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Dear Editor in Chief,
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Please find enclosed the electronic version of the manuscript:

"LCA analysis of small scale pellet boilers characterized by high efficiency and low emissions"

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The manuscript is mostly focused on the environmental impact assessment (through LCA analysis) of two innovative and high efficiency residential pellet boilers and results have been compared to LCA analysis results performed on an oil boiler, a natural gas boiler and a standard pellet boiler, representative of the average EU technology. Input data for the innovative pellet boiler technologies come from experimental tests (mainly efficiency and emission factors measurements representative of real boilers operating conditions), manufacturer and literature data.

To our knowledge very few studies exist that evaluate the environmental impacts of domestic pellet boilers along all their lifecycle. Most of LCA analysis research available in literature is only focused on specific phases of a pellet boiler lifecycle: forestry operations, pellet production and transport, pellet production and boiler use phase, pellet transport on long distances and boiler use phase. The advance 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 (pelletisation, boiler construction, boiler operation, boiler transports, boiler and ashes disposal) with respect to all the impact subcategories foreseen by the chosen life cycle impact assessment method (Ecoindicator 99 – HA version). In addition, input data coming from literature (i.e. energy mix, disposal data, pellet transport data) have been selected only considering the EU territorial framework so that our LCA analysis results could represent an average European case study (and not a global case study).

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best regards
Maria Chiesa

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Highlights

- LCA analysis were 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 LCA analysis
- The environmental impact due to all life cycle phases was envisaged
- Sensitivity tests evidenced realistic ways for pellet boilers impact reduction

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

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Abstract

This study focuses on the environmental impact assessment (through LCA analysis) of three different residential pellet boilers: a 15 kW pellet boiler, representative of the state of the art of EU technology and two innovative 10 kW pellet boilers manufactured by an Austrian company.
A second LCA analysis has been carried on for a 15 kW oil boiler and a 15 kW natural gas boiler to compare all LCA analysis results.
The SimaPro software was used for the LCA analysis and the Eco-Indicator 99 Hierarchist version was used to assess the environmental impact on three main damage macrocategories (human health, ecosystems quality and resources) and on 11 subcategories. For the pellet boilers, emission factors measured during laboratory tests have been used as input data in the LCA analysis. Results showed that pellet boilers had an overall environmental impact in the range 30-47% with respect to the oil boiler impact while the natural gas boiler had about 85% of the oil boiler impact. The LCA analysis of pellet boilers evidenced that the pelletisation process represents 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 recent boiler showed the reduction of its overall environmental impact when decreasing its PM10 and NO_X emission factors. Moreover, the reduction of the boiler weight and the adoption of new electronic components led to a consistent reduction (-35%) of the innovative boiler environmental impact with respect to the old technology.

Keywords

LCA analysis, load cycle tests, full load tests, small scale pellet boilers, high efficiency, low emissions.

List of Abbreviations

BW10	BioWin pellet boiler 10kW
BW10 2	BioWin-2 pellet boiler 10kW
EU	European Union
FP7	Seventh Framework Programme
CO	Carbon Monoxide
CO_2	Carbon Dioxide
NO_X	Nitrogen Dioxide
O_2	Oxygen
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
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

1. Introduction

This work presents the evaluation of the environmental impact of small scale pellet boilers tested in the framework of the EU FP7 "BioMaxEff" project. [1].

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 [2]. Nonetheless, biomass use for residential heating may lead to high emissions of particulate matter (PM) [3,4], polycyclic aromatic hydrocarbons (PAHs) [5-7] and volatile organic compounds (VOCs) [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 [4]. 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, 17-19] 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 lifecycle: 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].

The advance 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. In addition, input data coming from literature (i.e. energy mix, disposal data, pellet transport data) have been selected only considering the EU territorial framework so that the here presented LCA analysis results could represent an average European case study (and not a global case study). Moreover, in this study the environmental impact assessment (EIA) of innovative pellet boiler technologies is compared with the EU average pellet boiler technology and conventional technologies like oil and natural gas.

2. Materials and methods

2.1. Boilers under investigation

In this study LCA analysis was performed on five different boilers (one oil boiler, one natural gas boiler and three pellet boilers).

The JetWin 155 (JW155) (**Boiler 1**): A non-condensing oil boiler with a very efficient and innovative burner technology manufactured by the Austrian company Windhager Zentralheizung Technik GmbH.

The NG boiler (**Boiler 2**): A non-modulating natural gas boiler with natural draught burner. It represents the European state of the art technology.

The standard pellet boiler (**Boiler 3**): Representative of the European state-of-the art technology with automatic fuel supply and automatic control technique.

Innovative pellet boilers: Boilers 4 and 5 are pellet boilers manufactured by the Austrian company Windhager Zentralheizung Technik GmbH. 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) (Boiler 4) 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. Quality labels such as the Blaue Engel [27] and the Austrian Ecolabel [28] testify its quality and environmental credentials. The pellet boilers BioWIN and BioWIN 2 were tested in the laboratory according to two different test methods. The first method consisted of a steady state test at nominal load according to EN 303-

5 [29]. The second method was a dynamic load cycle including stationary operation at different loads, as well as transient operation, in order to reproduce the heating and domestic hot water demand of a single family house [30,31]. CO, VOCs, NOx, and PM emission factors as well as boilers efficiencies were determined with both test methods.

Table 1 presents the technical specifications, efficiency and emission factors (resulting from both full load and load cycle tests) of the boilers investigated in the present study. Emission factors are presented at 13% O_2 in dry flue gas.

Approximate location of Table 1

The laboratory tests were conducted using ENplus certified wood pellets manufactured by the Austrian company RZ Pellets GmbH [32]. The chemical composition and thermal properties of the pellets were determined according to the standard methods reported in Table 2.

Approximate location of Table 2

2.2 LCIA methodology

The SimaPro software (version 8.1) has been used to perform LCA analysis since it is a widespread and accredited LCA analysis tool and its transparent life cycle inventory (LCI) data are regularly updated [39, 40]. It also includes different impact assessment methods and the most updated Ecoinvent database libraries [41, 42]. Global supply chains for products are also present in the database. LCIA analysis has been performed according to ISO standards [43-47]. Eco-Indicator 99 Hierarchist Average version (HA) has been chosen as impact assessment method [48] since it is the most used impact assessment method in literature. It evaluates the environmental load of a product expressed as a final score expressed in adimensional units (Points, Pt, or its submultiples, mPt). HA version is chosen since it only evaluates scientifically based impacts of a product or a process (the precautionary principle, adopted in the Egalitarian version, is not adopted).

According to Eco-Indicator 99 the environmental impact has been quantified on three main damage macrocategories (Human Health, Ecosystems Quality and Resources Depletion) and on their specific subcategories (11 in total: Carcinogens, Respiratory Organics, Respiratory Inorganics, Climate Change, Radiation, Ozone Layer, Ecotoxicity, Acidification and Eutrophication, Land use, Minerals and Fossil Fuels). In this study we assumed an average EU pelletisation process and raw biomass only coming from sawmill and forestry residues. It’s thus important to underline that the actual version of the Ecoinvent database (v. 3.01) overestimates the environmental impact of forestry residues use as raw biomass for pellet production since a weighed contribution due to the “forest impact” (that takes into consideration forest planting, management and land use) is included in the calculations [49] .

1 MJ of useful heat was chosen as functional unit in this study, in order to compare LCA results of boilers with different nominal power outputs. An average boiler lifetime of 20 years was assumed (personal communication from boiler manufacturer). Figure 1 shows the system boundaries for pellet boilers.

Five different life cycle phases have been analysed:

1. **Boiler construction:** electricity and heat come from the Austrian energy production mix for the boiler technologies locally manufactured while an EU average mix is considered for the standard pellet and the natural gas boilers [50,51]: BW10, BW10 2 and JW155 materials have been provided by the manufacturer while for the other boilers the Ecoinvent database has been used. Fossil fuels are used to carry raw materials before boiler construction. Metals recovery is considered too as well as land use given by the production plant facility [52,53];
2. **Pellet production:** average EU pellet production technologies are considered and EU energy mix is used as input data. LDPE is considered since 20% of produced pellet is supposed to be sold in 15 kg bags [52]. Raw biomass transport from the field till the pelletisation plant is included [52];
3. **Boiler transport:** only boiler transports are considered in this phase. Transports from manufacturer to customer (100 km, [52]) and from customer to final disposal site (100 km [52]) are included;
4. **Boiler operation:** efficiency and emission factors determined during the BioMaxEff project have been used for the two innovative pellet boilers while data coming from the Ecoinvent database have been used for the standard pellet and natural gas boilers. For the oil boiler efficiency manufacturer data has been used while emission factors have been taken from literature [11];
5. **Boiler Disposal:** on average metals are recovered up to 50% while the other 50% is sent to landfill, as part of the electronic components and all plastic, insulation and painting materials [52,53]. Ashes are equally sent to landfill and landfarming activities [54].

Approximate location of Figure 1

3. Results and discussion

3.1 LCA analysis results and discussion

3.1.1. Comparison of fossil fuel boilers and pellet boilers

At first the overall environmental impact of the five boilers under investigation has been evaluated considering 1 MJ of useful heat as functional unit.
It was found that the oil boiler presented the highest impact (nearly 10 mPt), therefore the impact of the other boilers has been evaluated in terms of percentage reduction with respect to the oil boiler.
Full load emission factors have been used in the comparison in order to use the same type of input data for the operational phase. From Figure 2 we can see that pellet boilers show an overall environmental impact in the range 30-47% with respect to the oil boiler impact while the NG boiler presents about 85% of oil boiler impact, significantly higher. This result is aligned with LCA results of Fantozzi and Buratti [19] where the standard pellet boiler showed an overall environmental impact reduction by about 40% with respect to the natural gas boiler using the same life cycle impact assessment method (Ecoindicator 99). A similar result is shown in Cespi D. et al [17] even if their comparison concerns pellet stoves and the final comparison with a natural gas boiler was performed only considering 5 impact subcategories of the Recipe Endpoint LCIA method (Fossil Depletion, Particulate Matter Formation, Human Toxicity, Climate Change on Ecosystems and Climate Change on Human Health).
Innovative pellet boilers show the lowest environmental impacts and BW10 2 represents the best technology (presenting only a 30% impact with respect to the reference boiler system). The Ecoindicator 99 subcategories that contribute most to the overall boilers environmental impact depend on the boiler technology considered: while the “Respiratory Inorganics” subcategory is important for all boiler technologies (with contributions in the range 20-30%), the “Fossil fuels” subcategory contribution is dominant for NG and oil boiler technologies (followed by the “Climate Change” subcategory) while different subcategories (i.e. “Fossil fuels”, “Ecotoxicity”, “Land use”, “Carcinogens” subcategories) have not negligible but small and more balanced contributions for pellet boilers technologies. The specific subcategories that contribute most to the environmental impact of pellet and natural gas boilers confirm the previous results obtained by Fantozzi and Buratti [19] with the addition of a not negligible contribution given by the acidification and eutrophication subcategory (mainly due to the use of fertilizers, herbicides and pesticides) since in [19] energy crops are considered as raw biomass entering the pelletisation phase.

Approximate location of Figure 2

3.1.2. Environmental impact of different pellet boilers

Focusing on the best technology emerged (BW10 2), its overall environmental impact has been splitted according to the main different life cycle phases investigated: pelletisation, boiler construction, transport phase, boiler operational phase and boiler and ashes final disposal phase.
This investigation has been performed using both full load and load cycle emission factors as input data for the LCA analysis. The load cycle emission factors and efficiency are equivalent to the real life emissions factors and efficiency.
Considering the BW10 2 environmental impact presented in Figure 3, the boiler total environmental impact evaluated using load cycle emission factors has been set to 100 since load cycle test emissions and efficiency represent the real life operational condition which included start up, modulation and shut down phases. A first result is given by a reduction of 13% of the overall BW10 2 environmental impact adopting the full load emission factors.
Considering load cycle (LC) tests emission factors for BW10 2, the pelletisation process contributes most (about 45%) followed by the boiler operational phase (about 40%) , the boiler manufacturing phase (about 10%) and the boiler disposal phase (for the remaining 5%) to the total environmental impact. Contribution of the transports phase is almost negligible. Actually, only long-distance transports (i.e. ocean transports) could lead to significant environmental impacts, as reported by Pa et al. [24] and Forsberg [25].
Considering the reduced overall BW10 2 environmental impact due to the adoption of full load emission factors as input data (and excluding the negligible contribution of the transports phase), the pelletisation process contributes the most (about 41%) followed by the boiler operational phase (about 32%), the boiler manufacturing phase (about 10%) and the boiler disposal phase (for the remaining 4%). The high contribution of the pelletisation phase is mostly linked to the database that has been used (Ecoinvent v. 3.01) since local data were not available: actually, as already anticipated in the introduction section, the Ecoinvent database overestimates the environmental impact due to forestry residues since a weighed contribution of processes like forests planting, management and land use are included. These assumptions are even responsible for the not negligible contribution of the Land Use subcategory for pellet boilers represented in Figure 2. The managers of the Ecoinvent database are presently debating around this critical topic and a new updated version will thus be available in the near future. Other studies available in literature show

integrated contributions of the operational and pelletisation phases [18] or contributions due to pelletisation from biomass coming from energy crops [18,19] that make use of fertilizers, herbicides and pesticides (not considered in forestry processes included in the Ecoinvent database). Some other studies only consider the operational phase as the main representative of a pellet boiler life cycle [26] or do not show the contributions of all subcategories (in particular land use) when the total environmental impact is evaluated using the same database [17]. Direct comparisons with results from other studies only related to the pelletisation phase contribution and based on the same assumptions are thus not possible. Nevertheless, it is interesting to underline that, even if in [19] energy crops are considered as raw biomass for the pelletisation phase, the impact derived summing up energy crops cultivation and the pelletisation phase contributions, using local input data and thus not considering data and assumptions of the Ecoinvent database, presents a reduction by 23% with respect to the pelletisation contribution presented in this paper. A reduction by 10% to 20% of the here presented pelletisation phase contribution using local available pelletisation data and considering the only use of forestry residues as raw biomass could then be a realistic result to be associated to an average European case study.

Figure 3 even evidences that the adoption of load cycle emission factors determines the increase of the boiler impact due to both the pelletisation and operational phase: the first impact reduction is due to the better boiler efficiency during full load tests that implies a less pellet quantity needed for boiler operation while the second impact reduction is mainly associated to the lower emissions of respiratory inorganic compounds (mainly PM10) during full load tests.

Approximate location of Figure 3

3.2 Sensitivity analysis

3.2.1 Sensitivity to emission factors

Considering the BW10 2 pellet boiler, a sensitivity analysis has been performed on LCA results and different sensitivity tests have been carried on changing some key parameters (i.e. PM10 and NO_X emission factors related to the operational phase, boiler construction materials) and evaluating the boiler environmental impact reduction according to the different Eco-Indicator 99 damage subcategories (Figures 4 and 5). Since the Respiratory Inorganics subcategory plays a dominant role in the evaluation of the overall boiler environmental impact since it is strictly linked to the main contributing LCA phases (i.e. the pelletisation and operational phases), the first sensitivity tests have concerned the reduction of PM10 (Figure 4a) and NO_X (Figure 4b) emission factors by 20%, 30%, 50% and 70% respectively with reference to the actual boiler emission factors during full load cycle tests. Actually, a reduction of PM10 emission factor up to 70% with respect to the state of the art of the pellet boiler technology can be realistically achieved with the integration of commercially available pollution abatement systems (i.e. electrostatic precipitators) into the boiler. A parallel analysis considering the same percentage reductions of the NO_X emission factor has been performed since PM10 and NO_X emissions are both drivers of the evaluation of the environmental impact of the main damage subcategory (Respiratory Inorganics) related to the boiler operational phase.

As can be seen in Figure 4a, the base case scenario (Scenario 1) shows a reference impact set to 100%. The boiler impact according to the other Scenarios always shows a decrease with respect to the base case scenario.

In particular, Scenarios 2,3,4 and 5 present 2,6%, 4%, 6,6% and 9,2% reductions of the boiler environmental impact respectively. The 70% reduction of BW10 2 PM10 emission factor with respect to the base case could lead to the maximum (9,2%) reduction of BW10 2 overall environmental impact.

Focusing the attention on Figure 4b, the base case scenario (Scenario 1) shows a reference impact set to 100%. The boiler impact according to the other Scenarios always shows a decrease with respect to the base case scenario.

Scenarios 2, 3, 4 e 5 represent a 20%, 30%, 50%, 70% decrease of NO_X emission factor, starting from the value of 87,9 mg/MJ resulted from the project full load tests measurements. In particular, Scenarios 2,3,4 and 5 present 3%, 4,6%, 7,6% and 10,6% reductions of the boiler environmental impact respectively. The 70% reduction of BW10 2 NO_X emission factor with respect to the base case could lead to the maximum (10,6%) reduction of BW10 2 overall environmental impact.

Approximate location of Figure 4

3.2.1 Construction materials and weight

Considering the boiler construction phase (Figure 5), the sensitivity analysis has concerned the real variation of the quantity or quality of materials in BW10 2 with respect to the quantities and/or qualities of the standard boiler ones (BW10). The overall environmental impact reduction for BW10 2 by 35% is shown, along with the specific contributions due to the construction materials. The analysis has been performed focusing on the following materials and energy vectors needed for the construction phase: electricity, electronics, metals and other minor contributions (insulation, packaging, plastic, painting). The reduction by 14% of the boiler weight (from BW10 to BW10 2, mainly due to metals weight reduction by 7% and the remaining 7% given by insulation and packaging materials reduction) justifies the lower BW10 2 environmental impact due to metals (Figure 5c) and electronic components (Figure 5b) by 35% and 40% respectively. The other materials and electricity contributions are negligible (Figures 5a and 5d).

Approximate location of Figure 5

4. Conclusions

In this study an LCA analysis has been performed for standard (representative of the most diffused technologies at European level) and innovative small scale pellet boilers as well as standard fossil fuel (oil and natural gas) boilers. Results evidenced the pro and cons of advanced and high efficiency pellet boiler technologies with respect to traditional ones along all the specific life cycle phases (pelletisation, boiler construction, boiler operation, transports and final disposal). The SIMAPRO software (v. 8.01, Ecoinvent 3.01 database) has been used and the Eco-Indicator 99 LCIA method has been chosen for the evaluation of all boilers impact on 11 subcategories that can be summed up into three main damage macrocategories (human health, ecosystems quality and resources).

For pellet boiler technology, it was found that the pelletisation process contributes most to the overall environmental impact (on average 45%) followed by the boiler operational phase (about 40%), the boiler manufacturing phase (about 10%) and the boiler disposal phase (for the remaining 5%). The boiler transports phase always represented a negligible contribution. A critical result related to the pelletisation phase impact is due to the assumptions of the most updated available version of the Ecoinvent database (v. 3.01) that associates to forestry residues use a weighed impact coming from forest planting, management and land use. The use of local data could lead to a reduction of the pelletisation impact by 10% to 20% (which is true for Austria) with respect to the here presented results.

Pellet boilers show an overall environmental impact in the range 30-47% with respect to the oil boiler impact while the natural gas boiler presents about 85% of oil boiler impact, significantly higher. BW10 and BW10 2 boilers in particular have shown the lowest environmental impacts and BW10 2 represents the best technology (presenting only a 30% impact with respect to the reference boiler system).

The sensitivity tests performed on the best pellet boiler technology (BW10 2) were focused on the boiler operational phase and showed a decrease of both PM10 and NO_X emission factors (from 20% up to 70% with respect to the 2 different base case Scenarios, characterised by the full load test emission factors). Results from both tests have evidenced a maximum 10% overall boiler environmental impact reduction. Considering the boiler construction phase, the sensitivity analysis has concerned the real variation of the quantity and/or quality of materials in BW10 2 with respect to the quantities and/or qualities of the standard boiler ones (BW10). The interesting results have validated the overall environmental impact reduction for BW10 2 by 35% with respect to BW10, mainly due to the reduced boiler (mainly metals) weight and to the adoption of different electronic components.

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Figure captions

Fig. 1: LCA system boundaries (representing materials and main processes related to the 5 different life cycle phases).

Fig. 2: Comparison among LCA results of standard, BW10 and BW10 2 pellet boilers and fossil fuelled (oil and natural gas) boilers. Single histograms show the impact on each Eco-Indicator 99 damage subcategory.

Fig. 3: LCA results of BW10 2 pellet boiler expressed in terms of impact on each Eco-indicator 99 subcategory using full load and load cycle emission factors, depending on the single LCA phases.

Fig. 4: Sensitivity analysis results changing only NO_X (a) or PM10 (b) emission factors and keeping fixed all other input of the base case scenario. The different scenarios (1-4) represent the overall environmental impact reduction due to the adoption of reduced emission factors with respect to the base case (-20%; -30%; -50%; -70%).

Fig. 5: Sensitivity analysis results changing the quality and quantity of construction materials (from BW10 to BW10 2).

Figure

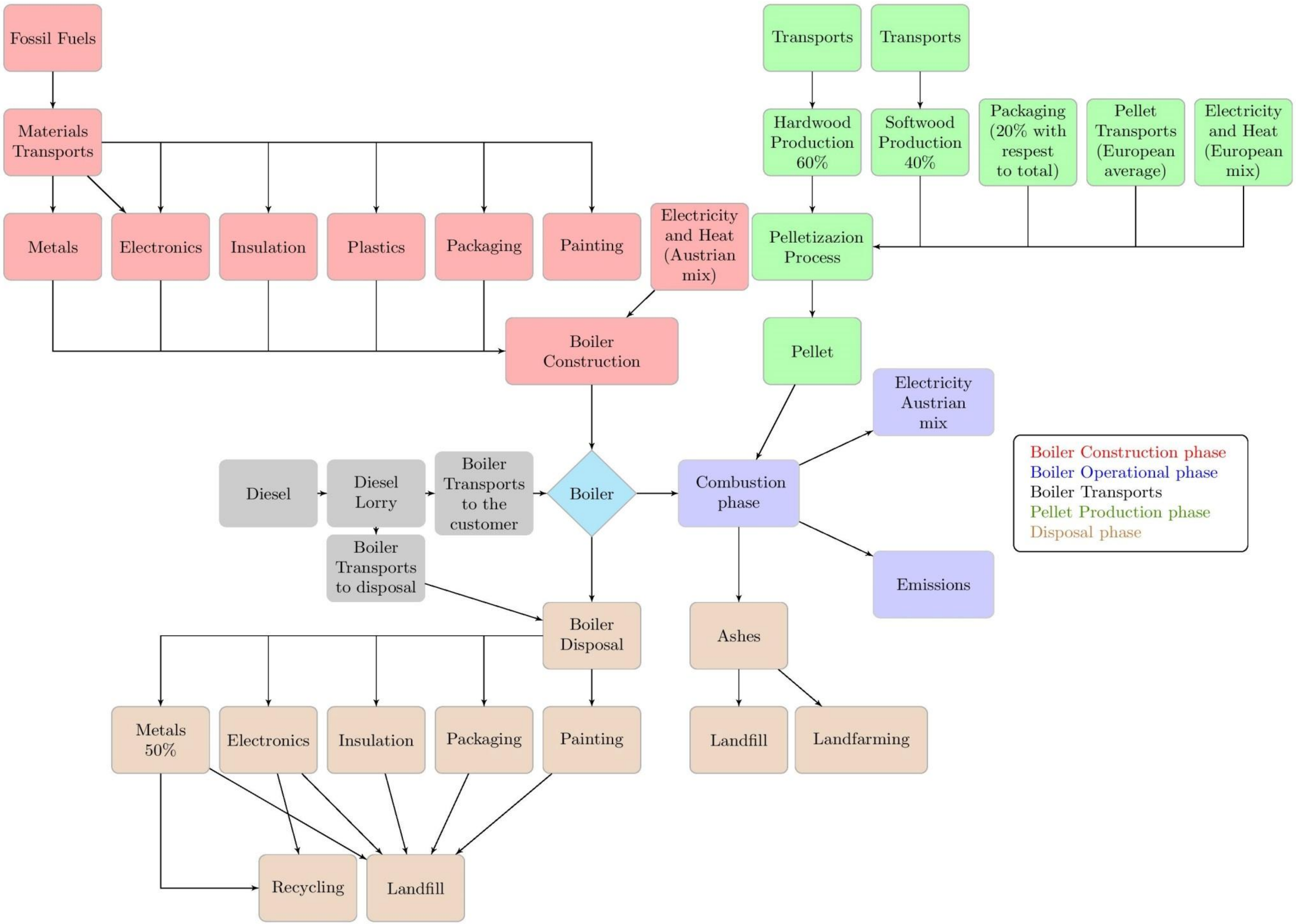
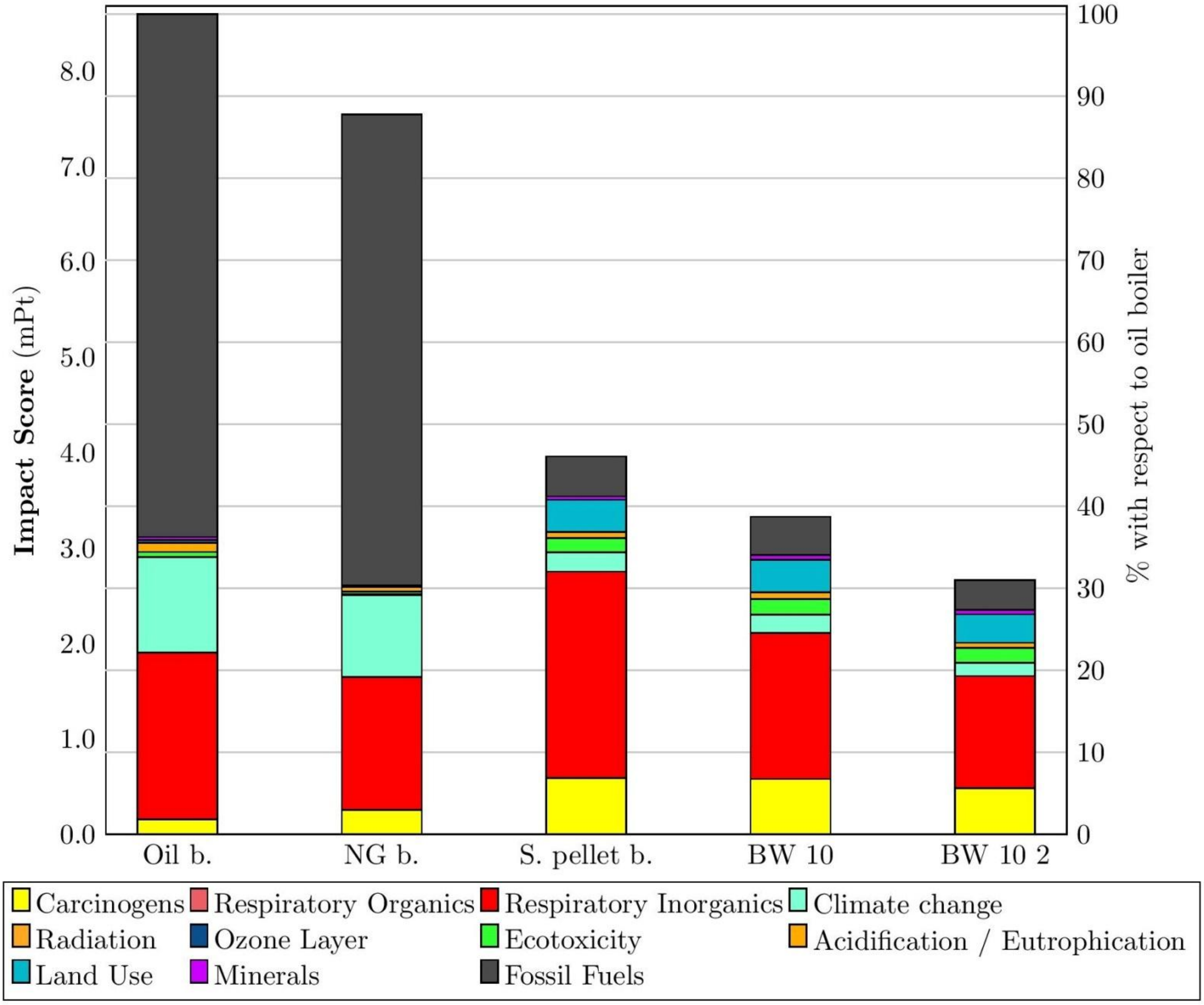


Figure N. 1



Impact Score (mPt)
% with respect to oil boiler
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
0
10
20
30
40
50
60
70
80
90
100
Oil b.
NG b.
S. pellet b.
BW 10
BW 10 2
Carcinogens
Respiratory Organics
Respiratory Inorganics
Climate change
Radiation
Ozone Layer
Ecotoxicity
Acidification / Eutrophication
Land Use
Minerals
Fossil Fuels

Figure N. 2

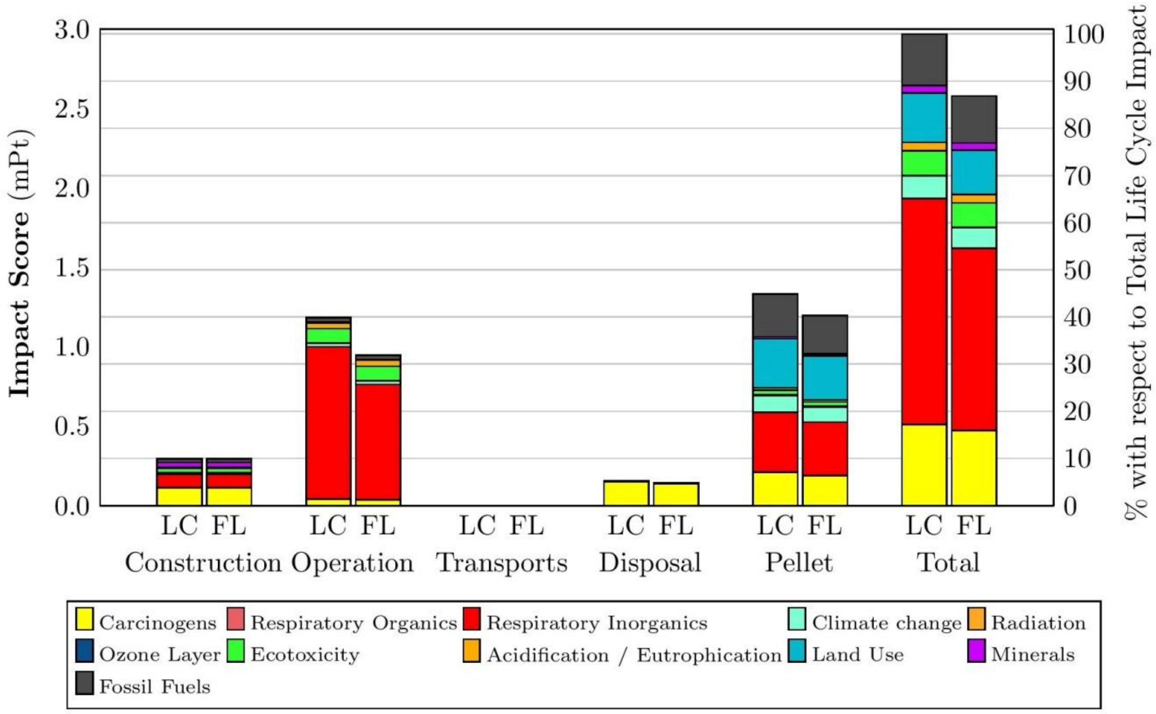
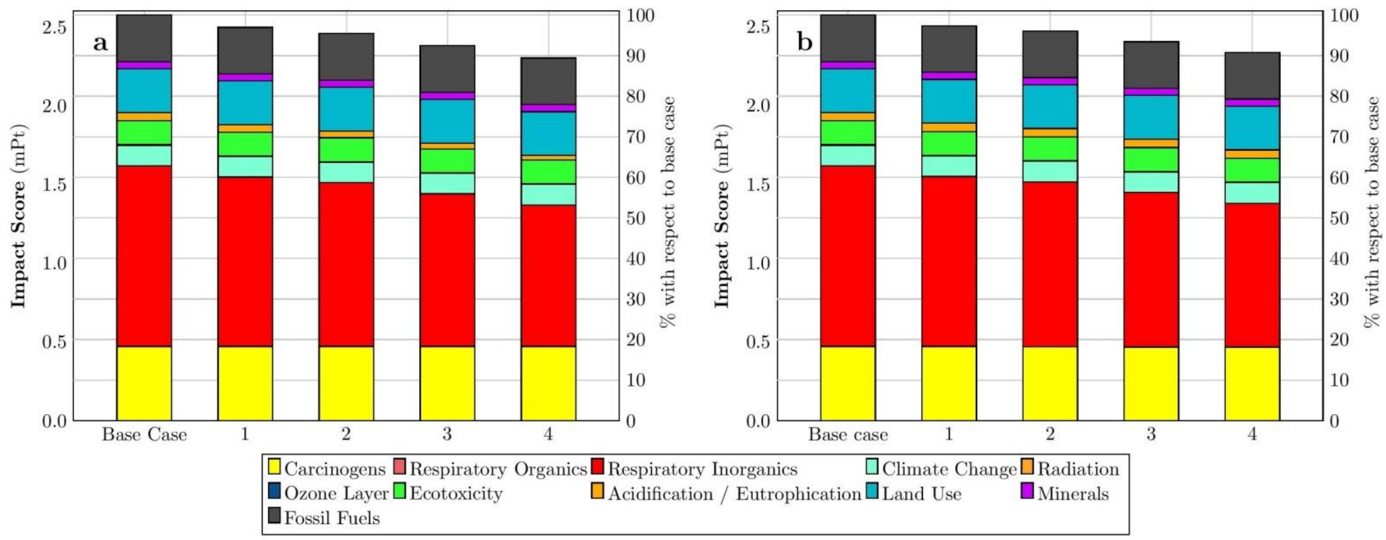
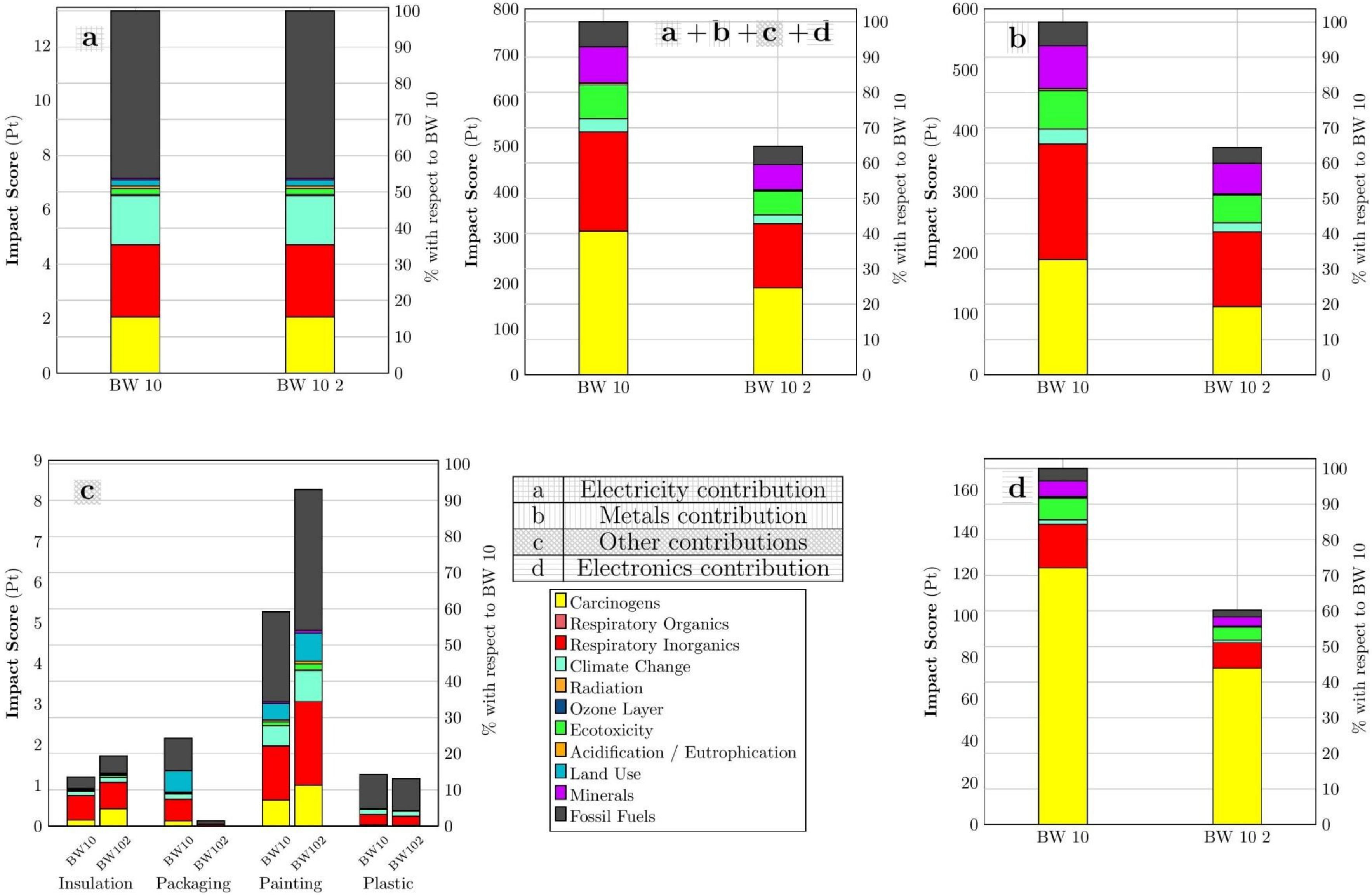


Figure N. 3



N. Scenario	Base case	1	2	3	4
Scenario "a": PM10 EF (mg/Nm^3)	15.89	12.71	11.12	7.95	4.77
Scenario "b" : NO_X EF (mg/Nm^3)	133.64	106.91	93.55	66.82	40.09

Figure N. 4



a
a + b + c + d
b
c
d
Impact Score (Pt)
% with respect to BW 10
BW 10
BW 10 2
BW10
BW102
Insulation
Packaging
Painting
Plastic
a Electricity contribution
b Metals contribution
c Other contributions
d Electronics contribution
Carcinogens
Respiratory Organics
Respiratory Inorganics
Climate Change
Radiation
Ozone Layer
Ecotoxicity
Acidification / Eutrophication
Land Use
Minerals
Fossil Fuels

Figure N. 5

Table

		BOILER TECHNOLOGY						
		BW10	BW10	BW10-2	BW10-2	EU pellet boiler	Oil	NG
Parameter	Unit	FL	LC	FL	LC	FL	FL	FL
Nominal P	kW	10,00	10,00	10,00	10,00	15,00	15,50	15,00
CO	mg/Nm³	98,52	434,33	33,02	415,08	175,50	24,00	37,50
NOx	mg/Nm³	160,78	158,04	133,64	127,98	128,10	225,00	75,00
VOCs	mg/Nm³	3,25	23,66	0,10	3,18	3,90	1,50	4,02
PM10	mg/Nm³	15,74	30,10	15,89	27,19	47,58	60,00	0,30
Efficiency	%	84,73	75,23	91,89	81,12	75,00	89,50	99,00

Table 1: Technical features (nominal power and efficiency) and full load (FL) and load cycle (LC) emission factors of the 5 boiler technologies envisaged

Parameter	Unit	Lab tests pellet data	Testing standard	Literature data [33]
Moisture	w-% (w.b.)	8,10	EN 14774-1[34]	10
C	w-% (d.b.)	50,01	EN 15104 [35]	50
H	w-% (d.b.)	6,18	EN 15104 [35]	6
O	w-% (d.b.)	43,37	by difference	44
N	w-% (d.b.)	0,06	EN 15104 [35]	0,08
S	w-% (d.b.)	< 0,01	EN 15289 [36]	0,01
Cl	w-% (d.b.)	< 0,01	EN 15289 [36]	< 0,001
Ash content	w-% (d.b.)	0,38	EN 14775 [37]	0,1-1
HHV	MJ/kg (d.b.)	20,20	EN 14918 [38]	N.A.
LHV	MJ/kg (d.b.)	18,85	EN 14918 [38]	18,5

Table 2: Quality labels and chemical and physical properties of the pellet used for lab tests compared to average pellet data used for LCA analysis (column "Literature data").