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# Environmental assessment of domestic boilers: A comparison of condensing and traditional technology using life cycle assessment methodology

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ABSTRACT

This study has carried out a life cycle assessment of two different domestic natural gas boilers in Italy, taking into account 3 different climatic regions and two dwellings with different energy classes. The aim of this research was to compare traditional and condensing boiler technologies. Primary data relating to the two products under analysis was supplied by an international boiler manufacturer, whilst the Ecoinvent database v2.2 was used as a secondary source of data. The assessment was performed using the CML and Cumulative Energy Demand (CED) methods, by considering the categories required by "Environmental Product Declaration" (EPD) certification systems. The results of the analysis show that on average, the condensing technology has a 23% lower environmental impact than its traditional counterpart for each scenario in the six impact categories considered. This is essentially due to its lower fuel consumption during the use phase and the lower levels of CO and $NO_x$ emitted during the combustion of natural gas. The study also shows that the use phase is by far the biggest contributor to the environmental impact, and on average is responsible for more than 90% of the total impact.



## 1. Introduction

Heating is a fundamental need, in particular in regions with harsh climates. It is necessary to limit the costs and improve the environmental sustainability of heating systems. Household heating is in fact one of the main contributors to the impact on the environment as underlined by Tukker et al. (2006) and more recently discussed by Nemry et al. (2010), due to the high levels of energy required. In 2010, it represented over a quarter of the total energy consumption in the EU-27, exceeding both the industry and service sectors (Bertoldi et al., 2012).

In the EU-27, domestic heating and hot water systems are the main source of household energy consumption; in particular, space heating and hot water accounted for 70% and 14% of the total annual energy consumption in 2009 (European Commission, 2012a). The residential sector plays an important role in energy efficiency programmes and policies. For this reason, the EU has adopted an energy performance Directive for buildings (European Commission, 2010), with the aim of reducing the building sector's annual energy consumption. Comparative studies on the energy performance and environmental impact of household heating systems are currently a key topic of interest (Ibrahim et al., 2014). During the last decade, several household heating systems were designed and studied in order to reduce their energy consumption and environmental impact (Al-Ghandoor et al., 2009), and also compared to district heating systems (Andrić et al., 2017). Among the various heating system alternatives in Europe, individual central heating boilers with gas-fired systems have a market share of 79%, but less than 10% are equipped with condensing technology (European Commission, 2012b). Although more efficient than their traditional equivalents, condensing boilers are in fact considered the best available technology on the market, with only a small margin for improving efficiency (European Commission, 2012b).

In order to evaluate the actual sustainability of domestic heating systems, reliable scientific tools which take into account the entire lifetime of a product must be used. Life Cycle Assessment (LCA) is the most reliable methodology for evaluating the environmental impact of a product throughout its life cycle, known as "cradle to grave" analysis. This method provides a systematic process for measuring improvements made in resource use, in order to promote cleaner manufacturing and improved product use (Strazza

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et al., 2011). It is regulated by the ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) international standards. Several LCA studies have been performed on domestic heating systems but, as shown in Section 2, none of them systematically evaluates the differences between condensing and traditional gas boilers.

The aim of this study is to apply the LCA methodology to evaluate two boilers for heating and hot water production. The systems studied are: (a) a conventional combi boiler, and (b) a condensing boiler. These two systems are evaluated in three Italian locations with different climatic conditions (Belluno, Florence and Palermo), with the aim of covering the whole Italian range of climates.

On the basis of these premises, a literature review on the environmental impact of domestic heating systems has been performed in order to show some findings generated by existing studies and compare our results with them.

## 2. Literature review on the environmental impact of domestic heating systems

The LCA technique has already been used in several studies to assess the environmental impacts of an entire building or domestic heating system. It is fundamental to gain an understanding of the global environmental impact of one system compared to another, rather than evaluating environmental emissions or fuel consumption alone. The importance of LCA was underlined in a study by Bribián et al. (2009), which supported the need for an LCA to evaluate the environmental impact of buildings and examined several approaches and software packages able to achieve this. As demonstrated in the study by Ochoa et al. (2005), the energy consumption for space heating and cooling in a residential building represents the biggest impact on the environment, yet the manufacture of the heating systems themselves must also be evaluated. The location of the heating systems influences the environmental evaluation and some authors have defined the environmental impacts as a function of the geographical position. Shah et al. (2008) studied three domestic heating and cooling systems (furnace and air conditioning (AC), boiler and AC, and air–to-air heat pump) at four locations in the United States, reporting that for Minnesota, Oregon, Pennsylvania and Texas, several impacts are also due to the mix of energy sources adopted. They compared the three systems with normalised indicators, showing that boiler and AC systems have the largest impacts associated with the appliances and distribution systems. In Lithuania Šulga (2011) analysed domestic solid fuel boiler manufacturing. This study also compared the environmental impact of two different fuels (wood and coal) and described a new ecological boiler, again using normalised indicators. The LCA approach was also used by Koroneos and Nanaki (2012), who studied the environmental performance of a domestic solar water heater in Thessaloniki (Greece) also using normalised indicators and approaching the problem from an economic point of view. Gajewski et al. (2013) analysed the environmental performance of various heating systems (including a condensing boiler) in Europe, considering carbon dioxide emissions only. Several studies have been recently performed on biomass boiler systems, which are considered a more environmentally sustainable form of energy for domestic heating, but results are often discordant. Laschi et al. (2016) demonstrated that some environmental impacts derive from the production of pellets. For a 1 kg bag of wooden pellets, the authors obtained an impact on the Global Warming Potential (GWP) of 0.4 kg $CO_{2eq}$, mainly due to the pellet production in the factory (ranging from 71.6% to 96.2% for several categories), but no mention was made of the final impact of domestic pellet boilers. Data about the environmental impact of pellets boilers have been reported recently by Chiesa et al. (2016), who described an average impact of 0.01 kg $CO_{2eq}$ for 1 MJ of useful heat (functional unit), considering an average boiler lifetime of 20 years. Their evaluation appears highly promising also as far as the air quality in the region is concerned, because one of the main disadvantages of the biomass solution reported in literature is air pollution.

Condensing boilers are evaluated by few studies: Giuntoli et al. (2015) recently compared the domestic heating from forest logging residues with that generated by a condensing boiler, by considering an annual thermal efficiency of 90% of the latter. However, the characteristics of the condensing system, which produces 77 g of $CO_{2eq}$ for 1 MJ of useful heat compared to 15 g by pellet systems, were not fully described. Cellura et al. (2014) also compared biomass-fuelled systems with a condensing boiler, reporting for the latter that the use phase represents 99% of the environmental impact. In this case, pellet boilers have an average impact of 1.30 kg of $CO_{2eq}$ for 1 GJ of net thermal energy produced. Blom et al. (2010) studied some climate systems including individual non-condensing boilers, condensing boilers and exhaust air heat pumps for heating and hot water, either combined with collective mechanical exhaust ventilation or individual balanced ventilation with heat recovery. The aim of their research was to compare the environmental impact of the use of different heating and ventilation systems in a pre-defined dwelling, using life cycle assessment methodology. However, this study again only provided normalised values for a comparative analysis. Only one of the studies on condensing or other types of boilers has evaluated their environmental performance on the basis of their manufacture and the differing climatic conditions in which they are used. This recent study by Monteleone et al. (2015) carries out a life cycle assessment of small scale pellet boilers, but the values in the 18 impact categories used have again been normalised. Manufacturing and the end of life of energy systems have, however, been evaluated in solar energy systems, in order to establish their impact in respect of the use phase (Lamnatou et al., 2015).

Based on these premises, this study aims to compare the environmental impact of condensing and traditional boilers, by considering three Italian locations with different climatic conditions (Belluno, Florence and Palermo), with the aim of covering the whole Italian range of climate. In each climate region, a dwelling with the same layout but different thermal insulation performance is considered.

## 3. System description

This study is a comparative LCA of two domestic boilers based on two different technologies produced by the company Immergas S.p.A. located in Reggio Emilia (Italy) (Immergas). The first boiler considered is a conventional combi-boiler while the second is a condensing boiler. The following sub-sections describe the two systems analysed.

### 3.1. Conventional combi-boiler

This boiler is a wall-hung system for central heating and instantaneous domestic production of hot water. The model considered is “Maior Eolo 24”. It has a sealed chamber, forced draft, with a rated thermal input of 24 kW. It is a high efficiency boiler with forced circulation, which operates between 9.3 and 24 kW. It is a class II2H3 + model and can run on natural gas and LPG (Liquefied Petroleum Gas). The boiler is supplied with wells for combustion analysis, a lower grille, a connection unit with adjustable fittings and depth cocks for gas and cold water. It can also be run on propane-air (50% air − 50% propane) by installing a special conversion kit.

Fig. 1 shows the main components of the traditional boiler evaluated. The burner (5) is composed of a multi-gas system

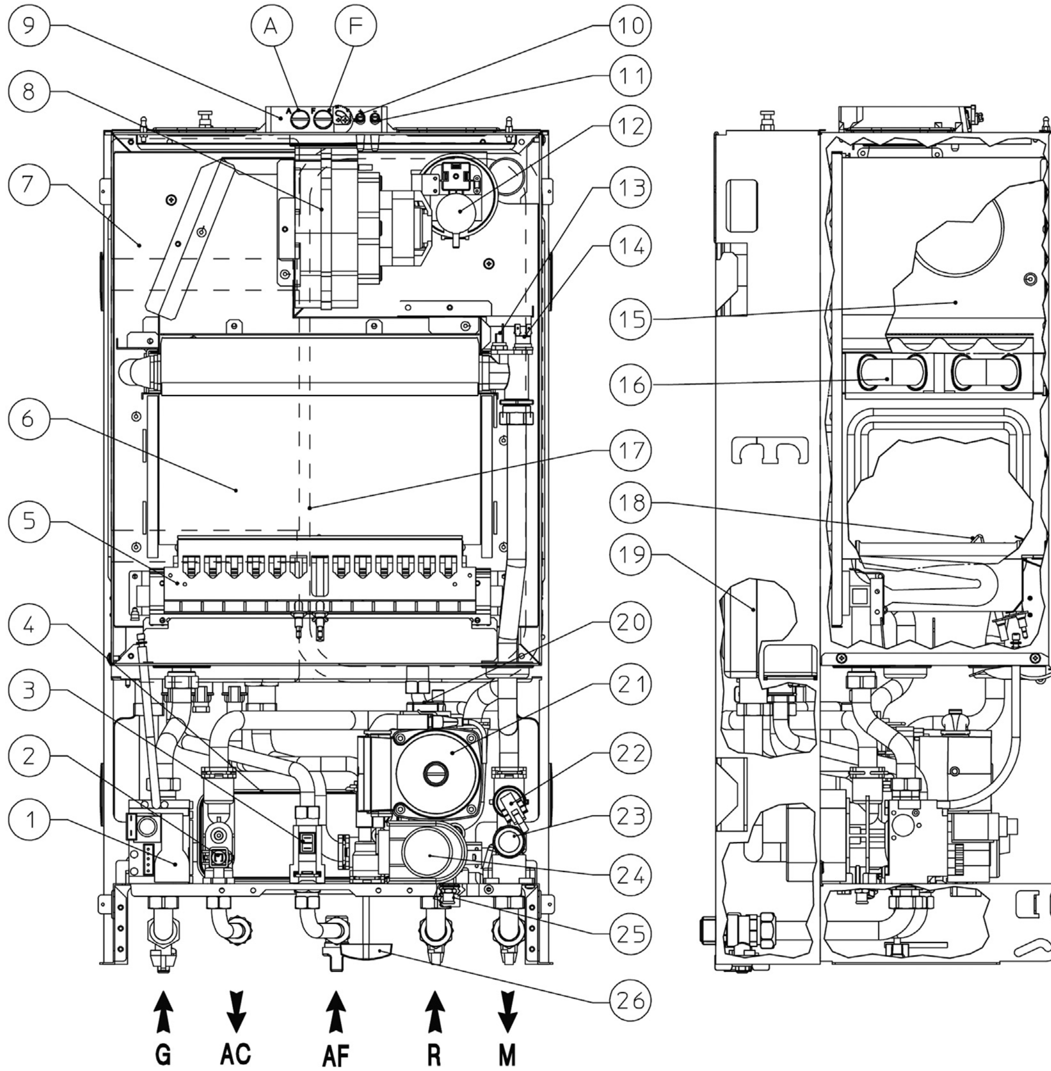


**Fig. 1.** Main components of the conventional “Maior Eolo” combi-boiler (Immergas S.p.A). Note: 1 - Gas valve; 2 - Domestic water probe; 3 - Domestic water flow switch; 4 - Domestic water exchanger; 5 - Burner; 6 - Combustion chamber; 7 - Sealed chamber; 8 - Fan; 9 - Intakes (air A) - (flues F); 10 - Positive signal pressure point; 11 - Negative signal pressure point; 12 - Flue pressure switch; 13 - Delivery probe; 14 - Safety thermostat; 15 - Draught diverter; 16 - Primary exchanger; 17 - System expansion tank; 18 - Ignition and detection electrodes; 19 – “Aqua celeris” system; 20 - Air venting valve; 21 - Boiler circulator; 22 - System pressure switch; 23 - Safety valve; 24 - Three-way valve (driven); 25 - System draining cock; 26 - System filling cock.

equipped with 11 ramps and aspirated air. It is made of stainless steel and comes complete with ignition and detection electrodes (18). The gas valve (1) has a double shutter with a built-in modulating coil.

The primary exchanger (16) is a high-efficiency gas/water system made of copper and consisting of four pipes connected in series in lamellar coils protected by a non-corroding alloy. The combustion chamber (6) in steel plate is internally insulated with ceramic panels. The sealed chamber (7) is composed of steel plates with a fixed speed fan for exhaust fumes (8), a differential pressure switch (12) to ensure the fan and the intake circuit of exhaust fumes/air function correctly. The hydraulic unit consists of a 3-way electric valve (24), an adjustable speed circulator (21) with built-in air separator, an adjustable by-pass, an absolute pressure switch (22) for the primary circuit, a 3-bar primary circuit safety valve (23), a system draining union (25) and a ball cock to fill the system (26).

As far as the production of hot domestic water is concerned, the boiler is equipped with a stainless steel water/water exchanger (4) with 16 plates and a flow switch (3), which detects when domestic water is used.

The tank is a 10 L diaphragm expansion tank (17) with a preload of 1.0 bar, a 3-bar system safety valve, a thermometer and a pressure gauge (2). The risk of over-temperature is controlled by means of a safety thermostat (14). A particular feature of this boiler is the “Aqua Celeris” system (19), which consists of a small storage tank installed in the primary circuit and maintained at the right temperature by a small modulating electric heating element. This system immediately heats domestic water to the right temperature, reducing the time needed by users for the delivery of hot water.

Wall-hung radiator heating has been considered in this analysis to calculate fuel consumption since it is the most frequent heating device coupled with this type of boiler.

### 3.2. Condensing boiler

The second boiler is an instantaneous combi boiler with a heat output of 24 kW for the heating function and 26 kW for the sanitary function able to guarantee a large quantity of hot tap water. It is also wall-mounted and comes with a storage tank, which ensures constant availability of domestic hot water at the desired temperature. This model, which is called "Victrix", is equipped with a condensing module composed of a stainless steel central unit contained within a composite material shell. It has an extensive power range (starting from 3 kW), making this system particularly suitable for new buildings with low heating requirements. Both natural gas and LPG can be used as fuels.

Fig. 2 shows the main components of this second boiler. The burner (11) is composed of a multi-gas system made entirely from stainless steel, and comes with ignition and detection electrodes. The gas valve (4) is pneumatic and has a double shutter. The primary exchanger is a gas/water heat exchange system with a shell in composite material and an internal stainless steel coil. The combustion chamber is in stainless steel and is insulated on the inner side with ceramic panels. The boiler is also equipped with a secondary water/water plate heat exchanger (3) for the production of domestic hot water. It has 14 plates, made entirely from stainless steel. The hydraulic unit of the boiler consists of a motorised 3-way valve (30), a pump with an adjustable working speed and built-in air separator (27), an adjustable and excludable by-pass system (29), a system pressure switch (26), a safety valve (28) and a system filling valve (32). The Victrix model is designed for use with underfloor heating, which is the standard radiator system for condensing technology.

The main difference between the two boilers is that the condensing boiler, i.e. the Victrix model, is equipped with a condensation module (13) which allows part of the exhaust fumes to be used to pre-heat the water that feeds the system, increasing the energy efficiency of the boiler.

The main technical specifications of both boilers are summarised in Table 1.

## 4. Life cycle assessment

LCA is considered by the European Commission to be the best

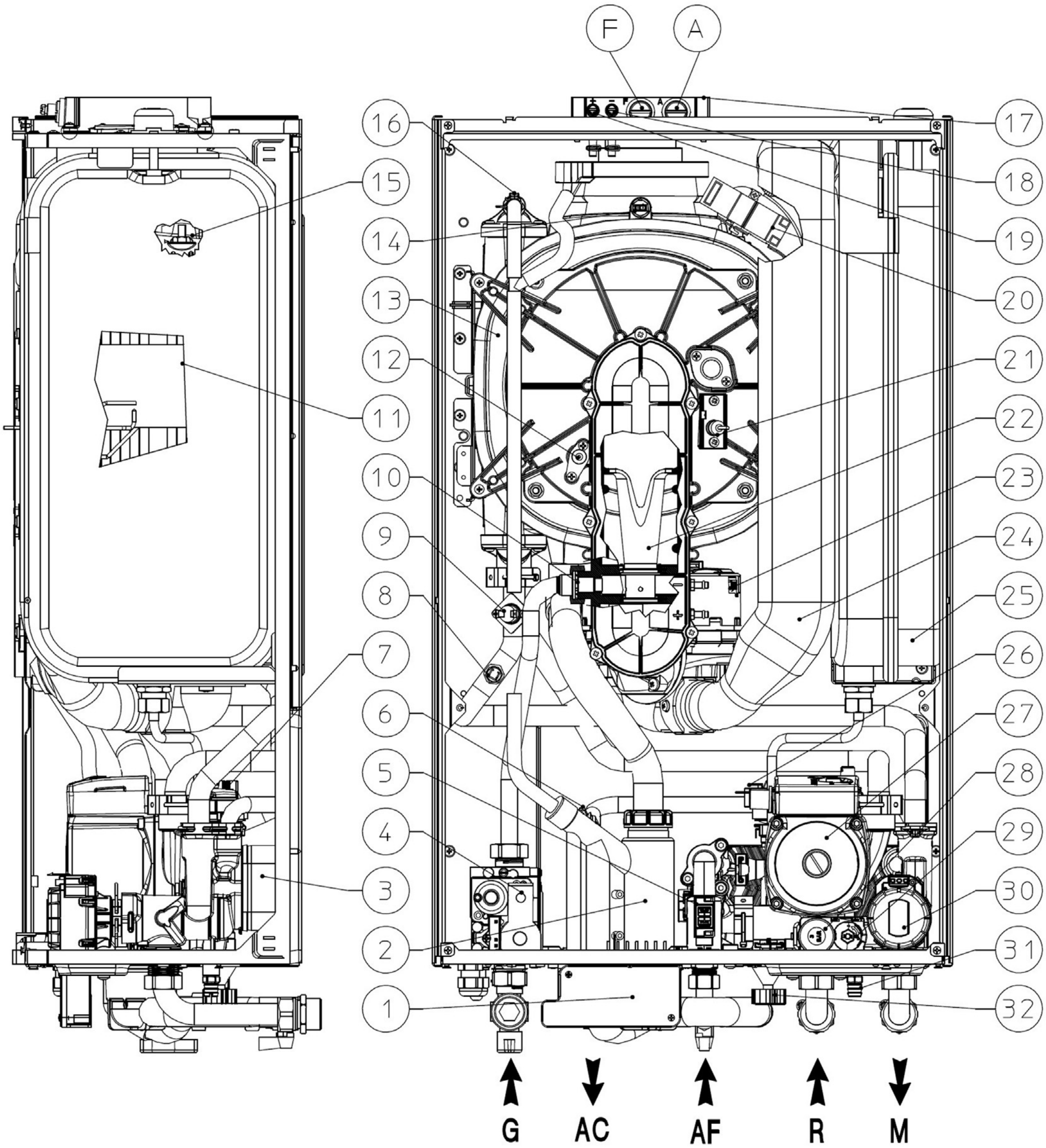


**Fig. 2.** Main components of the condensing boiler "Victrix" (Immergas S.p.A). Note: 1 – Electrical connection terminal board; 2 – Condensate drain trap; 3 - DHW heat exchanger; 4 – Gas valve; 5 – Domestic hot water flow switch; 6 – Domestic hot water probe; 7 – Air vent valve; 8 – Flow probe; 9 – Safety thermostat; 10 – Gas nozzle; 11 - Burner; 12 – Detection electrode; 13 – Condensation module; 14 – Flue probe; 15 – Heat exchanger safety thermofuse; 16 – Manual air vent valve; 17 – Sample points (air A) – (flue gases F); 18 – Negative signal pressure point; 19 – Positive signal pressure point; 20 - Igniter; 21 – Ignition Electrode; 22 - Venturi; 23 - Fan; 24 – Air Intake Pipe; 25 - System expansion vessel; 26 - System pressure switch; 27 – Boiler pump; 28–3 Bar safety valve; 29 – By-pass; 30 – 3-way valve (motorised); 31 – System draining valve; 32 – System filling valve.

**Table 1**
Technical data of the two boilers.

| Technical Data | Unit | Conventional combi boiler | Condensing boiler |
|---|---|---|---|
| Electrical power consumption | kW | 0.115 | 0.120 |
| Nominal Heat Input | kW | 25.9 | 26.7 |
| Minimum Heat Input | kW | 10.7 | 3.2 |
| Nominal Heat Output | kW | 24 | 23.6 |
| Minimum Heat Output | kW | 9.3 | 3 |
| Heating efficiency at 100% of nominal production | % | 92.8 | 108.1 |
| Heating efficiency at 30% of nominal output | % | 90.7 | 102.1 |
| Continuous service supply capacity with ΔT 30 °C | L/min | 11.4 | 12.9 |
| Minimum pressure for sanitary hot water | bar | 0.3 | 0.3 |
| Minimum hot water supply | L/min | 2 | 1.5 |
| Weight of boiler full of water | kg | 44 | 42.4 |

tool to evaluate the environmental performance of a product or system (European Commission, 2003, 2013). The methodology is composed of four main stages of analysis: (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment and (iv) interpretation (ISO, 2006b). This study follows a methodological pattern consistent with the requirements of the EPD environmental label, as defined in the document "General Programme Instructions for Environmental Product Declarations, EPD" (International EPD System, 2015). This method has been followed in order to allow comparability of approaches and results. In particular, the guidelines adopted form the general framework of the International EPD System and Product Category Rules (PCR) regarding central heating boilers and water heaters (PCR, 2011).

### 4.1. Aim and scope

The aim of this study is to compare the environmental impact of two different boilers for domestic use and evaluate the critical aspects of their life cycles. This analysis is relates to Italian climatic conditions and considers two dwelling energy classes for two regions, which are representative of the different climate conditions in Italy (northern and southern geographical locations).

#### 4.1.1. Functional unit

The purpose of the Functional Unit (FU) is to provide a reference unit, for which the inventory data are normalised (ISO, 2006a). The functional unit is essential since it facilitates the comparison of alternative products and services (ISO, 2006b). The functional unit adopted in this analysis is a single boiler. The expected lifespan of the boiler is presumed to be 15 years.

#### 4.1.2. System boundary

In order to quantify the impact of the analysed product, system boundaries will be determined. The boundary systems adopted in this study have been determined following those proposed by the PCR and are shown in Fig. 3.

The first phase of the system boundaries includes the production of raw materials, the production and manufacturing of the components, the assembly and testing activities at the production plant and the packaging. It represents the "*upstream processes*" of the system.

The delivery of the boiler to customers and all the processes relating to the consumption of natural gas and electricity, which occurs during the use phase (i.e. fuel extraction, electricity generation, fuel and electricity use during boiler operations, the heating cycle, the hot domestic water cycle and combustion emissions), are included in the analysis and represent the "core process" of the system. Natural gas has been selected as the fuel for all the scenarios evaluated.

Lastly, the end of life is also assessed, considering the end-of-life management activities of the boiler after the estimated life span use; this part represents the "*downstream processes*" of the boiler life cycle.

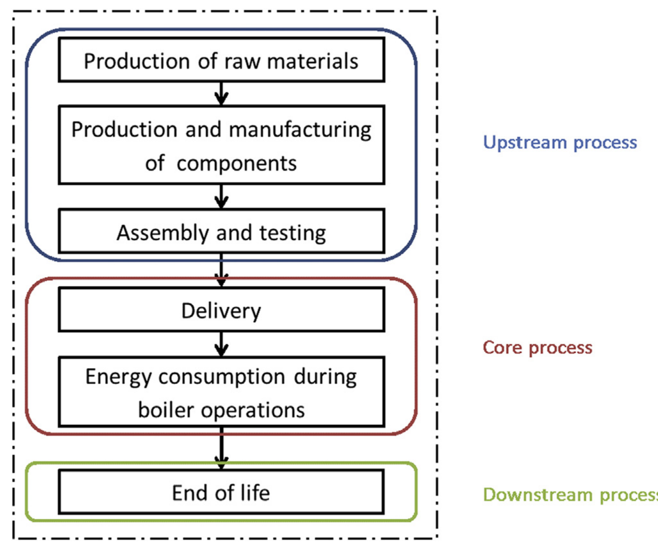


**Fig. 3.** System boundaries of boiler life cycle.

The manufacture of the radiators and their transportation are not taken into account in the study, since they are not produced by the company, which provided the information regarding the boilers, and generate a low impact on the environmental categories considered (being less than 1% impact according to the imposed cut-off criteria). This evaluation was carried out considering the number and weight of the radiators and the type of materials used to build them (cast iron), as well as the piping used to build roof systems, again in accordance with the PCR for Central heating boilers and water heaters (PCR, 2011).

### 4.2. Life cycle inventory analysis

The life cycle inventory analysis quantifies the resource use, energy use and environmental release associated with the system, which have been evaluated by means of a mass and energy balance (ISO, 2006b). All primary data were gathered from Immergas personnel via a questionnaire and personal interviews. The Ecoinvent database v2.2 (Swiss Centre for Life Cycle Inventories, 2010) was used as a secondary source of data, by considering data relating to the Italian context when available or alternatively to the rest of Europe.

In respect of the upstream process, the cut-off applied to the gross weight of material was set at 99% as required by the PCR (PCR, 2011). Since the impact of the manufacturing phase is always less than 5% on all of the main environmental impact indicators, the PCR provides for the adoption of a simplified procedure to take into account the system components and their materials, which groups them by material type.

*4.2.1. Upstream processes*

The bills for the materials of the two boilers were provided by the company and are shown in Table 2.

There are slight differences between the two products; the main difference is the use of stainless steel in the condensing boiler for the condensing module. This material is required since the condensate produced is slightly acidic and it is therefore necessary to use materials able to withstand these conditions. More copper is used in the traditional boiler since its primary heat exchanger is made entirely from this material.

As far as the assembly and testing phases are concerned, it was impossible to obtain data closely related to these phases since the company has no control over the manufacturing consumption of each product. For this reason, these data are obtained by dividing the company's electricity and natural gas consumption by the number of boilers produced per year. This allocation method is not completely accurate because not every product requires the same amount of energy during the manufacturing phase, but it has been considered acceptable (Cherubini et al., 2011), since the consumption in this phase is significantly lower than that during the use phase.

The energy requirements for the manufacturing phase are as follows:

- Electricity consumption is 22.2 kWh per boiler; 25% of the electricity consumed is generated by photovoltaics whilst the remaining 75% is supplied by the grid.
- The thermal energy used is obtained from natural gas amounts to 116.6 MJ.

The input stream transportation has been included, considering a Euro 4 16-32 t lorry as the means of transport.

*4.2.2. Core processes*

The energy consumption was estimated by evaluating the efficiency of the boilers in different scenarios, i.e. by combining the degree of thermal insulation in the building and the climatic zone. As mentioned, Italy has very different climatic zones and a comparison between the two different boiler systems should be made on the basis of several possible situations. Fig. 4 provides a map of climatic zones for the various Italian provinces, based on a Decree of the President of the Italian Republic (DPR no. 412, 1993). As can be seen from the figures for the north and south of Italy, there are significant differences in the “Degree day” values. This unit of measurement is equal to a difference of one degree between the mean outdoor temperature on a certain day and a reference temperature, used to estimate the energy required to heat a building. An interesting evaluation of heating and cooling degree days in Italy has recently been performed by De Rosa et al. (2015), who show the trend of these values based on the climate evaluation in Italy.

The standard dwelling considered has a surface of 135 $m^2$ on one floor, as shown in Fig. 5. This represents a typical dwelling for a family composed of two adults and two children.

The energy consumption was calculated considering the various scenarios described below.

Based on the same layout of the standard dwelling reported in Fig. 5, two different thermal insulation efficiencies were considered for each Italian climatic zone analysed. In the first scenario, the dwelling encompasses modern and green insulation systems adopted since 2000 (dwelling 1), while in the second scenario, the dwelling adopts the insulation system typical of dwellings built during the 1990s (dwelling 2). Different insulation systems were considered in order to evaluate the performance of the heating systems when applied to different building types.

In this study, three different Italian provinces (corresponding to three different climatic zones as shown in Fig. 4) were considered:

- Belluno (Geographical class F).
- Florence (Geographical class D).
- Palermo (Geographical class B).

The characteristics in terms of the energy requirements of climatic zones B, D and F are as follows:

- The “Degree days” of the zones considered are: 751 for zone B, 1821 for zone D and 3043 for zone F, calculated according to the Presidential Decree (DPR no. 412, 1993) and subsequent amendments and additions.
- The heating days per year are: 121 for zone B, 161 for zone D and 200 for zone F.
- The average monthly temperatures (in °C), determined in accordance with UNI (the Italian National Unification body) 10349 (UNI, 2016), are shown in Table 3 below.

The overall gas required by the two combi boilers analysed (with traditional and condensing technology) is the sum of domestic heating and hot water consumption. The energy performance of

**Table 2**
Inventory data for components and packaging.

| Material | Conventional boiler “Eolo” [Kg] | Condensing boiler “Victrix” [Kg] |
|---|---|---|
| Silicone | 0.040 | 0.115 |
| EPDM | 0.031 | 0.064 |
| ABS | 0.911 | 1.171 |
| PVC | 0.002 | 0.005 |
| Aluminium | 0.125 | 1.905 |
| Steel | 23.075 | 22.879 |
| Stainless steel | 1.211 | 6.736 |
| Brass | 2.889 | 3.215 |
| Copper | 5.061 | 2.290 |
| Electronic components | 0.248 | 0.248 |
| Wiring | 0.372 | 0.372 |
| PE film | 0.042 | 0.073 |
| Wood | 0.899 | 0.852 |
| Paper | 3.750 | 2.022 |
| Polystyrene | – | 1.008 |

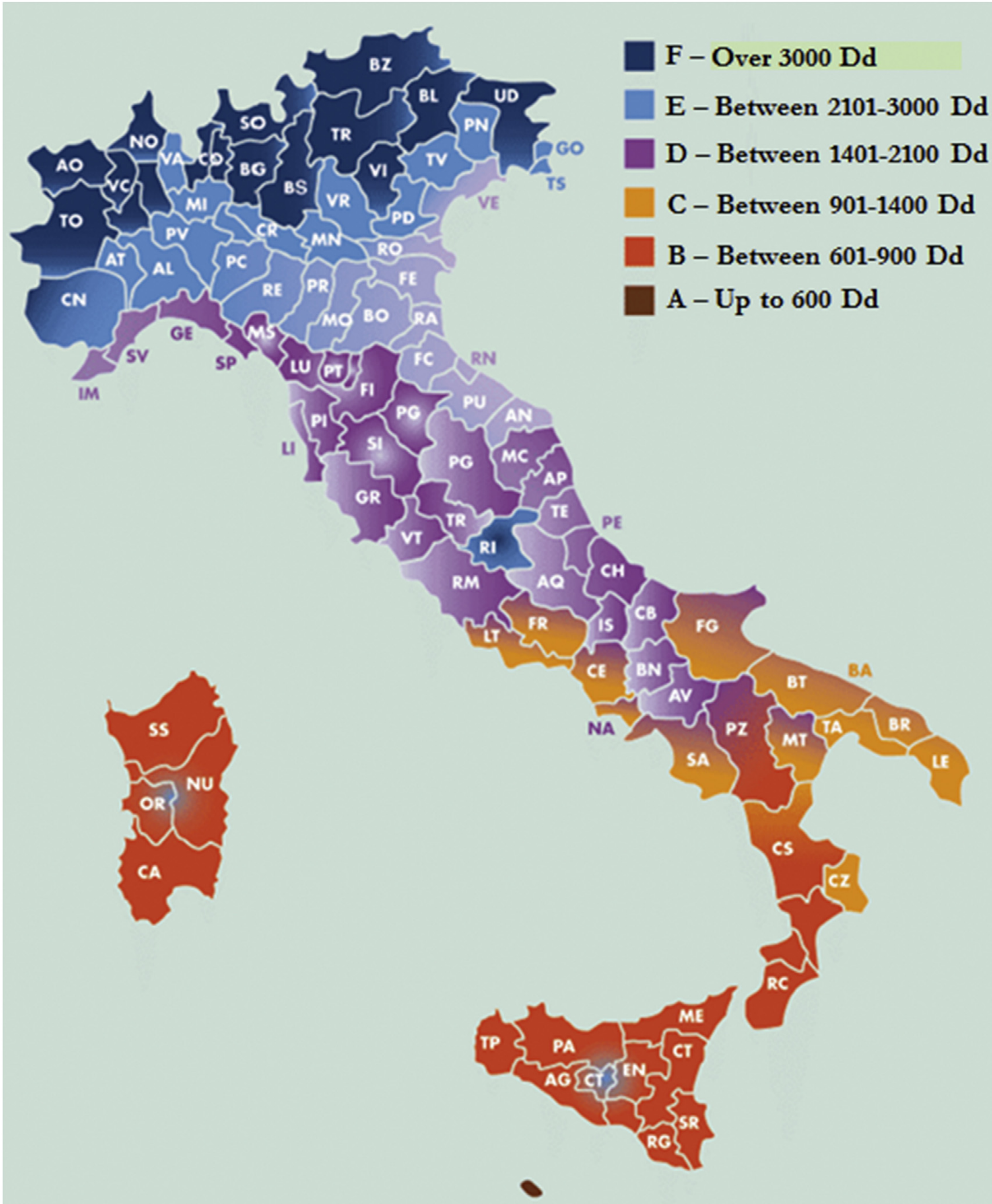


**Fig. 4.** Italian climate zones[1]; Dd = Degree days.

domestic heating depends on the characteristics of the building and the heating system. A building energy performance index indicates the amount of energy required by the building and is expressed in equivalent kWh/m$^2$ year. The EPI (Energy Performance Index) of a building envelope for heating indicates the theoretical thermal energy demand of a building for winter heating, not considering the performance of the heating systems. The EPI for the building envelope of the dwellings considered in this analysis are calculated using the TERMUS software (Acca), which adopts calculation methods complying with the UNI/EN/ISO 13790 and UNI/TS 11300-1 (UNI EN ISO, 2008; UNI, 2014a) technical standards.

These methods consider: (i) the climatic parameters of the reference zone; (ii) the technical-constructive data of the building, which is the subject of the calculation; (iii) the heating system data; and (iv) the calculated results relating to the considered scenario.

The annual energy required to heat the given building area is then calculated by summing the calculated energy need per period, taking into account possible weightings for different heating modes:

$$QH_{n,an} = \sum i\ QH_{n,i}$$

[1] Available online at: www.oopen.it/trasmittanza-termica/(accessed on 12th October 2016).

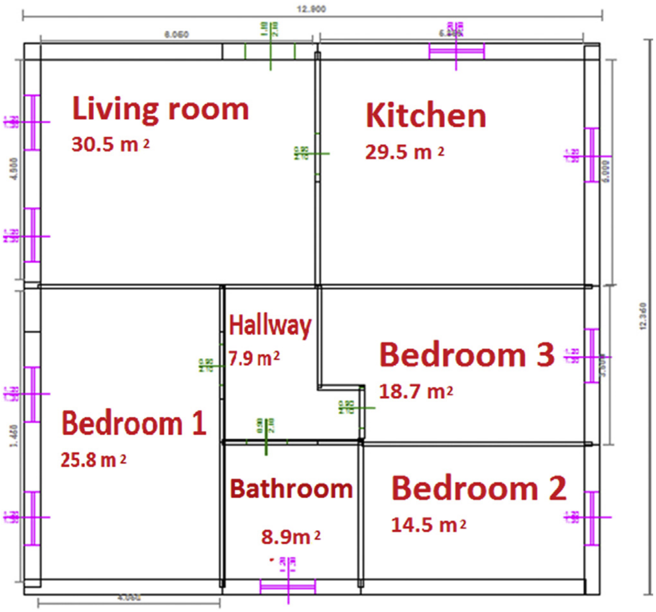


**Fig. 5.** Layout of the dwelling considered.

**Table 3**
Average monthly temperatures in different climate zones.

| Zone | Jan | Feb | Mar | Apr | May | Jun |
|---|---|---|---|---|---|---|
| B | 11.10 °C | 11.60 °C | 13.10 °C | 15.50 °C | 18.80 °C | 22.70 °C |
| D | 5.30 °C | 6.50 °C | 9.90 °C | 13.80 °C | 17.80 °C | 22.20 °C |
| F | 0.10 °C | 2.30 °C | 6.80 °C | 11.20 °C | 14.90 °C | 18.90 °C |
| Zone | Jul | Aug | Sep | Oct | Nov | Dec |
| B | 25.50 °C | 25.40 °C | 23.60 °C | 19.80 °C | 16.00 °C | 12.60 °C |
| D | 25.00 °C | 24.30 °C | 20.90 °C | 15.30 °C | 10.20 °C | 6.30 °C |
| F | 21.20 °C | 20.80 °C | 17.70 °C | 12.40 °C | 6.50 °C | 1.70 °C |

where $QH_{,n,an}$ is the annual energy need required to heat the area considered, in MJ;

$QH_{,n,i}$ is the energy required to heat the area considered per calculation period (month in this case), determined in accordance with 7.2 of ISO (UNI EN ISO 13790, 2008) in MJ;

According to these calculations, the EPI values obtained for dwellings 1 and 2 in the area considered are shown in Table 4.

The energy required for the production of hot water, calculated in accordance with the technical standard UNI/TS 11300-2 (UNI, 2014b) is about 20.000 kWh/m$^2$ year in all the scenarios assessed. This value was obtained starting from (i) the water temperature at the delivery point [°C]; (ii) the domestic cold water inlet temperature [°C]; (iii) the number of days of the calculation period G [G] and (iv) the available area [m$^2$], which has been considered the same in all the locations considered (i.e. respectively 40 °C, 15 °C, 365 G and 135 m$^2$).

**Table 4**
Energy Performance Index for the envelope in the scenarios considered.

| EPI | City | | |
|---|---|---|---|
| | Palermo | Florence | Belluno |
| Dwelling 1 [kWh/m$^2$year] | 38.503 | 65.788 | 83.734 |
| Dwelling 2 [kWh/m$^2$year] | 79.662 | 177.654 | 226.127 |

For each scenario analysed, the annual natural gas consumption calculated for heating and hot water production are shown in Table 5, considering part-load operations, and not providing any (i) remote thermal plant management system, (ii) any climate control system in thermal power plant (iii) and any climate control unit. No temperature programming over the 24 h period was considered. This consumption accounted for the calculation of impacts considering a life span of 15 years. This calculation derived from the performance indexes of each boiler system. As far as the thermal zone of the dwelling is concerned, the following data are used to calculate the energy consumption for each boiler:

Ventilation: Natural, with an air change rate of 0.30 (1/h)

The seasonal efficiency of the project (Rosa and Tosato, 1990) is obtained by considering:

- Emission performance (η Eh);
- Adjustment performance (η Rh)

The heating system performance (e.g. a Victrix system) is instead assessed by considering,

- The project performance;
- The production performance (η pH)
- The abovementioned Emission (η Eh) and Adjustment (η Rh) performances, which relate to a specific zone.
- The distribution performance

The Fossil combustion system is lastly evaluated by considering.

- The production performance (ηpH)
- The heating generation performance (η GN), which varies from month to month.

Compared to conventional technology, the condensing technology reduces the natural gas consumption for the heating demand by about 15% and for domestic hot water by about 12%.

Table 5 shows the annual natural gas consumption of each boiler. The estimated consumption of electricity during the life span of the two boilers depends on the numbers of hours they operate. The Presidential Decree (DPR, 1993) sets restrictions on the use of thermal plants, with significant differences between the various climatic zones.

Table 6 summarizes the calculated electricity consumption for each boiler in the three geographical areas considered. These values have been estimated assuming that, on average, the boilers operate for half the maximum time allowed. Additional considerations could be made based on the work done by Lazzarini (2014) regarding fuel consumption, using the modulation ratio for boilers installed in refurbished buildings.

Euro 4 16-32 t lorries were considered to evaluate the boiler transportation to customers, assuming an average customer

**Table 5**
Natural gas consumption of the two boilers.

| Region | Demand for heating [Nm$^3$/year] | | | Demand for domestic hot water [Nm$^3$/year] | | |
|---|---|---|---|---|---|---|
| | Belluno | Florence | Palermo | Belluno | Florence | Palermo |
| Dwelling 1 | | | | | | |
| Eolo | 1367 | 1074 | 623 | 306 | 307 | 291 |
| Victrix | 1146 | 902 | 535 | 268 | 271 | 260 |
| % variation | 16.2% | 16.0% | 14.1% | 12.6% | 11.9% | 10.7% |
| Dwelling 2 | | | | | | |
| Eolo | 3786 | 2973 | 1304 | 306 | 307 | 291 |
| Victrix | 3213 | 2515 | 1086 | 269 | 272 | 257 |
| % variation | 15.1% | 15.34% | 16.7% | 12.0% | 11.5% | 11.5% |

**Table 6**
Electricity consumption of the two boilers.

| Region | Demand for electricity [kWh/year] | | |
|---|---|---|---|
| | F - Belluno | D - Florence | B - Palermo |
| Conventional combi boiler - Eolo | 193 | 114 | 55 |
| Condensing boiler -Victrix | 202 | 119 | 58 |

distance of 195 km. This value has been taken from the average distance between the boilers manufacturer and its customers, but its influence on the environmental impact will be negligible, as demonstrated later in the text.

Data on $NO_x$ and CO emissions, which occur during natural gas combustion, were taken from the technical sheets of the two boilers. In respect of the Eolo model, $NO_x$ emissions total 128 mg/kWh and CO emissions total 84 mg/kWh, whereas for the Victrix $NO_x$ emissions total 36 mg/kWh and CO emissions total 15 mg/kWh. $CO_2$ emissions were calculated by means of a stoichiometric analysis.

### 4.2.3. Downstream processes

Regarding the downstream process, the transportation of the boiler to landfill is included in the analysis, considering a distance of 50 km from the customer to the disposal site. A Euro 4 3.5–7.5 t lorry was used to evaluate this phase. The end of life scenario considered is 100% landfill, using a conservative approach, since the company has no control over this phase. Over the last decade, some studies were performed to work out potential savings which could be made from the recovery of the waste boiler, but until now their impact (in particular that connected to boiler recovery) has been assessed at below a value of 1%, in line with the cut-off applied to this study (Li et al., 2013).

## 4.3. Method of impact assessment

The data collected in the inventory analysis form the basis for the impact assessment phase, which aims to evaluate the potential environmental impacts of the system (European Commission, 2012a). The SimaPro version 7.3.3 software package was used for the analysis of the environmental impacts, selecting the CML2001 (Guinée, 2001) life cycle impact assessment method at the mid-

**Table 7**
Absolute environmental impacts of the two boilers.

| | | Belluno | | Florence | | Palermo | |
|---|---|---|---|---|---|---|---|
| | | Conventional b | Condensing b | Conventional b | Condensing b | Conventional b | Condensing b |
| Dwelling 1 | | | | | | | |
| AP | kg $SO_2$ eq. | 7.21E+01 | 5.33E+01 | 5.76E+01 | 4.21E+01 | 3.77E+01 | 2.79E+01 |
| EP | kg $PO_4^{3-}$ eq. | 8.40E+00 | 4.74E+00 | 6.86E+00 | 3.82E+00 | 4.69E+00 | 2.67E+00 |
| GWP | kg $CO_2$ eq. | 1.64E+04 | 1.42E+04 | 1.31E+04 | 1.14E+04 | 8.52E+03 | 7.53E+03 |
| ODP | kg $CFC_{11}$ eq. | 6.83E-03 | 5.80E-03 | 5.60E-03 | 4.78E-03 | 3.70E-03 | 3.22E-03 |
| POP | kg $C_2H_4$ eq. | 4.56E+00 | 3.55E+00 | 3.69E+00 | 2.86E+00 | 2.43E+00 | 1.92E+00 |
| CED | MJ | 1.05E+06 | 8.86E+05 | 8.61E+05 | 7.33E+05 | 5.70E+05 | 4.97E+05 |
| Dwelling 2 | | | | | | | |
| AP | kg $SO_2$ eq. | 1.61E+02 | 1.15E+02 | 1.27E+02 | 9.01E+01 | 6.26E+01 | 4.42E+01 |
| EP | kg $PO_4^{3-}$ eq. | 1.83E+01 | 9.56E+00 | 1.47E+01 | 7.58E+00 | 7.49E+00 | 3.95E+00 |
| GWP | kg $CO_2$ eq. | 3.72E+04 | 3.20E+04 | 2.94E+04 | 2.52E+04 | 1.44E+04 | 1.22E+04 |
| ODP | kg $CFC_{11}$ eq. | 1.65E-02 | 1.40E-02 | 1.32E-02 | 1.12E-02 | 6.41E-03 | 5.41E-03 |
| POP | kg $C_2H_4$ eq. | 1.05E+01 | 8.03E+00 | 8.33E+00 | 6.36E+00 | 4.10E+00 | 3.11E+00 |
| CED | MJ | 2.54E+06 | 2.16E+06 | 2.03E+06 | 1.73E+06 | 9.91E+05 | 8.35E+05 |

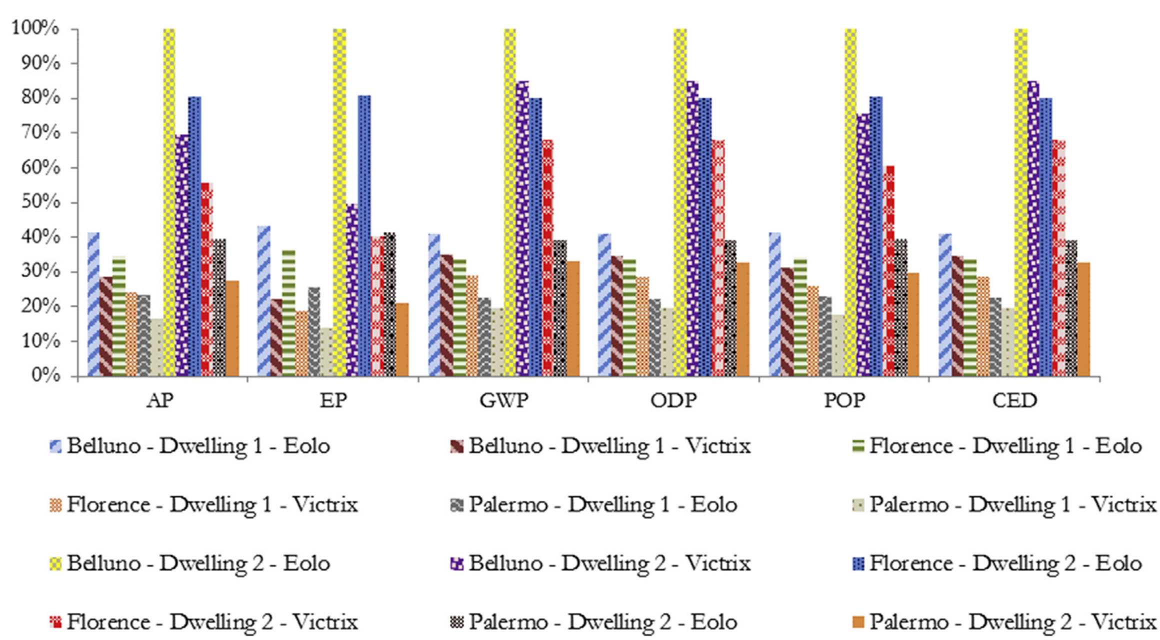


**Fig. 6.** Relative environmental impacts of the two boilers (conventional “Eolo” and condensing “Victrix”).

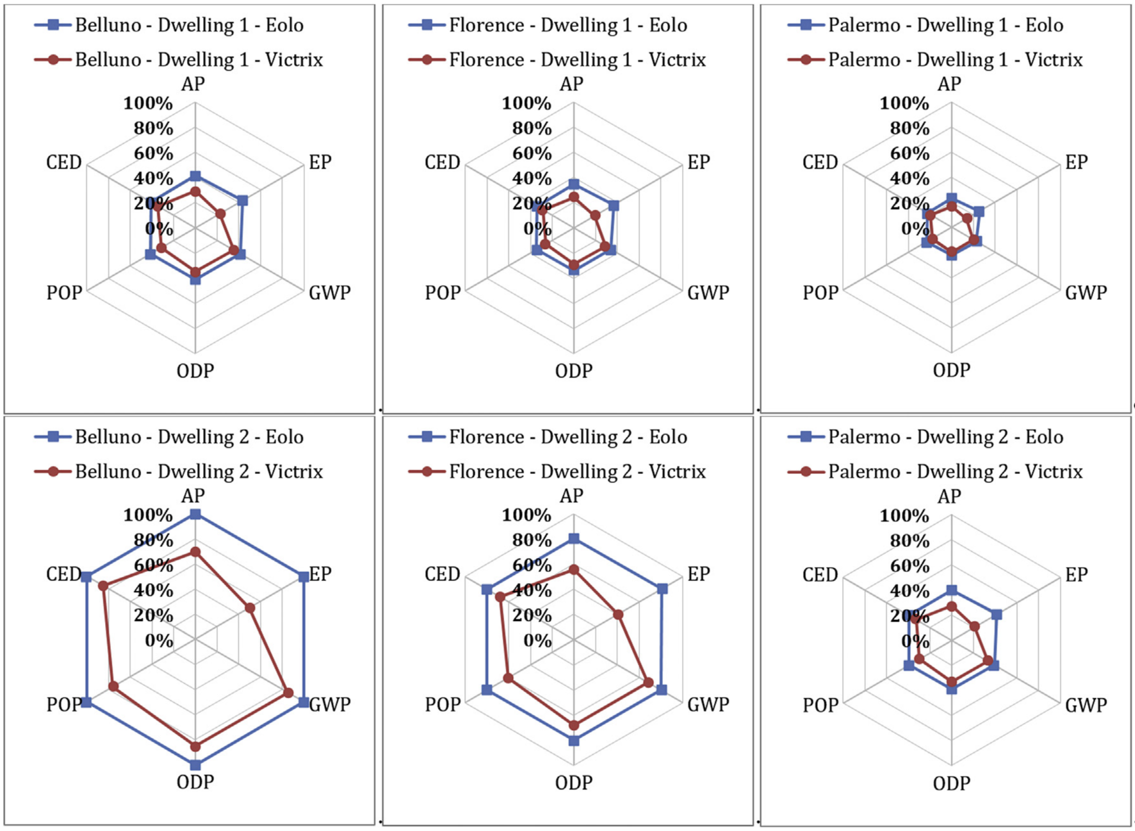


**Fig. 7.** Relative environmental impacts of the two boilers.

point level to evaluate the environmental impacts of the two boilers. Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential for time horizon 100 years (GWP100), Photochemical Ozone Creation Potential (POCP) and Stratospheric Ozone Depletion Potential (ODP) are the impact category indicators considered. Energy consumption was accounted for using the Cumulative Energy Demand (CED), a single score method published by Ecoinvent and further developed by PRé Consultants, which calculates the energy used by a system expressed in MJ (PRé Consultants, 2010).

## 5. Results and discussion

Table 7 shows the absolute environmental contributions to the various impact categories for the two boilers. Fig. 6 shows the relative impact of all scenarios (considering 100% as having the highest impact) for each impact category considered. Fig. 7 instead compares the two different boilers using a relative scale, considering the worst case scenario (Belluno-dwelling2-Eolo) as 100% impact. The results are shown considering the different geographical regions and thermal insulation of the dwellings.

The impacts of the conventional Eolo combi boiler are consistently higher than the condensing Victrix boiler for each scenario. On average, the impacts of the Victrix system are lower than those of the Eolo; by 30% on the AP, 48% on the EP, 24% on the POP and 15% on the GWP, ODP and CED. The highest percentage of impact reduction for the Victrix system compared to that of the Eolo (considering an average value between the six categories considered) occurs in Palermo and Florence for Dwelling 2 (25%); the lowest reduction occurs in Palermo for Dwelling 1 (22%). Generally, the percentage variation decreases with a transition from a geographical region with a higher thermal demand to a region with a lower temperature demand in the case of dwelling 1, while the opposite trend occurs in the case of dwelling 2. This can be explained by analysing the natural gas consumption calculated with the TERMUS software shown in Table 4, which follows the same trend. Natural gas consumption is the main source of impacts. With the aim of obtaining the GWP impact for 1 GJ of energy

**Table 8**
Environmental impacts of the two boilers for 1 MJ of energy produced.

| | Dwelling 1 | | | | | | Dwelling 2 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Belluno | | Florence | | Palermo | | Belluno | | Florence | | Palermo | |
| | Eolo | Victrix | Eolo | Victrix | Eolo | Victrix | Eolo | Victrix | Eolo | Victrix | Eolo | Victrix |
| kg $SO_2$ eq | 9.40E-05 | 6.94E-05 | 9.12E-05 | 6.66E-05 | 8.78E-05 | 6.50E-05 | 8.93E-05 | 6.38E-05 | 8.80E-05 | 6.24E-05 | 8.60E-05 | 6.08E-05 |
| kg $PO_4$— eq | 1.10E-05 | 6.17E-06 | 1.09E-05 | 6.04E-06 | 1.09E-05 | 6.22E-06 | 1.02E-05 | 5.32E-06 | 1.02E-05 | 5.25E-06 | 1.03E-05 | 5.43E-06 |
| kg $CO_2$ eq | 2.13E-02 | 1.85E-02 | 2.07E-02 | 1.80E-02 | 1.98E-02 | 1.75E-02 | 2.07E-02 | 1.78E-02 | 2.04E-02 | 1.75E-02 | 1.98E-02 | 1.68E-02 |
| kg CFC-11 eq | 8.91E-09 | 7.56E-09 | 8.87E-09 | 7.56E-09 | 8.61E-09 | 7.51E-09 | 9.17E-09 | 7.82E-09 | 9.13E-09 | 7.77E-09 | 8.82E-09 | 7.44E-09 |
| kg $C_2H_4$ eq | 5.94E-06 | 4.62E-06 | 5.84E-06 | 4.53E-06 | 5.66E-06 | 4.47E-06 | 5.83E-06 | 4.47E-06 | 5.78E-06 | 4.41E-06 | 5.63E-06 | 4.27E-06 |
| MJ | 1.36E+00 | 1.15E+00 | 1.36E+00 | 1.16E+00 | 1.33E+00 | 1.16E+00 | 1.41E+00 | 1.20E+00 | 1.41E+00 | 1.20E+00 | 1.36E+00 | 1.15E+00 |

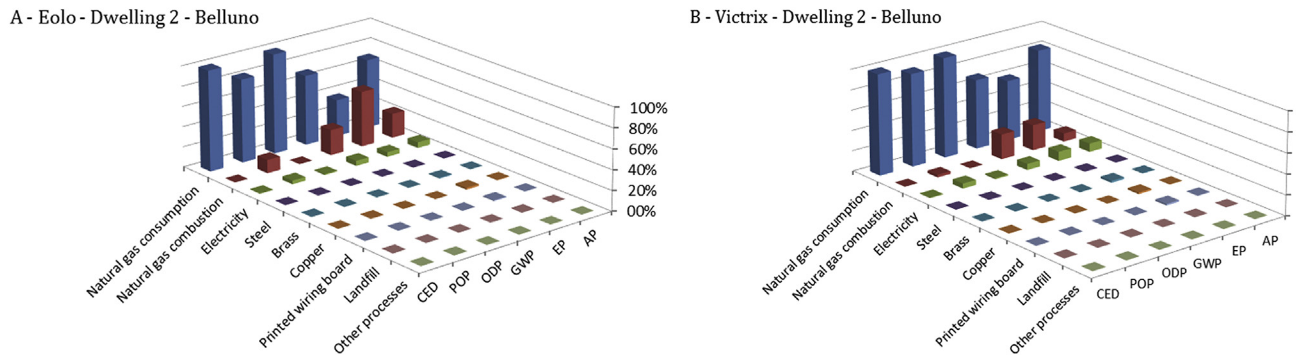


**Fig. 8.** Percentage contributions of all the life cycle inputs in the case of maximum consumption (Belluno; thermal insulation of dwelling 2).

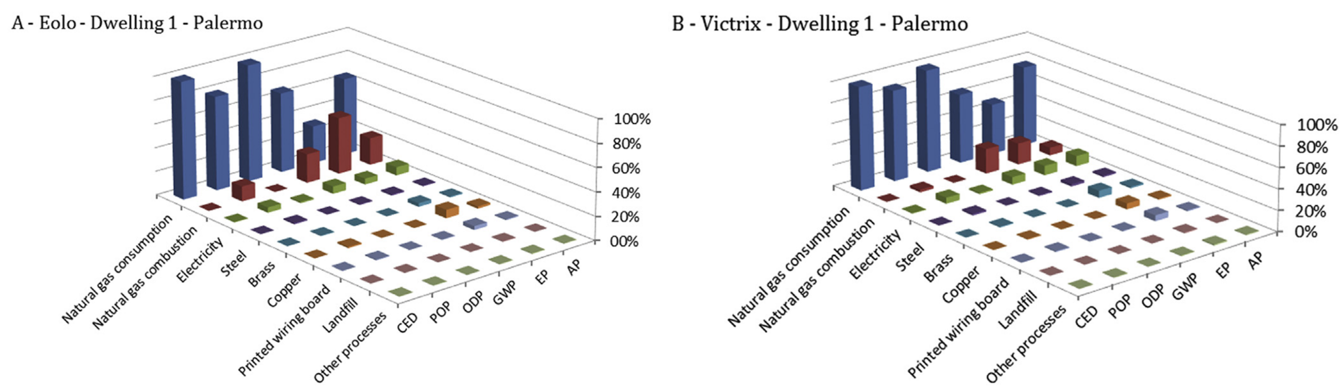


**Fig. 9.** Percentage contribution of all the life cycle inputs for the case of minimum consumption (Palermo; thermal insulation of dwelling 1).

produced, considering the case of dwelling 1 in Palermo, we calculated (using the EPI index previously indicated) 2079.162 MJ/ $m^2$ in 15 years and 28,0686.870 MJ produced for domestic heating. Adding the energy value required for the hot water production of 40,500 MJ (which we assumed to be the same for all the dwellings and locations) and the electrical consumption in Table 6 for 15 years, we obtained a global energy requirement of 321,186.87 MJ. The GWP associated with this energy requirement is 8520 kg $CO_{2eq}$ for conventional boilers and 7530 kg $CO_{2eq}$ for condensing boilers. Based on these values, we obtained an impact of 0.0265 kg $CO_{2eq}$ for conventional boilers and 0.023 kg $CO_{2eq}$ for condensing boilers analysed for 1 MJ of energy produced. Using the same criteria,

**Table 9**
Environmental impacts of the upstream and downstream processes for the Eolo boiler.

| | GWP | ODP | POP | AP | EP | CED |
|---|---|---|---|---|---|---|
| Unit | kg $CO_2$ eq | kg CFC-11 eq | kg $C_2H_4$ eq | kg $SO_2$ eq | kg $PO_4^-$ eq | MJ eq |
| Total | **131.50** | **1.26E-05** | **0.1700** | **1.3826** | **1.7935** | **2103.03** |
| Steel | 42.39 | 2.18E-06 | 0.0396 | 0.1445 | 0.0975 | 642.21 |
| Copper | 9.544 | 7.97E-07 | 0.0444 | 0.6012 | 0.8338 | 146.01 |
| Brass | 7.078 | 5.16E-07 | 0.0216 | 0.2788 | 0.3558 | 106.18 |
| Connectors | 1.969 | 1.45E-07 | 0.0035 | 0.0224 | 0.0248 | 40.27 |
| Packaging | 3.959 | 5.23E-07 | 0.0025 | 0.0120 | 0.0081 | 62.42 |
| ABS | 3.956 | 2.24E-08 | 0.0051 | 0.0103 | 0.0018 | 90.08 |
| Pallet | 0.254 | 1.90E-08 | 0.0009 | 0.0010 | 0.0005 | 5.93 |
| Cardboard paper foil | 0.291 | 2.61E-08 | 0.0002 | 0.0013 | 0.0009 | 5.79 |
| Printed wiring board | 38.18 | 4.93E-06 | 0.0368 | 0.2390 | 0.4282 | 617.08 |
| Nylon 66 | 0.333 | 6.29E-11 | 0.0002 | 0.0011 | 0.0003 | 5.71 |
| Aluminium | 0.722 | 3.57E-08 | 0.0003 | 0.0020 | 0.0010 | 7.25 |
| Silicone | 0.108 | 1.11E-08 | 0.0001 | 0.0004 | 0.0001 | 2.21 |
| PVC | 0.004 | 6.24E-12 | 0.0000 | 0.0000 | 0.0000 | 0.12 |
| Transport out | 0.861 | 1.26E-07 | 0.0011 | 0.0032 | 0.0009 | 14.73 |
| Shipping to | 2.396 | 3.49E-07 | 0.0031 | 0.0090 | 0.0026 | 41.00 |
| Electricity | 10.60 | 1.22E-06 | 0.0050 | 0.0460 | 0.0127 | 163.21 |
| Electricity end of life treatment | 0.385 | 1.22E-07 | 0.0005 | 0.0016 | 0.0012 | 6.17 |
| Gas | 1.378 | 1.57E-06 | 0.0032 | 0.0050 | 0.0005 | 134.74 |
| Water | 0.026 | 1.41E-09 | 0.0000 | 0.0001 | 0.0001 | 0.46 |
| Landfill for metals | 0.461 | 4.73E-09 | 0.0003 | 0.0015 | 0.0129 | 5.04 |
| Landfill for plastics | 0.069 | 1.39E-09 | 0.0000 | 0.0002 | 0.0005 | 1.11 |
| Landfill for wood and paper | 6.537 | 6.64E-09 | 0.0016 | 0.0020 | 0.0092 | 5.30 |

Table 8 shows the values for each dwelling and location for each impact category.

Figs. 8 and 9 present the percentage contribution of the various inputs and outputs of the boiler life cycle for the two extreme cases:

1. The case of maximum consumption, which occurs in the coldest region (Belluno), considering the worst insulation system (dwelling 2);
2. The case of minimum consumption represented by the warmer region (Palermo), considering the best insulation system (dwelling 1).

In all the cases, natural gas consumption and combustion are the main causes of impact in all the categories considered.

In the case of maximum consumption, the contribution of natural gas is higher than 85% in all the categories, reaching about 99% in ODP and CED as shown in Fig. 8. The natural gas contribution considers both the impact associated with natural gas production (consumption) and the impact associated with its combustion (shown in two separate columns in Fig. 8). The input with the second highest impact is the consumption of electricity, which contributes 4–6% to the AP, EP, GWP and POP in the traditional combi boiler and 6–10% to the AP, EP, GWP and POP in the condensing boiler. In both cases, its contribution is lower than 1% in the ODP and CED.

Even in the case of minimum consumption (Fig. 9), gas energy

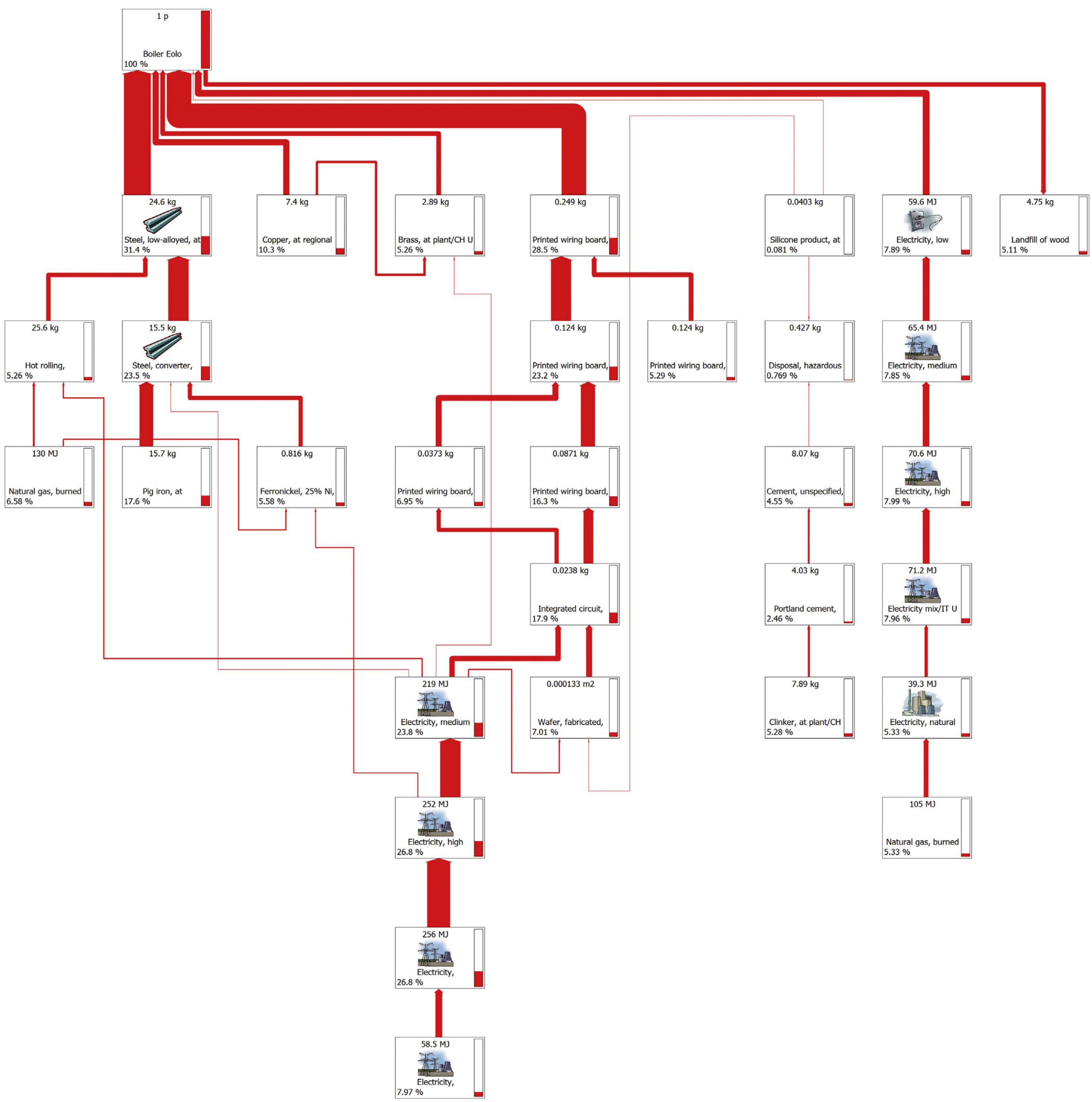


**Fig. 10.** Impact tree of the upstream and downstream processes for the Eolo boiler.

**Table 10**
Environmental impacts of the upstream and downstream processes for the Victrix boiler.

| | GWP | ODP | POP | AP | EP | CED |
|---|---|---|---|---|---|---|
| Unit | kg $CO_2$ eq | kg CFC-11 eq | kg $C_2H_4$ eq | kg $SO_2$ eq | kg $PO_4^-$ eq | MJ eq |
| Total | **157.12** | **1.41E-05** | **0.1731** | **1.2778** | **1.4706** | **2549.43** |
| Steel | 35.04 | 1.80E-06 | 0.0327 | 0.1194 | 0.0806 | 530.78 |
| Stainless steel | 30.011 | 1.73E-06 | 0.0197 | 0.1376 | 0.0596 | 422.91 |
| Brass | 9.102 | 6.64E-07 | 0.0277 | 0.3585 | 0.4576 | 136.53 |
| Copper | 4.318 | 3.61E-07 | 0.0201 | 0.2720 | 0.3773 | 66.07 |
| Aluminum | 11.009 | 5.44E-07 | 0.0042 | 0.0298 | 0.0148 | 110.48 |
| Cardboard packaging | 1.984 | 2.62E-07 | 0.0013 | 0.0060 | 0.0040 | 31.28 |
| ABS | 5.086 | 2.88E-08 | 0.0066 | 0.0133 | 0.0024 | 115.79 |
| Polystyrene packaging | 3.347 | 1.60E-07 | 0.0059 | 0.0095 | 0.0011 | 89.92 |
| Cardboard paper foil | 0.30 | 2.68E-08 | 0.0002 | 0.0014 | 0.0009 | 5.94 |
| Printed wiring board | 38.181 | 4.93E-06 | 0.0368 | 0.2390 | 0.4282 | 617.08 |
| Connectors | 1.969 | 1.45E-07 | 0.0035 | 0.0224 | 0.0248 | 40.27 |
| Silicone | 0.309 | 3.18E-08 | 0.0002 | 0.0010 | 0.0003 | 6.36 |
| Pallet | 0.235 | 1.76E-08 | 0.0009 | 0.0010 | 0.0004 | 5.49 |
| Nylon 66 | 0.578 | 1.09E-10 | 0.0004 | 0.0019 | 0.0006 | 9.92 |
| PVC | 0.010 | 1.56E-11 | 0.0000 | 0.0000 | 0.0000 | 0.30 |
| Glass fiber | 0.02 | 2.82E-09 | 0.0000 | 0.0001 | 0.0000 | 0.40 |
| Transportation out | 0.861 | 1.26E-07 | 0.0011 | 0.0032 | 0.0009 | 14.73 |
| Transport | 2.396 | 3.49E-07 | 0.0031 | 0.0090 | 0.0026 | 41.00 |
| Electricity | 10.596 | 1.22E-06 | 0.0050 | 0.0460 | 0.0127 | 163.21 |
| Electricity end of life treatment | 0.385 | 1.22E-07 | 0.0005 | 0.0016 | 0.0012 | 6.17 |
| Gas | 1.378 | 1.57E-06 | 0.0032 | 0.0050 | 0.0005 | 134.74 |
| Water | 0.026 | 1.41E-09 | 0.0000 | 0.0001 | 0.0001 | 0.46 |
| Landfill for metals | 0.49 | 5.08E-09 | 0.0003 | 0.0016 | 0.0139 | 5.41 |
| Landfill for plastics | 0.165 | 3.32E-09 | 0.0001 | 0.0005 | 0.0011 | 2.65 |
| Landfill for wood and paper | 3.563 | 3.62E-09 | 0.0008 | 0.0011 | 0.0050 | 2.89 |

(considering both production and combustion) is the main source of impacts causing over than 70% of the total burden in all the impact categories and is over 98% in ODP and CED. In this case, the percentage contribution of electricity is slightly higher than the previous case, reaching 4–7% in AP, EP, GWP and POP in the traditional combi boiler and 5–9% in AP, EP, GWP and POP in condensing boiler. The contribution remains lower than 1% in ODP and CED.

The impacts of all the other phases appear to be almost negligible in respect of the use phase, apart from the impacts generated by some raw materials. In particular, the production phase of copper is 7% in EP in the case of the Eolo, considering the dwelling with the lowest primary energy consumption and Palermo as the geographical context, while its impact is about 2% in the case of Victrix, which contains less copper, considering the dwelling with the highest primary energy consumption and Belluno as the geographical context. The boiler's electricity consumption contributes to 1–2% of the impacts on AP, EP and GWP, and less than 1% in the remaining impact categories.

From an analysis of the upstream and downstream processes alone (manufacturing activities, raw materials used to manufacture the two boiler systems and their landfill disposal), it is evident that the differences between the impacts generated by the two systems may be significant, but they are overwhelmed by those generated during the core process considered (15 years).

As far as the Eolo boiler upstream and downstream processes are concerned, the following impacts are generated (Table 9).

As far as the results shown in Table 9 are concerned, the following considerations can be made:

- steel, copper and brass were found to be extremely high-impact materials because of the machining processes of metals, characterized by high energy consumption;
- the printed wiring board (electronic board) is a critical component as it consists of high-impact elements;
- the consumption of gas and electricity in manufacturing activities generates impacts for ODP, GWP and CED.

Fig. 10 below also illustrates the impact tree diagram for the conventional Eolo Boiler for GWP (cut at 5% detail so as not to provide an overly complex picture). As demonstrated by this picture, the finished steel represents a contribution of 31.4% to the GWP for the manufacturing phase of Eolo boiler, followed by the production of the printed wiring board, which contributes 28.5%. Other materials, such as copper (10.3%), or the use of electricity (7.89%) in manufacturing generate a lower impact. The downstream phase has a low impact on the GWP, as well as on the other phases.

As far as the Victrix system is concerned, the following impacts are generated (Table 10).

Again, the highest-impact components are steel (low alloy and stainless), copper, brass, electronic cards, gas and electricity consumption. The substantial differences in the Eolo Maior model are the addition of stainless steel (used for the condensing module) and the packaging, which has an inner polystyrene shell instead of cardboard.

As shown in the following impact tree for GWP 100 (Fig. 11, cut at 5% detail so as not to provide an overly complex picture), which only relates to the upstream and downstream processes, steel, stainless steel and the printed wiring board are the main contributors to the impact of production and landfill.

The overall impact of the upstream and downstream processes of the condensing Victrix system is higher than that of the conventional Eolo, but considering the core process for all the dwelling and location configurations considered, the environmental impacts of the condensing technology are lower than those of a traditional one.

The best way to improve the environmental sustainability of boilers is therefore to optimize the energy efficiency of these systems. Improved building insulation could also be an essential element in reducing the environmental impacts associated with household heating systems.

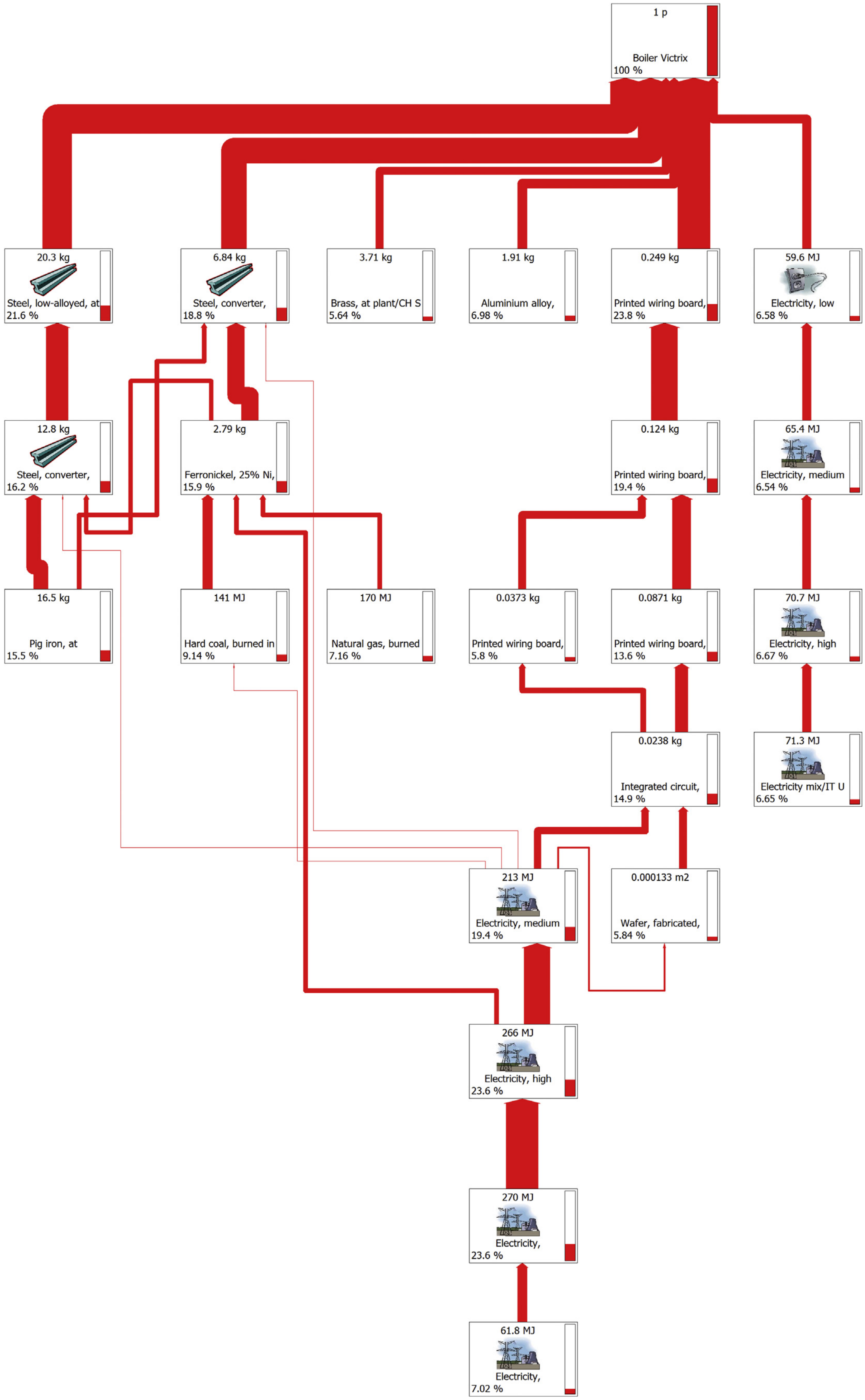


**Fig. 11.** Impact tree of the upstream and downstream processes for the Victrix boiler.

## 6. Conclusions

Two residential domestic wall-mounted boilers were compared using life cycle assessment methodology. . A traditional combi boiler was compared to a condensing system, with the aim of understanding the environmental impacts for each of their lifecycle phases. These systems were studied at three locations (Belluno, Florence and Palermo), which represent different climatic conditions, and two dwellings with different energy classes were considered.

The impact of the traditional combi boiler (Eolo) is consistently higher than that of the condensing boiler (Victrix) for each scenario, by an average of 23% in the six impact categories considered. The difference in terms of environmental impacts between the two boilers is due to two main reasons: the different amount of energy required by the two systems and the different emissions of polluting gases.

A comparison of these results with those found in the literature on the environmental assessment of domestic boilers confirms that the use phase has the highest impact (between 85% and 99% in the case of maximum consumption, and between 70% and 98% even in the case of minimum consumption for both boilers). As far as the absolute impact values are concerned, the value obtained for both the conventional and condensing boiler are slightly lower than the existing ones reported in the literature review. As shown by Table 8, for the various scenarios, a value of 16.8 g–18.5 g of $CO_{2eq}$ for 1 MJ of energy produced for condensing boilers and 19.8 g–21.3 g of $CO_{2eq}$ for 1 MJ of energy produced for conventional boilers was found, instead of 77 g of $CO_{2eq}$ for 1 MJ, which was reported for a condensing boiler in the recent study by Giuntoli et al., 2015. The values in this study are more similar to those reported for pellet boilers by the same authors (15 g of $CO_{2eq}$ for 1 MJ) but higher than those reported by Cellura et al. (2014) always for a pellet's boiler (3.84 g and 2.94 g of $CO_{2eq}$ for 1 MJ). The latter publications compared condensing boilers to new pellet boilers but did not include many details about the environmental impact calculated for the boilers using fossil fuels. In this regard, the study aims to generate detailed data about recent models of conventional and condensing boiler, in order to provide a useful comparison for the results of other authors. The detailed description of the impact generated by the different phases will also help conventional boiler manufacturers to understand where it is possible to reduce the environmental impact of their systems. Based on the reported data, the best way to improve the environmental sustainability of boilers is to optimize the energy efficiency of these systems. Improved building insulation, although not related to the companies which design these systems, could be another essential element in reducing the environmental impacts associated with household heating systems.

In the future, further evaluations could be made by comparing the economic and social aspects of fossil fuel systems with those based on renewable sources, in order to have a full comparison of the sustainability of these systems, which are one of the main contributors to the impact on the environment.

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