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Local Energy Use of Biomass from Apple Orchards—An LCA Study

Arkadiusz Dyjakon [1,*], Jan den Boer [1], Antoni Szumny [2] and Emilia den Boer [3]

1. Institute of Agricultural Engineering, Wrocław University of Environmental and Life Sciences, 51-630 Wroclaw, Poland; jan.denboer@upwr.edu.pl
2. Department of Chemistry, Wroclaw University of Environmental and Life Science, 50-375 Wroclaw, Poland; antoni.szumny@upwr.edu.pl
3. Faculty of Environmental Engineering, Wroclaw University of Technology, 50-370 Wroclaw, Poland; emilia.denboer@pwr.edu.pl

* Correspondence: arkadiusz.dyjakon@upwr.edu.pl; Tel.: +48-71-320-5945

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Abstract: Generation of heat in small and medium-size energy systems using local sources of energy is one of the best solutions for sustainable regional development, from an economic, environmental, and social point of view. Depending on the local circumstances and preferences of the agricultural activity, different types and potentials of biomass are available for energy recovery. Poland is the third-largest producer of apples in the world. The large cumulative area of apple orchards in Poland and necessity of regular tree pruning creates a significant potential for agricultural biomass residues. In this paper, the LCA analysis of a new and integrated process chain focused on the conversion of cut branches coming from apple orchards into heat is conducted. Furthermore, the obtained results of the environmental indices have been compared to traditional mulching of pruned biomass in the orchard. It was shown that in terms of the LCA analysis, the biomass harvesting, baling, and transportation to the local heat producer leads to an overall environmental gain. The cumulative Climate Change Potential for pruning to energy scenario was 92.0 kg CO_2 equivalent·ha^{-1}. At the same time, the mulching and leaving of the pruned biomass in the orchard (pruning to soil scenario) was associated with a CO_2 equivalent of 1690 kg·ha^{-1}, although the soil effect itself amounted to −5.9 kg CO_2 eq.·ha^{-1}. Moreover, the sensitivity analysis of the LCA showed that in the case of the PtE chain, the transportation distance of the pruned bales should be limited to a local range to maintain the positive environmental and energy effects.

Keywords: pruning residues; heat production; life cycle assessment; environmental impact; sustainability

1. Introduction

The use of renewable energy sources (RES) is one of the main ways to mitigate climate change in the future. The European Commission (EC) published the White Paper for a Community Strategy and Action Plan [1], favoring the use of local resources, and thus supporting indigenous development. Moreover, as biomass plays an important role among RES, the European Commission adopted the Biomass Action Plan for the EU [2], promoting its efficient and environmentally-friendly use. Finally, the Council of the European Union (EU) set three important targets: to increase the share of RES in the total consumption to 20%, to reduce carbon dioxide (CO_2) emissions by 20%, and to improve energy efficiency by 20% by the year 2020 [3]. In order to intensify the activity in these fields, the European Parliament passed Directive 2009/28/EC on the promotion of the use of energy from renewable sources [4]. These goals should be reached in a sustainable way, possibly in coherence with the bio-economy development [5]. This EU policy is also to be continued beyond 2020 and new targets have been proposed (i.e., a 40% reduction of greenhouse gas emissions (GHG) in relation to 1990 levels and the achievement of 27% of renewable energy share in the energy consumption by 2030) [6].

The average annual biomass production in the land-based sectors (agriculture and forestry) of the EU is 1466 Mt in dry mass (DM). The total agricultural biomass gained annually in the EU was estimated at 956 MtDM, out of which 46% (442 MtDM) is referred to as residue production [7]. The agricultural residues (ARs) are the remaining fractions of the biomass, which is not the primary aim of the production process (e.g., dry biomass from leaves, stems, grass, pomace, vinasse, straw, branches). Depending on their chemical and physical properties, different treatment options to produce energy can be applied. Some of them are rich in organic matter and more suitable for the anaerobic digestion process [8,9]. Others are characterized by high lignin and cellulose content more adequate for thermal processes [10]. This group includes prunings from regular cutting of permanent crops, including apple orchards.

The apple orchards area in Europe (namely in 28 EU countries) is approximately 450,000 ha, presenting theoretical pruning residue (PRs) potential of 29.11 PJ·year^{-1} [8]. In countries like Poland, being leaders in world apple production, this potential is especially significant, and it amounts to 9.3 to 12.5 PJ·year^{-1} [11,12]. Those residues must be removed from the field before the start of any other agricultural activities. Therefore, proper orchard management is required, taking into account economic, environmental, and energetic aspects. The amount of biomass residues produced during the winter-spring apple tree pruning depends on numerous factors (e.g., age of the orchard, apple variety, management strategy, planting density, climate conditions, etc.) and amounts to 3.5 t·ha^{-1} (fresh mass) [12]. Until recently, apple pruning residues have been considered as waste, generating only problems and costs. The common practice to get rid of the prunings was mulching or burning them on-site [13]. Lately, as specialized machinery to harvest and bale the cut branches has appeared on the market [14], a new alternative to use this residual biomass for energy purposes has gained significance. The pruned bales, after a few months of open-air drying, may become a very valuable biofuel to be burnt in local middle-sized boilers for heat production.

Pruning residues may generate farm income when harvested and used for energy purposes, but they might also be crucial for other applications, including ecosystem services, such as maintaining organic carbon levels in soils or preventing soil erosion [15]. Due to bio-economy development, with prioritized demand for food and feed products, an increased interest in residue biomass for material and energy purposes may be expected. However, to satisfy sustainability criteria [16], a comprehensive assessment of biomass production from agriculture is required. One of the criteria is the environmental impact of pruning residue application and utilization.

The amount of the environmental impact due to energy use of biomass depends on a number of factors, such as harvesting technology, transportation distance, seasonal availability of agricultural biomass, among others [17–19]. Therefore, a simple logistic chain, short transportation distance, and local use of biomass residues are key points to maintain a sustainable process and low environmental impacts [20,21]. To determine the environmental consequences of the processes and other activities, the methodological approach called Life Cycle Assessment (LCA) recommended by International Standards Organization [22] has come into common use. As a result, the identification and quantification of the environmental loads, evaluation of the potentiality of those loads, and proposals of environmental effects reduction can be performed [23]. Therefore, also during the thermal utilization of biomass, along the energy and economic balance, the LCA analysis is applied to provide a clearer view on the process and its influence on the environment [24]. The LCA of agricultural residues and other biomass has been used before, e.g., by Paolotti et al. [17] for agro-energy wood biomass supply chains and Boschiero et al. [25] for orchard wood residues in Northern Italy. Boschiero et al. [25] analyzed a hypothetical production of bioenergy from apple pruning using the LCA methodology with the system boundaries, including its harvesting, chipping, transport, and thermal conversion into heat and power in a gasifier. The results have been compared with two reference systems (electricity from coal, electricity from natural gas) based on fossil fuels. In other work [26], Boschiero et al. carried out a LCA to investigate the environmental performance of a hypothetical bioenergy chain, applying a middle size combined heat and power plant fueled by apple wood chips. However, the authors changed the system boundaries depending on the pruning residue allocations (i.e., by-product or co-products). Pergola et al. [27], however, performed an assessment of environmental impact and energy consumptions of three apricot orchards, managed according to two cultivation systems (integrated and biodynamic). Nevertheless, in this analysis, the authors focused on fruit production systems. In relation to the energetic value chain, only pruning activities were considered.

However, in the literature, no data has been found related to the existing complete logistic chain implementing pruning residues from apple orchards for energy purposes. Moreover, no LCA analysis dealing with pruning residues harvested in the form of bales has been detected. The lack of data in this issue provided a space for the research and LCA analysis in that field.

The aim of this study is to assess the environmental performance of using ARs from apple orchards as bioenergy feedstock for heating. The system produces heat from pruning residues, using primary data for the agricultural operations and logistics, and it is scaled to the annual volumes of residues that could be produced using baling machinery. The results are compared to the mulching process as a reference solution that is commonly used in apple orchards. As a result, the main objectives of the study are: (i) to collect and provide site-specific data of the field operations for the life cycle inventory analysis; (ii) to assess the GHG emissions and other environmental effects derived from pruning to energy (PtE) and pruning to soil (PtS) value chains; and (iii) to compare the environmental consequences of those two scenarios.

However, prior to a decision based on economic and environmental impacts, it should be considered whether the removal of pruned materials will not have an adverse effect on the soil fertility and stability. In the Europruning project, these effects where thoroughly examined and the following general advice was established [28].

Prunings should not be removed, if:

- no vegetation cover >80% between trees (interrows) can be established and

  A soil structure is weak and tends to compaction, silting, or surface runoff; or
  B the orchards are prone to erosion and there are no alternative erosion protection measures; or
  C top soil tends to water logging or anoxic conditions; or

- no vegetation cover with >15 t·ha^{-1} per year of fresh biomass (3 t·ha^{-1} per year of dry mass) can be established and soil carbon content is low.

If one or more of the cases **A–C** apply, the dominant problem should be treated as follows:

- if **A** or **B**: prunings should be chipped and used as cover mulch;
- if **C**: prunings should be chipped and worked into the soil.

2. Materials and Methods

The environmental impact was determined using a methodology for the comprehensive assessment of the impact that a product or service has on the environment throughout its life cycle. The procedure used for the life cycle assessment was in accordance with the ISO 14040:2006 methodology [22]. The life cycle impact assessment, the LCA phase that connects the life cycle inventory to quantified potential environmental impacts, was done using the reference of the International Life Cycle Data (ILCD) system method [29]. For normalization, the methodology provided by the Joint Research Centre (JRC) was followed [30]. The LCA analysis was carried out using GaBi software professional 8.6 (Thinkstep company, Leinfelden-Echterdingen, Germany).

2.1. Goal and Functional Unit

The goal of the study is to assess the environmental impact in a life cycle perspective of the energetic use of pruning residues (PtE scenario) coming from apple orchards. The results are compared to the typical management system of pruned residues based on the mulching technology (PtS scenario).

The reference functional unit for the inventory analysis is the use of pruning residues generated from 1 ha, and it assumed that both systems achieve the same end targets. Therefore, in the case of PtE scenario, additional fertilizing is required that substitutes the pruning residues removed from the orchard. In the case of PtS, however, the alternative heat production by conventional system fired by bituminous coal is assumed to balance the final energy gained from pruning combustion in the PtE scenario. The adoption of bituminous coal as a reference fuel in the PtS scenario results from the fact that in Poland over 50% of households are heated using this fuel. Moreover, about 84% of households in EU-28 countries that are heated by coal are located in Poland [31].

2.2. System Boundaries

Two scenarios (Figure 1) were defined for the potential treatment of the pruning residues taking into account all processes related with the biomass management. Those scenarios are:

- the use of pruning residues for energy purposes (PtE scenario);
- the mulching of pruning residues as a source of organic matter for soil (PtS scenario).

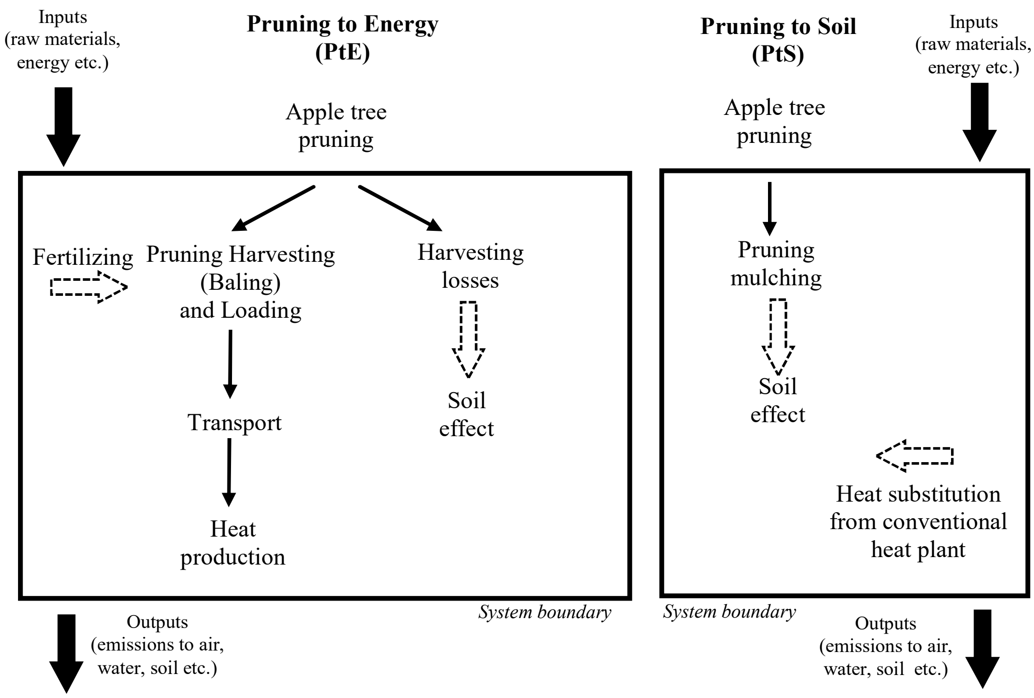

Figure 1. System boundaries for the pruning to energy and pruning to soil scenarios.

In this study, the strategy of PtE is focused on the effective pruning harvesting in an apple orchard. Within this scenario, baling technology is applied that enables production of large bales that are stored on site and then transported to a final consumer. The final consumer burns the bales in a suitable boiler to generate heat. The biomass and the heat are produced locally. As a result, the prunings are removed from the field and the apple orchard is ready for further activities related to fruit production. However, the removal of prunings involves some additional fertilizing to ensure the proper balance of nutrients in the soil.

However, the PtS scenario included mulcher operation in the orchard. A tractor with a mulcher passed in the interrows and comminuted the cut branches into small wood chips and left them in the soil as an organic material. That technology does not generate heat that could be utilized for energy purposes. However, after the mulching the farmer can follow further actions aimed at apple production.

In both scenarios, prior to the pruning harvesting and mulching procedure, the cut branches were windrowed in the middle of the tree corridor to increase the efficiency of both processes.

2.3. Description of Biomass Sources

The LCA analysis was performed applying data gained during pruning harvesting realized in an apple orchard situated in the Mazowieckie Province (Poland). The size of the apple orchard was 36 ha. The field was flat and grass covered. The biomass residues were harvested using a professional baler Wolagri R98 attached to a Kubota M7040DHC tractor. Next, the produced bales were transported by a forklift equipped with rakes to the field side for open-air drying and storage (approximately 6 months). Finally, the bales were loaded on-to the trailer and delivered to a local heat plant located at a distance of 6 km from the orchard.

Selected data used in the LCA study is shown in Table 1. More data related to the research (experimental design of the harvesting process, data collection, fuel quality) and the machinery used (technical data) are presented by Dyjakon [32].

Table 1. Apple orchard and pruning characteristic.

Parameter	Unit	Value	Parameter	Unit	Value
Theoretical pruning potential	$tFM \cdot ha^{-1}$	1.39	Higher heating value	$MJ \cdot kgDM^{-1}$	19.31
Pruning biomass yield	$tFM \cdot ha^{-1}$	1.25	Lower heating value	$MJ \cdot kgDM^{-1}$	18.05
Harvesting losses	$tFM \cdot ha^{-1}$	0.14	Ash content (DM)	%	0.8
Moisture content (FM)	%	45.15	Density of pruned bale	$kgFM \cdot m^{-3}$	230
Mass of pruning after 6 months of storage	$t \cdot ha^{-1}$	1.02	Pruning capacity	$ha \cdot h^{-1}$	0.95
Moisture content after 6 months of storage	%	18.64			

FM—fresh mass, DM—dry mass.

2.4. Description of Materials and Energy Flows

In the LCA of pruning harvesting, two processes were taken into account: the production of the machines and the environmental impact of the working set in the apple orchard. The considered materials and energy were consequently incorporated in the model by standard modules that are included in the GaBi or Ecoinvent databases for a tractor, a forklift, and a trailer for the PtE, and a tractor and a mulcher for the PtS scenario. For the baler production, data adopted from PIMR [33] was used. The energy needed for the construction was estimated based on the energy intensity (per unit of mass) of the standard agricultural machinery module included in Ecoinvent (Table 2).

Table 2. Material and energy balance of the baler used in the considered scenarios.

Parameter	Unit	Value	Standard Process
Steel	kg	1930	Steel plate (World Steel, GaBi)
Plastics	kg	4.6	Polyvinylchloride pipe (PVC) (PlasticsEurope, GaBi)
Rubber	kg	22.9	Styrene-Butadiene Rubber (SBR) Mix (GaBi)
Hydraulic oil	kg	1.3	Lubricants at refinery (GaBi)
Paint	$kg \cdot kg^{-1}$	0.007	Alkyd paint, 60% in solvent, at plant (GaBi)
Electricity	$MJ \cdot kg^{-1}$	7.02	Electricity, low voltage, at grid, country specific (Ecoinvent)
Heat from coal	$MJ \cdot kg^{-1}$	0.7	Hard coal, burned in industrial furnace 1–10 MW (Ecoinvent)
Heat from gas	$MJ \cdot kg^{-1}$	4.1	Natural gas, burned in industrial furnace >100 kW (Ecoinvent)
Heat from oil	$MJ \cdot kg^{-1}$	7.9	Light fuel oil, burned in boiler 100 kW, non-modulating (Ecoinvent)

The loading of the bales for transport was modelled by means of a standard Ecoinvent module for straw bale loading (diesel consumption adjusted to 0.081 $kg \cdot bale^{-1}$).

For the transport, a standard tractor with trailer transportation processes from Ecoinvent was used, with a fuel consumption of 0.044 kg·tkm^{-1}. Fully loaded trucks were assumed, including empty return transports. Transport distance to the final user was set at 6 km. The transport modules included the emissions caused by the diesel combustion in the truck engine. The data related to the production of diesel based on country specific production processes (included in GaBi software).

As pruned bales (wooden solid fuel) were locally used for heat production, a small scale combustion unit was taken from Ecoinvent (boiler capacity 50 kW). The fuel input consisted of the pruning residues (dry basis). The average yearly combustion efficiency of 75% of the boiler was applied (including starts and stops). The emissions were adjusted accordingly, relative to the change of lower heating value (LHV). It was assumed that generated ashes during the combustion process were recycled by applying them to agricultural soil.

The mulching process was considered by using an Ecoinvent standard mulching process with a diesel consumption of 3.5 kg·ha^{-1}. The process standard fuel consumption was adjusted by the actual observed values for apple pruning residue mulching: 4.6 kg·ha^{-1} [22]. The combustion emissions were adjusted accordingly, relative to the change in fuel consumption. As a supplement to the missing heat in the PtS scenario, the combustion of bituminous coal (fossil fuel) was assumed.

Pruning residues that are leftover and mulched in the orchard cause the introduction into the soil of the nutrients and heavy metals contained in them. The additional artificial fertilizers entail, apart from the environmental effects of their production, similar soil effects. According to the Intergovernmental Panel on Climate Change (IPCC) and the Roundtable on Sustainable Biomaterials (RBS) GHG methodology, the emission factors for the nutrient caused soil emissions are different for nutrients contained in pruning residues and in artificial fertilizers only for ammonia, and consequently for nitrous oxide and nitrogen oxides (as they depend on the amount of emitted ammonia) [34,35].

Apart from the effects of pruning residues and fertilizers, the ashes remaining after the combustion process are also used as a fertilizing agent on agricultural fields, thus having an impact on the soil. Therefore, in total, there are four occasions of introduction of nutrients and heavy metals to the soil:

- Leftover mulched pruning residues within the PtS chain;
- Pruning residue harvesting losses within the PtE chain;
- Additional fertilizing within the PtE chain;
- Field application of the ashes of the combustion of pruning residues in the PtE chain.

The approach of the organic matter application to soil in this study was applied in accordance to previous studies [36,37]. This leads to the following soil effects for the prunings remaining in the field (in the PtS chain, as well as the losses in the PtE chain):

- Carbon sequestration (additional amount of stable organic carbon in the soil)—3% of the organic carbon contained in the pruning residues remains in the soil after a period of 100 years. In the case of already high values of soil organic carbon, the level of sequestration will be lower (in the current scenario, however, the level of 3% is applied);
- For N and K, a 1:1 substitution is assumed. For every kg of nutrients leaving the orchard, one kg of artificial fertilizer is produced and applied. For P an MFE (mineral fertilizer equivalent) of 50% is assumed. For every kg of P leaving the system with the pruning residues, 0.5 kg has to be applied in the form of artificial fertilizers. The applied fertilizers assumed are urea for N, raw phosphate (32% P_2O_5) for P, and potassium chloride (60% K_2O) for K. Application of urea leads to ammonia emissions (emission factor of 15%);
- In total, 80% of P and K and no amount of N is assumed to stay within the bottom ash of the boiler, and thus return to the field;
- Heavy metal contents of both the artificial fertilizers and the pruning residues cause emissions of heavy metals to the soil,

- Nitrogen contents of both the artificial fertilizers and the pruning residues cause emissions of ammonia, and consequently for nitrous oxide and nitrogen oxides (as they also depend on the amount of emitted ammonia).

2.5. Soil Management Issues in the Apple Orchard

The investigated apple orchard is characterized by flat terrain. The field is covered by grass (>80% interrows between trees) and along the apple trees rows there is an irrigation system. The major factors related to sustainable soil management are storage capacity for water and nutrients (provided by a good soil structure and high levels of humic substance in the top soil), GHG outputs to the atmosphere, erosion, fertility, and cultivation strategy. In this orchard a significant amount of cut branches is harvested and used for energy purposes, which can influence the soil properties. Results obtained by Morlat and Chaussod [38] revealed that soil with annual input of 2 $t \cdot ha^{-1}$ (fresh mass) of vineyard prunings for 28 years had 19% higher TOC content than the soil where the pruning was removed. Thus, the wood residue removal can affect the soil degradation. However, in typical apple orchards in Poland there are many other sources of nutrients and mineral supply, such as the branches from tree pruning in the summer (so-called lighting trimming), spoiled fruit that cannot be harvested, mowed grass, and leaves. Moreover, there are also cut branches coming from regular tree pruning in the winter-spring season that are left after the pruning harvesting process (in the corresponding amount of harvesting losses).

Considering the requirements for a sustainable soil management as formulated by the Europruning project [28], the studied Polish apple orchard allows for a removal of the pruned branches. The area between the trees (interrows) is covered over 80% with grass vegetation. This assures a sufficient input of organic carbon. In comparison with other agricultural production in the region, the removal of organic carbon is relatively low anyway. For the considered orchard, 312 $kgC \cdot ha^{-1} \cdot year^{-1}$ (690 kgDM pruned material multiplied by 0.455 $kgC \cdot kg^{-1}$ pruned material) compared to removal with wheat straw in agriculture (over 1200 $kgC \cdot ha^{-1} \cdot year^{-1}$ for Poland [28]), for example. Therefore, it can be assumed that the removal of those branches will not significantly influence reduction of organic carbon. The field studies performed within the Europruning project (olives, almonds, apricots in Spain, vineyards in France, apples in Brandenburg, Germany) [39] did not indicate substantial changes in carbon balance. Considering the potential impact on erosion, it should be underlined that apple orchards are provided by permanent vegetation cover (grass), which increases infiltration and avoids surface runoff. Erosion control is an important factor for sustainability on the semi-arid sloping areas (i.e., in Spain), and especially, in drier regions (e.g., Mediterranean climates). Overall, the energetic use of prunings was found to be in opposition to sustainable soil management and long term soil fertility at all demo sites [39]. Local factors, such as erosion control or alternative C input by other plant materials, must be taken into consideration to counteract potential problems [28].

In the case of the considered apple orchard in Poland, the abovementioned aspects do not cause a barrier for the use of pruning residues for energy purposes.

3. Results

The presented case study concerns a local Pruning-to-Energy scheme for apple pruning residues. This short transport distance is not only low cost, but also limits the impact on the environment.

3.1. Climate Change Potential

In Figure 2 the comparison of the Climate Change potential impact for PtE and PtS scenarios is shown. The cumulative CO_2 emission for PtE scenario was 171 kg CO_2 $eq. \cdot ha^{-1}$ (15 kg CO_2 $eq. \cdot GJ^{-1}$), whereas PtS scenario was characterized by cumulative CO_2 emission of 1720 kg CO_2 $eq. \cdot ha^{-1}$. Using the harvested pruning residues for energy purposes thus enables significant reduction of CO_2 emission. In the case of the studied apple orchard, a saving potential of 1540 kg CO_2 $eq. \cdot ha^{-1}$ or 135 kg CO_2 $eq. \cdot MJ^{-1}$ of the produced heat was achieved.

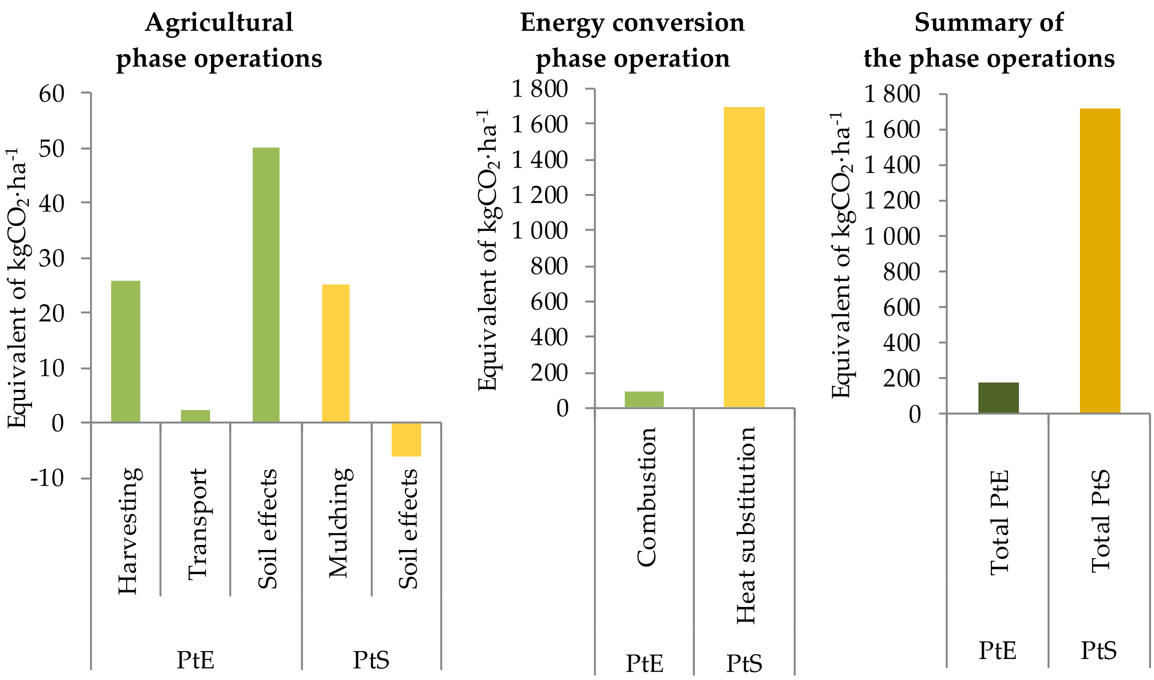

Figure 2. The Climate Change potential (excl. biogenic carbon) of pruning residues in a Polish apple orchard (theoretical pruning potential 1.39 tFM·ha^{-1}).

The Climate Change potential of the harvesting stage in the PtE scenario is similar to the mulching stage in the PtS scenario. Those values amounted to 26.0 and 25.1 kg CO_2 eq.·ha^{-1}, respectively. In the PtE scenario, the soil effects are caused by the application of additional fertilizers and the production thereof: 50.2 kg CO_2 eq.·ha^{-1}. Here, also the pruning residue combustion ashes returning to the field are included.

In the PtS scenario, the pruning residues remaining on the field gave a positive environmental result of −5.9 kg CO_2 eq.·ha^{-1}. However, in that scenario, the largest share in Climate Change potential had a process of heat substitution that was estimated at 1690 kg CO_2 eq.·ha^{-1}. In the case of PtE scenario, the combustion process of pruning residues amounted to 92 kg CO_2 eq.·ha^{-1} only.

3.2. Other Environmental Impacts

In Figure 3, the effects in the selected ILCD impact categories are presented for the PtE chain and the PtS chain. To provide a possibility for comparison, the results are expressed in inhabitant equivalents (IE) related to EU-27 for the year 2010.

For the impact categories of Photochemical Ozone Formation, Particulate matter/Respiratory inorganics, Ecotoxicity Freshwater, Acidification, and Climate Change, the impact of the use of pruning residues from one ha of apple orchard on the environment is clearly lower for the scenario where the residues are used for energy production (PtE). For example, in the case of PtS, the IE index for the Photochemical Ozone Formation category amounted to 0.25·ha^{-1}, where for PtE that value was 0.11·ha^{-1}. In the Particulate matter/Respiratory inorganics category, the IE index for PtS and PtE was determined as 0.32·ha^{-1} and 0.07·ha^{-1}, respectively. The highest value for PtS scenario was obtained for the Ecotoxicity Freshwater category, in which the IE index reached 0.66·ha^{-1}. For the same category, the IE index for the PtE scenario was more than ten times smaller (IE = 0.05·ha^{-1}). It should be noted that in the case of the PtS variant, the dominant share in the IE index values is the heat substitution (heat generation during coal combustion). In relation to the PtE scenario, the combustion process was also crucial, but it was not always the most important one. For instance, considering the Acidification category, the Ecotoxicity Freshwater category, or the Eutrophication Terrestrial category, the soil effects played the main role.

Only for the Eutrophication Terrestrial category it is better to apply the mulching procedure for pruning residues and to leave them in the orchard (PtS scenario). The calculated value for the PtE scenario was IE = 0.15·ha^{-1} and for the PtS scenario IE = 0.05·ha^{-1}.

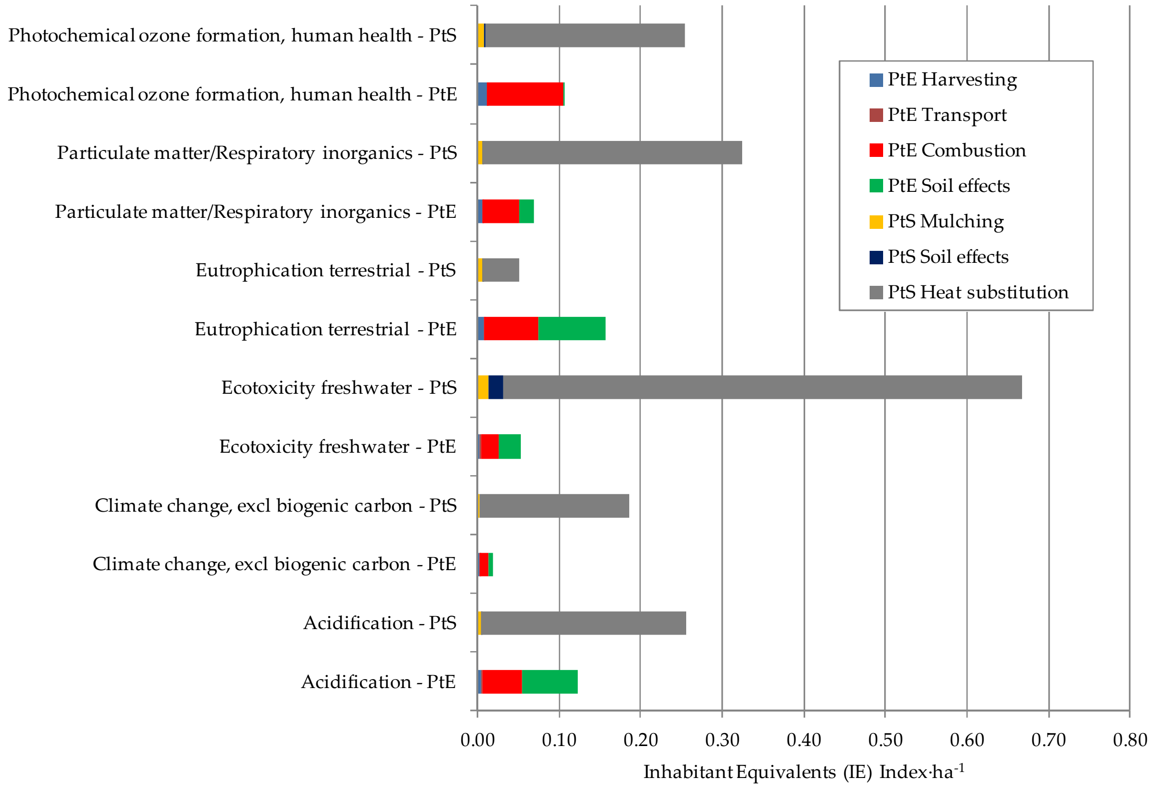

Figure 3. Environmental impacts of pruning residues in a Polish apple orchard (theoretical pruning potential 1.39 tFM·ha^{-1}). Detailed values are in supplementary materials.

4. Discussion

In terms of the Climate Change Potential (excluding biogenic carbon), the impact of the PtE is approximately 10 times smaller than the PtS scenario. The main reason for that is a significant difference between the equivalent of CO_2 emission related to the heat production process. For the PtE and PtS scenarios (Figure 2), the CO_2 equivalents are 92.0 kg·ha^{-1} and 1690 kg·ha^{-1}, accordingly. Thanks to the biomass combustion (cut branches in this study) in the boiler, no direct, additional carbon dioxides are emitted to the atmosphere, as this CO_2 is considered biogenic, and therefore climate neutral. On the other hand, in the case of the PtS, the applied heat substitution coming from coal combustion leads to substantial direct CO_2 release. For comparison, the indicators of CO_2 emission from combustion of other fuels are shown in Table 3. Considering only a direct CO_2 emission factor coming from combustion of a relatively clean fossil fuel, such as natural gas, in the amount of 56.10 kg CO_2·GJ^{-1} and assuming that 11.4 GJ of energy is accumulated in the pruning residues harvested from one hectare, the cumulative CO_2 emission will be 639 kg·ha^{-1}. This value is almost four times higher than total CO_2 emission for the PtE scenario, which amounted to 171 kg CO_2 eq.·ha^{-1}. It means that the PtE value chain is a very good alternative to traditional heating systems. Moreover, the transition from bituminous coal to natural gas allows a saving of about 41% of CO_2 emissions (calculations of data from Table 3). In the case of a change to biomass fuel (emission is approximately 15 kg CO_2·GJ^{-1}), the reduction is higher and reaches almost 85%. It is a very important result, as in Poland the main fuel for household heating is coal [31].

Table 3. Indicators of CO_2 emission from combustion of various fuels [40].

Source of Heat	CO_2 Emission, kg $CO_2 \cdot GJ^{-1}$	Source of Heat	CO_2 Emission, kg $CO_2 \cdot GJ^{-1}$
CHP (bituminous coal)	95.48	Natural gas	56.10
CHP (Lignite)	110.76	Petrol	69.30
HP (bituminous coal)	94.90	LPG	63.10
HP (lignite)	106.31	Heavy oil	77.40
Crude oil	73.30	Light oil	74.10

CHP—Combined Heat and Power, HP—Heat Plant.

Considering the direct sustainable aspects in agriculture (regardless of the thermal conversion process of biomass in the heating boiler), the results present a different picture. In relation to the processes performed within the apple orchard itself, the CO_2 emissions are similar to the harvesting process, and in the mulching process a comparable amount of diesel is consumed. The overall large disproportions prove that low fuel consumption combined with an efficient harvesting of pruned branches in the apple orchard results in obtaining not only a favorable energy balance [32], but also environmental benefits, like low CO_2 footprint.

Increased CO_2 emission on the PtE side should occur at the stage of biomass transport to the end user. However, the transport of the collected bales has a negligible effect (CO_2 equivalent is only 2.45 kg$\cdot$ha^{-1}) because of the limited transport distance of 6 km in the local energy supply scenario. Delivand et al. [41] reported even lower CO_2 emissions for the transport of prunings, as their more efficient vehicles were used (a truck instead of a tractor).

The consequence of branch combustion for energy purposes (PtE scenario) may be the need to use additional fertilizers to cover the deficiency of nutrients in the soil or some additional actions to protect the field against the erosion process. By taking the branches out of the orchard, N, P, and K are lost. Despite the occurrence of some losses in the branch collection and leaving them in the orchard, the production, spreading, and related soil effects of the additional fertilizers are related to an additional emission at the level of 50.2 kg CO_2 eq.$\cdot$ha^{-1}, whereas the erosion risk may occur mainly only in drier regions (e.g., Mediterranean climates) or in stony fields. If the orchards are covered by grass (as in the examined apple orchard) or other plants, the pruning removal does not significantly influence organic balance [28]. The research performed by Germer et al. [42] also indicated that the period of five month input rates of pruned biomass from cherry trees didn't affect soil chemistry.

In contrast, in the PtS scenario the pruning residues remain on the field, thus introducing both nutrients, organic carbon, and a limited amount of contained heavy metals to the soil. The introduction of nitrogen to the soil, in particular, causes emissions that are related to the Climate Change potential (ammonia, and consequently, for nitrous oxide and nitrogen oxides), which are similar to the PtE scenario. In the PtS scenario, more organic carbon remains in the orchard, causing a minor but significant sequestration effect by the long term stability of a share of the introduced carbon. That causes the environmentally benign effect of the soil effects stage within the PtS scenario. As a result, in the PtS scenario the value of CO_2 equivalent is -5.93 kg $CO_2 \cdot$ha^{-1}. As far as bioenergy production is concerned, however, the positive effect of leaving the pruned material in orchards or the negative effect of taking it out has been demonstrated by Nieto et al. [43,44] and Morlat et al. [38]. The applied methodology is explained by Den Boer et al. [36] and Den Boer and Den Boer [37]. Although the PtE involves an almost ten times higher release of CO_2 equivalent to the atmosphere in terms of soil effect, the value determined for PtS is not able to compensate the CO_2 emission from coal combustion. Thus, the overall PtE scenario shows significantly lower Climate Change potential than the PtS scenario. The low contribution of the soil processes to the overall effects when compared to the substituted fossil fuel combustion is also reported by Ruiz et al. [45], Boschiero et al. [25], and Cowie et al. [46].

The combustion of pruning residues in the PtE scenario causes minor Climate Change effects because of the use of electric energy and the emission of traces of non-CO_2 combustion gases causing global warming effects. The avoided production of heat from renewables by local coal combustion within the PtS scenario is the main contributor to the overall Climate Change potential because of the emission of fossil CO_2.

The impact category Photochemical Ozone Formation in the PtE scenario is dominated by the emission of NO_x through pruning residue combustion (IE = $9.36 \times 10^{-2} \cdot ha^{-1}$) and to a lesser extent by the harvesting machinery (IE = $1.12 \times 10^{-2} \cdot ha^{-1}$). Ethylene, SO_2, CO, and NO_x emissions through the combustion of hard coal (IE = $2.45 \times 10^{-1} \cdot ha^{-1}$) are the main causes within the PtS scenario.

Particulate matter/Respiratory inorganics is caused mainly by fine dust (PM2,5) emissions in heat production processes, both in the PtE and PtS scenario. Such a remarkable difference between these scenarios in this category (IE = $4.39 \times 10^{-2} \cdot ha^{-1}$ for PtE and IE = $3.18 \times 10^{-1} \cdot ha^{-1}$ for PtS) is assigned to combustion process and fuel properties. In the PtS scenario, the emission of SO_2 from coal combustion has a significant impact (the pruned biomass is free of sulphur). Additionally, higher amount of ash content in the bituminous coal (approximately 20%) is associated with the final result as well. Because of a low content of ash in the branches (0.8% only) and despite the combustion of a larger amount of biomass in the PtE (lower LHV for biomass), the amount of fly ash generated and emitted to the atmosphere is still much lower compared to the PtS. For the PtE, the emission of ammonia caused by artificial fertilizer application is a minor contributor.

The total Eutrophication Terrestrial (IE= $1.57 \times 10^{-1} \cdot ha^{-1}$) potential is mainly caused by ammonia emission (IE = $8.19 \times 10^{-2} \cdot ha^{-1}$) from artificial fertilizer application and NOx emission (IE = 6.67 $\times 10^{-2} \cdot ha^{-1}$) from the combustion of the harvested bales in the PtE scenario. The PtS scenario impact is dominated by the emission of NOx emissions during the substituted hard coal combustion (IE = $4.44 \times 10^{-2} \cdot ha^{-1}$).

Our results show that the energy production using agricultural wood residues (AWRs) generally presents better environmental indicators than the reference systems, although some trade-offs exist. For instance, whereas the bioenergy system saves up to about 85% of greenhouse gas (GHG) emissions and about 95% of non-renewable resources, it is usually associated with higher toxicity impact potentials [25].

The main causes for problems with the Ecotoxicity Freshwater are the emission of zinc and copper by the application of pruning residue combustion ashes (IE = $2.61 \times 10^{-2} \cdot ha^{-1}$), as well as zinc emission from pruning residue combustion within the PtE scenario (IE = $2.15 \times 10^{-2} \cdot ha^{-1}$). The larger impact in the PtS scenario is dominated by chromium (VI), vanadium, copper, nickel, and zinc emission from the combustion of hard coal (IE = $6.35 \times 10^{-1} \cdot ha^{-1}$). To a minor extent, the copper and zinc contained in the pruning residues that are left in the orchard contribute here (IE = $1.82 \times 10^{-2} \cdot ha^{-1}$). Another minor contributor is the heavy metal emission related to the production of machinery (IE = $1.38 \times 10^{-2} \cdot ha^{-1}$).

Acidification is caused by a limited number of substances. For the PtE scenario, the main contributors are ammonia emission resulting from the additional application of artificial fertilizers (IE = $6.83 \times 10^{-2} \cdot ha^{-1}$) and NO_x emission from the combustion of the apple twigs (IE = $4.93 \times 10^{-2} \cdot ha^{-1}$). In the PtS, the impact is dominated mainly by SO_2 and to a lesser extent by NO_x emission from the coal combustion for heat production (IE = $2.52 \times 10^{-1} \cdot ha^{-1}$).

As in practice, two significant parameters (distance to the final user and boiler capacity) can affect the environmental consequences for the PtE scenario. Their sensitivity was determined towards the following changes:

- An increase in the transport distance of the collected bales from 6 km to 60 km and 600 km;
- An increase in boiler capacity from a domestic 50 kW stove fired by hard coal briquettes to an industrial 1–10 MW boiler.

4.1. Sensitivity Analysis—Higher Transport Distance

In Figure 4, the effects in the selected ILCD impact categories are provided for three scenarios: 6 km (reference value in this study), 60 km, and 600 km.

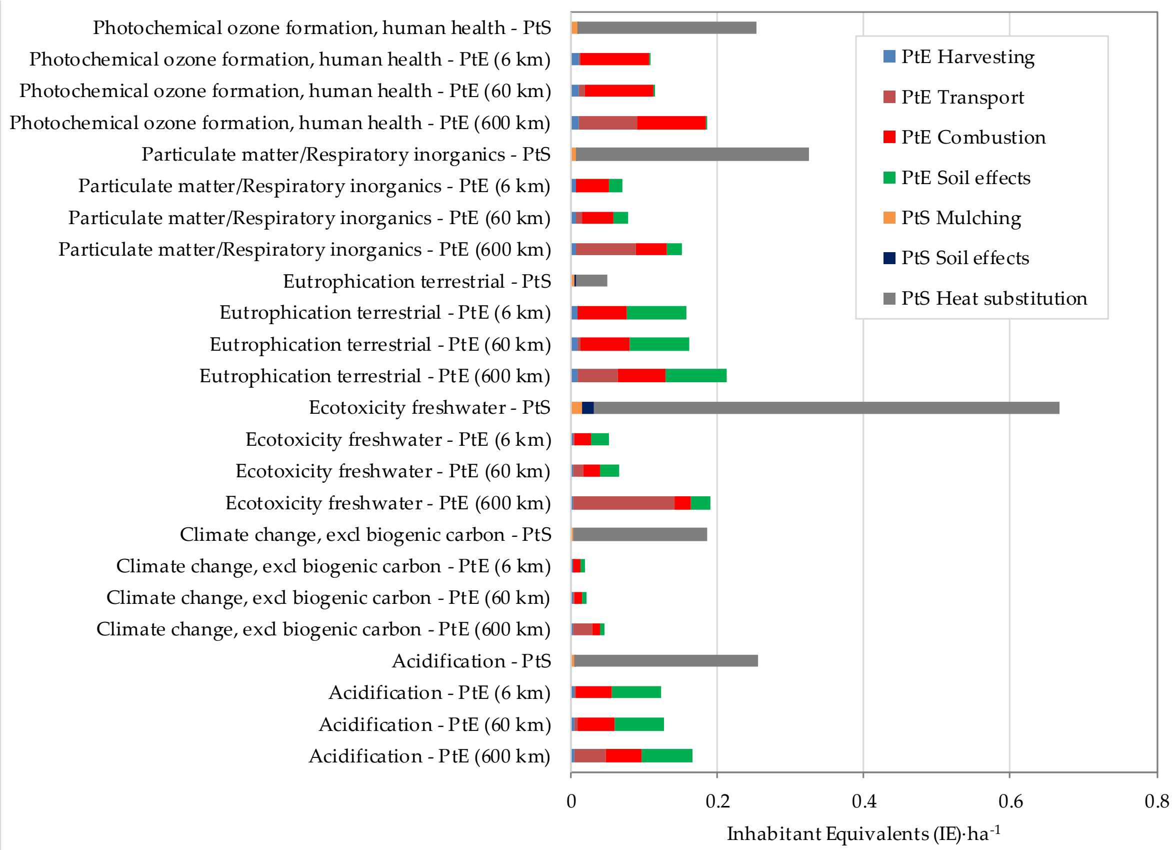

Figure 4. Influence of transport distance on environmental aspects of energetic use of pruning residues (theoretical pruning potential 1.39 tFM·ha^{-1}). Detailed values are in supplementary materials.

The results showed that the increase of the bale transport distance to 60 km does not lead to a significant change in the obtained values. Although the impact of the transport is more significant, especially in the Particulate matter/Respiratory inorganics and Ecotoxicity Freshwater categories, the other stages still cause the dominating environmental impacts. Assuming an increase in the transport distance from 6 to 60 km, from an environmental point of view, it is better to use apple pruning residues energetically than leave them in the orchard. It also proves that the transportation of the biomass on a local level is acceptable.

However, in the case of an increase in the transport distance to 600 km, the results are not so clear. First of all, in such categories as Particulate matter/Respiratory and Ecotoxicity Freshwater, the emissions related to transport start to be dominant within the PtE chain. Moreover, the Eutrophication Terrestrial factor for the PtE achieved a value four times higher than for the PtS. At the same time, the equivalents for the Photochemical Ozone Formation and Acidification in the PtE got much closer to the values for the PtS. However, the cumulative Ecotoxicity Freshwater and Climate Change Potential factors for the PtS are still much higher in comparison to the PtE. It seems that although the PtE scenario is still more appropriate, longer distances for the pruned biomass transportation should be avoided.

4.2. Sensitivity Analysis—Larger Coal Combustion Unit

In Figure 5, the consequences of the selected ILCD impact categories are provided for both scenarios using the 1–10 MW industrial coal combustion unit for heat production, which is larger and equipped with better flue gas cleaning technology.

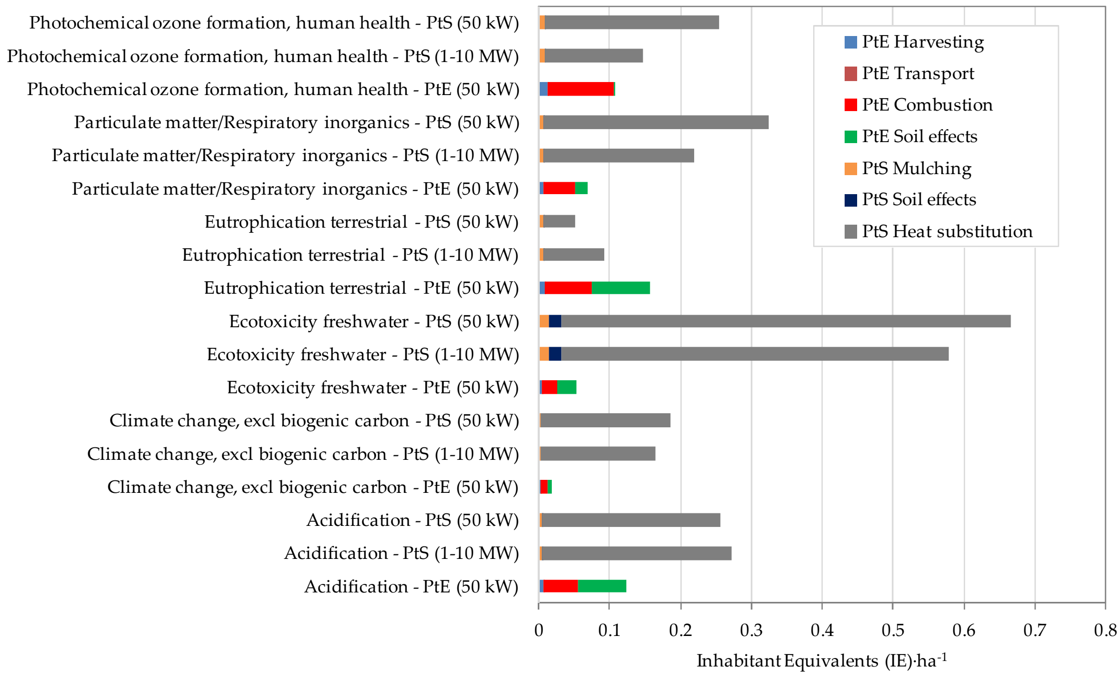

Figure 5. Influence of boiler capacity on environmental aspects of energetic use of pruning residues (theoretical pruning potential 1.39 tFM·ha^{-1}). Detailed values are in supplementary materials.

It is observed that the application of a larger coal combustion unit does not lead to an overall change in the impact. Although the differences between those two scenarios are smaller, still it can be generally stated that with the exception of the Eutrophication Terrestrial impact category, the energetic use of pruning residues (PtE) leads to an environmental gain compared to leaving the pruning residues in the orchard (PtS).

5. Conclusions

The LCA depicted in this study showed that the use of pruning residues from apple orchards for energy purposes (the production of heat) instead of leaving them in the orchards leads to a significant reduction in the Global Warming Potential. Thus, the bioenergy chain can generate significant GHG savings compared to the systems based on fossil fuels. Other impact categories investigated within the LCA analysis were also more beneficial for the PtE scenario. Only the Eutrophication Terrestrial factor shows an adverse picture. This could partly be improved by considering a larger furnace than the 50 kW considered in this study, but this seems to be possible only in locations with centralized heating systems. The environmental assessment also revealed that the impact of harvesting, storage, and transport of apple pruning residues is small compared to their combustion process. However, in order to maintain a proper balance, a transportation distance should be limited to several dozen kilometers only, which is crucial in terms of the sustainable and efficient development of rural areas.

From a practical and commercial point of view, the results provide useful data supporting the decision making in terms of pruning residue management, as next to the economic and social aspects the environmental consequences also become a crucial argument in use of such biomass for energy purposes. Therefore, as a sustainable criteria of the bioenergy market are a key issue, the policymakers should take it into account as well.

Further studies should be focused on comparison of the PtE strategy with logistic chains of other energy sources used locally for small and middle size heating systems. Other aspects are the limitation of fertilizer use to lower their negative impact on the environment, as well as on improvement of the combustion efficiency and flue gas cleaning technologies of small capacity boilers fired by pruning residues. From a sustainable development point of view, however, although environmental indicators related to the thermal process of branch combustion (heat production) and processes taking place in the orchard during their acquisition can be summed up, they should be considered separately (individually).

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/6/1604/s1, Detailed values for Figures 3–5.

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Abbreviations

ARs	agricultural residues
AWRs	agricultural wood residues
DM	dry mass
FM	fresh mass
GHG	greenhouse gas
IE	inhabitant equivalent
ILCD	international life cycle data
IPCC	intergovernmental panel on climate change
LCA	life cycle assessment
LHV	lower heating value
PRs	pruning residues
PtE	pruning to energy
PtS	pruning to soil
RBS	Roundtable on sustainable biomaterials
RES	renewable energy source

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