energies

MDPI

Article

Life-Cycle Assessment of the Use of Peach Pruning Residues for Electricity Generation

Jan Den Boer [1], Arkadiusz Dyjakon [1,*], Emilia Den Boer [2], Daniel García-Galindo [3,4], Techane Bosona [5] and Girma Gebresenbet [5]

1 Institute of Agricultural Engineering, Wrocław University of Environmental and Life Sciences, 51-630 Wroclaw, Poland; jan.denboer@upwr.edu.pl
2 Faculty of Environmental Engineering, Wroclaw University of Science and Technology, 50-370 Wroclaw, Poland; emilia.denboer@pwr.edu.pl
3 Avebiom–Spanish Biomass Association, 47004 Valladolid, Spain; danielgarcia@aviebom.org
4 Spain and Research Centre for Energy Resources and Consumption (CIRCE), 50018 Zaragoza, Spain
5 Department of Energy and Technology, Swedish University of Agricultural Sciences, 75232 Uppsala, Sweden; techane.bosona@slu.se (T.B.); girma.gebresenbet@slu.se (G.G.)
* Correspondence: arkadiusz.dyjakon@upwr.edu.pl; Tel.: +48-71-320-5945

Received: 26 April 2020; Accepted: 27 May 2020; Published: 29 May 2020

Abstract: Biomass residues from permanent crops might be an alternative fuel for energy generation in a local market with limited transport distances. Moreover, as activities related to CO_2 reduction are of special attention in the European Union (EU), sustainable use of resources plays an important role in climate change mitigation. In this paper, a life-cycle assessment (LCA) of the integrated value chain from peach pruning residues for electricity generation is presented and compared with the common practice including the mulching process of the pruned biomass in an orchard. It was shown that biomass harvesting, chipping and its delivery to a power plant—the Pruning-to-Energy (PtE) scenario—is feasible from an environmental point of view. The total global warming potential (GWP) of this value chain was 200 kg CO_2 eq.$\cdot$ha^{-1} (or 27 kg CO_2 eq.$\cdot$GJ^{-1}). In turn, the mulching and leaving of the pruned biomass in an orchard—the pruning-to-soil (PtS) scenario—is characterized by a CO_2 equivalent of 2360 kg$\cdot$ha^{-1}. Other impact categories showed a lower environmental impact for the PtE scenario as well. When considering the Spanish electricity-mix instead of coal-based electricity, the PtS scenario score better in most impact categories, but the GWP for the PtE scenario remains lower.

Keywords: peach pruning residues; electricity production; life cycle assessment; LCA; biomass-to-energy

1. Introduction

The European Biomass Action Plan (BAP) formulated by the European Commission in 2005 presented a clear vision of the energetic utilization of biomass from forestry, agriculture, and waste materials until 2020 [1]. It is expected that beyond 2020, the biomass will still play a major role in the energy sector of the European Union (EU) reaching a share of 50% of overall renewable energy production by 2030 [2]. Moreover, the ambitious scenarios of the carbon-neutral EU assume the achievement of greenhouse gas (GHG) emissions reductions between 80% and 100% by 2050, compared to 1990 [3]. Therefore, the increase of biomass residues usage in energy production is one of the main means to mitigate climate change [2]. It is important to ensure that the biomass is used locally, in other words to minimize activities related to long-distance transportation (increased environmental impacts) and long-term storage (risk of biomass losses). Moreover, the local use of biomass is in line with the sustainable development of agriculture and rural areas [4–7], although many aspects must be considered with due care. These aspects may be the harvesting yield of biomass waste and its dispersion, the method of the harvesting process and transportation management, the distance between the place of acquisition and their utilization, the utilization method, as well as the impact of the removed biomass share on the yield of food products [8,9].

In Europe (EU27 + Switzerland) the cumulative theoretical potential of residual biomass (sources: agriculture, forestry, urban greenery management, and food waste) accounted as a key feedstock for the European bioeconomy, amounts to 8500 PJ·yr^{-1} [10].

The solid biomass stream suitable for thermal conversion encompasses inter alia prunings from permanent crops (orchards, plantations) [11,12]. Depending on the region, the pruning biomass may originate from different crops (olives, vineyards, apples, cherries, peaches, etc.). Moreover, the permanent crops are characterized by different harvesting potential of the pruning (wooden residues) obtained during regular trees cutting (Figure 1).

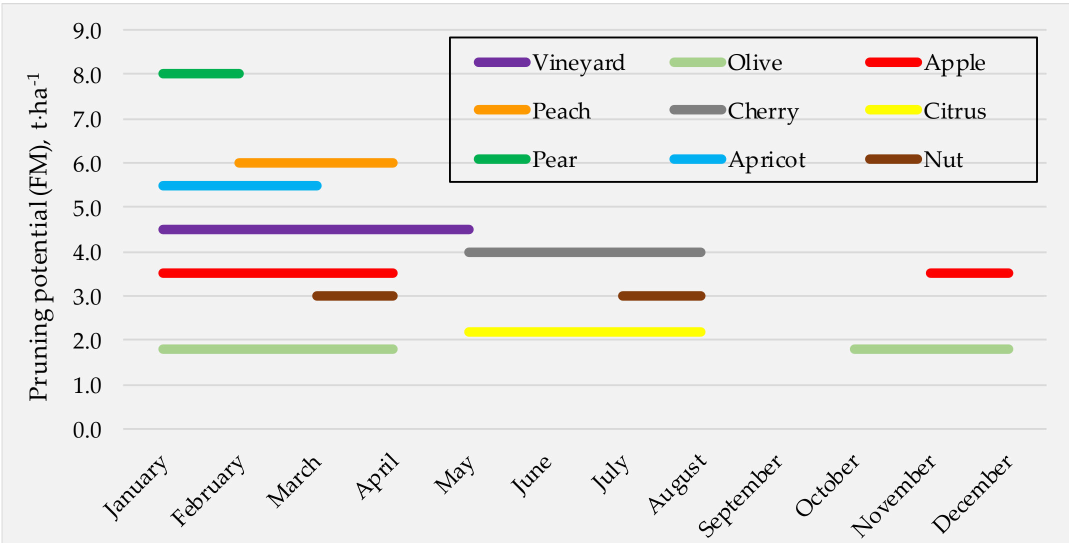


Figure 1. Average pruning potential from different permanent crops [13].

The theoretical potential of pruning from permanent crops in Europe is 252.0 PJ·yr^{-1} [14]. Although peach orchards are not the dominant ones (their total area in the world is ca. 1,712,000 ha, and in Europe ca. 210,000 ha [15]), the raw prunings generated during their regular cutting (2.7 t·ha^{-1}·yr^{-1} [16–19]) can locally play an important role in heat/electricity production. However, thermal utilization of peach prunings requires many activities, such as harvesting, conversion, and transportation to the final user, resulting in costs and pollutants emission as well as energy use. Therefore, economic, environmental, and energy-related issues should be considered to determine their influence on the whole logistic chain [20,21]. In terms of environmental aspects, the life-cycle assessment (LCA) is a very popular method of process evaluation in the agriculture sector [22–28] as well as in the energy sector. For instance, applying LCA analysis, Carvalho et al. [7] showed that the electricity generation using urban pruning waste from the municipality resulted in a much lower carbon footprint than their disposal at landfill site (without methane management) or incineration for heat generation. Perilhon et al. [29] performed LCA analysis comparing the electricity generation from biomass in 2 MW and 10 MW boilers, using an organic Rankine cycle (ORC) plant and steam plant, respectively. The research revealed that the overall efficiency of the system and the applied technology have a significant impact on the environmental consequences. Beagle and Belmont [30] discussed the advantage of wood chips and pellets utilization for electricity production in relation to hard coal. It was underlined that the transportation type and distance play an important role in the final results of the LCA analysis.

In the literature, not too much data has been found related to a full-scale LCA analysis of a complete logistic chain of pruning residues from peach orchards for energy purposes. This study aims to assess the environmental impacts of the utilization of pruning residues from peach orchards for energy purposes (electricity). This scenario is assessed against the reference procedure of pruning management, consisting of the mulching process and leaving the material in the field. Therefore, the main issues of the study are: (i) to determine and collect site-specific data related to the field operations for the life-cycle inventory analysis; (ii) to identify the GHG emissions and other environmental consequences resulted from thermal conversion of peach pruning (Pruning-to-Energy scenario, PtE) and leaving the shredded pruning in the field (pruning-to-soil scenario, PtS); and (iii) to compare this two value chains (scenarios) in terms of the environmental aspects.

2. Materials and Methods

2.1. Goal and Scope

The option of using the peach prunings for energy purposes assumes that the removal of pruned biomass from an orchard does not have a negative impact on soil stability and fertility. According to the Europruning report [31], the favorable approval conditions for biomass pruning removal occur when the vegetation cover in the orchard exceeds 20% of the surface area (or more than 3 $t \cdot ha^{-1}$ per year of dry biomass can be established as a vegetation cover), and the carbon content and the potential of additional organic compounds are sufficient (i.e., leaves after pruning or branches remaining after harvesting). Moreover, the soil is in good condition, without the tendency to silting, compaction, erosion, or surface runoff.

The presented LCA was performed following the ISO 14040:2006 methodology [32] using the references of the International Life-Cycle Data (ILCD) system method [33]. Thus, the classification and characterization of the life-cycle inventory was undertaken according to the ILCD 2011 Midpoint methodology (v1.09).

The number of impact categories was limited to six parameters. The basis for the limitation was in the first place the overall impacts (normalized) in each of the considered scenarios and in the second place the level of differences between the scenarios. The choice of impact categories follows the Europruning project, in which several types of Pruning Residues were studied [34]. Out of the available impact categories, Climate Change, Photochemical Ozone Formation, Particulate matter/Respiratory, Ecotoxicity Freshwater, and Eutrophication Terrestrial were selected. To normalize the results, the methodology provided by the Joint Research Centre (JRC) was followed [35]. No weighting of the results was undertaken. Finally, the GaBi software professional 9.2 (Sphera^{tm}, Leinfelden-Echterdingen, Germany) tool was used in the LCA analysis.

In the utilization of the pruning residues two scenarios were considered (Figure 2): the use of pruning residues for energy purposes (PtE scenario) and the use of mulched pruning residues as a source of organic matter for the soil (PtS scenario). The latter is the standard and a very common way of managing pruning residues in orchards. In both scenarios, all steps related to these residue treatment options were taken into account in the analysis. In both cases, before the pruning harvesting (or mulching), the cut branches were collected in the middle of the passing lane to increase the efficiency of these activities.

In the PtE scenario, chipping technology was applied. The harvesting losses of the peach pruning residues (PPR) remain in the orchard. The produced wood chips are stored at a central storage site and after storage transported to a final consumer. Next, the final consumer burns the wood chips in a thermal boiler to generate electricity. The biomass and the electricity are produced locally, as the distance between the orchards and power plant does not exceed 50 km. In the PtS scenario, the biomass mulcher application was considered. Both sets of machinery were towed and powered by a tractor.

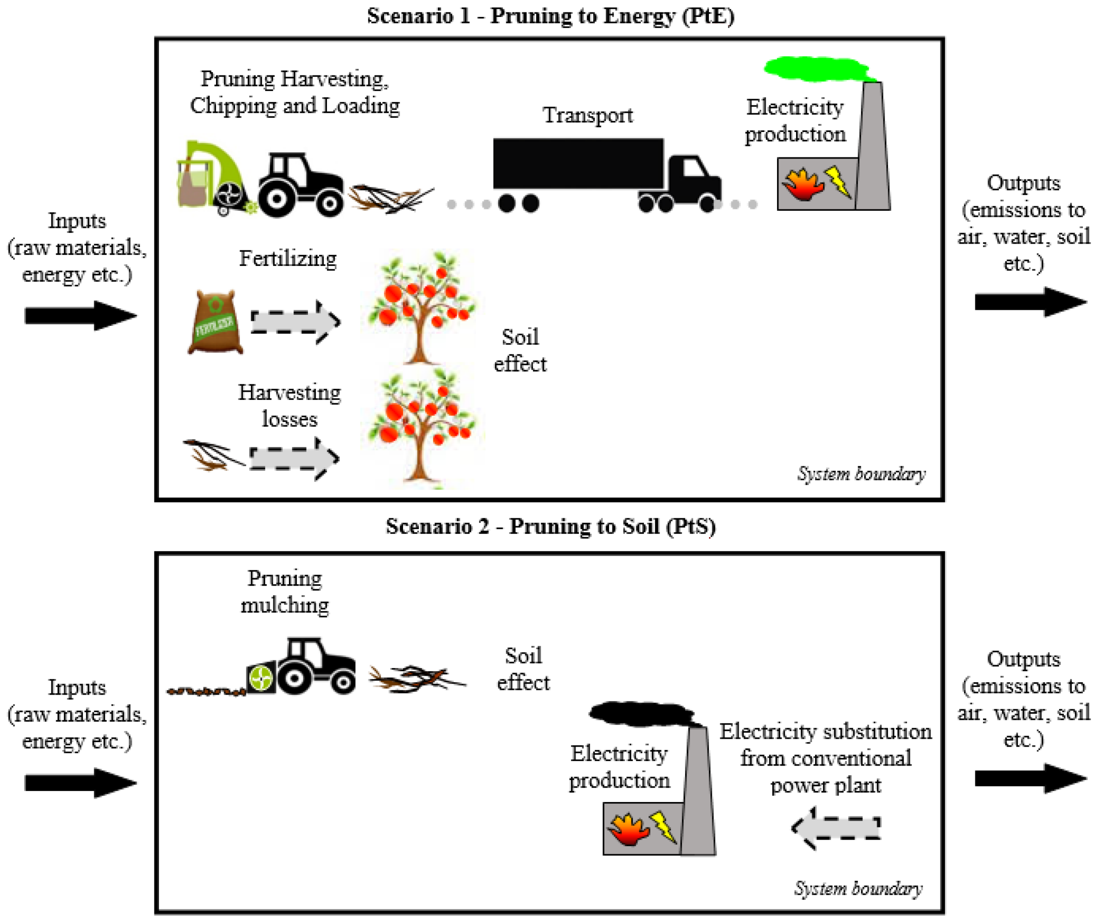


Figure 2. System boundaries both scenarios: pruning to energy (PtE, Scenario 1) and pruning to soil (PtS, Scenario 2).

The functional unit of the assessment assumes the management of 2.59 tFM (fresh mass) pruning residues generated from 1 ha of the peach orchard by both systems (PtE, PtS) (Figure 2). To enable a comparison of two scenarios, these scenarios should perform the same function. To assure these system boundaries were expanded: by electricity generation from hard coal in the PtS scenario and by additional fertilizing in the PtS scenario.

Additional fertilizing for substitution of the removed pruning residues from the orchard in the PtE scenario was included (22.1 kg·ha^{-1} urea; 5.0 kg·ha^{-1} raw phosphate (32.4% P_2O_5); 19.3 kg·ha^{-1} potassium chloride (60% K_2 O)). The applied substitution ratio was 0.5: for P (0.5 kg of P in artificial fertilizer for 1 kg of P in the removed PPR) and 1:1 for N and K, according to [34]. In turn, in the PtS scenario, the compensating electricity production (7.4 GJ·ha^{-1}) by conventional system fired by bituminous coal was considered to balance the final energy produced from pruning combustion in the PtE scenario. The substitution of electricity from coal was considered (and not other sources of electricity) even though that is likely to make the results for the PtS scenario look worse because of the relatively high pollution caused by coal combustion. However, this is in practice a good reason to replace and shut down these plants first. Moreover, in practice, only a hard coal power plant allows for a change in fuel from hard coal to pruning residues. Thus in an existing power plant, the PPR can be (co-)combusted. In other electricity generation technologies, this is not possible. Apart from that, coal power plants tend to be older than the more recent renewable plants and therefore the first in line to be closed down. To check the robustness of the results in this aspect, a sensitivity analysis was performed. In this analysis, the environmental effects of the scenarios were compared to a situation where the produced electricity in the PtE scenario would be substituting the average Spanish electricity generation mix instead of electricity from coal. In Table 1 the considered Spanish electricity mix is shown.

Table 1. The mix of energy sources for electricity generation in Spain (2016) [36].

Energy Source	Share in the Electricity Mix
Nuclear	21.35%
Lignite	0.67%
Hard coal	12.59%
Coal gases	0.37%
Natural gas	19.23%
Heavy fuel oil	6.16%
Biomass	1.47%
Biogas	0.33%
Waste	0.54%
Hydro	14.51%
Wind	17.81%
Photovoltaic	2.94%
Thermal solar	2.03%

2.2. Life-Cycle Inventory: Description of Biomass Sources

The data for the LCA analysis was gained during pruning harvesting realized in the peach orchards situated in Zaragoza, in the Aragón Region, North-East Spain (41.63 N, 0.88 W). It is a location characterized by the Mediterranean dry climate, typical for inland in Spain. The average rainfall is 340 mm and the average year temperature is 14.8 °C. The selected fields were irrigated. The fields consisted principally in a peach of different age tree fields, with an inter-row distance between 5 and 6 m (Figure 3).

(**a**) orchard before harvesting (**b**) the harvesting process (**c**) comminuted peach pruning residues after harvesting

Figure 3. Pruning harvesting in the peach orchard (PtE scenarios). (**a**) orchard before harvesting; (**b**) the harvesting process; (**c**) comminuted peach pruning residues after harvesting.

The cut branches were harvested using a pick-up system and chipper attached to a tractor. Next, the produced wood chips were collected and transported to be stored in piles for open-air drying (approximately 6 months). Finally, the wood chips were loaded onto a truck and delivered to the power plant located at a distance of 50 km from peach orchards. Selected data used in the LCA study are shown in Table 2.

Table 2. Peach orchard and pruning characteristics. FM—fresh mass, DM—dry mass.

Parameter	Unit	Value	Parameter	Unit	Value
Theoretical pruning potential	tFM·ha^{-1}	3.15	Moisture content (storage end)	%	16.1
Pruning biomass yield	tFM·ha^{-1}	2.59	Lower heating value	MJ·kgDM^{-1}	18.0
Harvesting losses	tFM·ha^{-1}	0.34	Ash content (DM)	%	3.79
Moisture content (storage begin)	%	20.6	Bulk density (storage end)	kgFM·m^{-3}	166
Bulk density (storage begin)	kgFM·m^{-3}	175	Pruning capacity	tFM·h^{-1}	1.13
Mass of pruning after 6 months of storage	tDM·ha^{-1}	1.38	Carbon	kg·tDM^{-1}	501
Chlorine	mg·kgDM^{-1}	110	Mercury	mg·kgDM^{-1}	0.005
Major elements in ash			Minor elements in ash		
Al	g·kg^{-1}	4.09	As	mg·kg^{-1}	3.50
Si	g·kg^{-1}	112	Cd	mg·kg^{-1}	0.775
K	g·kg^{-1}	51.4	Cr	mg·kg^{-1}	25.2
Na	g·kg^{-1}	2.10	Cu	mg·kg^{-1}	727
Ca	g·kg^{-1}	334	Mn	mg·kg^{-1}	162
Mg	g·kg^{-1}	13.2	Ni	mg·kg^{-1}	25.8
Fe	g·kg^{-1}	2.65	Pb	mg·kg^{-1}	4.05
P	g·kg^{-1}	15.4	V	mg·kg^{-1}	5.79
Ti	g·kg^{-1}	0.117	Zn	mg·kg^{-1}	583

2.3. Life-Cycle Inventory: Description of Materials and Energy Flows

The life-cycle assessment analysis includes all direct and indirect emissions related to the harvesting/mulching processes, such as the production and operation of the machinery engaged in the peach orchards (a tractor, a trailer, a chipper, a mulcher). The appropriate materials and energy were implicated in the model by standard modules defined in the GaBi database. In case of the lack or not of fitting processes, the Ecoinvent database was used. In the case of the production of the newly developed chipper, data adopted from CREA (Council for Agricultural Research and Economics) [37] was used. The energy required for the construction of the developed chipper was implemented from the energy intensity (referred to the unit of mass) for a standard agricultural machinery module included in Ecoinvent (Table 3).

Table 3. Material and energy balance of the chipper used in the considered scenarios.

Parameter	Unit	Value	Standard Process
Stainless steel	kg	5	Stainless steel white-hot rolled coil (304) (eurofer, GaBi)
Steel	kg	4050	Steel plate (World Steel, GaBi)
Aluminum	kg	80	Aluminum extrusion profile (GaBi)
Copper	kg	1	Copper Wire Mix (DKI/ECI)
Plastics	kg	10.0	Polyvinylchloride pipe (PVC) (PlasticsEurope, GaBi)
Rubber	kg	30.0	SBR Mix + Natural rubber tapped latex (not conserved, 36%) (GaBi)
Tires	kg	45	SBR Mix + Natural rubber tapped latex (not conserved, 36%) (GaBi)
Rubber pipes	kg	40	SBR Mix + Natural rubber tapped latex (not conserved, 36%) (GaBi)
Hydraulic oil	kg	105	Lubricants at the refinery (GaBi)
Paint	$kg{\cdot}kg^{-1}$	0.007	Alkyd paint, 60% insolvent, at the plant (GaBi)
Electricity	$MJ{\cdot}kg^{-1}$	7.02	Electricity, low voltage, at the 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)

DKI—The Deutsches Kupferinstitut, ECI—The European Copper Institute, GaBi—Life Cycle Assessment Software.

For transportation processes, data for a standard truck with a trailer from the GaBi database was used. The fuel consumption was assumed to be 0.044 $kg{\cdot}tkm^{-1}$. Fully loaded trucks for the final consumer and empty returns were applied. Transport distance to the final user was set at 50 km. The emissions related to the diesel combustion in the truck engine during the wood chips transportation are included in the analysis. Similarly, the data concerning the production of a diesel included in GaBi software was applied.

The harvested biomass in the form of wood chips was burnt in the power plant with a capacity of 6.7 MW, adopted from Ecoinvent. The feedstock to the boiler consisted of the chipped pruning residues (dry basis). The amount of fuel used was calculated as dry mass. The emissions were adopted accordingly, related to the lower heating value (LHV). As in the boiler, only biomass was utilized, the recycling of the ashes generated during the combustion process to agricultural soil was adopted.

The mulching (shredding) process of the peach branches in the orchards was adopted by using an Ecoinvent standard mulching process. Basic diesel consumption in this operation was 3.5 $kg{\cdot}ha^{-1}$. The necessary changes in fuel consumption (15.4 $kg{\cdot}ha^{-1}$) were adjusted, accordingly. The lack of electricity production in the PtS scenario was supplemented by the combustion of hard coal.

In the case of the pruning residues that were not collected and removed from the peach orchard, they were considered as a source of the nutrients and heavy metals for the soil. The addition of artificial fertilizers implies similar soil effects to the pruning residues (apart from their environmental effects caused during the production process). However, for ammonia, nitrous oxide, and nitrogen oxides, the emission indices to the soil are different for pruning residues and artificial fertilizers [38,39]. Therefore, depending on the scenario, the following options of application of nutrients and heavy metals to the soil were considered, namely: (i) mulched pruning residues within the PtS chain (2.59 $tFM{\cdot}ha^{-1}$), (ii) pruning residues as the harvesting losses within the PtE chain (0.34 $tFM{\cdot}ha^{-1}$),

(iii) additional fertilizing within the PtE chain (based on the lacking (2.26 tFM·ha^{-1}), (iv) use of the ashes from combustion of peach pruning wood chips in the boiler in the PtE chain (64.2 kg FM·ha^{-1}).

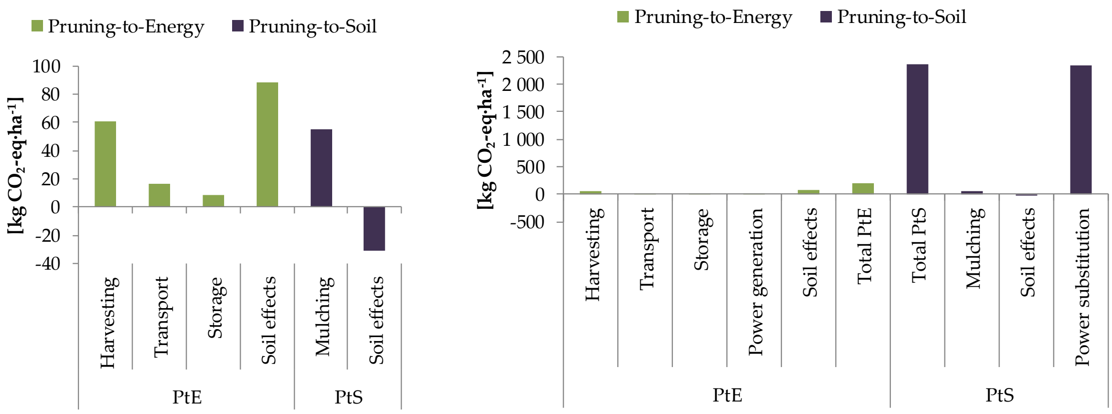
The application of organic matter to the soil in this study was in line with the methodology applied in the previous studies [40–43]. The details are described in the research performed by Dyjakon et al. [44], as well. A sequestration rate of 3% of the organic carbon contained in the PPR was applied.

3. Results: Life-Cycle Impact Assessment (LCIA)

In the considered case study a Pruning-to-Energy (PtE) supply chain is compared to a pruning-to-soil (PtS) scheme for peach pruning residues in Aragón, Spain. The schemes related to a total measured amount during pilot harvesting of 2.59 t·ha^{-1} fresh mass (FM) pruning residues before harvesting.

3.1. Climate Change Potential

In Figure 4 the comparison of the Climate Change Potential impact for Pruning-to-Energy and pruning-to-soil scenarios is shown. The agricultural operations (cradle-to-gate) are first shown separately (Figure 4a), followed by the overall picture including the energy generation phase (Figure 4b). The values of Figure 4a are a magnification (see a difference in scale) of the first part of the values in Figure 4b.



(**a**) agricultural phase operations (**b**) Summary of all operations

Figure 4. The Climate Change Potential (excl. biogenic carbon) of pruning residues in Spanish peach orchards (pruning residues before harvest: 2.59 tFM·ha^{-1}). (**a**) agricultural phase operations; (**b**) Summary of all operations.

The overall GHG emissions for the Pruning-to-Energy scenario was 200 kg CO_2 eq.·ha^{-1} (27 kg CO_2 eq.·GJ^{-1}), whereas the pruning-to-soil scenario was causing an overall amount of GHG emissions of 2360 kg CO_2 eq.·ha^{-1}. The use of harvested pruning residues for energy generation purposes thus can provide for a significant decrease in CO_2 emission. For the peach orchard studied, a reduction potential of 2160 kg CO_2 eq.·ha^{-1} or 294 kg CO_2 eq.·GJ^{-1} of the generated electricity was realized.

In the first stage, the Climate Change Potential for both the Pruning-to-Energy (harvesting) and PtS (mulching) scenario is similar, resulting in 60 and 55 kg CO_2 eq.·ha^{-1}, respectively. The soil effects in the Pruning-to-Energy scenario are caused by additional fertilizer production and application, amounting to 89 kg CO_2 eq.·ha^{-1}. This includes returning to the field of ashes of the combustion of chips of peach branches as well.

In the pruning-to-soil scenario, the peach branches staying in the orchard gave an environmentally benign effect of −31 kg CO_2 eq.·ha^{-1}. In the PtS scheme, however, the process of power substitution (hard coal) caused the by far largest share in Climate Change Potential (2340 kg CO_2 eq.·ha^{-1}). For the Pruning-to-Energy scenario, the process of power generation from peach pruning residues (PPR) amounted to merely 26 kg CO_2 eq.·ha^{-1}.

3.2. Other Environmental Impacts

In Figure 5, the life-cycle impact assessment (LCIA) results from both considered scenarios are shown for the selected ILCD impact categories. For reasons of comparison, the results are expressed in inhabitant equivalents (IE) per hectare, related to the EU-27 for the year 2010.

For all categories except the Eutrophication Terrestrial, the impact of the use of the PPR from one ha on the environment is higher for the scenario where the residues are left in the orchard (PtS). The values for Eutrophication Terrestrial category were similar, with 0.26 IE·ha^{-1} for PtS and 0.27 IE·ha^{-1} for PtE. For the Photochemical Ozone Formation category, the PtS scenario was three times higher than Pruning-to-Energy scenario (0.38 IE·ha^{-1} vs. 0.13 IE·ha^{-1}). The impacts in the category of Particulate matter/Respiratory were estimated at 0.61 IE·ha^{-1} for pruning-to-soil and 0.11 IE·ha^{-1} for Pruning-to-Energy. The highest impact (1.71 IE·ha^{-1}) was caused in the category of Ecotoxicity Freshwater for the pruning-to-soil scheme for the Pruning-to-Energy scenario is was much smaller (0.32 IE·ha^{-1}). In general, the PtS scenario was dominated by power substitution (electricity generation from coal combustion). In the Pruning-to-Energy scenario, the power generation process was also essential, but it was not always the most important one. Apart from electricity generation, the soil-related processes also played a main role, mainly caused by the production and application of artificial fertilizers.

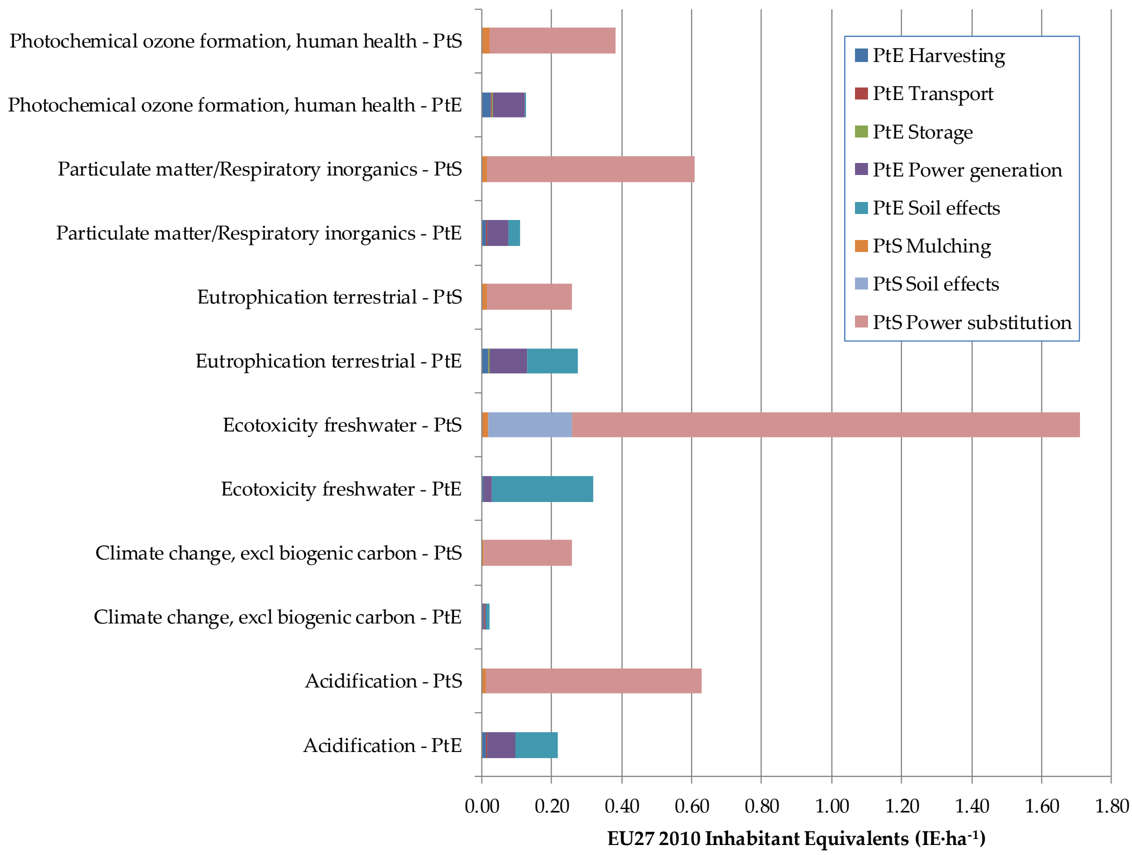


Figure 5. Environmental impacts of pruning residues in Spanish peach orchards (pruning residues before harvest: 2.59 tFM·ha^{-1}).

The only impact category showing an inverted picture was Eutrophication Terrestrial. Here the Pruning-to-Energy scenario scores slightly worse than the PtS scenario (0.28 IE·ha^{-1} and 0.26 IE·ha^{-1} respectively).

4. Discussion: Life-Cycle Interpretation

4.1. General

The Climate Change Potential (excluding biogenic carbon of the PtE scheme is approximately 12 times smaller than of the PtS scheme. This is mainly caused by a substantial difference in CO_2 emissions within the power generation processes. For the PtE and PtS value chains (Figure 4), the Climate Change Potential of the combustion process for power generation is 26 kg CO_2 eq.·ha^{-1} and 2340 kg CO_2 eq.·ha^{-1}, respectively. The incineration of pruned peach branches in the power plant does not cause direct, additional carbon dioxides emissions, as the carbon dioxide here released is assumed to be biogenic, and for this reason climate neutral. However, in the PtS scheme, the applied electricity substitution stemming from the thermal conversion of hard coal causes significant amounts of fossil carbon dioxide to be released directly.

When only the cradle-to-gate processes are considered (without the power generation processes), the results show a more varied picture. The agricultural processes the peach orchard cause similar CO_2 emissions for the chipping and collection process (PtE) and the mulching process (PtS). In both scenarios the total consumption of diesel is comparable. The large differences in total Climate Change Potential between the scenarios show that a combination of efficient harvesting of the PPR together with low fuel consumption leads to both an advantageous energy balance [11] as well as a lower CO_2 footprint.

In the PtE scenario, there is an additional transport stage, which is lacking in the Pruning-to-Soil scenario. This transport of the PPR to the end user could lead to additional environmental effects by fuel combustion in trucks. In the considered scenario, however, the PPR transport (as loose chips) has a small Climate Change Potential effect (17 CO_2 eq.·ha^{-1}), whereas the covered distance of 50 km (25 km to storage + 25 km to end-user) is relatively large for local biomass-to-energy schemes. Even with larger distances, the impact of the transport to the overall results stays limited, as it was shown by Dyjakon et al. [44], where the transport distance (by tractor) was increased from 6 to 600 km.

The result of the PPR incineration for power generation (PtE scenario) might be the application additional fertilizers to make up for the deficit of soil nutrients or some additional measures to prevent erosion in the orchard. The exporting of the PPR causes a loss in nitrogen, phosphorous, and potassium. The additional fertilizing (production, spreading, emissions stemming from biochemical soil processes) leads to combined extra emissions of 89 kg CO_2 eq.·ha^{-1}. A risk of erosion caused by not leaving the branches in the orchards is likely to be expected in less humid regions (e.g., Mediterranean climates) or in orchards with lots of rocks. Grass-covered soils (or by other plants) do not show substantial differences in the balance of organic carbon when the pruning residues are removed [31]. Before planning a PtE scheme, it should be assessed, whether an erosion risk can be expected in the given circumstances [12].

In the PtS scenario, on the other hand, the PPR remain in the orchard. In this way both, heavy metals (that are contained in the peach branches), with negative environmental consequences and nutrients and organic carbon, with positive environmental consequences, are introduced to the soil in small amounts. The introduction in particular of nitrogen, contained in the peach pruning residues, to the soil leads to Climate Change related emissions (NH_3, and consequently, of N_2O and NO_x). These are similar to the PtE scenario (with nitrogen contained in artificial fertilizer). In the PtS scheme, the additional amount of organic carbon remaining in the field leads to a limited sequestration effect, as a small share of the organic carbon remains in the soil for a long time. This results in a negative Climate Change Potential of the PtS scenario amounting to −31 CO_2 eq.·ha^{-1}. This reduction of GHG emissions is therefore positive to the environment. These results of energy production from biomass leading to positive GHG emissions for collecting and combustion the biomass and negative GHG emissions for remaining the pruned branches are also reported by Nieto et al. [45,46] and Morlat et al. [42]. The soil effects methodology applied is described in more detail by Den Boer et al. [40] and Den Boer and Den Boer [41]. Even though in the PtE scheme considerably higher soil-related Climate Change Potential effects were found, the overall results still show an over ten times, lower Climate Change Potential than the PtS scenario. The limited contribution to the combined results of the soil-related processes, in comparison to the traditional fuel incineration for energy production, is also shown by Ruiz et al. [47], Boschiero et al. [48], and Cowie et al. [49].

The PPR incineration for power generation in the PtE scheme still leads to limited emissions of GHG because of the use of chemicals for the flue gas cleaning, the construction of infrastructure, and the emission of small amounts of non-CO_2 flue gas components affecting Climate Change. The prevented generation of electricity from hard coal incineration within the PtS scheme is the dominant cause of the joint Climate Change Potential as a result of the avoided fossil CO_2 emissions.

In the PtE scheme, the Photochemical Ozone Formation category is dominated by the PPR combustion for power generation (9.1×10^{-2} IE·ha^{-1}), mainly caused by the emission of nitrogen oxides, and less so by harvesting machinery production and use (2.6×10^{-2} IE·ha^{-1}). Ethylene, sulphur dioxide, carbon monoxide, and nitrogen oxides emissions caused by hard coal burning (3.6×10^{-1} IE·ha^{-1}) are the predominant drivers in the PtS scheme.

Particulate matter/Respiratory inorganics effects are mainly caused by fine dust (PM2.5) emissions in power generation processes in both of the considered scenarios. The significant difference between the overall scenarios (6.0×10^{-2} IE·ha^{-1} for PtE and 5.9×10^{-1} IE·ha^{-1} for PtS) is can be lead back to the incineration process and properties of the applied fuels. In the PtS scheme, sulphur dioxide emissions stemming from the incineration of hard coal have a dominating impact (compared to the PPR combustion, as the PPR is very low in sulfur). Also, the higher the ash content in hard coal (approximately 20%) impacts the overall results. The lower content in the pruned peach branches (3.7% only), notwithstanding the higher amounts of biomass to be combusted in the PtE (accompanied with a lower LHV), leads to a lower emission of fly ash than in the PtS scheme. Ammonia emission resulting from artificial fertilizer application is a small contributor in the PtE scenario. The total Eutrophication Terrestrial potential (2.8×10^{-1} IE·ha^{-1}) is dominated by NH_3 emissions (1.4×10^{-1} IE·ha^{-1}) from the use of artificial fertilizer and emission of nitrogen oxides (1.1×10^{-1} IE·ha^{-1}) from the PPR incineration in the PtE scheme. In the alternative scenario, the impact is predominantly caused by the nitrogen oxides emitted during the combustion of substituted hard coal (2.4×10^{-1} IE·ha^{-1}).

Overall, the production of energy based on agricultural wood residues has better environmental results than the alternative scenario system, even though in some cases trade-offs may occur. As an example, with bioenergy systems saving up to 92% of Climate Change Potential, it generally is accompanied by a higher potential in toxicity impacts [48]. In the specific case of the use of peach pruning residues for electricity generation however, also the toxicity impacts are limited.

Heavy metal (Zn and Cu) to soil emissions caused by the landspreading of the PPR combustion ashes (2.9×10^{-1} IE·ha^{-1}) and Zn emissions stemming from the PPR burning for electricity generation in the PtE scheme (2.3×10^{-2} IE·ha^{-1}) are the main reasons for Ecotoxicity Freshwater impacts. The impact of the PtS scheme (which is larger) is mainly caused by Cr (VI), V, Cu, Ni, and Zn emissions from hard coal incineration (1.5 IE·ha^{-1}). A lesser effect has the Cu and Zn in the PPR stay behind in the peach orchard (2.4×10^{-1} IE·ha^{-1}). A subsequent lesser contributor constitutes the emissions of heavy metal caused by the mulching machinery (1.9×10^{-2} IE·ha^{-1}).

In general, the impact category Acidification is related to a limited number of emissions only. In the PtE scheme, the foremost contributors are NH_3 emissions caused by additional artificial fertilizers application (1.2×10^{-1} IE·ha^{-1}) and the emission of nitrogen oxides caused by the incineration of the PPR (7.9×10^{-2} IE·ha^{-1}). In the PtS scheme, the impacts are dominated by mainly Sulphur dioxide and, as a smaller contributor, by the emission of nitrogen oxides from the hard coal incineration for power generation (6.2×10^{-1} IE·ha^{-1}).

In practice, the two major significant parameters affecting the environmental impacts for the PtE scenario are the overall distance (orchard-final user) and the type of substituted energy. As mentioned above, it was shown by Dyjakon et al. [43], that even with larger distances, the impact of the transport to the overall results stays limited, even where the transport distance is increased by a factor of up to 100. Therefore, the sensitivity of the considered scenarios was determined towards a change in energy source for the modeling of the substituted power generation. In the basic scenario, electricity from coal was used, which was changed to the Spanish electricity mix.

4.2. Sensitivity Analysis—Change in Substituted Energy Source for Power Generation

In Figure 6, the effects in the considered ILCD LCIA categories are given for the two investigated scenarios: energetic use of the PPR for electricity production (PtE) and leaving the PPR in the orchard with consequent additional power generation according to the Spanish electricity mix.

The results showed that the change in energy source drastically changes the environmental impacts. The PtE scenario remains the same, as no changes were introduced there (see also Figure 5, which scale was kept in Figure 6 for the sake of comparison). For the PtS scenario, however, the impact in all impact categories is strongly reduced. Now, the PtS scenario shows smaller impacts than the PtE scenario in all considered impact categories except for the Climate Change Potential. The Climate Change Potential for the PtS scenario also significantly drops, but it stays larger than for the PtE scenario.

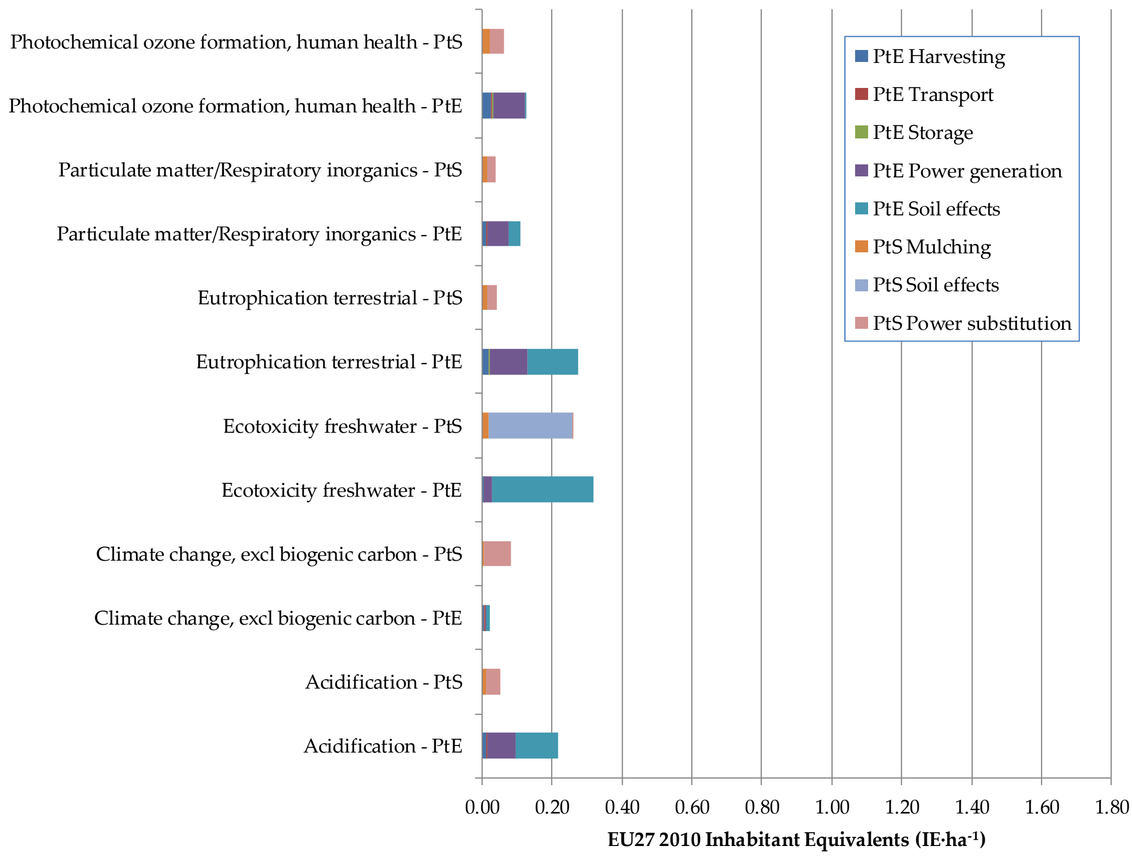


Figure 6. Influence of the change of substituted source of electricity generation: Spanish electricity mix (shown in the PtS scenario) instead of power from hard coal. (theoretical peach pruning potential 2.59 tFM·ha^{-1}).

The strong decrease in impacts observed in the PtS scenario due to change from the substitution of coal power to the Spanish electricity mix is not surprising, considering the high share of low emission energy carries in that mix.

It can be noted (Table 1) that almost 60% of the energy sources in Spain cause no emissions in the use phase (wind, hydro, photovoltaic, thermal solar, and nuclear). Also, the emissions from natural gas and biogas combustion are significantly lower, whereas the emission limits for waste incineration are more stringent than those for other energy sources. Thus the strong decrease in environmental impacts caused by the change in energy source for the substituted electricity generation can be explained.

Notwithstanding the above, the choice for the substitution of electricity generation based on hard coal is justified. In the first place, in practice, only a hard coal power plant allows for a change in fuel from hard coal to pruning residues. As a result, without any significant changes, in the existing power plant, the PPR can be burnt. In other electricity generation technologies, this is not possible. Secondly, hard coal power plants are the most polluting ones, with the highest GHG emissions, and are therefore the most likely to be replaced by a renewable energy source, as the pruning residues are. Thirdly, coal power plants tend to be older than the more recent renewable plants and, therefore, the first in line to be closed down.

5. Conclusions

The LCA analysis presented in this study revealed that the utilization of pruning residues from peach orchards for energy purposes (the generation of electricity), in contrast to leaving them in the orchards, contributes to a meaningful (12-fold) reduction in the Global Warming Potential. This is mainly caused by a substantial difference in CO_2 emissions within the power generation processes. For the PtE and PtS value chains, the Climate Change Potential is 200 kg CO_2 eq.·ha^{-1} (or 27 kg CO_2 eq.·GJ^{-1}) and 2360 kg CO_2 eq.·ha^{-1}, respectively. As a consequence, the bioenergy logistic chain can cause significant GHG savings in relation to the solutions based on fossil fuels. For the peach orchard studied, a reduction potential of 2160 kg CO_2 eq.·ha^{-1} or 294 kg CO_2 eq.·GJ^{-1} of the generated electricity was realized.

In terms of other impact categories considered within the LCA analysis, the obtained values were better for the PtE scenario: Photochemical Ozone Formation was three times lower than the PtS (0.38 IE·ha^{-1} vs. 0.13 IE·ha^{-1}); Particulate matter/Respiratory 0.61 IE·ha^{-1} for PtS and 0.11 IE·ha^{-1} for PtE; Ecotoxicity Freshwater (1.71 IE·ha^{-1} vs. 0.32 IE·ha^{-1}). Only the Eutrophication Terrestrial index indicated slightly other values (0.27 IE·ha^{-1} vs. 0.26 IE·ha^{-1}). In general, the PtS scenario was dominated by power substitution (electricity generation from coal combustion). In the PtE scenario, the power generation process was also essential, but it was not always the most important. The environmental assessment also showed that the impact of the intermediate processes (harvesting, storage, and transport of peach pruning residues) was small compared to the impact of their thermal conversion process (combustion). Also, with an increase of the arbitrary chosen total transport distance of 50 km the energetic use of peach pruning residues in Aragón, Spain, will be environmentally benign, although financially this may be less interesting.

In the current study, the harvested peach pruning residues are assumed to replace electricity generation based on hard coal. A choice for a replacement of the electricity based on the Spanish electricity mix would strongly change the outcomes, however, a choice for hard coal substitution is the most likely.

In practice, the results are very valuable as they provide useful data not only for an orchard's owners (the biomass residues producers) but also for other participants in this logistic chain. Moreover, the regional and external authorities dealing with the building/planning of the bioenergy market can use them in the creation of the proper strategy for sustainable development comprising also economic, social, and environmental issues.

This work opens a space for a wider analysis of different case studies focused on PtE strategy as well as on the utilization of competing energy sources applied for electricity generation or heat production. Also, the use of pruning residues for energy production in other climatic regions, with other circumstances, e.g., for storage, is worth investigating.

Author Contributions: Conceptualization, J.D.B.; methodology, J.D.B., and A.D.; software, J.D.B.; validation, J.D.B., and A.D.; formal analysis, J.D.B., and A.D.; investigation, A.D., and D.G.-G.; resources, A.D.; data curation, J.D.B., A.D., and E.D.B.; writing—original draft preparation, J.D.B., and A.D.; writing—review and editing, J.D.B., A.D., E.D.B., T.B., and G.G.; visualization, A.D., J.D.B., and E.D.B.; supervision, J.D.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: This scientific paper was partly co-financed by the European Union Seventh Framework Programme (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 (Grant Agreement Nr 2896/7.PR/2013/2 from 18.11.2013) on the realization of the international project EuroPruning: "Development and implementation of a new and non-existent logistics chain for biomass from pruning".

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

BAP	biomass action plan
DM	dry mass
FM	fresh mass
GHG	greenhouse gas
GWP	Global Warming Potential
IE	inhabitant equivalent
ILCD	international life cycle data
IPCC	intergovernmental panel on climate change
ISO	The International Organization for Standardization
LCA	life cycle assessment
LHV	lower heating value
ORC	Organic Rankine Cycle
PPR	peach pruning residues
PtE	pruning to energy
PtS	pruning to soil
SBR	Styrene–Butadiene Rubber

References

1. European Commission (EC). *Biomass Action Plan*; COM (2005)628 Final; European Commission: Brussels, Belgium, 2005.
2. European Commission (EC). *Going Climate Neutral by 2050. A Strategic Long Term Vision for a Prosperous, Modern, Competitive and Climate Neutral EU Economy*; Publications Office of the European Union: Luxembourg, 2019.
3. European Commission (EC). *Sustainable and Optimal Use of Biomass for Energy in the EU Beyond 2020*; Final Report; European Commission: Brussels, Belgium, 2017; Available online: https://ec.europa.eu/energy/studies/sustainable-and-optimal-use-biomass-energy-eu-beyond-2020_en?redir=1 (accessed on 8 April 2020).
4. Gavrilescu, M. Biomass power for energy and sustainable development. *Environ. Eng. Manag.* **2008**, *7*, 617–640. [CrossRef]
5. Scarlat, N.; Dallemand, J.-F.; Monforti-Ferrario, F.; Nita, V. The role of biomass and bioenergy in a future bioeconomy: Policies and facts. *Environ. Dev.* **2015**, *15*, 3–34. [CrossRef]
6. Nunes, L.J.R.; Causer, T.P.; Ciolkosz, D. Biomass for energy: A review on supply chain management models. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109658. [CrossRef]
7. Carvalho, M.; Rommel, Y.; Araújo, V.; de Góis, L.M.; Coelho Junior, L.M. Urban Pruning Waste: Carbon Footprint Associated with Energy Generation and Prospects for Clean Development Mechanisms. *Rev. Árvore* **2019**, *43*. [CrossRef]
8. Beuchelt, T.D.; Nassl, M. Applying a sustainable development lens to global biomass potentials. *Sustainability* **2019**, *11*, 5078. [CrossRef]

9. Sagani, A.; Hagidimitriou, M.; Dedoussis, V. A Study of Burning Olive Tree Pruning Biomass for Electricity Generation. In Proceedings of the World Bioenergy Conference, Jönköping, Sweden, 3–5 June 2014; The Swedish Bioenergy Association, Ed.; The Swedish Bioenergy Association: Stockholm, Sweden, 2014; pp. 66–70.
10. Hamelin, L.; Borzęcka, M.; Kozak, M.; Pudełko, R. A spatial approach to bioeconomy: Quantifying the residual biomass potential in the EU-27. *Renew. Sustain. Energy Rev.* **2019**, *100*, 127–142. [CrossRef]
11. Dyjakon, A. Harvesting and baling of pruned biomass in apple orchards for energy production. *Energies* **2018**, *11*, 1680. [CrossRef]
12. EuroPruning. Best Practice Brochure for a Sustainable and Sound Utilization of Wood Prunings as Biomass Feedstock. Deliverable report D8.4. 2016. Available online: www.europruning.eu (accessed on 14 February 2020).
13. García-Galindo, D.; Gómez-Palmero, M.; Pueyo, E.; Germer, S.; Pari, L.; Afano, V.; Dyjakon, A.; Sagarna, J.; Rivera, S.; Poutrin, C. Agricultural Pruning as Biomass Resource: Generation, Potentials and Current Fates. An Approach to its State in Europe. In Proceedings of the 24th European Biomass Conference and Exhibition, Amsterdam, The Netherlands, 6–9 June 2016; pp. 1579–1595. [CrossRef]
14. Dyjakon, A.; García-Galindo, D. Implementing agricultural pruning to energy in Europe: Technical, economic and implementation potentials. *Energies* **2019**, *12*, 1513. [CrossRef]
15. FAOSTAT. 2018. Available online: http://www.fao.org/faostat/en/#data/QC/ (accessed on 24 March 2020).
16. Cavalaglio, G.; Cotana, S. Recovery of vineyards pruning residues in an agro-energetic chain. In Proceedings of the 15th European Biomass Conference and Exhibition, Berlin, Germany, 7–11 May 2007.
17. Bilandzija, N.; Voca, N.; Kricka, T.; Matin, A.; Jurisic, V. Energy potential of fruit tree pruned biomass in Croatia. *Span. J. Agric. Res.* **2012**, *10*, 292–298. [CrossRef]
18. Pruning Biomass Potential for Energy in Europe. Available online: http://www.gruppo-panacea.it/home/en/residual-biomass2/125-pruning-biomass-potential-for-energy-in-europe/173-pruning-biomass-potential-for-energy-in-europe (accessed on 24 March 2020).
19. Pari, L.; Alfano, V.; Garcia-Galindo, D.; Suardi, A.; Santangelo, E. Pruning biomass potential in Italy related to crop characteristics, agricultural practices and agro-climatic conditions. *Energies* **2018**, *11*, 1365. [CrossRef]
20. Bosona, T.; Gebresenbet, G.; Dyjakon, A. Implementing life cycle cost analysis methodology for evaluating agricultural pruning-to-energy initiatives. *Bioresour. Technol. Rep.* **2019**, *6*, 54–62. [CrossRef]
21. Dyjakon, A.; Den Boer, J.; Gebresenbet, G.; Bosona, T.; Adamczyk, F. Economic analysis of the collection and transportation of pruned branches from orchards for energy production. *Wood* **2020**, *205*. [CrossRef]
22. Intini, F.; Kühtz, S.; Rospi, G. Life Cycle Assessment (LCA) of an energy recovery plant in the olive oil industries. *Int. J. Energy Environ.* **2012**, *3*, 541–552.
23. Gaspar, J.P.; Gaspar, P.D.; Dinho da Silva, P.; Simões, M.P.; Espírito Santo, C. Energy life-cycle assessment of fruit products—Case study of Beira Interior's Peach (Portugal). *Sustainability* **2018**, *10*, 3530. [CrossRef]
24. Kowalczyk, Z.; Kwaśniewski, D. Life cycle assessment (LCA) in energy willow cultivation on plantations with varied surface area. *Agric. Eng.* **2019**, *23*, 11–19. [CrossRef]
25. Recchia, L.; Boncinelli, P.; Cini, E.; Vieri, M.; Garbati Pegna, F.; Sarri, D. *Multicriteria Analysis and LCA Techniques: With Applications to Agro-Engineering Problems*; Springer: London, UK, 2011.
26. Caldeira-Pires, A.; Benoist, A.; da Luz, S.M.; Silverio, C.S.; Silveira, C.M.; Machado, F.S. Implications of removing straw from soil for bioenergy: An LCA of ethanol production using total sugarcane biomass. *J. Clean. Prod.* **2018**, *181*, 249–259. [CrossRef]
27. Christoforou, E.A.; Fokaides, P.A. Life Cycle Assessment (LCA) of Olive Husk Torrefaction. *Renew. Energy* **2016**, *90*, 257–266. [CrossRef]
28. Chary, K.; Aubin, J.; Guindéa, L.; Sierra, J.; Blazy, J.-M. Cultivating biomass locally or importing it? LCA of biomass provision scenarios for cleaner electricity production in a small tropical island. *Biomass Bioenergy* **2018**, *110*, 1–12. [CrossRef]
29. Perilhona, C.; Alkadeea, D.; Descombes, G.; Lacour, S. Life cycle assessment applied to electricity generation from renewable biomass. *Energy Procedia* **2012**, *18*, 165–176. [CrossRef]
30. Beagle, E.; Belmont, E. Comparative life cycle assessment of biomass utilization for electricity generation in the European Union and the United States. *Energy Policy* **2019**, *128*, 267–275. [CrossRef]
31. EuroPruning. *Report with Recommendation for Wood Prunings Utilisation for Sustainable Soil Management*; Project Report D7.3; Project (FP7–312078); EuroPruning: Fraga, Spain, 2016.

32. ISO. *14040:2006—Environmental Management—Life Cycle Assessment—Principles and Framework*; International Organisation for Standardisation (ISO): Geneva, Switzerland, 2006.
33. EC—JRC. *Recommendations Based on Existing Environmental Impact Assessment Models and Factors for Life Cycle Assessment in European Context*; EC—JRC: Brussels, Belgium, 2011; ISBN 978-92-79-17451-3.
34. EuroPruning. *Report on Environmental Evaluation of the Supply Chain*; Project Report D8.1; Project (FP7–312078); EuroPruning: Fraga, Spain, 2016.
35. Benini, L.; Mancini, L.; Sala, S.; Manfredi, S.; Schau, E.M.; Pant, R. *Normalisation Method and Data for Environmental Footprints*; European Commission, JRC, Publications Office of the EU: Luxembourg, 2014; ISBN 978-92-79-40847-2.
36. Thinkstep. ES: Electricity Grid Mix ts. GaBi Process, 2020 Database. Available online: http://www.gabi-software.com/international/databases/gabi-data-search/?id=8323&no_cache=1&tx_fufgabilcidocumentation_pi1%5BAdvancedSearch%5D=0&tx_fufgabilcidocumentation_pi1%5Bsuchbegriff%5D=ES%3A+Electricity+grid+mix+ts.+GaBi+process%2C+2020+database&search=Search&tx_fufgabilcidocumentation_pi1%5Bmatch%5D=2&tx_fufgabilcidocumentation_pi1%5BCountry%5D=&tx_fufgabilcidocumentation_pi1%5BProcessTypeName%5D=&tx_fufgabilcidocumentation_pi1%5BDatabaseName%5D=&tx_fufgabilcidocumentation_pi1%5BProcessDataSource%5D= (accessed on 14 February 2020).
37. Suardi, A.; Council for Agricultural Research and Economics, Rome, Latium, Italy. Personal Communication, 2016.
38. Eggleston, S.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K. *IPCC Guidelines for National Greenhouse Gas Inventories*; Institute for Global Environmental Strategies: Hayama, Japan, 2006; Volume 5.
39. Faist, M.; Reinhard, J.; Zah, R. *RBS GHG Calculation Methodology*; Version 2.1; EPFL: Lausanne, Switzerland, 2011.
40. Den Boer, J.; Gomez-Palmero, M.; Sebastian, F.; García-Galindo, D.; Dyjakon, A.; Bukowski, P.; Den Boer, E.; Germer, S.; Bischoff, W.-A. Pruning residues: Energy production or mulching? Environmental impacts of almond pruning residues use. In Proceedings of the 24th European Biomass Conference and Exhibition, Amsterdam, The Netherlands, 6–9 June 2016; pp. 1485–1489. [CrossRef]
41. Den Boer, E.; Den Boer, J. Environmental effects of the management of municipal waste, including the impact of organic recycling. In *Microbiological Environmental Hygiene*; Hakalehto, E.E., Ed.; Nova Science Publishers: New York, NY, USA, 2018; pp. 293–315.
42. Morlat, R.; Chaussod, R. Long-term additions of organic amendments in a Loire Valley Vineyard. I Effects on properties of a calcareous sandy soil. *Am. J. Enol. Vitic.* **2008**, *59*, 353–363.
43. EuroPruning. *Summary of Organic Matter and Nutrient Balances in Permanent Crop Agro-Systems*; Project report D7.2; Project (FP7–312078); EuroPruning: Fraga, Spain, 2016.
44. Dyjakon, A.; Den Boer, J.; Szumny, A.; Den Boer, E. Local energy use of biomass from apple orchards-An LCA study. *Sustainability* **2019**, *11*, 1604. [CrossRef]
45. Nieto, O.; Castro, J.; Fernandez, E. Long-term effects of residue management on soil fertility in Mediterranean olive grove: Simulating carbon sequestration with RothC model. In *Principles, Application and Assessment in Soil Science*; Burcu, E., Ozkaraova, G., Eds.; IntechOpen: London, UK, 2011; ISBN 978-953-307-740-6.
46. Nieto, O.; Castro, J.; Fernandez, E.; Smith, P. Simulation of soil organic carbon stocks in a Mediterranean olive grove under different soil-management systems using the RothC model. *Soil Use Manag.* **2010**, *26*, 118–125. [CrossRef]
47. Ruiz, D.; San Miguel, G.; Corona, B.; Lopez, F.R. LCA of a multifunctional bioenergy chain based on pellet production. *Fuel* **2018**, *215*, 601–611. [CrossRef]
48. Boschiero, M.; Cherubini, F.; Carla, N.; Zerbe, S. Life cycle assessment of bioenergy production from orchards woody residues in Northern Italy. *J. Clean. Prod.* **2016**, *112*, 2569–2580. [CrossRef]
49. Cowie, A.L.; Smith, P.; Johnson, D. Does soil carbon loss in biomass production systems negate the greenhouse benefits of bioenergy? *Mitig. Adapt. Strat. Glob. Chang.* **2006**, *11*, 979–1002. [CrossRef]