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

Elsevier Editorial System(tm) for Journal of Cleaner Production

Manuscript Draft

Manuscript Number: JCLEPRO-D-16-03400R2

Title: Environmental assessment of domestic boilers: a comparison of condensing and traditional technology using Life Cycle Assessment methodology

Article Type: Original article

Keywords: Life Cycle Assessment; Environmental impact; Domestic boilers; Sustainability of energy systems

Corresponding Author: Professor. Giuseppe Vignali, Ph.D

Corresponding Author's Institution: University of Parma

First Author: Giuseppe Vignali, Ph.D

Order of Authors: Giuseppe Vignali, Ph.D

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 NOx 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.

UNIVERSITÀ DEGLI STUDI DI PARMA
DIPARTIMENTO DI INGEGNERIA INDUSTRIALE
Viale delle Scienze 181/A, 43124 Parma (Italy)

The Editor-in-Chief of Journal of Cleaner Production
Prof. Jiří Jaromír Klemeš
Pázmány Péter Catholic University, Budapest, Hungary

Parma, ITALY, Friday, 04 November 2016

Dear Prof. Klemeš,

Please find enclosed an electronic copy of the revised version of the manuscript entitled:

“Environmental assessment of domestic boilers: a comparison of condensing and traditional technology using Life Cycle Assessment methodology”

Dear Editor, I have revised the article following your comments and the suggestions of all the reviewers, trying to meet all the different requests.

Please consider this article for a possible publication on a regular issue of “Journal of Cleaner Production”.

We wish to take this opportunity to send to You our best regards.

Looking forward to hearing from You soon,

Yours sincerely

Giuseppe Vignali

Giuseppe VIGNALI,
Eng, Ph.D., Associate Professor
Department of Industrial Engineering –
University of Parma, viale delle Scienze 181/A, 43124 Parma (Italy)
phone +39 0521 906061
email: giuseppe.vignali@unipr.it

Paper title: "Environmental assessment of domestic boilers: a comparison of condensing and traditional technology using Life Cycle Assessment methodology"

Ms. Ref. No.: JCLEPRO-D-16-03400R1

Comments to editors	
Editors' comments	***Our notes***
1. Dear Professor. Giuseppe Vignali, Please see the comments of the reviewers on the article you submitted to Journal of Cleaner Production. I suggest you consider these comments, suggestions and questions and revise your article accordingly. We would like to receive your revised submission within the next 60 days.	
2. The manuscript has been nearly ready to be accepted. Some small formal issues to be still addressed:	
3. Last three references - where been published? What mean UNI - not all readers are Italians. Also [20] and [21]. Ref [18] where published? Place?	I have now added the place of publication of UNI documents, which are published in Milan (Italy). I have also translated UNI into English for the benefit of non-Italian readers.
4. Would you remove http:// as recent browsers do not require them and it will make the URL reference more focused?	I have removed the prefix http://from all the parts of the text, as you suggested.
5. The hyperlinks (blue colour and underlining) should be removed from email addresses and web references.	I have removed the hyperlinks from my email address and web references.
6. This should be in the list of references: //www.immergas.com/en/home_eng (accessed on 12th October 2016	As in the case of Acca software, I have removed the footnote and put the link in the web references section.

In the hope that our amendments meet your requests, we sincerely wish to thank you for your time and attention in reviewing the paper.

Paper title: "Environmental assessment of domestic boilers: a comparison of condensing and traditional technology using Life Cycle Assessment methodology" **Ms. Ref. No.:** JCLEPRO-D-16-03400R1		
Comments to reviewer #2		
	Reviewer's comments	***Our notes***
	Dear Author, In general, the quality of this manuscript was improved greatly with most of the comments addressed. My suggestion for this manuscript is to publish after minor revision (especially for the conclusion). Below are the suggestions:	
1.	Suggest to delete " taking the whole life cycle into consideration" as life cycle has been mentioned in the earlier line. Suggest to remove "All transportation involved in the entire supply chain of the two products was considered" from the abstract.	According to your suggestion, I have removed these two sentences from the abstract.
2.	Please revise the structure of the first sentences (pg 3, line 6-8). Suggest to remove "although" and break down into two sentences.	I have divided this sentence in two short ones, as you suggested
3.	Pg 4, line 6-10. Suggest to mention "Section 2" instead of "below". Delete "ones"	I changed the description of "section below" with "Section 2" as suggested and I removed "ones", rewording the sentence.
4.	Mixtures of America and British English are not allowed. Eg. NormaliZed, analySed, optimiZed	I changed all the terms written in American English to British English. In particular the term "normalized" has been changed in "normalised".
5.	Please proofread the Section 2. There are few typos on the usage of ",". This section provides the informative background of the study, however, a better presentation is needed. Suggest to synthesize the findings rather than just rehashing.	Thank you for your suggestion to improve the use of comma. Some of them are placed in wrong position especially in section 2. I have corrected them to make this section clearer. Honestly, I do not understand what you mean by synthesize the findings rather than just rehashing. I have tried to summarise the main findings resulting from a literature review, explaining in particular the results relating to traditional and condensing boilers.
6.	CONCLUSION: Suggest to delete the 1st and 2nd sentences. Please focus on underscore the scientific value of your paper, and/or the APPLICABILITY of your findings/results instead of summarizing. The current conclusion looks like results & discussion section (eg. this value is in agreement with previous	I have partially revised the conclusions following your suggestion to focus more on the applicability of results/findings instead of summarising them. Some parts are not removed but synthetized, to give more space to discussions. For example, I have removed the sentence "this value is in agreement with previous

	studies by Cellura AL. (2014) and Giuntoli et al. (2015)……………)	studies by Cellura AL. (2014) and Giuntoli et al. (2015)” and added also possible future researches.
7.	In the scientific research paper, we prefer if you use the third person singular, instead of the first person singular or plural (e.g. avoid using 'we', "author" in the manuscript).	I have deleted the use of “we” and “author” in the text, putting all the sentences in impersonal form.
8.	The use of lump/multiple references are not encourage unless a short definition is given to justify the use of each reference.	I have tried to limit at maximum citations to multiple references, using more than one only when associated with an old reference there is a new one, which update some concepts and data. I hope you agree with use of the citations in the text.

In the hope that our amendments meet your requests, we sincerely wish to thank you for your time and attention in reviewing the paper.

Paper title: "Environmental assessment of domestic boilers: a comparison of condensing and traditional technology using Life Cycle Assessment methodology" **Ms. Ref. No.:** JCLEPRO-D-16-03400R1	
Comments to reviewer #3	
Reviewer's comments	***Our notes***
This manuscript is in excellent form. There are only a few typographical errors that need to be addressed and then it will be ready for publishing.	Thank you for your suggestions. I revised also the manuscript according to those of reviewer #2.
1. Page 20. 1st line. Should be "Figures".	Thank you for your suggestion. I have inserted the plural form in this sentence.
2. Figure 4. The first item in the legend should be "Over 3000 Dd".	I have changed the legend of Figure 4 according to your suggestion.
3. Figure 8b. The top input is misspelled. Should be "...consumption"	Thank you for the suggestion, I have changed the word in consumption.
4. Figure 9b. The top input is misspelled. Should be "...consumption"	Thank you for the suggestion, I have changed the word in consumption

In the hope that our amendments meet your requests, we sincerely wish to thank you for your time and attention in reviewing the paper.

Highlights

- A life cycle assessment of two different domestic natural gas boilers has been carried out.
- The assessment used the CML and CED methods, by considering the EPD certification systems. categories
- The condensing boiler technology has a lower environmental impact than the traditional one in all the impact categories.
- The study shows that the use phase is the biggest contributor to the environmental impact.

Environmental assessment of domestic boilers: a comparison of condensing and traditional technology using Life Cycle Assessment methodology

Giuseppe Vignali[1]*

**Department of Industrial Engineering, University of Parma, Viale delle Scienze 181/A, 43124, Parma – Italy (giuseppe.vignali@unipr.it)*

[1] Corresponding author, e-mail: giuseppe.vignali@unipr.it, tel.: +390521906061

Environmental assessment of domestic boilers: a comparison of condensing and traditional technology using Life Cycle Assessment methodology

Giuseppe Vignali*

**Department of Industrial Engineering, University of Parma, Viale delle Scienze 181/A, 43124, Parma – Italy (giuseppe.vignali@unipr.it)*

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.

Keywords: Life Cycle Assessment; Environmental impact; Domestic boilers; Sustainability of energy systems

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., 2016). 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 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. Gajewsky 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.[2] 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.

Here Figure 1

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

2

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.

Here Figure 2

Figure 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.

Here Table 1

----

4 Life cycle assessment

LCA is considered by the European Commission to be the best 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, 2013). 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 (International EPD System, 2010) and Product Category Rules (PCR) regarding central heating boilers and water heaters (PCR, 2001).

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 Figure 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.

Here Figure 3

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.

Here Table 2

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. Figure 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.

Here Figure 4

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

Here Figure 5

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

Based on the same layout of the standard dwelling reported in Figure 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, 1,821 for zone D and 3,043 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.

Here Table 3

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 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[3] (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:

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

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.

Here 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) .

---

[3]

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 %.

Here Table 5

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.

Here Table 6

Euro 4 16-32 t lorries were considered to evaluate the boiler transportation to customers, assuming an average customer 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-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. Figure 6 shows the relative impact of all scenarios (considering 100 % as having the highest impact) for each impact category considered. Figure 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.

Here Table 7

Here Figure 6

Here Figure 7

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 produced, considering the case of dwelling 1 in Palermo, we calculated (using the EPI index previously indicated) 2,079.162 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 8,520 kg CO_{2eq} for conventional boilers and 7,530 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, the Table 8 shows the values for each dwelling and location for each impact category.

Here Table 8

Figures 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 Figure 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 Figure 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.

Here Figure 8a and 8b

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

Here Figure 9a and 9b

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).

Here 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 and GWP NRADP.

Figure 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.

Here Figure 10

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

Here 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 (Figure 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.

Here Figure 11

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.

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 to 18.5 g of CO_{2eq} for 1 MJ of energy produced for condensing boilers and 19.8 g to 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 (15g 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 2.94g 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.

References

[1] Al-Ghandoor, A., Jaber, J.O., Al-Hinti, I., Mansour, I.M. 2009. Residential past and future energy consumption: Potential savings and environmental impact. Renewable and Sustainable Energy Reviews, 13 (6-7), 1262-1274

[2] Andrić I., Pina A., Ferrão P., Lacarrière B., Le Corre O., 2016. On the performance of district heating systems in urban environment: an emergy approach, Journal of Cleaner Production, dx.doi.org/10.1016/j.jclepro.2016.05.124.

[3] Bertoldi P., Hirl B., Labanca N., 2012. Energy Efficiency Status Report 2012, European Commission DG Joint Research Centre.

[4] Blom I., Itard L., Meijer A., 2010. LCA-based environmental assessment of the use and maintenance of heating and ventilation systems in Dutch dwellings, Building and Environment, 45 (11), 2362-2372

[5] Bribián I. Z., Usón A. A., Scarpellini S., 2009. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification, Building and Environment, 44 (12), 2510-2520

[6] Cellura M., La Rocca V., Longo S., Mistretta M., 2014. Energy and environmental impacts of energy related products (ErP): a case study of biomass-fuelled systems, Journal of Cleaner Production, 85, 359-370.

[7] Cherubini F., Strømman A. H., Ulgiati S., 2011. Influence of allocation methods on the environmental performance of biorefinery products—A case study, Resources, Conservation and Recycling, 55 (11), 1070-1077.

[8] Chiesa M., Monteleone B., Venuta M.L., Maffeis G., Greco S., Cherubini A., Schmidl C., Finco A., Gerosa G., Ballarin Denti A., 2016. Integrated study through LCA, ELCC analysis and air quality modelling related to the adoption of high efficiency small scale pellet boilers, Biomass and Bioenergy, 90, 262-272.

[9] De Rosa M., Bianco V., Scarpa F., Tagliafico L.A., 2015. Historical trends and current state of heating and cooling degree days in Italy, Energy Conversion and Management, 90 (15), 323-335

[10] DPR no. 412, 1993. Decree of the President of the Italian Republic no. 412, 26/08/93 and subsequent modifications. Published on Gazzetta Ufficiale 14 ottobre 1993, n. 242, S.O. Italy.

[11] European Commission, 2003. Communication from the Commission to the Council and the European Parliament - Integrated Product Policy - Building on Environmental Life-Cycle Thinking Context. EC-JRC, Luxembourg.

[12] European Commission, 2010. EU-Directive 2010/31/EC of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Strasbourg (France).

[13] European Commission, 2013. Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. 2013/179/EU. Annexes II and III: Product Environmental Footprint (PEF) Guide and Organisation Environmental Footprint (OEF) Guide.

[14] European Commission, Joint Research Centre, Institute for Energy and Transport, 2012a. Heat and cooling demand and market perspective. Luxembourg.

[15] European Commission, Joint Research Centre, Institute for Energy and Transport, 2012b. Best available technologies for the heat and cooling market in the European Union, Luxembourg.

[16] Gajewski A., Siergiejuk J., Szulborski K., 2013. Carbon dioxide emission while heating in selected European countries, Energy and Buildings 65, 197–204.

[17] Giuntoli J., Caserini S., Marelli L., Baxter D., Agostini A., 2015. Domestic heating from forest logging residues: environmental risks and benefits, Journal of Cleaner Production, 99, 206-216.

[18] Guinée J.B., 2001. Life Cycle Assessment: an Operational Guide to the ISO Standards, Ministry of Housing, Spatial Planning and Environment (VROM) and Centre of Environmental Science (CML), The Netherlands, 2001.

[19] Ibrahim, O., Fardoun, F., Younes, R., Louahlia-Gualous, H. 2014. Review of water-heating systems: General selection approach based on energy and environmental aspects, Building and Environment, 72, 259-286.

[20] ISO, 2006a. Environmental Management—Life cycle assessment—Principles and Framework, ISO 14040:2006(E), International Organization for Standardisation, 2006.

[21] ISO, 2006b. Environmental management—Life cycle assessment, in: Requirements and Guidelines, ISO 14044:2006(E), International Organization for Standardisation, 2006.

[22] Koroneos C.J., Nanaki E.A., 2012. Life cycle environmental impact assessment of a solar water heater, Journal of Cleaner Production 37, 154-161.

[23] Lamnatou C., Notton G., Chemisana D., Cristofari C., 2015. The environmental performance of a building-integrated solar thermal collector, based on multiple approaches and life-cycle impact assessment methodologies, Building and Environment, 87, 45-58.

[24] Laschi A., Marchi E., González-García S., 2016. Environmental performance of wood pellets' production through life cycle analysis, Energy, 103, 469-480.

[25] Lazzarini R. M., 2014. The importance of the modulation ratio in the boilers installed in refurbished buildings. Energy and Buildings, 75, 43-50

[26] Li D.Z., Chen H.X., Hui E.C.M., Zhang J.B., Li Q.M., 2013. A methodology for estimating the life-cycle carbon efficiency of a residential building, Building and Environment, 59, 448-455

[27] Monteleone B., Chiesa M., Marzuoli R., Verma V.K., Schwarz M., Carlon E., Schmidl C., Ballarin Denti A., 2015. Life cycle analysis of small scale pellet boilers characterized by high efficiency and low emissions, Applied Energy, 155, 160-170

[28] Nemry F., Uihlein A., Makishi Colodel C., Wetzel C., Braune A., Wittstock B., Hasan I., Kreißig J., Gallon N., Niemeier S., Frech Y., 2010. Options to reduce the environmental impacts

of residential buildings in the European Union—Potential and costs, Energy and Buildings, 42, (7), 976-984

[29] Ochoa L., Ries R., Matthews H.S., Hendrickson C., 2005. Life cycle assessment of residential buildings, in: American Society of Civil Engineers Construction Research Congress, San Diego, CA, April, 2005.

[30] PCR, 2011. Product Category Rules (PCR) for central heating boilers and water heaters. Version 1, 02/02/2011.

[31] PRé Consultants, 2010. SimaPro 7, Database Manual. Available at: www.pre-sustainability.com/download/manuals/DatabaseManualEU-DKIODatabase.pdf. (accessed on 14th October 2016).

[32] Rosa L., Tosato R., 1990. Experimental evaluation of seasonal efficiency of condensing boilers, Energy and Buildings, 14 (3), 237-241

[33] Shah V.P., Debella D.C, Ries R.R., 2008. Life cycle assessment of residential heating and cooling systems in four regions in the United States. Energy and Buildings 40, 503–513.

[34] Strazza C., Del Borghi A., Gallo M., Del Borghi M., 2011. Resource productivity enhancement as a means for promoting cleaner production: analysis of coincineration in cement plants through a life cycle approach. Journal of Cleaner Production 19, 1615-1621.

[35] Šulga, M. 2011. Life Cycle Assessment (LCA) Based Environmental Impact Minimization of Solid Fuel Boilers in Lithuanian Industry. Environmental Research, Engineering and Management 4 (58), 74-84.

[36] Swiss Centre for Life Cycle Inventories, 2010. Ecoinvent Data, Dübendorf, Switzerland.

[37] Tukker A., Huppes G., Guinée J.B., Heijungs R., Koning A., Oers L., Suh S., Geerken T., Holderbeke M., Jansen B., Nielsen P., 2006. Environmental Impacts of Products (EIPRO), European Commission, Luxembourg.

[38] UNI EN ISO, 2008. UNI EN ISO 13790:2008, Energy performance of buildings—Calculation of energy use for heating and cooling, Milan (Italy).

[39] UNI, 2014a. UNI/TS 11300-1:2014, Energy performance of buildings - Part 1: Determination of the thermal energy demand of the building for summer and winter conditioning (In Italian: Prestazioni energetiche degli edifici – Parte 1: Determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione estiva e invernale), Milan (Italy).

[40] UNI, 2014b. UNI/TS 11300-2: 2014, Energy performance of buildings - Part 2: Determination of primary energy demand and yields for winter heating and for the production of domestic hot water "(In Italian: Prestazioni energetiche degli edifici – Parte 1: Determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione estiva e invernale), Milan (Italy).

[41] UNI, 2016. UNI 10349, Heating and cooling of buildings. Climatic data (In Italian: Riscaldamento e raffrescamento degli edifici. Dati climatici), Milan (Italy).

Web references:

Immergas company. Information available at the company website: www.immergas.com/en/home_eng (accessed on 12th October 2016

Acca Software Company. Information available at the company website: www.acca.it (accessed on 12th October 2016)

Tables and table captions

TABLE 1

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

Table 1: Technical data of the two boilers.

TABLE 2

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

Table 2: Inventory data for components and packaging.

TABLE 3

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

Table 3: average monthly temperatures in different climate zones.

TABLE 4

	City		
EPI	Palermo	Florence	Belluno
Dwelling 1 *[kWh/m²year]*	38.503	65.788	83.734
Dwelling 2 *[kWh/m²year]*	79.662	177.654	226.127

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

TABLE 5

Dwelling 1	Demand for heating [Nm³/year]			Demand for domestic hot water [Nm³/year]		
Region	Belluno	Florence	Palermo	Belluno	Florence	Palermo
Eolo	1,367	1,074	623	306	307	291
Victrix	1,146	902	535	268	271	260
% variation	16.2 %	16.0 %	14.1 %	12.6 %	11.9 %	10.7 %

Dwelling 2	Demand for heating [Nm³/year]			Demand for domestic hot water [Nm³/year]		
Region	Belluno	Florence	Palermo	Belluno	Florence	Palermo
Eolo	3,786	2,973	1,304	306	307	291
Victrix	3,213	2,515	1,086	269	272	257
% variation	15.1 %	15.34 %	16.7 %	12.0 %	11.5 %	11.5 %

Table 5: natural gas consumption of the two boilers.

TABLE 6

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

Table 6: electricity consumption of the two boilers.

TABLE 7

		Dwelling 1					
		Belluno		Florence		Palermo	
		Conventional b.	Condensing b.	Conventional b	Condensing b	Conventional b	Condensing b
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					
		Belluno		Florence		Palermo	
		Conventional b	Condensing b	Conventional b	Condensing b	Conventional b	Condensing b
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

Table 7: Absolute environmental impacts of the two boilers.

TABLE 8

	Dwelling 1						Dwelling 2					
	Belluno		Florence		Palermo		Belluno		Florence		Palermo	
	Eolo	Victrix	Eolo	Victrix	Eolo	Victrix	Eolo	Victrix	Eolo	Victrix	Eolo	Victrix
kg SO2 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 PO4--- 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 CO2 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 C2H4 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

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

TABLE 9

	GWP 100	ODP 100	POCP	AP	EP	NRADP
Unit	kg CO2 eq	kg CFC-11 eq	kg C2H4 eq	kg SO2 eq	kg PO4--- eq	MJ eq
Total	**131.50**	**1.26E-05**	**0.1700**	**1.3826**	**1.7935**	**2,103.03**
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 9: Environmental impacts of the upstream and downstream processes for the Eolo boiler.

	GWP 100	ODP 100	POCP	AP	EP	NRADP
Unit	kg CO2 eq	kg CFC-11 eq	kg C2H4 eq	kg SO2 eq	kg $PO4^{---}$ eq	MJ eq
Total	**157.12**	**1.41E-05**	**0.1731**	**1.2778**	**1.4706**	**2,549.43**
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

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

Figure 1

Click here to download high resolution image

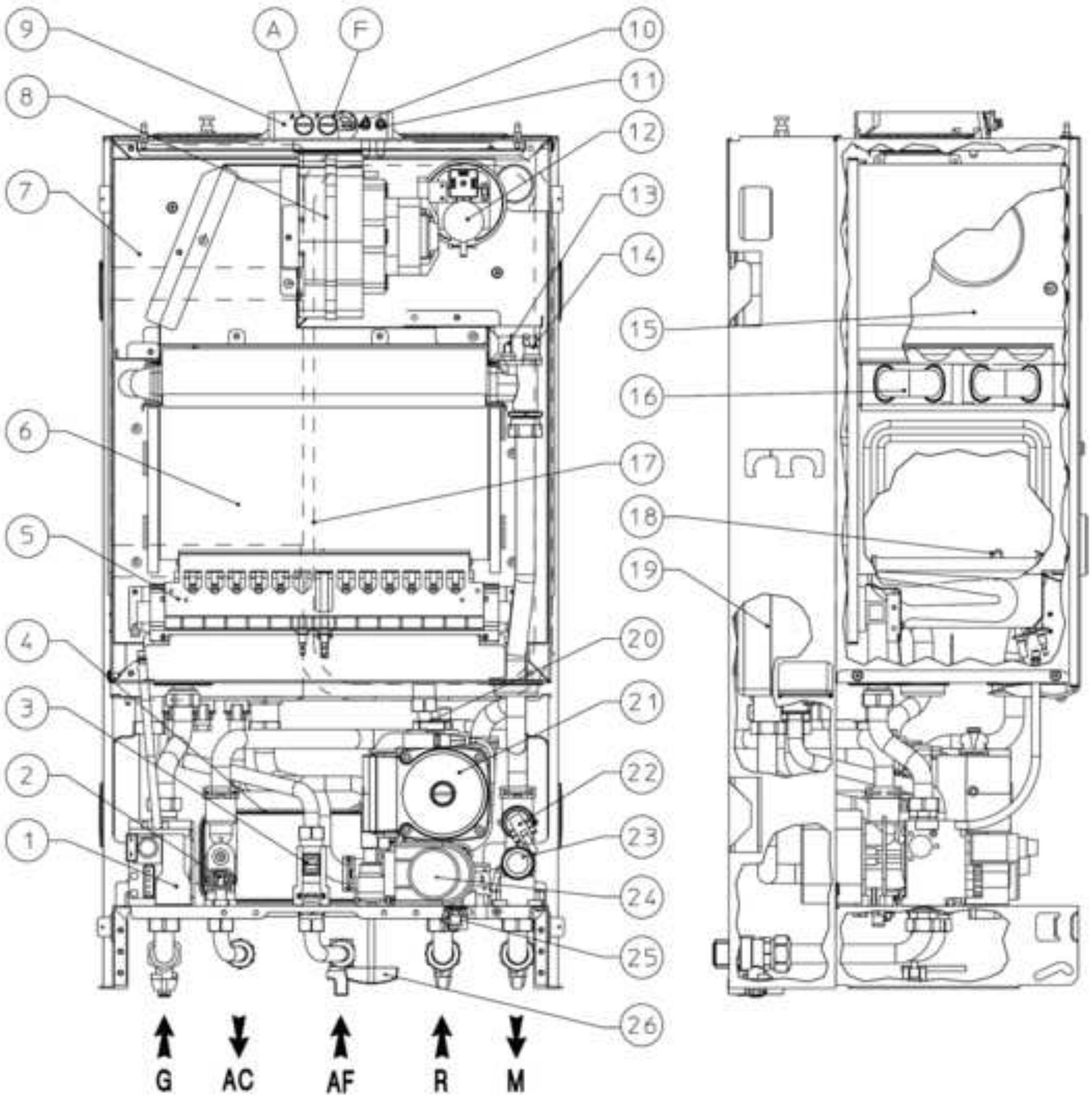

Figure 2
Click here to download high resolution image

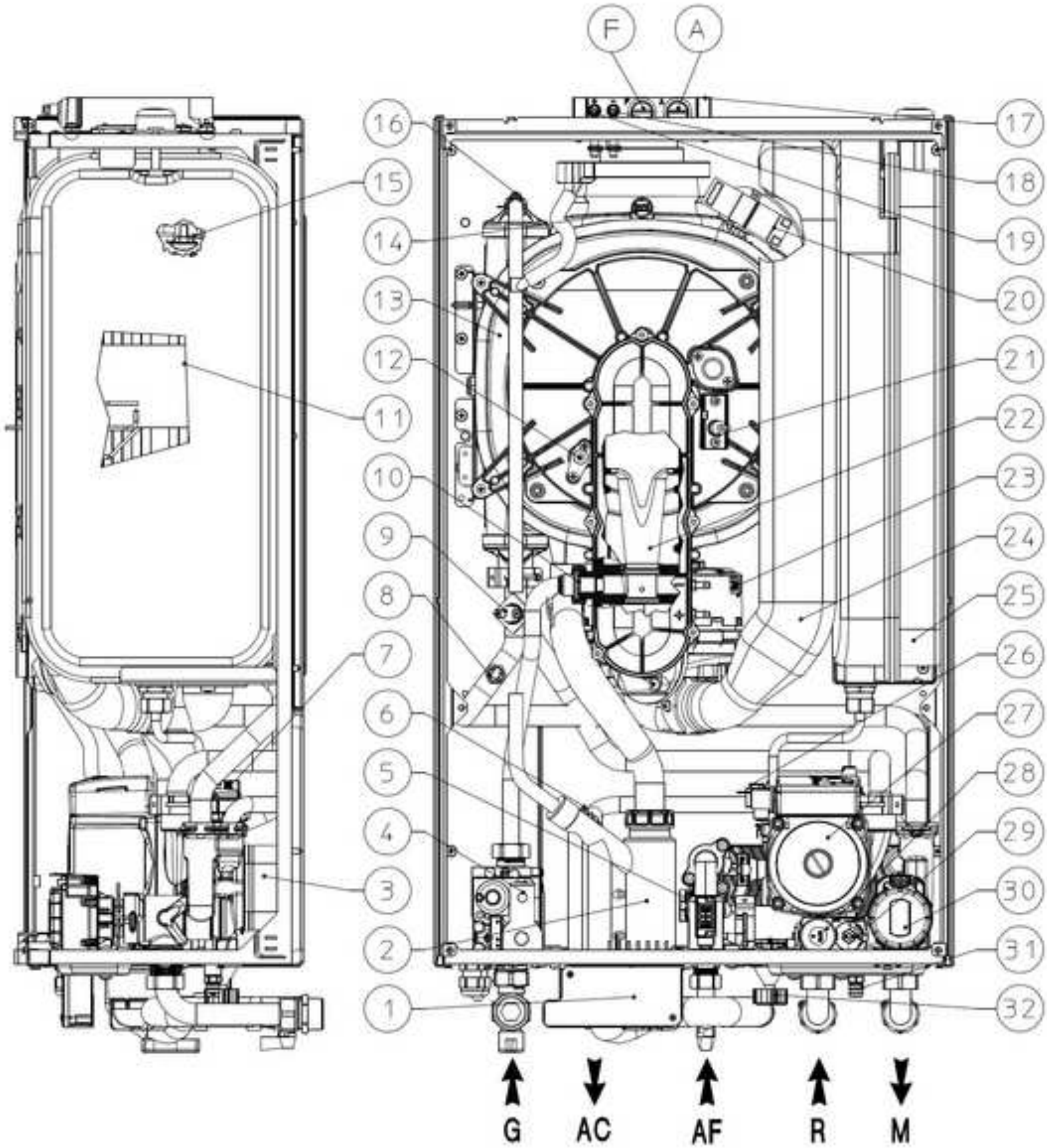

Figure 3
Click here to download high resolution image

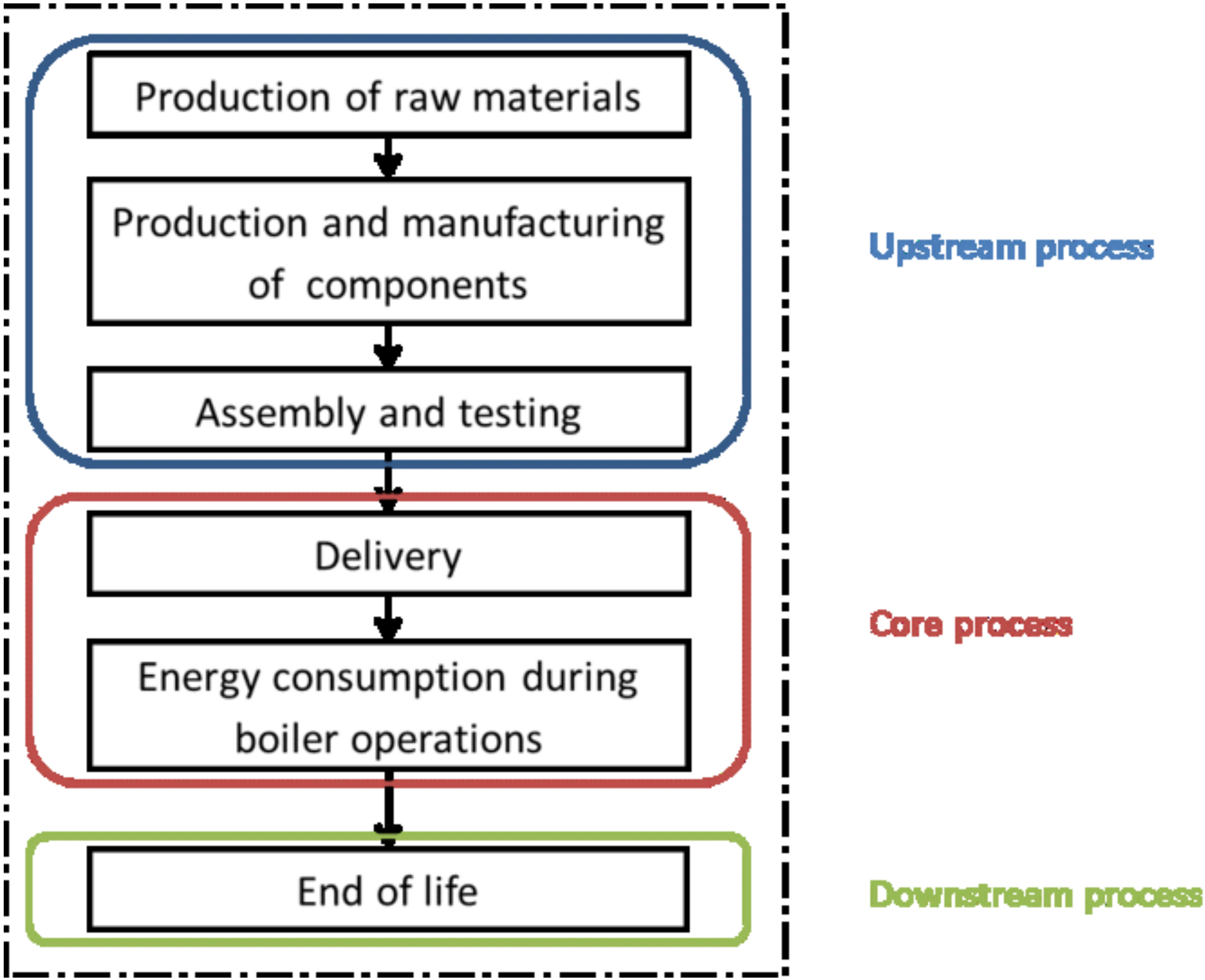

Figure 4

Click here to download high resolution image

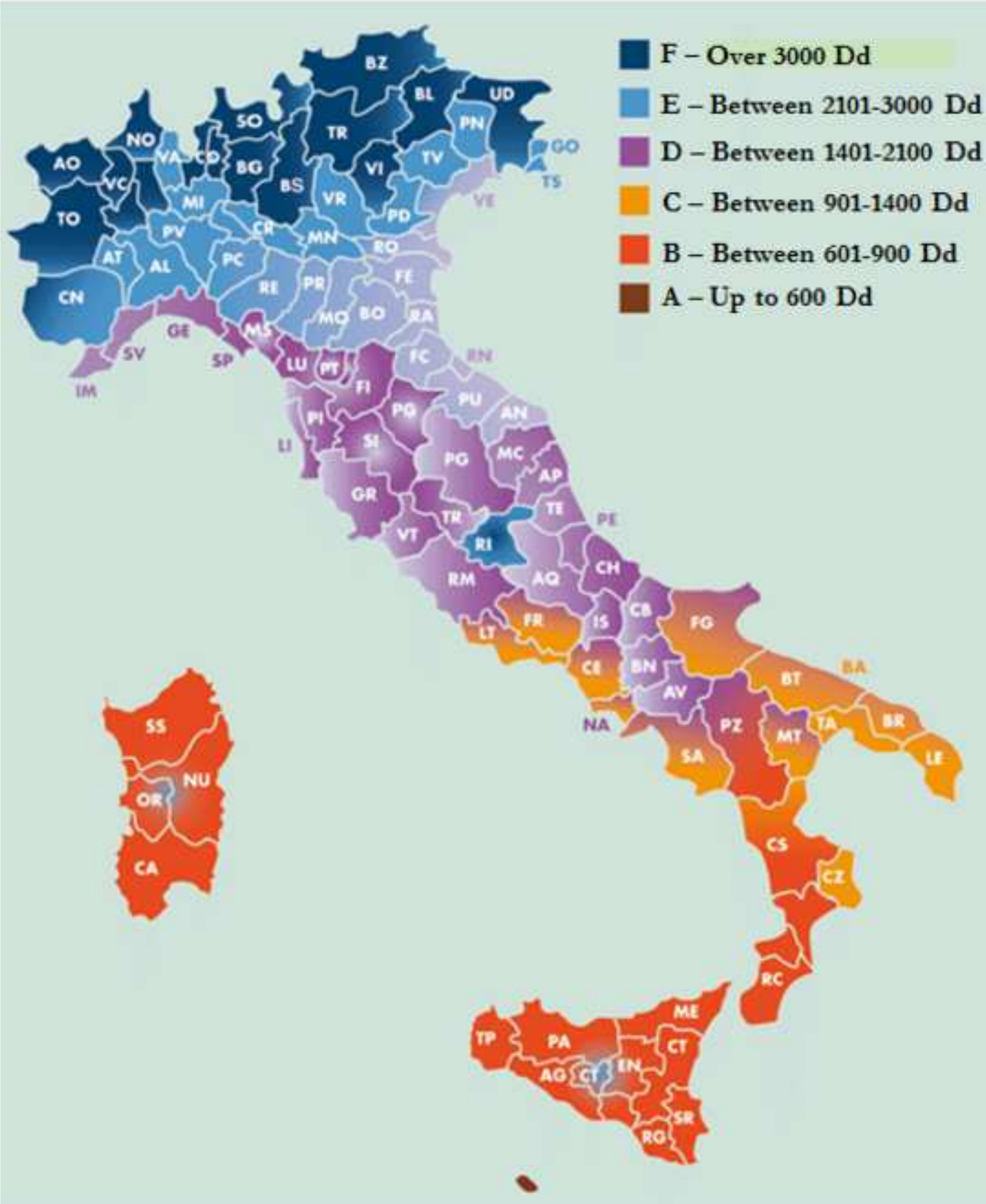

Figure 5
Click here to download high resolution image

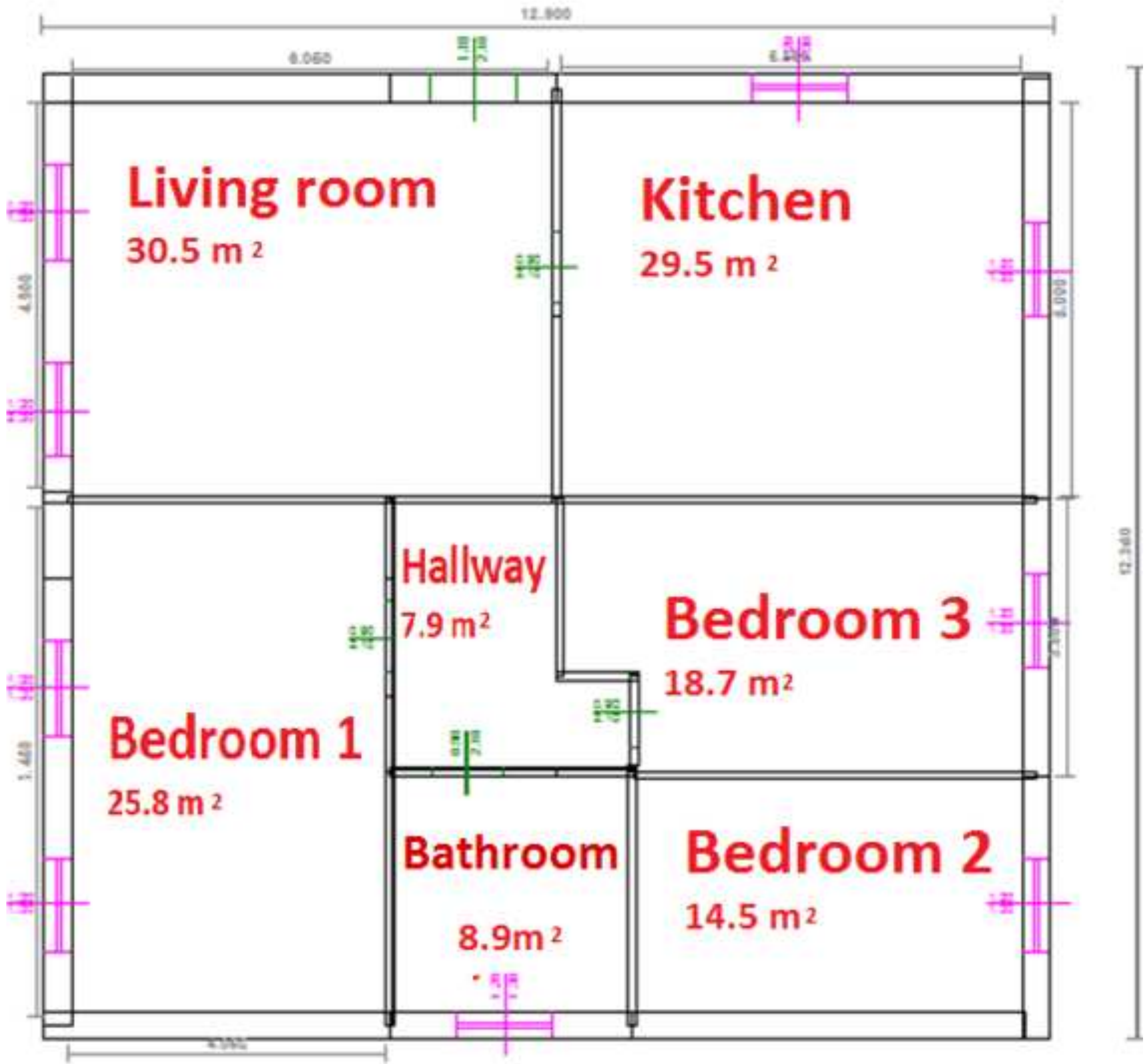

Figure 6
Click here to download high resolution image

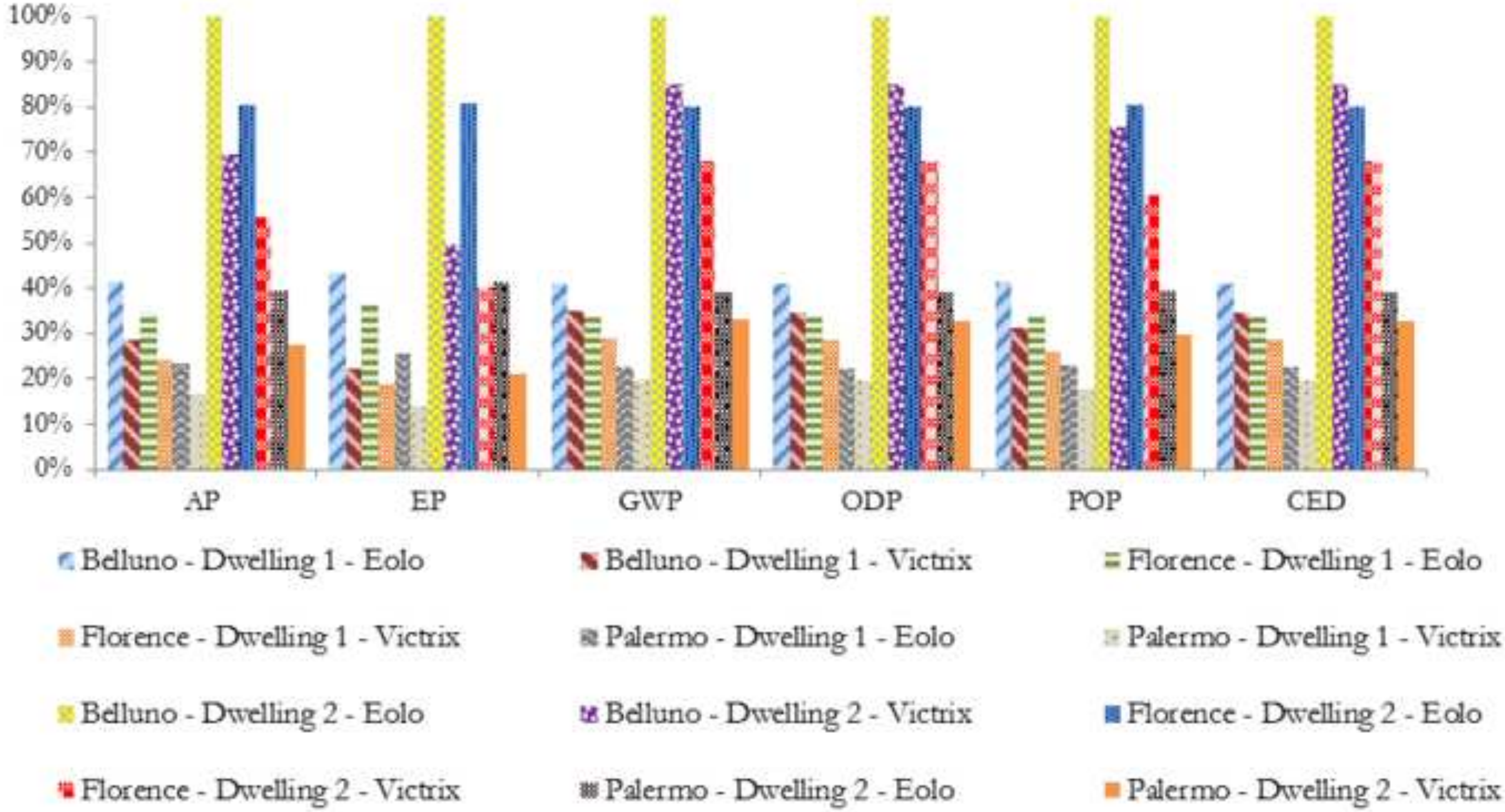

Figure 7
Click here to download high resolution image

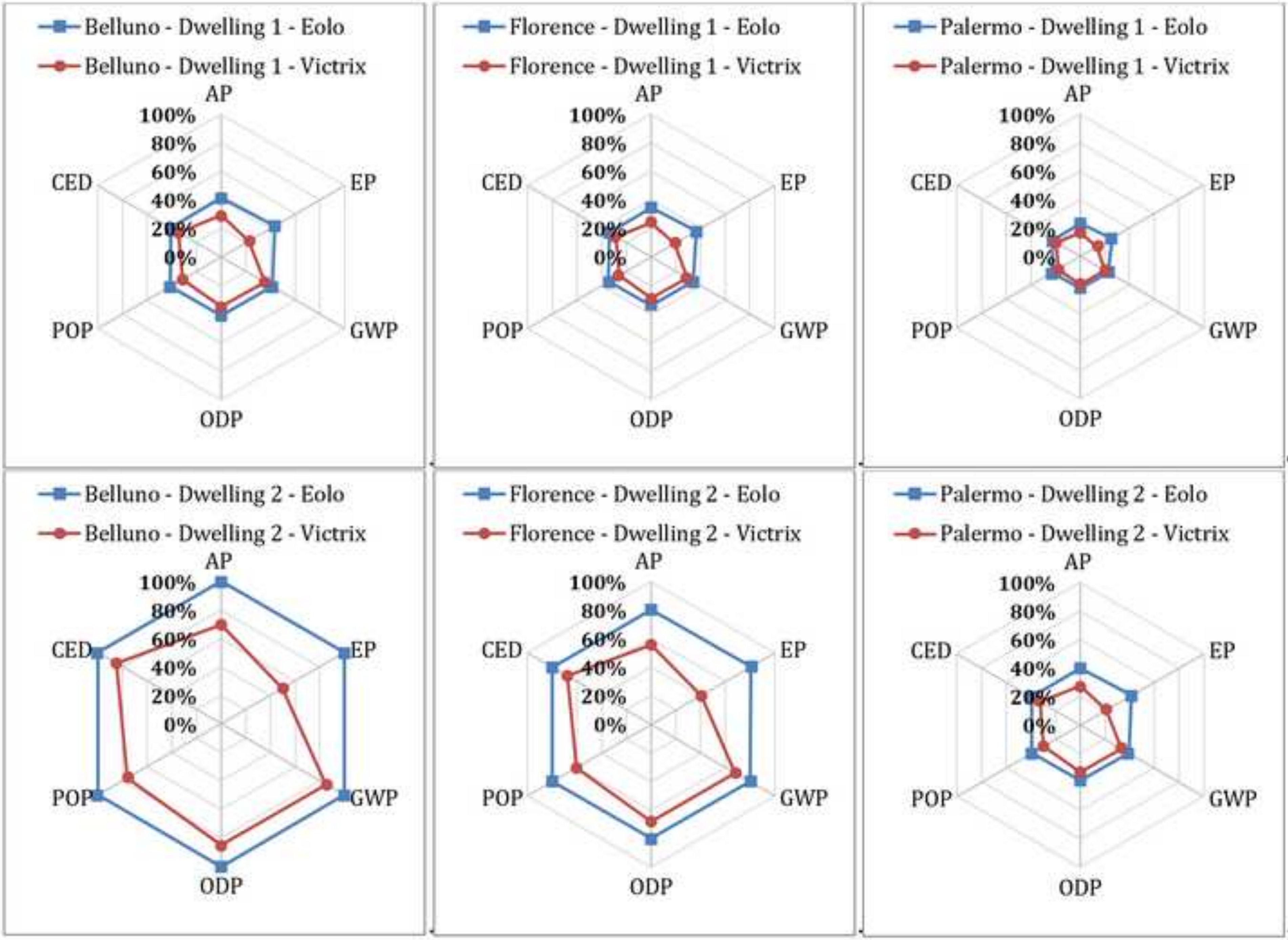

Figure 8a
Click here to download high resolution image

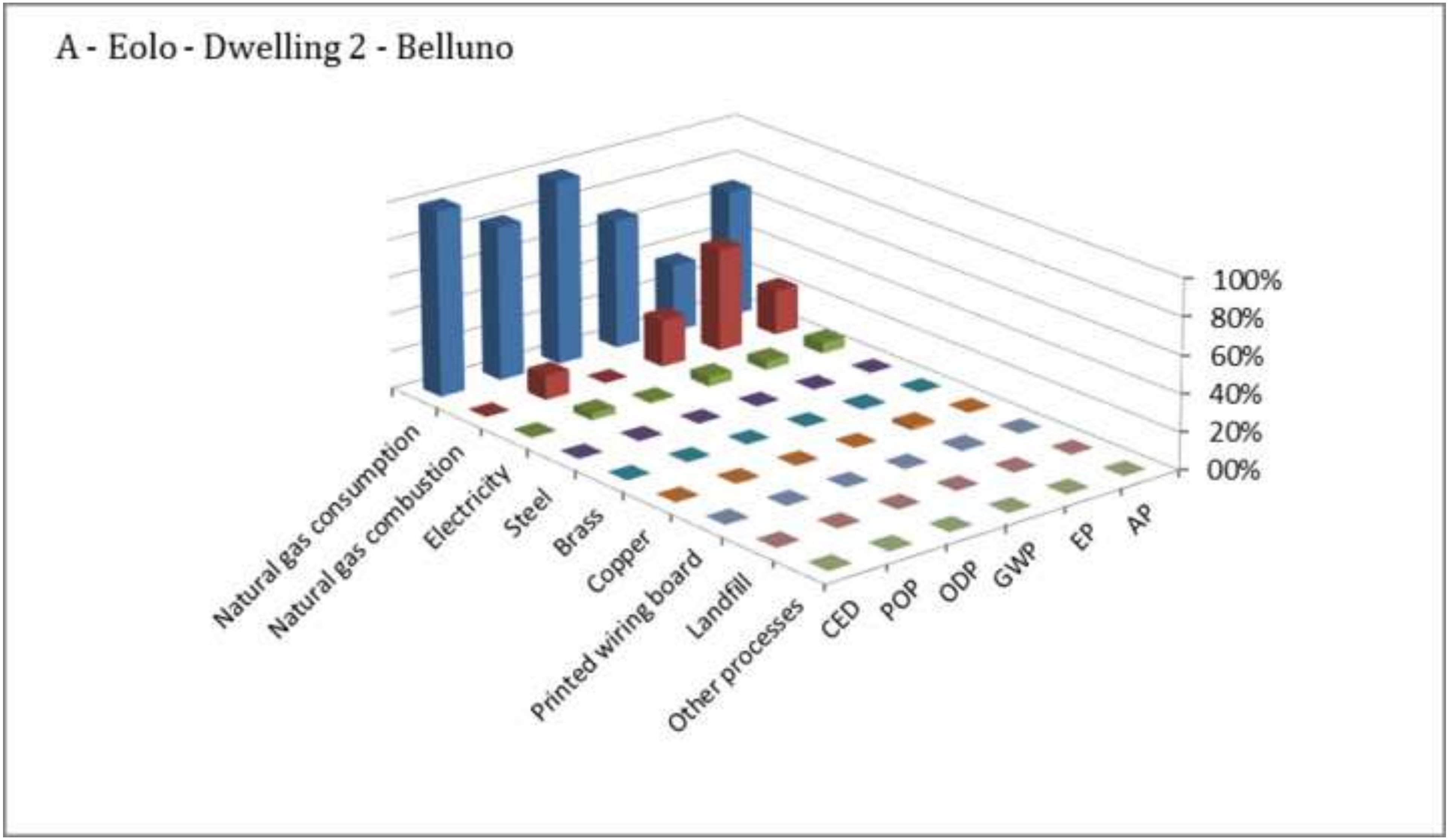

Figure 8b
Click here to download high resolution image

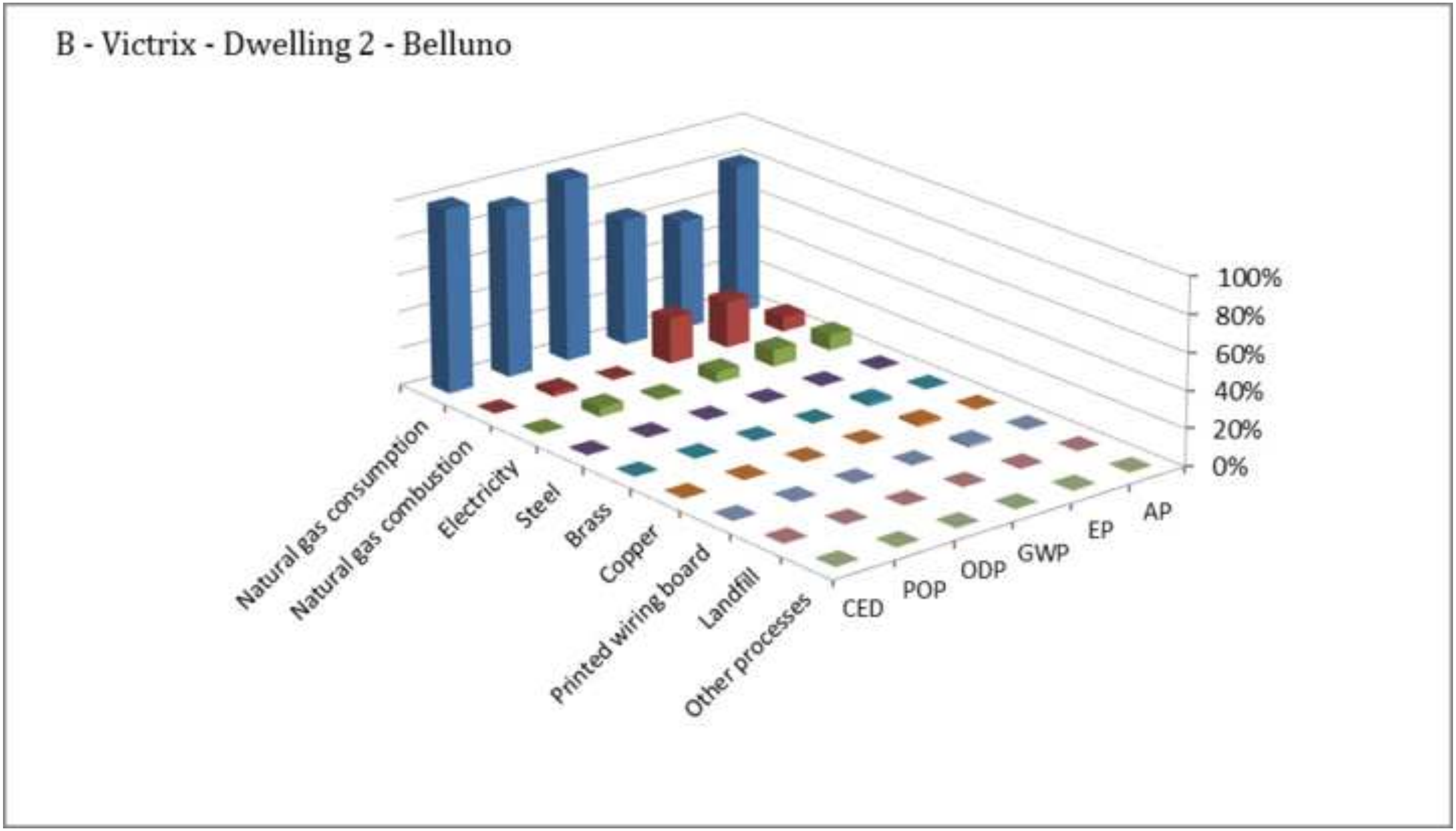

Figure 9a
Click here to download high resolution image

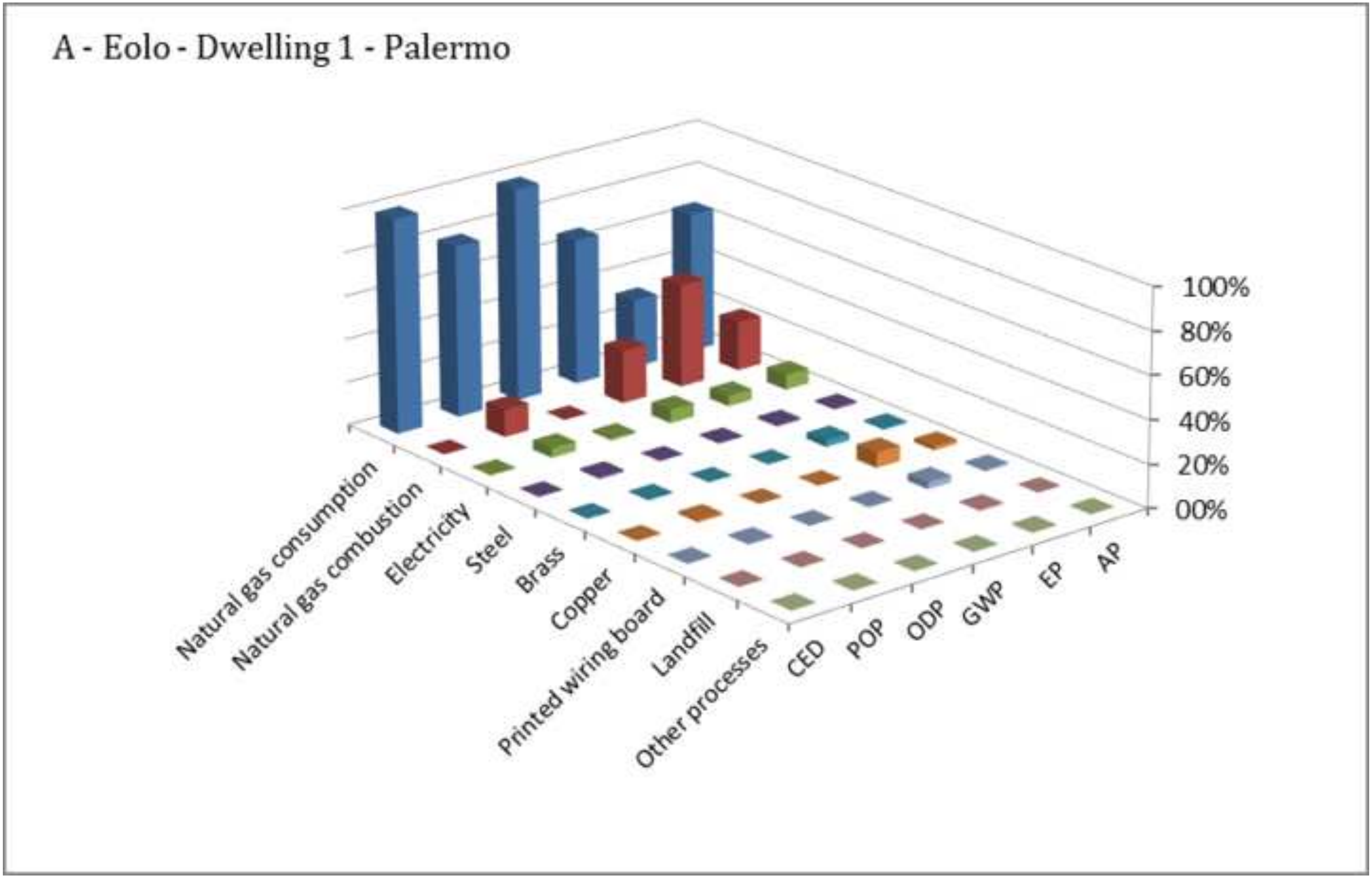

Figure 9b
Click here to download high resolution image

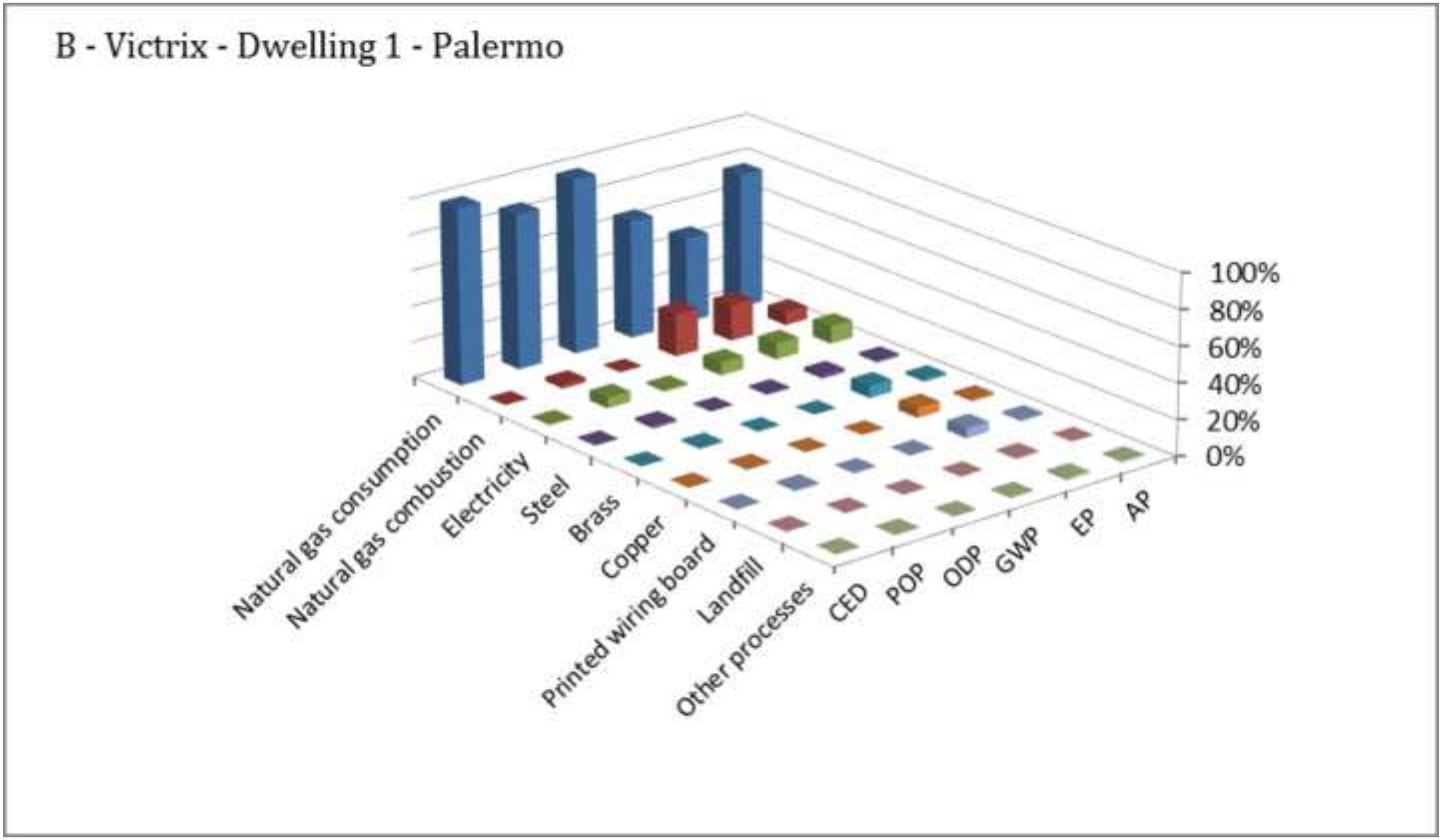

Figure 10

Click here to download high resolution image

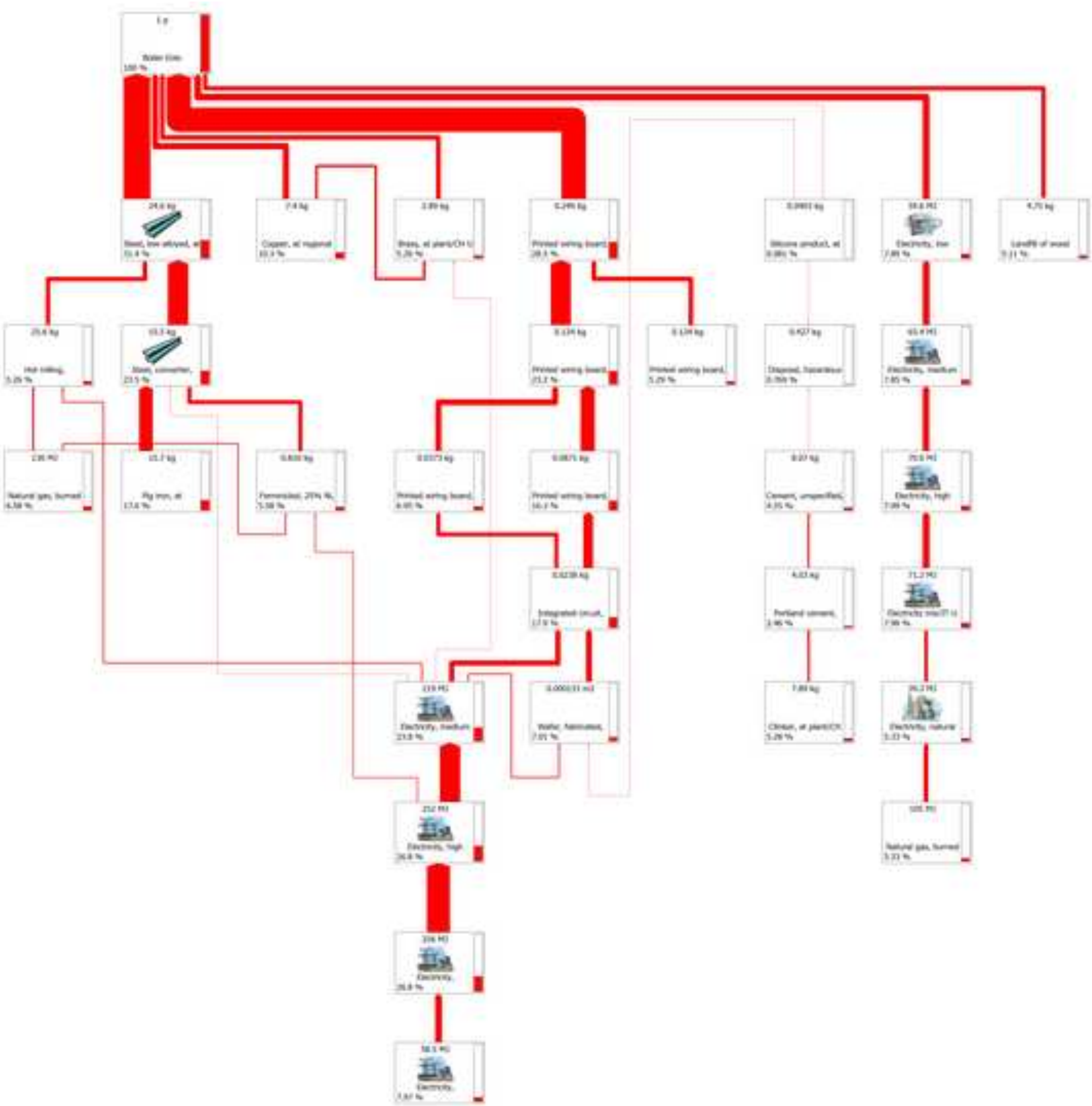

Figure 11

Click here to download high resolution image

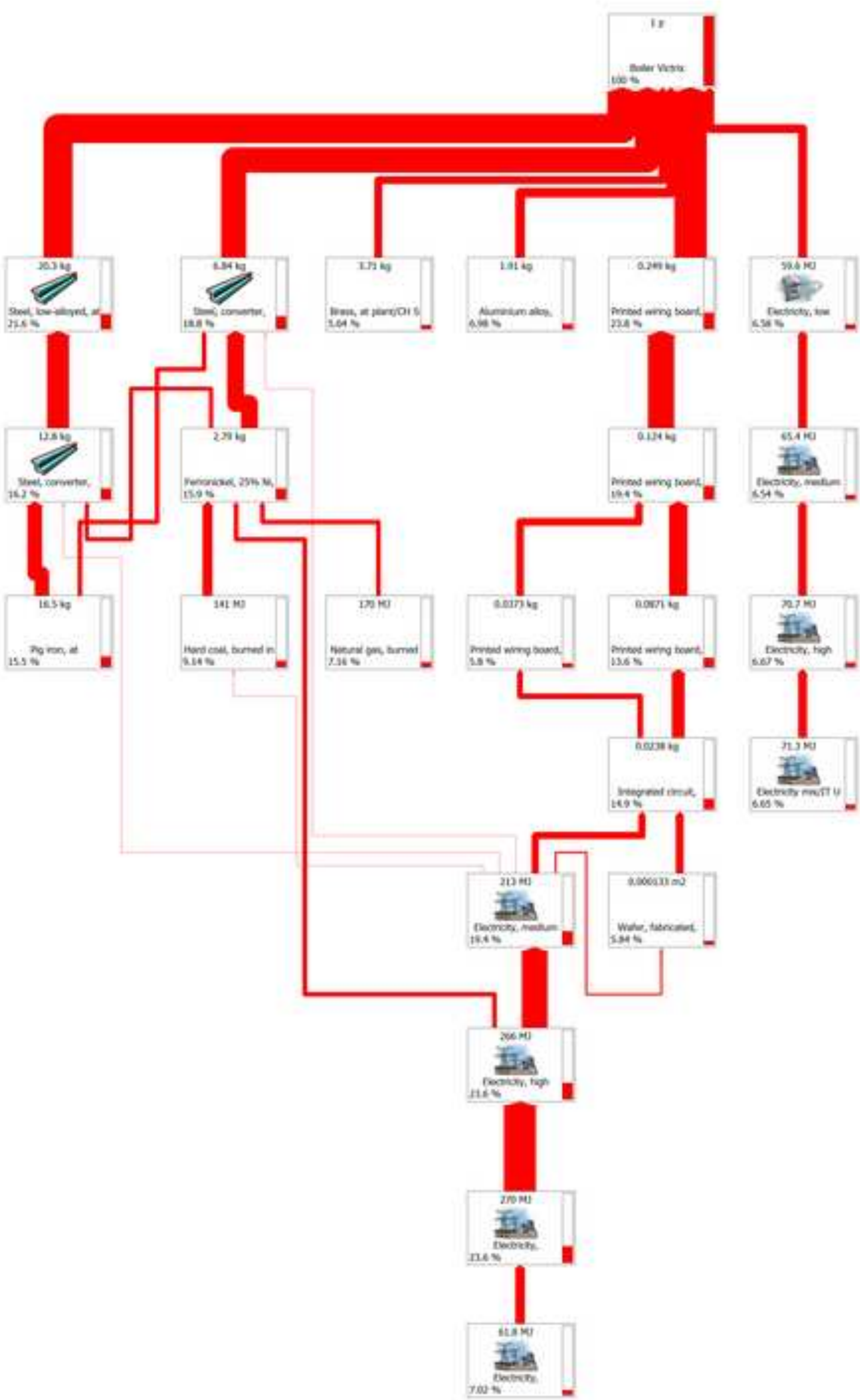

Figure captions

Figure 1: main components of the conventional “Maior Eolo” combi-boiler (Immergas S.p.A).

Figure 2: main components of the condensing boiler “Victrix” (Immergas S.p.A).

Figure 3: System boundaries of boiler life cycle.

Figure 4: Italian climate zones[1]; Dd = Degree days.

Figure 5: Layout of the dwelling considered.

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

Figure 7: Relative environmental impacts of the two boilers.

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

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

Figure 10: impact tree of the upstream and downstream processes for the Eolo boiler.

Figure 11: impact tree of the upstream and downstream processes for the Victrix boiler.

Legend of Figure 1:

LEGEND:
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

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

Legend of Figure 2:

LEGEND:
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