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Research article

Embodied energy and environmental impacts of a biomass boiler: a life cycle approach

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Abstract: The 2030 policy framework for climate and energy, proposed by the European Commission, aims towards the reduction of European greenhouse gas emissions by 40% in comparison to the 1990 level and to increase the share of renewable energy of at least the 27% of the European's energy consumption of 2030. The use of biomass as sustainable and renewable energy source may be a viable tool for achieving the above goals. However, renewable energy technologies are not totally clean because they cause energy and environmental impacts during their life cycle, and in particular they are responsible of air pollutant emissions. In this context, the paper assesses the energy and environmental impacts of a 46 kW biomass boiler by applying the Life Cycle Assessment methodology, as regulated by the international standards of series ISO 14040, ISO 21930 and EN 15804. The following life-cycle steps are included in the analysis: raw materials and energy supply, manufacturing, installation, operation, transport, and end-of-life. The results of the analysis, showing a life-cycle primary energy consumption of about 2,622 GJ and emissions of about 21,664 kg CO_{2eq}, can be used as a basis for assessing the real advantages due to the use of biomass boilers for heating and hot water production.

Keywords: life cycle assessment; embodied energy; biomass boiler; environmental impacts; renewable energy technology; greenhouse gas emissions

Abbreviations: AD: Abiotic Depletion; AP: Acidification Potential; EP: Eutrophication Potential; FU: Functional unit; GER: Global Energy Requirement; GWP: Global Warming Potential; LCA: Life Cycle Assessment; LCIA: Life Cycle Impact Assessment; ODP: Ozone Depletion Potential; POCP: Photochemical Oxidation; RES: Renewable energy sources

1. Introduction

People's well-being, industrial competitiveness and the overall functioning of society are dependent on safe, secure, sustainable and affordable energy [1]. Climate change, increasing dependence on oil and other fossil fuels, growing imports, and rising energy costs are making our societies and economies vulnerable. These challenges would require a comprehensive and ambitious response [2].

Renewable energy sources (RES) have an important role to play in securing diversified energy supplies and in fighting climate change [3], considering that the energy sector is the highest contributor to human related greenhouse gas emissions [1]. RES may be a relevant tool for the achievement of a 40% and 80% domestic reduction in greenhouse gas emissions by 2030 and 2050, respectively, compared to 1990 levels [1,4].

Over the last years bioenergy was, in absolute terms, the fastest growing RES in the European Union and the major source, accounting for almost 62% of European renewable energy and showing steady growth patterns across the different market segments. The contribution of biomass to the energy supply in terms of gross inland energy consumption increased from 53 Mtoe in 2000 to 115 Mtoe in 2011 (68% of the total RES). One of the main reasons for the large share of bioenergy within renewables is the important advantage that it can easily be stored, transported and used with flexible load and applications on site [5]. Therefore, the future development of bioenergy will be crucial to reach the RES and greenhouse gas reduction targets set to all European member states [6]. Biomass for energy is used in solid, liquid and gas forms. It can originate from agricultural crops and residues, from forestry, from the wood processing industry and from organic waste streams. After conversion biomass delivers heat, electricity and transport fuels as final energy. In the European Union, in 2011, biomass accounted for 8.4% of the total final energy consumption and the final energy of biomass was delivered to 12% for transport, 12% for electricity and 72% for heat [7].

As a feedstock for producing electricity or heat, biomass has a number of advantages over fossil fuels. It is widely distributed, relatively easy to collect and use and can produce less net CO_2 emissions than fossil fuels per unit of useful energy delivered, if sourced sustainably. In addition, biomass usually contains less sulphur than coal or oil. However, environmental issues need to be addressed to ensure the overall impact of bioenergy is positive compared to that of fossil fuels [8].

Renewable energy technologies that use biomass for energy production cannot be considered totally clean. They require energy consumption and have environmental impacts that cannot be neglected during their life cycle [9]. In particular, relevant air pollutant emissions (including fine dust) generated during the use of biomass should be taken into account, representing a relevant environmental issue.

In this context the Life Cycle Assessment (LCA) is a useful tool to quantify the energy and environmental impacts of products and services, to locate the system's components or sub-processes responsible of the highest impacts, and to compare the performances of different products or technologies that provide the same service [10,11]. The results of a LCA study can be used to support the development of low impact production systems, to provide decision makers with information on the environmental effects of different choices and policies, to promote the "green purchases".

2. Materials and Method

In this paper, a LCA approach assesses the life cycle energy and environmental impacts of a biomass boiler. The results of the analysis can be used as a basis for the assessment of the real advantages in the use of biomass boilers for heating and hot water production.

The LCA study is described in the following paragraphs, including the description of the product (Section 2.1), the goal and scope definition (Section 2.2), the inventory analysis (Section 2.3) and the summary of the energy and environmental impacts of the boiler (Section 2.4). Finally, in Section 3 the authors provide some final remarks.

2.1. The product studied

The studied product is a 46 kW biomass boiler, a renewable energy technology that can be used for building heating, domestic hot water and for the generation of heat to be delivered to industrial and agricultural sectors. Different kinds of solid fuel can be used to feed the boiler as wood, pellets, almond shells, pine nut shells, and pistachio shells. Moreover, the boiler can also use liquid bio-fuels.

The boiler is thermally insulated in order to reduce the heat losses and increase its efficiency: a thick layer of glass wool insulates the body of the boiler, fiberglass seals allow the closures of the flap to be hermetic, and a thick layer of refractory material insulates the flap. The brazier is made from stainless steel and cast iron. The fuel is stocked in a 190 liters silo. A cochlea activated by an electric motor moves the fuel inside the burner. The combustion air is inserted by a side duct.

The heat developed in the combustion chamber is transferred to the carrier fluid (water), which circulates in the system. The products of combustion, after the heat exchange with the carrier fluid in a shell and tube heat exchanger, are filtered with the aim to remove the particulate and are then sent to the chimney. It is possible to produce domestic hot water with a heat exchanger fed by the carrier fluid placed into the boiler.

The technical features of the boiler are listed in Table 1.

Table 1. Technical characteristics of the biomass boiler.

Rated output	46 kW
Efficiency	92%
Weight	380 kg
Width–Length–Height	1350 mm–980 mm–1276 mm
Carrier fluid	Water
Maximum allowable working temperature	90 ℃
Maximum allowable working pressure	0.3 MPa

2.2. Goal and scope definition

The main goals of the study are: to assess the energy and environmental impacts caused by a 46 kW biomass boiler made in a Sicilian firm; to estimate the incidence of each life-cycle step on the total impacts; to identify qualitative options for improving the energy and environmental performances of the product.

The analysis was carried out according to the international LCA standards of ISO 14040 series [12,13], ISO 21930 [14] and EN 15804 [15].

An attributional approach was followed, in which the life cycle is modeled by depicting the existing supply-chain of the product and including the input and output flows of all system processes as they occur [16].

One of the first steps of a LCA study is the definition of the functional unit (FU) that is the quantified performance of a product system for use as a reference unit [12].

The selected FU is one biomass boiler including the components used for the boiler installation (valves, expansion vase, pumps and other hydraulic components), with a useful life that is expected to be 15 years, as suggested by the producer company.

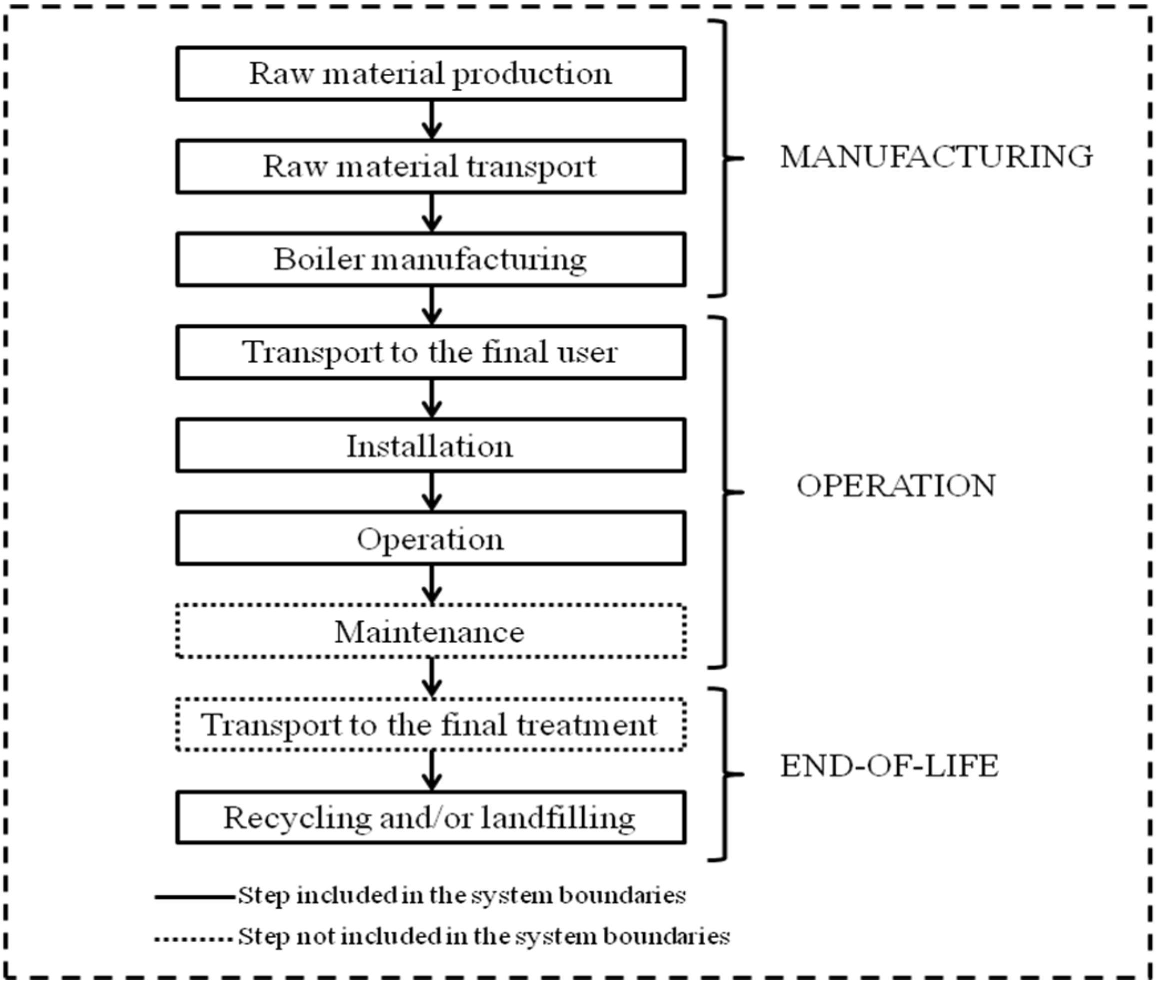

Figure 1. System boundaries.

The following life-cycle steps were investigated (Figure 1):

- production and delivery of raw materials, materials and energy sources used in the manufacturing process. Concerning the transport of materials, only national transports occur by road lorry and ferry-boat;
- FU's manufacturing process, that includes the steps of cutting, turning, folding, welding, seal test, painting, assembly and packaging;
- transport of the boiler to the final users, with a medium distance of about 140 km;
- installation, including the transport of the technician (medium distance of about 20 km);
- operation step, including the biomass consumption during the useful life of the system;
- end-of-life, excluding the transport of waste to the final treatment. Concerning this step, the following options were assumed: recycling process for aluminum, steel and packaging materials, a mixed process (manual disassembly, treatment of mechanical chipping and materials separation) for the electric components, and landfill for the other ones.

The impacts related to the maintenance step were assumed as negligible, considering that the maintenance routine consists in the removal of ashes, and that no emergency maintenance is required if the boiler is used correctly.

In line with the attributional approach, the benefits of the recycling process were not included in the analysis.

2.3. Life cycle inventory analysis

The inventory phase started from the analysis of the biomass boiler manufacturing and installation processes. Primary data on energy and materials consumption (including packaging), transports, and waste production during the manufacturing process were collected by means of direct investigations and estimations, carried out with the support of the firm's workers.

A qualified installer supported the estimation of inputs and outputs related to the installation process.

The electricity consumption during the manufacturing step was accounted for by considering the power and timework of the machinery by neglecting their inactivity time. The energy and environmental impacts of the following items are assumed to be negligible: lubricant oil consumption, raw materials and semi-finished products' storage and handling, dust production during the cutting, turning and welding steps.

Table 2 shows the main inputs and outputs related to the manufacturing process of the boiler. Information on the installation step is showed in Table 3.

Since the system to be studied is a multiple-output process that produces different kind of boilers, an allocation procedure was applied to estimate the varnish and refractory material consumption, following a mass criterion.

The international databases Ecoinvent [17], Buwal [18], and ELCD [19] were used to calculate the eco-profiles of raw materials and energy sources, transport and end-of-life processes. Data from the selected databases are calculated according to the ISO 14040 standard [12–13] and following a "from cradle-to-grave" approach.

The eco-profile of electricity consumed during the manufacturing step refers to the Italian electricity mix, where 15.1% of the overall energy provided is obtained by coal, 16.1% by crude oil, 45.7% by natural gas, 1.9% by industrial gas, 19.9% by hydropower, 0.7% by wind and 0.6% by biomass and biogas cogeneration [17].

Table 2. Main inputs and outputs during the manufacturing step.

Materials and energy sources	Quantity
Steel (kg)	406.0
Copper (kg)	30.2
Cast iron (kg)	20.0
Refractory material (kg)	4.0
Varnish (kg)	2.9
Glass wool (kg)	3.9
Glass fibre (kg)	1,5
Aluminium (kg)	3.0
Nylon (kg)	0.3
Oxygen (kg)	5.4
Nitrogen (kg)	1.6
Carbon dioxide (kg)	3.0
Water (used in the cutting and seal test steps) (kg)	18.5
Wood packaging (kg)	44.0
Plastic packaging (kg)	0.3
Electricity (MJ)	686.3
Pellet (used during the painting process) (MJ)	282.6
Waste	**Quantity**
Packaging plastic (kg)	0.1
Packaging cardboard and paper (kg)	1.8
Steel scraps (kg)	64.3
Waste water (kg)	18.6

Table 3. Main inputs and outputs during the installation step.

Components	Quantity
Valves (brass and polyvinylchloride) (kg)	3.3
Hydraulic fittings (brass) (kg)	1.8
Expansion vase (steel) (kg)	6.0
Tubes (copper) (kg)	1.1
Packaging (cardboard) (kg)	1.3
Pump (units)	1
Waste	**Quantity**
Packaging plastic (kg)	0.2
Packaging cardboard (kg)	1.3
Packaging wood (kg)	44

Referring to the operation step, it is depending on the climatic features of the installation site, the level of insulation of the building and the users' behaviors. In order to include this step in the assessment, the authors calculated the energy loads by means of both detailed building simulation in non-steady state and the standards in force in Italy. The building location is the city of Agrigento, Sicily, located at 37°N, 13°E. Weather data used is a "Meteonorm" one [20] for the location of Agrigento. The building loads for the boiler are simulated in non-steady state conditions as heating needs for a residential building, made of 5 households with an overall area of 600 m^2. The households are built one on top of the other, so that the roof of the lower one is connected as boundary condition to the basement of the top one. The simulation environment is Energy Plus [21]. Thermal loads are calculated in Energy Plus with a set point of 20 ℃ during the heating period established by the Italian law (8 hours a day, from the 1st of December to the 31st of March) [22]. Domestic hot water average daily needs are calculated according to the UNI TS 11300 standards [23], assuming average values for households larger than 200 m^2 (around 37.7 Wh/(day*m^2)), for the whole heating period. The main results are recapped below:

- overall energy needs required are 36,831.38 kWh;
- ratio between heating loads an overall loads is 91.5%.

The biomass used to feed the boiler is pellet.

3. Results and Discussion

Life Cycle Impact Assessment (LCIA) is carried out to assess the energy and environmental impacts of the examined product by means of suitable and meaningful indicators. LCIA includes the following steps [12,13]: selection of impact categories, indicators and characterization factors; initial aggregation of data from inventory into the selected environmental impact categories (classification); assessment of the impact wideness within each of the classification category using specific characterization factors (characterization).

The selected impact categories are the following: Global Energy Requirement (GER) (GJ); Global Warming Potential (GWP) (kg CO_{2eq}); Ozone Depletion Potential (ODP) (kg CFC-11_{eq}); Photochemical Oxidation (POCP) (kg C_2H_{4eq}); Acidification Potential (AP) (kg SO_{2eq}); Eutrophication Potential (EP) (kg $PO_4{}^{3-}{}_{eq}$); Abiotic Depletion (AD) (kg Sb_{eq}).

The energy characterization factors refer to the Cumulative Energy Demand [24, 25] method, that enables the estimation of the consumption of renewable (biomass, wind, solar, geothermal, water) and non-renewable (fossil, nuclear) energy sources. The environmental characterization factors refer to the EPD 2013 impact assessment method [26].

The life cycle energy and environmental impacts of the selected FU are showed in Table 4.

The calculated GER is 2,622.2 GJ, of which 83% is obtained from non renewable energy sources. The results show that the operation step is responsible for about 98.7% of GER, followed by the manufacturing step, which is responsible of about 0.74% of overall energy consumption. The transport, installation and end-of-life steps have a share on the total of 0.3%, 0.04% and 0.22%, respectively.

Table 4. Energy and environmental impacts related on the life cycle of the examined FU.

GER (GJ)	2,622.24
GWP (kg CO_{2eq})	21,664.2
ODP (kg CFC-11_{eq})	1.30E-03
POCP (kg C_2H_{4eq})	9.74
AP (kg SO_{2eq})	214.85
EP (kg $PO_4{}^{3-}{}_{eq}$)	98.87
AD (kg Sb_{eq})	0.08

A detailed analysis of the manufacturing step shows (Figure 2) that a relevant share of GER (approximately 13.4 GJ) is caused by the cutting and turning steps, that are characterized by higher electricity and raw materials consumption and by higher scraps production that have to be disposed. The assembly step and the folding and welding steps cause an energy consumption of about 3.2 GJ and 1.5 GJ, respectively. A consumption of about 1.3 GJ is due to the other remaining steps.

Examining the contribution of each life-cycle step on the environmental impacts (Figure 3), the following considerations can be made:

- the operation step is the main contributor to all the examined impacts, with the only exception of AD, mainly caused by the manufacturing step;
- a dominance analysis of the manufacturing process (Figure 4) shows that the cutting and turning steps cause a relevant contribution of about 76% on GWP, POCP (about 58% of the total) and ODP (about 72% of the total); the main contributor to AP (about 58% of the total), EP (about 77% of the total) and AD (about 84% of the total) is the assembly step; the incidence of the folding and welding step is variable from about 2% (EP) to about 9% (ODP); the seal test, varnish and packaging steps give a contribution lower than 1%;

- the installation step contributes to less than 1% to all the environmental impacts, except for AD (about 9.7%);
- the percentage share of the transport step is variable from about 0.6% (EP) to about 5.5% (ODP);
- the contribution of the end-of-life step is lower than 1.9% for all the examined impacts.

The results of the analysis show similar trends to those traceable from the outcomes of different studies on LCA of boilers, and in particular of biomass boilers [27–31]. In fact, all these studies showed that in the case of biomass boilers, the highest impacts life cycle step is the operation, with a share variable from about 80% to about 99%.

Referring to the quantitative results obtained for biomass boilers, the total impacts of the examined boiler cannot be compared with the outcomes of literature studies, due to different assumptions during the operation and end-of-life steps. However, referring to the manufacturing step, a comparison with the study carried out by Diaz et al. [28] can be made. The authors assessed the environmental performances of a 140 kW_{th} biomass boiler. The following results are obtained: GWP 3,080 kg CO_{2eq}; ODP 18.3 mg CFC-11_{eq}; POCP 3.3 kg C_2H_{4eq}; AP 22.5 kg SO_{2eq}; EP 0.4 kg $PO_4{}^{3-}{}_{eq}$; AD 28.3 kg Sb_{eq}. Most of the results, if expressed per kW of thermal power and referred to the manufacturing step, have the same order of magnitude if compared with the results of the 46 kW biomass boiler.

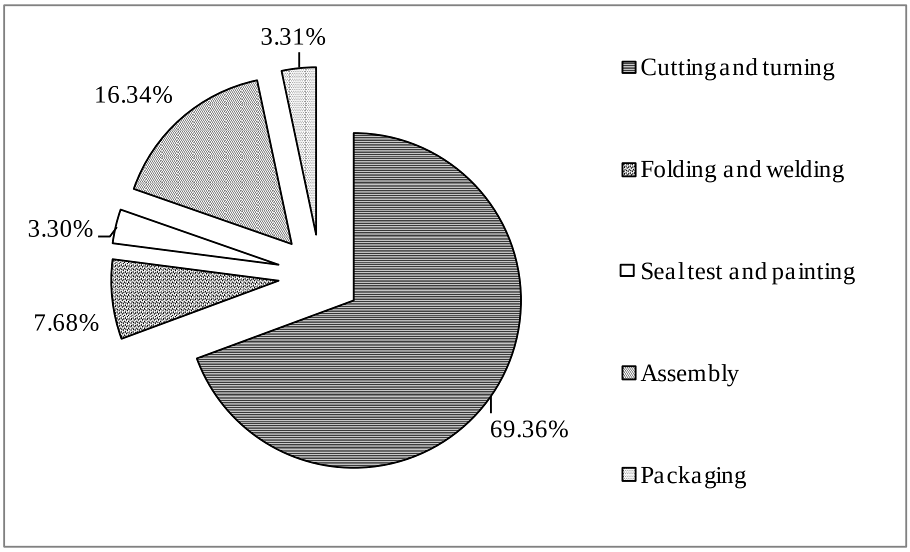

Figure 2. GER of the manufacturing step.

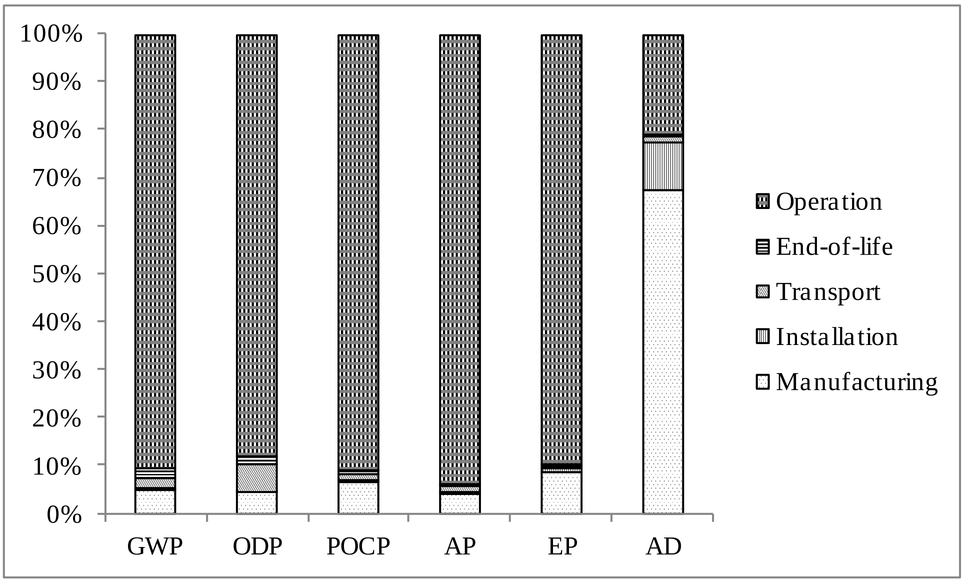

Figure 3. Life-cycle environmental impacts.

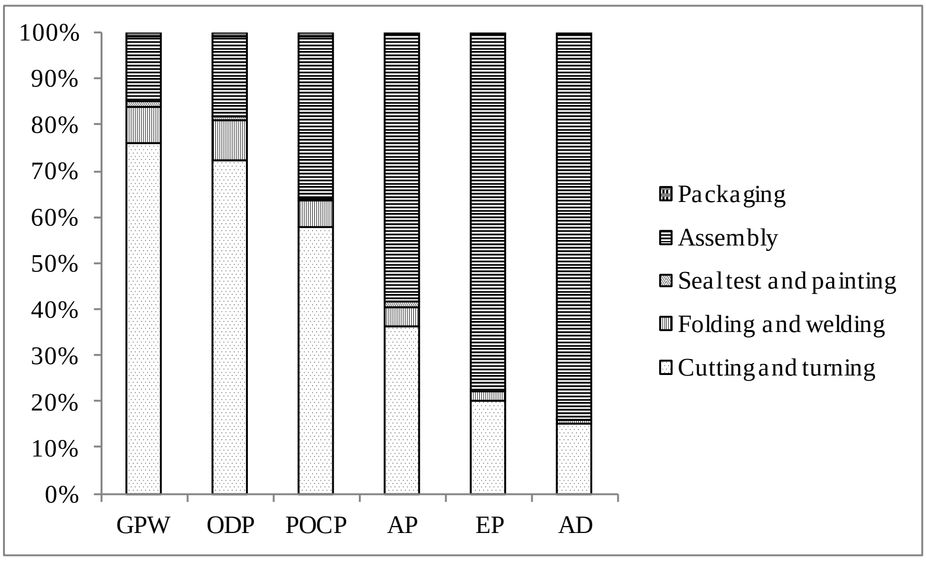

Figure 4. Environmental impacts of manufacturing step.

Finally, it is important to investigate the potential benefits of biomass boilers with respect to coal-based boilers, in terms of reduction of greenhouse gas emissions and increase of renewable energy consumption. Table 5 shows a comparison of the energy and environmental impacts of coal-based and biomass fuels. The comparison focuses only on the operation step, considering its high share on the total impacts. The results show that the use of biomass as fuel generally causes a higher GER than coal-based fuels. However, biomass is a renewable energy source and can contribute to the European goal of 27% of renewable in total energy consumption. In addition, using biomass instead of coal-based fuels may allow a reduction of about 90% of GWP. Referring to the other impact indicators, biomass causes lower impacts than coal-based fuels, with the only exception of impacts on ODP and AD.

Table 5. Energy and environmental impacts of the operation step: biomass versus coal-based fuels.

	Biomass	Hard coal briquette	Hard coal coke	Anthracite
GER (GJ)	2,588.1	2,082.7	2,798.1	1,770.7
GWP (kg CO_{2eq})	19,621.4	203,319.6	228,090.2	187,503.2
ODP (kg CFC-11_{eq})	1.15E-03	2.58E-03	1.04E-03	5.67E-04
POCP (kg C_2H_{4eq})	8.8	405.6	332.6	487.6
AP (kg SO_{2eq})	201.8	1,162.9	1,253.1	899.9
EP (kg $PO_4{}^{3-}{}_{eq}$)	88.8	223.2	334.1	207.8
AD (kg Sb_{eq})	1.65E-02	3.50E-03	6.50E-03	2.68E-03

4. Conclusions

The study aims at assessing the energy and environmental impacts of a biomass boiler, following a life-cycle approach. The collected information could become an important starting point to reduce the energy and environmental impacts of the product.

In detail, the results showed that the highest energy and environmental impacts are caused by the operation step, except for AD that is mainly caused by the manufacturing step.

Considering the high quantity of electricity and raw materials consumed in the manufacturing process and the relevant production of scraps, the life-cycle impacts of the boiler can be decreased by reducing the direct energy consumption during the manufacturing step, by increasing the share of renewable energy, and by reducing the amount of raw materials and scraps.

Finally, an important finding of the study is that renewable energy technologies cannot be considered fully “clean” because they cause energy and environmental impacts during their life cycle. Thus, all components and aspects of the examined technology should be taken into account following a life-cycle approach.

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Conflict of interest

All authors declare no conflicts of interest in this paper.

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