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Biomass Residues to Renewable Energy: A Life Cycle Perspective Applied at a Local Scale

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Abstract: Italy, like every country member of the European Union (EU), will have to achieve the objectives required by the Energy Roadmap 2050. The purpose of the study was to evaluate the environmental impacts of residue recovery arising from the management of public and private green feedstocks, activity of the cooperative "Green City" in the Bologna district, and usage in a centralized heating system to produce thermal energy for public buildings. Results, obtained using the ReCipe impact assessment method, are compared with scores achieved by a traditional methane boiler. The study shows some advantages of the biomass-based system in terms of greenhouse gases (GHGs) emissions and consumption of non-renewable fuels, which affect climate change (−41%) and fossil resources depletion (−40%), compared to the use of natural gas (NG). Moreover, scores from network analysis denote the great contribution of feedstock transportation (98% of the cumulative impact). The main reason is attributable to all requirements to cover distances, in particular due to stages involved in the fuel supply chains. Therefore, it is clear that greater environmental benefits could be achieved by reducing supply transport distances or using more sustainable engines.

Keywords: life cycle assessment (LCA); thermal energy; recovery; energy efficient city; small community

1. Introduction

According to the International Energy Agency (IEA) [1], Italian final energy consumption reached 117 million tons oil equivalent (Mtoe) in 2014, about 69% of which is still based on fossil resources. However, Italy has limited traditional energy source reserves and this results in a high impact on the trade balance (around 115 Mtoe were imported in 2014 [1]). Moreover, the present energy system is responsible for the emission of a large amounts of greenhouse gases (GHGs) and other pollutants: in 2014 CO_2 emissions from fossil fuels combustion only were estimated around 320 Mt [1]. This means that Italian energy system has to be deeply rethought, to take steps towards both a higher independence and environmental sustainability, promoting lower energy consumption, increasing efficiency, developing renewable and clean sources. Nevertheless, the energy transition is a complex task: according to the scenarios described by the Energy Roadmap 2050 [2], it will take 40–50 years to reduce the greenhouse gases emissions by 80% compared to 1990 and a reduction over 95% is expected for the electricity sector by 2050. However, in the last years, an increased percentage of renewables in the Italian energy mix is helping to switch from a centralized to a more distributed energy system, facilitating the transition. In fact, renewable energy sources are naturally spread throughout the entire territory, but this wide distribution requires strict regulations to promote a rational exploitation and to meet shared targets.

Italy adopted the European regulatory framework on renewables implementing European Union (EU) Directive 2009/28 [3], which commits the country to produce 17% of its primary energy from renewables by 2020, including a 10% target for biofuels. The renewable energy share of the European gross final energy consumption was 15.9% in 2014, compared to 15% in 2013, while the target towards 2020 is 20% [4]. The Italian Action Plan indicates the way to meet these goals. An exchange mechanism among the Member States is permitted in the calculation of national energy budget (checked every two years). In addition, a burden sharing mechanism is defined: it implies an apportionment of the mandatory quotas among local authorities, which would allow the states to achieve their renewable targets by 2020. In the case of Italy, this distribution is carried out among the Regions, which should arrange a further partition among their Municipalities. Therefore, it looks evident that each Municipality has to develop its own energy strategy, based on a regional plan. In Emilia-Romagna (ER), one of the twenty Italian regions, the strategy to meet 2020 targets includes the reduction of energy consumption and GHGs emissions by 14.7% and 20% respectively (compared to 2005). Furthermore, an implementation of renewables up to the 8.9% of the 2005 gross final consumption required. In addition, Municipal Action Plans for Sustainable Energy highlight how the local production, through the implementation of small and medium cogeneration plants, represents the right choice to improve urban energy system [5]. The ER region identified the following mix of renewables to meet 2020 targets: photovoltaic, solar thermal, wood biomass and biogas. Among these, biomass represents an interesting and affordable solution, considering that solid biomass provides the largest contribution to renewable thermal energy both in Europe and in Italy (Figure 1).

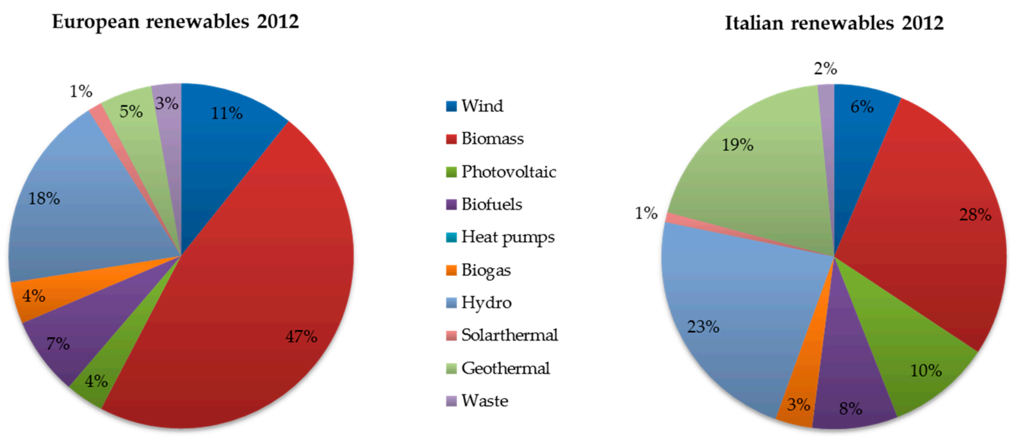

Figure 1. European and Italian renewables in 2012 [4].

In general, biomass is considered a renewable source of energy if two main conditions are satisfied: (i) the biomass regeneration cycle must be respected and (ii) no alterations of natural areas are made to promote the cultivation. Moreover, the use of biomasses differs from other renewable sources since its sustainability is strictly influenced by an advantageous cost/benefit ratio, which can be achieved if the exploitation is performed at a short distance from its end use. Together with these limitations, further problems are related to the use of biomass in cogeneration systems, such as:

- low social acceptability, as well as for combustion processes in general;
- difficult employment of excess thermal energy during warm seasons;
- increase of particulate emissions.

Viable solutions to overcome these problems may include:

- a development of local supply chains for the pruning management of public/private green areas;
- an implementation of small district heating systems;
- a production of pellets or wood chips to feed small domestic boilers.

In this context, an interesting example of a "smart" valorization of the residues for biomass to energy purposes is represented by Castello D'Argile, a small Municipality in the province of Bologna (Central-Northern Italy). The main goal is to integrate the current domestic heating system by using centralized wood boilers, fed with biomass residues resulting from local pruning practices. This action, together with the reduction of consumptions and the implementation of green energy procurement for industries, will contribute to reach the territorial targets by 2020 (and those related to the period 2030–2050).

Therefore, the purpose of the present study is to assess the impacts on the environment and human health associated with the energy production using wood chips from pruning residues and to compare it to a traditional and widespread decentralized system of gas boilers. Life Cycle Assessment (LCA) methodology was adopted as a predictive tool to estimate potential environmental burdens. The application of LCA in this field is reported also in previous studies, which investigated renewable energy production from biomass. Cespi et al. [6] assessed an Italian case study, comparing the impacts of logs and pellets stoves. Wolf et al. [7] focused the attention on the Bavarian situation, stressing that it is necessary to focus on regional aspects when assessing the environmental impacts of heat provision. The use of different logging residues to produce bioenergy was also investigated by Hammar et al. [8], taking into account Swedish conditions. Another work outlines the importance of an integrative resources management aimed to close the loop of the production systems, to implement a suitable strategy in line with the regulatory framework [9]. Moreover, Thornely et al. [10] emphasized that medium scale district heating boilers, fed by wood chips, lead to the highest GHGs reduction per unit of harvested biomass.

In order to provide a comprehensive description of the methodology and a clear evaluation of the case study, the main text is structured as follows. Section 2 defines the methodology: after a general overview of LCA, a detailed description of the system boundaries and an inventory analysis stage is performed. Then, Section 3 collects the main results achieved by each scenario, following ReCiPe impact assessment method [11]. Final scores are discussed in detail and sensitivity analysis is also provided. Finally, in Section 4 the appropriate conclusions are drawn.

2. Materials and Methods

LCA is an objective and standardized methodology able to investigate the environmental behavior of products, processes or systems during their entire life cycle. The general framework (Figure 2), defined by the ISO 14040 and 14044 [12,13], consists of four conceptual phases, namely: Goal and Scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation. LCA is an extremely versatile methodology, useful to investigate different sectors, such as the renewable energy from biomass [6–10], the bio-based industry [14,15], the chemical and pharmaceutical sectors [16,17] and the waste management systems [18]. The simulation was carried out using SimaPro software (version 8.0.4.30) [19], which integrates a set of dedicated processes and libraries. Among these, the Ecoinvent database (version 3.1) [20] and the ReCiPe (version 1.11) [11] analysis tool were selected to complete the LCI and LCIA stages in order to identify environmental critical factors and potential benefits of the scenario under investigation.

The recovery of inert green residues and street furniture in the investigated Municipality is carried out by a cooperative Society, named "Città Verde" ("Green City"). Around 4000 t of wood residues are collected each year, and recovered by the cooperative according to the Italian Legislative Decree 152/2006 [21].

This company collects also wood-based packaging and materials, which, together with the previous residues, are chipped and stored in a cooperative plant. The two final destinations of wood residues presently considered are: (i) a biomass combustion plant (located about 70 km away from the place of collection) or (ii) a composting plant (about 14 km away). For comparison purposes, only this second destination has been taken into account. On the other hand, the future, alternative purpose is to use these residues as fuel to meet the energy needs of some public buildings located in Castello d'Argile, currently fueled by natural gas (NG): a nursery, a junior high school and a gym, with a total installed power of 660 kW (60, 350 and 250 kW, respectively).

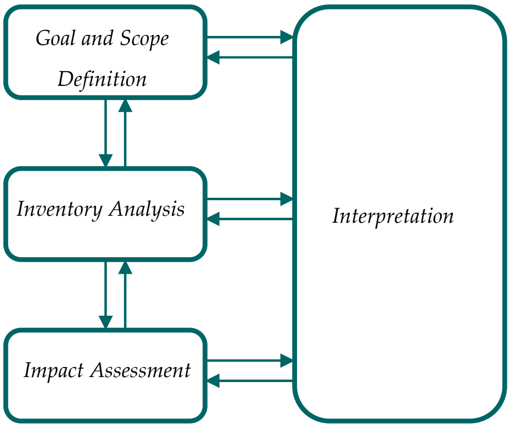

Figure 2. Life Cycle Assessment (LCA) framework, adapted from ISO 14040 [12].

In this framework, LCA was applied to verify the overall impacts of a wood-based centralized appliance and to identify potential benefits if compared with traditional gas boilers. For this purpose, the production of 1 MWh of thermal energy was selected as functional unit in order to complete the models which simulate the cradle-to-gate boundaries: from the raw materials extraction up to the thermal valorization of residues. System boundaries for the traditional and alternative scenarios are depicted in Figure 3A,B.

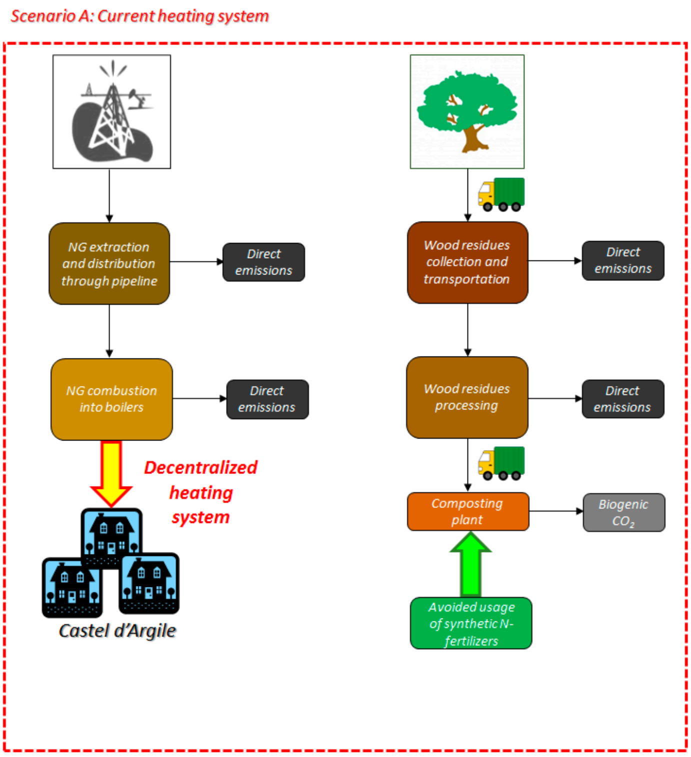

Figure 3. *Cont.*

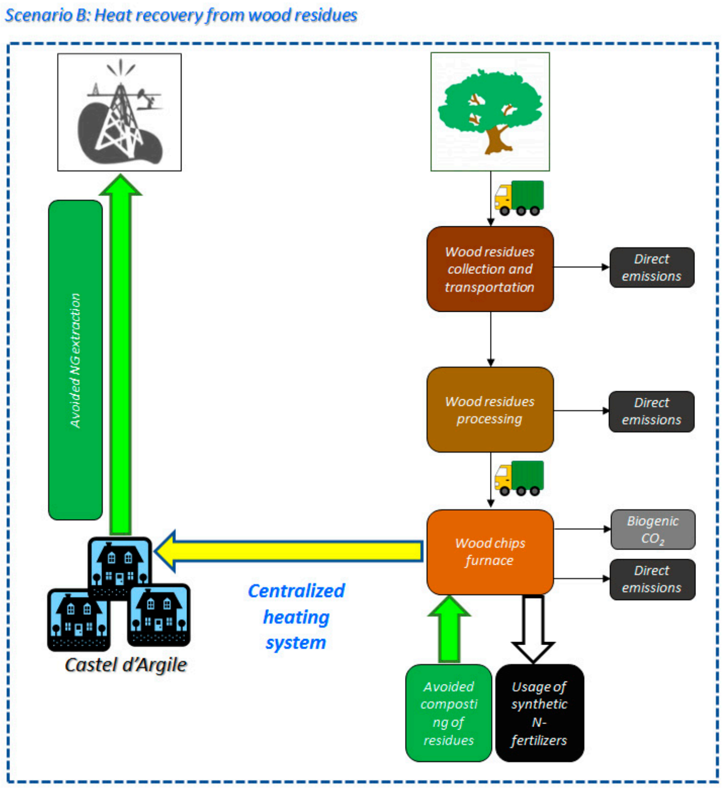

Figure 3. System boundaries LCA for (**A**) the current heating system and (**B**) the alternative bio-based system.

2.1. Current Heating System: Inventory Description

The current situation is depicted in Figure 3A, which describes all the stages involved. Among these are:

- Timber collection, transportation and processing. These stages are common to both scenarios and describe all the treatment procedures necessary to collect wood and reduce their volume.
- The extraction of all the resources (renewables and fossil fuel) to feed the entire supply chain, among which: fuels, electricity, other auxiliaries, infrastructure, etc.

NG is the fuel used in decentralized appliances to cover the thermal requirements of the three public buildings (e.g., nursery, junior high school and gym), presently equipped by individual heating systems. Primary data concerning the decentralized system are not available. Therefore, in order to simulate the production of 1 MWh of thermal energy by NG, which corresponds to around 95 m^3 of NG burned in dedicated appliances, secondary data from the Ecoinvent database have been used to create the model. The default process *Heat, NG, at industrial furnace >100 kW* [15] was selected as a good approximation of the actual situation, for two main reasons: (1) it was developed using average European data (including Italy); (2) methane represents the most widespread fuel in Italian heating appliances [6]. This default process simulates the European production of thermal energy through NG burned in an average >100 kW industrial module. The process includes the upstream stages involved in the fuel extraction and transportation through high pressure pipelines, and all input and output flows to simulate the boiler construction (usually called infrastructure requirements) and the electricity needed for the operation. In this case, being unavailable the data concerning the local energy mix used in the Municipality, Italian mix was assumed as a suitable approximation in order to simulate the electricity production. The Ecoinvent database provides also a full list of substances emitted during the NG burning procedure within the appliance. In addition to the emissions from combustion, system boundaries include all the direct and embodied environmental releases for each stage considered. Direct emissions concern all the substances released during the wood processing (e.g., NO_x and Particulate Matter (PM), see Table 1) and transportation. On the other hand, the term *embodied* refers to all the other chemicals emitted during the other stages which characterize the whole cradle-to-gate chain, such as: infrastructures construction (e.g., boiler and truck), electricity and fuel production, resources extraction, etc.

Table 1. Annual consumption and emissions in the wood chip production step. PM: particulate matter.

Parameter	Unit	Chipper	Bucket	Shredder
Energy requirements	kWh/year	2.1×10^5	9.1×10^4	4.3×10^4
PM emissions	kg/year	6.40×10^1	2.70×10^1	1.30×10^1
NO_x emissions	kg/year	8.51×10^2	3.64×10^2	1.72×10^2

As depicted by the figure and described above, timber residues are now collected and treated at the cooperative plant. Then, they are sent to the nearest composting plant (14 km) in order to obtain soil improver with 35 wt% efficiency with respect to the input material (wood residues). Distances are assumed to be covered by diesel-based lorry, with an average capacity of 2.5 t. In general, the production of compost leads to the saving of synthetic fertilizers. Therefore, in agreement with literature [22], the model assumes an avoided production of 0.6 kg of *N*-fertilizer per kg of compost produced.

Figure 3B represents the alternative scenario in which residue wood chips are used as renewable fuel to cover the heating requirements of public buildings. As in the previous scenario, boundaries include the wood residues collection, transportation and processing, together with all the direct and indirect emissions, considering the whole supply chain. However, in this case the scenario simulates the thermal recovery of wood residues to produce the described centralized district heating.

2.2. Wood Residues Chain: Inventory Description

According to the National Inventory of Forests and Forest Carbon Tanks (INFC) [23], the majority of residues collected within the ER region belongs to the hardwood family. Therefore, average value for the Lower Heating Value (LHV) and density (18.12 MJ/kg and 640 kg/m^3 respectively) were estimated based on literature data [24]. In general, the selection of input materials is crucial, since the separation after treatment would require more time and energy: inappropriate pretreatments could interrupt the machines or force reprocessing of the material. The removal of leaves, wider logs and other residual materials (e.g., plastic and metals) is an example of pre-treatment procedures.

Chips are produced using a wood chipper and a shredder. The model includes all the energy requirements for the machinery used in the chip manufacture and the related emissions in terms of particulates and NO_x. The wood chips production phase was modeled using annual data per appliance, reported in Table 1.

Italian mix was assumed to cover the electricity needs. According to the Italian Energy Services Operator (GSE) data from 2013 [25], renewables cover only the 30% of the entire production, while fossils fuels are still predominant (59%, of which NG represents 54%).

In addition, a distance of 30 km (round trip) was considered for supplying the wood, assuming an average truck capacity of 2.5 t. This results in around 1600 journeys/year, to cover an overall distance of 4800 km. By the use of the reference process listed in Ecoinvent database (*Transport, lorry 3.5–7.5 t, EURO5/RER U*), a new model to simulate an average 2.5 t lorry capacity was created. In addition, the wood-based scenario includes all the inputs and outputs for the construction of a 170 kW chips furnace (e.g., steel, aluminum, concrete, etc.). Further facilities needed to distribute the heat among the three buildings have not been considered, since primary data were not available; however, according to previous studies, it is known that infrastructure has a very low environmental impact in heating systems [6].

As in the case of methane-based appliance, without primary data available for the emissions, average air releases from wood chips combustion were collected from Ecoinvent library (*Wood chips, from forest, hardwood, burned in furnace/CH U*) [15] and then recalculated on the basis of new values for density, LHV and combustion efficiency (95%).The usage of wood residues as a source of thermal energy implies the avoided extraction of NG to produce 1 MWh. In addition, it prevents the transportation to the composting plant and the subsequent transformation. Therefore, system boundaries include both processes as avoided flows. Detailed inventories for both scenarios are depicted in Tables 2 and 3, respectively.

Table 2. Life Cycle Inventory (LCI) for the current heating system scenario. NG: natural gas.

LCI Stage	Process	Unit	Amount
Input Wood Chips Chain	Transportation 2.5 t lorry	tkm	9537.9
	Electricity—chipper	kWh	10.6
	Electricity—bucket	kWh	4.5
	Electricity—shredder	kWh	2.1
Input NG Chain	NG	MWh	1.1
	Electricity, at grid/UCTE U	kWh	3.1×10^{-7}
	Industrial furnace NG	p	7.9×10^{-13}
Output Wood Chips Chain	Particulates—chipper	kg	3.2×10^{-3}
	NO_x—chipper	kg	1.8×10^{-2}
	Particulates—bucket	kg	1.3×10^{-3}
	NO_x—bucket	kg	1.8×10^{-2}
	Particulates—shredder	kg	5.2×10^{-3}
	NO_x—shredder	kg	8.5×10^{-3}
Output NG Combustion	Heat, waste	MJ	3.1×10^{-4}
	Acetaldehyde	kg	2.8×10^{-13}
	Benzo(a)pyrene	kg	2.8×10^{-15}
	Benzene	kg	1.1×10^{-10}
	Butane	kg	2.0×10^{-10}
	Methane, fossil	kg	5.7×10^{-10}
	Carbon monoxide, fossil	kg	6.0×10^{-10}
	Carbon dioxide, fossil	kg	1.6×10^{-5}
	Acetic acid	kg	4.3×10^{-11}
	Formaldehyde	kg	2.8×10^{-11}
	Mercury	kg	8.5×10^{-15}
	Dinitrogen monoxide	kg	2.8×10^{-11}
	Nitrogen oxides	kg	5.1×10^{-9}
	Polycyclic aromatic hydrocarbons	kg	2.8×10^{-12}
	Particulates, <2.5 µm	kg	5.7×10^{-11}
	Pentane	kg	3.4×10^{-10}
	Propane	kg	5.7×10^{-11}
	Propionic acid	kg	5.7×10^{-12}
	Sulfur dioxide	kg	1.6×10^{-10}
	Dioxin	kg	8.5×10^{-21}
	Toluene	kg	5.7×10^{-11}
Input Composting Step	Residues sent to composting plant	kg	294.1
	Compost produced (35% efficiency)	kg	102.9
	Transportation 2.5 t lorry	tkm	2.5

Table 3. LCI for the wood-residues scenario.

LCI Stage	Process	Unit	Amount
Input Wood Chips Chain	Wood residues	kg	294.1
	Transportation 2.5 t lorry	tkm	14,117.6
	Electricity—chipper	kWh	10.6
	Electricity—bucket	kWh	4.5
	Electricity—shredder	kWh	2.1
	170 kW Furnace	p	2.9×10^{-11}
Output Wood Chips Chain	Particulates—chipper	kg	3.2×10^{-3}
	NO_x—chipper	kg	1.8×10^{-2}
	Particulates—bucket	kg	1.3×10^{-3}
	NO_x—bucket	kg	1.8×10^{-2}
	Particulates—shredder	kg	5.2×10^{-3}
	NO_x—shredder	kg	8.5×10^{-3}
Output from Wood Chips Combustion	Benzene	kg	6.7×10^{-3}
	Benzene, ethyl-	kg	2.2×10^{-4}
	Benzo(a)pyrene	kg	3.7×10^{-6}
	Bromine	kg	4.4×10^{-4}
	Cadmium	kg	5.1×10^{-6}
	Calcium	kg	4.3×10^{-2}
	Carbon dioxide, biogenic	kg	7.9×10^{2}
	Carbon monoxide, biogenic	kg	8.7×10^{-1}
	Chlorine	kg	1.3×10^{-3}
	Chromium	kg	2.9×10^{-5}
	Chromium VI	kg	2.9×10^{-7}
	Copper	kg	1.6×10^{-4}
	Dinitrogen monoxide	kg	2.2×10^{-2}
	Dioxins	kg	2.3×10^{-10}
	Fluorine	kg	3.7×10^{-4}
	Formaldehyde	kg	9.5×10^{-4}
	Heat, waste	MJ	7.9×10^{3}
	HC aliphatic, alkanes	kg	6.7×10^{-3}
	HC aliphatic, unsaturated	kg	2.3×10^{-2}
	Lead	kg	1.8×10^{-4}
	Magnesium	kg	2.6×10^{-3}
	Manganese	kg	1.2×10^{-3}
	Mercury	kg	2.2×10^{-6}
	Methane, biogenic	kg	5.1×10^{-3}
	m-Xylene	kg	8.8×10^{-4}
	Nickel	kg	4.4×10^{-5}
	Nitrogen oxides	kg	9.5×10^{-1}
	Non-methane volatile organic compounds	kg	6.6×10^{-3}
	Polycyclic aromatic hydrocarbons	kg	8.1×10^{-5}
	Particulates, <2.5 µm	kg	2.5×10^{-1}
	Pentachlorophenol	kg	5.9×10^{-8}
	Phosphorus	kg	2.2×10^{-3}
	Potassium	kg	1.7×10^{-1}
	Sodium	kg	9.5×10^{-3}
	Sulfur dioxide	kg	1.8×10^{-2}
	Toluene	kg	2.2×10^{-3}
	Zinc	kg	2.2×10^{-3}
Avoided Processes	Avoided compost produced (35% efficiency)	kg	102.9
	Avoided t residues transportation 2.5 t lorry	tkm	2.5
	Avoided NG combustion	MWh	1.1

3. Results and Discussion

As outlined above, the LCIA stage was carried out using the ReCiPe analysis method, considering four impact categories at a midpoint level, such as: climate change, human toxicity, particulate matter formation (PMF) and fossil fuels depletion. Table 4 collects the results for each category selected. Moreover, the selection of ReCiPe allows the calculation of a cumulative score (expressed in points, Pt), which indicates the more sustainable scenario, following a holistic perspective. This cumulative result, also called single score, is obtained by summing up (algebraically) the results achieved for each midpoint category, taking into account all the embodied impacts for every stage involved within the boundaries. Single score results are shown in Figure 4.

Table 4. Comparison between the current heating system and the wood-based scenario for the production of 1 MWh of thermal energy, at midpoint level. The expression eq. stands for equivalent; and PMF: particulate matter formation.

Impact Category	Unit	Current Heating System	Heat Recovery from Wood Residues
Climate change	kg CO_2 eq.	3980	2398
Human toxicity	kg 1,4-DB eq.	76.9	69.4
PMF	kg PM10 eq.	4.3	3.2
Fossil fuels depletion	kg oil eq.	1237	752

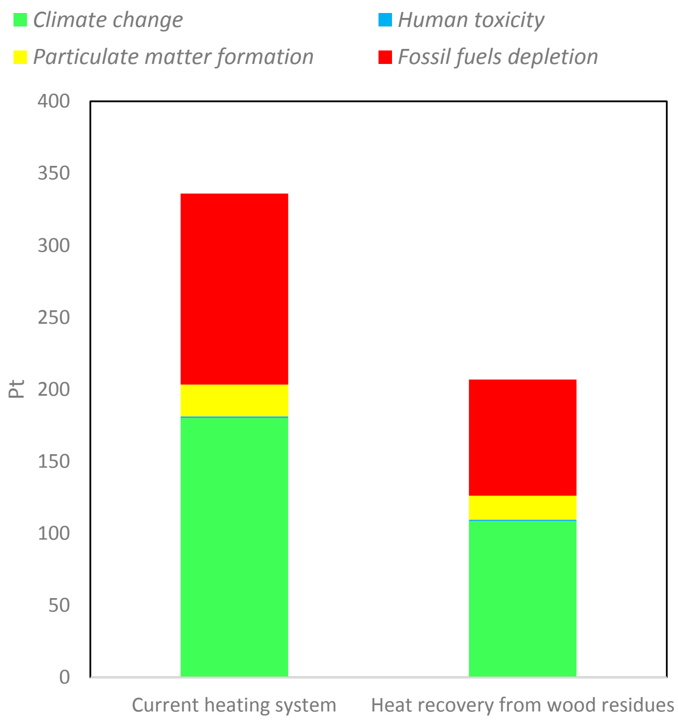

Figure 4. Single score assessment: comparison between the current heating system and the wood-based scenario for the production of 1 MWh of thermal energy.

As depicted, the use of wood residues leads to considerable benefits in terms of climate change (considering a 100-years perspective) and of fossil fuels depletion, −41% and −40%, respectively. Similar GHGs mitigation trend was already outlined by previous works [7,8], which suggested the importance of using wood-based appliances to reduce climate change effects. Furthermore, Paredes-Sánchez et al. [26] studied the valorization of residues in Asturias, Spain, where the use of biomass offers the opportunity to create a new path to economic development with a reduction of

CO_2 emissions. A similar topic has been discussed, regarding the wood residues in British Columbia (Canada) [27]: for small scale community cogenerating plant the use of wood residues generated the cheapest electricity. Wolf et al. [7], studying the energetic use of wood in a German region, outlined that the magnitude of mitigation can vary greatly depending on the current thermal energy mix. Despite the reductions, all the flows involved within the entire biomass chain lead to a non-neutral emission of GHGs. The greatest contribution to GHGs emissions for both scenarios is due to transport, but the difference in GHGs emission is due to the production of NG, which is greater in the traditional scenario. However, it must be reminded that the energy use of biomass requires primary energy both for transportation and fuel production stages, nowadays still covered by fossil resources.

Table 3 reports all the emissions deriving from combustion: substances such as benzene, toluene, PAH, dioxins, mercury and formaldehyde reach significantly higher values than the releases resulting from gas burning. These results could be improved, because they represent average emissions of a wood chip furnace not equipped with innovative pollution abatement technologies [20]. More accurate and primary data concerning the combustion phase are expected in the near future, resulting from dedicated monitoring campaigns. The same revision is desirable for the NG-based scenario, which is modelled considering average data from EU appliances, not primary values. Nevertheless, it is expected that these limitations do not affect significantly the final scores.

Interesting results are achieved in terms of PMF, where no significant differences between the scenarios are detected. According to a contribution analysis run for the PMF category, wood chips combustion affects the release of PM only for 15%. This is due to the characteristic of fuel: combustion of chips releases around 0.47 kg PM10 eq. per MWh, lower than the average 0.52 kg PM10 eq. for the wood logs [20]. A detailed inventory analysis was also run to determine which substances contribute most to PM for the whole scenario: primary particulate (e.g., PM > 2.5 and <2.5 µm) affects the category for 32% (mainly fine particulate, 19%), on the other hand 67% is due to secondary particles, which form starting from gases as NO_x (59%) and SO_2 (14%). Even if considerations on each category are important, single score is useful to show which scenario is more sustainable if compared globally. As can be seen from Figure 4, the centralized system using wood-based appliances seems more competitive. This trend is depicted by the performance pie chart (Figure 5): it shows the overall impacts reduction of the alternative scenario if compared with the traditional decentralized system. The cumulative score is reduced by 38%, with considerable benefits for the community. However, it is interesting to notice that the potential benefits coming from possible future implementations (grey), could prevail.

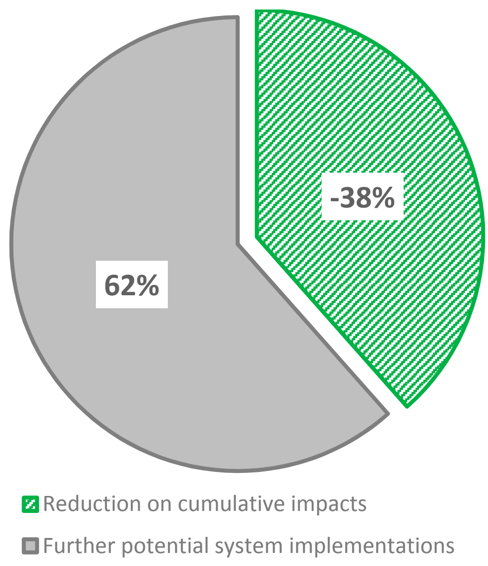

Figure 5. Contribution on cumulative score and potentialities of improvement.

A contribution analysis using the SimaPro network tool (Figure 6) illustrates where these potentialities are concentrated. The Sankey-based diagram shows that transportation of the biomass residues contributes for 97.9% to the single score. However, the network tool helps to understand the reasons for this high contribution, which is related to the embodied processes in the transportation step.

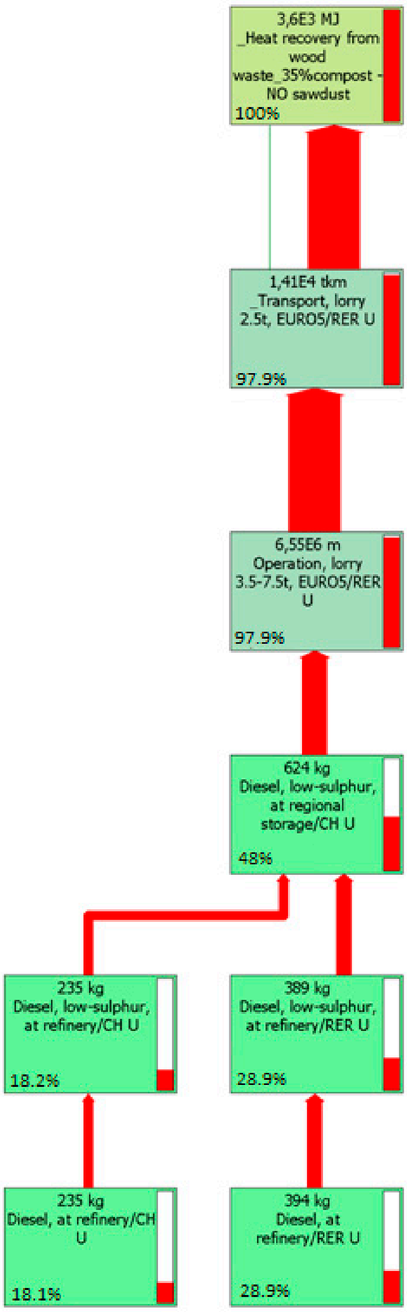

Figure 6. Network tool on cumulative score.

Among these, the diesel chain seems to have the highest contribution, as a consequence of the greater amount of resources and energy requirements for extraction and refinery procedures. According to a personal communication from the working company, an average EURO 5 lorry with 2.5 t capacity is assumed to cover the entire distances and collect all the prunes. In line with the Italian case study, a diesel-fueled truck has been considered in the model. This great usage of fossil-based transportation seems to affect all the impact categories considered. Although the higher contribution (near 91%) is due to the cumulative effects on climate change and depletion of fossil fuels, it is worth noting the harmful consequences due to the human-related categories: 83% contribution for the release of toxic substances and 84% for the PM. Therefore, a fossil-based transportation still represents a strong limitation for the biomass to energy systems, even if local (e.g., 30 km) prunings are considered.

In fact, as reported [28–30] the replacement of diesel with NG in vehicles such as trucks and tractor trailers seems to contribute greatly to CO_2 emission mitigation, reducing the potential impact on climate change. Differently from the CO_2 reduction, which is detected within the whole life cycle of a vehicle (and in particular during its operation procedures), SO_x and PM decrease is achieved if the total amount is taken into account [30]. In addition, further reduction is obtained if hybrid trucks are considered: this technology seems to contribute to the climate change mitigation, reducing the operation emissions of around −25% if compared with a traditional diesel truck [31]. Moreover, according to Tong et al. [29], the use of the full electric MHDVs (medium and heavy-duty vehicles) leads to a greater overall GHGs reduction, estimated around 31%–40%.

Therefore, given the large contribution of transportation, a sensitivity analysis has been run, showing how the overall impacts may vary if a smaller collection distance is taken into account. In particular, 10 km roundtrip have been assumed. As depicted in Figure 7, results are strictly affected by the provision distance: alternative scenario (10 km) achieved around 1/3 of the overall impact evaluated for the 30 km scenario.

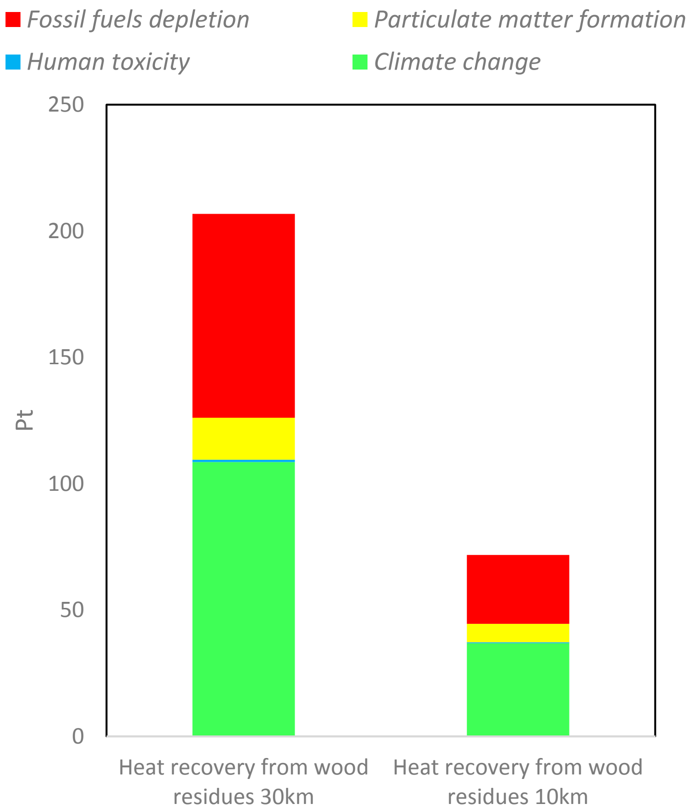

Figure 7. Single score assessment: comparison between the traditional wood-based scenario with the scenario with less km, for the production of 1 MWh of thermal energy.

In addition to the use of cumulative score, ReCiPe method makes it possible to convert the results at midpoint level to potential impacts on different receptors. LCA methodology usually refers to three macro-categories of damage: human health, ecosystem quality and resources depletion. Figure 8 collects these results, showing that the adoption of a centralized heating system based on the use of biomass residues (locally collected and burned) contributes to a considerable reduction on each damage indicator, estimated around 38%–40% of the total.

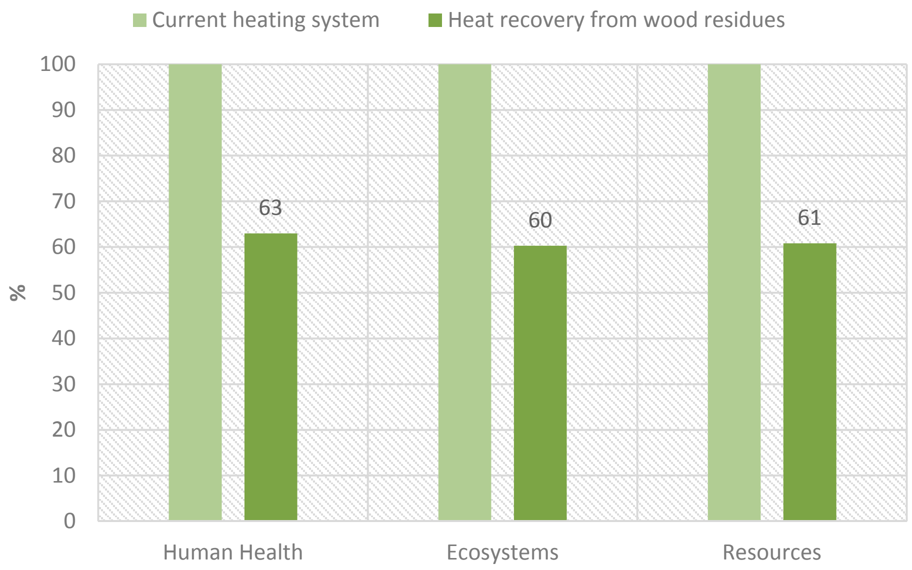

Figure 8. Damage assessment distribution among the two scenarios.

4. Conclusions

The exploitation of wood residues to produce renewable energy for a small Italian municipality was investigated by the use of LCA methodology. Burdens were evaluated considering all the negative effects on environment, resources depletion and human health within the entire biomass handling chain: from wood handling, up to its transportation and utilization to produce chips, and the burning in a dedicated appliance, to satisfy the heat requirements of some public buildings. Moving from a decentralized system based on fossil resources (e.g., NG) to a district heating system which implies the usage of local biomass residues, some global environmental impacts appear reduced, such as the GHGs emissions and the depletion of non-renewable fuels. Therefore, this approach based on the collection of the wood scraps deriving from pruning activities could help small communities achieve the targets fixed by European guidelines for 2020: 15% energy reduction and 20% GHGs mitigation. In addition, the consumption of local resources contributes to increase the energetic independence of these small territories, avoiding to be influenced by socio-economic fluctuations to which all feedstocks are subjected. However, as expected, biomass combustion results in the worst effects in terms of toxic substances emitted. This aspect should be investigated in depth by the use of dedicated monitoring campaigns, to collect primary and updated data to fill in the LCA models. Moreover, all the movements still represent a critical issue, in particular when diesel vehicles are used to cover the distances. Transportation contributes to the global impact by 98%, even if distances are restricted to a 30 km roundtrip. Thus, to meet EU targets for pollution mitigation, an implementation of more sustainable engines (e.g., NG, hybrid and full electric) is certainly recommended. The literature has already shown that the usage of NG-fueled or hybrid trucks, replacing traditional diesel-based vehicles, contributes significantly to GHGs reduction [30,31]. Nevertheless, emissions from electric vehicles greatly vary depending on the electricity mix: when low-carbon energy grids are implemented, vehicles are close to neutral CO_2 emissions, while if carbon-intensive electricity mix is used, biofuels usage leads to a lower carbon footprint than hybrid [32]. This is the reason why the sustainability should be evaluated case by case, taking into account all the variables and limitations (e.g., economic, geographical, social and political) which affect the system under investigation.

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