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Assessment of environmental impact of biomass power plants to increase the social acceptance of renewable energy technologies

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A R T I C L E I N F O

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A B S T R A C T

Objective: The objectives of the European Union (EU) policy agenda are to reduce the greenhouse gas emissions and to decrease the dependence of EU member countries from fossil fuel sources. In order to achieve these policy objectives, in the last decades the number of biomass power plants has increased throughout the EU. This study analyzed the environmental impacts of the bioenergy systems at global and local level to support communication and information strategies to increase social acceptance and to reduce conflicts between stakeholders. The environmental impacts were estimated to a sample of biomass power plants in North Italy selected based on the size, feedstock and type (cogeneration or heating). The study aims to identify and evaluate the environmental impacts associated with the thermal energy production in biomass power plants using a Life Cycle Assessment (LCA) approach.

Materials and methods: For each biomass district plant an LCA analysis was performed to: compare the environmental impacts associated with the production of the same functional unit, quantifying and valuating the environmental performance deriving from the production process life cycle, and highlighting the production phases with greater impact.

Results: The results show an average climate change impact by biomass energy plant of 45.84 $gCO_{2eq}\ MJ^{-1}$ and a range between 14.93 $gCO_{2eq}\ MJ^{-1}$ and 90.70 $gCO_{2eq}\ MJ^{-1}$. The results show that the size of the biomass energy plant (less than 1 MW or more than 1 MW) and the feedstock used (forest or sawmill woodchip) are two main variables that influence many categories of environmental impact.

1. Introduction

In the last decades, increasing the share of renewable energy has become a priority of the European Union (EU) energy policy agenda [1, 2, 3]. The main objectives of the EU energy policy are to reduce of greenhouse gas (GHG) emissions in the Earth's atmosphere in accordance with the targets established by the Paris Conference of Parties 21 (CoP21), and to decrease the fossil fuel energy dependence of EU member countries [4, 5]. To achieve these objectives, the EU energy policy agenda has identified a set of measures to reduce the overall energy consumption, to enhance energy efficiency, and to increase the use of renewable energy sources [6, 7].

In 2009, the EU adopted the Renewable Energy Directive (2009/28/EC) that provides the following objectives: the reduction of GHGs emissions by at least 20% within 2020 (compared to the levels registered in 1990), the increase of the share of renewable energy to at least 20% of total consumption and the saving of 20% of energy. Recently, the 20-20-20 targets were updated targets for 2030 with the EU Climate and Energy Framework (2014). The new target includes: a 40% cut in GHG emissions compared to 1990 levels; a 27% share of renewable energy consumption; and a 27% energy savings compared with the business-as-usual scenario. The EU renewable energy policy has had a strong influence on the national energy policies of the EU member countries aimed at increasing the share of renewable energy on total consumption [8]. Each EU member country has adopted a national energy policy aimed to implement the Renewable Energy Directive (2009) and the Climate and Energy Framework (2014) to achieve the above-mentioned targets.

In this context, the bioenergy production from forests is of strategic importance to meet the growing energy demand [9]. Recently, the use of biomass from forests and wood processing industries for energy purposes

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has substantially increased, due to the high potential exploitation of wood residues [10, 11]. In the period 2000–2014, 46% of current EU-28 biomass power plants (42% of bioenergy production capacity) were built with a rapid increase in demand for solid biomass for energy use due to the EU energy policy [12]. Public funding and governmental incentives aimed to increase the competitiveness of biomass combustion systems in the existing European energy market conditions have supported the diffusion of biomass power plants [13]. Besides, the EU has set up programs for financial support of research and development activities based on biomass energy. The European Commission (EC) with the "Innovating for Sustainable Growth. A Bioeconomy for Europe" (2012) – better known as EU Bioeconomy Strategy – has emphasized that the demand for timber and fuelwood in the context of increasing renewable energy demand is a strong stimulus for increasing forest growth and productivity, and for improving management practices. The EU Bioeconomy Strategy has also stimulated the use of woody biomass for energy use and the development of new biomass power plants. The use of renewable heating systems – such as biomass systems and cogeneration systems – is of primary importance to reduce the GHG emissions and energy consumption [14]. Consequently, in the EU member countries the small biomass power plants (less than 1 MW) and the medium biomass power plants (between 1 MW and 3 MW) have increased rapidly in the last two decades. The biomass installed capacity in Europe in 2000 was of 10,566 MW, increased to 19,158 MW in 2015 with the biggest increment in the residential sector, followed by the biomass district heating plants (two thirds of the plants installed are for heat generation). Within 2020, the biomass installed capacity is expected to increase of 8,000–9,000 MW [15, 16]. In 2010, leading countries in biomass heat production were: Germany (11,513 ktoe), France (10,840 ktoe), Sweden (8,948 ktoe), Finland (262 ktoe) and Poland with 192.6 PJ (4,596 ktoe), instead, regarding the number of installations, the 60% of all installations at the EU level are located in the following five countries: Austria, Germany, France, Finland, and Sweden. Austria is the first country in Europe in term of total installed plants mostly for heat appliances, but the general size of Austrian installations remains one of the smallest in Europe. The prospective for 2020 in EU28 is that the heat production from renewable energy will rise to 80,000 ktoe, of which 30,000 ktoe for residential purpose [16].

In this rapidly changing context, social acceptance of renewable energy technology is a fundamental aspect for renewable energy policy implementation [17, 18]. Social acceptance is both a matter of individual feelings and perceived risks and benefits and a social process where the actors influence each other through various types of interaction [19]. However, the term social acceptance risks oversimplifying the interactions between societies, communities, collective actors and individuals and energy technology and further risks perpetuating a normative top-down perspective of these relationships [20]. In the international literature, there are three different dimensions of social acceptance to be considered [21, 22]: socio-political acceptance, community acceptance and market acceptance. The socio-political acceptance can be defined as the acceptance of renewable energy technologies by key stakeholders and policy makers [23], while community acceptance relates to acceptance of siting decisions and renewable energy projects by local stakeholders such as residents and local authorities. The last dimension of social acceptance – market acceptance – considers adoption of renewable energy technology by consumers, suppliers and other market players [22].

Several studies highlighted that community acceptance for renewable energy technologies and policies is quite high, while the level of acceptance decreases as the decisions affect a specific site or project [24]. This aspect is linked to the "NIMBY" (Not In My Back Yard) syndrome that it can be defined as local resistance towards the construction of specific sites (e.g., biomass power plant) or the implementation of renewable energy projects [7, 25]. In the "NIMBY" syndrome, there is a negative correlation between perceived proximity and community acceptance. The perceived proximity can be defined as people perceive the location of a site in relation to where they live [25]. The opposition of local community to the new biomass power plant installed nearby is due to many potential limitations to their quality of life such as undesired landscape's changes, noise, gases and fine dust emissions [26, 27]. In addition to the perceived proximity, the main variables that influence the community acceptance are distributional justice – sharing of costs and benefits at local and global level – and trust [28]. Regarding the first variable, the new renewable energy projects should avoid that costs are at local scale, while benefits are at global scale. These projects should share costs and benefits fairly so that local communities are the first beneficiaries. Trust can be defined as the expectation that arises within a community of regular, honest, and cooperative behaviour, based on commonly shared norms [29]. From the theoretical point of view, it is important to distinguish between trust in the institutional actors (public authorities) and trust in the other members of the community. According to Gallo et al. (2018) [30], trust in institutional actors has a key importance in co-management because distrust in institutions lowers the degree of participation of individuals and groups in the decision-making process. In order to overcome the opposition of the local community and increase community acceptance for new renewable energy projects, the public authorities must adopt a communication and information plan for citizens or a community co-ownership model [7]. To prepare an effective and transparent communication and information plan it is essential to have a detailed knowledge of environmental impacts at local level of new renewable energy projects compared with possible alternatives.

According to Balest et al. (2018) [31], one of the key dimensions of technological system that influence the local community's actions shaping energy system renewability is: "substance". The substance dimension can be divided in five sub-dimensions: characteristics, siting, ownership, decision support tools, and climate change. In this context, there is a communication channel – research system – between social and technological system through which they exchange information on uses and needs.

The Life Cycle Assessment (LCA) is a good decision support tool for gathering and assessing information as to the environmental implications of a productive process [32]. Therefore, LCA can be considered an interesting tool for providing information to citizens and increasing social acceptance for renewable energy technology. In the international literature, some authors used LCA approach to analyze the environmental impacts of renewable energy technologies regarding the wood biomass. Seppälä et al. (1998) [33] carried out an LCA of the Finnish forest industry considering five life cycle stages: forestry; production; energy production outside the forest industry; chemicals production; waste management outside the Finnish forest industry; transports inside and outside Finland. Berg and Lindholm (2005) [34] investigated energy use and environmental impacts of forest operations (i.e. seedling production, silviculture, logging and secondary haulage to forest industries) in Sweden using an LCA approach. Fantozzi and Buratti (2010) [35] employed the LCA methodology to evaluate the efficiency and sustainability of wood pellet production in Italy considering raw material provided by poplar (*Populus spp.*) short rotation coppices. Valente et al. (2011) [36] preformed an LCA for evaluating the impacts of a woody biomass supply chain for heating plants – considering an innovative logging system – in a case study in Alpine region (Fiemme Valley in Trentino region), while Buonocore et al. (2014) [37] evaluated direct and indirect inputs of matter and energy as well as emissions and related impacts due to forestry operations using a using LCA perspective. Fitzpatrick (2016) [38] investigated the environmental sustainability of using forest wood biomass for heat generation in Ireland, by assessing the sustainable supply of forest biomass for energy purpose as well as the environmental impacts along the life cycle of the energy production. Murphy et al. (2016) [39] performed an LCA assessment of agro-forest biomass-based energy systems modeled with biomass supply chain optimization based on GHG emission reduction. Recently, Nikodinoska et al. (2018) [40] assessed the environmental, economic, and social sustainability of one biomass-based district heating plant (DHP) and one combined heat and power plant (CHP) in the Italian Alps using an LCA approach to estimate the global warming potential.

Starting from these considerations, the main aim of the present study is to investigate the environmental impacts of the bioenergy systems at local level – climate change sub-dimension of the substance dimension [31] – to support communication and information strategies to increase social acceptance and to reduce conflicts between stakeholders. The second aim of the study is to identify the internal variables of the biomass systems (i.e. size, feedstock used and type) that most influence the different types of environmental impacts using an LCA approach. The environmental impacts were estimated to a sample of 14 biomass power plants in Trentino-Alto Adige region (Italy) selected based on the size and feedstock used. The innovative aspect of this study is to analyze in a comparative and multi-dimensional way the environmental impacts of biomass energy plants.

2. Materials and methods

2.1. Study area

The study area is the Trentino-Alto Adige region (46° 04′ N, 11° 07′ E) located in North-East of Italy and divided in two administrative provinces: Trento and Bolzano.

The province of Trento covers an area of 621,200 ha with a population of 538,579 inhabitants (density of 0.87 inh. ha^{-1}). The forest area is approximately of 473,133 ha of which 350,000 ha are managed with a forest management plan. The 75% of the managed area (350,000 ha) is covered by forests and 25% by grasslands and unproductive lands. Furthermore, 78% of forest area has a priority productive role (timber and bioenergy production). The growing stock is estimated in 60,000,000 m^3 of which 473,000 m^3 yr^{-1} are harvested annually (around 50% of annual volume increment). The wood processing sector accounts approximately 140 industries of first wood processing with more than 1,220 employers (253 owners and 30 family collaborators, 156 employees, 728 workers, 50 between apprentice and seasonal workers). In 2016, the wood processing industries have worked 347,100 m^3 of raw wood materials, coming for 77% from the province of Trento, 18% from other national forests and 6% from foreign countries. The amount of wood residues from the wood processing industries is around 908,500 bulk cubic meter (bcm) divided in 410,500 bcm of woodchips, 392,500 bcm of sawdust, 65,500 bcm of bark, and 40,000 bcm of trimmings [41]. In particular, 94% of woodchips, 34% of bark, 28% of trimming and 9% of sawdust are used in the biomass district heating plants (DHPs) and combined heat and power plants (CHPs). The sawdust is mainly sold to industries for pellet production, instead bark and trimming are generally purchased from other industries for bedding and wood flour production. In the province of Trento, there are 26 operating biomass energy plants for a global installed power of 72 MW_{th}, 65% of the installation are below 1,5 MW, 6 plants are above 10 MW, and 3 among 3–10 MW. Only 7 are CHPs. The overall electric power installed is around $5MW_{el}$.

The province of Bolzano, which counts 527,750 inhabitants, extends over an area of approximately 7,400 km^2. Its territory is mainly mountainous (86% of land is above 1,000 m a.s.l.) and forests covers more than 372,000 ha, which are approximately 50% of the province [42]. Currently, the growing stock is above 105,000,000 m^3 with an average stock of approximately 310 m^3 ha^{-1}. The annual growth is 1.85 million m^3, leading to an average growth of 5.5 m^3 ha^{-1}. The main forest types are Norway spruce forests (around 60%), European larch forests (19%) and Scots pine forests (10%), followed by Swiss stone pine (6%), silver fir (3%) and other broadleaved forests (2%) [43]. Around 566,000 m^3 of wood are annually harvested, of which 25% are used as biomass for energy production [42]. Within the province, forest management tools depend on the forest size: forests above 100 ha are managed according to a forest management unit plan, whereas forests under 100 ha through a "forest register". Forest sector economy is relevant for the province of Bolzano. More than 2,200 companies work in the timber sector, which involves more than 25,500 people, 650,000 m^3 of wood processed yearly and a forecasted revenue of 1.3 billion of € (2013). Around 75% of logs produced in province of Bolzano are also processed within the province, whereas the remaining ones are exported [42]. Concerning energy production from biomass, the province of Bolzano has intensely supported the conversion to this kind of energy in past years. Currently, 77 DHPs (20 of which combine thermal and electric production) are functioning in the area and consume about 1,500,000 bcm of biomass. The total installed electric power of the 77 plants is 12.5 MW, they produce 70 GWh yr^{--1}. The share of biomass produced within the province is approximately 68% of the used one (45% from sawmills and wood processing enterprises, 23% from farmers and forest owners' woodchips) the remaining part is imported [42]. Wood residues represent a relevant part of the biomass used in DHPs. Due to the regional demand for heat and the dense DHPs net, almost 100% of the available residues coming from the 90 sawmills – that are processing yearly approximately 350,000 m^3 of roundwood – are used for energetic use [43].

2.2. Research framework

2.2.1. Steps of the study

In order to investigate the environmental impacts of the bioenergy system in Trentino-Alto Adige region to increase the social acceptance of renewable energy technologies, the study was structured in three steps: (1) data collection through the administration of a semi-structured questionnaire to the managers of 14 biomass energy plants; (2) data processing step using LCA approach for each biomass energy plant; (3) interpretation of LCA results to identify the variables that most influence the environmental impacts.

From the theoretical point of view, Life Cycle Assessment (LCA) is a widely used method for assessing the environmental impacts throughout a product's (or service's) lifecycle [44, 45]. LCA provides a large set of environmental indicators, identifying air and waterborne emissions as well as resources consumption associated with the good or service's production process [46]. The assessment of the environmental impacts can be carried out by means of [40, 47]: (1) mid-point assessment, calculating the amount of emissions and assigning them to specific impact categories (i.e., global warming potential, ozone depletion potential, photochemical ozone formation potential, acidification potential, eutrophication potential and resource depletion); or (2) end-point assessment, quantifying to what extent a damage (i.e., damage to human health, to ecosystems, and to resources) actually or potentially occurs.

In the present study, LCA was applied to assess the environmental impact of 14 biomass energy plants in Trentino-Alto Adige region and was set using the methodology defined by the International Organization for Standardization (ISO), dividing the study into four main phases [44]:

1. Goal and Scope – ISO 14044:2006: it is the preliminary phase in which the aim of the study, the functional unit, the boundaries of the system studied, the reliability of the data, the assumptions and limits of the study are established;
2. Life Cycle Inventory LCI – ISO 14044:2006: this is the data collection and calculation phase to estimate the mass and energy flows entering and leaving the production system, considering all the transformation and transport processes;
3. Life Cycle Impact Assessment LCIA – ISO 14044:2006: in this phase the environmental impacts caused by the process or activity are quantified, to show the modifications generated by the process analyzed, in terms of resource consumption and substances release in the environment.
4. Life Cycle Interpretation – ISO 14044:2006: this is the final part of an LCA in which the results from previous phases are analyzed to identify which parts of the system can be modified to reduce the overall environmental impact.

2.2.2. Life Cycle Assessment (LCA) approach applied to the case study

2.2.2.1. Goal and Scope. District heating is a system to distribute the heat generated in a centralized plant, through a system of insulated pipes, to satisfy the requirement of space and water heating in residential and industrial buildings. In Italy, the centralized plants are mainly powered with natural gas or biomass (wood waste, sawdust, woodchips). The objective of this study is the identification and assessment of the environmental impacts associated with the production of energy in biomass energy plants, highlighting the production phases that have the greatest impact, comparing the data of 14 different biomass energy plants in Trentino-Alto Adige region.

In order to understand which variables of biomass energy plant – size, type of biomass energy plant, feedstock used – more influence the environmental impacts the non-parametric Mann-Whitney U test and Kruskal-Wallis test were performed. The non-parametric Mann-Whitney U test was used to identify the statistically significant differences between small biomass energy plants (less than 1 MW) and medium biomass energy plants (more than 1 MW), and between DHPs and CHPs. The non-parametric Kruskal-Wallis test was applied to highlight the statistically significant differences among biomass energy plants that use a different feedstock mix (share between forest woodchip and sawmill woodchip).

The non-parametric Mann-Whitney and Kruskal-Wallis tests were performed applying a significance level of $\alpha = 0.05$ using the XLStat 2017 software. The LCA was performed using the SimaPro 8 software.

2.2.2.2. Functional unit and system boundaries. The functional unit has been defined as 1 MJ of thermal energy (MJ_{th}). The study is carried out according to a "Cradle to Gate" approach [48], considering the phases that start from the extraction and processing of raw materials up to the final product (Fig. 1). In particular, the following five forest-wood chain phases were considered: (1) extraction of raw materials (tree felling and harvesting); (2) forest chipping; (3) roundwood processing; (3) transport of roundwood/woodchips/ash; (4) production of thermal and electric energy (energy conversion).

2.2.2.3. Input data and starting assumptions. In carrying out the study, the following assumptions were made:

- Impact of electricity consumption have been calculated based on the national energy mix;
- Impacts due to the construction of the infrastructures (sawmills and biomass energy plants) have not been considered;
- A fixed average value of energy consumption for wood processing in the sawmills – 1 MJ of electrical energy (MJ_{el}) for m^3 of roundwood and 1 MJ of thermal energy (MJ_{th}) for m^3 of roundwood – has been used for all simulations;
- The emissions caused by roundwood, woodchips and ash transport have been calculated considering the same track for all journeys (diesel truck, Euro 5, transport capacity 70 m^3).

The data were collected with a structured questionnaire administered face-to-face to the managers of biomass energy plants integrated with

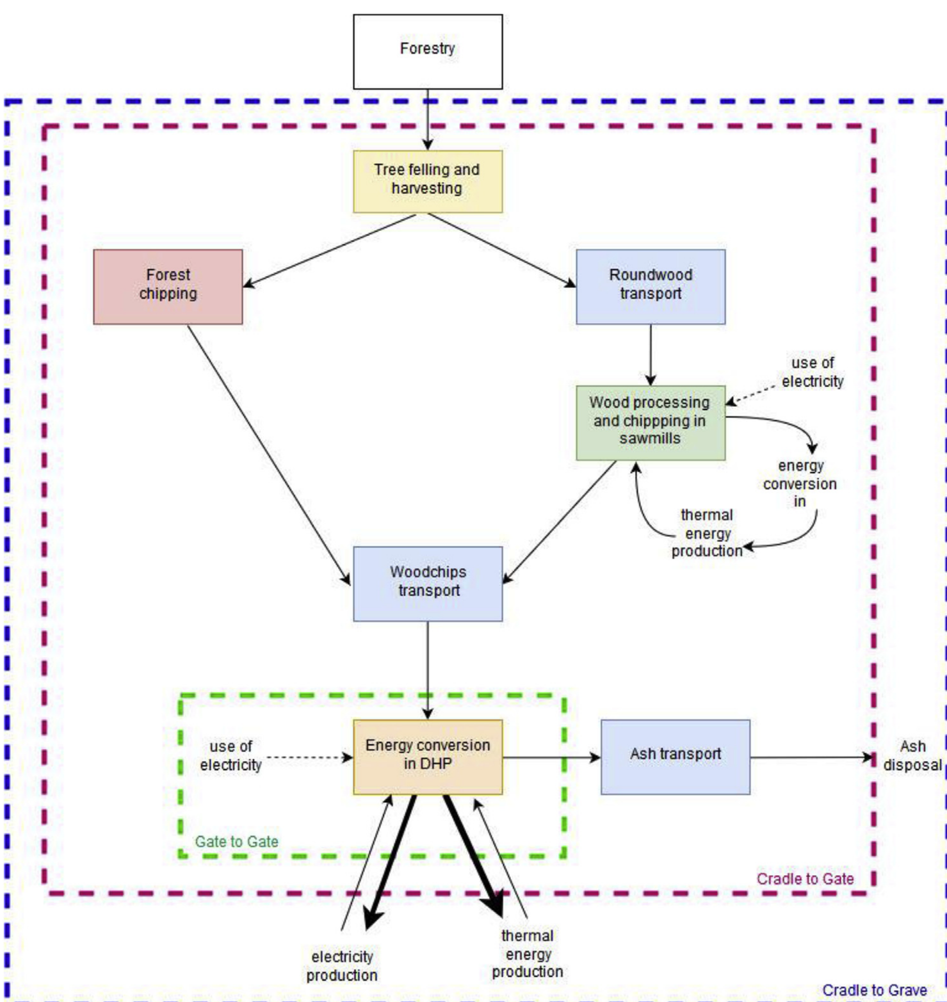


Fig. 1. System boundaries adopted for the LCA analysis.

additional information provided by other actors of the forest-wood supply chain (i.e. forest enterprises and sawmills). The aim of the survey has been to collect the following key information:

- Amount of wood processing residues (sawdust, woodchips, bark, waste) and final destination of wood residues;
- Amount and origin of processed roundwood and forest woodchips;
- Yearly produced energy;
- Plant emissions values (PM_{10}, CO, NO_x, SO_x);
- Water and energy consumption in biomass energy plants;
- Amount of ash produced by biomass energy plants and disposal methods.

Supplementary data have been taken from literature or from the Ecoinvent database available on SimaPro 8 software. The data collection has been carried out from May to August 2018.

2.2.2.4. Life Cycle Inventory (LCI) of the data collected. In the LCI phase, the data collected with the semi-structured questionnaire administered to the managers of biomass power plants has been processed using SimaPro 8. In Table 1, the input and output associated to the functional unit of 1 MJ of thermal energy (MJ_{th}) for each forest-wood supply chain phase are listed.

2.2.2.5. Extraction of raw materials and chipping. The forestry operations have been divided in two phases: (1) tree felling and harvesting to extract raw material; (2) forest chipping. In the context of study, the forestry operations were hypothesized using the following machines: two medium chainsaws Stihl MS180 for tree felling phase; two Lamborghini tractors with winch and a Terex TC125 crawler with Deutz TCD 2012 L04 engine (engine power 74.0 kW) equipped with forest gripper for harvesting phase; one chipper fixed on the rear axle of a TIMBERJACK OY forwarder model Timberjack 1110D for chipping phase.

The data on the productivity and fuel consumption of the chainsaws, forest tractors with winch and chipper have been taken from Paletto et al. (2018) [49]. For tree felling and harvesting, the average fuel consumptions is 0.6 $l\ h^{-1}$ of gasoline for the medium chainsaws (productivity of 5.81 $m^3\ h^{-1}$) and 4 $l\ h^{-1}$ for the forest tractor with winch (productivity of 7.55 $m^3\ h^{-1}$) respectively. For the wood chipping phase, the average consumption of chipper is 20 $l\ h^{-1}$ of gasoline (productivity of 15.11 $m^3\ h^{-1}$).

2.2.2.6. Roundwood processing. The annual quantity of woodchips purchased by the biomass energy plant from the sawmills or directly from the forest enterprises was collected through questionnaire survey. On average, the wood residues produced from the roundwood processing is approximately 30% of the roundwood volume and the woodchips cover half of the total wood residues. Starting from this data, it has been possible to estimate the total quantity of wood residues produced. Additionally, by means of *ad hoc* questionnaire given to the local sawmills, it was possible to identify the origin of the roundwood processed by sawmills (local, national or foreign roundwood).

Table 1
Input and output values for Life Cycle Assessment (LCA) analysis.

Input	Output
Virgin wood (m^3)	Main wood (m^3)
Felling phase hours (h)	Woodchips (m^3)
Diesel oil consumption (kg)	Ash (kg)
Diesel consumption in wood chipping phase (kg)	Thermal energy yield (MJ)
Distance travelled for roundwood, woodchips and ash transport (expressed in tkm - tons per km)	Electric energy yield from cogeneration unit (kWh)
Energy consumption in sawmill (kWh)	Biomass plant emissions: kg CO_2, kg CO, kg NO_x, kg SO_x, kg PM_{10}
Electric energy consumption in DHP (kWh)	Sawmills -Emissions from biomass boilers: kg CO_2, kg CO, kgNO_x, kg SO_x, kg PM_{10}
Diesel oil consumption in the back up boiler (kg)	
Natural gas consumption (Nm^3)	

2.2.2.7. Transport. The transport phase includes the following three transport sub-phases: the transport of roundwood from forest to sawmill, the transport of woodchips from forest or sawmill to the biomass energy plant, and the ash transport to landfill. For the calculation of the emission values, 70 m^3 diesel-powered truck, costing Euro 5 has been considered.

The wood ash produced by the combustion process is collected by specialized companies. The wood ash could be potentially used for compost, road foundations or as additive in the concrete production (building materials). In the present study, only the landfill has been considered as final destination in accordance with the information provided by the managers of biomass energy plants in Trentino-Alto Adige region.

The distances between forests, sawmills, biomass energy plants and landfills have been calculated using the data collected during the interviews. The tkm indicator (tons of wood moved multiplied by the distance - km) has been computed as required input in SimaPro 8 for the LCA analysis.

2.2.2.8. Energy conversion. An average value of the energy consumption (thermal and electrical – MJ m^{-3} of wood processed) for the roundwood processing in the sawmill (roundwood cutting, chipping, drying) has been taken from literature [50]. The data on the energy consumptions of the DHPs and CHPs (hot water pumping, starting boilers) were collected during the interviews. For the calculation of the environmental impact in the LCA of the electric energy generation, the package of the Italian national energy mix was chosen in SimaPro 8, which therefore includes both renewable and non-renewable sources.

The main pollutants of a biomass combustion process are Carbon Dioxide (CO_2), Carbon Monoxide (CO), Nitrogen dioxide (NO_2), Particulates (PM_{10}) and Sulfur dioxide (SO_2). The data on the emission values of the DHPs and CHPs collected during the survey, were given as input data in the SimaPro 8. All the biomass energy plants involved in the survey are equipped with a gas cleaning system: 55% of them has a cyclone or a sleeve filters, 27% an electrostatic filter, and the remaining 18% both types of filter. For the data on the emission values of the wood boilers used in the sawmills – the energy required by the sawmills is often generated by wood boilers, fed with timber process residues – data have been adopted from literature.

2.2.3. Life Cycle Impact Assessment (LCIA)

The results can be presented according to two methods: (1) problem-oriented method; (2) damage-oriented method. In the first method, the inputs and outputs are linked to different impact categories according to their effect on the environment (e.g., acidification, eutrophication, global warming). These are the so-called midpoint effects. The second method utilizes the consequences of the effects obtained with the first method which are grouped in three macro-categories. These three macro-categories are called endpoint effects. In the present study, the ReCiPe (I) 2016 method has been adopted [51], which includes both midpoints and endpoints impacts categories, estimated according to one of the three possible perspectives (I = individualist). The inputs and outputs of the process are included in the 18 categories of midpoint impact, and then grouped in three macro-categories of endpoint impact: damage to human health, damage to ecosystems, and damage to environmental resources (Fig. 2).

Regarding the three macro-categories, the damage to human health is measured through the concept of DALY (Disability-Adjusted Life Years). DALY is used to quantify the burden of human disease resulting from environmental pollution and attribute it to the life cycle of product. It

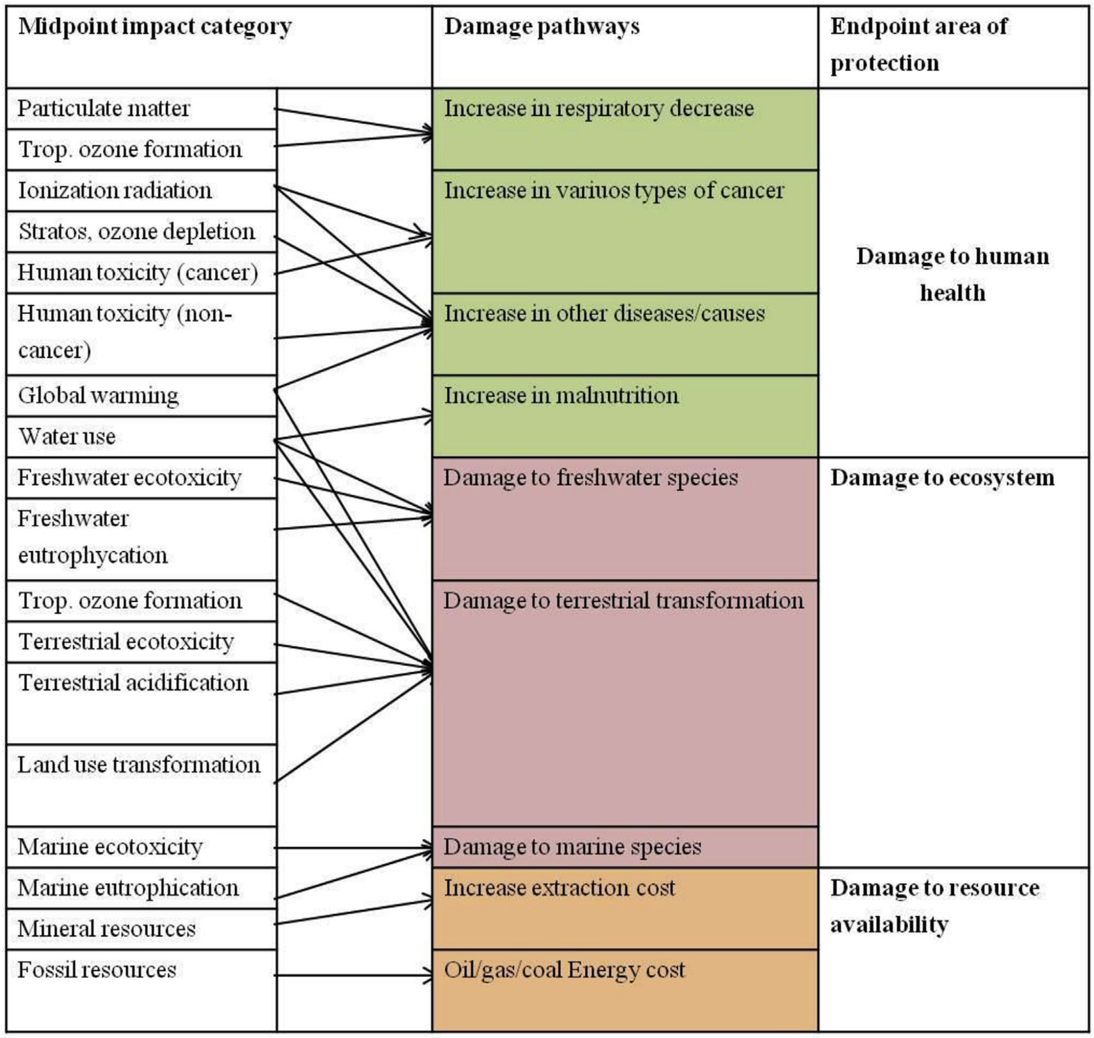


Fig. 2. Relation between midpoint categories and endpoints. Modified from Huijbregts et al. (2017) [51].

measures the gap between an ideal situation in which everyone lives to the standard life expectancy in perfect health and the actual situation (Eq. 1):

$$DALY = YLD + YLL \tag{1}$$

Where:
YLD = years of life lost due to disability when living with the disease or its consequences;
YLL = years of life lost due to premature mortality.

Generally, several causes related to the environmental pollution can lead to human health damage such as direct and indirect effects of climate change, ozone layer depletion, exposure to toxic chemicals, to ionizing radiation, or to particulate matter.

The damage to ecosystems is measured in term of loss of species during a year due to some impact categories (e.g., Climate Change, Terrestrial Acidification, Freshwater Eutrophication, Ecotoxicity, Agricultural Land Occupation, Urban Land Occupation and Natural Land Transformation) that can compromise the natural ecosystem quality.

The damage to environmental resources is quantified through the marginal increase of cost due to extraction of resources, measured in dollars per kilogram ($/kg, economic). The main impact categories related to the environmental resources are Fossil Depletion and Metal Depletion.

3. Results

3.1. Characteristics of the sample of biomass energy plants

The LCA has been applied to 14 biomass energy plants for heating or combined heat and power generation (DHPs and CHPs) in Trentino-Alto Adige region characterized by different size and feedstock used (Table 2). The CHPs are 35% of total biomass energy plants interviewed, while the remaining 65% of plants are DHPs. All 14 biomass energy plants involved in the survey are powered by woodchips from forests and/or wood processing enterprises, no biomass energy plants are powered by agricultural solid waste.

Six biomass energy plants have a thermal power below 1 MW, while the remaining eight biomass energy plants have a thermal power greater than 1 MW. In addition, it is interesting to highlight that the smallest biomass energy plant (P) serves six private and public users with a net length of 4 km, while the largest biomass energy plant (M) serves 979 private users with a net length of 45 km.

With regard to the feedstock used, the majority of biomass energy plants use sawmill woodchips as feedstock. Woodchip from forest (forest W) is preferably used together with woodchip from sawmill (sawmill W), mainly in biomass energy plants with a power greater than 1 MW. The managers of plants prefer sawmill woodchips compared to forest woodchips for the following two reasons: low moisture content (approximately

Table 2
Main characteristics of the biomass energy plants involved in the study.

ID	Size	Start date	Users	Net length	Cogeneration	Sawmill W	Forest W	Diesel oil	Natural gas
	MW	year	n.	km	Yes/No	bcm	bcm	kg	Nm^3
A	0.85	2009	22	2.5	No	1,600		167	
B	0.54	2005	8	1	No	944		1,252	
C	0.98	2016	6	4	No	1,600		4,175	
D	0.5	2012	8	3	No	1,525		835	
E	6	2003	340	10	Yes	20,000		1,113	
F	1	1999	8	1	No	4,000		0	
G	9.5	1999	597	30	No	85,800	5,100	0	1,242,000
H	2.9	2002	136	4	Yes	6,200	5,573	477,516	
I	14.8	2010	979	45	Yes	31,000	62,000	190,000	
L	9.24	2002	271	15	Yes	12,400	24,800	250,000	
M	2.75	2007	11	1.6	No	7,000		3,340	
N	2.5	2015	151	9	Yes	17,000	3000	6,680	
O	1.4	2009	75	5.2	No	3,980	857	560	
P	0.84	1996	13	1	No	3,825	675	167	

20–30% rather than 35–50%) and low presence of bark and soil traces. Therefore, sawmill woodchip ensures better performance and less maintenance actions. In the present study, 50% of biomass energy plants uses 100% of sawmill woodchip, 25% of them uses a small amount of forest woodchips (less than 30% of the total feedstock used), and only in 3 biomass energy plants the forest woodchips represent 30–50% of the total feedstock used.

3.2. Midpoint effects – climate change impact

ReCiPe (I) 2016 accounts 18 environmental impact categories at the midpoint level. The results show a wide range of minimum, maximum and mean values concerning these 18 environmental impact categories of different biomass energy plants (Table 3). The most efficient biomass energy plant for the majority of environmental impact categories (e.g., climate change, terrestrial acidification, freshwater ecotoxicity, metal and fossil depletion) is a greater plant (9.24 MW) powered both with local forest woodchip and sawmill woodchip (plant L). Conversely, the biomass energy plant with the worst environmental performance is a small plant (0.98 MW) powered mainly with sawmill woodchip (plant C).

In the international literature, the most used category is the impact on the climate change, quantified by $gCO_{2eq}\ MJ^{-1}$, which represent the global warming potential (GWP), with a perspective of 20 years' time horizon. The results show an average climate change impact by biomass energy plant of 45.84 $gCO_{2eq}\ MJ^{-1}$ (with a standard deviation of 22.53 $gCO_{2eq}\ MJ^{-1}$) and a range between a minimum impact of 14.83 $gCO_{2eq}\ MJ^{-1}$ (biomass energy plant L) and a maximum impact of 90.70 $gCO_{2eq}\ MJ^{-1}$ (biomass energy plant C).

In Table 4, Figs. 3 and 4, the data on the climate change impact (CO_{2eq} emissions) for each forest-wood supply chain phase has been reported. The results show that the felling and harvesting phase accounts for 1% and 4.5% of total climate change impact (the average value for felling and harvesting phase is equal to 0.754 $gCO_{2eq}\ MJ^{-1}$), while the chipping phase has a very low climate change impact (the average value is 0.026 $gCO_{2eq}\ MJ^{-1}$) strictly related to the biomass energy plants that use forest woodchips as feedstock. The transport and the sawmill processes are the main phases in terms of climate change impact. The impact of the transport phase ranges from 7% and 65% due to the origin of the used roundwood: if roundwood comes from local forests (in a maximum of 50 km) it accounts for 25–30% of total climate change impact (the average value is 16.63 $gCO_{2eq}\ MJ^{-1}$); conversely, if roundwood comes from foreign countries (i.e. Slovenia, Austria, Germany) or from the Central Italy (i.e. Tuscany, Emilia-Romagna regions), it accounts more than 50% of total climate change impact. The climate change impact of the sawmill processes phase is between 30 and 70% of the total according to the quantity of woodchips bought from sawmills (the average value is 21.67 $gCO_{2eq}\ MJ^{-1}$), while the energy conversion phase accounts from 5% to 25% of total climate change impact depending on type of feedstock (the average value is 6.76 $gCO_{2eq}\ MJ^{-1}$).

Table 3
Min, max and mean values of the environmental impact categories for the sample of biomass energy plants investigated.

Impact categories	Unit	Min	Mean	Max
Climate change	kg $CO_{2\ eq}\ MJ^{-1}$	0.01493	0.04584	0.09070
Terrestrial acidification	kg $SO_{2\ eq}\ MJ^{-1}$	8.4E-05	0.000208	0.000393
Freshwater eutrophication	kg $P_{eq}\ MJ^{-1}$	1.27E-05	3.4E-05	5.24E-05
Marine eutrophication	kg $N_{eq}\ MJ^{-1}$	5.61E-06	1.49E-05	2.62E-05
Particulate matter formation	kg $PM_{10\ eq}\ MJ^{-1}$	3.77E-05	0.000108	0.000229
Human toxicity	kg 1,4-$DB_{eq}\ MJ^{-1}$	0.00073	0.002660	0.006762
Agricultural land occupation	$m^2a\ MJ^{-1}$	-0.01345	-0.00559	0.001748
Urban land occupation	$m^2a\ MJ^{-1}$	0.00021	0.001011	0.002979
Natural land transformation	$m^2\ MJ^{-1}$	3.8E-06	1.01E-05	2.44E-05
Fossil depletion	kg $oil_{eq}\ MJ^{-1}$	0.006714	0.013759	0.028336

In the power plants for energy production that use not only woody biomass but also fossil fuels (i.e. diesel oil or natural gas), the impact of the energy conversion phase increases of 40–50% of the total climate change impact of all forest-wood chain supply phases (e.g., G, H, I, L plants). This difference is due to the fact that, in the estimation of the impact value of the climate change category, the emissions of the wood combustion process are neglected (biogenic emissions) due to the renewable characteristics of the wood resource. Conversely, the use of fossil fuels in energy conversion increases the CO_{2eq} value of the combustion phase.

In addition, the LCA results have been grouped and compared according three variables (Table 5):

- Biomass energy plant size: =< 1 MW or >1 MW;
- Feedstock used: 100% sawmill woodchips; 70–99% of sawmill woodchips; <70% sawmill woodchips;
- Biomass energy plant type: DHP or CHP.

The results show that the small biomass energy plants have greater climate change impacts rather than medium biomass energy plants. This difference is related to two forest-wood chain phases: roundwood process and transport. The small biomass energy plants use 100% of sawmill woodchips as feedstock, but the roundwood processed in the sawmills often comes from non-local forests (foreign countries or other Italian regions). Therefore, in the small biomass energy plants the climate change impact of the transport phase (as shown in Fig. 3) is of major importance than medium biomass energy plants. In fact, the latter mainly use woodchips from local forests. The non-parametric Mann-Whitney U

Table 4
Carbon dioxide (CO_2) equivalent emission values of each forest-wood chain phase (LCA - output of the SimaPro 8).

	Size	Felling and harvesting	Chipping	Sawmill process	Transport	Energy conversion	Total
	MW	(gCO_{2eq} MJ^{-1})	(gCO_{2eq} MJ^{-1})	(gCO_{2eq} MJ^{-1})	(gCO_{2eq} MJ^{-1})	(gCO_{2eq} MJ^{-1})	(gCO_{2eq} MJ^{-1})
A	0.85	0.89	0.00	30.22	3.27	8.25	42.64
B	0.54	0.95	0.00	32.26	22.13	10.22	65.56
C	0.98	0.77	0.00	25.92	54.65	9.36	90.70
D	0.50	0.76	0.00	25.76	54.41	4.58	85.52
E	6.00	0.63	0.00	21.15	23.04	3.15	47.97
F	1.00	0.71	0.00	24.15	10.26	3.08	38.21
G	9.50	0.77	0.01	24.58	8.48	11.73	45.57
H	2.90	0.50	0.04	10.97	2.12	15.97	29.60
I	14.80	0.97	0.15	10.97	4.28	5.34	21.72
L	9.24	0.52	0.08	5.82	2.29	6.22	14.93
M	2.75	0.50	0.00	16.83	9.14	4.03	30.50
N	2.50	1.27	0.04	36.39	18.79	3.02	59.50
O	1.40	0.54	0.02	15.97	8.53	3.34	28.40
P	0.84	0.78	0.03	22.33	11.44	6.39	40.96

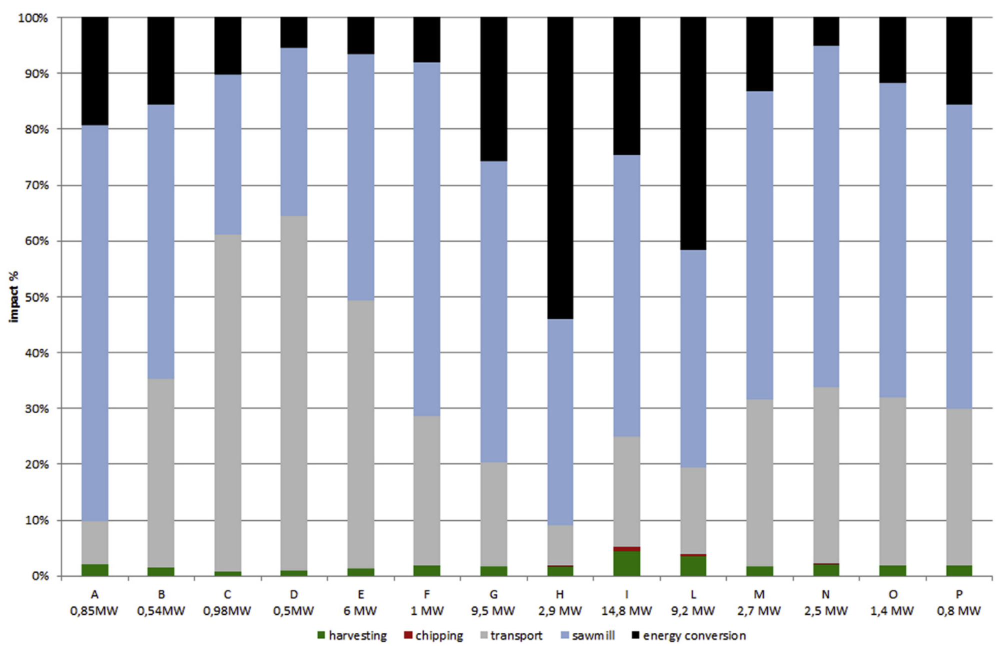


Fig. 3. Impact percentage (%) of each forest-wood chain phases on the total impact on climate change for the 14 biomass energy plants.

test shows no statistically significant differences between small and medium biomass energy plants.

Concerning the feedstock used in the biomass energy plants, the results show that the climate change impact decreases (even 50%) when the percentage of forest woodchip on total woodchip used increases. This difference is because the forest woodchip comes from Trentino-Alto Adige forests, while the sawmill woodchip is produced with non-local roundwood. The non-parametric Kruskal-Wallis test shows statistically significant differences among biomass energy plants characterized by different feedstock mix ($p = 0.005$).

Lastly, the results show a higher CO_{2eq} emissions value of the DHPs due to a higher contribution of transport and sawmill processes phases compared to the CHPs one. On average, the DHPs have smaller plant size and use mainly sawmill woodchips; conversely, CHPs accept forest woodchips due to the bigger boiler size and the energy conversion technology installed. From the statistical point of view, the non-parametric Mann-Whitney U test shows no statistically significant differences between DHPs and CHPs regarding the climate change impact.

In Fig. 3 the impact percentage of each forest-wood chain phase on climate change is reported. It is worth to underline that for the category "sawmill W < 70%", the high percentage of the energy conversion phase is due to the remarkable utilization of fossil fuels (i.e. diesel oil) in some biomass energy plants belonging to this group.

3.3. Midpoint effects and endpoint effects

The impact on the climate change can be considered the most important environmental impact in a communication and information strategy towards the local community (citizens and decision makers). The climate change is a relatively simple concept to understand even for ordinary people. However, it is important to consider in the global assessment other 17 environmental impact categories provided by LCA.

In the present study, the environmental impact categories with values below 10^{-5} have been considered negligible and not reported in the outputs (i.e. ozone depletion, marine and freshwater eutrophication, terrestrial ecotoxicity). Equally, agricultural land occupation and ionizing radiation, show negative values – avoided impacts – and have not been reported (order of magnitude 10^{-4}). The environmental impacts of the remaining 11 categories are briefly described according to the ReCiPe (I) 2016 method (Table 6).

Human toxicity is a calculated index that accounts for the potential harm of a unit of chemical released into the environment, due to its

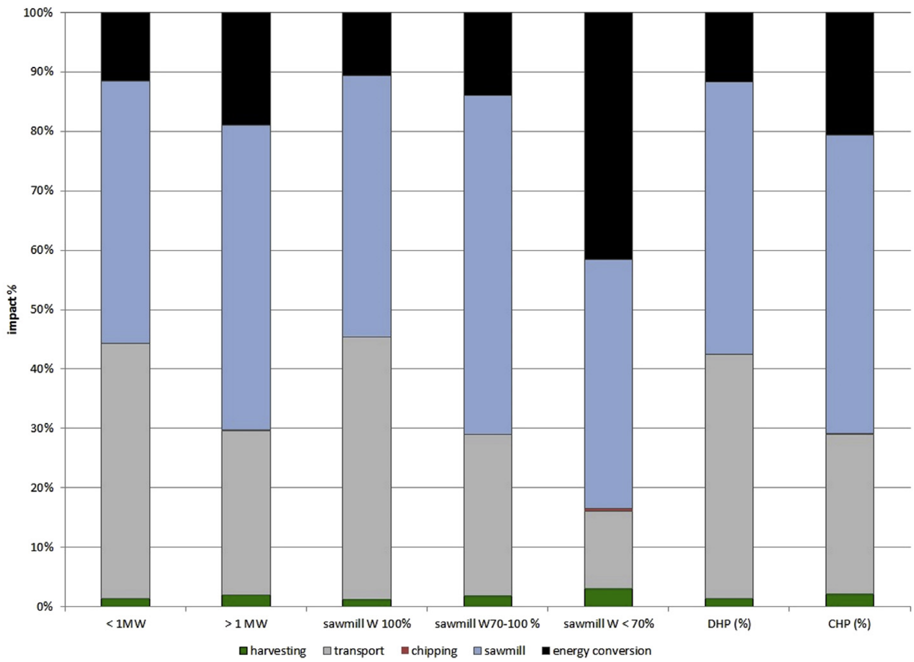


Fig. 4. Average percentage of impact on the climate change of the different forest-wood chain phases.

Table 5
Average climate change impact by size, feedstock, and biomass energy plant type (*SW = sawmill woodchip).

	Biomass energy plants	Felling and Harvesting (CO_{2eq} MJ^{-1})	Chipping (CO_{2eq} MJ^{-1})	Energy conversion (CO_{2eq} MJ^{-1})	Roundwood process (CO_{2eq} MJ^{-1})	Transport (CO_{2eq} MJ^{-1})	Total (CO_{2eq} MJ^{-1})
Size							
≤1MW	A, B, C, D, F, P	0.81	0.00	6.98	26.77	26.03	60.60
>1MW	E, G, H, I, L, M, N	0.71	0.04	6.60	17.84	9.58	34.77
Feedstock							
100% SW*	A, B, C, D, E, F, M	0.75	0.00	6.09	25.19	25.27	57.30
70–99% SW*	G, N, O, P	0.84	0.02	6.12	24.82	11.81	43.61
<70% SW*	H, I, L	0.67	0.09	9.18	9.25	2.90	22.08
Type							
DHP	A, B, C, D, F, M, O, P	0.74	0.01	6.16	24.18	21.73	52.81
CHP	E, G, H, I, L, N	0.78	0.06	7.57	18.31	9.83	36.55

Table 6
Average environmental impacts by size, feedstock and biomass energy plant type (S-W = sawmill woodchip).

Impact category	Unit/MJ	<1 MW	>1 MW	100% S-W	>70% S-W	<70% S-W	DHP	CHP
Terrestrial acidification	kg SO_{2eq}	6.1E-02	3.5E-02	5.7E-02	5.1E-02	2.2E-02	4.9E-02	3.2E-02
Human toxicity	kg 1.4-DBeq	2.8E-04	1.5E-04	2.5E-04	2.2E-04	1.2E-04	2.2E-04	1.5E-04
Photochemical oxidant	kg NMVOC	3.8E-03	1.8E-03	3.7E-03	3.3E-03	9.2E-04	3.0E-03	1.6E-03
Particulate matter	kg PM_{10eq}	3.7E-04	1.8E-04	3.3E-04	2.8E-04	1.3E-04	2.9E-04	1.7E-04
Freshwater ecotoxicity	kg 1.4-DB_{eq}	1.6E-04	6.9E-05	1.4E-04	1.1E-04	5.4E-05	1.2E-04	6.5E-05
Marine ecotoxicity	kg 1.4-DB_{eq}	1.8E-03	1.2E-03	1.7E-03	1.5E-03	8.4E-04	1.5E-03	1.1E-03
Urban land occupation	m^2a	7.8E-04	5.1E-04	7.4E-04	6.6E-04	3.6E-04	6.5E-04	4.6E-04
Water depletion	m^2a	1.5E-03	6.4E-04	1.5E-03	1.3E-03	2.9E-04	1.2E-03	5.6E-04
Metal depletion	m^3	2.7E-04	1.7E-04	2.5E-04	2.3E-04	1.8E-04	2.1E-04	1.8E-04
Fossil depletion	kg Fe_{eq}	2.5E-03	1.3E-03	2.4E-03	2.1E-03	7.5E-04	2.0E-03	1.2E-03
Terrestrial acidification	kg oil_{eq}	1.7E-02	1.2E-02	1.6E-02	1.4E-02	1.1E-02	1.3E-02	1.3E-02

persistence and accumulation in the human food chain and toxicity. These by-products, mainly arsenic, sodium dichromate, and hydrogen fluoride, are caused, for the most part, by electricity production from fossil sources. These are potentially dangerous chemicals to humans through inhalation, ingestion, and even contact. The impact category is measured in 1.4-dichlorobenzene equivalents and the outgoing impact values is 10^{-3} kg 1.4-DB_{eq} (order of magnitude). The results show an average value of Human toxicity equal to 0.002660 kg 1.4-DB_{eq} MJ^{-1} (range between 0.00073 kg 1.4-DB_{eq} MJ^{-1} of the biomass energy plant L and 0.006762 kg 1.4-DB_{eq} MJ^{-1} of the biomass energy plant C).

Environmental toxicity is measured considering two separate impact categories: freshwater and marine ecotoxicity. These categories are mainly related to the emissions due to the fossil fuels combustion (for energy and transport) of some substances (e.g., heavy metals).

Assessment of toxicity has been based on maximum tolerable concentrations in water ecosystems. Ecotoxicity Potentials are calculated with the USES-LCA, which is based the EU's toxicity model. This provides a method for describing fate, exposure and the effects of toxic substances on the environment. Characterization factors are expressed using the reference unit, kg 1.4-dichlorobenzene equivalent (1.4-DB) and are measured separately for impacts of toxic substances on the three ecosystems (freshwater and marine - magnitude order of impact values: 10^{-3}-10^{-4} kg 1.4-DB_{eq}). In this study, the average values of environmental toxicity are: 7.62E-06 kg 1.4-DB_{eq} MJ^{-1} for Terrestrial toxicity, 0.001472 kg 1.4-DB_{eq} MJ^{-1} for Freshwater toxicity, and 0.000629 kg 1.4-DB_{eq} MJ^{-1} for Marine toxicity.

Terrestrial acidification is quantified using the reference unit of kg SO_{2eq}, and accounts for acidification caused by SO_2 and NO_x. In the atmosphere, the acidic sulphur dioxide (SO_2) react with water to form "acid rain", a process known as acid deposition. The main gases that cause acid deposition include ammonia (NH_3), nitrogen oxides (NO_x) and sulphur oxides (SO_x). In this study, the results concerning the14 biomass energy plant investigated show an average Terrestrial acidification of 0.000208 kg $SO_{2eq.}$ MJ^{-1} with a range from a minimum of 8.4E-05 kg $SO_{2eq.}$ MJ^{-1} (biomass energy plant L) and a maximum of 0.000393 kg $SO_{2eq.}$ MJ^{-1} (biomass energy plant C).

Particulate Matter is a complex mixture of extremely small particles. Particle pollution can be made up of several components, including acids (e.g., nitrates and sulphates), organic chemicals, metals, and soil or dust particles. A multitude of health problems, especially of the respiratory tract, are linked to particle pollution. PM is measured in PM10 equivalents, and the order of magnitude is 10^{-3}-10^{-4} kg $PM10_{eq}$. The results show an average particular matter formation of 0.000108 kg $PM10_{eq}$ MJ^{-1} with a range from a minimum of 3.77E-05 kg $PM10_{eq}$ MJ^{-1} (biomass energy plant L) and a maximum of 0.000229 kg $PM10_{eq}$ MJ^{-1} (biomass energy plant C).

Photochemical oxidant formation considers the ozone formation at ground level which is toxic to humans in high concentration. Photochemical ozone is formed by the reaction of volatile organic compounds and nitrogen oxides in the presence of heat and sunlight. The impact depends largely on the amounts of carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxide (NO), ammonium and NMVOC (non-methane volatile organic compounds).

The impacts on use of *agricultural land occupation* or *urban land occupation* are expressed as "the amount of land transformed or occupied" per m^2 yr (square meter of land per year). The biomass energy plants have a small negative impact on the agricultural land occupation, and a positive impact on the urban land occupation (order of magnitude 10^{-3}-10^{-4} m^2 yr).

The last environmental impact categories are *water, metal and fossil depletion*. The water depletion has an order of magnitude of 10^{-4} m^3 and indicates the amount of freshwater consumed. The metal and fossil fuel depletion are referred to the consumption of non-renewable resource and expressed in kg Fe_{eq} and kg oil_{eq}. The average impacts values of the biomass energy plants investigated are of 10^{-3} kg Fe_{eq} and 10^{-2} kg $oil_{eq.}$ In this study, the average values are: 0.000208 m^3 MJ^{-1} for water depletion, 0.001821 kg Fe_{eq} MJ^{-1} for metal depletion, and 0.013759 kg oil_{eq} MJ^{-1} for fossil depletion.

The results show that the most important environmental impact categories are fossil depletion and human toxicity, followed by metal depletion, urban land occupation and freshwater toxicity (Table 7). Globally, lower impact on the environment is registered in the CHPs with size greater than 1 MW, which used also forest woodchip as feedstock. These results can be explained considering that the smaller biomass energy plant (<1 MW), are all DHPs, and operate only with sawmill woodchip (sawmill woodchip is drier and cleaner than forest woodchip, therefore, it generates fewer problems of blocking, fouling and maintenance actions).

The use of sawmill woodchip in the biomass energy plants implies both higher consumption of electric and thermal energy and higher km for timber supplying (which means higher fossil fuel consumption) compared then the forest woodchip production. In this study, the woodchip to the small biomass energy plant is often provided by pallet manufacturers, which often buy roundwood from foreign countries. Generally, the pallet manufacturers prefer to buy roundwood from foreign countries because it is cheaper than local roundwood.

The non-parametric Mann-Whitney U test shows statistically significant differences between small and medium biomass energy plants for eight environmental impacts: human toxicity ($p = 0.043$); freshwater ecotoxicity ($p = 0.020$); marine ecotoxicity ($p = 0.029$); terrestrial acidification ($p = 0.020$); particulate matter ($p = 0.001$); photochemical oxidant ($p = 0.001$); urban land occupation ($p = 0.020$); and metal d depletion ($p = 0.059$). Regarding the biomass energy plant type, the non-parametric Mann-Whitney U test shows no statistically significant differences for all environmental impact categories. Conversely, the non-parametric Kruskal-Wallis test shows statistically significant differences among biomass energy plants characterized by different feedstock used for almost all environmental impacts: human ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, terrestrial acidification, particulate matter, photochemical oxidant, marine ecotoxicity, metal depletion, and urban land occupation ($p = 0.001$); fossil depletion ($p = 0.002$); natural resource occupation, water depletion, and ozone depletion ($p = 0.003$); agricultural land occupation ($p = 0.009$).

In summary, the results of the LCA empathize that, from one side the environmental impact of a DHP or CHP is anyway lower than a fossil fuel plant, thanks to the renewable properties of the biomass. From other side, the results highlight the key role of the short wood supply chain for the energy production and the potential economic and ecological value of the forest woodchips. However, since the forest woodchip is less desired or refused by the biomass plant managers, is necessary to improve the forest woodchip quality and to guarantee working performance comparable with the sawmill woodchip.

The endpoints are three macro-categories that are identified using the midpoint effect and are quantified using different units of measure. The damage to "human health" is measured in DALY (Disability Adjusted Life Years), which identifies the gap between an ideal situation in which everyone lives in perfect health, the standard life expectancy and the real situation compromised by the damage caused by the process. The damage to "ecosystems" is measured in species/yr, which represents the loss of species in a specific area during a fixed period (years). The "resources" category is expressed in U.S. dollars ($) corresponding to future costs for the extraction of resources as a consequence of the current exhaustion.

The endpoint values of the three macro-categories are determined by the impacts of the midpoint categories. The damage to human health includes the climate change and human toxicity categories. Instead, damage to ecosystems, is linked with climate change, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity and the transformation of natural soils.

In Table 7 the average endpoints values for each group of plants is reported. As previously mentioned, categories of damage to human

Table 7
Average environmental impacts by size, feedstock, and biomass energy plant type (S-W = sawmill woodchips) for the three macro-categories (endpoints effects).

Impact category	Unit	<1 MW	>1 MW	100% S-W	>70% S-W	<70% S-W	DHP	CHP
Human Health	DALY	1.17E-07	6.05E-08	1.07E-07	7.77E-08	4.09E-08	1.00E-07	6.39E-08
Ecosystems	species.yr	4.94E-10	2.78E-10	4.70E-10	3.31E-10	1.92E-10	4.26E-10	2.96E-10
Resources	$	1.04E-03	6.94E-04	9.86E-04	7.42E-04	6.35E-04	8.94E-04	7.70E-04

health and damage to ecosystem are influenced by climate change, and therefore by the amount of CO_{2eq} emitted by the process analyzed. The values of the first category are mainly due to pollutant and CO_{2eq} emissions caused by transport and energy consumption of sawmill process phases, instead the second category is influenced by the consumption of diesel fuel in the transport and in the energy conversion phases. The endpoints values of each phase of the forest wood chain (not reported here) show that the highest contribution to the endpoints effects is given by the transport and the sawmill phases.

For three of the biomass energy plants (B, D, E), the transport phase is particularly impactful (50–60% on the total climate change impact) due to the timber origin (high percentage of timber from foreign countries), which means high tkm values (roundwood tons per km travelled) and consequently high diesel consumption. The plants B, D, E fall in the first, third and sixth group (<1MW, 100% sawmill W and DHP). In these groups fall the plants B, D and E, which are characterized by high CO_{2eq} MJ^{-1} emission values for the transport phase, which accounts for the 50–60% of the total impact on the climate change.

In Fig. 5 the three macro-categories have been reported to the same unit measure (mPt) by means of a normalization process. As can be seen, the major impacts are on human health and ecosystems. The lower impact is on the resources, since the biomass plant operate mainly with renewable source. The first, third and sixth group have the highest total values.

Analyzing the total damage of each group to human health, ecosystems and resources, the smaller plants (less than 1 MW), that purchase 100% sawmill woodchips, impact heavier on all three endpoints (A, B, C, E, D, F, P plants). On the contrary, the medium plants (more than 1 MW) fed with mixed woodchips (sawmill and forest) have lower impact on all three macro-categories of environmental impact (H, I, L, O), even if the plant G, H, I, L use a discrete amount of methane or diesel oil for energy generation. Conversely, for the plants that used also fossil fuels, the energy conversion phase accounts more on the total climate change impact respect to the other biomass energy plants. In four biomass energy plants (M, N, O, P), the energy conversion phase has impact values equal or greater than transport phase.

Overall, the biomass energy plants which utilized mainly local wood and an amount of forest woodchips above 30% (short wood supply chain) have globally smaller impacts on the three macro-categories than the other biomass energy plants. Among all phases, the forest chipping phase is the less harmful for all three macro-categories of environmental impact.

4. Discussion

The results of this study show that the two main variables that influence the environmental impacts are: size and feedstock used. It is interesting to highlight that small size plants (less than 1 MW) have more environmental impacts in all categories than medium size plants (more than 1 MW). This difference is probably due to fact that the small size plants buy almost 100% of the woodchips from sawmills, which often works roundwood coming from foreign countries. The purchase of roundwood from foreign countries requires a greater consumption of fuel for the transport phase, thus causing an increase in the total environmental impact. On the other hand, the medium size plants use obviously a higher quantity of woodchips, which mainly comes from local forests or sawmills working local roundwood. In this way, the environmental impact caused by the transport phase is lower, and consequently the environmental effect (per functional unit) of medium size biomass energy plants is much better than that of smaller ones. Summarizing, the results of the present study highlight that the origin of the raw material (roundwood and woodchips) is the key variable to reduce the environmental impacts related to the use of wood biomass for energy production. This result is in line with several authors that emphasize the importance of the short wood supply chain to reduce the environmental impacts in forestry operations [52, 53, 54]. In order to increase social acceptance for new biomass energy plants it is necessary to emphasize the role of the short wood supply chain in the raw material supply (forest and sawmill woodchips) highlighting the positive impacts in terms of job opportunities and local economy growth. As emphasized by Paolotti et al. (2017) [54], the short wood supply chain has many environmental, economic and social advantages such as: it minimizes transport emissions; it reduces the number of operators involved in the value chain, ensuring greater distributional equity and profitability for producers; it creates green jobs locally. Besides, the local community's involvement in the early phases of the decision-making process is a key issue that must be considered by decision makers to reduce potential conflicts between decision makers and local community. During the participatory process, the potential environmental impacts deriving from the realization of the new biomass plant must be presented in a comprehensible way to all the participants.

The results of the present study can be compared with the results of other similar studies. Cherubini et al. (2009) [32] quantified energy and GHG balances of bioenergy systems using software tool GEMIS (Global Emission Model for Integrated Systems). Those authors showed that GHG emissions for the electricity and cogeneration plant powered by woodchips or pellets is 15–30 gCO_{2eq} MJ^{-1}, while for the district heating plant powered by woodchips or pellets is 5–20 gCO_{2eq} MJ^{-1}.

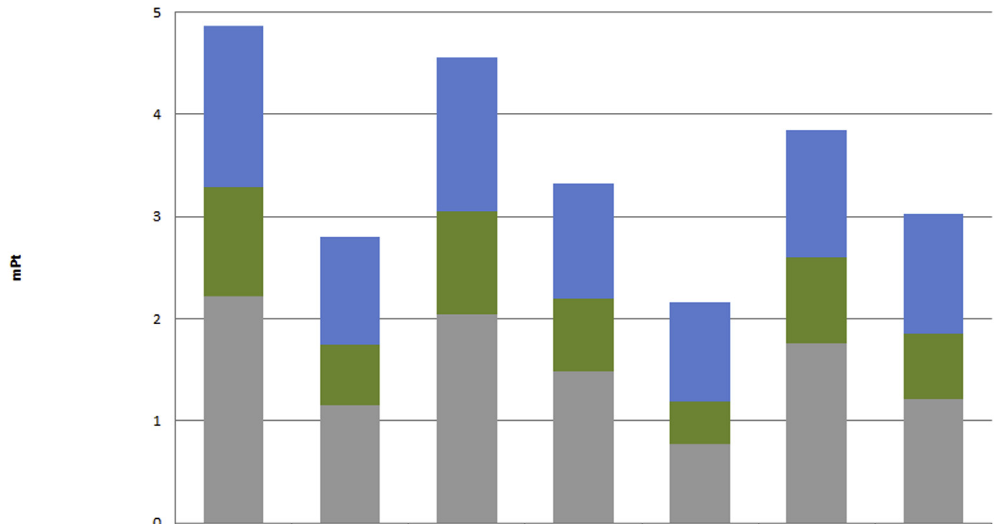
In two case studies in the Alpine region, Nikodinoska et al. (2018) [40] have estimated – through an LCA approach – that CHPs have a higher impact on global warming potential rather than DHPs: 7.6 $gCO_{2eq.}$ MJ^{-1} for the DHP and 62 $gCO_{2eq.}$ MJ_{eu}^{-1} for CHP. This difference between CHPs and DHPs was not confirmed by the results of the present study presumably because we focused on producing thermal energy.

Havukainen et al. (2018) [55] have calculated the environmental impacts of a small-scale CHP (540 kW) powered with woodchips or pellets. The results show, excluding the biogenic carbon emissions, an environmental impact of 2.2–5.1 gCO_{2eq} MJ^{-1}, which grows to 59–66 gCO_{2eq} MJ^{-1} with the biogenic carbon emissions. The acidification potential ranges between 136 and 175 $mgSO_2$ MJ^{-1}. Those authors have emphasized that by using forest biomass instead of natural gas in energy production, the global climate impacts are reduced when biogenic carbon is disregarded. The calculated climate benefit decreases if the biogenic carbon is included, since the total emissions are 4–7% over those of natural gas use. The impact of the transport phase is between 8-17% of total climate change impact.

With regard to the environmental impacts of forestry operations, Berg and Lindholm (2005) [34] quantified the climate change global warming potential by forest operation in three areas of Sweden (North, Central and South: seedling production from 386 CO_{2eq} m^3 to 599 CO_{2eq} m^3, silviculture from 299 CO_{2eq} m^3 to 1730 CO_{2eq} m^3, logging operations from 5100 CO_{2eq} m^3 to 5910 CO_{2eq} m^3, and for secondary haulage from 7060 CO_{2eq} m^3 to 9510 CO_{2eq} m^3. Similarly, those authors estimated the other three environmental impacts (photochemical ozone formation, acidification, eutrophication) by forest operations.

Valente et al. (2011) [36] estimated that the global warming potential of the wood biomass supply chain in Fiemme Valley (Italy) is 13.2 $kgCO_{2eq}$ m^{-3} solid over bark divided in the following way between phases: 40% of overall emissions for chipping (5.29 $kgCO_{2eq}$ m^3), 27% for transportation (3.54 $kgCO_{2eq}$ m^{-3}); 23% for landing operation (3.02 $kgCO_{2eq}$ m^3), 9% (1.25 $kgCO_{2eq}$ m^3) for extraction, and the remaining 1% (0.10 $kgCO_{2eq}$ m^3) for felling. The results of the present study confirmed the low environmental impact of felling and harvesting phase, while the impact of transportation phase in our case studies is higher than the one highlighted by Valente et al. (2011) [36].

Buonocore et al. (2014) [37] estimated the CO_2 released due to the timber and woodchip production in a case study in the Italian Alps (Fiemme and Fassa Valleys, Trentino-Alto Adige region) taking into account the direct use of fuel in forestry activities and the indirect fuel consumption for fuel refining, extraction of metals, and machinery manufacture. Those authors quantified the CO_2 released in 8.55×10^8 g yr^{-1} for timber production and in 1.33×10^8 g yr^{-1} for woodchip



	< 1MW	> 1 MW	100% Sawmill W	70-100% Sawmill W	< 70% Sawmill W	DHP	CHP
Resources mPt/MJ	1,58	1,06	1,50	1,13	0,97	1,25	1,17
Ecosystems mPt/MJ	1,06	0,60	1,01	0,71	0,41	0,84	0,64
Human Health mPt	2,22	1,15	2,04	1,48	0,78	1,75	1,22

Fig. 5. Average impact on the Midpoints categories of the biomass energy plants involved in the study (grouped by size, feedstock and type).

production.

The results of this study are in line with the literature data for the biomass energy plants powered in accordance with the short wood supply chain principles. When the woodchip is made 100% from sawmill processes and roundwood comes from foreign countries or from more than 200 km far away, the global impact value on the climate change is higher than the literature data because the transport phase can account for 50–60% of the total global impact value. The average value on the 14 biomass energy plants, of the climate change impact is of 50 gCO_{2eq} MJ^{-1} (considering all phases of forest-wood supply chain) and of 7 gCO_{2eq} MJ^{-1} considering only the energy conversion phase. The analysis has been run neglecting the CO_{2eq} emissions due to the biogenic carbon. In some cases, the transport phase can increase considerably the climate change impact due to the origin of roundwood. As reported by Havukainen et al. (2018) [55], if the biogenic carbon is included, the impact of biomass plants is almost equivalent with the impact of a natural gas plant. Conversely, the average values on the climate change impact for the heat district plant fueled with natural gas or oil are 70–85 gCO_{2eq} MJ^{-1} and 90–120 gCO_{2eq} MJ^{-1} respectively [32].

5. Conclusions

The research system is the key to facilitating communication channel between social and technological system to increase the social acceptance and reduce conflicts between decision makers and local community related to new biomass energy plants.

The present study highlighted that size of biomass energy plant and feedstock used are the most important variables that influence climate changes and other environmental impacts. A high degree of knowledge about these variables is of considerable importance for preparing an effective communication and information plan aimed at highlighting the real impacts on human health, ecosystems and resources. In the definition of a communication and information plan the differences in the environmental impacts between renewable energy sources (i.e. woody biomass) and fossil fuels should be emphasized in a simple and direct way. The results provided by the LCA concerning the three macro-categories of endpoint impact (damage to human health, to ecosystems, and to environmental resources) are easy to understand for citizens and decision makers. Therefore, the communication and information plan should focus on human disease and loss of biodiversity resulting from environmental pollution due to the use of fossil fuels rather than renewable energy sources. In order to communicate these results more effectively, workshops and meetings should be organized with the aim of explaining the real risks to human health related to the environmental pollution generated by biomass energy plants at local level. During these workshops and meetings, an open participatory process should be conducted by an external facilitator in order to take into account all local interests and points of views. In addition, this inclusive participatory process has the advantage of increasing citizens' trust in the public authority and reducing conflicts between users.

From the methodological point of view, the main advantage of proposed method is to provide detailed data on 18 environmental impacts (midpoints) and three macro-categories of environmental impacts that are human health, ecosystems and resources (endpoints). The robustness and completeness of this data is a strength to support decision makers in the choice of technologies with a low environmental impact.

Conversely, the main disadvantage is that the LCA implementation requires many data on the biomass energy plants, and the LCA analysis itself can vary according to the system boundaries chosen. The developed analysis has underlined the importance of a short wood supply chain, to decrease the environmental impact of the biomass energy plant. Furthermore, the utilization of forest woodchips should be favored, since it implies environmental and economic advantages, improving the quality of the forest woodchips by means of debarking and drying process.

The future steps of this study will be to analyze further biomass energy plants in the Alpine region and increase the number of investigated variables related to the biomass energy plant's characteristics.

Declarations

Author contribution statement

Alessandro Paletto: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Silvia Bernardi: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Elisa Pieratti: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Francesca Teston: Performed the experiments; Analyzed and interpreted the data.

Manuela Romagnoli: Conceived and designed the experiments; Performed the experiments.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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