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Life cycle analysis of small scale pellet boilers characterized by high efficiency and low emissions

B. Monteleone [a], M. Chiesa [a,*], R. Marzuoli [a], V.K. Verma [b], M. Schwarz [b], E. Carlon [b,c], C. Schmidl [b], A. Ballarin Denti [a]

[a] Università Cattolica del Sacro Cuore, DMF, Via Musei 41, 25121 Brescia, Italy
[b] Bioenergy 2020+GmbH, Gewerbepark Haag 3, A 3250 Wieselburg, Austria
[c] Free University of Bozen-Bolzano, Universitätsplatz – Piazza Università 5, 39100 Bozen-Bolzano, Italy

HIGHLIGHTS

- LCA was performed on innovative small scale pellet boilers.
- Pellet boilers impacts were compared to oil and natural gas boilers impacts.
- Both literature and experimental data were used for life cycle analysis.
- The environmental impact due to all life cycle phases was envisaged.
- Sensitivity tests evidenced realistic ways for pellet boilers impact reduction.

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ABSTRACT

This study focuses on the environmental impact assessment through Life Cycle Analysis (LCA) of two innovative 10 kW pellet boilers. In particular, the second boiler represents a technological evolution of the first one developed to improve its performance in terms of efficiency and environmental impact. For both boilers, emission factors measured during laboratory tests (full load tests and specific load cycle tests representative of real life boiler operation) have been used as input data in the life cycle analysis. The SimaPro software (v.8.0.4.30) was used for the LCA and the ReCiPe Midpoint method (European version H) was chosen to assess the environmental impact of all boilers (according to LCA ISO standards). In addition, the ReCiPe Endpoint method was used to compare the final results of all 5 boilers with literature data.

The pelletisation process represented the most relevant share of the overall environmental impact followed by the operational phase, the manufacturing phase and the disposal phase. A sensitivity analysis performed on the most efficient pellet boiler evidenced the variation of the boiler's environmental impact as a function of PM10 and NO_X emission factors with respect to emission factors monitored during boiler full load operation. Moreover, the reduction of the boiler's weight and the adoption of new electronic components led to a consistent reduction (−18%) of its environmental impact with respect to the previous technology. A second LCA has been carried on for a 15 kW oil boiler, a 15 kW natural gas boiler and a 15 kW pellet boiler, representative of the state of the art of EU technology, to finally compare all LCA results. Results showed the environmental impact reduction of BW10 and BW10 2 pellet boilers with respect to fossil fuelled boilers mainly due to their reduced impact on CC (reductions by 86–90% and

Abbreviations: BW10, BioWIN pellet boiler 10 kW; BW10 2, BioWIN-2 pellet boiler 10 kW; EU, European Union; FP7, Seventh Framework Programme; CO, Carbon Monoxide; CO_2, Carbon Dioxide; NO_X, Nitrogen Oxides; O_2, Oxygen; LCA, Life Cycle Analysis; LCI, life cycle inventory; LCIA, life cycle impact assessment; H, Hierarchist; HA, Hierarchist Average; EIA, environmental impact assessment; PM, particulate matter; PM10, particulate matter with an aerodynamic diameter below 10 μm; PAHs, polycyclic aromatic hydrocarbons; VOCs, volatile organic compounds; JW155, JetWIN 155, a non-condensing oil boiler; NG, natural gas; FL, full load; LC, load cycle; PL, partial load; HHV, higher heating value; LHV, lower heating value; CC, Climate Change; CC ECO, Climate Change on Ecosystems; CC HH, Climate Change on Human Health; OD, Ozone Depletion; TA, Terrestrial Acidification; FE, Freshwater Eutrophication; ME, Marine Eutrophication; HT, Human Toxicity; POF, Photochemical Oxidant Formation; PMF, Particulate Matter Formation; TET, Terrestrial Ecotoxicity; FET, Freshwater Ecotoxicity; MET, Marine Ecotoxicity; IR, Ionising Radiation; ALO, Agricultural Land Occupation; ULO, Urban Land Occupation; NLT, Natural Land Transformation; WD, Water Depletion; MD, Metals Depletion; FD, Fossil Depletion.

* Corresponding author.
E-mail address: maria.chiesa@unicatt.it (M. Chiesa).

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88–91% with respect to the NG and oil boilers respectively), NLT (reductions by 77–79% and 86–87% with respect to the NG and oil boilers respectively) and FD (reductions by 89–92% and 90–93% with respect to the NG and oil boilers respectively) ReCiPe Midpoint subcategories.

1. Introduction

The use of biomass instead of fossil fuels for residential heating contributes to CO_2 emissions reduction since CO_2 emissions along the boiler life cycle are negligible with respect to CO_2 emissions produced by fossil fuelled boilers. As the recent European policies encourage the use of renewable energies, biomass consumption for residential heating is growing at EU level [1]. Nonetheless, biomass use for residential heating may lead to high emissions of particulate matter (PM) [2–4], polycyclic aromatic hydrocarbons (PAHs) [5–7] and volatile organic compounds (VOCs) [4,8–10] depending on biomass technology adopted [11]. PM, COVs and PAHs emissions along the whole pellet boiler life cycle (not only considering the boiler operational phase) are important since they affect human health. Actually, different studies from literature [8,9] have evidenced that emissions of aldehydes during pellet storage lead to upper airway, mucous membranes and eyes irritation while methanal and ethanal are suspected carcinogens. During the combustion phase other certified or suspected carcinogenic compounds (i.e. benzene, 1–3 butadiene, formaldehyde and acetaldehyde) are emitted [12–14], though with the choice of good combustion technology and high quality fuels, these emissions can be minimized to almost negligible.

Concerning PM emissions, epidemiological and experimental studies evidence a correlation between wood smoke particles and health impacts like decreased lung function, reduced resistance to infections and increased incidences of acute asthma [3]. Exposure to wood smoke could also induce cardiovascular effects [15]. Small particles, showing a large surface area per unit of mass, show a more pronounced inflammatory effect with respect to bigger particles with the same composition. Due to PM metals contents (mainly Vanadium, Copper, Zinc, Nickel, Iron) as well as organic compounds (PAHs), health effects are enhanced due to the toxicity and/or carcinogenic properties. Actually, several PAHs are carcinogenic. According to the International Agency for Research on Cancer [16], benzo[a]pyrene is carcinogenic to humans (Group 1), benz[a]anthracene, dibenz[a,h]anthracene are probable human carcinogens (Group 2A), and benzo[b] fluoranthene, benzo[j]fluoranthene, benzo[k]fluoranthene, dibenzo[a,e]pyrene, dibenzo[a,h]pyrene, dibenzo[a,i]pyrene, dibenzo[a,l]pyrene, and indeno[1,2,3-cd]pyrene are possible human carcinogens (Group 2B).

Only few literature studies aimed at evaluating the environmental impacts of domestic pellet stoves or boilers [11,17] along all their lifecycle. The results of these studies are often not declined into all the specific lifecycle phases considered in the LCA system boundaries [11,18] and the only contribution of specific impact subcategories (Climate Change, Human Toxicity, Air Acidification, Photochemical Ozone Formation, Particulate Matter Formation and Fossil Fuels depletion) was envisaged [11,17]. Furthermore, pellet boilers [18,19] fired with pellets deriving from energy crops have a higher environmental impact than the average European case study where raw biomass for the pelletisation process mainly comes from agricultural and forestry residues.

Most of the LCA research studies available in literature are only focused on specific phases of a pellet boiler life cycle: forestry operations [20,21], pellet production and transport [22], pellet production and boiler use phase [23], pellet transport on long distances [24,25], and boiler use phase [26].

This work presents the evaluation of the environmental impact of small scale pellet boilers tested in the framework of the EU FP7 "BioMaxEff" project. [27].

The novelty of the present research in comparison to the state of the art consists in the identification of the environmental impact of all the different life cycle phases included in the system boundaries with respect to all the impact subcategories foreseen by the chosen life cycle impact assessment method. Actually, at present the ReCiPe Midpoint method in our field, apart from the already mentioned Ref. [17], has been mainly adopted for the evaluation of the environmental impact of big pelletisation plants [28,29] or of large scale CHP plants [30] so that our results are among the first results of application of this method on residential pellet boilers. In addition, our input data not only come from literature (i.e. energy mix, disposal phase) but from project and boilers manufacturer data so that the here presented LCA results could be representative of a Central European case study (and not of a global case study). Moreover, in this study the environmental impact assessment (EIA) is evaluated on innovative pellet boiler technologies beyond the state of the art represented by average pellet boiler technologies presently installed at EU level so that the final comparison with the presently diffused boiler technologies (including oil and natural gas technologies) is interesting in order to understand the potential environmental impact abatement due to the diffusion of more efficient pellet boilers at EU level in the short-to-mid term.

2. Materials and methods

2.1. Boilers under investigation

The innovative pellet boilers under investigation are two 10 kW pellet boilers manufactured by the Austrian Company Windhager Zentralheizung Technik GmbH (BioWIN 10 and BioWIN 10 2 models).

Both boilers consist of a steel body with a fully insulated cladding. The boilers can modulate the power output in the range between 30% and 100% of the nominal power. The burner pot is made of high-temperature-resistant stainless steel and equipped with two automatic ignition and automatic ash removal systems. A speed controlled vacuum fan regulates the primary and secondary air supply. Hot flue gases generated during combustion pass through a vertical heat exchanger, which is automatically cleaned by a spiral mechanism and deliver heat to the circulating water. The control concept of the combustion process is based on the flue gas temperature, which is measured directly at the exit of the combustion chamber (i.e. thermo-control combustion control concept). The pellet boiler BioWIN 10 (BW10) has a fully automatic pellet feed system and its stainless steel burner ensures low pellet consumption and high efficiency. The main feature of the BioWIN 10 2 (BW10 2) is a new ignition element that is extremely durable, maintenance free, and ignites silently. Even the direction of secondary air inlet nozzles is optimized to improve combustion efficiency. Quality labels such as the Blaue Engel [31] and the Austrian Ecolabel [32] testify its quality and environmental credentials.