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The Influence of the Use of Windrowers in Baler Machinery on the Energy Balance during Pruned Biomass Harvesting in the Apple Orchard

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Received: 18 October 2018; Accepted: 20 November 2018; Published: 21 November 2018

Abstract: The effective operation of machinery in agricultural processes is crucial in terms of energy efficiency, economic consequences, and environmental footprint. The agricultural sector provides many opportunities to bring biomass to the market. An interesting option is to collect the branches after a regular pruning of apple orchards in the winter-spring season. As the harvesting of pruning residues in apple orchards for energy purposes demands additional primary energy, any measures that increase the amount of collected biomass are desirable. In this study, the influence of pruning harvesting using a baler with and without windrowers on pruning biomass yield, energy input and output flow, energy balance, CO_2 emission reduction, and costs of that operation in apple orchards was investigated. The performed analysis, based on the results from two apple orchards, revealed that the energy balance was positive for both variants. However, in comparison with the harvesting process without windrowers, the use of windrowers in these two orchards caused an increase in pruning biomass yield by 0.45 tDM·ha^{-1} per year (25%) and 0.54 tDM·ha^{-1} per year (33%), respectively. The energy balance increased up by ca. 0.8–1.0 GJ·ha^{-1}, although the fuel consumption by the tractor was higher. The use of windrowers did not significantly increase the costs, but resulted in remarkably better income from biomass selling (ca. €30–40 ha^{-1}). Finally, the increase in the mass of harvested biomass led to a higher potential CO_2 emission reduction. As a result, pruning biomass is an attractive source of energy, especially for local markets.

Keywords: pruning; agricultural residues; biomass harvesting; baler; energy balance

1. Introduction

Concerns about climate change have increased interest in agricultural efficiency and energy usage. Modern agriculture requires energy input at all steps of agricultural production. Direct usages of energy include farm machinery, water management, irrigation, cultivation, or harvesting processes. Additional energy is required for food and waste processing, storage and in product transport to final consumers. The final energy consumption by the agricultural sector in EU-28 is ca. 2.2% [1]. However, agriculture is a disproportionately high contributor to climate change, adding 10% of total EU-28 greenhouse gas (GHG) emissions [2]. Agriculture, forestry, and fishery have the second highest GHG intensity factor (the ratio of greenhouse gas emissions to gross value added) in the EU-28. In 2014, this index was estimated to be 2.7 kg of CO_2 equivalents per euro [3]. Therefore, improvements in all stages of the logistic chain of agricultural activity are important in terms of energy savings, energy effectiveness, and reduction in the pollutants released to the atmosphere.

The agricultural sector is not only an energy consumer, it also has the potential to produce and supply energy to the market, especially in various forms of biomass. Because of its local availability, biomass can increase fuel security and reduce carbon dioxide emissions [4]. Biomass represents more than 60% of the current renewable energy production in the EU-28, and the majority is sourced from solid biomass [5]. Due to the numerous advantages of using biomass, much attention has been paid to developing advanced technologies to enable its conversion to energy and fuels. The main source of solid biomass is forestry [6], but significant amounts are produced by agriculture as well, including energy crops and agricultural residues [7]. Agricultural residues can be divided into three main groups: primary crop residues, secondary crop residues, and animal farming residues. Primary crops residues are produced on the field (like straw, prunings, and other cuttings). Secondary crop residues are generated during processing of harvested products (like pomace or sunflower husks). Animal farming residues are produced during animal breeding (like manure).

Primary crops residues require collection using suitable machinery [8,9]. Agriculture residues are generally collected in the form of round bales, square bales, or in their chopped form [10]. As a result, there is a demand for additional energy for recovery, harvesting, processing, storage, and transportation to prepare such biomass for energy purposes [11,12]. The limited season for harvesting crop residues results in seasonal supply of agriculture-based biomass [13]. Among the crop residues, the seasonal pruning of fruit orchards requires special technology as the harvesting machinery must operate between the tree rows. Notably, pruned biomass harvesting within an orchard is the most energy consuming operation across all the steps (collection, storage, and short distance transportation) of the pruning-to-energy strategy. Many parameters and factors influence the biomass harvesting yield and losses and thus the energy balance. Therefore, considerable attention is being paid to the energy balance and efficiency during this process within the orchard. In Spinelli et al. [14], the tests revealed that the pick-up settings (pick-up height above ground level) of the harvester influenced the harvesting productivity and losses. Higher settings caused an increase in harvesting losses (mean harvesting losses varied from 0.4 to 6%). The authors concluded that the harvesting losses were mainly dependent on machine type. The use of small balers in a mountainous region showed that the pruning harvesting efficiency might be also affected by the slope of the terrain. Higher harvesting losses were observed for greater slopes in vineyards [15]. Finally, the amount of energy output might be improved by the better management of the residues, as farmers are not yet familiar with pruning recovery operations. For instance, the manual pruning of vineyards led to lower harvesting losses in comparison to mechanized cutting (17–38% for manual and ca. 48% for mechanized) [16]. Another problem is that the machine is rather narrower than the distance between the rows of trees and the cut branches are scattered along the route of the machine. So, any effort to gather cut branches at the center of the inter-row is one method to improve the process. Therefore, to limit harvesting losses, the machinery might be equipped with special windrowers that scrape the branches into the pick-up system of the harvesting machinery [17]. However, the use of windrowers might result in an increase in fuel consumption, leading to higher costs and energy input of the operation system.

The goal of this study was to investigate the energy flow in an apple orchard during the pruned biomass harvesting for energy purposes in two operation variants: (1) baler operation without windrowers and (2) baler operation with windrowers. The costs of these activities were estimated as well as energy indices including net energy, energy ratio, energy productivity, and specific energy.

2. Materials and Methods

2.1. Study Site, Experimental Design, and Data Collection

The tests were carried out in two apple orchards, 8 and 13 years old, located in the district of Potsdam-Mittelmark in Brandenburg, Germany. Both fields were flat and covered by grass. The width of inter-row spaces was 3.5 m, and tree spacing in a row was 1.2 m. For pruning harvesting in the orchard, a PRB 1.75 (Industrial Institute of Agricultural Engineering, Poznań, Poland) baler was applied. The baler produced bales with a 1.2 m diameter and a height of 1.2 m. The baler machine was powered by a Massey Ferguson 4270 (AGCO Corporation, Duluth, Georgia, US) tractor with a power of 84 kW. The machine working set was prepared to operate in two configurations: with and without windrowers (Figure 1).

Figure 1. Pruning round baler PRB 1.75 with windrowers.

Without the windrowers, the available collection width for pruned residues harvesting by the baler was limited to 1.75 m. With windrowers, however, the collection width for baler operation was 3.4 m. The windrowers were propelled hydraulically from the tractor system and their task was to improve the pruned biomass harvesting process (Figure 2).

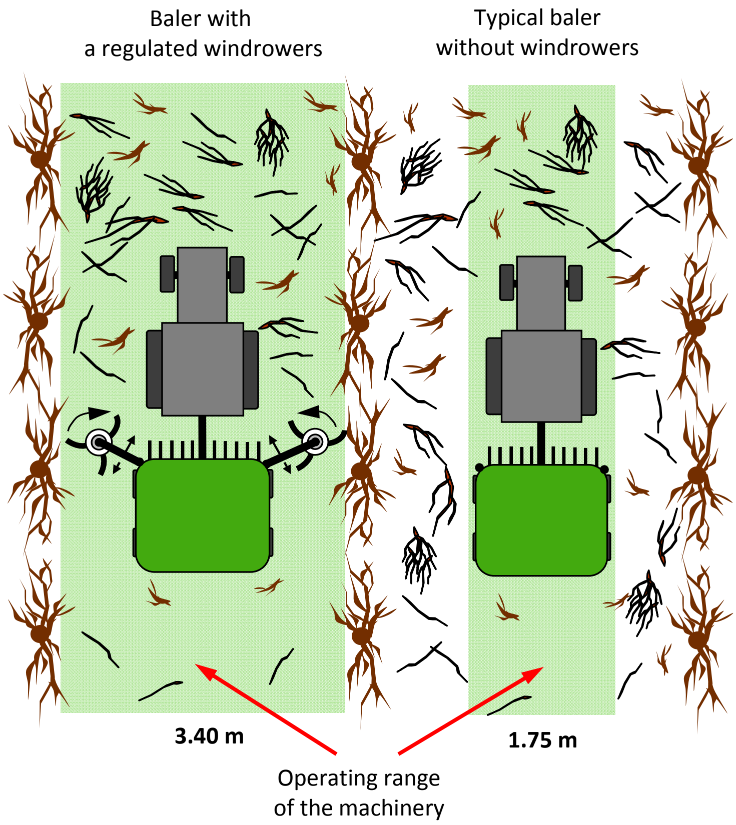

Figure 2. Operating range of the baler machinery (PRB 1.75) in the apple orchard.

This research focused only on the harvesting process in apple orchards. The boundary conditions applied during the energy balance analysis of the pruned biomass harvesting are shown in Figure 3.

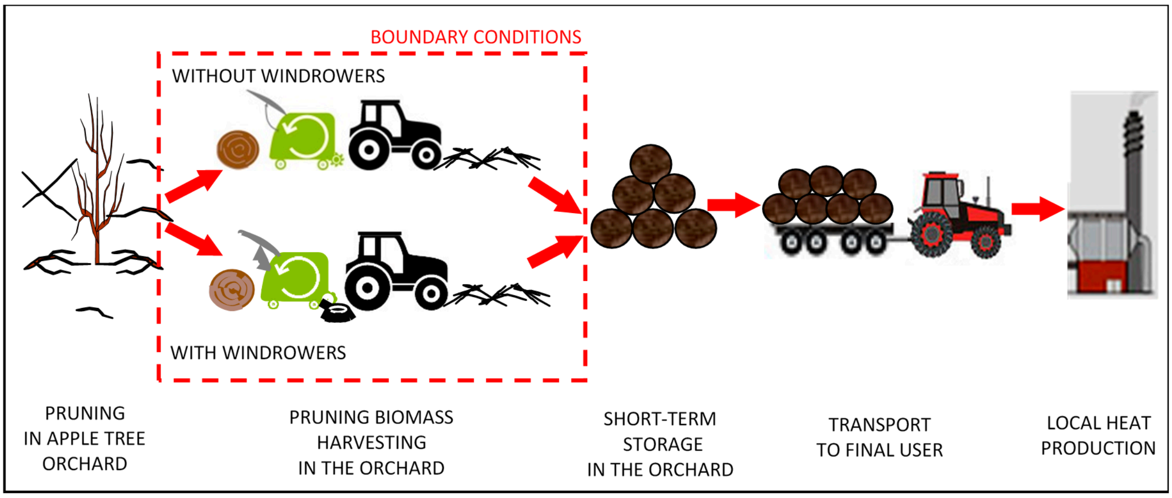

Figure 3. Boundary conditions for the energy balance analysis in this study.

2.2. Pruned Biomass Characterisation and Productivity

The moisture content was estimated in accordance with European Standard ISO 18134-1:2015 [18]. The caloric value of the harvested biomass was determined according to the European Standard ISO 18125:2017 [19]. 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 [20,21]:

$$LHV = HHV \times (1 - MC) - r \times MC \tag{1}$$

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}).

A detailed description of the measurements procedure and the obtained results during pruned biomass harvesting (pruning biomass yield, harvesting losses, fuel consumption) used in this analysis are presented in Dyjakon et al. [22].

2.3. Energy Analysis

Energy analysis is related to the determination of commercial energy employed during the defined process to produce a service or good [23,24] without considering renewable energy flows [25]. It considers the direct and indirect fossil energy flows. Direct energy (*DE*) includes the energy used during the production process (i.e., pruned biomass harvesting in the apple orchard). In turn, indirect energy (*IDE*) concerns the energy embedded in machines and tools that were used during the service performance or goods production [26,27]. The *DE* index was calculated using following equation [28]:

$$DE_{F,L} = M_{F,L} \times E_{F,L} \tag{2}$$

where $M_{F,L}$ is a total fuel (*F*) or lubricant (*L*) consumption (in kg) by the machinery during pruned biomass harvesting, $E_{F,L}$ is its energetic value (51.50 MJ·kg^{-1} for diesel and 83.7 MJ·kg^{-1} for lubricants [29]). The fuel consumption by the tractor during the experiment was estimated by weighing the mass of the canister with fuel with a hand scale prior to and after refilling the tractor's tank. In the case of lubricants, a value of 2% of the fuel consumption was applied [30]. Aligned with Canakci et al. [31], the *IDE* index was determined using the formula:

$$IDE = \left(\frac{M_M \times E_M}{t_{SLM} \times t_M}\right) \times t_{OP} \tag{3}$$

where M_M is the mass of machine in kg, E_M is the energy used for machine production in MJ·kg^{-1}, t_{SLM} is a total service life of the machine in years, t_M is the assumed yearly use of the machine in the orchard in scheduled machine hours (SMH)·year^{-1}, and t_{OP} is the cumulated SMH in the orchard to harvest the pruned biomass in SMH.

Consequently, the total energy input flow (*EIF*) being a sum of *DE* and *IDE* was calculated. Next, the energy intensity (*EI*), expressed in energy units per physical unit of good produced, was determined [32]:

$$EI = \frac{EIF}{PB_{FM,\ DM}} \tag{4}$$

where the pruning biomass (*PB*) yield is expressed in tons of harvested biomass (fresh mass, FM, or dry mass, DM) per hectare (tFM·ha^{-1}; tDM·ha^{-1}).

The energy output flow (*EOF*) of the biomass harvested during the baling process with and without the windrowers was estimated according to the following formula [32]:

$$EOF = PB_{FM} \times \left(\frac{100 - MC_{FM}}{100}\right) \times LHV \tag{5}$$

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

Based on the data obtained, some other indices related to energy flow, such as the energy balance (*EB*) [33], the energy return on investment (*EROI*) [32], the energy input share (*EIS*) [34], and the energy productivity (*EP*) [35], were calculated using given equations:

$$EB = EOF - EIF \tag{6}$$

$$EROI = \frac{EOF}{EIF} \tag{7}$$

$$EIS = \frac{EIF}{EOF} \times 100\% \tag{8}$$

$$EP = \frac{PB_{FM}}{EIF} \tag{9}$$

2.4. Cost Analysis

The harvesting cost of pruned biomass with and without windrowers was calculated from the hourly machine costs used during these two operation variants in the apple orchard. The operation and maintenance (O&M) costs were updated at their current value and calculated according to Schulter et al. and Edwards [36,37]. The annual scheduled machine hours (SMH) for the tractor and for the baler were assumed to be 1500 and 550 SMH, respectively (Table 1). The retention values of the initial investments for a tractor was 20% and 28% for a baler. For both machines, a depreciation period of 10 years was considered. Considering the wages and taxes in the agricultural sector [32,38], labor costs of €19 h^{-1} was established, including obligatory health and social insurance. The assumed cost of fuel and lubricant was €1.25 and €5.0 dm^{-3}, respectively [39]. Finally, the overhead costs were estimated at 20% of the total operational cost [40,41]. Considering an average price of €185 t^{-1}DM for dry firewood and €125 t^{-1}DM for dry wood chips [42,43], a sale price for pruned biomass bale of 90.0 €·t^{-1}DM was assumed.

Table 1. Operation and maintenance costs for evaluated pruned biomass harvesting variants in the apple orchards.

Operation/Action		**Biomass Harvesting in Orchard 1**				**Biomass Harvesting in Orchard 2**			
		Without Windrowers		**With Windrowers**		**Without Windrowers**		**With Windrowers**	
	Machine	**Tractor**	**Baler**	**Tractor**	**Baler**	**Tractor**	**Baler**	**Tractor**	**Baler**
	Unit	**MF4270**	**PRB1.75**	**MF4270**	**PRB1.75**	**MF4270**	**PRB1.75**	**MF4270**	**PRB1.75**
Investment	€	30,000	27,000	30,000	28,500	30,000	27,000	30,000	28,500
Power	kW	84.0	0	84.0	0	84.0	0	84.0	0
Service life	years	10	10	10	10	10	10	10	10
Crew	no.	1	0	1	0	1	0	1	0
Labor cost	€·SMH^{-1}	19	0	19	0	19	0	19	0
Usage	SMH·year^{-1}	1500	550	1500	550	1500	550	1500	550
Fixed cost	€·SMH^{-1}	2.4	5.6	2.4	5.6	2.4	5.9	2.4	5.9
Variable cost	€·SMH^{-1}	26.68	2.90	27.22	3.04	26.81	2.90	27.49	3.04
Overheads (20%)	€·SMH^{-1}	5.82	1.70	5.92	1.79	5.84	1.70	5.98	1.79
Unit cost	€·SMH^{-1}	34.89	10.20	35.54	10.74	35.05	10.20	35.86	10.74
Total cost	€·SMH^{-1}	45.09		46.28		45.25		46.60	

3. Results

3.1. Pruned Biomass Characterisation and Productivity

The calorimetric analysis and further calculations resulted in an *LHV* of 17.98 MJ·kg^{-1}DM (8.53 MJ·kg^{-1}FM, at moisture content *MC* = 46.30%) for biomass residues in Orchard 1, and an *LHV* of 18.12 MJ·kg^{-1}DM (9.02 MJ·kg^{-1}FM), at moisture content (*MC*) of 44.25% for Orchard 2.

The theoretical potential of pruning residues was 5.30 tFM·ha^{-1} in Orchard 1 and 4.90 tFM·ha^{-1} in Orchard 2 (Table 2). The use of windrowers affected the pruning biomass yield. Without windrowers, the *PB* was 3.31 tFM·ha^{-1} and 2.89 tFM·ha^{-1} for Orchard 1 and Orchard 2, respectively. The harvesting process with use of the baler equipped with the windrowers led to a *PB* increase up to 4.15 tFM·ha^{-1} in Orchard 1 and 3.85 tFM·ha^{-1} in Orchard 2. The increase in the *PB* caused an increase in the harvesting time by the baler. The duration time of this process in Orchard 1 with windrowers operation was 1.32 SMH per hectare, in comparison to 1.09 SMH per hectare when the windrowers were turned off. Similar results were obtained in Orchard 2: the time required to harvest one hectare changed from 0.92 SMH·ha^{-1} to 1.18 SMH·ha^{-1}.

Table 2. Main data of the machinery performance and biomass potential.

Parameter	Unit	Biomass Harvesting in Orchard 1		Biomass Harvesting in Orchard 2	
		Without Windrowers	With Windrowers	Without Windrowers	With Windrowers
Productivity	$tFM \cdot SMH^{-1}$	3.05	3.15	3.15	3.27
	$tDM \cdot SMH^{-1}$	1.64	1.69	1.76	1.82
Pruning biomass yield (*PB*)	$tFM \cdot ha^{-1}$	3.31	4.15	2.89	3.85
	$tDM \cdot ha^{-1}$	1.78	2.23	1.61	2.15
Pruning capacity	$SMH \cdot ha^{-1}$	1.09	1.32	0.92	1.18
	$ha \cdot SMH^{-1}$	0.92	0.76	1.09	0.85
Harvesting losses	%	37.3	22.1	41.3	20.9
	$tFM \cdot ha^{-1}$	1.97	1.18	2.03	1.02
Theoretical potential	$tFM \cdot ha^{-1}$	5.28	5.33	4.92	4.87
Theoretical productivity	$tFM \cdot SMH^{-1}$	4.86	4.04	5.37	4.13
Moisture content, *MC*	%	46.30		44.25	
Lower heating value, *LHV*	$MJ \cdot kg^{-1}FM$	8.53		9.02	
	$MJ \cdot kg^{-1}DM$	17.98		18.12	

3.2. Energy Analysis

The energetic data of the equipment employed in terms of fuels and lubricants consumed throughout the duration of the study, mass, service life, and operation time of the machinery are presented in Table 3.

In Orchard 1, for the variant without windrowers operation, the cumulated *DE* input was 294.2 $MJ \cdot ha^{-1}$ (165.5 $MJ \cdot t^{-1}DM$), whereas *IDE* input was 92.0 $MJ \cdot ha^{-1}$ (51.7 $MJ \cdot t^{-1}DM$). For operation with windrowers, the cumulated *DE* input was 388.0 $MJ \cdot ha^{-1}$ (174.1 $MJ \cdot t^{-1}DM$), whereas the *IDE* input was 111.7 $MJ \cdot ha^{-1}$ (50.1 $MJ \cdot t^{-1}DM$).

Similar results were obtained in Orchard 2. For operation without windrowers, the total *DE* input was 254.1 $MJ \cdot ha^{-1}$ (157.7 $MJ \cdot t^{-1}DM$), and the *IDE* input was 77.8 $MJ \cdot ha^{-1}$ (48.3 $MJ \cdot t^{-1}DM$). For operation with windrowers, the cumulated *DE* input was 360.5 $MJ \cdot ha^{-1}$ (167.9 $MJ \cdot t^{-1}DM$), whereas *IDE* input was 99.8 $MJ \cdot ha^{-1}$ (46.5 $MJ \cdot t^{-1}DM$).

From an energy point of view, the energy outputs for the evaluated variants were crucial (Table 4). Without the windrowers, the *EOF* gained in Orchard 1 and Orchard 2 was ca. 12.8 TJ and 11.7 TJ, respectively. Applying the windrowers to the baler, the *EOF* for Orchard 1 was slightly above 16.0 TJ and for Orchard 2 was roughly 15.5 TJ.

Based on the obtained data, other energy indexes were calculated as shown in Table 5. The *EB* of pruning to energy strategy (*PtE*) was positive for both systems and varied from 28.86 to 39.57 $GJ \cdot ha^{-1}$. However, higher values were related to the variants with operated windrowers. Important also is the *EIS* index, which was very low (below 2%). As a consequence, the *EROI* factor was substantial for all cases (above 80). The *EP* and *EI* during biomass harvesting in the apple orchard without windrowers were 8.57 $kgFM \cdot MJ^{-1}$ and 116.7 $MJ \cdot t^{-1}FM$, respectively, for Orchard 1. The use of windrowers in Orchard 1 caused a drop in the *EP* factor (8.31 $kgFM \cdot MJ^{-1}$), but an increase in the *EI* factor (120.4 $MJ \cdot t^{-1}FM$). A similar correlation was obtained for Orchard 2.

Table 3. Direct and indirect energetic input for evaluated pruned biomass harvesting variants in the apple orchards (assumed operated orchard area 400 ha).

			Biomass Harvesting in Orchard 1				Biomass Harvesting in Orchard 2			
			Tractor	**Baler**	**Tractor**	**Baler**	**Tractor**	**Baler**	**Tractor**	**Baler**
			MF4270	**PRB1.75**	**MF4270**	**PRB1.75**	**MF4270**	**PRB1.75**	**MF4270**	**PRB1.75**
			Without Windrowers		**With Windrowers**		**Without Windrowers**		**With Windrowers**	
Direct Input	Fossil product (diesel)	kg	2146	0	2837	0	1854	0	2638	0
	Energetic value (diesel)	$MJ \cdot kg^{-1}$	51.5	51.5	51.5	51.5	51.5	51.5	51.5	51.5
	Energy input (diesel)	MJ	110512	0	146083	0	95502	0	135878	0
	Fossil product (lubricant)	kg	42.9	42.9	56.7	52.1	37.1	36.3	52.8	46.6
	Energetic value (lubricant)	$MJ \cdot kg^{-1}$	83.7	83.7	83.7	83.7	83.7	83.7	83.7	83.7
	Energy input (lubricant)	MJ	3592	3592	4748	4361	3104	3037	4417	3897
Indirect Input	Mass	kg	3880	3300	3880	3300	3880	3300	3880	3300
	Energetic value	$MJ \cdot kg^{-1}$	92	69	92	69	92	69	92	69
	Total energy input	MJ	356960	227700	356960	227700	356960	227700	356960	227700
	Service life	SMH	15000	5500	15000	5500	15000	5500	15000	5500
	Harvesting time	SMH	564	564	685	685	477	477	612	612
	Energy input	MJ	13429	23363	16303	28362	11353	19751	14569	25346

Table 4. Direct energetic output for evaluated pruned biomass harvesting variants in the apple orchards (operated orchard area 400 ha).

			Biomass Harvesting in Orchard 1		Biomass Harvesting in Orchard 2	
			Without Windrowers	**With Windrowers**	**Without Windrowers**	**With Windrowers**
Direct Output	Pruning biomass yield	tDM	712	892	644	860
	LHV (dry mass)	$MJ \cdot kg^{-1}$	17.98	17.98	18.12	18.12
	Energy output	GJ	12 783	16 028	11 678	15 557

Table 5. Energy flows and indices for evaluated pruned biomass harvesting variants in the apple orchards.

Parameter		Unit	Biomass Harvesting in Orchard 1		Biomass Harvesting in Orchard 2	
			Without Windrowers	With Windrowers	Without Windrowers	With Windrowers
	Total Energy Input (direct + indirect)	$GJ{\cdot}ha^{-1}$	0.39	0.50	0.33	0.46
	Pruning energy output	$GJ{\cdot}ha^{-1}$	31.96	40.07	29.19	38.89
EB	Energy balance (net energy)	$GJ{\cdot}ha^{-1}$	31.57	39.57	28.86	38.43
EIS	Energy input share	%	1.21	1.25	1.14	1.18
EROI	Energy return on investment (energy ratio)	-	82.75	80.20	87.97	84.50
EP	Energy production (productivity)	$kgFM{\cdot}MJ^{-1}$	8.57	8.31	8.71	8.36
		$kgDM{\cdot}MJ^{-1}$	4.60	4.46	4.85	4.66
EI	Energy Intensity (energy specific)	$MJ{\cdot}t^{-1}FM$	116.7	120.4	114.8	119.6
		$MJ{\cdot}t^{-1}DM$	217.3	224.2	206.0	214.4

3.3. Cost Analysis

For the operation variant without windrowers, the harvesting and baling costs calculated for one hectare in the considered apple orchard were €48.93 ha^{-1} for Orchard 1, and €41.52 ha^{-1} for Orchard 2 (Table 6). In case of the variant with windrowers, these costs were €60.97 ha^{-1} for Orchard 1 and €54.87 ha^{-1} for Orchard 2. Relating the harvesting costs to the pruning biomass yield, the values for operation without windrowers were slightly higher in comparison to the variants with incorporated windrowers. For Orchard 1 (Orchard 2), these values amounted to €14.78 t^{-1}FM (€14.37 t^{-1}FM) and €14.69 t^{-1}FM (€14.25 Mg^{-1}FM).

Table 6. Unit costs and potential profits for evaluated pruned biomass harvesting variants in the apple orchards.

		Biomass Harvesting in Orchard 1		Biomass Harvesting in Orchard 2	
		Without Windrowers	With Windrowers	Without Windrowers	With Windrowers
Harvesting and Baling	$€{\cdot}SMH^{-1}$	45.09	46.28	45.25	46.60
	$€{\cdot}ha^{-1}$	48.93	60.97	41.52	54.87
	$€{\cdot}t^{-1}FM$	14.78	14.69	14.37	14.25
	$€{\cdot}t^{-1}DM$	27.53	27.36	25.77	25.56
Bale (pruning) price	$€{\cdot}t^{-1}DM$	90.0	90.0	90.0	90.0
Income (prunings residues selling)	$€{\cdot}ha^{-1}$	160.0	200.6	145.0	193.2
Profit net	$€{\cdot}ha^{-1}$	111.0	139.6	103.5	138.3

The application of windrowers also has financial consequences. For example, the net profit from one hectare in Orchard 1 was €111.0 ha^{-1} (without windrowers) and €139.6 ha^{-1} (with windrowers). Notably, the costs related to storage and transport were excluded from this analysis.

4. Discussion

Without windrowers, the pruning biomass yield in the investigated orchards was 3.31 tFM·ha^{-1} (Orchard 1) and 2.89 tFM·ha^{-1} (Orchard 2), which was achieved at ca. 40% of harvesting losses. These high harvesting losses were caused by the very narrow range of the baler operation, limited to a width of only 1.75 m. The application of windrowers resulted in an increase in the operation range to 3.4 m, leading to an improvement in the harvesting process and a considerable decrease in harvesting losses in both apple orchards to a level of ca. 20%. As a result, the *PB* increased significantly to a value of 4.15 tFM·ha^{-1} (Orchard 1) and 3.85 tFM·ha^{-1} (Orchard 2). These values are higher than the average pruned biomass potential (3.50 tFM·ha^{-1}) determined for apple orchards in Poland, which is the third largest apple producer in the world [44]. High pruned biomass potential is very important in terms of *PtE* strategy as it makes this technology attractive for farmers. The pruning residues from apple orchards are characterized by a satisfactory energetic potential. The determined lower heating value for the pruned biomass samples was ca. 18.00 MJ·kg^{-1} DM, which is a typical value for wood residues from permanent crops, like vineyards or olive pruning [45].

However, the use of windrowers caused an increase in fuel consumption by the machine set as well as the operation time required to harvest one hectare of apple orchard. This increase occurs because, for the machinery to collect more cut branches from a wider area, the machine must move slower to enable the windrowers to forward the material into the pick-up system of the baler. Similar observations were made by other researchers during miscanthus harvesting using baling technology [46]. Consequently, the operation time extended from 1.09 SMH·ha^{-1} to 1.32 SMH·ha^{-1} (Orchard 1) and from 0.92 SMH·ha^{-1} to 1.18 SMH·ha^{-1} (Orchard 2). As a result, this index increased by more than 21% and 28%, respectively. Higher operation time values achieved for Orchard 1 in comparison to Orchard 2 additionally confirm this correlation as Orchard 1 had a higher pruning biomass production, as shown in Table 2. Larger amounts of harvested biomass influenced the baler loading as more power was required to press the branches in the rolling chamber. This resulted in higher fuel consumption by the tractor (Table 3), which propelled the baler through the power take-off (*PTO*).

These parameters affect both the direct *EIF* required during the harvesting process in an apple orchard and the *EOF* represented by the energy accumulated in the collected biomass. Considering these dependences, it is crucial to estimate if the pruning harvesting process (without windrowers) is characterized by a positive or negative *EB*, as well as if the use of windrowers has additional energy benefits for the *PtE* strategy.

The performed calculations revealed that the total energy balance is positive for both operation variants, with and without use of windrowers. Contrarily, if the pruning biomass is left on the field and is consequently mulched, the *EB* is negative [32,38]. However, the variants using windrowers were characterised by higher *EB* values. In the considered cases, the increase was 25% in Orchard 1 and 33% in Orchard 2. More energy accumulated in the total amount of harvested biomass in comparison to the additional energy employed in fuel and lubricant for powering the tractor and the baler. This correlation is confirmed by a very low *EIS* index that was slightly above 1% and a high *EROI* index exceeding a value of 80. Other indexes, such as *EP* and *EI*, were also satisfactory. The achieved results promote harvesting activity for energy purposes and are in line with recommendations of other researchers [38,47,48]. It must be underlined that the *EB* value in this study only includes the harvesting and baling process in the orchards (Figure 3, boundary conditions of the analysis). Other energy inputs related to storage or delivery of biomass to final consumer should be considered. Regardless, according to previous studies [32,38], the cumulated *EB* factor of the entire logistics chain will be greater than from mulching, which is characterized by a negative *EB*. When using windrowers, this difference will be even greater. In comparison to harvesting and chipping process (an alternative option), the *EB* value from harvesting and baling is higher [38].

As the use of windrowers affects two opposing parameters in the energy balance (fuel consumption and pruning biomass yield), a sensitivity analysis was performed in order to determine which parameter is more important concerning the energy benefits. A change in the biomass yield influences both the power demand and the fuel consumption. So, based on the test data from the investigated orchards, a fuel consumption coefficient for the tractor of 0.1 dm^3 per 0.1 $tFM \cdot ha^{-1}$ for additional harvested biomass was assumed. The results proved that fuel consumption variations during harvesting process are not as crucial as the pruning biomass yield in terms of *EB* (Figure 4). From an energy point of view, a significant decrease in *PB* (–50%) maintained the *EB* positive (*EB* was still ca. 20 000 $MJ \cdot ha^{-1}$).

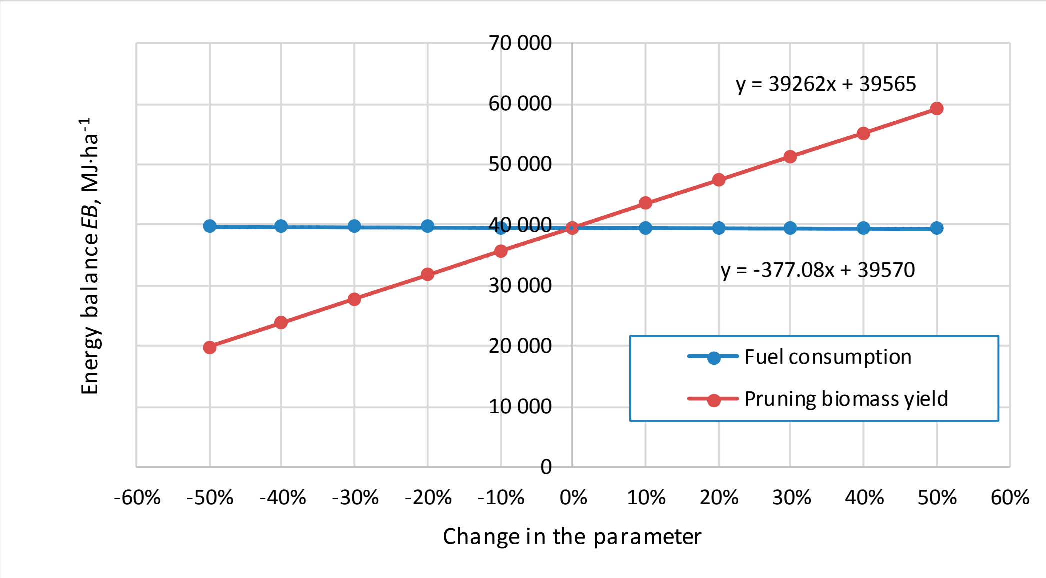

Figure 4. Sensitivity analysis of the main parameters influencing *EB*.

Apart from energy considerations, the economic aspects are essential for the introduction of *PtE* schemes. The analysis indicated that for both orchards, the hourly operation costs were the same, at ca. €46 SMH^{-1}. This cost seems to be high, as the common management of pruning residues with the use of a mulcher attached to a tractor is usually 15–20% lower [32]. However, the baling technology is cheaper than a chipping system, whose costs are estimated to be roughly €65 SMH^{-1} [38]. Considering the operation costs related to one hectare of apple orchard, the difference between the variants with and without windrowers is significant. The use of windrowers increased the harvesting costs of one hectare by 23% in Orchard 1, and by 30% in Orchard 2. The main reason for this was the longer operation time required to harvest the pruning residues from one hectare, which is related to labor and variable costs [49]. However, the use of windrowers increases the *PB*, which leads to higher cash flows from pruning residues selling. Due to the improved harvesting process with the use of windrowers (more biomass harvested) and the relatively high price of dry biomass (€90 t^{-1}DM), the additional harvesting costs are outweighed by higher incomes for the windrowers scenarios, amounting to an additional €29–35 t^{-1}DM.

Notably, we did not consider the whole logistic chain; however, the harvesting process is the most energy- and costs-consuming among all the steps (harvesting, storage, short transportation distance) [32,38]. Therefore, the improvement in the harvesting process efficiency is a key point to increase the energetic balance, economic value, and environmental profits, which have been an area of interest in other studies related to this issue [50–52].

The environmental aspect, besides the energy and economic profits, is a significant added value in terms of sustainable use of bioenergy. The pruned biomass use for energy purposes contributes to a decrease in CO_2 emissions. The CO_2 emission factor from bituminous coal combustion is 94.7 $kg \cdot GJ^{-1}$ [53]. Assuming the combustion efficiency in biomass heating boilers (0.92) and a *LHV* of 18.0 GJ per ton dry mass of pruned biomass, the avoided gross CO_2 emission is 1568 $kg \cdot t^{-1}$DM. As the difference in *PBs* between the two considered variants (with and without windrowers) were determined at 0.45 tDM·ha^{-1} per year (Orchard 1) and 0.54 tDM·ha^{-1} per year (Orchard 2), the equivalent of additionally-avoided CO_2 emission for Orchard 1 would be ca. 705 kg·ha^{-1} per year, and ca. 846 kg·ha^{-1} per year for Orchard 2.

5. Conclusions

Pruning biomass harvested from apple orchards can be a new alternative regional energy source if the energy balance is positive and the operation costs are economically justified. Among the entire logistics chain for the *PtE* strategy, the harvesting step is the most energy consuming. However, the pruning biomass yield depends on many factors, including the machinery construction. To improve the energy efficiency and energy balance of that operation, different measures can be applied. One of the opportunities is the use of windrowers during harvesting in apple orchards, which was the focus of this paper. The achieved results provide new data about the energy balance, productivity, pruning biomass yield, and economic aspects of this process. The investigated harvester (baler), equipped with additional windrowers, increased the collection width by a factor of two and proved to be suitable for recovering wood biomass from apple orchards, producing a solid biofuel of good quality, suitable for energy production in middle size boilers.

Due to the increased operation range of the harvesting machinery, more branches were collected, reducing the harvesting losses and significantly increasing the *PB* and the *EOF*. As a consequence, the *EB* index was improved by ca. 25%. The financial profits were higher by at least 20%. The outcome of the sensitivity analysis revealed that the effort to increase the pruning yield is important in terms of *EB*. However, the results should be treated with care, as boundary conditions excluded the storage and transport steps. Nevertheless, the advantages of windrower application was proven, providing clear direction for the improvement of the effectiveness of the harvesting procedure in the apple orchards or other plantations.

In addition to the improved capacity of the harvesting technology, the use of windrowers causes a CO_2 reduction, as more biomass may be delivered to the local market, increasing the share of renewables in the energy mix, thus replacing fossil fuels.

However, some aspects could still be improved or need further research, namely the optimization of passing speed in the orchard by the machinery. Also, the minimal pruning yield to maintain a positive energy balance as well as the economy of whole logistic chain have yet to be assessed. The correlations between the other machine settings and characteristics of the orchard/branches on the energetic consequences, and fuel consumption or pruning quality resulting from windrowers use are unknown. The efficiency of the windrowers operation in stony fields and under wet soil conditions is interesting from a practical point of view as well.

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

Funding: Part of the data used in this scientific paper were co-financed by the European Union Seventh Framework Program (FP7/2007-2013) under grant agreement n° 312078, and by funds on science in the years 2013–2016 granted by the Polish Minister of Science and Higher Education on the realization of the international project EuroPruning: "Development and implementation of a new and non-existent logistics chain for biomass from pruning". This research received no external funding.

Acknowledgments: Special thanks to Florian Adamczyk, PhD Eng. from Industrial Institute of Agricultural Engineering (Poland) for his consultancy.

Conflicts of Interest: The author declares no conflict of interest.

Abbreviations

DM	dry mass
DE	direct energy
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
EU-28	28 member states that belong to the European Union
FM	fresh mass
HHV	higher heating value
IDE	indirect energy
LHV	lower heating value
MC	moisture content
O&M	operation and maintenance
PtE	pruning to energy
PTO	power take-off
PB	pruning biomass yield
SMH	scheduled machine hours

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