woody biomass? *Clim. Chang.* **2017**, *144*, 195–206. [CrossRef]
27. Ameray, A.; Bergeron, Y.; Valeria, O.; Montoro Girona, M.; Cavard, X. Forest Carbon Management: A Review of Silvicultural Practices and Management Strategies Across Boreal, Temperate and Tropical Forests. *Curr. For. Rep.* **2021**, *7*, 245–266. [CrossRef]
28. Baral, A.; Malins, C. *Assessing the Climate Mitigation Potential of Biofuels Derived from Residues and Wastes in the European Context*; International Council on Clean Transportation: Washington, DC, USA, 2014; Available online: https://theicct.org/wp-content/uploads/2021/06/ICCT_biofuels_wastes-residues_20140130.pdf (accessed on 20 March 2024).

29. Giuliana, Z.; Naomi, P.; Bird, N. Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *Bioenergy* **2012**, *4*, 761–772. [CrossRef]
30. Batista, R.M.; Converti, A.; Pappalardo, J.; Benachour, M.; Sarubbo, L.A. Tools for Optimization of Biomass-to-Energy Conversion Processes. *Processes* **2023**, *11*, 854. [CrossRef]
31. Keith, K.; Castillo-Villar, K.K. Stochastic Programming Model Integrating Pyrolysis Byproducts in the Design of Bioenergy Supply Chains. *Energies* **2023**, *16*, 4070. [CrossRef]
32. Abusaq, Z.; Habib, M.S.; Shehzad, A.; Kanan, M.; Assaf, R. A Flexible Robust Possibilistic Programming Approach toward Wood Pellets Supply Chain Network Design. *Mathematics* **2022**, *10*, 3657. [CrossRef]
33. Lozano-García, D.F.; Santibañez-Aguilar, J.E.; Lozano, F.J.; Flores-Tlacuahuac, A. GIS-based modeling of residual biomass availability for energy and production in Mexico. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109610. [CrossRef]
34. Sahoo, K.; Hawkins, G.L.; Yao, X.A.; Samples, K.; Mani, S. GIS-based biomass assessment and supply logistics system for a sustainable biorefinery: A case study with cotton stalks in the Southeastern US. *Appl. Energy* **2016**, *182*, 260–273. [CrossRef]
35. Wang, Y.; Wang, J.; Schuler, J.; Hartley, D.; Volk, T.; Eisenbies, M. Optimization of harvest and logistics for multiple lignocellulosic biomass feedstocks in the northeastern United States. *Energy* **2020**, *197*, 117260. [CrossRef]
36. Zyadin, A.; Natarajan, K.; Latva-Käyrä, P.; Igliński, B.; Iglińska, A.; Trishkin, M.; Pelkonen, P.; Pappinen, A. Estimation of surplus biomass potential in southern and central Poland using GIS applications. *Renew. Sustain. Energy Rev.* **2018**, *89*, 204–215. [CrossRef]
37. Wu, J.; Zhang, J.; Yi, W.; Cai, H.; Li, Y.; Su, Z. Agri-biomass supply chain optimization in north China: Model development and application. *Energy* **2022**, *239*, 122374. [CrossRef]
38. Nienow, S.; McNamara, K.T.; Gillespie, A.R. Assessing plantation biomass for co-firing with coal in northern Indiana: A linear programming approach. *Biomass Bioenergy* **2000**, *18*, 125–135. [CrossRef]
39. Abdelhady, S.; Shalaby, M.A.; Shaban, A. Techno-Economic Analysis for the Optimal Design of a National Network of Agro-Energy Biomass Power Plants in Egypt. *Energies* **2021**, *14*, 3063. [CrossRef]
40. Ferretti, I. Optimization of the Use of Biomass Residues in the Poplar Plywood Sector. *Procedia Comput. Sci.* **2021**, *180*, 714–723. [CrossRef]
41. Reis, S.A.d.; Leal, J.E.; Thomé, A.M.T. A Two-Stage Stochastic Linear Programming Model for Tactical Planning in the Soybean Supply Chain. *Logistics* **2023**, *7*, 49. [CrossRef]
42. Kwiatkowski, A. Forum Biomasy. Available online: https://powermeetings.eu/konferencja/forum-biomasy/wp-content/uploads/sites/19/2018/05/04-ENEA-Adam-Kwiatkowski-Forum-Biomasy-powermeetings.eu-Mielec-2018.pdf (accessed on 19 February 2024).
43. Forest Data Bank. Available online: www.bdl.lasy.gov.pl/portal/en (accessed on 20 January 2024).
44. State Forests. Information on Sales of Selected Groups of Wood in Forest Districts State Forests. Available online: https://drewno.zilp.lasy.gov.pl/drewno/ (accessed on 15 February 2024).
45. Gradziuk, P.; Gradziuk, B.; Trocewicz, A.; Jendrzejewski, B. Potential of Straw for Energy Purposes in Poland—Forecasts Based on Trend and Causal Models. *Energies* **2020**, *13*, 5054. [CrossRef]
46. Agroprofil Agricultural Portal. Available online: https://agroprofil.pl/wiadomosci (accessed on 20 March 2024).
47. Petersson, H.; Holm, S.; Ståhl, G.; Alger, D.; Fridman, J.; Lehtonen, A.; Lundström, A.; Mäkipää, R. Individual tree biomass equations or biomass expansion factors for assessment of carbon stock changes in living biomass—A comparative study. *For. Ecol. Manag.* **2012**, *270*, 78–84. [CrossRef]
48. Lehtonen, A.; Mäkipää, R.; Heikkinen, J.; Sievänen, R.; Liski, J. Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. *For. Ecol. Manag.* **2004**, *188*, 211–224. [CrossRef]
49. Krejza, J.; Světlík, J.; Bednář, P. Allometric relationship and biomass expansion factors (BEFs) for above- and below-ground biomass prediction and stem volume estimation for ash (*Fraxinus excelsior* L.) and oak (*Quercus robur* L.). *Trees* **2017**, *31*, 1303–1316. [CrossRef]
50. The Engineering ToolBox. Wood Species-Densities. Available online: https://www.engineeringtoolbox.com/wood-density-d_40.html (accessed on 10 March 2024).
51. Bettinger, P.; Boston, K.; Siry, J.P.; Grebner Donald, L. *Forest Management and Planning: Linear Programming*; Elsevier: San Diego, CA, USA, 2009.
52. *Gurobi Optimizer*; Gurobi Optimization, LLC: Beaverton, OR, USA, 2023. Available online: https://www.gurobi.com/solutions/gurobi-optimizer/ (accessed on 20 March 2024).
53. *QGIS Geographic Information System. QGIS Association*. QGIS.org. 2024. Available online: https://www.qgis.org/id/site/ (accessed on 20 March 2024).
54. Frombo, F.; Minciardi, R.; Robba, M.; Rosso, F.; Sacile, R. Planning woody biomass logistics for energy production: A strategic decision model. *Biomass Bioenergy* **2009**, *33*, 372–383. [CrossRef]
55. Latterini, F.; Stefanoni, W.; Suardi, A.; Alfano, V.; Bergonzoli, S.; Palmieri, N.; Pari, L. A GIS Approach to Locate a Small Size Biomass Plant Powered by Olive Pruning and to Estimate Supply Chain Costs. *Energies* **2020**, *13*, 3385. [CrossRef]
56. Perpiñá, C.; Alfonso, D.; Pérez-Navarro, A.; Peñalvo, E.; Vargas, C.; Cárdenas, R. Methodology based on Geographic Information Systems for biomass logistics and transport optimisation. *Renew. Energy* **2009**, *34*, 555–565. [CrossRef]
57. Zhao, X.; Ma, X.; Wang, K.; Long, Y.; Zhang, D.; Xiao, Z. A Spatially Explicit Optimization Model for Agricultural Straw-Based Power Plant Site Selection: A Case Study in Hubei Province, China. *Sustainability* **2017**, *9*, 832. [CrossRef]

58. Nordin, I.; Elofsson, K.; Jansson, T. Optimal localisation of agricultural biofuel-Swedish case. *Eur. Rev. Agric. Econ.* **2021**, *49*, 910–941. [CrossRef]
59. Ahmadi, L.; Kannangara, M.; Bensebaa, F. Cost-effectiveness of small scale biomass supply chain and bioenergy production systems in carbon credit markets: A life cycle perspective. *Sustain. Energy Technol. Assess.* **2020**, *37*, 100627. [CrossRef]
60. Furubayashi, T.; Nakata, T. Analysis of woody biomass utilization for heat, electricity, and CHP in a regional city of Japan. *J. Clean. Prod.* **2021**, *290*, 125665. [CrossRef]
61. Berndes, G.; Hoogwijk, M.; van den Broek, R. The contribution of biomass in the future global energy supply: A review of 17 studies. *Biomass Bioenergy* **2003**, *25*, 1–28. [CrossRef]
62. Lauri, P.; Havlík, P.; Kindermann, G.; Forsell, N.; Böttcher, H.; Obersteiner, M. Woody biomass energy potential in 2050. *Energy Policy* **2014**, *66*, 19–31. [CrossRef]
63. Vera, I.; Hoefnagels, R.; van der Kooij, A.; Moretti, C.; Junginger, M. A carbon footprint assessment of multi-output biorefineries with international biomass supply: A case study for the Netherlands. *Biofuels Bioprod. Bioref.* **2020**, *14*, 198–224. [CrossRef]
64. Bentsen, N.S.; Jack, M.W.; Felby, C.; Thorsen, B.J. Allocation of biomass resources for minimising energy system greenhouse gas emissions. *Energy* **2014**, *69*, 506–515. [CrossRef]

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