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A simplified methodology for estimating the Carbon Footprint of heat generation by forest woodchips as a support tool for sustainability assessment in decision-making

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ABSTRACT

Energy production from biomass is very strategic for the achievement of global sustainability goals and the use of biofuels for decentralized energy production in medium-small size plants, which conforms to global fossil energy and GHG reduction targets, is expected to increase in the short-medium term.

This paper proposes a simplified methodology for estimating the Carbon Footprint associated with heat generation by forest woodchips. The methodology includes all the relevant life cycle phases and is based on the specific fuel and plant characteristics, so it can effectively support sustainability assessment in decision-making regarding biomass projects through proper Carbon Footprint estimates.

The application of the methodology showed results in the range of about 6–12 gCO_2eq/MJ, depending on the case study characteristics, that agree with the impact values range observed from previous literature. The basic idea that the use of forest woodchips is particularly strategic for sustainable energy production within a “local” wood-energy supply chain (short transport distance) was confirmed. Furthermore, the methodology allowed to estimate indicative transportation distances for which forest woodchips can be considered environmentally competitive compared to alternative renewable sources such as, for instance, wood pellets.

1. Introduction

Bioenergy can be considered one of the most relevant resources for the achievement of global sustainability goals, given the wide availability of materials (residual, agricultural and forestry biomass, second harvest, and coverage crops), their potential exploitation for different energy purposes, and also due to the climate change mitigation associated with the CO_2 absorption along the biomass supply chains.

Modern bioenergy is the largest source of renewable energy globally, accounting for 55% of renewable energy and more than 6% of the global energy supply. In recent years, due to higher levels of policy support, bioenergy for electricity and transport biofuels has been growing quickly, but the heating sector remains the largest source of bioenergy (International Energy Agency, 2022) and, in this context, solid biofuels represent one of the main primary resources.

About 85% of the global supply of biomass (56.9 EJ in 2019 (World Bioenergy Association, 2021)) derives from solid biomass sources including woodchips, wood pellets, and traditional biomass sources. In the EU27, solid biofuel primary energy consumption in 2021 increased by +8.1% over the previous year’s level, reaching 104.2 Mtoe. This increase can be ascribed to several causes and one of them is the hike in fossil energy prices in the second half of the year that made biomass fuels more competitive (EUROBSERV ’ ER, 2022). Italy is one of the main users, with a primary energy gross domestic consumption equal to 8,874 Mtoe (compared to a production of 7,590 Mtoe), a gross production of electricity equal to 4,529 TWh, and heat consumption of 7,464 Mtoe (EUROBSERV ’ ER, 2022). Furthermore, the recent transposition of the European Directive “Renewable Energies” (known as RED II) (EU, 2018), coherently with the Italian Integrated National Plan for Energy and Climate (PNIEC) (Italian Ministry of the Environment and Energy Security, 2020), deals with the relevant aspects for a further increase in renewable energies (reference legal framework, support schemes, …) to achieve the 2030 objectives, also referring to the use and sustainability of biomass.

In this context characterized by a significant increase in the price of conventional energy sources (in particular, natural gas) and uncertainty

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in their supply, an increasing use of biofuels for decentralized heat generation in small-to medium size plants is predictable in the short-to medium-term. In addition to the economic advantages for the end-user, this kind of biomass exploitation is particularly strategic to enhance energy supply security, reducing the dependence on imported fossil fuels, diversifying supply patterns, and broadening the diversity of energy sources facilitating the transition towards a renewable energy supply (Kouchaki-Penchah et al., 2022). Moreover, it is also in line with the PNIEC (Italian Ministry of the Environment and Energy Security, 2020), which calls for the use of efficient and low-emission plants based on biomass from short supply chains that meet sustainability and circularity (valorization of agricultural residues) criteria.

Given the above, residual forest biomass for heating represents a strategic alternative to fossil fuels that conforms to global fossil energy and GHG reduction targets. Anyway, direct biomass exploitation for heating can generate issues for human health and the environment, both locally and globally. Therefore, even if the advantages of biomass exploitation projects can be significant, their potential impacts should not be neglected and properly assessed in a framework of sustainability evaluation.

Decision support tools for the sustainability assessment of forest bioenergy have been developed in recent years to evaluate and communicate the benefits and impacts of energy conversion systems and to support the deployment of bioenergy policies. According to Scott et al. (2012) (Scott et al., 2012) the existing tools are focused on the choice of the most suitable technological solution (27% of the tools studied) rather than on the assessment of the sustainability of projects (only 14% of tools studied) and there is a lack of joint evaluation of social, economic and environmental dimensions in multi-objective approaches (Zahraee et al., 2020). The environmental dimension is the one generally considered, referring to several indicators and GHG emissions represent one of the criteria used for quantitative analyses in the framework of sustainability assessment, with default values gathered from literature to allow the evaluation when specific information is not available (Dias Brandao et al., 2022).

Therefore, a proper sustainability assessment of forest biomass exploitation for energy generation is related to the opportunity of having more accurate preliminary estimates of GHG emissions based on the specific case study/fuel characteristics. Considering this, moreover, it is evident that a useful tool in this regard should account for all the relevant environmental issues of the biomass supply chain and rely on a solid calculation methodology.

A literature review in this regard showed that several LCA-based studies related in general to forest operations have been carried out (Aldentun, 2002; Berg and Lindholm, 2005; Gonzalez-Garcia et al., 2009a, 2009b; Michelsen, 2007; Michelsen et al., 2008; Mirabella et al., 2014), highlighting that machinery use is in most cases responsible for the greatest environmental burdens due to their fuel consumption. Consistently with these studies, most of the literature that analyzed woodchips (of different types and for different uses), such as for instance (Murphy et al., 2014; De La Fuente et al., 2017; Weyrens et al., 2022; Laina et al., 2022; Perić et al., 2020; Ferreira et al., 2014), is focused on their supply chain without considering the energy conversion phase. This specialized literature showed transport and production as relevant phases and identified specific environmental hotspots within the life cycle. In particular, chipping emerged as the process with the greatest contribution to the impact in most of the studies, followed by other forest operations such as fertilization, harvesting, and extraction. The literature that investigated wood-to-energy chains, also including woodchips from forest/residues in the studied fuels, instead, highlighted the environmental convenience of using biomass both for heat (in district heating systems (Neri et al., 2016) and at a single house level (Pelletier et al., 2019)) and power generation, also showing the relevance of the plant size and the combustion specifics (Thakur et al., 2014; Corona et al., 2020; Tagliaferri et al., 2018).

The general evidence that is possible to figure out is that extensive literature regarding LCA of heat generation by woodchips is still missing and, therefore, it can be considered interesting to be explored more in detail, having in mind those parameters that can appreciably affect life cycle impact results, i.e. specific characteristics of fuel, fuel supply chain, and generation plant.

The work presented in this paper was therefore aimed at defining a simplified methodology to preliminary evaluate the Carbon Footprint (CF) associated with the use of forest woodchips for heat generation, considering all the relevant life cycle phases and based on the specific case study characteristics. CF refers to the total amount of GHG emissions directly or indirectly related to an activity or a product life cycle, evaluated as the CO_2 equivalent (CO_2eq) mass based on 100 years Global Warming potential (GWP) and can be effectively used to evaluate the main environmental hotspots/mitigation or improvement measures (Scrucca et al., 2021). Since it is based on the fuel and plant characteristics, as well as on the production methods and the sale/distribution distance, the methodology allows to evaluate the impact at their variation. Moreover, it also allows to identify the conditions for which the use of forest woodchips is environmentally competitive compared to other (conventional and non-conventional) energy sources.

Such a methodology, which to the authors' best knowledge is missing in the literature, is considered useful to more accurately preliminary estimate CF based on a solid and comprehensive approach and, therefore, to support sustainability assessment in decision-making regarding biomass projects.

2. Material and methods

2.1. The proposed simplified methodology

The simplified methodology for the preliminary estimation of the impacts associated with the use of forest woodchips for 1 MJ heat generation here proposed considers all the key aspects of the fuel life cycle (production, transport, and combustion) and, in particular, it calculates the CF in $kgCO_2eq$ as follows:

$$CF_{tot} = \alpha \bullet \frac{GWP_{prod}}{NCV \bullet \eta} + \frac{GWP_{transp}}{NCV \bullet \eta} \bullet d_{transp} + GWP_{plant} \qquad (1)$$

being:

- CF_{tot} the total Carbon Footprint [$kgCO_2eq/MJ$];
- GWP_{prod} the specific life cycle emissions for the woodchips production phase [$kgCO_2eq/t$];
- GWP_{transp} the specific life cycle emissions for the woodchips transport to the energy production plant [$kgCO_2eq/tkm$];
- GWP_{plant} the specific life cycle emissions associated with the fuel combustion in the energy production plant [$kgCO_2eq/MJ$];
- α a coefficient that accounts for the exclusion/inclusion of the cultivation phase and the fertilization or not within it;
- NCV the net calorific value of forest woodchips [MJ/t];
- η the generation efficiency of the energy production plant [%];
- d_{transp} the distance travelled to transport the woodchips to the energy production plant [km].

As structured, Eq. (1) allows to estimate the CF reflecting the potential variability that can occur in the characteristics of the woodchips (variations of NCV) and the generation plant (variations of η), as well as the effects of the production conditions (variation of α) and the transport distances.

Furthermore, Eq. (1) can also be used for estimating the maximum sale/distribution distance for which the use of forest woodchips for heat production is environmentally competitive compared to other energy sources (conventional and non-conventional). As a matter of fact, once the characteristics of the forest woodchips, its production conditions, and the generation efficiency of the plant have been defined (i.e. once NCV, α and η are known) given the total CF value associated with another specific energy source ($CF_{tot,\ alt\_source}$), the $d_{transp,MAX}$ value can be easily obtained equalling the life cycle impacts of the two fuels (Eq. (2)).

$$d_{transp,MAX} = \frac{CF_{tot,alt\_source} - \alpha \bullet \frac{GWP_{prod}}{NCV \bullet \eta} - GWP_{plant}}{\frac{GWP_{transp}}{NCV \bullet \eta}} \tag{2}$$

The following sections describe in detail the estimation of the parameters included in Eq. (1) and Eq. (2), i.e. α, GWP_{prod}, GWP_{transp}, and GWP_{plant}. Particular attention was posed in the modelling of the woodchips production phase (GWP_{prod}) since, according to the previous literature, it represents the key life cycle phase in terms of environmental impact (mainly due to the fossil fuel consumption in the forest machinery, e.g. chipper, truck and trailer, forwarder, …).

Life cycle impact assessment was carried out according to the IPCC2021 method included in SimaPro v9.3 (SimaPro Software, 2022), considering the GWP climate change factors of the sixth IPCC assessment report (IPCC et al., 2021) with a timeframe of 100 years.

The assessment was focused only on the Climate Change impact category since the results of such a calculation are considered relevant to properly identify and quantify environmental issues and are also easy to understand. The CF, in fact, represents one of the most widespread indicators to evaluate the environmental impact of products and communicate results to different audience typologies. The additional environmental information that could be given to the users through a multi-indicator methodology is considered not beneficial (indicators very difficult to understand such as, for instance, acidification, eutrophication, etc.) and not justified by the effort of developing a simplified calculation for different impact categories. Therefore, even if it could represent a limitation of the study, the use of a single and widespread indicator was deemed as a proper choice to develop a simplified calculation methodology to support sustainability assessment in decision-making.

2.2. *Modelling of the woodchips production phase*

The modelling of the woodchips production chain was based on a specific LCA case study in Italy, which was carried out in the framework of the ARCADIA project ("Life cycle approach in public contracts and Italian LCA database for the efficient use of resources") (https://www.arcadia.enea.it/, 2022), financed by the 2014–2020 National Operational Programme on Governance and Institutional Capacity (http://www.pongovernance1420.gov.it/it/progetto/arcadia-approccio-ciclo-di-vita-nei-contratti-pubblici-e-banca-dati-italiana-lca-per-luso-efficiente-delle-risorse/, 1420), that has the creation of an Italian LCA database (https://bancadatiitalianalca.enea.it/Node/, 2022) among its goals. The forest woodchips supply chain, in fact, is one of the key supply chains identified for the four defined priority sectors in the framework of ARCADIA: agri-food, construction, energy, and wood furniture.

The specific case study concerns the supply chain of forest woodchips produced in Friuli Venezia Giulia, a region in the north of Italy, and it can be considered representative (both in geographical and technological terms) of a production chain developed in a mountain environment. Such a production can be considered characteristic of the North-East of Italy, where the most important productive high forests are located, or in general of other Italian (and not only) regions where the production of woody biomass occurs mainly in mountainous (or similar) areas.

The source of forest biomass is a mix of silver fir and spruce wood obtained from trees cut at a typical age of 30–40 years, i.e. from mature stands managed within a management system that promotes the natural regeneration of tree species, in the framework of which commercial thinnings are conducted to maintain the density and composition of trees at a level that helps meet a variety of management objectives.

The studied forest woodchips can be considered a good quality product according to the specifications of the ISO 17225-4 standard (ISO 17225-4, 2021), being representative of woodchips produced with sharp tools from virgin wood or chemically untreated wood residues. The studied product is representative of the A1 and A2 quality classes identified by the ISO 17225-4, being as such normally used in small-sized plants for heat generation or for cogeneration purposes.

The LCA study was developed in compliance with ISO 14040 (ISO 14040, 2006) and 14044 (ISO 14044, 2006) standards, adopting a "cradle-to-gate" approach, i.e. considering all processes up to the company gate and excluding the subsequent use and end-of-life phases (Fig. 1). The production of the machinery and equipment used for the various forestry activities, as well as their maintenance, were excluded from the system boundaries, according to methodological documents related to forest products available in the literature (EPD ® System, 2020), (SCS Global, 2016) and due to the negligible impact contribution that could be attributed to the single forestry worksite. According to (EPD ® System, 2020), (SCS Global, 2016) also the following was excluded from the study: construction and maintenance of roads dedicated to forestry; business travel of personnel, travel to and from work by personnel, and land-use transformation and occupation. The accounting of business travel of personnel and travel to and from work by personnel are beyond the scope of the study (and can also be considered similar to those related to other fuels production), while land-use transformation and occupation can be reasonably considered to have occurred more than 20 years before harvesting and, therefore, not relevant according to (EPD ® System, 2020). Regarding road construction and maintenance activities, the forest worksite of the reference case study was already set, and no new infrastructure was realized to give access to the forest: no primary data and no information for modelling them based on secondary data were therefore available. Moreover, no solid secondary data could be gathered from the literature for this specific process, since forest roads are generally kept aside from the system boundaries of LCA studies and since, due to overall complexity and high differences characterizing them, data on road construction and maintenance should be taken from a higher level and with a higher detail (Đuka et al., 2017).

Moreover, the net biogenic carbon dioxide emissions were assumed to be zero, since the emissions and removals of biogenic carbon dioxide to and from the forest carbon stocks caused by forest management activities are assumed to have the same magnitude. Authors are aware that the timing of emissions from forest resources represents a significant aspect regarding their contribution to climate change. Growing forest biomass, in fact, can generate a non-neutral biogenic carbon balance due to land-use change emissions and the sequestration of immediate combustion emissions could take several years, with short-term warming effects (Kouchaki-Penchah et al., 2022). The real potential of forest-based bioenergy to reduce GHG emissions should therefore be assessed over time and considering forest carbon implications related to biomass harvest, integrating life cycle assessment LCA and forest carbon analysis (McKechnie et al., 2011). Anyway, since the biogenic carbon balance is widely accepted to be zero in the long term, the assumption of net zero carbon emissions is acceptable and coherent with the aim of the study. Furthermore, it is still not clear if the best carbon emission mitigation in the short- and long-term is obtained through carbon storage in forest biomass and soil or through the production of biomass fuels and wood products in substitution of fossil fuels and fossil fuel-based materials (Taeroe et al., 2017). In fact, even if afforestation generally represents a carbon dioxide removal measure with larger climate benefits than bioenergy, bioenergy with carbon capture and storage can deliver high mitigation (Gvein et al., 2023).

The selected Functional Unit (FU) for the modelling of the production phase is 1 ton of forest woodchips. All other additional aspects regarding the LCA case study are included in the study report (in Italian) available on the ARCADIA project website (https://www.arcadia.enea.it/, 2022).

Data used in the LCA study were both primary and secondary. Fossil fuels consumption in the forest machinery was directly collected as

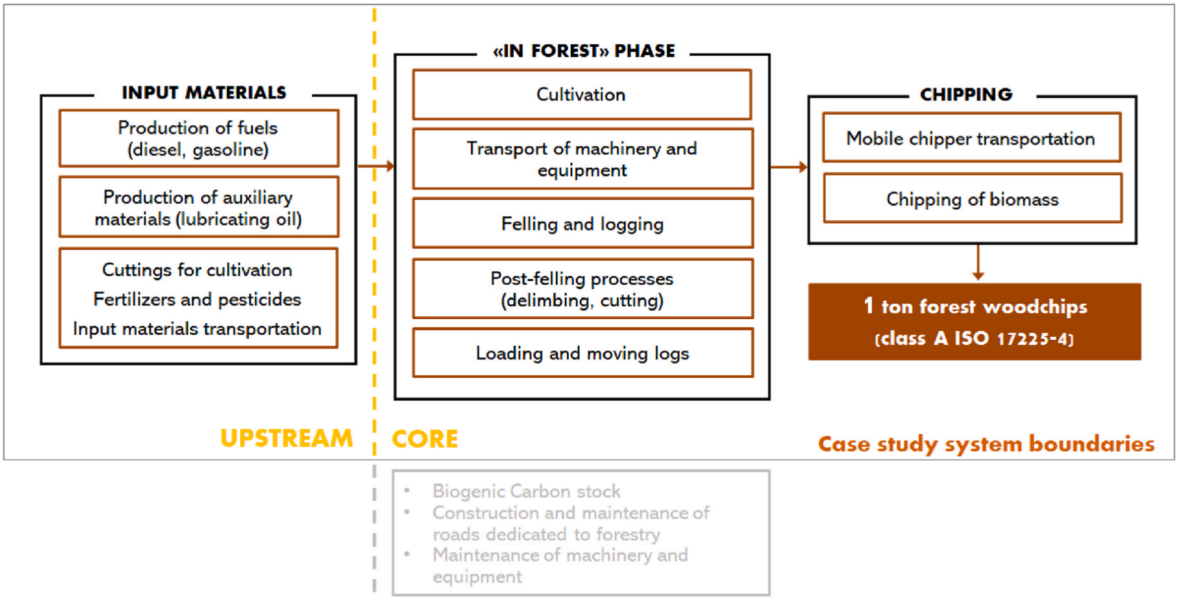

Fig. 1. LCA case study system boundaries.

primary data from the partners of the ARCADIA working group, all located in the Friuli Venezia Giulia Region, focussing on the specific forest worksites. Secondary data were instead used to model the cultivation phase and mobile chipper transportation since primary data regarding them were not directly available from the partners of the ARCADIA working group.

Inventory data used for cultivation were estimated based on previous literature studies and production guidelines (Giuntoli et al., 2016)-(Corona et al., 2018), considering the different approaches to cultivation with and without fertilization. Vegetative propagation by cuttings was considered as the reproductive method of the plants and the following common stages were taken into account: planting material production (i.e. production of plants ready for transplanting starting from the cuttings), soil preparation (i.e. preliminary ploughing operations to ensure the appropriate conditions of aeration and water capacity of the soil) and cultivation care (i.e. weeds control through the application of synthetic products). An organic method of fertilization was hypothesized and, according to existing production guidelines (Giuntoli et al., 2016; VV, 2006; https://agricoltura.regione.emilia-romagna.it/produzioni-agroalimentari/temi/bio-agro-climambiente/agricoltura-integrata/disciplinari-produzione-integrata-vegetale/Collezione-dpi/2019/disciplinari-2019, 2019; Corona et al., 2018), preliminary fertilization (distribution of mature manure and its burying during soil ploughing) and top fertilization (fertilizer distribution and burying during the years of plant growth) were considered to estimate the amount of fertilizers used. For both cultivation options, also the field application of fertilizers and pesticides was included in the analysis and assessed using the available dataset in ecoinvent (Wernet et al., 2016). The inventory data regarding the mobile chipper was estimated based on technical datasheets (Gandini,

Table 1
Inventory data for the case study.

Flow/processes	Value	U.M.	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation
Cultivation with fertilization							
Cuttings	4	kg	3	2	2	3	4
Organic fertilizer	1,071	kg	3	2	2	3	4
Diesel	2.9	kg	3	2	2	3	4
Pesticides	0.14	kg	3	2	2	3	4
Cultivation without fertilization							
Cuttings	5.5	kg	3	2	2	3	4
Organic fertilizer	–	kg	3	2	2	3	4
Diesel	4.3	kg	3	2	2	3	4
Pesticides	0.29	kg	3	2	2	3	4
Transport of machinery and equipment							
Diesel	0.023	kg	1	1	2	1	1
Felling							
Gasoline	0.310	kg	1	1	2	1	1
Lubricating oil	0.106	kg	1	1	2	1	1
Delimbing and cutting							
Gasoline	0.973	kg	1	1	2	1	1
Lubricating oil	0.045	kg	1	1	2	1	1
Logging							
Diesel	1.464	kg	1	1	2	1	1
Loading and moving logs							
Diesel	1.573	kg	1	1	2	1	1
Chipping							
Mobile chipper transportation	2.05	tkm	2	2	2	3	1
Diesel	2.392	kg	1	1	2	1	1

2021), (Pezzolato and 2021, 2021) and previous studies (Botta and Derchi, 2012), (Grigolato et al., 2020) related to supply chains of other regions considered similar to the case study in terms of characteristics of the geographical area in which the supply chain is developed (mountain and similar environment) and technologies used within it (types of machinery, equipment, etc.).

Inventory data for the case study referred to the FU are summarized in Table 1, together with the Data Quality Indicators (DQIs) assigned to each one of them based on the data quality matrix provided by Weidema and Wesnaes (Weidema and Suhr Wesnæs, 1996).

As it is possible to see, according to DQIs the overall quality of the data can be considered good, with the main issues regarding the secondary data and, in particular, the ones used to model the cultivation phase. This data quality assessment agrees with the one carried out referring to the specific requirements defined within the ARCADIA project that allows to evaluate:

- the reliability of the data as "good" (data are partly calculated or gathered from the literature, but all checked by experts);
- the temporal representativeness of the data as "acceptable" (no data refers to a period 5 years before the supply chain study);
- the geographical representativeness of the data as "good" (data from areas with production conditions similar to the case study and fully representative of its geographical location, based on expert judgment);
- the technological representativeness of the data as "very good" (data describe in detail the current market technology for the reference supply chain).

2.3. Modelling of the woodchips transport to the energy production plant

The collection and transport of woody biomass are key steps in the wood-to-energy chain and, in general, they are hampered due to the constraints caused by some intrinsic characteristics of the biomass themselves (e.g. low density, heterogeneity, and territorial dispersion) (Nunes Leonel et al., 2023). Transport operations generally represent a significant share of the final price of biomass for energy and they are responsible for not negligible GHG emissions (Schnorf et al., 2021). Therefore, in general, there is also the need for very versatile vehicles able to operate under different conditions (for instance, capability of direct loading with standard farm equipment) with low operating costs, and both "agricultural convoys'' (tractor + trailers) and trucks are used in this regard (Manzone and Balsari, 2015).

Previous LCA literature studies (among the others, for instance (Gonzalez-Garcia et al., 2009b), (Michelsen, 2007), (Michelsen et al., 2008), (Murphy et al., 2014), (De La Fuente et al., 2017), (Laina et al., 2022), (Paletto et al., 2019)) widely adopted the assumption of considering trucks to model biomass transport, also using secondary data and background data from existing LCA databases.

Therefore, at the aim of this study, the specific emissions associated with the woodchips transport ($GWPt_{ransp}$) were estimated using background data from the ecoinvent database (Wernet et al., 2016), considering, in particular, a 7.5–16 ton EURO4 truck.

2.4. Modelling of the woodchips combustion in the energy production plant

Biomasses are generally directly used without being converted to higher forms of fuels, in particular for heat generation. Such kind of utilization is normally considered carbon-neutral since the carbon dioxide released during biomass combustion represents an integral part of the carbon cycle (Schnorf et al., 2021). Anyway, both at the local and global scale, direct biomass exploitation as an energy source can cause emissions harmful to human health and to the environment (Caserini et al., 2010). Combustion of biomass, in fact, causes the emission of not negligible amounts of greenhouse gases such as CO_2, CO and hydrocarbons, other gaseous pollutants such as SO_2 and NOx, and particulate matter which can also seriously affect atmospheric processes and human health (Proto et al., 2021).

Therefore, the impact related to the combustion of woodchips in the energy production plant was included in the assessment. Due to the variability of specific emissions according to the typology, chemical, and physical characteristics of biomass (Casal et al., 2010), (Caposciutti et al., 2020), according to the aim of developing a simplified methodology, this phase was modelled with a life cycle approach, using background data from the ecoinvent database (Wernet et al., 2016) related to a 50 kW woodchip boiler. The dataset used for the combustion of natural woodchips, in particular, includes the infrastructure, the emissions to air, the electricity needed for the boiler operation, and the disposal of the ashes (default transport inventory data was excluded). The net efficiency used to convert heat of combustion to heat for end uses in the considered ecoinvent dataset was equal to 80%.

3. Results

The results obtained from the modelling of the different life cycle phases according to the above sections, allowed to define the impact parameters included in Eq. (1), i.e. to finalize the methodology to preliminarily estimate CF associated with 1 MJ heat generation from forest woodchips based on its specific characteristics, its production conditions, the transport distances and the peculiarity of the generation plant.

In particular, the value of life cycle emissions associated with the production phase was equal to 20.1 $kgCO_2eq/t$ when cultivation is not included in the assessment, 45.3 $kgCO_2eq/t$ when cultivation with fertilization is considered and 26.3 $kgCO_2eq/t$ in case of cultivation without fertilization. Therefore, the reference value of GWP_{prod} was set at 20.1 $kgCO_2eq/t$, (value related to woodchips production without considering cultivation), while the values of α were fixed at 2.2 (45.3/20.1) for the option of cultivation with fertilization and 1.3 (26.3/20.1) for the option of cultivation without fertilization.

The impact parameters related to the transport of woodchips and its combustion in the energy production plant, as previously described, were estimated considering the dataset of a 7.5–16 ton EURO4 truck and a 50 kW woodchip boiler available in the ecoinvent database (Wernet et al., 2016). According to this assumption, GWP_{transp} was set at 0.211 $kgCO_2eq/tkm$, without any further adjustment. GWP_{plant} was instead slightly adjusted to explicitly include in Eq. (1) the ratio between the net efficiency of the reference ecoinvent plant and the generation efficiency of the case study plant since it can generate sensible variability in the results. The calculation of GWP_{plant} was therefore refined as $(\eta_{REF}/\eta) \bullet GWP_{plant,REF}$, being η_{REF} the efficiency of the reference ecoinvent plant and $GWP_{plant,REF}$ its life cycle emissions. As mentioned in section 2.4, the reference ecoinvent plant efficiency was equal to 0.8 and GWP_{plant} was therefore set as $(0.8/\eta) \bullet 0.005$ $kgCO_2eq/MJ$. The simplified calculation methodology presented in Eq. (1) was therefore updated with the calculated impact parameters and finalized as follows:

$$CF_{tot} = \alpha \bullet \frac{20.1}{NCV \bullet \eta} + \frac{0.211}{NCV \bullet \eta} \bullet d_{transp} + \frac{0.8}{\eta} \bullet 0.005 \tag{3}$$

being:

- $\alpha = 1$ when the cultivation phase is excluded;
- $\alpha = 1.3$ when the cultivation is considered without fertilization;
- $\alpha = 2.2$ when the cultivation is considered including fertilization.

The methodology was applied to calculate the CF of a hypothetic case study considering the average characteristics of the forest woodchips ($NCV = 15{,}500$ MJ/t) and the energy production plant ($\eta = 92\%$) and also transport distances representative of a "local" (50 km) and "long" supply chain (300 km). Results are summarized in Table 2 and Fig. 2.

As it is possible to see focussing on the results for the "local" supply chain, with the inclusion of the cultivation without fertilization ($\alpha = 1.3$)

Table 2
Results - Total CF for “local” and “long” woodchips supply.

Study boundaries	kgCO$_2$eq/MJ	
	d$_{transp}$ = 50 km	d$_{transp}$ = 300 km
Cultivation phase excluded ($\alpha = 1$)	0.0065	0.0102
Cultivation without fertilization ($\alpha = 1.3$)	0.0069	0.0106
Cultivation with fertilization ($\alpha = 2.2$)	0.0082	0.119

in the assessment an increase in CF of about 6.5% is observed, while if the option of cultivation with fertilization ($\alpha = 2.2$) is considered the increase is about 26.1%. Analysing the different life cycle phases, the woodchips combustion in the energy generation plant emerged as the major contributor to the impact in all the production cases, with a share on the total CF that decreases when cultivation is considered. Including the cultivation, in fact, there is an increase in the life cycle emissions related to the woodchips production phase, with a contribution to the total impact that rises to 26.5% in the case of cultivation without fertilization and to 37.9% in the case of cultivation with fertilization (compared to the share of 21.7% related to the case of production without considering cultivation). The contribution of the woodchips transport is instead less significant and quite similar for all the production cases considered, due to the “local” supply of the woodchips. In this regard, it is instead worth noting that setting d_{transp} to 300 km (“long” supply chain), the contribution of woodchips transport becomes comparable to the one of its combustion in the energy plant, being both about 37–43% depending on the production option considered. Therefore, for “medium to long” supply chains, the overall impact associated with heat generation by forest woodchips is mainly associated with fuel transport and use (about 75–85% in all the production cases), with the contribution of the production phase that becomes less significant (from about 14% of the total when the cultivation is not included, to about 26% in the case of cultivation with fertilization).

The methodology was also applied for estimating the maximum transport distance beyond which heat production from forest woodchips is no longer environmentally convenient compared to the production from other similar alternative sources, such as, for instance, wood pellets. Having estimated for wood pellets an indicative value of $CF_{tot,\ alt\_source}$ equal to 15 gCO$_2$eq/MJ based on existing literature (Unnasch and Buchan, 2021; Chiesa et al., 2016; Manuilova and Johnston, 2011; Martín-Gamboa et al., 2020; Ruiz et al., 2018), values of $d_{transp,MAX}$ varying between about 460 km and 550 km were obtained considering the different production options for the forest woodchips (i.e. different α values). Therefore, forest woodchips can be considered environmentally beneficial compared to wood pellets also in “long” wood-energy supply chain.

3.1. Uncertainty analysis

In order to have a picture of the uncertainty that can affect the results obtained through the application of the proposed simplified methodology, an uncertainty analysis focused on the parameters used in Eq. (3) was carried out using the Monte Carlo method, a technique widely used and recommended for including uncertainty in LCA studies (Heijungs, 2020). The uncertainty analysis was carried out through the Monte Carlo Analysis simulation tool included in the SimPro software setting 1,000 runs and the obtained results are summarized in Table 3. As it is possible to see, the variability of the calculated parameters is not so high, and, therefore, the uncertainty affecting the estimates through the proposed methodology can be considered acceptable for preliminary CF calculations aimed at supporting sustainability assessment in decision-making.

3.2. Sensitivity analysis

A sensitivity analysis was performed to evaluate the influence on the results related to the modelling choices regarding the woodchips transport and its combustion in the energy plant, i.e. to those parameters that were estimated using background data from the ecoinvent database (Wernet et al., 2016), and also identified as relevant in terms of share on the overall impact. In particular, two different means of transport (a 3.5–7.5 ton EURO4 truck and a 16–32 ton EURO4 truck) and also an energy production plant with different characteristics (300 kW woodchips furnace) were considered. The sensitivity analysis was carried out considering the “local” woodchips supply chain ($d_{transp} = 50$ km) and showed variability of results in the range of about - 7% and about +17%. In detail, as shown in Table 4, the use of a smaller truck for woodchips transportation generated the highest variability in results, with an increase of the impact in the order of about 13–17%, while the variability associated with the use of a larger mean of transport was not significant (about 1–2%). On the other hand, the combustion of woodchips in a larger plant resulted in a decrease in the overall impact, with variability in the estimates in the order of about - 6–7%.

4. Discussion

The results obtained through the simplified calculation methodology here proposed should be considered as indicative preliminary estimates of the CF associated with the use of forest woodchips for heat generation.

Applying the methodology to a hypothetic case study representative of average conditions characterizing a “local” supply chain, a variability of the CF in the range 6–8 gCO$_2$eq/MJ was observed, while for a “long” supply chain results increased to 10–12 gCO$_2$eq/MJ. Even if a comparison with other literature studies is quite difficult – due to the geographic representativeness, the production system (forest residues, short rotation, …), the wood species considered, and the case study characteristics (functional unit, modelling choices, …) – these results can be considered in line with previous literature. In particular, our preliminary CF estimates are aligned with the range 5–9 gCO$_2$eq/MJ shown in (EU, 2018) for different types of woodchips with a transport distance up to 500 km and also with the results of other previous studies such as (Unnasch and Buchan, 2021), that showed impact values in the range 3–7 gCO$_2$eq/MJ, and (Balcioglu et al., 2023) that calculated a value of 31 kgCO$_2$eq/MWh$_{th}$ (i.e. 8.61 gCO$_2$eq/MJ).

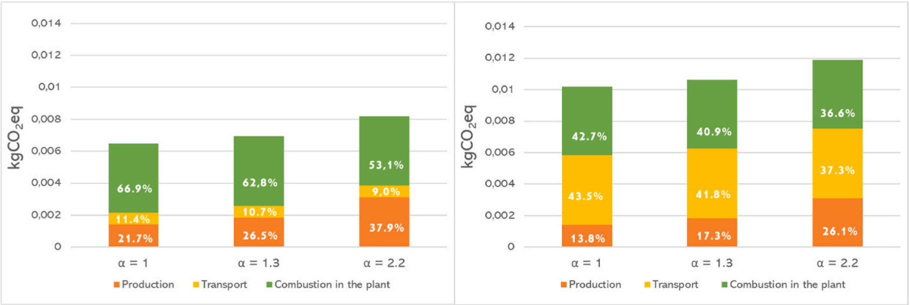

Fig. 2. Results - Breakdown of CF by life cycle phase. On the left results for d$_{transp}$ = 50 km, on the right results for d$_{transp}$ = 300 km.

Table 3
Results of the uncertainty analysis.

Modeling assumptions	$kgCO_2eq$						
	Mean	Median	SD	CV	2.5%	97.5%	Stn. err. of the mean
GWP_{prod} with $\alpha = 1$	20.28	20.05	3.14	15.49	14.87	27.45	0.099
GWP_{prod} with $\alpha = 1.3$	26.26	25.86	3.11	11.84	20.98	33.48	0.098
GWP_{prod} with $\alpha = 2.2$	45.28	44.96	3.04	6.72	40.10	52.07	0.096
GWP_{transp}	0.210	0.209	0.012	5.700	0.192	0.240	0.0004
$GWP_{plant,ref}$	0.0050	0.0049	0.0011	22.3316	0.0035	0.0080	0.00004

Table 4
Results of the sensitivity analysis ($d_{transp} = 50$ km).

Modeling assumptions	gCO_2eq/MJ		
	$\alpha = 1$	$\alpha = 1.3$	$\alpha = 2.2$
Woodchips transport with a 3.5–7.5 ton EURO4 truck	7.59 (+16.8%)	8.02 (+15.8%)	9.29 (+13.3%)
Woodchips transport with a 16–32 ton EURO4 truck	6.40 (−1.5%)	6.83 (−1.4%)	8.10 (−1.2%)
Woodchips combustion in a 300 kW furnace	6.02 (−7.4%)	6.45 (−6.9%)	7.72 (−5.8%)

More in detail, our value of 1.41 gCO_2eq/MJ representative of the woodchips production without including the cultivation phase, is comparable with the value of 1.6 gCO_2eq/MJ shown in (EU, 2018) for the processing of woodchips from forest residues. Similarly, the 1.84 gCO_2eq/MJ and the 3.11 gCO_2eq/MJ representative respectively of the cultivation without and with fertilization options in our case study are quite comparable with the 2.2 gCO_2eq/MJ and 3.9 gCO_2eq/MJ shown in the same previous work (EU, 2018) (even it has to be highlighted that it refers to poplar). Focussing on the woodchips transport contribution, instead, the values of 0.74 gCO_2eq/MJ and 4.4 gCO_2eq/MJ obtained in our case study respectively for a transport distance equal to 50 km and 300 km, are quite different from the 3.0–3.5 gCO_2eq/MJ calculated by (EU, 2018) for a transport distance of 500 km and this could be attributed (even if it was not possible to verify it) to the different mean of transport adopted in the life cycle modelling. Anyway, our results regarding transportation are quite in line with those of (Unnasch and Buchan, 2021), that considered a 50-mile distance (about 80 km) to model emissions associated with transport, showing impact values in the range 0.74–1.26 gCO_2eq/MJ depending on the woodchips type.

Regarding woodchips combustion, our result of 4.35 gCO_2eq/MJ is quite higher than the one calculated in (Unnasch and Buchan, 2021), equal to 1.86 gCO_2eq/MJ, and also this could be attributed (even if it was not possible to verify it) to the different choices adopted in the life cycle modelling. Anyway, the result we obtained seems to be in line with the one related to the "energy conversion" process in (Balcioglu et al., 2023), which appears as about half of the overall life cycle impact, i.e about 15 $kgCO_2eq/MWh_{th}$ (4.17 gCO_2eq/MJ). More in general, our main evidence showing woodchips combustion as one of the main hotspots is coherent with other specialized literature, such as for instance (Esteban et al., 2014) that showed a contribution of this process up to 77.8% in the GWP results, and (Quinteiro et al., 2019) that more recently studied different wood-based combustion systems for residential heating showing thermal energy generation as the most relevant process for all the considered impact categories.

5. Limitations

The CF calculation through the proposed methodology has potential limitations related to the various assumptions made in the study.

First of all, the production phase of the forest woodchips was modelled based on a specific Italian supply chain and, moreover, the different cultivation conditions (with and without fertilization) were approximated through simplified simulations based on previous literature studies and production guidelines data. Furthermore, specific methods of cultivation (by cuttings) and fertilization (organic) with their specific characteristics were chosen among the existing ones (e.g. production from seeds and synthetic fertilization). Therefore, the value of GWP_{prod} should be considered as representative of these specific conditions and potential sensible variability of its value is likely to occur as the characteristics of the supply chain/cultivation method and the level of detail in the modelling of the cultivation phase vary. Anyway, the obtained results can be reasonably considered generally valid to approximate the production of woodchips in a mountain (or similar) environment, and the uncertainty affecting them acceptable for the aim of the study, that is to provide preliminary CF calculations useful to support sustainability assessment in decision-making regarding biomass projects.

Regarding the production phase, it must be highlighted that in cases of poor forest management biomass may not be climate neutral and be, on the contrary, characterized by significant contribution to GWP. A proper understanding of that should be based on detailed landscape-level forest carbon modelling, which is beyond the scope of the study. Therefore, the assumption of net zero biogenic carbon dioxide emissions represents another noteworthy limitation of the study.

Secondly, the forest woodchips transport and the energy production plant were modelled based on specific ecoinvent datasets, so the values of GWP_{transp} (deriving from the dataset of a 7.5–16 ton EURO4 truck) and GWP_{plant} (deriving from the dataset of a 50 kW woodchip boiler) are representative of the selected processes and susceptible to significant variations if other processes/datasets are considered. In this regard, the sensitivity analysis focused on the means of transport showed that a sensible impact variation (about +17% maximum) occurs if the transport of woodchips is performed with a smaller truck (3.5–7.5 ton), while the use of a 16–32 ton truck generates negligible impact variations (about -1−2%). If the size of the plant where the woodchips are used increases, instead, the overall impact decreases and the variability of the results is in the order of about -6−7%.

It has also to be highlighted that a real validation of the methodology to confirm its estimates (e.g. through an in-depth comparison with other literature studies results) and/or refine the proposed impact parameters (e.g. through an extensive application to specific case studies) was not carried out, while it can be considered relevant.

Despite the limitations affecting the CF estimations through the proposed methodology, according to the authors' best knowledge, similar simplified approaches that allow calculations based on specific fuel and plant characteristics, as well as on the production methods and the transport distance, are not available in the literature.

6. Conclusions

Energy production from biomass is particularly strategic for the achievement of global sustainability goals and the use of biofuels for decentralized energy production in medium-small size plants – an option in line with global fossil energy and GHG reduction targets – is expected to increase in the short-medium term.

In this paper, a simplified methodology to preliminary estimate the CF associated with heat generation by forest woodchips, as a support tool for sustainability assessment in decision-making regarding biomass projects, is proposed. The methodology is based on the fuel and plant characteristics, as well as on the production methods and the transport distance and it allows the impact assessment considering their variation.

The woodchips combustion in the energy generation plant emerged as the major contributor to the impact in all the production cases for a "local" supply chain, with the production phase that gains significance when the cultivation and, in particular, the option with fertilization is considered. The contribution of the woodchips transport, instead, is less relevant and becomes comparable to the one of its combustion in the energy plant when a "long" supply chain is considered.

In general, the methodology supports the basic idea that good quality forest woodchips are particularly strategic for sustainable energy production within a "short" wood-energy supply chain but results also showed that forest woodchips can be considered competitive from an environmental point of view compared to alternative sources, such as wood pellets, even within "long" wood-energy supply chain.

A specific analysis focused on the parameters used in the simplified methodology showed an acceptable uncertainty for preliminary CF calculations coherent with the aim of the study and that impact variations occur in a range that does not significantly affect the suitability of the CF estimates to support sustainability assessment in decision making. The methodology can be therefore reasonably considered generally valid to preliminarily estimate from the CF associated with the use of forest woodchips and to support their sustainability assessment in a mountain (or similar) environment.

Author contributions statement

Flavio Scrucca: Conceptualization, Methodology, Investigation, Writing - Original draft preparation, Writing - Review & Editing; **Grazia Barberio:** Supervision, Validation, Writing - Review & Editing; **Laura Cutaia, Caterina Rinaldi**: Supervision, Validation, Writing - Review & Editing, Project administration.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

Aldentun, Y., 2002. Life cycle inventory of forest seedling production from seed to regeneration site. J. Clean. Prod. 10, 47–55. https://doi.org/10.1016/S0959-6526(01)00012-9.

Balcioglu, G., Jeswani, H.K., Azapagic, A., 2023. Energy from forest residues in Turkey: an environmental and economic life cycle assessment of different technologies. Sci. Total Environ. 874, 162316 https://doi.org/10.1016/j.scitotenv.2023.162316.

Berg, S., Lindholm, E.L., 2005. Energy use and environmental impacts of forest operations in Sweden. J. Clean. Prod. 13, 33–42. https://doi.org/10.1016/j.jclepro.2003.09.015.

Botta, E., Derchi, P., 2012. Filiere corte in Liguria – Energia dal bosco per le coltivazioni in serra: l'esperienza del Progetto BIOMASS. https://www.compagniadelleforeste.it/pubblicazioni-cdf.html?download=32:filierecorte-in-liguria.

Caposciutti, G., Barontini, F., Galletti, C., Antonelli, M., Tognotti, L., Desideri, U., 2020. Woodchip size effect on combustion temperatures and volatiles in a small-scale fixed bed biomass boiler. Renew. Energy 151, 161e174. https://doi.org/10.1016/j.renene.2019.11.005.

Casal, M.D., Gil, M.V., Pevida, C., Rubiera, F., Pis, J.J., 2010. Influence of storage time on the quality and combustion behaviour of pine woodchips. Energy 35, 3066–3071. https://10.1016/j.energy.2010.03.048.

Caserini, S., Livio, S., Giugliano, M., Grosso, M., Rigamonti, L., 2010. LCA of domestic and centralized biomass combustion: the case of Lombardy (Italy). Biomass Bioenergy 34, 474–482. https://doi:10.1016/j.biombioe.2009.12.011.

Chiesa, M., Monteleone, B., Venuta, M.L., Maffeis, G., Greco, S., Cherubini, A., Schmidl, C., Finco, A., Gerosa, G., Ballarin Denti, A., 2016. Integrated study through LCA, ELCC analysis and air quality modelling related to the adoption of high efficiency small scale pellet boilers. Biomass Bioenergy 90, 262–272. https://doi.org/10.1016/j.biombioe.2016.04.019.

Corona, P., Bergante, S., Castro, G., Chiarabaglio, P.M., Coaloa, D., Facciotto, G., Gennaro, M., Giorcelli, A., Rosso, L., Vietto, L., Nervo, G., 2018. Linee di indirizzo per una pioppicoltura sostenibile. Rete Rurale Nazionale, Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria, Roma, 978-88-99595-96-8.

Corona, B., Shen, L., Sommersacher, P., Junginger, M., 2020. Consequential Life Cycle Assessment of energy generation from waste wood and forest residues: the effect of resource-efficient additives. J. Clean. Prod. 259, 120948 https://doi.org/10.1016/j.jclepro.2020.120948.

De La Fuente, T., Athanassiadis, D., González-García, S., Nordfjell, T., 2017. Cradle-to-gate life cycle assessment of forest supply chains: comparison of Canadian and Swedish case studies. J. Clean. Prod. 143, 866–881. https://doi.org/10.1016/j.jclepro.2016.12.034.

Dias Brandao, R., Thiffault, E., Levasseur, A., 2022. Development of a multi-criteria analysis decision-support tool for the sustainability of forest biomass heating projects in Quebec. Sustainability 14, 13200. https://doi.org/10.3390/su142013200.

Đuka, A., Vusić, D., Horvat, D., Šušnjar, M., Pandur, Z., Papa, I., 2017. LCA studies in forestry – stagnation or progress? Croat. J. For. Eng. 38, 2.

EPD® System, 2020. Product Category Rules: Basic Products from Forestry.

Esteban, B., Riba, J.R., Baquero, G., Puig, R., Rius, A., 2014. Environmental assessment of small-scale production of wood chips as a fuel for residential heating boilers. Renew. Energy 62, 106e115.

EU Directive 2018/2001 of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources.

EUROBSERV'ER, 2022. Solid Biofuels Barometer. Available on-line at: https://www.eurobserv-er.org/solid-biofuels-barometer-2022/. (Accessed 28 March 2023).

Ferreira, J.V., Viana, H., Esteves, B., Cruz Lopes, L.P., Domingos, I., 2014. Life cycle assessment of residual forestry biomass chips at a power plant: a Portuguese case study. Int. J. Energy. Environ. Eng. 5, 86. https://doi.org/10.1007/s40095-014-0086-4.

Gandini, 2021. International Chippers Line. https://www.gandinimeccanica.com/33/chipperenergy.

Giuntoli, J., Agostini, A., Edwards, R., Marelli, L., 2016. Solid and gaseous bioenergy pathways: input values and GHG emissions. EUR 27215 EN, 2017 Calculated according to the methodology set in COM 767. https://doi.org/10.2790/27486. Available on-line at: https://ec.europa.eu/energy/sites/ener/files/documents/Solid%20and%20gaseous%20bioenergy%20pathways.pdf. (Accessed 27 December 2022).

Gonzalez-Garcia, S., Berg, S., Feijoo, G., Moreira, M.T., 2009a. Environmental impacts of forest production and supply of pulpwood: Spanish and Swedish case studies. Int. J. Life Cycle Assess. 14 (4), 340–353. https://doi.org/10.1007/s11367-009-0089-1.

Gonzalez-Garcia, S., Berg, S., Feijoo, G., Moreira, M.T., 2009b. Evaluation of forest operations in Spain under a life cycle assessment. Scand. J. For. Res. 24 (2), 160–1726. https://doi.org/10.1080/02827580902773462.

Grigolato, S., Cadei, A., Argnani, A., Baldo, M., Campeotto, S., 2020. Cippato forestale, l'efficienza dei cantieri si valuta con la telemetria. https://logisticiplus.it/index.php/pubblicazioni.

Gvein, M.H., Hu, X., Næss, J.S., et al., 2023. Potential of land-based climate change mitigation strategies on abandoned cropland. Commun. Earth Environ. 4, 39. https://doi.org/10.1038/s43247-023-00696-7.

Heijungs, R., 2020. On the number of Monte Carlo runs in comparative probabilistic LCA. Int. J. LCA 25, 394–402. https://doi.org/10.1007/s11367-019-01698-4.

http://www.pongovernance1420.gov.it/it/progetto/arcadia-approccio-ciclo-di-vita-nei-contratti-pubblici-e-banca-dati-italiana-lca-per-luso-efficiente-delle-risorse/. (Accessed 20 December 2022).

https://agricoltura.regione.emilia-romagna.it/produzioni-agroalimentari/temi/bio-agro-climambiente/agricoltura-integrata/disciplinari-produzione-integrata-vegetale/Collezione-dpi/2019/disciplinari-2019.

https://bancadatiitalianalca.enea.it/Node/. (Accessed 20 December 2022).

https://www.arcadia.enea.it/. (Accessed 20 December 2022).

International Energy Agency, 2022. Bioenergy. Available on-line at: https://www.iea.org/fuels-and-technologies/bioenergy. (Accessed 20 December 2022).

IPCC, 2021. In: Zhai, V.P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://doi.org/10.1017/9781009157896 (in press).

ISO 14040, 2006. Environmental Management — Life Cycle Assessment — Principles and Framework.

ISO 14044, 2006. Environmental Management — Life Cycle Assessment — Requirements and Guidelines.

ISO 17225-4, 2021. Solid Biofuels — Fuel Specifications and Classes — Part 4: Graded Wood Chips.

Italian Ministry of the Environment and Energy Security, 2020. Integrated national plan for energy and climate. Available on-line at: https://www.mase.gov.it/comunicati/pubblicato-il-testo-definitivo-del-piano-energia-e-clima-pniec. (Accessed 20 December 2022).

Kouchaki-Penchah, H., Bahn, O., Vaillancourt, K., Levasseur, A., 2022. The contribution of forest-based bioenergy in achieving deep decarbonization: insights for Quebec (Canada) using a TIMES approach. Energy Convers. Manag. 252, 115081 https://doi.org/10.1016/j.enconman.2021.115081.

Laina, R., Herrero, S.J., Corona, B., Tolosana, E., De La Fuente, T., San Miguel, G., 2022. Economic and environmental assessment of a multifunctional poplar plantation for roundwood and wood chip production in Spain. For. Syst. 31 (1), e002. https://doi.org/10.5424/fs/2022311-18485, 2022.

Manuilova, A., Johnston, M., 2011. Greenhouse Gas Emissions Assessment - the Substitution of Fossil Fuels with Woody Biomass in the Northwest Territories. Saskatchewan Research Council Publication No. . 13069-1C11, Prepared for Government of the Northwest Territories.

Manzone, M., Balsari, P., 2015. The energy consumption and economic costs of different vehicles used in transporting woodchips. Fuel 139, 511–515. https://doi.org/10.1016/j.fuel.2014.09.003.

Martín-Gamboa, M., Marques, P., Freire, F., Arroja, L., Ana Dias, A.C., 2020. Life cycle assessment of biomass pellets: a review of methodological choices and results. Renewable Sustainable Energy Rev. 133, 110278 https://doi.org/10.1016/j.rser.2020.110278.

McKechnie, J., Colombo, S., Chen, J., Mabee, W., MacLean, H.L., 2011. Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. Environ. Sci. Technol. 45 (2), 789–795. https://doi.org/10.1021/es1024004.

Michelsen, O., 2007. Assessment of land use impact on biodiversity. Proposal of a new methodology exemplified with forestry operations in Norway. Int. J. Life Cycle Assess. 13 (1), 22–31. https://doi.org/10.1065/lca2007.04.316.

Michelsen, O., Solli, C., Strømman, A.H., 2008. Environmental impact and added value in forestry operations in Norway. J. Ind. Ecol. 12, 69–81. https://doi.org/10.1111/j.1530-9290.2008.00008.x.

Mirabella, N., Castellani, V., Sala, S., 2014. Forestry operations in the alpine context. Life cycle assessment to support the integrated assessment of forest wood short supply chain. Int. J. Life Cycle Assess. 19, 1524–1535. https://doi.org/10.1007/s11367-014-0756-8.

Murphy, F., Devlin, G., McDonnell, K., 2014. Forest biomass supply chains in Ireland: a life cycle assessment of GHG emissions and primary energy balances. Appl. Energy 116, 1–8. https://doi.org/10.1016/j.apenergy.2013.11.041.

Neri, E., Cespi, D., Setti, L., Gombi, E., Bernardi, E., Vassura, I., Passarini, F., 2016. Biomass residues to renewable energy: a life cycle perspective applied at a local scale. Energies 9 (11), 922. https://doi.org/10.3390/en9110922.

Nunes Leonel, J.R., Casau, M., Ferreira Dias, M., Matias, J.C.O., Teixeira, L.C., 2023. Agroforest woody residual biomass-to-energy supply chain analysis: feasible and sustainable renewable resource exploitation for an alternative to fossil fuels. Results Eng. 17, 101010 https://doi.org/10.1016/j.rineng.2023.101010.

Paletto, A., Bernardi, S., Pieratti, E., Teston, F., Romagnoli, M., 2019. Assessment of environmental impact of biomass power plants to increase the social acceptance of renewable energy technologies. Heliyon 5, e02070. https://doi.org/10.1016/j.heliyon.2019.e02070.

Pelletier, C., Rogaume, Y., Dieckhoff, L., Bardeau, G., Pons, M.N., Dufour, A., 2019. Effect of combustion technology and biogenic CO_2 impact factor on global warming potential of wood-to-heat chains. Appl. Energy 235, 1381–1388. https://doi.org/10.1016/j.apenergy.2018.11.060.

Perić, M., Antonijević, D., Komatina, M., Bugarski, B., Rakin, M., 2020. Life cycle assessment of wood chips supply chain in Serbia. Renew. Energy 155, 1302–1311. https://doi.org/10.1016/j.renene.2020.04.026.

Pezzolato, 2021. https://www.pezzolato.it/greenline/categorie/elenco-macchine-greenline/cippatori-atamburo/cippatori-a-tamburo-presa-di-forza/.

Proto, A.R., Palma, A., Paris, E., Papandrea, S.F., Beatrice Vincenti, B., Carnevale, M., Guerriero, E., Bonofiglio, R., Gallucci, F., 2021. Assessment of wood chip combustion and emission behavior of different agricultural biomasses. Fuel 289, 119758. https://doi.org/10.1016/j.fuel.2020.119758.

Quinteiro, P., Tarelho, L., Marques, P., Martín-Gamboa, M., Freire, F., Arroja, L., Dias, A. C., 2019. Life cycle assessment of wood pellets and wood split logs for residential heating. Sci. Total Environ. 689, 580–589. https://doi.org/10.1016/j.scitotenv.2019.06.420.

Ruiz, D., San Miguel, G., Corona, B., López, F.R., 2018. LCA of a multifunctional bioenergy chain based on pellet production. Fuel 215, 601–611. https://doi.org/10.1016/j.fuel.2017.11.050.

Schnorf, V., Trutnevyte, E., Bowman, G., Burg, V., 2021. Biomass transport for energy: cost, energy and CO2 performance of forest wood and manure transport chains in Switzerland. J. Clean. Prod. 293, 125971 https://doi.org/10.1016/j.jclepro.20.21.125971.

Scott, J.A., Ho, W., Dey, P.K., 2012. A review of multi-criteria decision-making methods for bioenergy systems. Energy 42, 146–156. https://doi.org/10.1016/j.energy.2012.03.074.

Scrucca, F., Barberio, G., Fantin, V., Porta, P.L., Barbanera, M., 2021. Carbon Footprint: concept, methodology and calculation. In: Muthu, S.S. (Ed.), Environmental Footprints and Eco-Design of Products and Processes. Springer, Singapore, pp. 1–31.

SCS Global, 2016. Product Category Rule Module for Roundwood.

SimaPro Software. Available online: https://simapro.com/. (Accessed 20 December 2022).

Taeroe, A., Fayez Mustapha, W., Stupak, I., Raulund-Rasmussen, K., 2017. Do forests best mitigate CO2 emissions to the atmosphere by setting them aside for maximization of carbon storage or by management for fossil fuel substitution? J. Environ. Manag. 197, 117–129. https://doi.org/10.1016/j.jenvman.2017.03.051.

Tagliaferri, C., Evangelisti, S., Clift, R., Lettieri, P., 2018. Life cycle assessment of a biomass CHP plant in UK: the Heathrow energy centre case. Chem. Eng. Res. Des. 133, 210–221. https://doi.org/10.1016/j.cherd.2018.03.022.

Thakur, A., Canter, C.E., Kumar, A., 2014. Life-cycle energy and emission analysis of power generation from forest biomass. Appl. Energy 128, 246–253. https://doi.org/10.1016/j.apenergy.2014.04.085.

Unnasch, S., Buchan, L., 2021. Life Cycle Analysis of Renewable Fuel Standard Implementation for Thermal Pathways for Wood Pellets and Chips, Life Cycle Associates Report LCA.6161. 209.2021 (Prepared for Technology Transition Corporation).

VV, A.A., 2006. Pioppicoltura: produzioni di qualità nel rispetto dell'ambiente. Available on-line at: https://lombardia.confagricoltura.it/file_upload/lombardia/files/libretto_pioppicoltura.pdf. (Accessed 27 December 2022).

Weidema, B., Suhr Wesnæs, M., 1996. Data quality management for life cycle inventories—an example of using data quality indicators. J. Clean. Prod. 4, 167–174. https://doi.org/10.1016/S0959-6526(96)00043-1.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

Weyrens, J.P., Therasme, O., Germain, R.H., 2022. Quantifying the life cycle greenhouse gas emissions of a mechanized shelterwood harvest producing both sawtimber and woodchips. Forests 13, 70. https://doi.org/10.3390/f13010070.

World Bioenergy Association, 2021. Global Bioenergy Statistics 2021. Available on-line at: https://www.worldbioenergy.org/news/640/47/Global-Bioenergy-Statistics-2021/. (Accessed 20 December 2022).

Zahraee, S.M., Shiwakoti, N., Stasinopoulos, P., 2020. Biomass supply chain environmental and socio-economic analysis: 40-Years comprehensive review of methods, decision issues, sustainability challenges, and the way forward. Biomass Bioenergy 142, 105777. https://doi.org/10.1016/j.biombioe.2020.105777.