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Harvesting and Baling of Pruned Biomass in Apple Orchards for Energy Production

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Abstract: Pruning residues belong to the agricultural wastes generated in the agro-food processing sector, whose energetic potential can have a significant influence on the local energy market. This study is focused on the assessment of the feasibility of using apple tree pruning residues in the form of bales for energetic purposes. The research was performed in a commercial apple orchard located in the central-western part of Poland, an area characterized by the largest concentration of apple orchard in Europe. The biomass yield, pruned bales quality, energy input and output flow, as well as the economic sustainability of the pruning-to-energy strategy were evaluated. The results indicated the available collected biomass potential in an amount of 0.69 $t_{DM}·ha^{-1}$ per year. Pruned biomass analysis showed a moisture content of 45.1% in the fresh material, the ash content was 0.8% dry mass, and the lower heating value was 18.05 MJ·kg^{-1} dry mass. Total production cost, including all steps and avoided cost of mulching, was 74.7 €·t^{-1} dry mass. Moreover, the net energy balance of this value chain was very positive, giving a value of ca. 12,000 MJ·ha^{-1} per year. As a result, the yearly harvested pruned biomass may be considered a good energy source for local heating systems.

Keywords: pruning; agricultural residues; biomass harvesting; bales; energy; production cost

1. Introduction

The main objectives for the European Union in terms of energy production and environmental aspects until 2020 is to cut down greenhouse emissions by 20% (concerning 1990 levels), to increase the use of renewable energies by 20%, to improve energy efficiency by 20%, and to achieve a 10% share of renewables in the transport sector [1]. Moreover, to stimulate better development of the second-generation biofuels for transportation and to minimize climate impact, the European Commission proposed limiting the use of food-based biofuels from 10 to 5% in this sector [2]. This change raises the interest of non-feedstock substrates coming from agricultural and industrial processes that do not directly interfere with food production. The utilization of agricultural residues from non-food parts (i.e., straw, hay, branches from pruning, urban green waste, and other by-products) may also bring many additional advantages including lower greenhouse gases emissions, increased energy efficiency, reduced energy dependency, and lower overall costs of biofuel production [3–5].

One of the directions aimed to reach these targets is waste biomass utilization. Biomass, as a widely available renewable energy source, is characterized by a high energetic potential that might be gained from various residues of agricultural and industrial activities. In most cases, the higher heating value (*HHV*) of waste biomass is in the range 17–21 MJ·kg^{-1} [6,7]. This value is high enough to be an alternative fuel to fossil fuels, especially in heat production units. Moreover, the use of biomass residues for energetic purposes contributes to the reduction of fossil carbon dioxide (CO_2) emissions that is mostly responsible for global warming and climate change [8]. This is very important taking into account that greenhouse gas emissions from the energy sector represent roughly 65% of all anthropogenic emissions [9]. The limitation of fossil fuel combustion for heat and electricity production and the sustainable development of regions are also fundamental concerns for Europe [10]. As a result, attention is paid to new resources of renewable energy, especially to those that are available locally and that have a potential for use [11,12]. These conditions might be fulfilled by the biomass residues obtained from the pruning operations carried year by year in the fruit plantations. Main permanent crop areas in Europe are occupied by olive trees, vineyards, and fruit trees. The assumed theoretical potential of pruned biomass from permanent crops in EU28 is ca. 246 PJ per year [13]. Apple orchards represent a share in the permanent crops area of 4.2% [14], and accounts for ca. 450,000 ha. The largest apple producer in the EU is Poland with over 143,000 ha. In effect, the yearly potential of apple pruning in 28 EU countries is ca. 29 PJ, out of which more than 9 PJ is attributed to Poland [15]. This indicates that apple pruning residues, as a wooden biomass, could partly replace typical wood assortments for small and middle size boilers and commercial power plants [16], supporting the energy units with renewable fuel. Even more, the use of pruned biomass to generate heat is in line with EU developments, like waste to energy (WtE), zero waste or circular bioeconomy trends [17]. Pruning-to-energy (PtE) may be especially important in rural areas characterized by limited access to the forest resource and large share of apple orchards in the region. Unfortunately, most of this potential is wasted, and the technology is not commercialized. The common practice (more than 90% of cases) regarding the management of pruned biomass from tree cutting is to mulch the branches or to push them out from the orchard and burning on-site [18]. These practices do not bring any profits to the farmer, and burning of biomass is prohibited in many countries. However, the use of apple pruned biomass for energetic purposes requires some energy input, manpower engagement, and investment in indispensable machinery [19,20]. To follow the pruning to energy strategy, good logistics performance should be in place [21]. The total logistics costs of the whole chain including pruned biomass harvesting, storage, and transportation to the final consumer must be lower than the incomes from the biomass selling. There are two general options of the pruning harvesting in the orchards. The most popular is pruning residues harvesting and chipping [22]. The alternative solution is pruned biomass baling [19]. Storage is also an important part of the logistic chain. Different storage options may be applied: open air storage, under cover storage, storage tank, silo, storage with drying, etc. The storage may take place in the orchard, at the final consumer, but an intermediate storage is also possible [23]. In the case of baling, the significant advantage is the possibility of easy and very low-cost open-air storage of the bales on the field site. As inside the bale there is still much free space for air flow, natural drying takes place, leading to the decrease in moisture content to a level acceptable for energetic use.

In the logistic chain of PtE, a crucial issue is transportation. The distance between the orchard and the final consumer, as well as the amount of pruned biomass to be transported, is of critical importance in the estimation of the total costs of the supply chain [24]. It seems that for biomass utilization in the small and middle size boilers the distance should not exceed 50 km (preferably below 25 km) [25].

Finally, the price of the pruned biomass delivered to the consumer as a source of heat is a deciding parameter regarding the sustainability of the biomass utilization for energetic purposes. It should fulfill customer requirements and be competitive to other fuels available on the market [26]. The PtE strategy is in line with the sustainable development of the agricultural sector. Properly organized, it should bring economic, environmental, and social benefits.

In the literature, there are several publications related to olive, vineyards, and some fruit tree pruning, and they deal with energy input and output flow, unit costs, biomass production, and investments. However, the results have been focused on the production of wood chips as a final product [16,27–29]. In the case of baling, much less is known [20], especially concerning all logistics steps.

In the frame of this study, the technical potential of pruned residues harvesting for energetic purposes in apple orchards was verified, applying a baler designed for direct collecting and baling of the cut branches. The logistic system (Figure 1) included biomass baling, internal shuttle, and temporary storage of generated bales as well as their transport to the boiler house located at the short distance from the orchard. It was compared with the common practice of leaving the comminuted branches onto the soil using a commercial mulcher attachment.

Figure 1. Pruning-to-energy (PtE) strategy in an apple orchard: (**a**) apple orchard; (**b**) pruned apple tree biomass; (**c**) baler and pruned biomass bale; (**d**) on-site storage in the orchard; (**e**) pruned bales trailer; (**f**) boiler house (2 × 300 kWth).

As a result, the study here aimed to (i) quantify the productivity and costs of these two systems, (ii) estimate and compare the energy balance of the pruning-to-energy strategy vs. mulching in the orchard, and (iii) evaluate the influence of the yearly operating hours of the baler, potential of pruned residues and distance from the orchard to the boiler house (final user) on the economic aspects of energetic use of apple pruning.

2. Materials and Methods

2.1. Study Site

The research was performed in an apple orchard situated in the Mazowieckie Province (Poland). This region is characterized by the largest continuous apple orchards area in Poland, covering about 73,700 ha [30]. The apple orchard considered in the study had an area of 36 ha. Most of the trees were spaced 3.5 × 1.0 m (2850 trees per hectare, rootstock M9) and trained with the spindle system. The surface investigated in this study was 6.0 ha, located on flat terrain. The variety of apple was Jonagold. The investigated apple orchard was established in 2012. The space between the apple trees was covered by grass. Trial area and the row spacing were measured by the laser distance measure Bosch GLM-150.

2.2. Experimental Design and Data Collection

After pruning of the apple trees in the orchard (February–April period), the biomass residues were harvested using a professional baler Wolagri R98 attached to the tractor Kubota M7040DHC. The main characteristics of the machines are shown in Table 1.

The generated bales were left in between the rows for further treatment. Next, a forklift equipped with rakes transported the bales to the field edge for open-air storage (ca. 6 months). Finally, the bales were loaded on the trailer by the forklift and delivered to the final user (local heat plant) located at a distance of 6 km from the orchard. The transportation took place prior to the heating season (October–November period).

Table 1. Basic technical data of the baler and tractor used in the PtE strategy.

Feature	Biomass Baler	Feature	Tractor
Model	Wolagri R98	Model	KUBOTA M7040DHC
Bale diameter, cm	120	Engine	V3307-DI (4 cyl.)
Bale width, cm	98	Net Power, HP/kW	68/50.7
Pick-up width, cm	130 or 190 disc end	Total displacement, cc	3331
Pressing chamber	fixed 32 crossbars	Max. travel speed, km·h^{-1}	31
PTO shaft	homokinetic	PTO power, HP/kW	62/46.3
Tires supplied as standard	11.5/80–15	PTO type	Live-independent, hydraulic
Lubrication	optional	Tire size front/rear	9.5 × 24/16.9 × 30
Swivelling eyebolt Ø35	standard	Overall length, mm	3445
Road signaling kit	standard	Overall height, mm	2545
Road homologation	standard	Overall width, mm	1860
Required power (kW/HP)	38/50	Turning radius, m	3.6
Transport width, m	1.71	Lift capacity, kg	1500
Weight, kg	1940	Tractor weight, kg	2440

2.3. Working Time, Productivity, and Pruning Potential

The net pruning biomass potential (PBP) was determined by weighing the produced bales obtained during the harvesting activity from one hectare of the apple orchard. The bales were weighted using industrial scale (Radwag® WPT/4P, Radom, Poland). The harvested biomass was expressed in tons per hectare concerning the fresh mass (*FM*) as well as dry mass (*DM*). The productivity was calculated from available biomass per unit of orchard area divided by the time required to process the cut branches into bales. The time included the effective operation time of the tractor with the attached baler and turns between the tree rows at the ends of the field. Unexpected delays and time spent on bales weighing were excluded from this calculation, because they might be not representative and do not correspond to real conditions. However, for cost analysis, an adequate delay factor of 30% for harvesting and 15% for mulching were applied [31].

2.4. Pruned Biomass Quality

Characteristics of the harvested apple tree biomass were based on the determination of the main parameters, such as mass, size and bulk density of the bale, moisture content (*MC*), ash content (*A*), and lower heating value (*LHV*). Two samples of the biomass residues (every sample consisted of approximately 1 kg of material) were sealed in plastic bags and delivered to the laboratory for quality analysis. The moisture content (as received, 300 g, 2 samples) was measured in an KBC-65W oven (WAMED®, Warszawa, Poland) in accordance with the European Standard ISO 18134-2:2017 [32]. For further analysis, the samples were ground in a laboratory knife Retsch SM 2000 mill (Retsch®, Haan, Germany) equipped with a 1.0 mm sieve. For the ash content determination, the samples (20 g, 2 samples) were placed in an SNOL 8,2/1100 LSM01 muffle furnace (SNOL®, Utena, Lithuania), and the European Standard EN-14775 was applied [33]. The caloric value was determined according to the European Standard EN 14918 [34], and the tests were carried out using an IKA 200 calorimeter (1 g, 2 samples). Next, the lower heating value (*LHV*) was calculated as a function of the higher heating value (*HHV*) and moisture content in the biomass according to the formula [35,36]:

$$LHV = HHV \cdot (1 - MC) - r \cdot MC, \quad (1)$$

where *HHV* is the higher heating value (MJ·kg^{-1}), *MC* is moisture content, and *r* is the latent heat of water vaporization (r = 2.44 MJ·kg^{-1}).

2.5. Cost Analysis

The production cost of pruned biomass bales was calculated from the hourly machine costs used in all steps. The operation and maintenance (O&M) costs of the two systems were calculated according to [37,38]. The annual utilization was assumed to be 550 scheduled machine hours (SMH) for the baler attachment, 500 SMH for the mulcher attachment, 1500 SMH for the tractor (also used for other activities), and 1000 SMH for the trailer and forklift (Table 2). Depending on the machine, retention values of the initial investments in the range of 20–28% were considered, as well as a depreciation period of 10 years were assumed. Data related to the maintenance, repair, and insurance costs for machineries and attachments were provided by the owner of the experimental farm or adopted from [39]. All indices were updated at their current value. Furthermore, based on [40,41], for manpower an average labor cost of 19 €·h^{-1} was established, including obligatory health and social insurance. The implied cost of fuel and lubricant was 1.1 and 5.0 €·dm^{-3}, respectively [42]. Finally, the overheads to include administration costs were comprised as 20% of the total operational cost. To analyze the economic sustainability of the bales production from apple tree pruning, additional costs were determined by considering different biomass potential available per hectare and orchards area. Thus, in the sensitivity analysis, the change in the initial orchards area (from 25 to 500 ha) and pruning biomass potential (from 0.5 to 5.0 t_{FM}·ha^{-1}) was applied, accordingly.

Table 2. Operation and maintenance costs for pruned biomass recovery and mulching.

Operation/Action		Recovery					Mulching	
		Harvesting + Baling		Storage + Loading	Transportation		Mulching	
Machine		Carrier	Attachment	Carrier	Carrier	Attachment	Carrier	Attachment
		Tractor	Baler	Forklift	Tractor	Trailer	Tractor	Mulcher
		KUBOTA M7040DHC	Wolagri R98	AUSA C150H	KUBOTA M7040DHC	No Data	KUBOTA M7040DHC	HUMUS KM 230
Investment	€	30,000	28,500	15,000	30,000	1 500	30,000	10,000
Power	kW	50.7	0	22.7	50.7	0	50.7	0
Service life	years	10	10	10	10	10	10	10
Crew	no.	1	0	1	1	0	1	0
Labour cost	€·h^{-1}	19	0	19	19	0	19	0
Usage	h·year^{-1}	1500	550	1000	1500	1000	1500	500
Fixed cost	€·h^{-1}	2.4	6.0	1.7	2.4	0.2	2.4	2.4
Variable cost	€·h^{-1}	26.00	3.06	23.18	26.00	0.08	26.00	1.29
Overheads at 20%	€·h^{-1}	5.68	1.80	4.98	5.68	0.05	5.68	0.73
Total cost	€·h^{-1}	34.08	10.81	29.91	34.08	0.30	34.08	4.37

The boundaries of this study exclude obligatory pruning costs (tree cutting and placing of the branches in the middle of the inter row corridor), as this activity must be done regardless of the final treatment strategy with the biomass residues by the orchards owner.

2.6. Energy Analysis

Typical energy analysis is a process of determining the commercial energy required directly and indirectly to allow a system to produce a specified good or service [43]. It is known as energy intensity (*EI*) expressed in energy units per physical unit of good or service delivered and is concerned only with the depletion of fossil energy (renewable energy flow is not considered). Direct energy input is related to energy employed during the production process (i.e., machine construction), while indirect energy input corresponds to the energy embedded in machines and tools, deployed during the goods production or service performance. Indirect energy inputs were defined by multiplying the energetic value embedded in tools and machines [44,45] deployed in the recovery phase by their mass, dividing by total service life and finally multiplying by the amount of its operation hours [46]. On the other hand, direct energy inputs were calculated by multiplying the amounts of consumed fuel/lubricant and its energetic values (51.50 MJ·kg^{-1} for diesel and 83.7 MJ·kg^{-1} for lubricants) [46,47]. Fuel consumption was estimated based on the refilling of the tractor after finishing of the baling process (start and finish of works on one hectare) [48]. In case of lubricants, the value of 2% of the fuel consumption was applied [49]. The sum of direct and indirect energy inputs were divided by harvested orchard area and expressed as total energy input flow (*EIF*) related to one hectare of field. As a source of energy output the biomass harvested during the baling process and delivered to the local boiler house, the total energy output flow (*EOF*), was estimated, according to the following formula:

$$EOF = PBP_{FM} \cdot \left(\frac{100 - MC_{FM}}{100} \right) \cdot LHV, \quad (2)$$

where PBP_{FM} is a fresh mass (*FM*) of pruned biomass harvested per hectare (kg·ha^{-1}), MC_{FM} is a moisture content in the fresh mass of harvested biomass, and *LHV* is a lower heating value of the pruned dry apple tree biomass (*DM*) (MJ·kg^{-1}).

Furthermore, some indices related to energy flow were determined. The energy balance (*EB*) was calculated as a difference between all inputs and output energy flows, given by the following equation:

$$EB = EOF - EIF. \quad (3)$$

Then, the energy return on investment (*EROI*) of the considered activity was calculated as a ratio between energy output flow and energy input flow (direct and indirect) [50]:

$$EROI = \frac{EOF}{EIF}. \quad (4)$$

Moreover, the energy input share (*EIS*), energy productivity (*EP*), and energy intensity (*EI*) were determined using Equations (5) and (6), respectively [50]:

$$EIS = \frac{EIF}{EOF} \cdot 100\%, \quad (5)$$

$$EP = \frac{PBP_{FM}}{EIF} \quad (6)$$

$$EI = \frac{EOF}{PBP_{FM}}. \quad (7)$$

In case of pruned biomass harvesting, the *EP* and *EI* factors might be related to the yield of the fresh mass (*FM*) as well as dry mass (*DM*).

To enable a more legible comparison of the energy flow between pruned biomass baling and mulching, the issue of the potential negative or positive influence of the comminuted branches of the apple tree on soil properties was excluded in this study [41].

3. Results

3.1. Harvested Biomass Analysis

The harvested pruning residues were in the form of cylindrical bales with a diameter of 1.10 m ± 0.05 m and a height of 1.15 m ± 0.05 m. Moreover, the processed data indicated the pruning biomass potential *PBP* equals 1.25 t_{FM}·ha^{-1} (0.69 t_{DM}·ha^{-1}) of collected biomass. The average weight of the bales was 251 ± 10 kg including a moisture content of 45.15% ± 0.45%, whereas a bulk density was 230 kg_{FM}·m^{-3}. The ash content was 0.8% ± 0.03% (*DM*). In turn, the calorimetric analysis and further calculations resulted in an *HHV* of 19.31 ± 0.11 MJ·$kg_{DM}{}^{-1}$ and an *LHV* of 18.05 MJ·$kg_{DM}{}^{-1}$ (9.52 MJ·$kg_{FM}{}^{-1}$), respectively. The obtained *HHV* value is very close to other wooden residues coming from agricultural processes [6,7].

3.2. Working Time and Productivity

The duration time of branches harvesting from one hectare was 1.05 h·ha^{-1}, resulting in a capacity of 0.95 ha·h^{-1} and the pruned biomass productivity of 1.19 t_{FM}·h^{-1} (0.65 t_{DM}·h^{-1}). Taking into account all activities related to the full transport of biomass (30 bales) to the local boiler house located 6 km away from the orchard, the cumulated time required to complete the full cycle was 12.4 working hours. In relation to one hectare of harvested apple orchard, the value of 2.1 $h \cdot ha^{-1}$ was determined. In the considered logistic chain, the highest manpower demanded harvesting and baling (51%), storage and loading (24%), delays (15%), and bales transportation (10%) (Figure 2).

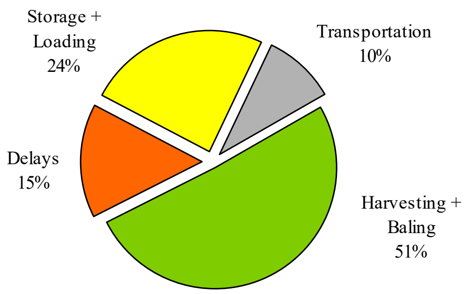

Figure 2. Manpower required in the PtE strategy for apple pruning residues.

3.3. Energy Analysis

In Table 3, the energetic data of the equipment employed in terms of fuels and lubricant consumed along the duration of the study, own mass, service life and operation time are presented. For PtE strategy, the direct energy input amounted to 355.7 $MJ \cdot ha^{-1}$ (517.4 $MJ \cdot t_{DM}{}^{-1}$) for the whole cycle, while indirect energy input accounted to 82.1 $MJ \cdot ha^{-1}$ (119.4 $MJ \cdot t_{DM}{}^{-1}$) (Table 4). In the case of sole mulching, the direct energy input was 248.4 $MJ \cdot ha^{-1}$, while the indirect energy resulted in 28.7 $MJ \cdot ha^{-1}$, giving a total energy outflow of about 277.2 $MJ \cdot ha^{-1}$.

Additionally, the energy indices calculated on the basis of the obtained data are shown in Table 5. The energy balance is very positive amounting to close to 12,000 $MJ \cdot ha^{-1}$. As an energy input, share (*EIS*) is very low (below 4%), and the PtE logistic chain is characterized by a high *EROI* factor, reaching a value of ca. 28.3. In turn, the energy productivity and intensity was 2.86 $kg_{FM} \cdot MJ^{-1}$ (1.57 $kg_{DM} \cdot MJ^{-1}$) and 350 $MJ \cdot t_{FM}{}^{-1}$ (637 $MJ \cdot t_{DM}{}^{-1}$), respectively.

3.4. Cost Analysis

The production cost of the complete cycle calculated for the available pruned biomass amount (1.25 t_{FM}) from one hectare of apple orchard was 66.6 €$\cdot t_{FM}{}^{-1}$ (121.1 €$\cdot t_{DM}{}^{-1}$). In relation to the orchards area, it gives a production cost of 83.3 €$\cdot ha^{-1}$. Among the costs of individual operations, the harvesting and baling process was the most expensive, reaching a value of 73.6% of the total cost, followed by storage and loading activities (18.0%) and biomass transportation (8.4%) (Figure 3). The low share of transportation cost (5.6 €$\cdot t_{FM}{}^{-1}$) resulted mainly from the investigated scenario, including only 6 km of delivery distance to the boiler house. It should be marked that, in terms of the operation hourly unit costs, the highest were due to harvesting and baling (44.9 €$\cdot h^{-1}$) and the second highest, due to transportation activity (29.9 €$\cdot h^{-1}$). The lowest were due to storage and loading (34.4 €$\cdot h^{-1}$) (Figure 3).

Table 3. Direct and indirect energetic input for PtE and mulching (operated orchard area 400 ha).

Equipment (Role)	Fossil Product	Fuel Consumption	Energetic Value	Energy	Mass	Energetic Value	Total EV	Service Life	Operation Time	Energy
	-	kg	$MJ \cdot kg^{-1}$	MJ	kg	$MJ \cdot kg^{-1}$	MJ	h	h	MJ
			PtE Direct Input				PtE Indirect Input			
Tractor (harvesting)	Diesel	2076.2	51.5	106,922	2440	92	224,480	15,000	546	8171
	Lubricant	41.5	83.7	3476	-	-	-	-	-	-
Baler (harvesting)	Diesel	0	51.5	0	1940	69	133,860	5500	546	13,289
	Lubricant	41.5	83.7	3476	-	-	-	-	-	-
Forklift (storage-loading)	Diesel	388.7	51.5	20,018	2600	92	339,200	10,000	200	4784
	Lubricant	15.2	83.7	1273	-	-	-	-	-	-
Tractor (transport)	Diesel	101.4	51.5	5222	2440	92	224,480	15,000	80	1197
	Lubricant	22.5	83.7	1886	-	-	-	-	-	-
Trailer (transport)	Diesel	0	51.5	0	2120	69	146,280	10,000	280	4096
	Lubricant	0	83.7	0	-	-	-	-	-	-
Total				142,273						31,537
			Mulching Direct Input				Mulching Indirect Input			
Tractor (mulching)	Diesel	1836.6	51.5	94,585	2440	92	224,480	15,000	483	7228
	Lubricant	36.7	83.7	3074	-	-	-	-	-	-
Mulcher (shredding)	Diesel	0	51.5	0	640	69	44,160	5000	483	4266
	Lubricant	20.4	83.7	1708	-	-	-	-	-	-
Total				99,368						11,494

Table 4. Direct and indirect energetic balance for PtE and mulching (operated orchard area 400 ha).

Energetic Balance (PtE)				Energetic Balance (Mulching)			
Input	$MJ \cdot ha^{-1}$	Input	$MJ \cdot t_{DM}{}^{-1}$	Input	$MJ \cdot ha^{-1}$	Input	$MJ \cdot t_{DM}{}^{-1}$
Direct	355.7	Direct	517.4	Direct	248.4	Direct	-
Indirect	82.1	Indirect	119.4	Indirect	28.7	Indirect	-
Total	437.7	Total	636.7	Total	277.2	Total	-
Output	12,375	Output	18,000	Output	0	Output	-
Balance	11,937.3	Balance	17,363.3	Balance	−277.2	Balance	-

Table 5. Energy indices for PtE strategy.

Indices		Value	Unit
Energy balance (Net energy)	*EB*	11,937	$MJ \cdot ha^{-1}$
Energy return on investment (Energy ratio)	*EROI*	28.27	-
Energy input share	*EIS*	3.54	%
Energy productivity	*EP*	2.86	$kg_{FM} \cdot MJ^{-1}$
		1.57	$kg_{DM} \cdot MJ^{-1}$
Energy Intensity	*EI*	350	$MJ \cdot t_{FM}^{-1}$
		637	$MJ \cdot t_{DM}^{-1}$

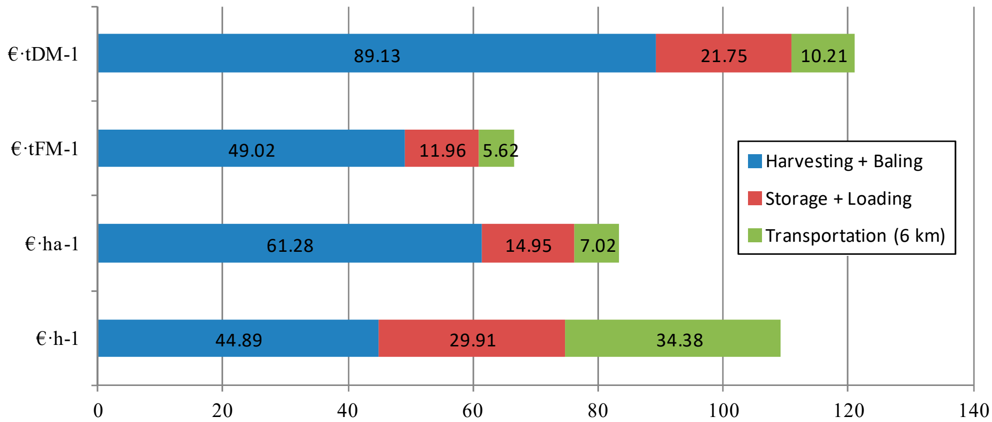

Figure 3. Cost distribution of single operations in the PtE strategy.

4. Discussion

The biomass available per hectare of harvested apple pruning calculated in this study was 1.25 $t_{FM} \cdot ha^{-1}$, which is within the range of data obtained in permanent orchards and plantations by other researchers [20,41,51]. Moreover, the total energy balance is positive (*EB* = 11.94 $GJ \cdot ha^{-1}$), which promotes this activity in contrast to the mulching process characterized by negative energy balance rated on the value of *EB* = −0.28 $GJ \cdot ha^{-1}$. Furthermore, the energy balance for harvesting and baling was more than two times higher than that obtained for harvesting and chipping of the apple tree pruning (*EB* = 5.24 $GJ \cdot ha^{-1}$). The direct energy input itself for harvesting and chipping was 1.25 $GJ \cdot t_{DM}^{-1}$, where in the case of harvesting and baling the value was 0.51 $GJ \cdot t_{DM}^{-1}$ [40]. Such difference is caused mainly by the higher energy needed to chip (to comminute) the branches. Lower energy requirements for baling are very good in terms of economic balance, but it is only valid if there is an adequate boiler in the local market prepared for whole bale combustion. It should be underlined that, in the case of biomass, there is a recommendation not to transport the solid biofuel over greater distances (up to 30–50 km). Therefore, the biomass is treated as a local renewable energy source. On the market, there are many differences in size and capacity of boiler units adopted to pruning/straw/hay bale combustion. The boilers are rather focused on heat production. Typical customers are farms, public buildings in small cities, rural schools, food/fruit processing enterprises, or small heat plants. If whole bale combustion units are lacking, it is necessary to convert the biomass bales into a more convenient form of biofuel, such as chips, pellets, or briquettes, which may significantly change the energy and economic balance of the cycle. As a result, the market analysis should be performed with care to avoid unexpected energetic expenditures.

Besides the energetic benefits, there is also an environmental aspect that is of added value to this logistics chain. The pruned biomass utilization for energetic purposes contributes to the reduction of CO_2 emission. The CO_2 emission factor from coal combustion (as the alternative conventional fuel) is 94.7 kg·GJ^{-1} [52] or 357 kg·MWh^{-1} [53]. Taking into account the combustion efficiency in the heating boilers (0.92) and the lower heating value for pruned biomass (*LHV* = 18.05 GJ·t_{DM}^{-1}), the avoided carbon dioxide emission amounts to 1572 kg·t_{DM}^{-1}. As the biomass residues productivity in the considered case was determined at 0.69 t_{DM}·ha^{-1} per year, the CO_2 emission equivalent would be ca. 1085 kg·ha^{-1} per year.

From a practical point of view, the costs of biomass harvesting are also important. In this study, the final cost was estimated as high as 83.3 €·ha^{-1} (121.1 €·t_{DM}^{-1}). However, in the case of apple orchards, this value might be reduced because the cost of mulching is avoided. Including the cost of mulching in the amount of 46.43 €·ha^{-1}, the cost of the PtE cycle decreases to the level of 36.8 €·ha^{-1} or 74.7 €·t_{DM}^{-1}, accordingly. This value seems to be attractive in comparison to the market value of wood chips varying from 100 to almost 300 €·t_{DM}^{-1} [36,41]. This positive result is limited to the condition that in the close surrounding from the apple orchard there is a combustion unit adapted to bale utilization. It should be underlined that the total cost of harvesting and baling depends on the size of the orchard managed by the farmer. For small orchards and ineffective machine utilization, the cost might increase significantly (Figure 4).

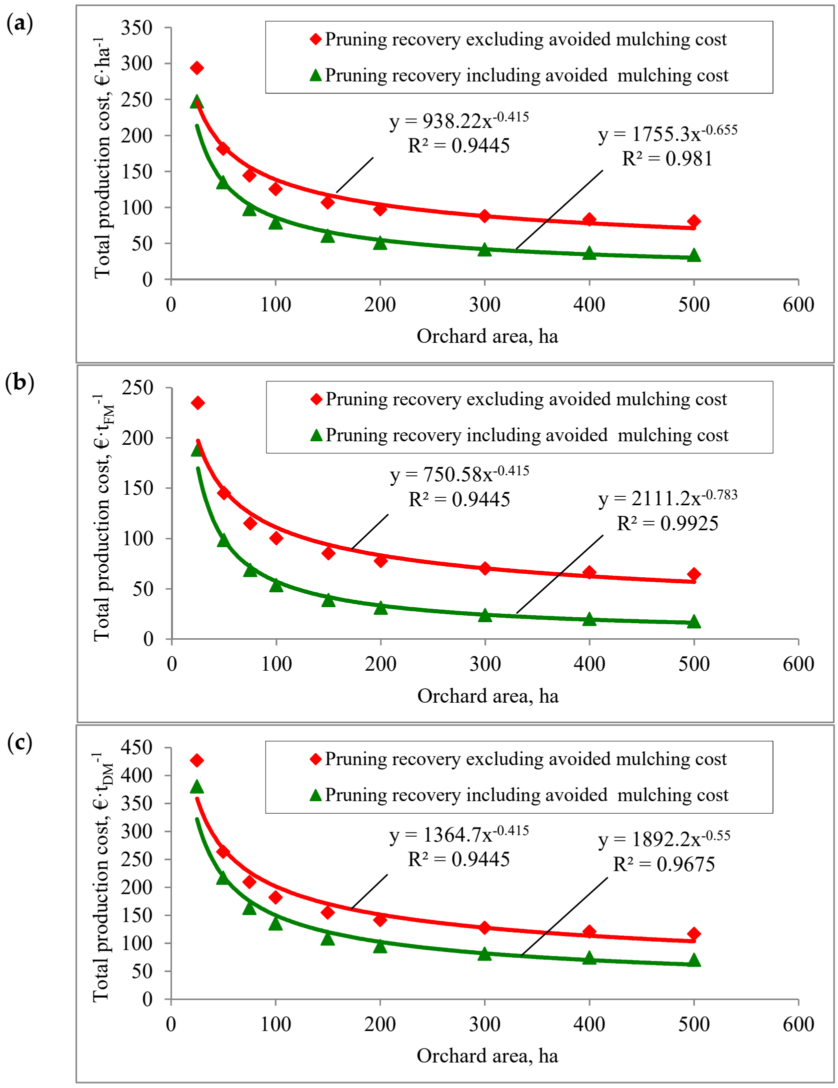

Figure 4. Influence of harvested orchard area on production costs: (**a**) related to one hectare of surface area; (**b**) related to one tone of harvested fresh mass; (**c**) related to one tone of harvested dry mass.

Even more, the costs and pruning biomass potential in apple orchards depend also on other factors [54], such as orchards age, apple variety, density of plantings, harvested machine operation, experience of the workers, etc. As a result, different amounts of pruned biomass might be harvested by the machine set [41]. Therefore, in Figure 5, the influence of the *PBP* on the total cost of the PtE strategy is shown. Additionally, as the increase in pruning potential causes a decrease in the driving speed of the harvesting unit in the orchard (tractor with baler) [55] and consequently the rise of fuel consumption, the adequate factor for both technologies (an increase of 20% in fuel consumption per ton of additional harvested biomass per hectare) was applied. On the one hand, a very low biomass potential increases drastically the total production cost. It proves that there is a limit below which the harvesting is economically not justified. On the other hand, an increase in biomass amount to be harvested slightly reduces the production cost.

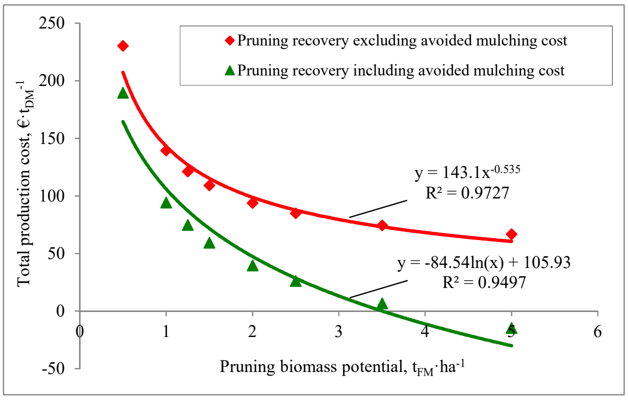

Figure 5. Production cost as a function of pruning biomass potential.

Even more interesting is whether the production cost is reduced by the mulching cost (avoided cost for orchard owner). There is a point at which the total production costs of biomass recovery become negative (Figure 5). This means that, from an economic point of view, it is recommended that the PtE strategy be followed, as the costs of biomass harvesting are lower than the mulching procedure itself. Therefore, the decision about the way to proceed with pruned residues should be supported by a case-specific analysis to make a right decision.

5. Conclusions

Pruning residues harvested from apple orchards may be a significant and economically justified alternative source of energy for the local market. The results of this study indicated reasonable productivity, a very good energy balance, and positive economic outcomes, especially in relation to the avoided mulching strategy. Taking into account the average market value of dry wood chips, the potential of the collected biomass covers the costs of harvesting, baling, on-site storage, loading, and transportation to the final user. The quality of biofuel is satisfactory, and the typical proximate parameters of the pruned biomass do not differ from forest biomass. However, it should be clearly emphasized that the final positive result (environmental, economic, and social) is conditioned by the possibility of whole bale combustion at the local heat plant. Otherwise, additional steps of biomass conversion will have to be applied to adopt the biomass form to other boiler requirements.

Author Contributions: A.D. performed the experiments, analyzed the data, and wrote the paper.

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Abbreviations

A	ash content
DM	dry mass
EB	energy balance
EI	energy intensity
EIF	energy input flow
EIS	energy input share
EOF	energy output flow
EP	energy productivity
EROI	energy return on investment
FM	fresh mass
HHV	higher heating value
LHV	lower heating value
MC	moisture content
O&M	operation and maintenance
PtE	pruning to energy
PBP	pruning biomass potential
SMH	scheduled machine hours
WtE	waste to energy

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