Local waste agroforestry management – biomass to energy analysis with LCA

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ABSTRACT: To enable the protection of forests against rural fires are foreseen a set of measures for planning and intervention, reduction their risk and impacts. Forest residues collecting centers are being created in Portugal, to reduce undesired thermal charge in nature and for biomass further valorization.

Keeping this in mind, one of the strategies is the energy recovery from these residues in biomass power plants that were built in strategic locations. The biomass is mostly natural residual forest, agricultural and garden wood and green materials The present work aims to study its environmental impact.

The Life Cycle Assessment methodology, using SimaPro 9.3.0.3 PhD software, was applied to identify the burden of this process and the environmental categories most relevantly affected.

Data achieved showed the importance of the valorization of residual biomass for energy production, reduction the impact categories of abiotic depletion due to fossil fuels, global warming, human toxicity and eutrophication.

1 INTRODUCTION

The rise in global temperature has the potential to worsen desertification and wildfires, with highly serious negative effects on the economy, the environment and society. Although, fire occurrence also arises from wrong practices in the management of agricultural and forest residues (AFRs) (Parente et al., 2018). It is very important to manage these materials to reduce the risk of fire and it is crucial to have more forest areas in order to reduce climate change and increase CO_2 sequestration (d'Angelo et al., 2000; Gomes, 2006; van Doorn et al., 2007; Nunes et al., 2021). Portuguese legislation also emphasizes the obligation to collect residues in forests or pastures (Decree law n°. 82/2021 October 2021). The proper management, including the proper supervision of forest fuels, and the use of biomass waste for energy and material recovery, promotes the environmentally sustainable management of this waste, enhancing the reduction of the practice of burning and slash-and-burn and the valorization of an important resource.

The establishment of residual biomass collection centers (RBCC) was one of the national management strategies for these renewable fuels. Studies have been conducted to understand the potential of energy valorization of forest residues, namely following the methodology of life cycle assessment (LCA), which is one of the most thorough analytical methods for examining the advantages and trade-offs of sustainability in complex systems (Ciacci & Passarini, 2020). Some are based on an attributional approach (Tagliaferri et al., 2018; Gonzales-Garcia et al., 2019), others on a consequential approach (da Costa et al., 2020) for system boundaries definition. The attributional, characterized by the use of average life cycle inventory analysis (LCI) data and co-product allocation, aims to evaluate the environmental impacts of a product from cradle to grave, in a static system. The consequential LCA consists of the evaluation of environmental consequences in a dynamic system, oriented by changes, namely the reduced impacts of traditional processes or product usage arising from the changes introduced with the new approaches proposed. In all cases, the need to consider the impacts of such development on other categories besides climate change and photochemical oxidation emerged. Among the impact categories that are normally assigned, besides these two, special focus will be given to ozone depletion, acidification, eutrophication – freshwater, marine and terrestrial, photochemical ozone formation, depletion of abiotic resources, minerals/metals and fossil fuels, human toxicity, eco-toxicity (freshwater), water use, land use, particulate matter emissions and ionizing radiation (human health).

The purpose of this study was to evaluate the environmental impact of the energetic valorization of the biomass resulting from forest and agriculture managing harvesting (agroforest residues – AFRs), engaging their management from the wastes producing spot transportation to the RBCC, the operations for their preparation for further usage, the transportation to the biomass power plant and consequent transformation.

2 METHODOLOGY

The International Reference Life Cycle Data System (ILCD) manual (EC/JRC/IES, 2010b) and ISO 14040 (2006a), ISO 14044 (2006b), were used to perform a life cycle assessment of the thermal valorization processes of local agroforestry wastes following real assumptions from collection to the use. Goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), interpretation, and presentation of findings are the four steps that make up the LCA process, which was conducted with SimaPro 9.3.0.3 PhD software (PRé 2021). This software simulates several processes and data yields. The CML-IA baseline V3.07 / World 2000 (PRé 2020) method of impact assessment was used to realize the waste-to-energy process.

2.1 Study area

The Biomass Power Plant (BPP) that receives the AFRs for energetic valorization is in the council parish of Mundão, Viseu. The RBCC that collects the AFRs for this BPP is located in Bodiosa, a council parish in the northwestern part of the municipality of Viseu, in northern Portugal. Currently, AFRs are transported from the RBCC to the BPP for further energetic valorization.

2.2 Goal and scope definition

The goal of the study is to assess the potential environmental burden of producing electricity from AFRs. From the local analysis of AFRS, it was possible to realize that they were mainly set up of natural residual forest pecks and branches direct from harvesting, agricultural and garden woody and green materials arising from pruning activities. The function of the system under examination is to enhance the residues thermal valorization, and the system boundary was outlined according to Figure 1.

The system accounts for the transportation of AFRs to the RBCC, where the shredding is performed, their transportation from the RBCC to the BPP, as well as the combustion process, the feed water and the resulting fly ashes and bottom ashes treatment. AFRs are considered waste, with no economic value. Therefore, their production phase is not considered ('zero-load assumption') once impacts are connected to the fundamental items based on their monetary value. If it has no impact on the conclusions reached, the zero-burden assumption is a proper methodologically to be followed (ISO, 2006a).

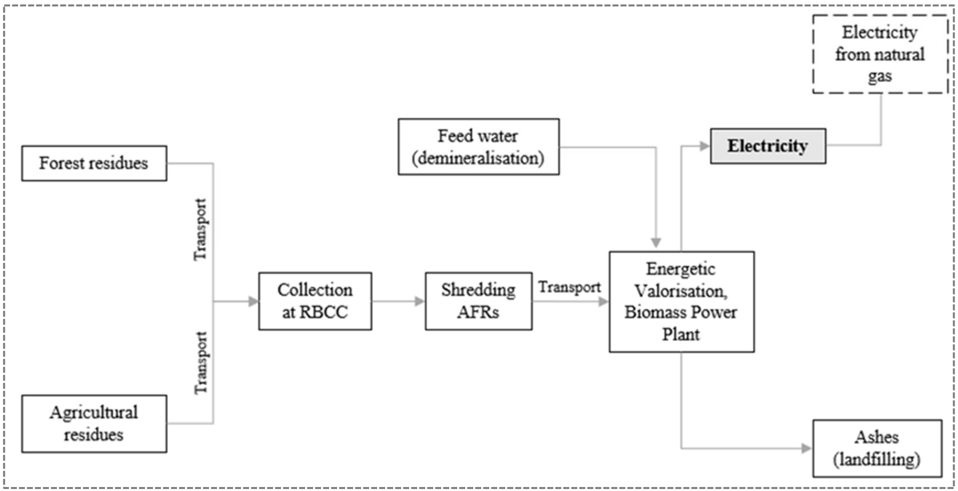

Figure 1. Definition of the system boundaries in the valorization of AFRs for electricity production.

All the input and output loads are referred to as the functional unit (FU) of the study, which is 1 tonne, wet basis, as used by Quinn et al (2020), of AFRs collected at the RBCC of Bodiosa. The moisture content of the AFRs was considered 37%, according to experimental procedures.

2.3 *Inventory data*

The most elaborate phase of an LCA study is the Life Cycle Inventory, in which it is necessary to collect data for the processes under investigation as closely as possible to reality. To ensure consistency of inventory analysis and impact assessment with the goals of the study, the data collected must be temporally and geographically significant, and technologically representative. The data used for the study was obtained from the laboratory namely the biomass characterization (data not published). Further data, secondary data, were provided by the BPP, from scientific publications and the Ecoinvent 3.8 database (Moreno et al., 2021). To relate the outputs with the functional unit of the study, a density of 0.4 ton/m3 was considered. Due to the lack of data, the production of the agricultural residues has been neglected.

2.4 *Transportation of AFRs*

The first stage of the analysis is the delivery of AFRs from the production to the RBCC, considering the working time of the agricultural vehicles typically used to transport biomass, its fuel consumption and related emissions.

According to BPP, the biomass collection centres should have a 10-kilometer effect zone (Unidade de Biomassa – Centro da Biomassa para a Energia, 2021). Larger distances will not be justified by the users. To quantify the required time parameter, Geographic Information System (GIS) analysis was performed after considering the distribution of forest and agricultural soils (CLC, 2018) in the RBCC influence area, considering the OpenStreetMap road network. Data reported by Fernandes and Costa (2010) was the basis of the annual residual biomass productivity rate (ton/ha) for several plant species. This information, along with the above information about the soil occupation, was the basis for the AFRs annual production estimate. A centroid, representing the entire corresponding area, was associated with each CLC region, selected for the beginning of each trip from a homogeneous zone. It was also considered that each tractor had a capacity of 1 tonne, and the time required to complete each journey was estimated through ORS Tools. Through Equation 1 it was evaluated an average time for the delivery of residual biomass.

$$t_f = \frac{\sum_i b_i \cdot t_i}{C} \tag{1}$$

Where b_i is the fraction of biomass transported, ton, t_i the time required to transport, min and C is the capacity of the transport vehicle, ton.

2.5 *AFRs shredding*

In the RBCC, when adequate, the biomass is shredded previous to the BPP shipment. Biomass is taken through an excavator with a grapple and fed into a crushing machine with a hammer mill. The productivity is 20 ton/h. Ecoinvent 3.8 database was accessed for data analysis.

2.6 *Biomass to energy impacts evaluation*

Specific considerations were done considering the characteristics of the BPP of Mundão, Viseu, which has a turbine with an installed capacity of 15 MW. The AFRs are transported by lorries from the RBCC to the plant by Euro5 category vehicles, assuming an average age of 10 years. A quantity of 15 ton/h of biomass is required to produce 15 MWh of electricity, while 1 MWh is required to electrically support all the plant's components. The overall net electricity production is 14 MWh. For the vapor production in the boiler, water from three existing wells is used, after a proper demineralization treatment, namely microfiltration, osmosis and an electro deionization unit to reduce the ion concentration. The water consumption associated with the boiler is 2.5 m^3/h. Specific data for further impact evaluation was retrieved from Ecoinvent 3.8 database.

The output from the boiling process are exhaust gases that are treated by a cyclone and a bag filter. To assess conformity with legal limits, CO, NO_x, Total Particles, Volatile Organic Compounds, and CO_2 emissions are periodically monitored. The latter is supposed to be biogenic (Manfredi et al., 2011; Tagliaferri, 2018; Corona et al., 2020).

The bottom ashes were estimated to be equal to the average ash value determined during the characterization of the AFRs (data not published), which came to 3.38% on a dry basis. They are disposed of in a landfill. Considering the low amount of ashes produced per 1 tonne of biomass, the effects of transporting them to the landfill aren't taken into account.

Currently, the least-performing energy source used for electricity production is natural gas, and according to Portuguese directives, electricity generation from natural gas will be maintained until 2040 (IEA, 2021). Following the consequential approach for the LCA analysis, it was considered that electricity produced by the BPP will avoid the emissions produced by the natural gas power plant. Data referred to the FU of the study are shown in Table 1.

Table 1. Data collected for the energetic valorization of 1 tone of biomass in the BPP

	Process/material	Quantity	Unit measure
Inputs	Shredded biomass	0.980	ton
	Transportation to Biomass Power Plant	17.3	ton km
	Water (treatment)	98	kg
Emissions to air	CO	0.226	kg
	NO_x, as NO_2	0.879	kg
	TP	0.067	kg
	VOC	0.103	kg
	CO_2	1108	kg
Outputs	Electricity	0.549	MWh_{el}
	Ashes (landfilling)	20.879	kg
Avoided products	Electricity, from natural gas	0.549	MWh_{el}

2.7 *Impact assessment*

Using the findings from the LCI, the impact assessment stage of the LCA aims to determine the significance of potential environmental consequences, combining inventory data with specific environmental impact categories and category indicators (ISO, 2006a).

Since they represent the life cycle impact of a reference flow, with a functional unit, the impacts evaluated using LCA are potential rather than actual, keeping also in mind that the data used arises from inventories that have their specificities. The chosen impact assessment method, CML-IA baseline V3.07 / World 2000 (PRé 2020), was developed in 2001 and uses a midpoint approach. The impact assessment was done through the analysis of the impact categories: abiotic depletion (AD), abiotic depletion associated with fossil fuels (ADff), global warming (GW), ozone layer depletion (OD), human toxicity (HT), fresh-water aquatic ecotoxicity (FWET), marine ecotoxicity (ME), terrestrial ecotoxicity (TET), photochemical oxidation (PO), acidification (AC), eutrophication (EU).

3 RESULTS

The process under study is biomass valorization in a power plant for electricity production, considering the overall process. It was studied biomass producers' collection, transportation to the RBCC, shredding, transport to the BPP and the combustion and electricity production, also considering the input of water and its treatment as well as the final deposition of the ashes resulting from the combustion. Following the methodology previously described, it was considered the annual production of 5115 tonnes of AFRs, with 73% and 27% of forest and agricultural, respectively. Practical analysis of local activities allowed to verify that three minutes were required to crush 1 tonne, the operating time of both machines. There is a 2% loss of biomass as a result of shredding (Forsberg, 2000; Whittaker et al., 2011).

Figure 2 presents the results of the assessment for the biomass-to-energy impact process, with the impacts produced in the positive sector of the diagram, and those avoided in the negative one. The most important fact that arises from Figure 2, and Table 2, is the benefit of producing energy from biomass instead of natural gas, in all the impact categories, represented in the negative sector of the diagram of the operation – Electricity production from natural gas. It is worthwhile to verify that all the impacts in Table 2 have in fact a negative value. As the CO_2 generated by biomass combustion (Operation AFRs Combustion) is biogenic, its impact on GW is null. Without electricity production from natural gas, which is a fossil fuel, advantages accrue to all impact categories. Those most positively affected are abiotic depletion due to fossil fuels, global warming, human toxicity and marine ecotoxicity, because of the lower emissions of carbon dioxide and methane. As assessed by Tagliaferri (2018), the overall greenhouse gas emissions from BPP have a negative balance, hence a positive effect on the environment, when compared to the avoided burdens of conventional electricity production. In contrast, the AFRs combustion is remarkably important for the photochemical oxidation, acidification and eutrophication categories, where it generates 82-90% of the impacts. Nitrogen dioxide emission is the substance with the greatest influence on AC (0.259 $kgSO_2{}^{-}{}_{eq}$) and EU (0.0672 $kgPO_4{}^{2-}{}_{eq}$). The same substance, combined with carbon monoxide, also impacts on PO (0.0181 kg C_2H_{4eq}). The outcomes are comparable to those obtained by da Costa et al. (2020), as they found that electricity production from biomass has a significant environmental impact in categories such as AC, PO and EU.

The biomass shredding stage appears to be the main contributor to impacts in the AD and HT categories, accounting for 51% and 30% of all impacts, while its influence on the TET category is not marginal (36%). Therefore, the use of higher-efficiency equipment should be considered to decrease the environmental impacts of this operation.

Transport processes are the main contributor to the impacts in the ADff (50%) and OD (51%) categories. They also constitute the hotspot for the categories GW (50%), mainly due to CO_2 emissions from oil combustion, and TET (43%), due to the release of substances such as mercury, zinc, and chromium. Is important to point out that the transportation of biomass is a significant source of greenhouse gas emissions, so it should be taken into account when determining the forest industry's carbon neutrality. One important improvement should be the technological development of management tools to improve transportation efficiency, namely with the use of larger and heavier vehicles fully loaded (Palander et al., 2020).

Considering the deposition of the resulting ashes in landfill it is verified an important outcome in environmental impacts like freshwater ecotoxicity, marine ecotoxicity and human toxicity, due to the potential leaching of heavy metals, such as vanadium, nickel, molybdenum, and arsenic into water. With adequate valorization of these ashes, the impacts will significantly decrease. Several methodologies may arise in the fly ashes valorization, namely in agriculture once they contain significant amounts of nutrients, like, potassium and microelements, but also the remediation of degraded land, environmental protection, synthesis of zeolites, recovery of rare earth metals or production of plastics (Odzijewicz et al., 2023).

Table 2. Characterization of the impacts of Energetic Valorisation

Operation	AD	ADff	GW	OD	HT	FWET	ME	TET	PO	AC	EU
	kg Sb_{eq}	MJ	kg CO_{2eq}	kg CFC-11_{eq}	kg 1,4-B_{eq}	kg 1,4-DB_{eq}	kg 1,4-DB_{eq}	kg 1,4-DB_{eq}	kg C_2H_{4eq}	kg SO_{2eq}	kg $PO_4^{3-}{}_{eq}$
AFRs combustion	0.00 E+00	0.00 E+00	0.00 E+00	0.00 E+00	6.20 E-01	0.00 E+00	0.00 E+00	0.00 E+00	1.81 E-02	2.59 E-01	6.72 E-02
AFRs shredding	1.28 E-05	8.00 E+01	5.77 E+00	9.60 E-07	1.64 E+00	1.38 E+00	2.06 E+03	4.06 E-03	9.21 E-04	1.53 E-02	3.51 E-03
Transportation	1.09 E-05	8.69 E+01	6.12 E+00	1.08 E-06	1.52 E+00	7.78 E-01	1.42 E+03	4.92 E-03	9.20 E-04	2.12 E-02	4.72 E-03
Water treatment, deionisation	4.12 E-07	3.22 E-01	2.82 E-02	1.59 E-08	3.12 E-02	2.17 E-02	4.26 E+01	9.06 E-05	1.06 E-05	2.39 E-04	4.50 E-05
Ashes landfilling	9.62 E-07	5.29 E+00	3.74 E-01	5.58 E-08	1.66 E+00	1.44 E+01	7.82 E+03	2.35 E-03	1.56 E-04	3.04 E-03	6.77 E-03
Electricity production, from natural gas	-7.11 E-05	-4.05 E+03	-2.40 E+02	-3.14 E-05	-6.68 E+00	-5.55 E+00	-8.85 E+03	-2.80 E-02	-1.57 E-02	-1.74 E-01	-3.04 E-02
Total	-4.60 E-05	-3.88 E+03	-2.27 E+02	-2.93 E-05	-1.21 E+00	1.10 E+01	2.49 E+03	-1.66 E-02	4.42 E-03	1.24 E-01	5.19 E-02

AD-abiotic depletion; ADff-abiotic depletion associated with fossil fuels; GW-global warming; OD-ozone layer depletion; HT-human toxicity; FWET-fresh-water aquatic ecotoxicity; ME- marine ecotoxicity; TET-terrestrial ecotoxicity; PO-photochemical oxidation; AC-acidification; EU-eutrophication.

Advantages for OD are gained by the avoided emissions of Halon 1211 and HCFC-22. Due to the extraction of raw materials such as tellurium and copper, energy production from natural gas also has a significant impact on AD, while mercury emissions impact on TET.

The water treatment process is shown to be neglectable for all the considered impact categories. The transportation activity caused significant impacts mainly by the emissions resulting from fuel combustion. Due to emissions of sulphur dioxide, nitrogen oxides, volatile non-methane organic compounds primary particulate matter (PM 2.5), and carbon monoxide, fuel combustion in transportation is one of the main drivers of air pollution (Pergola et al., 2020).

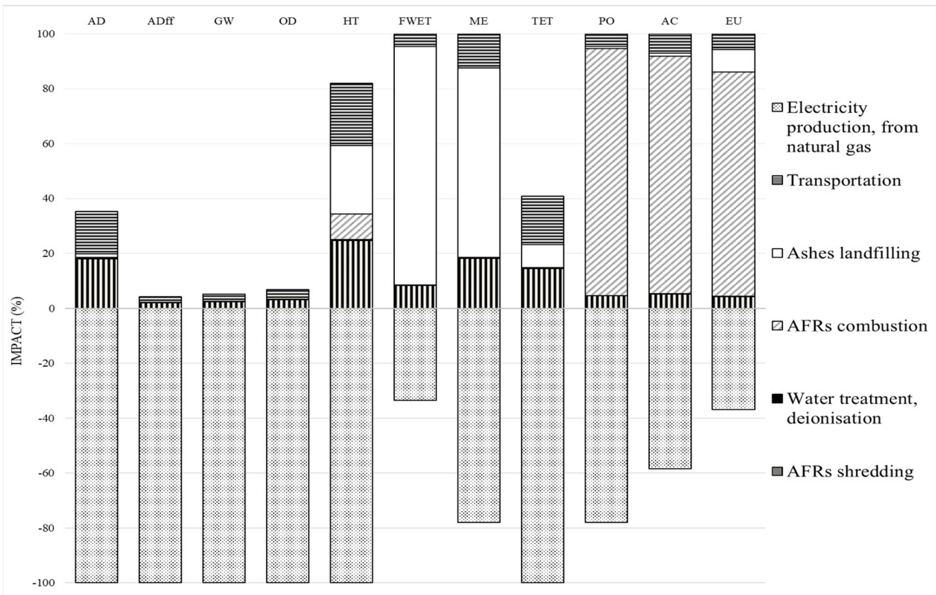

Figure 2. LCA characterization showing the contributions of the biomass operations to impact categories (all impact scores are displayed on a 100% scale) - AD-abiotic depletion; ADff-abiotic depletion associated with fossil fuels; GW-global warming; OD-ozone layer depletion; HT-human toxicity; FWET-fresh-water aquatic ecotoxicity; ME- marine ecotoxicity; TET-terrestrial ecotoxicity; PO-photochemical oxidation; AC-acidification; EU-eutrophication.

Considering other valorization processes like composting or mulching of AFRs (data not shown), composting tends to have a better environmental performance for most impact categories analysed, namely due to the nutrient content, which avoids the production of a larger quantity of conventional fertilisers. Further considerations concerning the carbon capture potential of compost should be pointed out, namely the potential increase of organic matter content in soils and the amount of C that is stored in the soil for long periods, which can be regarded as avoided emissions of CO_2 (Favoino & Hogg, 2008). Franz et al. (2009) estimated a carbon sequestration rate (over 100 years) of 8.2%, while Luske (2010) presented an amount between 0-22% of the organic carbon in compost sequestered, even though factors such as the application rate, soil management, temperature, moisture level and crop types affect this sequestration ratio.

4 CONCLUSION

Considering the LCA of the AFRs energetic valorization in a local BPP, accounting for the overall process since collection in the harvesting to the electrical energy production, it was verified that the greater impact was the reduction of abiotic depletion due to fossil fuels, global warming, human toxicity and eutrophication resulting for the decrease of energy production by fossil fuels (specifically natural gas). The overall operations of AFRs management in this process were considered in the LCA. From this assessment, is possible to recognize that the operations that use fossil fuels, namely the ARFs shredding and transportation, have the highest impact, mainly in the categories of AD (fossil fuels), GW, HT and ME.

It is expected that the reduction of utilization of fossil fuels will reduce the environmental burden of energy production, mainly with its substitution by AFRs or other biomass-based fuels, mainly due to the reduction of greenhouse gases emission and therefore, global warming. Although the use of AFRs showed to be a promising technology for the environment and the economy, context-specific parameters such as quality standards for material inputs and combustion efficiency should be taken into consideration for their use in the BPP. Considerations should be made like the mix of different biomass, with higher quality standards.

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