

## Article

# Solid Biomass Energy Potential as a Development Opportunity for Rural Communities

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**Abstract:** Conventional energy sources often do not fully satisfy the needs of a modern economy, especially given the climate changes associated with them. These issues should be addressed by diversification of energy generation, including the development of renewable energy sources (RES). Solid biomass will play a major part in the process in Poland. The function of rural areas, along with a well-developed agricultural and forest economy sector, will be a key aspect in this as these areas are suitable for solid biomass acquisition in various ways. This study aimed to determine the solid biomass energy potential in the commune of Goworowo to illustrate the potential in the smallest administrative units of Poland. This research determined the environmental and natural conditions in the commune, which helped to identify the crucial usable solid biomass resources. The total energy potential of solid biomass resources in the commune of Goworowo amounted to 97,672 GJ  $y^{-1}$ . The highest potential was accumulated in straw surplus (37,288 GJ  $y^{-1}$ ) and the lowest was in wood from roadside maintenance (113 GJ  $y^{-1}$ ). This study showed that rural areas could soon play a significant role in obtaining solid biomass, and individual communes could become spaces for the diversification of energy feedstock.

**Keywords:** solid biomass; bioenergy potential; rural communities; forest residues; agricultural residues; straw; energy crops



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## 1. Introduction

A region's economic development depends on access to energy and conventional resources such as coal, natural gas and oil are no longer sufficient to satisfy the increasing demand from the economy. Moreover, non-renewable energy sources contribute to climate changes, making it necessary to seek alternative options, including renewable solutions (RES) [1–3]. Energy generation in Poland is based on hard coal and brown coal, which boosts the greenhouse effect and, since fossil fuel resources are highly likely to be exhausted, measures should be taken to promote RES, whose supply is unlimited. Since coal accounted for 77% of all energy carriers used in Poland in 2019, it is claimed that the proportion of RES in the energy mix in Poland is insufficient [1,4]. Pressure from both society and the international community necessitates changes in the energy source structure, and the removal of coal from power generation in Poland is still too slow [3,4]. However, pressure is growing, as the solutions proposed by the European Commission at the UN COP25 climate summit in Madrid assume that the European economy will have achieved climatic neutrality by 2050 (The European Green Deal). The realization of this idea would require the implementation of multiple measures covering all aspects of EU citizens' lives, including bioeconomy—a topic which is not covered by any Polish strategic document [5,6].

Energy from RES includes energy from biomass, solar energy, energy from water, wind, geothermal sources and energy from the environment obtained using heat pumps.

The proportion of energy from RES in the structure of energy generation in Poland has been increasing in recent years, but it is still small. RES accounted for 16.0% of the total primary energy in 2019; more than in 2014–2018 (by 3.9, 2.9, 2.4, 1.7 and 1.5 percentage points, respectively). At the same time, the average proportion of energy from renewable sources in the total primary energy in the EU-28 increased much faster—from 26.1% in 2014 to 32.8% in 2019 [7–10]. This situation necessitates a greater use of renewable energy to increase the proportion of RES in energy generation.

Solid biomass is the dominant RES in Poland and it accounted for 65.6% of the total in 2019, with 55% of the amount being consumed by end-users without being converted to another energy carrier. Solid biomass is the leader in heat generation from RES in Poland (90.1% in 2019) and it also accounted for 25.1% of electricity generation in 2018, with only wind energy having a larger share [11]. The proportion of biomass can increase since individual solid fuel-fired boilers do not increase total operating costs compared to fossil fuel-fired boilers. Nearly 60% of the EU-28 population live in houses that require heating boilers, many of which have to be replaced [12].

Diversified renewable energy is now the most promising sustainable energy system instead of non-renewable and centralized systems. Local generation and distribution of energy increases the system reliability and reduces the distribution related loss, which is the case with the centralization of energy sources [13]. Therefore, a single region should be regarded as a not-fully-used energy system considering the RES resources present in it. Such activities align with the concept of sustainable development and circular economy [1] because seeking local and renewable energy sources guarantees their development, which is important given the crisis resulting from the exhaustion of conventional energy sources [4]. Therefore, sustainable development can be achieved through the development of society, which is guided by a comprehensive approach to products and/or services concerning materials and energy and ensures raw material effectiveness and economic growth throughout the product life cycle [14].

The territory of Poland is divided into regions, with the administrative division being the most common manifestation of regionalization. Poland is divided into 16 voivodships, 314 districts and 2477 communes as the smallest administrative units. There are 302 urban communes, 642 urban–rural communes and 1533 rural communes [15]. Considerable parts of rural areas contain potential sources of solid biomass which could play a special role in the local energy system, especially since the average commune size is 12,500 ha [16]. It should be noted that rural communes have good conditions for the diverse use of green energy. This applies particularly to agriculture, which can facilitate the transition from a fossil fuel-based economy to an economy based on renewable energy [4,6]. Significant benefits from solid biomass use as energy feedstock include regional energy independence, the prevention of low emissions, the creation of new jobs, the use of marginal land, agricultural and forest residue management, local communities becoming motivated to act for the benefit of the environment and, primarily, the opportunity to obtain clean energy [1]. Agriculture in EU countries is consuming increasing amounts of energy, which has resulted in the diversification of its resources and the growing importance of RES. Introducing green energy presents an opportunity for agriculture modernization without intensifying its adverse impact on the environment [17].

To date, the energy potential of agricultural residues in 294 countries of the world has been determined [18], as well as the solid biomass energy potential in Switzerland [19] and Turkey [20]. Stolarski et al. [21] determined the bioenergy potential of the countries bordering the Baltic Sea, including Poland. Smaller regions, i.e., districts, were dealt with by Kowalczyk-Juśko et al. [22]. However, there were no detailed papers in the literature that provided a comprehensive methodology of the conducted studies or analyses of the biomass energy potential in individual communes considering their specific local conditions. Although such studies are of significance to the diversification of local energy sources which ultimately affects the country's energy balance, the number of in-depth scientific papers on the topic is low. Therefore, taking up this subject was justified since

this forecast could affect the investment decisions concerning energy generation and consequently increase the RES proportion in the local generation structure. This study aimed to determine the solid biomass resources and the energy potential in the Commune of Goworowo. This analysis should be used as the basis for changes in the local strategies of regional development, raising social awareness of the potential and local use of RES in rural areas.

## 2. Materials and Methods

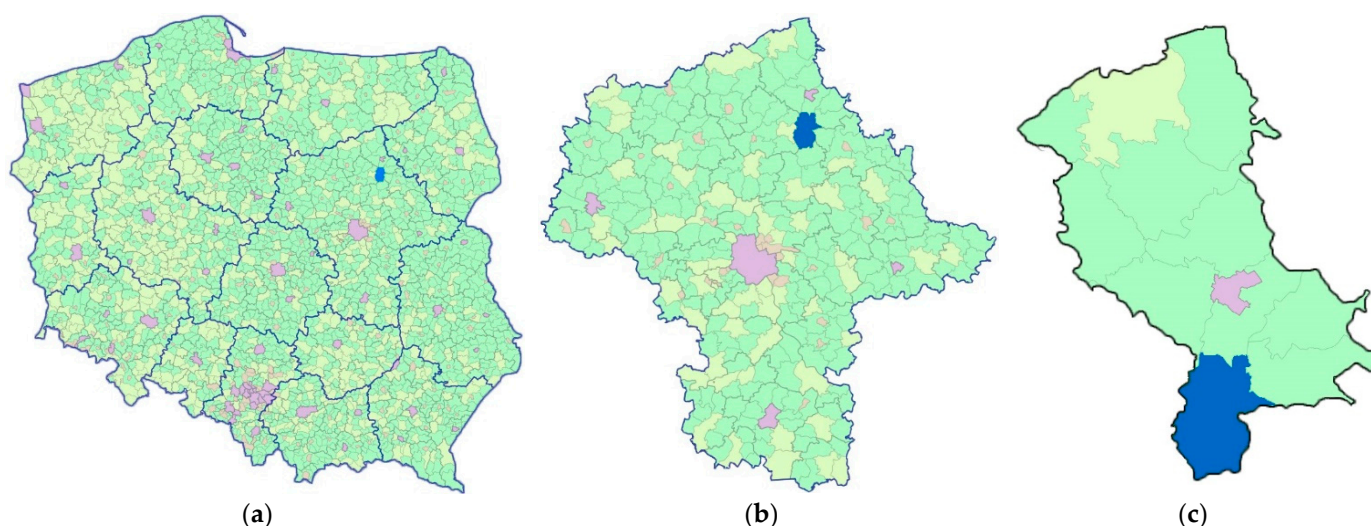
The research was conducted in the commune of Goworowo (the commune is the basic unit in the administrative division of Poland). Goworowo is a typical rural commune in the north Mazovian Lowland, whose conditions are representative of those of central-eastern Poland. The methodological work was started by determining the environmental and natural conditions in the commune with respect to the solid biomass acquisition potential. The materials that were originally accumulated were used to identify the most significant and usable sources within the administrative unit under study. Data were mainly gathered using the official, up-to-date administrative databases. It is noteworthy that there are often no data solely concerning the administrative area of a commune in Poland as there may be several managing bodies whose authority extends over a commune, as is the case with forest lands.

The next stage involved the determination of the solid biomass amount from various sources based on the processed data and the methodology presented further in the paper. As a consequence, the total solid biomass energy potential could be referred to hard coal—the most common energy source in Poland, including rural areas [9]. The specific local conditions in the commune were considered when the solid biomass resources in it were determined.

### 2.1. Characteristics of the Commune

#### 2.1.1. Administrative Affiliation and General Information

The commune of Goworowo covered an area of 21,909.44 ha in 2020 [23]. Administratively, it is part of the Mazowieckie Voivodship and is situated in the north-east of the voivodship, in the southern part of the Ostrołęcki District, 52°54' N 21°33' E [24]. The relative position of the commune in the administrative units is shown in Figure 1.



**Figure 1.** Position of the commune of Goworowo (blue): (a) in Poland; (b) in the Mazowieckie Voivodship; (c) in the Ostrołęcki District.

It had a population of 8455 people at the end of December 2019, which accounted for 9.5% of the population of the Ostrołęcki District. The population density in the commune was 39 people per km<sup>2</sup>. The unit under analysis was a commune with a medium-

sized population and area when compared to the other communes in the Ostrołęcki District [23,25]. When compared to all 2478 communes in Poland, Goworowo had a nearly twice smaller population (an average of 15,500 people) and its area was nearly twice larger than the average (12,500 ha) [16,23].

It is an agricultural commune, with dominating individual farming oriented towards dairy cattle breeding. Swine are also bred. In crop production, grain crops, corn for silage and root crops dominate. Non-agricultural business activities include services—mainly food industry related, forestry related and in the repair and construction and transport area. Industry includes only production and service facilities. Currently, the agriculture, construction and processing industries enjoy the greatest development opportunity in the commune, along with rural tourism, including agrotourism and organic farms. Therefore, using RES would be in line with this development trend. There were no industrial facilities within the commune that posed an increased or high risk of industrial failure [23,26].

### 2.1.2. Land Use

The commune land was mainly covered by forest or used for agriculture, with farmland accounting for 61.87% of the total area and forest for 32.36% (Table 1). The other lands accounted for 5.77% of the commune area [23].

**Table 1.** Land use structure in the commune of Goworowo.

Item	Proportion of the Area (%)
Farmland	61.87
Farmland with trees and bushes	0.80
Forest land	32.36
Wasteland	0.97
Built-up and urbanized area	2.86
Land under waters	1.05
Other land	0.09

Residential buildings occupied the greatest part of the built-up area (41%) followed by farmstead buildings (39%). Approximately 8% of the area was occupied by recreational buildings and 2% by service and industrial facilities [23,26].

The soil classification system in Poland includes soils from class I (best) to class VI (poorest). Arable land class V and VI in the commune of Goworowo (excluding orchards) altogether accounted for 56.1%. Permanent grassland was dominated by poor and very poor quality soils (62.8%), with larger complexes of such land occurring in the north and in the south of the commune, where disadvantageous moisture content in the soil (requiring soil melioration) dominated [27]. Class IV soils dominated in orchards.

Better soils were formed on loams and glacial dust and were present in vast and compact areas in the commune center. These included medium and good soils, mainly acidic brown soils with occasional podsol or pseudo-podsolic soils. However, poor and very poor quality soils, brown acidic soils and podsol soils formed on glacial sand dominated in the south and the north of the commune [28]. The commune was among the areas of the Mazowieckie Voivodship with medium-advantageous conditions for agriculture development.

### 2.1.3. Structure of Agricultural Land

Arable land (9571.03 ha) dominated the farmland. Grassland—pastures (1784.00 ha) and meadows (1543.16 ha)—occupied a much smaller area. Orchards covered the smallest area (21.96 ha) [23].

The major crop area was determined based on the average crop production area structure in the Mazowieckie Voivodship [29]. Therefore, the area where crops were produced accounted for 77% of the entire arable land. The remaining 23% was occupied

by agriculture or horticulture supporting facilities and structures, fallow land and areas occupied by ornamental tree plantations and ornamental tree or bush nurseries [29–31].

The cultivated area of species constituting the most important, primary source of straw was 5556.15 ha (Table 2).

**Table 2.** Pattern of crops—exclusively main sources of straw.

Crop	Area (ha)
Triticale	1180.31
Wheat	1039.30
Cereal mixtures	968.70
Rye	913.76
Oat	526.98
Grain maize	367.29
Barley	297.95
Rape and turnip-like rape	261.86

## 2.2. Determination of Biomass Resources and Their Energy Potential

### 2.2.1. Straw

The amount of straw depends on the production area of crops which produce straw as a by-product, grain yield, crop species, fertilization, agricultural practices and climate and soil conditions [21]. The grain–straw coefficient index (Table 3) enables the theoretical determination of the straw amount per 1 ha of crop cultivation area [32–34].

**Table 3.** Yield and grain/straw coefficient for crops.

Crop	Mean Grain Yield (Mg ha <sup>−1</sup> )	Grain/Straw Coefficient
Wheat (mean for winter and spring yield)	4.47	0.93
Triticale (mean for winter and spring yield)	3.69	1.16
Rye (as winter crop)	3.24	1.45
Barley (mean for winter and spring yield)	4.22	0.78
Cereal mixtures (mean for winter and spring yield)	3.42	1.10
Oat	3.07	1.05
Rape and turnip-like rape	3.15	1.00
Grain maize	11.95	1.40

However, not all straw can be collected during harvest due to the field conditions or the height at which the harvester cuts down the crop. Moreover, some straw is lost while being collected, baled and transported. Since the analyses conducted in straw-fired boilers also showed that the available straw amount calculations based on the grain/straw coefficient produce excessive results, the technical and practical potential for straw acquisition in cereal and oily crop production was calculated to be 60% (coefficient 0.6). This means that the average yield of straw collected from the field in bales corresponded to 0.6 of the grain yield [21]. Therefore, the total straw yield was determined based on the yield of cereals, rape and turnip-like rape from the Equation (1):

$$Y_S = 0.6 \cdot Y_G \quad (1)$$

where:

$Y_S$ —straw yield (Mg y<sup>−1</sup>),

$Y_G$ —grain yield (Mg y<sup>−1</sup>).

Moreover, large amounts of straw are used in animal production as fodder and bedding. Straw should also be ploughed under and returned to the soil to maintain the organic matter balance. The straw surplus in Poland, usable as an energy feedstock, accounts for 33% of the total straw produced [35]. However, the surplus was adjusted in the current study due to the local conditions. The straw consumption coefficient was



increased because cattle and swine breeding in the bedding system dominated in the commune of Goworowo. Therefore, it was assumed for these analyses that the demand for straw as bedding, fodder and for ploughing-under in the commune was: 26%; 16% and 39% of the total straw yield, respectively, which gave a total of 81%. Therefore, the straw surplus unused in agriculture in the commune of Goworowo was only 19%. This figure was considered in calculations of the straw surplus potential, which can be used as energy feedstock (2), assuming that the mean lower heating value (LHV) was 14 GJ Mg<sup>-1</sup> [36] (3):

$$Y_{Se} = 0.19 \cdot Y_S \quad (2)$$

where:

$Y_{Se}$ —straw yield for energy purposes (Mg y<sup>-1</sup>),

$Y_S$ —straw yield (Mg y<sup>-1</sup>).

Subsequently, the straw energy value was determined:

$$Q_S = Y_{Se} \cdot LHV \quad (3)$$

where:

$Q_S$ —energy potential of straw (GJ y<sup>-1</sup>),

$Y_{Se}$ —straw yield for energy purposes (Mg y<sup>-1</sup>),

LHV—lower heating value (GJ Mg<sup>-1</sup>).

### 2.2.2. Orchard Wood Residue

Wood residue in orchards is produced mainly by annual pruning of trees [37], done to shape the tree crown and obtain the optimum fruit yield. Trees are usually pruned in winter and spring, depending on the local climate and the tree species [38]. The amount of wood collected after pruning ranges from 1.9 to 5 Mg ha<sup>-1</sup> in six-year-old orchards. The apple tree, which dominates in Polish orchards, produces 3.5 Mg of wood biomass per 1 ha from annual pruning. Part of the biomass is mulched and scattered as litter in orchards (in situ mulching). The Mazowieckie Voivodship has the greatest energy potential accumulated in wood residue from pruning apple orchards [38,39].

The majority of orchards in the commune of Goworowo were occupied by fruit tree nurseries in which pruning or soil mulching was not done. They were assumed to account for 60% of the total area. The remaining part was occupied by apple tree orchards, usually not large-scale orchards. They were not mulched, and the wood obtained in them was used as fuel or for recreational purposes. Therefore, since orchards were often situated on medium quality soils, it was assumed that 3.0 Mg of fresh wood biomass was produced by pruning 1 ha of an orchard.

Moreover, many small orchards (up to 2 ha) could not be cultivated properly or not pruned at all. Consequently, they were excluded from the potential calculations and assumed to account for 10% of the total. Trees in the commune were pruned manually, so no such limitations were observed as with machine pruning when losses in wood yield are caused by machine use or uneven ground [38]. It was calculated in this study that the potential loss associated with collecting the wood and its transport amounted to 5%. The weight of wood biomass from tree pruning was calculated from the Equation (4):

$$M_O = 0.4 \cdot A_O \cdot M \cdot 0.86 \quad (4)$$

where:

$M_O$ —mass of wood from the pruning of orchards (Mg y<sup>-1</sup>),

0.4—orchards, excluding fruit nurseries,

$A_O$ —orchards area,

$M$ —mass of wood from pruning (Mg<sup>-1</sup> ha<sup>-1</sup> y<sup>-1</sup>),

0.86—factor taking into account orchards not cultivated properly or excluded from regular pruning (0.90) and taking into account losses associated with harvest and transport (0.95).

Orchard biomass does not differ significantly from forest biomass in terms of its energy properties, which makes it usable as the substitute for the latter [39]. Fresh wood LHV is assumed to be  $8.0 \text{ GJ Mg}^{-1}$  [40] (5):

$$Q_O = M_O \cdot \text{LHV} \quad (5)$$

where:

$Q_O$ —energy potential of wood from orchards ( $\text{GJ y}^{-1}$ ),

$M_O$ —mass of wood from the pruning of orchards ( $\text{Mg y}^{-1}$ ),

LHV—lower heating value ( $\text{GJ Mg}^{-1}$ ).

### 2.2.3. Energy Feedstock from Forests

Forest land owned by the state in Poland is managed by the State Forests, divided into forest districts—basic forest economic units. The commune of Goworowo is located within three such units: Ostrołęka, Wyszaków and Pułtusk with the part managed by each of them occupying 82.37%, 1.38% and 16.25% of its area, respectively. The annual increment of wood resources in Poland in 2019 amounted to  $9.42 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  [41]. It was lower in the commune of Goworowo (as a weighted average from these forest districts)— $5.9 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  [42–44].

Logging residue is one of the most commonly used energy feedstock from forests. Wood obtained from forests in Poland, including logging residue, is classified into quality groups, with smallwood (M2) being one of them. M2 wood accounts for 8% to 15% of the whole above-ground wood biomass obtained from a logging area unit (in different administrative units) [45]. Apart from M2, middle-sized wood and logging residue, such as treetops and branches, can be used as fuel. Altogether, this energy feedstock accounts for 17% of the total wood yield in Poland [46]. It has been stressed that the proportion could be much higher if this category also included M1—wood of a different quality class, now used in industry [1,47].

The total forest biomass potential was determined under the assumption that 74.8% of the annual wood increment is obtained every year, as it is in Poland [48], with the energy feedstock accounting for 15% of the total wood yield. The wood loss during logging and transport to the final destination was not taken into account in the yield. Forest land in Poland also includes non-afforested land and land associated with forest management. This fact was considered in the calculations, with the average proportion of the afforested land in forest land calculated to be 0.97 [31,42–44].

The energy potential of logging residues was calculated using the following Equation (6):

$$V_F = A_F \cdot I \cdot H \cdot E \cdot F \quad (6)$$

where:

$V_F$ —volume of energy resources from forests ( $\text{m}^3 \text{ y}^{-1}$ ),

$A_F$ —forest area (ha),

$I$ —wood resources increase ( $\text{m}^3 \text{ ha}^{-1} \text{ y}^{-1}$ ),

$H$ —timber harvest in relation to timber increment (0.748),

$E$ —share of energy resources (0.15),

$F$ —share of afforested land in the forest land area (0.97).

Fresh wood LHV was assumed to be  $7.5 \text{ GJ m}^{-3}$  [49] (7):

$$Q_F = V_F \cdot \text{LHV} \quad (7)$$

where:

$Q_F$ —energy potential of energy resources from forests ( $\text{GJ y}^{-1}$ ),

$V_F$ —volume of energy resources from forests ( $\text{m}^3 \text{y}^{-1}$ ),  
 LHV—lower heating value ( $\text{GJ m}^{-3}$ ).

#### 2.2.4. Solid Biomass from Roadside Maintenance

Roadsides are in intensive use and are heavily polluted by transport. They are easily accessible and have to be maintained regularly, for example, to keep the traffic safe. All this makes them a promising source of biomass [50]. The road infrastructure in the commune of Goworowo comprised [26]:

- supralocal roads: 13.5 km of the trunk road and 101.3 km of district roads;
- local roads: 123.7 km of communal roads.

The roadside trees and bushes in the commune were not pruned regularly, although there is 0.4 ha of roadside maintenance area per 1 km of road, which shows their energy potential [51]. The roadside maintenance area was assumed as  $0.2 \text{ ha km}^{-1}$  for local roads. Approximately  $4 \text{ Mg ha}^{-1}$  of fresh woody biomass can be obtained from roadsides annually, but only 25% of this amount can be acquired in Poland [51], which is why  $1 \text{ Mg ha}^{-1} \text{year}^{-1}$  was taken for the calculations. Under the Polish Nature Conservation Act [52], only intervention pruning, such as removing dead boughs to improve safety, is allowed, but regular maintenance pruning is not.

It was assumed in the current research that 20% of the roadside with the maintenance area as given above was overgrown with trees and/or bushes and the yield resulted from all work done, including collection and transport. The following Equation was applied (8):

$$M_R = 0.2 (L_{SL} \cdot A_{SL} + L_L \cdot A_L) \cdot H_R \quad (8)$$

where:

$M_R$ —mass of wood from roadsides ( $\text{Mg y}^{-1}$ ),  
 0.2—factor taking into account roadsides covered with shrubs and/or trees,  
 $L_{SL}$ ,  $L_L$ —length of supralocal and local roads (km),  
 $A_{SL}$ ,  $A_L$ —area of supralocal and local roadsides ( $\text{ha km}^{-1}$ ),  
 $H_R$ —timber harvest from roadsides ( $\text{Mg ha}^{-1} \text{y}^{-1}$ ).  
 Fresh wood LHV is assumed to be  $8.0 \text{ GJ Mg}^{-1}$  [40] (9):

$$Q_R = M_R \cdot \text{LHV} \quad (9)$$

where:

$Q_R$ —energy potential of wood from roadsides ( $\text{GJ y}^{-1}$ ),  
 $M_R$ —mass of wood from roadsides ( $\text{Mg y}^{-1}$ ),  
 LHV—lower heating value ( $\text{GJ Mg}^{-1}$ ).

#### 2.2.5. Biomass from Perennial Energy Crops

Perennial energy crops should be grown mainly on soils of poorer quality, unusable for growing edible crops. Marginal soils, including sandy soils and/or those highly susceptible to erosion, are recommended for growing perennial grasses and short-rotation woody crops. However, poor quality soils are not often used for growing energy crops, although they should be used primarily for this purpose [53]. Growing energy crops can reduce water and wind erosion and enable carbon sequestration in soil [54]. It is therefore prudent to use land of lower agricultural productivity for energy crop plantations. Popular woody energy crops include basket willow (*Salix viminalis* L.) and grasses such as giant miscanthus (*Miscanthus × giganteus* J.M. Greef and M. Deuter) [55–57]. Miscanthus is a C4 plant which can be grown successfully in various climate conditions. It is cultivated on marginal soils and does not need irrigation or intensive fertilization. Owing to its deep root system, it uses water effectively and prevents soil erosion. These properties make its cultivation recommended in areas threatened with erosion and with poor water availability [58].

Aerenchyma cells present in stems and roots also improve the gas exchange effectiveness, enabling it to grow on wetlands [54]. *Miscanthus × giganteus* is regarded as one of



the best choices for low-cost bioenergy production in Europe [59]. It requires the minimum amount of nutrients and its cultivation is perceived as an advantageous way to use soils of low usability for food crop growing [60]. Willow can be grown on many types of agricultural land as it is highly tolerant of environmental conditions, with wetlands being preferred for this purpose [61–63]. Szczukowski et al. [64] demonstrated the potential for willow biomass production on excessively damp soil with a high groundwater table level. *Salix viminalis* can grow even when the soil profile is filled with water [65].

The present study showed that the commune of Goworowo has the right environmental conditions for growing perennial energy crops. There are 147 ha of usable marginal soils, with half of them being excessively humid and suitable for basket willow cultivation. The other half are sandy soils with a low groundwater table intended for giant miscanthus plantations. Based on the result of long-term experiments conducted by the University of Warmia and Mazury in Olsztyn [57,66], annual harvest rotations were used for the calculations. Based on the cited studies, it was assumed that willow and miscanthus would yield 15 and 12 Mg ha<sup>−1</sup> y<sup>−1</sup> of fresh biomass, respectively. The corresponding LHV was 8 and 12 GJ Mg<sup>−1</sup>, respectively. It should be noted that the yield depends on the soil and weather conditions, planting density and agricultural procedures. The energy potential of biomass from energy crop plantations for annual harvest rotations is (10):

$$Q_E = A_E \cdot Y_E \cdot LHV \quad (10)$$

where:

$Q_E$ —energy potential of biomass from *Salix viminalis* and *Miscanthus × giganteus* energy crops (GJ year<sup>−1</sup>),

$A_E$ —energy crops area (ha),

$Y_E$ —assumed average annual yield of fresh biomass (Mg ha<sup>−1</sup> y<sup>−1</sup>),

LHV—lower heating value (GJ Mg<sup>−1</sup>).

## 2.2.6. Hay from Meadows and Pastures

The high biodiversity of semi-natural grasslands can be maintained only by continuous management. The hay yield from meadows in Poland amounts to 4.9 Mg ha<sup>−1</sup> y<sup>−1</sup> and from pastures to 3.6 Mg ha<sup>−1</sup> y<sup>−1</sup> [67]. The demand for pasture fodder, hay and silage for ruminants is decreasing, which is why a surplus can be used as energy feedstock [68–70]. The demand for fodder from grasslands in Poland is dropping due mainly to the changing system of farm animal (mainly cattle) feeding and the decreasing profitability of their breeding with the following reduction of their stock. As a result, many meadows and pastures remain unused and the limited extent of their use causes damage to nature (e.g., soil degradation) and economic loss (unused production potential). Hay from grassland is a considerable biomass resource which can be used as energy feedstock [71,72]. It is noteworthy that biomass from unused grassland for energy generation may prevent its natural succession [73]. It is recommended that cattle grazing in pastures be replaced with mowing to maintain and increase biodiversity, with no interference in traditional management methods (e.g., no fertilizers). Hay produced in this way can also be used as energy feedstock [74].

Semi-natural mesophilic mesotrophic grassland dominates in the commune of Goworowo. The meadows are used extensively, with two cuts annually, and virtually all hay is used in animal breeding. However, some farms were found to harvest three cuts while other farms mowed pastures in the face of insufficient amounts of hay or silage. Therefore, it was assumed that three instead of two cuts could be obtained from 5% of the meadows, and the surplus produced amounting to 2 Mg ha<sup>−1</sup> year<sup>−1</sup> could be used as energy feedstock [75,76]. The potential of hay from meadows was calculated with the lower heating value taken as 13.5 GJ Mg<sup>−1</sup> [77] (11). The assumed yield was regarded as the amount of hay obtained from mowing and collection, including possible baling.

$$Q_M = 0.05 \cdot A_M \cdot S_H \cdot LHV \quad (11)$$

where:

$Q_M$ —energy potential of hay from meadows ( $\text{GJ y}^{-1}$ ),  
 0.05—share of area, which can be used for energy purposes,  
 $A_M$ —area of meadows (ha),  
 $S_H$ —surplus hay ( $\text{Mg ha}^{-1} \text{y}^{-1}$ ),  
 LHV—lower heating value ( $\text{GJ Mg}^{-1}$ ).

It was also assumed that 5% of pastures are not fully used (excluding fallows) and one cut of hay can be obtained annually as energy feedstock. The annual average energy potential of hay from pastures was taken as  $50 \text{ GJ ha}^{-1} \text{year}^{-1}$  [68,74] and it was included in the Equation (12). Late cut biomass from pastures can be used, which is beneficial as late swath is more flexible than early because of the weather conditions. Moreover, the hay quality had not deteriorated much by that time [70].

$$Q_P = 0.05 \cdot A_P \cdot E_P \quad (12)$$

where:

$Q_P$ —total energy potential of hay from pastures ( $\text{GJ y}^{-1}$ ),  
 0.05—share of area, which can be used for energy purposes,  
 $A_P$ —area of pastures (ha),  
 $E_P$ —energy potential of hay from pastures ( $\text{GJ ha}^{-1} \text{y}^{-1}$ ).

### 2.2.7. Landfilled Sludge and Municipal Waste

The possibility of using landfilled sludge and municipal biodegradable waste produced in the commune was analyzed. Sludge surplus will make it necessary to seek new solutions for its proper management and use [78]. Currently, fluidized bed technologies enable thermal conversion of mechanically dehydrated or partially dried sludge [79]; co-combustion of dehydrated (not dried) sludge is possible, e.g., in CHPs [80]. The importance of sludge from rural wastewater also increases as it does not contain excessive amounts of heavy metals [81], which is the case with sludge from heavily industrialized areas [82]. Mechanical–biological wastewater treatment of communal wastewater in 2019 produced 51 Mg (expressed as dry weight) of hydrated non-stabilized sludge (excessive sludge) [83], and 41 Mg of the sludge was transported to Ostrołęka where it was subjected to anaerobic stabilization followed by mechanical dehydration (the sludge was not dried—the construction of a drier is planned [84]). Ten megagrams of sludge was stored in the commune [83]. Collected municipal waste—apart from mixed waste—included biodegradable waste, comprising mainly tree branches and shrub branches, sawdust and bark, mowed grass, leaves, flowers, fruit and vegetable waste. A total of 1,454.98 Mg of mixed municipal waste and 10.76 Mg of biodegradable waste was collected from households in the commune in 2019 [85]. The biodegradable fraction accounts for 48% of the mixed municipal waste in rural areas [86]. The biodegradable waste amount was determined, assuming that it comprised the biodegradable fraction mentioned above (13).

$$M_T = M_{\text{Bio}} + 0.48 M_M \quad (13)$$

where:

$M_T$ —total mass of biodegradable waste ( $\text{Mg y}^{-1}$ ),  
 $M_{\text{Bio}}$ —mass of biodegradable fraction ( $\text{Mg y}^{-1}$ ),  
 0.48—factor taking into account share of biodegradable fraction in mixed waste,  
 $M_M$ —mass of mixed waste ( $\text{Mg y}^{-1}$ ).

## 3. Results and Discussion

### 3.1. Straw Potential

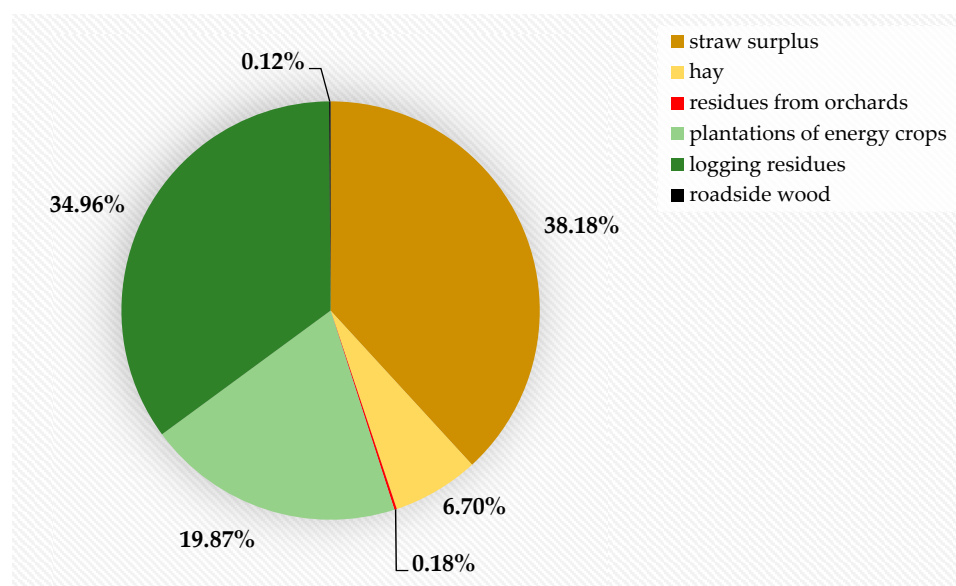
Given the local conditions in the commune of Goworowo, the mass of straw as energy feedstock amounted to  $2663 \text{ Mg y}^{-1}$  (Table 4). It was a small amount, as it accounted

for only 0.05% of the straw energy resources in Poland (5.1 million Mg y<sup>-1</sup>) [21]). However, it accounted for the largest part (38.18%) of the local solid biomass energy potential, 37,288 GJ y<sup>-1</sup> (Table 4, Figure 2). Moreover, maintaining food supply and soil quality while acquiring the straw necessary to replace fossil fuels is of key importance (straw use for energy generation is enabled by pellet or briquet technology) [87,88]. For this reason, the current study (quantitatively determining energy potential) took into account the straw residue depending on its use in agriculture—as straw for fodder, for bedding or to be ploughed under.

**Table 4.** The amount and energy potential of each solid biomass type.

Solid Biomass	Amount (Mg y <sup>-1</sup> )	Theoretical Energy Potential (GJ y <sup>-1</sup> )
Straw surplus	2663	37,288
Residue from orchards	23	180
Hay	475	6543
Plantations of energy crops	1985	19,404
Logging residue	4553 <sup>a</sup>	34,144
Roadside wood	14	113
Biodegradable waste	709 <sup>b</sup>	-
Landfilled sludge	10 <sup>c,b</sup>	-
Total	-	97,672

<sup>a</sup> m<sup>3</sup> y<sup>-1</sup>, <sup>b</sup> is not taken into account in the determination of the total potential (GJ y<sup>-1</sup>), <sup>c</sup> expressed per dry weight.



**Figure 2.** The proportion of individual solid biomass resources in the total energy potential of the commune of Goworowo (%).

Crop production diversity in the commune of Goworowo was not high because of the soil and climate conditions, with the local straw resources most affected by triticale, wheat, cereal mixes and rye, in accordance with their cultivation area. Managing crop residue is particularly important for biomass utilization and energy generation for solving environmental problems and using alternative energy sources. More importantly, the cereal production continuity ensures the permanent availability of straw resources, whose over-production is caused by a decreasing number of farm animals with an increasing proportion of cereals in the structure of crops [20,22].

Cereal straw resources are regarded as the greatest unused energy potential in agriculture. Unlike the area used for the cultivation of rape and turnip-like rape in the Mazovian Voivodship, the area that was used for cereal cultivation has been growing in recent years. Since the yield per ha of cereals as well as rape and turnip-like rape is continuously increasing [89], the straw energy potential in the commune of Goworowo is expected to increase, or at least to remain unchanged.

### 3.2. Orchard Potential

The estimated energy wood resources from orchards in Poland amount to 88,700 Mg y<sup>−1</sup> [90]. The small orchards area in the agricultural land in the commune of Goworowo—merely 21.96 ha—resulted in a small orchard wood biomass amount, i.e., 23 Mg y<sup>−1</sup> (Table 4). The orchard waste energy potential amounted to 180 GJ y<sup>−1</sup>, which accounted for merely 0.18% of the total (Figure 2). The biomass obtained by pruning fruit trees was often used in households, but this applies mainly to biomass from backyard gardens. The energy potential of the considerable amounts of waste from typical orchards is usually lost due to storing or burning it in the field [91], while it could be used as fuel [22]. Proper management of these resources may increase the effectiveness of biomass use in the future, as orchard biomass waste used for energy generation does not compete with food production [92], which may be the case with cereal straw or hay.

Moreover, pollution emissions from burning pruned biomass in appropriate boilers are low [92]. However, the orchard area in the commune decreased by over half over the 2017–2020 period [23,93] and the orchard area also decreased in the Mazowieckie Voivodship (by over 1100 ha over the 2017–2020 period) [30,94–96]. Therefore, the local resources of this biomass source are likely to decrease in future, especially given the drop in the proportion of fruit trees in orchards in the voivodship, which are being replaced by bushes and berry plantations [89,97].

It should be noted that pruning waste cannot always be used for energy production, although its impact on the greenhouse effect is smaller than in situ mulching. This happens when the absence of plant cover in the inter-row space exceeds 80% and the soil structure has a tendency for compaction, for becoming muddy or for surface runoff, and when the orchard is susceptible to erosion. The ground biomass should be mulched in the first and second case and ploughed under in the third. The local potential cannot then be fully utilized [98].

### 3.3. Forest Potential

Local resources of forest residues biomass in the commune of Goworowo were determined as 4553 m<sup>3</sup> y<sup>−1</sup>, which was equivalent to the energy potential of 34,144 GJ y<sup>−1</sup> (34.96% of the whole) (Table 4, Figure 2). The annual increment ratio was assumed at the level given for Poland—74.8% [48], although it was 116% in the Pułtusk Forest District and 114% in the Wyszaków Forest District [43,44]. The wood harvest in a calendar year depends on the area ratio of the final cutting sites to intermediate cutting sites. The energy potential of logging residue largely depends on the development phase of the forests in the area. When final cutting sites (with much thicker and slower growing trees than in intermediate cutting sites) dominate the forest structure, the harvest-to-increment ratio can exceed 100% and the logging residue amount then increases considerably. However, these indices are given for a whole forest district area and they do not provide data for individual communes. There are also data for 10 year periods, which is why a lower value was adopted to avoid overestimating the local resources.

The optimum wood amounts to be left in local forests should be determined to maintain biodiversity and conserve forest ecosystems. Perceiving the forest as a source of energy feedstock must be accompanied by ecological thinking [1]. Taking this factor into account in research is called “potential with increased biodiversity conservation” [99]. It is important because the forest area in Europe with satisfactory amounts of deadwood has been very small during the past few decades [100].

The forest area in the commune of Goworowo was larger in 2020 compared to 2017 by over 1000 ha, i.e., by 16% [23,93]. This increase reflects the increasing forestation level in Poland [101] and ensures the stability of forest residues as a source of solid biomass. The issues related to forest management are often left out of development strategies, due to which forests are not regarded as a factor of the region's socio-economic development [102]. Mentioning the bioenergy aspects of forests in strategic documents may prevent its marginalization in the political spheres and increase society's interest in it.

### 3.4. Roadside Potential

Roadside maintenance produces biomass for bioenergy generation, but only a small part of it is used due to dispersion [103]. This study has shown that roadsides in the commune of Goworowo constitute a local space concerning the solid biomass energy potential. About 14 Mg of wood biomass, with an energy potential of  $113 \text{ GJ y}^{-1}$ , can be obtained from the roadsides in the commune (Table 4). The presence of trees on roadsides ensures that biomass can be acquired by pruning, which is usually wasted [104]. The potential in this regard also increases as the process may contribute to roadside naturalization when the biomass of an invasive species is obtained, which can be replaced by native flora, thereby improving biodiversity [105].

A better choice of tree species and developing more diverse resources improves the ecosystem advantages provided by roadsides [106]. Managing wood from roadsides provides more benefits, e.g., ensuring the patency of roadside draining ditches [105]. Roads must be accessible to society, be convenient and safe, and integrate with their surroundings. Their development is accompanied by an increase in the roadside area, which connects forests, farms and traffic networks. The main purpose of roadside management is to ensure traffic safety (improving visibility and providing a space for emergency stops). It can produce biomass from tree and bush pruning, which can be used as fuel to maintain a positive energy balance. The promotion of ecosystem services from roadsides is a future line of sustainable management in such areas [105–107]. Growing urbanization will increase the roadside area, which makes proper management crucial. The roadside wood potential can help transition from conventional road management to a form based on a circular economy [105]. Even leaves from roadside trees can be used in the production of high-quality solid biofuels [108].

### 3.5. Potential of Perennial Energy Crops

The land in the commune of Goworowo allocated for perennial energy crop plantations could yield 1103 Mg of fresh willow biomass and 882 Mg of fresh miscanthus biomass annually (Table 4). The total energy potential of the plantations was  $19,404 \text{ GJ y}^{-1}$ , accounting for 19.87% (Figure 2). Only 1.5% of arable land was proposed for the plantations in the current study, and all of it belonged to the poorest quality class (class V and VI). Currently, winter rye and serradella are grown on the poorest quality soil in the commune and the cultivation effectiveness is low. Growing perennial energy crops on such soils, where the nutrient abundance is low, where biophysical restrictions exist and where the crop yield is low, is a more sustainable alternative than traditional food crops [109]. Since competition in soil used for food crop production requires spatial land segregation [110], choosing the poorest quality soils with the lowest effectiveness in food crop cultivation was justified. Growing perennial crops on this land could improve the soil properties by increasing its total organic carbon content, and decreasing its susceptibility to erosion [109,110].

Sustainable development stimulates an interest in bioenergy generation from renewable sources, and biofuel production from energy crops in Europe is expected to grow to meet the policy goals (The European Green Deal) [5,111]. Energy crops in Poland are grown in an area of approximately 17,900 ha [21]. No such plantations exist in the commune of Goworowo, even though it has appropriate potential for them. The use of 143 ha of marginal land for this purpose could considerably increase lignocellulosic biomass produc-



tion, especially since Poland is one of the major producers of SRC willow in Europe [61]. The crop species chosen for the commune of Goworowo—miscanthus and willow—are among the main candidates for lignocellulosic crop plantations in Europe. Their impact on biodiversity in the field is often regarded as beneficial compared to conventional food crops [112]. A similar impact is also expected in the commune as agricultural land was selected for such plantations, while permanent grassland and wasteland with high biodiversity (part of which is protected under the NATURE 2000 program) were excluded.

### 3.6. Potential of Permanent Grassland

The commune had a large area of permanent grassland—over 3327 ha—which can be used for energy generation despite some limitations connected with animal breeding [23]. The possibilities of the annual hay harvest amounted to 475 Mg of hay (321 Mg from pastures and 154 Mg from meadows) annually with an energy potential of 6543 GJ (4460 GJ from pastures and 2083 GJ from meadows) (Table 4). The difference in biomass yield from pastures and meadows was a consequence of local conditions. The meadows were mainly used extensively, not only at Nature 2000 sites but all over the commune. Therefore, increasing the number of cuts from two to three gave a surplus which could be used as fuel. Many pastures were not used to the full extent, reflecting the situation around the country, where most pastures are not used because of the drop in the farm animal stock [67].

Apart from the considerable benefits of using the hay surplus, certain difficulties are connected with obtaining it. These resources are not often easily accessible (wetlands) and their quality varies, depending on the moisture and mineral content [22]. Since the commune of Goworowo is situated in two NATURE 2000 Special Bird Protection sites—Dolina Dolnej Narwi PLB140014 and Puszcza Biała PLB140007—the grassland in them has to be mowed to maintain the bird populations covered by the Birds Directive. Abandoning the mowing results in natural succession and biocenotic evolution and poses a threat to the objects of protection in the commune. Mowing can prevent it, especially since protective measures include removing the produced biomass [113,114]. The permanent grassland area has been decreasing in recent years, both in the Mazowieckie Voivodship and in Poland [89,115,116]. The hay resources in the commune under study are expected to stay at the same level since they have remained unchanged over the years [23,93].

### 3.7. Potential of the Landfilled Sludge and Municipal Waste

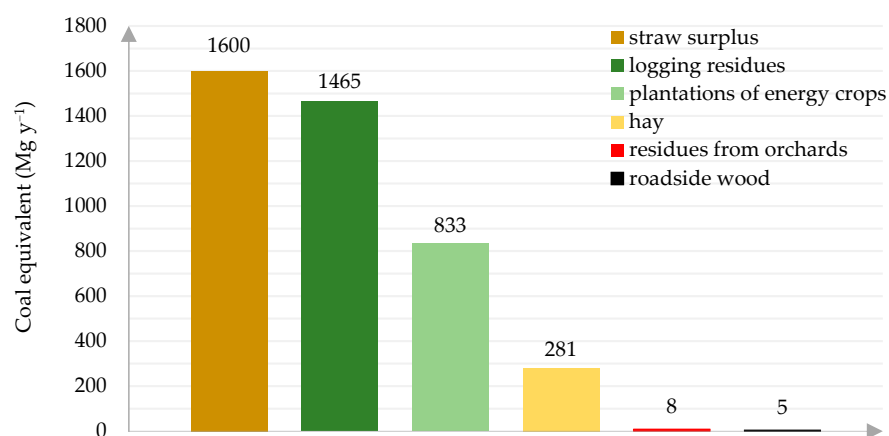
The analysis has shown that the sludge landfilled in the commune of Goworowo (10 Mg of dry weight) is stored only to recirculate to bioreactors when biogenic elements for microorganisms are absent (Table 4). Therefore, its storage helps to maintain the continuity of the wastewater treatment process. The sludge was therefore excluded as a potential source of solid biomass. There is 165,000 Mg  $y^{-1}$  of municipal sludge in Poland intended for energy recovery by combustion [21]. Typical stabilized and dehydrated sludge has a calorific value of approximately 0.5 GJ  $Mg^{-1}$  [117], which increases to 11 GJ  $Mg^{-1}$  after drying [118]. Any surplus of recirculated sludge from the commune of Goworowo which was not utilized in agriculture can be used for thermal conversion.

The annual production of biodegradable waste in the commune amounted to 709 Mg, but all of it was collected by external companies and transported to municipal waste processing installations (Table 4). In future, determination of the biodegradable waste potential will require an analysis of what part of mixed and separately collected municipal waste is stored despite being intended for processing and the acquisition of data on its amount. Annually, 2,724,000 Mg of waste is used as an energy source in Poland [21]. Potential biodegradable/green waste in the commune could be used for thermal conversion with energy recovery or biogas plant feedstock, increasing the RES use indices.

### 3.8. Commune Potential

The total energy potential of solid biomass resources in the commune of Goworowo amount to 97,672 GJ  $y^{-1}$  (Table 4). The amounts of individual types of solid biomass and

their potential varied significantly, which resulted from the local conditions. The solid biomass resources in the commune were equivalent to 4192 Mg of hard coal (the most commonly used heat source in the commune), assuming its calorific value of  $23.3 \text{ GJ Mg}^{-1}$  (for eco-pea coal) [36] (Figure 3). This shows that the solid biomass potential in the commune of Goworowo is high. Surplus straw accounted for the greatest part and wood from roadside maintenance accounted for the smallest part of the energy potential in the commune (Figure 3).



**Figure 3.** The potential of energy accumulated in solid biomass resources expressed as the coal equivalent ( $\text{Mg y}^{-1}$ ).

Kowalczyk-Juśko et al. [22] determined the energy potential of the Bialski District in the southeast of Poland, where the energy potential of communes ranged from 7690 to  $707,933 \text{ GJ y}^{-1}$ . However, that study also included solid biomass residues from wood industry facilities. It was not mentioned in the current research as there is no such facility in the commune. Moreover, the Bialski District is one of the three largest districts in Poland [119]. Moreover, 10% of marginal arable soils and permanent grassland were allocated for energy crop plantations in the majority of the communes in the cited research [22], whereas in the current study, it was only 1.5% arable land, all belonging to the poorest quality. However, the current findings for the commune of Goworowo confirm that the smallest territorial units (communes) have large solid biomass resources, which can (and should) be of great importance in satisfying energy needs, especially as fuel in local boilers and for individual recipients.

A high value of solid biomass must also be emphasized as referring to the price of hard coal (eco-pea coal). The retail price of this fuel, depending on its origin and quality, ranged from  $\text{EUR } 146 \text{ Mg}^{-1}$  to even more than  $\text{EUR } 225 \text{ Mg}^{-1}$  (average PLN/EUR exchange rate in 2020—4.4448/1.0). Assuming the average eco-pea coal price of  $\text{EUR } 180 \text{ Mg}^{-1}$ , the value of energy accumulated in solid biomass, referred to as the eco-pea coal price, amounted to  $\text{EUR } 754,487 \text{ y}^{-1}$ . Therefore, this is a high value when referred to the scale of the commune of Goworowo, which can potentially be used continuously for many years. It is particularly important from the point of view of the local supply of energy feedstock. There are no fossil fuel resources in the commune of Goworowo, so all the money spent to purchase it flows out of the commune and often out of the country. When biomass is used as an energy feedstock, the money for the biofuel remains in the commune, in local circulation. Owing to this system, the entities producing fuel or energy from biomass have funds for investment and development and can employ new personnel in the RES industry, which contributes to local development. Therefore, biomass use as energy feedstock can result in continuous stimulation for the infrastructure development in rural areas and can help to implement modern technologies of biomass conversion to energy and, in future, to various high-value bioproducts. This issue is extremely important as biomass—as feedstock, and unlike other RES—requires the involvement of many entities

to organize the whole logistics chain, from production and acquisition of biomass, through to its storage, warehousing, transport, preparation for technological processes, conversion and final use. Therefore, one can say that—unlike other RES—biomass is a “demanding” fuel. However, paradoxically, this demanding energy feedstock can provide a positive development stimulus for the commune and the region since it engages a considerable workforce.

#### 4. Conclusions

Much research into local biomass potential is needed to connect its management effectively with the development of renewable energy sources. This is of particular importance for further development of research in this domain and the subsequent application of the results in science and practice. Firstly, the current study shows that the smallest administrative unit in Poland—a rural commune—has solid biomass resources with considerable energy and financial potential for use. Secondly, the study also emphasizes the challenges, such as sustainable management of local solid biomass resources, taking into account the protection of biodiversity and the environment, e.g., the role of the space where solid biomass is present as a natural habitat. Thirdly, it was demonstrated that the commune could be a place where energy sources are diversified and where links are created between the economy and ecology by obtaining biomass. Fourthly, research should be continued to determine the technical potential of biomass resources and the link between local development and local community welfare.

Rural areas, such as the commune of Goworowo that has an agriculture and forestry sector in its area, could soon play a major role in producing and using solid biomass. Local communities and fragmented farms, which do not develop on an industrial scale, could be provided with many opportunities. Further research is also necessary in this field. Local communities must be given information on the resources in their area and about their value. They must be informed about effective technologies and their use and cost-effective logistics and management systems.

Moreover, policymakers and local governments should undertake appropriate measures to allow for the most effective use of these local resources. However, this study also has some limitations since it refers to a single commune existing under certain geographic and demographic conditions. Furthermore, it is necessary to have access to reference data to identify specific local features, which may be diverse even for neighboring communes.

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