Journal of Cleaner Production 221 (2019) 189–201

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Comparative life cycle assessment of electric and gas ovens in the Italian context: An environmental and technical evaluation

Daniele Landi [a, *], Andrea Consolini [a], Michele Germani [a], Claudio Favi [b]

[a] Università Politecnica delle Marche, via Brecce Bianche, Ancona, 60131, Italy
[b] Università di Parma, Parco Area delle Scienze 181/A, Parma, 43124, Italy

ARTICLE INFO

Article history:
Received 15 January 2018
Received in revised form
31 October 2018
Accepted 17 February 2019
Available online 28 February 2019

Keywords:
LCA
LCI
Electric oven
Gas oven
Cooking appliances
Environmental impacts

ABSTRACT

This paper aims to analyse and compare the environmental and technical performances of two domestic oven technologies (one powered by natural gas and one by electric energy) considering the Italian context, such as Italian social and food habits. These household appliances are subject to energy labelling and are the most diffused cooking systems along with hobs. This study was performed in accordance with the international standards ISO 14040/14044 and adopted the attributional LCA approach. The analysis is related to the functional unit “the baking of food, considering the Italian context and a lifetime of 10 years”. The analysis includes all phases of the life cycle except for maintenance and transport, which were considered negligible for this analysis. The materials and manufacturing phases necessary for the production of the two ovens were considered in the analysis, and the data were provided by the ovens' manufacturers. The products’ use phase was considered through the measurement of resources (both natural gas and electric energy) consumed during the cooking simulation by experimental tests that simulated a heating cycle of a standard load represented by a brick. The product end-of-life phase was considered in accordance with the current regulations and statistical data in this sector. The EcoInvent database was used as a reference for background data. The ReCiPe life cycle impact assessment method was used for the assessment of the environmental impact categories.

This study shows the dominance, in terms of the environmental impact, of the electric oven with respect to the gas oven in every indicator considered in the analysis. In particular, the electric oven accounts has an approx. 3 times greater impact than the gas oven on the climate change, freshwater ecotoxicity and marine ecotoxicity impact categories, while for the ozone depletion, fossil depletion metal depletion and natural land transformation categories, the results are similar, with a slight dominance of the electric oven (approx. 2–5%). This finding is related to the use phase and results from the different energy carriers used and the time required for cooking in the two cases. Indeed, the nature of the energy carrier for the electric oven and the time required for cooking (based on the energy efficiency test) is longer compared to those of the gas oven. This result, which is clearly in favour of the gas oven in the Italian context, leads to the conclusion that the main contribution to the environmental load of the electric oven is the Italian electricity grid mix, which is mainly based on non-renewable sources. Therefore, this analysis depends on the geographic area of interest, and the results can significantly change if different contexts are analysed.

1. Introduction

Currently, one of the most perceived problems in European and international policy is environmental pollution caused by the domestic sector, particularly from appliances. The European Union (EU) has enacted a specific directive to promote eco-sustainability, called the “Eco-design of Energy-Related Products Directive” (European Commission, 2011a,b,c,d). This directive provides an overview of green philosophy applied to the entire life cycle but is currently only applied to energy-related products (ErPs). ErPs are products that have an impact on energy consumption during use. This product category includes household appliances, which are subject to another directive called the “European energy labelling” (European Commission, 2010). Looking at European energy

* Corresponding author.
E-mail address: d.landi@univpm.it (D. Landi).

https://doi.org/10.1016/j.jclepro.2019.02.196
0959-6526/

consumption in domestic applications, cooking appliances represent the system with the greatest impact after building heating. Hobs and ovens are the most used domestic appliances for cooking and it has been estimated that an oven undergoes approx. 110 cycles per year, while a cooking hob undergoes approx. 438 cycles per year (Palmer et al., 2013; Landi et al., 2017). Currently, in Europe 27, electric ovens represent 96% of built-in ovens sales, while gas ovens constitute the remaining share. On the other hand, specifically considering the Italian context, the electric oven is owned by approx. 62%, while the gas oven is owned by approx. 20%. Looking at the domestic oven market, despite the large number of brands, approx. 25% of the European cooking products are not manufacturer by brands, but by an Original Equipment Manufacturer. Italy and France are the main producers of electric and gas ovens with approx. 10 million units produced.

Therefore, a life cycle comparison of domestic oven technologies may show interesting outcomes and support responsible choices by consumers with the aim of understanding which system is more sustainable from an environmental perspective. The literature has broad Life Cycle Assessment (LCA) comparisons related to different technologies for domestic appliances, such as refrigerators (Ma et al., 2012; Monfared et al., 2014; Xiao et al., 2015) water-heating boilers (Monteleone et al., 2015; Vignali, 2017), air conditioners (Grignon-Massé et al., 2011), cooker hoods (Bevilacqua et al., 2010), kettles (Ayoub and Irusta, 2014) and vacuum cleaners (Gallego-Schmid et al., 2016). However, few studies can be found in the literature on cooking appliances, such as cooking tops, ovens, microwaves, etc. Looking at the environmental analysis of cooking tops, Pina et al. (2015) investigated the influence of the design choice for manufacturing particular components excluding the use phase (Pina et al., 2015). On the same subject, Elduque et al. (2014) analysed the environmental burden created by the electronic boards of an induction hob (Elduque et al., 2014). Regarding the life cycle analysis, Favi et al. (2018) provided a comparison of two different hob technologies in the Italian context: the induction vs. the gas hobs (Favi et al., 2018). No recent analysis has focused on a comparative impact assessment of ovens built with different technologies. A dated study conducted by Jungbluth (1997) presents a comparison of different cooking alternatives using LCA (Jungbluth, 1997). The author investigated all the most common energy sources used in Switzerland, including the gas stove and the gas oven using natural gas or liquefied gas, the electric range and oven, the microwave oven and the wood stove. This study represents a very interesting analysis; however, the paper is more than 20 years old and, consequently, the results are not applicable due to the lack of data reliability and to the use of an old database and model to quantify the environmental impacts. Recent studies (Ardente et al., 2014; Iraldo et al., 2016) analysed the influence of the longer durability on the environmental impact connect to ErPs. In particular, the study conducted by Iraldo et al. assessed the different impacts between a durable and a standard electric oven, focusing on the environmental implications of the analysed models (Iraldo et al., 2016).

The present paper aims to investigate the environmental impact assessment of two domestic ovens, specifically a gas one and an electric one in the Italian context. This study uses the guidelines outlined by the attributional LCA (aLCA) approach. The aLCA system modelling approach has been chosen with the aim of making a comparative analysis of both types of equipment by using the inputs and outputs attributed to the functional units of a product system (Baitz, 2016). In this case, the attributional approach allows for an estimation of the environmental load of the two cooking alternatives in the same scenario, highlighting the differences in the results (e.g., climate change).

This study has been conducted considering the Italian scenario and its effect on the product use phase. In particular, the following technical aspects have been considered: (i) the energy carriers (both natural gas and electric energy), which come from the Italian national grid, and (ii) the product lifetime and cooking habits, which are based on Italian costumers' behaviour. Indeed, ovens belong to the ErPs and it is known how the use phase represents the largest share for the environmental impacts in a life cycle perspective (Bevilacqua et al., 2010; Xiao et al., 2015). Therefore, the energy carrier and the behaviour in use play a key role in the environmental load of the analysed appliances (Favi et al., 2018).

2. Material and methods

The paper illustrates a comparative analysis between two different technologies for food cooking: a gas oven vs. an electric oven. According to the normative (ISO, 2006a; ISO, 2006b), an attributional LCA comparison analysis requires a clear and fair definition of the goal and scope of the study. In particular, the functional unit must be suitable for the two objects and must describe the functionality for which they are intended. The functional unit selected for the comparison is defined as "the baking of a food, considering the Italian context and a lifetime of 10 years". In this section, the four stages of the life cycle assessment are presented, preceded by a description of the two systems.

2.1. Case study systems

The two ovens analysed in this study belong to the same brand and are manufactured by the same company. The electric model is EOB2200BOX, and the gas model is EOG2102BOX. Both models are built-in ovens with the same external dimensions and the forced air function through a fan in the rear wall of the cavity. Small differences regarding the internal cavity (68 [litres] vs. 64 [litres]) and the Energy Efficiency class (A vs. A+) are noticed (Fig. 1).

The electric oven presents an installed power of 2780 [W], represented by the top and bottom heating elements. The gas oven is equipped with an electric grill, but the main heating element is a gas burner place on the bottom part of the cavity. Both ovens have several assemblies and components that are either similar or exactly the same, except for some specific assemblies such as the heating elements and control/safety systems. The two oven technologies use the same insulation materials such as rock wool and glass fibre, and the same enamelled rolled steel material is used for the cavity. A difference in the quantities of materials is noticed due to the differences in the heating systems (gas burners vs. heating elements). Indeed, for the gas oven, an opening is provided for direct access to the gas burner covered on the top to ensure the proper operation during use. The two ovens have a similar glass door system with the same number of layers, which is very important for the heat losses along with the insulation. There are also functional differences, which are the temperature control system and the safety system necessary in the gas oven due to the presence of gas. All project and functional differences are summarized in Table 1.

The difference in the temperature control system is mainly caused by the different technology used for the thermostats; the electric one performs with an on-off type control, while the gas on performs with a modular control of the gas flow. This difference can be seen in the temperature profile inside the cavity of the two ovens as presented in Fig. 2.

The two ovens belong to different Energy Efficiency classes. This difference is mainly related to the use of different energy carriers, though the same test is conducted for measuring the energy consumption (IEC 60350-1, 2016; EN 15181, 2017). Indeed, the equation for calculating the energy efficiency index (EEI) is different

Fig. 1. Built-in gas oven (left) and built-in electric oven (right).

Table 1
Project and functional differences between the two ovens.

	Gas Oven	Electric Oven
Project differences		
Heating elements	Linear gas burner with a top electric grill	Bottom and Top Electric Resistances
Temperature control system	Gas Thermostat	Electric Thermostat
Volume of the cavity	64 [litres]	68 [litres]
	Accessible burner through a removable cover in the cavity	Bottom resistance not accessible
	Chimney for expulsion of fumes and vapours	Different chimney for only expulsion of vapours
Energy Efficiency class	A	A+
Functional difference		
Safety system	Flame supervision device (thermocouple and safety valve) and grounding system	Grounding system

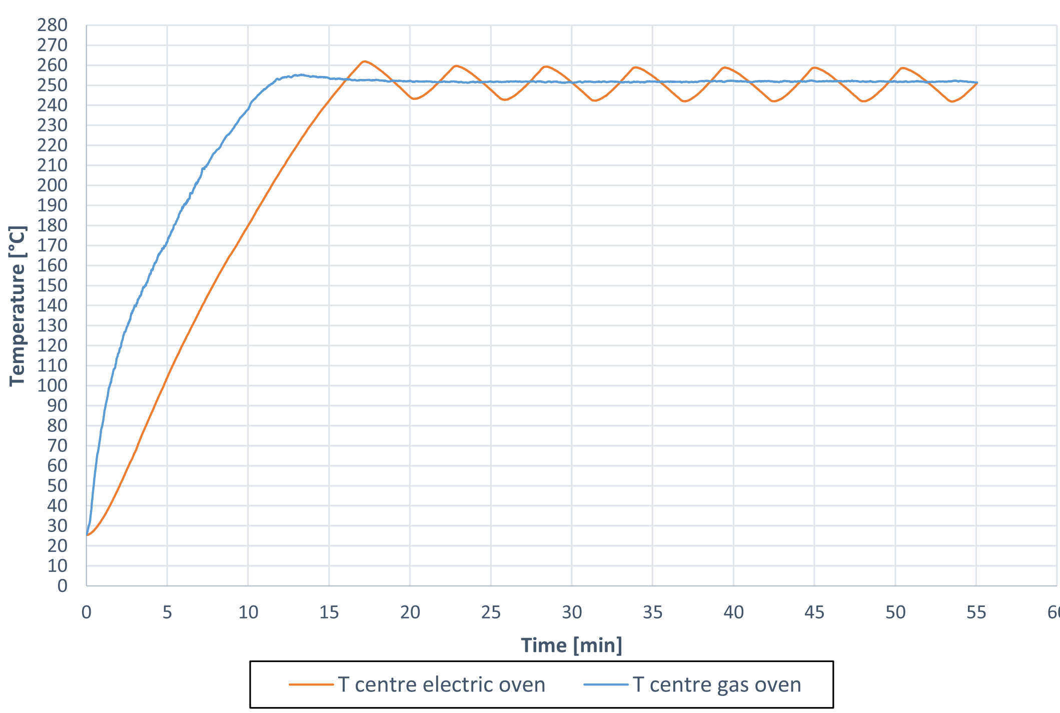

Fig. 2. Differences in temperature profile between the electric (red line) and gas (blue line) oven. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

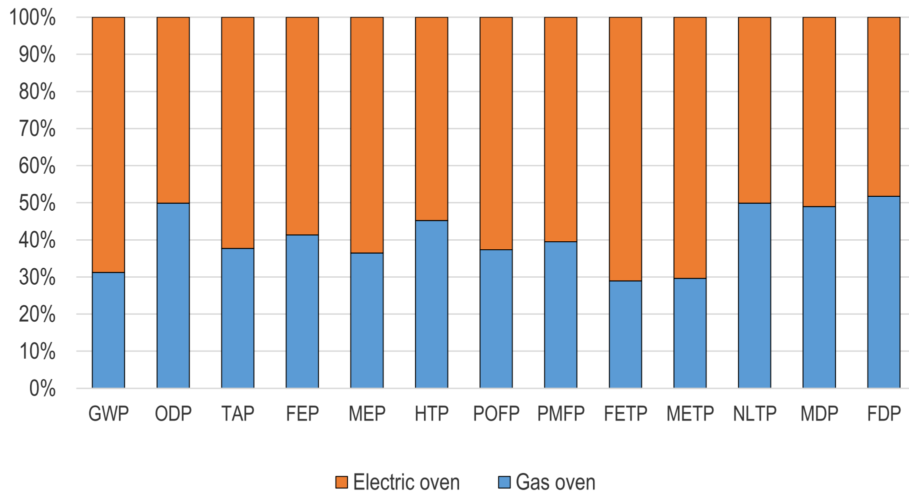

Fig. 3. Impact comparison between the two ovens with a “non-intensive” product use scenario and optimistic end-of-life scenario.

depending on the type of energy resource, gas or electricity. In particular, equations (1) and (2) are used for assessing the energy efficiency index (EEI) of electric ovens, while equations (3) and (4) are used for assessing the energy efficiency index (EEI) of gas ovens.

$$EEI_{cavity} = \frac{EC_{electric\ cavity}}{SEC_{electric\ cavity}} \times 100 \quad (1)$$

$$SEC_{electric\ cavity} = 0,0042\ x\ V + 0,55\ (in\ kWh) \quad (2)$$

$$EEI_{cavity} = \frac{EC_{gas\ cavity}}{SEC_{gas\ cavity}} \times 100 \quad (3)$$

$$SEC_{electric\ cavity} = 0,044\ x\ V + 3,53\ (in\ MJ) \quad (4)$$

where:

- EEI $_{cavity}$ is the numeric value related to the Energy Efficiency Index for the analysed cavity;
- V is the volume of the cavity of the domestic oven in litres [litres];
- SEC $_{electric\ cavity}$ is the Standard Energy Consumption (electricity) required for heating a standardized load in a cavity of a domestic electric heated oven during a standardized cycle;
- EC $_{electric\ cavity}$ is the energy consumption required to heat a standardized load in a cavity of an electric oven during a cycle, expressed in [kWh];
- SEC $_{gas\ cavity}$ is the Standard Energy Consumption (electricity) required for heating a standardized load in a cavity of a domestic gas heated oven during a standardized cycle;
- EC $_{gas\ cavity}$ is the energy consumption required to heat a standardized load in a cavity of a gas oven during a cycle, expressed in [MJ];

In this context, Regulation (EU) N. 66/214 provides ranges of the energy efficiency indexes for the oven cavities (Table 2). The minimum EEI class has to increase its efficiency by 30%; therefore, ovens must increase their efficiency to be sold and attractive to the EU market. Table 3 describes the correlation between EEI and the Energy Efficiency Class (Regulation (EU) N. 65/2014).

The energy consumption (EC) value is measured according with the energy consumption test, which is described in the following paragraph (section 2.3.2).

Table 2
Minimum efficiency levels for electrical and gas ovens, as established by Regulation (EU) N. 66/2014.

Tiers	Ovens
20/02/2015	EEI < 146
20/02/2016	EEI < 121
20/02/2019	EEI < 96

2.2. Goal and scope definition

The aim of this study is to perform a comparative analysis of the environmental performance of gas and electric ovens to determine if there is a substantial difference between the two technologies. The geographical context plays a key role in the quantification of the impact of entire life cycle, so the specific Italian context for the electricity mix and the supply of gas has been considered. The geographical background is also important for establishing the annual energy consumption, which is influenced by cooking and food habits (Fulkerson et al., 2014; Nuvoli, 2015). The system boundaries include the following phases: raw material extraction, the manufacturing processes for components production and product assembly, the product use phase and the product end-of-life. The only phases excluded from the analysis are: (i) the transport of finished appliances because both ovens are manufactured and distributed in Italy and (ii) maintenance because it can be considered negligible for this kind of product (Iraldo et al., 2016). The lifespan of 10 years is aligned with the average life of the products installed in Italy (Xiao et al., 2015; Iraldo et al., 2016).

2.3. Life cycle inventory

The life cycle inventory is the most time-consuming phase of the

Table 3
Energy Efficiency classes of domestic ovens.

Energy Efficiency Class	Energy Efficiency Index (EEI_{cavity})
A+++ (most efficient)	$EEI_{cavity} < 45$
A++	$45 \leq EEI_{cavity} < 62$
A+	$62 \leq EEI_{cavity} < 82$
A	$82 \leq EEI_{cavity} < 107$
B	$107 \leq EEI_{cavity} < 132$
C	$132 \leq EEI_{cavity} < 159$
D (least efficient)	$EEI_{cavity} \geq 159$

LCA analysis. The reliability and the origin of the data are essential for a correct impact assessment. Therefore, primary data have been used whenever possible, referring to the Ecoinvent 3.1 database as the background for secondary data. The quantity of energy and material resources as well as environmental releases have been evaluated in every phase of life cycle included in the system boundaries.

2.3.1. *Life cycle inventory: raw material extraction and manufacturing processes for production/assembly of components*

Manufacturing data available in the product bill of materials and provided by the ovens' manufacturers have been used as a baseline for the inventory, as shown in Tables 4 and 5. The ovens' features, already introduced in Table 1, highlight how the main differences between the two technologies are represented by the heating supply system and its regulation systems. Indeed, in the gas oven they are represented by a gas burner, a gas thermostat and the internal piping, while in the electric oven they are represented by two resistors, an electric thermostat and electric cables. There are also slight differences in the rear protection of the chassis and in the cavity of the gas oven to allow the correct aspiration of air for combustion. These design differences lead to a higher weight of the gas oven than the electric one; in particular, there is a greater quantity of metals, such as brass and aluminium.

2.3.2. *Life cycle inventory: product use phase*

The energy consumption of the two ovens has been evaluated by reproducing the standard test for the energy labelling certification. This test is common for both ovens and it has been conducted following the specific directives (IEC 60350-1, 2016; EN 15181, 2017). During this energy consumption testing, the oven is placed in a room in which the temperature is kept in a range of 23 ± 2 °C. The supply voltage and frequency are related to the country in which the oven is sold. The EEI test concerns the heating of a brick. For the electric oven, as regulated by IEC 60350-1, the sample to be used is pre-treated and prepared to obtain a wet brick. The weight of the wet brick is measured before and after the EEI test. The weight gap after the heating test and the duration of the test are parameters for the proof of the energy consumption. The IEC 60350-1 standard also regulates the position of the brick inside the oven cavity with the required thermocouple probes. In general, this test consists of heating an opportune thermal load, represented by a standard brick, which simulates the thermal proprieties of meat. The same procedure is followed for the gas oven test but regulated by EN 15181.

This kind of test is suitable for each one of the two ovens and it is representative of the functional unit defined before, according to requirements of ISO 14040. Moreover, the use of a standard load makes the test repeatable. However, it is necessary to define other parameters to characterize the product use phase, which depend on the social and food habits of the consumer. In this analysis the characterization of energy consumption per cycle of operation is sensitive to consumer uses, such as cooking time and mode, setting temperature and the frequency of opening the door. Therefore, a literature analysis to assess the use frequency and the expected lifetime of the appliances has been conducted (Palmer et al., 2013; Favi et al., 2018). Concerning the frequency of oven use, two different scenarios have been taken into account to cover different consumers' behaviour in the Italian context:

- a "non-intensive" use of two (2) times per week (approx. 110 cycle/year)
- an "intensive" use of five (5) times per week (approx. 260 cycle/year)

Concerning the characterization of the use phase, a lifetime of 10 years has been considered, which represents the expected life of the appliance provided by the manufacturer and close to the average life of the applications installed in Italy (Iraldo et al., 2016; Xiao et al., 2015).

The values of energy consumption for a year of use are presented in Table 6, specified in [kWh] for the electric one and in volume of methane [m^3] for the gas one. These values have obtained by measuring the methane consumption with a flow meter, while the electricity is measured with a suitable power meter. The following dataset from the Ecoinvent 3.1 database has been used to model the energy resources consumption:

Table 4
Inventory for gas oven manufacturing.

Category	Subcategory	Assemblies								
		Cavity	Chassis	Door	Front Panel	Hot Air Fan	Tangential Fan	Gas Plant	Packaging	Cables
Energy	Electricity [kWh]	2489	0,403	0120	0,042	0073	0,135	0029	0,011	0042
	Natural gas [m^3]	0,435	0338	0,072	0039	0,050	0112	0,014	0001	0,003
	Compressed air [m^3]	4406	2027	0,270	0170	0,343	0610	0,171	0000	0,000
Materials	Galvanized steel [kg]	1711	5584	0,482	0535	1156	1721	0,542	NA	0,008
	Enamelled steel [kg]	7907	NA	NA	NA	NA	NA	NA	NA	NA
	Stainless steel [kg]	0,215	NA	0,170	0,01	NA	0,002	0,01	NA	NA
	Nickel and chrome alloy [kg]	0,023	NA	NA	NA	NA	NA	NA	NA	NA
	Ferrite [kg]	NA	NA	NA	NA	0,1415	0,064	NA	NA	NA
	Aluminium [kg]	0,124	NA	0,234	NA	NA	0,0744	0,0348	NA	NA
	Glass [kg]	0,03	NA	4525	NA	NA	NA	NA	NA	NA
	Glass fibre [kg]	0,398	NA	NA	NA	NA	NA	NA	NA	NA
	Rock wool [kg]	1,63	NA	NA	NA	NA	NA	NA	NA	NA
	Brass [kg]	0,01	NA	NA	NA	NA	NA	0,2016	NA	NA
	Cooper [kg]	0,02	NA	NA	0,0062	0,12025	0,08	0,001	NA	0,049
	Nylon (PA) [kg]	NA	NA	0,0005	0,037	0022	0,165	NA	NA	NA
	Polypropylene (PP) [kg]	NA	0,003	NA	0,015	0010	NA	0,002	NA	0,02
	Ethylene vinyl acetate [kg]	NA	NA	NA	NA	0,015	0008	NA	NA	NA
	Magnesium oxide [kg]	0,088	NA	NA	NA	NA	NA	NA	NA	NA
	Ceramic [kg]	0,034	NA	NA	0,016	NA	NA	NA	NA	NA
	Glass fibre polyamide [kg]	NA	NA	0,387	0,04	NA	NA	NA	NA	NA
	Polystyrene foam [kg]	NA	NA	NA	NA	NA	NA	NA	0,88	NA
	Polyethylene low density (LDPE) [kg]	NA	NA	NA	NA	NA	NA	NA	0,29	NA
	Other Plastics	0,0006	NA	0,056	NA	NA	NA	NA	NA	0,106

Table 5
Inventory for electric oven manufacturing.

Category	Subcategory	Assemblies							
		Cavity	Chassis	Door	Front Panel	Hot Air Fan	Tangential Fan	Packaging	Cables
Energy	Electricity [kWh]	2307	0,393	0120	0,049	0065	0,133	0028	0,006
	Natural gas [m^3]	0,420	0335	0,072	0041	0,045	0111	0,001	0002
	Compressed air [m^3]	4035	2008	0,270	0184	0,303	0595	NA	NA
Materials	Galvanized steel [kg]	0,972	5634	0,482	0264	1024	1715	NA	0,009
	Enamelled steel [kg]	8817	NA	NA	NA	NA	NA	NA	NA
	Stainless steel [kg]	0,409	NA	0,17	0,445	NA	0,002	NA	NA
	Nickel and chrome alloy [kg]	0,052	NA	NA	NA	NA	NA	NA	NA
	Ferrite [kg]	NA	NA	NA	NA	0,128	0064	NA	NA
	Aluminium [kg]	NA	NA	0,234	NA	NA	NA	NA	NA
	Glass [kg]	0,03	NA	4525	NA	NA	NA	NA	NA
	Glass fibre [kg]	0,398	NA	NA	NA	NA	NA	NA	NA
	Rock wool [kg]	1,63	NA	NA	NA	NA	NA	NA	NA
	Brass [kg]	NA	NA	NA	NA	NA	NA	NA	NA
	Cooper [kg]	NA	NA	NA	0,008	0,1	0,08	NA	NA
	Nylon (PA) [kg]	NA	NA	0,0005	0,054	0012	0,165	NA	NA
	Polypropylene (PP) [kg]	NA	NA	NA	0,015	NA	NA	NA	NA
	Ethylene vinyl acetate [kg]	NA	NA	NA	NA	NA	NA	NA	NA
	Magnesium oxide [kg]	0,196	NA	NA	NA	NA	NA	NA	NA
	Ceramic [kg]	0,041	NA	NA	0,009	NA	NA	NA	NA
	Glass fibre polyamide [kg]	NA	NA	0,387	0,04	NA	NA	NA	NA
	Polystyrene foam [kg]	NA	NA	NA	NA	NA	NA	NA	NA
	Polyethylene low density (LDPE) [kg]	NA	NA	NA	NA	NA	NA	0,29	NA
	Other Plastics	0,002	NA	0,056	0,03	NA	NA	0,84	0,112

Table 6
Consumption measured for the use phase of the two ovens.

	Gas Oven		Electric Oven	
Functional unit	The baking of a food, considering the Italian context and a lifetime of 10 years, measuring the consumption through the standard test for labelling certification			
Energy consumption percycle	5,16 [MJ/cycle] (natural gas) 55 [Wh/cycle] (electricity)		0,88 [kWh/cycle]	
Lifetime	10 [years]		10 [years]	
Scenario	Non-intensive use 110 [cycle/year]	Intensive use 260 [cycle/year]	Non-intensive use 110 [cycle/year]	Intensive use 260 [cycle/year]
Energy consumption during lifetime	1573 [kWh] (natural gas) 60,5 [kWh] (electricity)	3718 [kWh] (natural gas) 143 [kWh] (electricity)	968 [kWh]	2288 [kWh]
SimaPro dataset	Natural gas, low pressure {IT}| market for | Alloc Rec, S		Electricity, low voltage {IT}| market for | Alloc Rec, S	

– Natural gas (methane) - Natural gas, low pressure {IT}| market for | Alloc Rec, S
– Electric energy - Electricity, low voltage {IT}| market for | Alloc Rec, S

2.3.3. *Life cycle inventory: product end-of-life*

The ovens end-of-life follow the European directive 2012/19/EU, which is regulating the Waste of Electric and Electronic Equipment (WEEE). Within this directive, the EU sets the recycling and/or the reuse rates of products and regulates the entire waste management system, from the collection and storage in the appropriate sites, to the preliminary treatments necessary until the final disposal. Shredding with metal recycling scenario has been chosen in this analysis as a baseline scenario because this is the current disposal scenario in Italy for this kind of product. The recycling rate has been evaluated for each component and then the recyclability rate of the entire equipment has been obtained. The percentage of recycled material depends on the type of material and the technological level reached for a given application (Favi et al., 2017). Indeed, the recycling rate of some materials, such as plastics, is reduced or increased if the preliminary processes of shredding or selective disassembly are performed. The values of the recycling rate have been set by following the guidelines provided by the IEC/TR 62635 directive. Three scenarios have been modelled to estimate how the benefits change if different recycling processes are considered and are as follows:

– “optimistic” scenario (OPT): manual disassembly process and complete material recycling;
– “realistic” scenario (STD): manual disassembly of only critical components and shredding of the entire product for metal recycling;
– “pessimistic” scenario (PST), landfill disposal of the entire appliance;

Specific components can be considered critical components because they contain hazardous or valuable substances. A list of these components is present in European directive 2012/19/EU. In the case of the two ovens, the electric motors and cables represent the hazardous and valuable components, which can be considered recyclable with a high recycling rate (Navarro et al., 2014). A landfill disposal scenario has been hypothesized for other materials that cannot be recycled, such as rock wool, glass fibre and mixed plastics. The purpose of this comparison is to understand if the current scenario, represented by the “realistic” case, has a substantial difference compared to the “optimistic” one and how much is the percentage of benefits compared to the impact of the other phases.

2.4. Life cycle impact assessment

The data collected during the Life Cycle Inventory have been processed using *SimaPro 8.05.13*. The midpoint *ReCiPe (H)* model has been used to characterize the results of LCI (Goedkoop et al., 2009; Goedkoop et al., 2013a,b). The chosen impact categories are shown in Table 7.

3. Results and discussion

The environmental impacts of the two ovens are shown in Tables 8 and 9 for all the analysed scenarios. The environmental impacts have been expressed by means of the ReCiPe impact assessment method at the midpoint level. As a general outcome, both the "non-intensive" and "intensive" product use scenarios where the gas oven performs better than electric oven in all impact categories.

Concerning the electric oven, the environmental impacts related to the product use phase are dominant compared with the other life cycle phases in both use scenarios. In particular, focusing on the "intensive" scenario, for most of the analysed indicators the product use phase is one order of magnitude higher compared with the other two life cycle phases (i.e., product use phase and product end-of-life). For example, the climate change indicator shows a noticeable difference between the raw material extraction + manufacturing processes for the components' production/assembly phase and the product use phase (1.99 E+02 [kg CO2 eq] vs. 1.46 E+03 [kg CO2 eq]).

Concerning the gas oven, differences between the raw material extraction + manufacturing processes for the components' production/assembly phase and the product use phase is less pronounced and for most of the midpoint indicators the raw material extraction + manufacturing processes for the components' production/assembly phase is more important compared with the use phase (e.g., Freshwater eutrophication, Marine eutrophication, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Freshwater ecotoxicity, Marine ecotoxicity and Metal depletion). Instead, looking specifically at the climate change indicator, the result is similar between the two phases (2.09 E+02 [kg CO2 eq] vs. 1.90 E+02 [kg CO2 eq]) for the "non-intensive" scenario.

Another interesting outcome deals with the Metal depletion indicator. Indeed, for both gas and electric ovens the value related to the raw material extraction + the manufacturing processes for components production/assembly phase is always an order of magnitude higher than the value related to the product use phase. This is due to the intensive use of metals when manufacturing ovens.

Focusing on the raw material extraction + manufacturing processes for the components' production/assembly phase, both ovens show a similar trend in the values of each environmental indicator. Only slight differences are noticeable between the two technologies and they are related to the differences in the product equipment as highlighted in section 2.1 (e.g., heating elements, temperature control system, the safety system, etc.).

Focusing at the product end-of-life phase, regardless of the analysed scenarios (i.e., optimistic, realistic and pessimistic), the midpoint indicators show a negligible amount if compared with the overall life cycle. Indeed, taking the CC indicator into account, the end-of-life accounts approx. 8% for the gas oven and approx. 5% for the electric oven in the "non-intensive" product use scenario, and this share decrease even more in the "intensive" scenario.

A specific comparison that keeps the same "optimistic" scenario for the end-of-life phase is reported in Figs. 7 and 8 for the "non-intensive" and "intensive" product use scenarios, respectively. In both graphs, the values are reported when considering the entire life cycle of the two products in a 100% stacked bar chart (the blue bar represents the contribution of the gas oven and the orange one the contribution of the electric oven). As a general outcome, the same trend can be noticed in both scenarios. Indeed, the two graphs show at a glance a notable dominance in terms of the environmental burdens of the electric oven, as it presents higher impacts in all midpoint impact categories. The results related to the "intensive" scenario (Fig. 7), which express the impacts deriving from a more intensive use phase, demonstrate how the trend in all midpoint categories are essentially equal to the result of the "non-intensive" scenario (Fig. 8) with a slight differences in the specific indicators (e.g., for the climate change indicator the share passes from 31% in the non-intensive scenario to 27% in the intensive scenario).

The analysis of each environmental indicator shows how in the case of Ozone depletion, Natural land transformation, Metal depletion and Fossil depletion, the gap between the two technologies in the entire life cycle is below the 2% threshold in the "non-intensive" scenario and below the 5% threshold in the "intensive" scenario. In contrast, for Climate change, Freshwater ecotoxicity and Marine ecotoxicity, the difference between the two technologies in the entire life cycle is very important and, in particular, they account for approx. 70% for the electric oven for the "non-intensive" scenario and approx. 80% for the "intensive" scenario (see Fig. 4).

Figs. 5 and 6 show the impacts and avoided impacts of the three phases included in the system boundaries for the gas oven and the electric oven, respectively. Looking at the first graph related to the gas oven (Fig. 5), the product use phase is the most impactful phase among the three in the following categories: Climate change, Ozone depletion, Terrestrial acidification, Photochemical oxidant formation, Natural land occupation and Fossil depletion. Product

Table 7
Midpoint impact categories in ReCiPe.

Impact category	Unit	Characterization factor Name	Abbreviation
Climate change	kg CO2 eq	global warming potential	GWP
Ozone depletion	kg CFC-11 eq	ozone depletion potential	ODP
Terrestrial acidification	Kg SO2 eq	terrestrial acidification potential	TAP
Freshwater eutrophication	kg P eq	freshwater eutrophication potential	FEP
Marine eutrophication	kg N eq	marine eutrophication potential	MEP
Human toxicity	kg 1,4-DB eq	human toxicity potential	HTP
Photochemical oxidant formation	kg NMVOC	photochemical oxidant formation potential	POFP
Particulate matter formation	kg PM10 eq	particulate matter formation potential	PMFP
Freshwater aquatic ecotoxicity	kg 1,4-DB eq	freshwater ecotoxicity potential	FETP
Marine aquatic ecotoxicity	kg 1,4-DB eq	marine ecotoxicity potential	METP
Natural land transformation	m2	natural land transformation potential	NLTP
Metal depletion	kg Fe eq	metal depletion potential	MDP
Fossil depletion	kg oil eq	fossil depletion kg oil eq potential	FDP

Table 8
Electric oven environmental impacts.

Electric oven													
Impact category	Unit	Materials + Manufacturing	Use		EoL			Non-intensive TOTAL			Intensive TOTAL		
Method: ReCiPe Midpoint (H) V1.12 Europe Recipe H			Non-intensive	Intensive	OPT	STD	PST	OPT	STD	PST	OPT	STD	PST
Climate change	*kg CO2 eq*	1.99 E+02	6.19 E+02	1.46 E+03	−4.25 E+01	−3.78 E+01	1.81 E+00	7.76 E+02	7.80 E+02	8.20 E+02	1.62 E+03	1.62 E+03	1.66 E+03
Ozone depletion	*kg CFC-11 eq*	2.96E-05	8.18E-05	1.93E-04	−2.06E-06	−1.98E-06	5.92E-08	1.09E-04	1.09E-04	1.11E-04	2.21E-04	2.21E-04	2.23E-04
Terrestrial acidification	*Kg SO2 eq*	1.41 E+00	2.36 E+00	5.59 E+00	−2.04E-01	−1.87E-01	1.50E-03	3.57 E+00	3.59 E+00	3.78 E+00	6.79 E+00	6.81 E+00	7.00 E+00
Freshwater eutrophication	*kg P eq*	1.30E-01	1.09E-01	2.58E-01	−1.69E-02	−1.64E-02	5.75E-05	2.22E-01	2.22E-01	2.39E-01	3.70E-01	3.71E-01	3.87E-01
Marine eutrophication	*kg N eq*	8.64E-02	7.31E-02	1.73E-01	−4.38E-02	−4.01E-02	1.39E-02	1.16E-01	1.19E-01	1.73E-01	2.15E-01	2.19E-01	2.73E-01
Human toxicity	*kg 1,4-DB eq*	2.25 E+02	1.15 E+02	2.71 E+02	−1.94 E+01	−1.90 E+01	1.86 E+00	3.20 E+02	3.20 E+02	3.41 E+02	4.76 E+02	4.76 E+02	4.97 E+02
Photochemical oxidant formation	*kg NMVOC*	7.95E-01	1.39 E+00	3.29 E+00	−2.12E-01	−2.00E-01	2.63E-03	1.98 E+00	1.99 E+00	2.19 E+00	3.88 E+00	3.89 E+00	4.09 E+00
Particulate matter formation	*kg PM10 eq*	6.40E-01	7.30E-01	1.73 E+00	−1.63E-01	−1.57E-01	6.55E-04	1.21 E+00	1.21 E+00	1.37 E+00	2.20 E+00	2.21 E+00	2.37 E+00
Freshwater aquatic ecotoxicity	*kg 1,4-DB eq*	7.65 E+00	1.86 E+01	4.40 E+01	−4.18E-01	−2.91E-01	5.92E-01	2.59 E+01	2.60 E+01	2.69 E+01	5.12 E+01	5.14 E+01	5.23 E+01
Marine aquatic ecotoxicity	*kg 1,4-DB eq*	7.53 E+00	1.62 E+01	3.82 E+01	−4.18E-01	−3.08E-01	4.94E-01	2.33 E+01	2.34 E+01	2.42 E+01	4.53 E+01	4.54 E+01	4.62 E+01
Natural land transformation	*m2*	3.23E-02	9.44E-02	2.23E-01	−4.21E-03	−4.07E-03	−1.17E-03	1.22E-01	1.23E-01	1.25E-01	2.51E-01	2.51E-01	2.54E-01
Metal depletion	*kg Fe eq*	1.35 E+02	1.70 E+01	4.02 E+01	−3.03 E+01	−3.03 E+01	1.09E-02	1.22 E+02	1.22 E+02	1.52 E+02	1.45 E+02	1.45 E+02	1.75 E+02
Fossil depletion	*kg oil eq*	5.19 E+01	1.85 E+02	4.38 E+02	−1.09 E+01	−9.50 E+00	1.19E-01	2.26 E+02	2.28 E+02	2.37 E+02	4.79 E+02	4.81 E+02	4.90 E+02

Table 9
Gas oven environmental impacts.

Gas oven													
Impact category	Unit	Materials + Manufacturing	Use		EoL			Non-intensive TOTAL			Intensive TOTAL		
Method: ReCiPe Midpoint (H) V1.12 Europe Recipe H			Non-intensive	Intensive	OPT	STD	PST	OPT	STD	PST	OPT	STD	PST
Climate change	*kg CO2 eq*	2.09 E+02	1.90 E+02	4.50 E+02	−4.72 E+01	−4.28 E+01	1.98 E+00	3.52 E+02	3.56 E+02	4.01 E+02	6.12 E+02	6.16 E+02	6.61 E+02
Ozone depletion	*kg CFC-11 eq*	1.93E-05	9.18E-05	2.18E-04	−2.31E-06	−2.21E-06	6.32E-08	1.09E-04	1.09E-04	1.11E-04	2.35E-04	2.35E-04	2.37E-04
Terrestrial acidification	*Kg SO2 eq*	1.50 E+00	9.43E-01	2.24 E+00	−2.85E-01	−2.55E-01	1.60E-03	2.16 E+00	2.19 E+00	2.45 E+00	3.46 E+00	3.49 E+00	3.74 E+00
Freshwater eutrophication	*kg P eq*	1.56E-01	3.31E-02	7.85E-02	−3.24E-02	−2.83E-02	6.29E-05	1.56E-01	1.60E-01	1.89E-01	2.02E-01	2.06E-01	2.34E-01
Marine eutrophication	*kg N eq*	9.74E-02	1.91E-02	4.52E-02	−5.02E-02	−4.59E-02	1.47E-02	6.63E-02	7.05E-02	1.31E-01	9.24E-02	9.67E-02	1.57E-01
Human toxicity	*kg 1,4-DB eq*	2.80 E+02	3.62 E+01	8.58 E+01	−5.27 E+01	−4.40 E+01	2.02 E+00	2.64 E+02	2.73 E+02	3.19 E+02	3.14 E+02	3.22 E+02	3.68 E+02
Photochemical oxidant formation	*kg NMVOC*	8.69E-01	5.50E-01	1.30 E+00	−2.42E-01	−2.27E-01	2.83E-03	1.18 E+00	1.19 E+00	1.42 E+00	1.93 E+00	1.95 E+00	2.18 E+00
Particulate matter formation	*kg PM10 eq*	6.71E-01	3.09E-01	7.33E-01	−1.92E-01	−1.82E-01	7.01E-04	7.89E-01	7.99E-01	9.81E-01	1.21 E+00	1.22 E+00	1.40 E+00
Freshwater aquatic ecotoxicity	*kg 1,4-DB eq*	9.05 E+00	2.43 E+00	5.76 E+00	−9.44E-01	−6.58E-01	6.47E-01	1.05 E+01	1.08 E+01	1.21 E+01	1.39 E+01	1.41 E+01	1.55 E+01
Marine aquatic ecotoxicity	*kg 1,4-DB eq*	8.90 E+00	1.87 E+00	4.44 E+00	−9.81E-01	−7.07E-01	5.42E-01	9.79 E+00	1.01 E+01	1.13 E+01	1.24 E+01	1.26 E+01	1.39 E+01
Natural land transformation	*m2*	3.58E-02	9.10E-02	2.16E-01	−4.95E-03	−4.74E-03	−1.24E-03	1.22E-01	1.22E-01	1.26E-01	2.47E-01	2.47E-01	2.50E-01
Metal depletion	*kg Fe eq*	1.52 E+02	5.97 E+00	1.42 E+01	−4.09 E+01	−3.84 E+01	1.18E-02	1.17 E+02	1.19 E+02	1.58 E+02	1.25 E+02	1.28 E+02	1.66 E+02
Fossil depletion	*kg oil eq*	5.48 E+01	2.00 E+02	4.74 E+02	−1.21 E+01	−1.07 E+01	1.27E-01	2.43 E+02	2.44 E+02	2.55 E+02	5.17 E+02	5.18 E+02	5.29 E+02

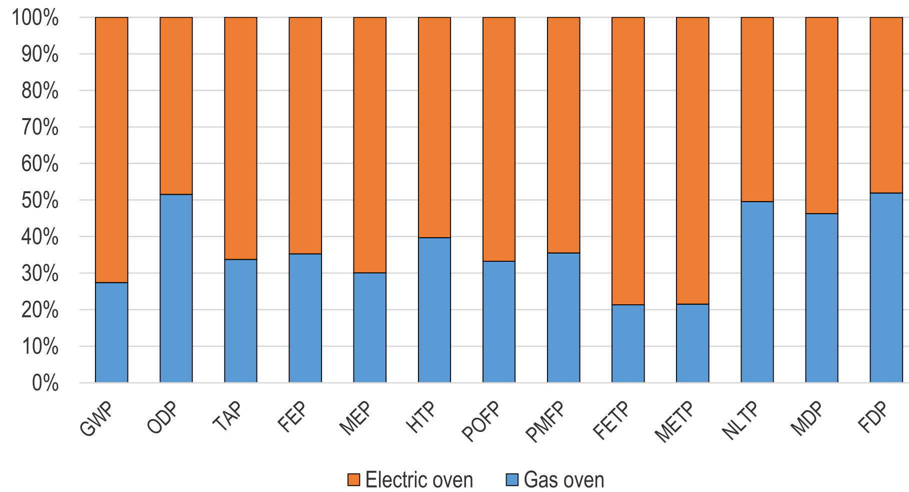

Fig. 4. Impact comparison between the two ovens with an "intensive" product use scenario and optimistic end-of-life scenario.

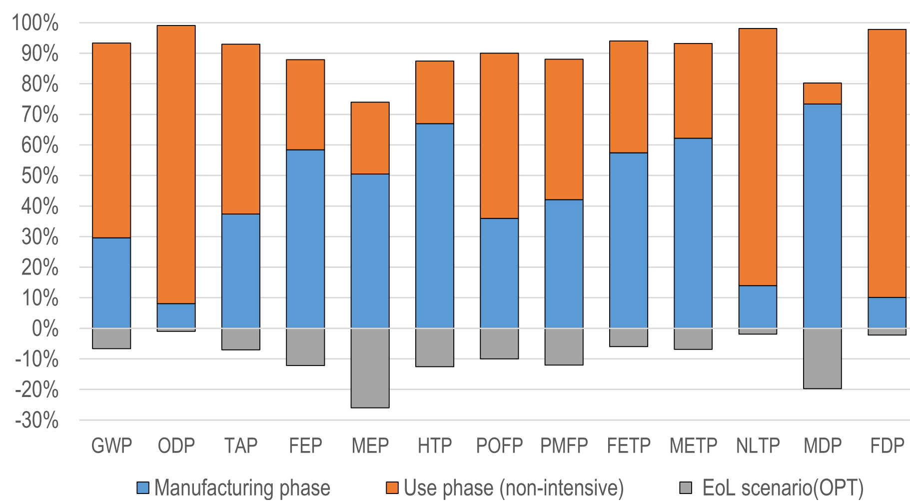

Fig. 5. Share of environmental impacts of the three life cycle phases for the gas oven.

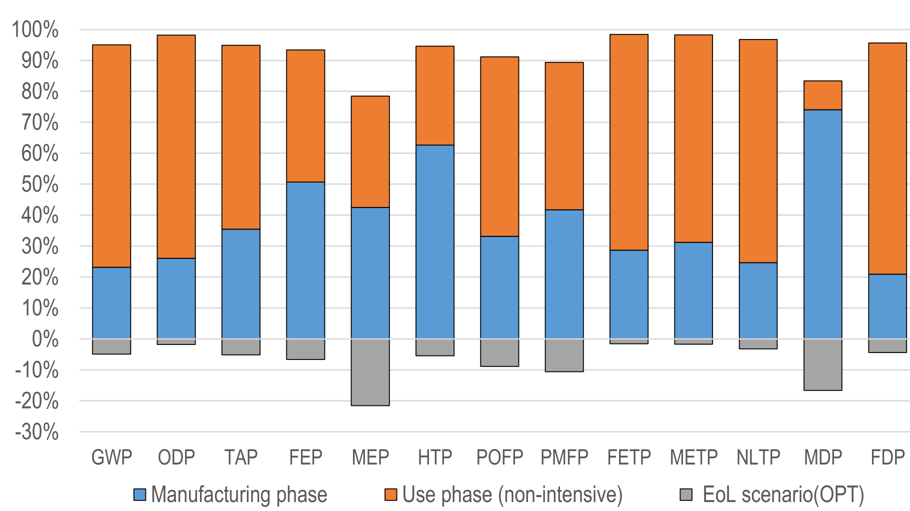

Fig. 6. Share of environmental impacts of the three life cycle phases for the electric oven.

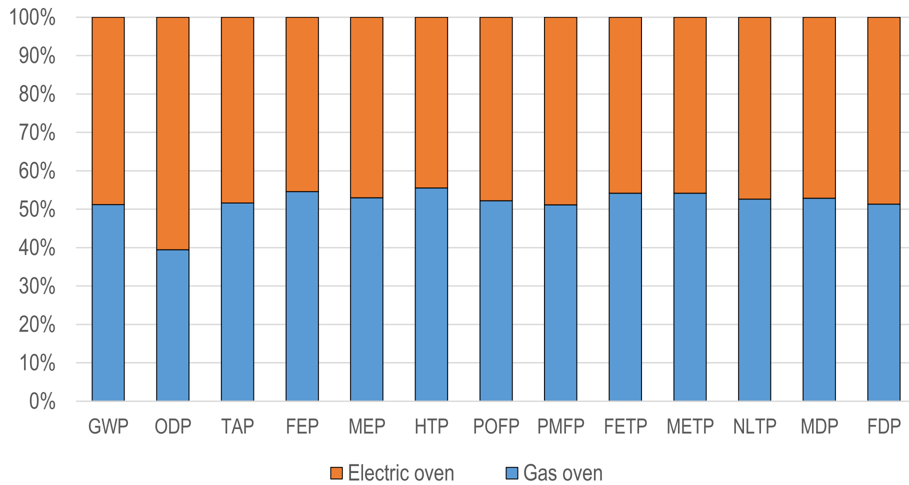

Fig. 7. Environmental impact of raw material extraction + manufacturing processes for components' production/assembly phase.

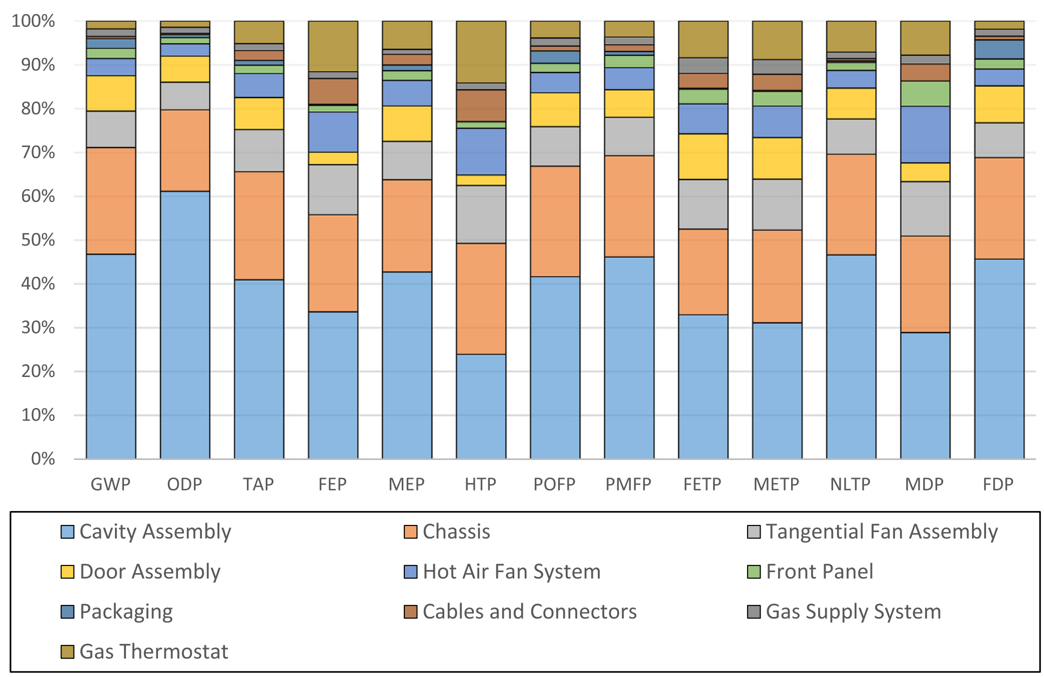

Fig. 8. Environmental impacts of gas oven product assemblies.

manufacturing, which includes the raw materials, becomes relevant in the gas oven for the following indicators: Marine eutrophication, Human toxicity, Freshwater ecotoxicity, Marine ecotoxicity and Metal depletion. On the other hand, looking at the second graph related to the electric oven (Fig. 6), the use phase is the most impactful phase among the three in all impact categories.

The highest share for the product use phase of the electric oven is the result of the Italian energy mix. Indeed, the Italian energy mix comprises power obtained from non-renewable fuels (e.g., gas, coal, etc.) produced at the power plants (IEA, 2016). The use of non-renewable resources together with the low efficiency at the power plant (approx. 40%) and the losses in the distribution network lead to enhanced differences in the environmental impact between the electric and the gas technology. Comparing the graphs of "non-intensive" and "intensive" scenarios (Figs. 5 and 6), it is worth highlighting how the gap between electric and gas ovens are even more marked.

From the overall life cycle perspective, a deeper and specific analysis has been performed for each life cycle phase, identifying the contribution of different aspects, such as: raw materials, manufacturing processes, components, assemblies or energy vectors. A first insight about midpoint indicators related to the raw material extraction + manufacturing processes for the components' production/assembly phase of the gas oven and the electric oven is shown in Fig. 7. From this general overview of manufacturing ovens, it is possible to highlight how the gas oven has a higher impact in almost all categories expect for ozone depletion. This outcome is in contrast with the life cycle analysis, which shows a more important contribute of the electric oven.

In detail, the shares of different product assemblies for the gas oven and the electric oven are shown in Figs. 8 and 9, respectively. From these two graphs, it is worth noting how the oven cavity and the structural frame (chassis) are the two assemblies with a higher share in the whole appliance, followed by the door and the cooling

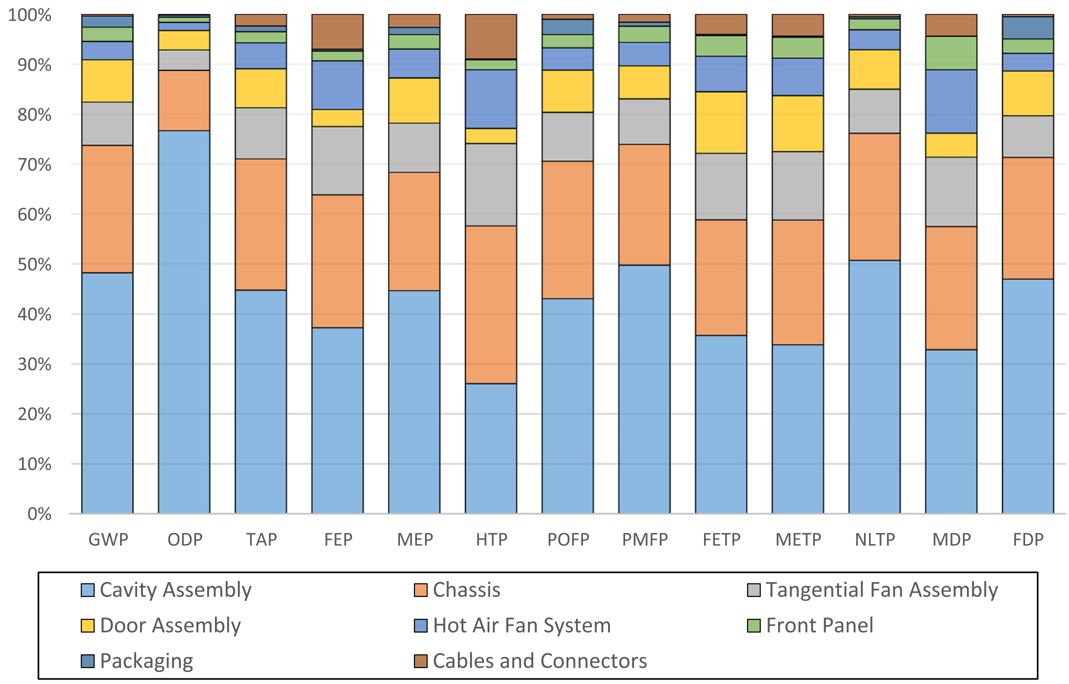

Fig. 9. Environmental impacts of electric oven product assemblies.

system (tangential fan). All four assemblies represent more than 70% of the environmental burden in all impact categories.

Concerning the gas oven, another important contribution in the environmental load is related to the manufacturing of the gas thermostat. This assembly is only present in gas ovens and leads to a relevant impact in the following categories: Freshwater eutrophication, Human toxicity, Freshwater ecotoxicity, and Marine ecotoxicity (approx. 30%). This is due to the presence in the resistors of polytetrafluoroethylene insulators, a plastic substance derived from the homopolymerization of tetrafluoroethylene, which exploits Chlorofluorocarbons (CFCs) gas in the synthesis process.

Looking at the differences in the product assemblies manufacturing between the two ovens, a slight difference can be noticed for the cavity assembly, which is higher for the electric oven due to the enamelling process of a larger surface. The thermostat assembly present in the gas oven has a significant relevance in the environmental impacts due to the use of metal alloys, such as brass and aluminium. These raw materials have a significant environmental impact if compared with the low-alloyed steel used in most other components. Moreover, the manufacturing processes used for these components are energy-consuming (e.g., high pressure die casting) and require a large amount of energy to melt and maintain the molten material bath at a high temperature.

With the aim of assessing the importance of the end-of-life phase and how it affects the environmental impacts of the two technologies, a comparison of the three end-of-life scenarios (OPT, STD and PST) in a “non-intensive” product use scenario are shown in Figs. 10 and 11 for gas ovens and electric ovens, respectively.

An obvious outcome is that the “pessimistic” end-of-life scenario (landfill disposal of the appliance) generates the highest environmental load for each midpoint category. The “optimistic” (recycling with manual disassembly) and “realistic” (shredding and mechanical separation process for metals recycling) scenarios generate a higher value of avoided impacts, even if the gap between these last two end-of-life scenarios is within 5%.

The adoption of the closed-loop end-of-life scenarios (realistic and optimistic) allow an important benefit to be reached in terms of Marine eutrophication and Metal depletion, which reduces the environmental load by more than 30% for gas ovens and approx. 20% for electric ovens. This aspect is related to the presence in the two ovens of a high quantity of metals (e.g., steels, aluminium, etc.) which can be recycled after a shredding and mechanical separation processes. For this reason, the “realistic” scenario can be considered the most suitable end-of-life scenario due to its feasibility, environmental sustainability and cost-effectiveness.

4. Conclusion

This study presents an environmental performance analysis of two different cooking technologies: the gas oven vs. the electric oven. The study analyses the overall product life cycle from cradle to grave, including the manufacturing and assembly phase of the products, the use phase and the product end-of-life. The Italian context has been chosen with the aim of evaluating the environmental performances in the same operative conditions. Differences in the product design as well as in the use of energy carriers (natural gas vs. electric energy) lead to a better performance of the gas oven compared with the electric oven.

In conclusion, the result of this comparison shows how the gas oven performs better than the electric one in all the midpoint impact categories. In particular, a comparable result has been observed in the Ozone depletion, Metal depletion and Fossil depletion considering both use scenarios (“non-intensive” and “intensive”). For all the other categories, the difference is more important. For example, the difference for the Climate change indicator is approx. 70% considering a “non-intensive” use scenario and 75% considering an “intensive” use scenario. In particular, by the analysis of the life cycle performances, it is determined that the product use phase represents the weak point for the electric oven. Despite the cooking test being performed following the current standard for product certification, the choice of Italian habits for the definition of the use profile and the characterization of the energy grid mix leads to an important consideration about the geographical context. Two different solutions can be adopted to decrease the

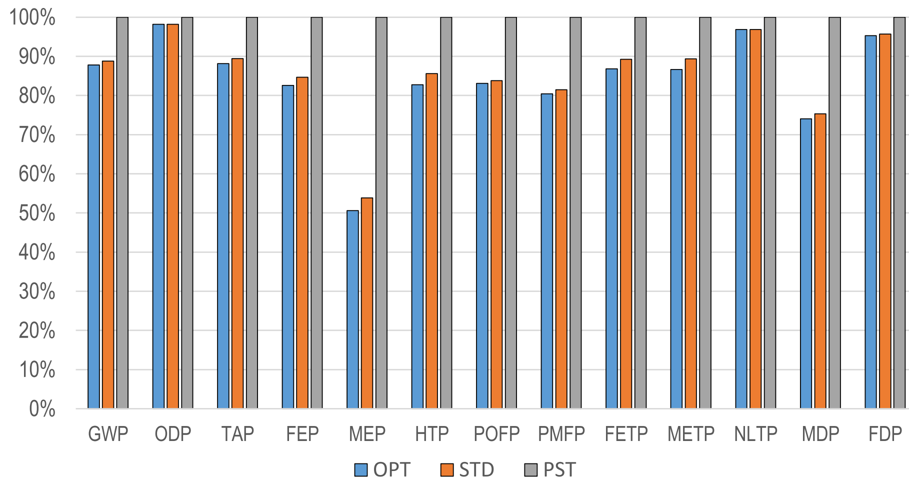

Fig. 10. Life cycle comparison of the gas oven in the three end-of-life treatments in a "non-intensive" use.

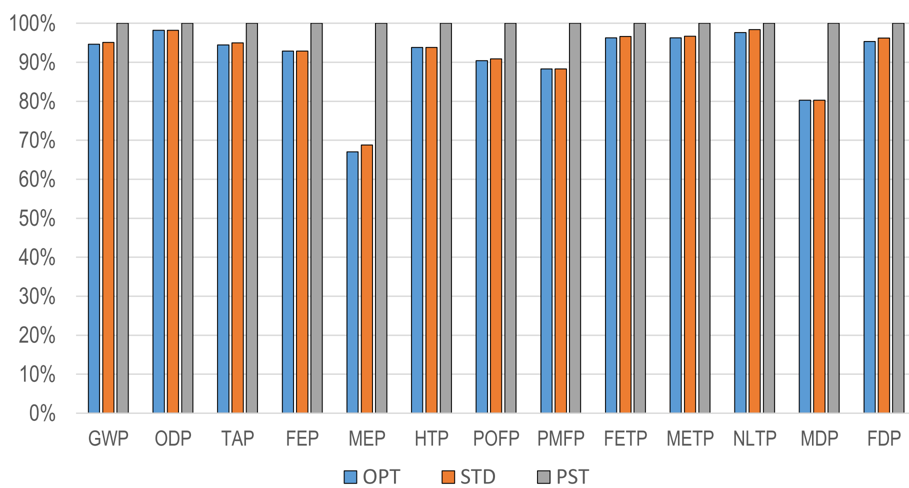

Fig. 11. Life cycle comparison of the electric oven in the three end-of-life treatments in a "non-intensive" use.

environmental load related to the electric oven use phase: (i) to reduce the energy consumption by increasing the energy efficiency class, and (ii) to change the feature of the electric grid mix towards a more sustainable solutions for the generation of electric energy. The first solution is technically feasible but with a marginal contribution to the final result, especially in a "non-intensive" use scenarios. On the other hand, the transition to a more renewable energy generation grid mix, by using renewable micro-scale technologies, largely affects the results of this study and leads to an important reduction in the environmental impacts of the electric technology.

Recalling the main design differences between the gas and electric oven, it is worth noting that the gas oven has a higher number of components, such as the gas supply system, gas thermostats, etc., which are not present in the electric oven. Given the current product configurations, from an environmental point of view the use of certain materials (e.g., aluminium alloys, brass, etc.) and energy-consuming manufacturing processes (e.g., high pressure die casting and metal chipping processes) determine the higher impacts of the gas oven.

Regarding the product end-of-life, manual disassembly with material recycling leads to negligible benefits if compared with product shredding for metal recycling. Indeed, this solution leads to a maximum benefit of 5% in all impact categories. Moreover, considering the "intensive" use, the benefits related to the avoided impacts are further reduced as the use phase becomes more relevant.

Future work will be dedicated to the economic assessment of the two technologies, taking the variability in the prices of the two energy carriers in a complex context such as the Italian one into account. Indeed, the cost and the availability of a certain energy carrier in reference to the other ones can affect the choice of consumers and the spread or the reduction of one technology in place of the other.

References

Ardante, F., Mathieux, F., 2014. Environmental assessment of the durability of energy-using products: method and application. J. Clean. Prod. 74 (1), 62–73. July 2014.
Ayoub, A., Irusta, C., 2014. Comparison between Electric Kettle and Stovetop Kettle - Life Cycle Assessment - Group LCA 2. Universiteit GENT.
Baitz, M., 2016. Attributional life cycle assessment. In: Curran, M. (Ed.), Goal and Scope Definition in Life Cycle Assessment. LCA Compendium – the Complete World of Life Cycle Assessment. Springer, Dordrecht. https://doi.org/10.1007/978-94-024-0855-3_3.
Bevilacqua, M., Caresana, F., Comodi, G., Venella, P., 2010. Life cycle assessment of a domestic cooker hood. J. Clean. Prod. 18 (18), 1822–1832. December 2010.
Elduque, D., Javierre, C., Pina, C., Jiménez, E., 2014. Life cycle assessment of a domestic induction hob: electronic boards. J. Clean. Prod. 76, 74–84. https://doi.org/10.1016/j.jclepro.2014.04.009.

EN 15181, 2017. Measuring Method of the Energy Consumption of Gas Fired Ovens.
European Commission, 2010. Energy Labelling Framework Directive (2010/30/EU), on the Indication by Labelling and Standard Product Information of the Consumption of Energy and Other Resources by Energy-Related Products.
European Commission, 2011a. Eco-design of Energy-Related Products Directive (EuP), Direttiva 2009/125/CE.
European Commission, 2011b. Preparatory Studies for Ecodesign Requirements of EuPs. Lot 22, Domestic and Commercial Ovens (Electric, Gas, Microwave), Including when Incorporated in Cookers. Task 3, Consumer Behaviour and Local Infrastructure. Final Version. European Commission, Brussels.
European Commission, 2011c. Preparatory Studies for Ecodesign Requirements of EuPs. Lot 22, Domestic and Commercial Ovens (Electric, Gas, Microwave), Including when Incorporated in Cookers. Task 4, Technical Analysis of Existing Products. Final Version. European Commission, Brussels.
European Commission, 2011d. Preparatory Studies for Ecodesign Requirements of EuPs. Lot 22, Domestic and Commercial Ovens (Electric, Gas, Microwave), Including when Incorporated in Cookers. Task 5, Definition of Base-Case. Final Version. European Commission, Brussels.
European Commission, 2012. Recommendations for Life Cycle Impact Assessment in the European Context-Based on Existing Environmental Impact Assessment Models and Factors European Commission, 2012. Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE).
Favi, C., Germani, M., Luzi, A., Mandolini, M., Marconi, M., 2017. A design for EoL approach and metrics to favour closed-loop scenarios for products. Int. J. Sustain. Eng. 10 (3), 136–146.
Favi, C., Germani, M., Landi, D., Mengarelli, M., Rossi, M., 2018. Comparative life cycle assessment of cooking appliances in Italian kitchens. J. Clean. Prod. 186, 430–449. https://doi.org/10.1016/j.jclepro.2018.03.140.
Fulkerson, J.A., Larson, N., Horning, M., Neumark-Sztainer, D., 2014. A review of associations between family or shared meal. Frequency and dietary and weight status outcomes across the lifespan. J. Nutr. Educ. Behav. 46 (1).
Gallego-Schmid, A., Mendoza, J.M.F., Jeswani, H.K., Azapagic, A., 2016. Life cycle environmental impacts of vacuum cleaners and the effects of European regulation. Sci. Total Environ. 559, 192–203, 15 July 2016.
Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., van Zelm, R., 2009. ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation - First edition - VROM–Ruimte en Milieu, Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer. Retrieved from. http://www.lcia-recipe.net. last access September 2017.
Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., van Zelm, R., 2013a. ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation - First edition (version 1.08) - VROM–Ruimte en Milieu, Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer (Retrieved from. http://www.lcia-recipe.net. September 2017.
Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryve, A., 2013b. ReCiPe 2008, A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level.
Grignon-Massé, L., Rivière, P., Adnot, J., 2011. Strategies for reducing the environmental impacts of room air conditioners in Europe. Energy Policy 39, 2152–2164. https://doi.org/10.1016/j.enpol.2011.02.004.
IEA, 2016. International Energy Agency, Energy Policies of IEA Countries, 2016. https://www.iea.org/publications/freepublications/publication/EnergiePoliciesofIEACountriesItaly2016Review.pdf.
IEC 60350-1, 2016. Household electric cooking appliances - Part 1: ranges, ovens, steam ovens and grills - methods for measuring performance.
IEC/TR 62635, 2012. Guidelines for End-Of-Life Information provided by Manufacturers and Recyclers and for Recyclability Rate Calculation of Electrical and Electronic Equipment.
Iraldo, Fabio, Facheris, C., Nucci, B., 2016. Is product durability better for environment and for economic efficiency? A comparative assessment applying LCA and LCC to two energy-intensive products. J. Clean. Prod. 140 (3), 1353–1364, 1 January 2017.
ISO, 2006a. 14040:2006 - Environmental Management - LCA - Principles and Framework.
ISO, 2006b. 14044:2006 -Environmental Management - LCA - Requirements and Guidelines.
Jungbluth, N., 1997. Life-Cycle-Assessment for Stoves and Ovens. UNS Working Paper No. 16.
Landi, D., Capitanelli, A., Germani, M., 2017. Ecodesign and energy labelling: the role of virtual prototyping. In: Procedia CIRP, vol. 61, pp. 87–92.
Ma, J., Yin, F., Liu, Z., Zhou, X., 2012. The eco-design and green manufacturing of a refrigerator. Procedia Environ. Sci. 16, 522–529. https://doi.org/10.1016/j.proenv.2012.10.072.
Monfared, Behzad, Furberg, Richard, Palm, Björn, 2014. Magnetic vs. vapor-compression household refrigerators: a preliminary comparative life cycle assessment. Int. J. Refrig. 42, 69–76. June 2014.
Monteleone, B., Chiesa, M., Marzuoli, R., Verma, V.K., Schwarz, M., Carlon b,c, E., Schmidl, C., Ballarin Denti, A., 2015. Life cycle analysis of small scale pellet boilers characterized by high efficiency and low emissions. Appl. Energy 155 (1 October 2015), 160–170.
Navarro, J., Zhao, F., Sutherland, J., 2014. Comparative LCA of NdFeB and ferrite motors used in the microfabrication industry, 9th International Workshop on microfactories. Procedia CIRP 48 (2016), 45–50.
Nuvoli, Gianfranco, 1 June 2015. Family meal frequency, weight status and healthy management in children, young adults and seniors. A study in Sardinia, Italy. Appetite 89, 160–166.
Palmer, J., Terry, N., Kane, T., Firth, S., Hughes, M., Pope, P., Young, J., Knight, D., Godoy-Shimizu, D., 2013. Further Analysis of the Household Electricity Use Survey Electrical Appliances at Home: Tuning in to Energy Saving. Cambridge Architectural Research Limited. Reference 475/09/2012.
Pina, C., Elduque, D., Javierre, C., Martínez, E., Jiménez, E., 2015. Influence of mechanical design on the evolution of the environmental impact of an induction hob. Int. J. LCA. 20, 937–946. https://doi.org/10.1007/s11367-015-0890-y.
Vignali, G., 2017. Environmental assessment of domestic boilers: a comparison of condensing and traditional technology using life cycle assessment methodology. J. Clean. Prod. 142 (4), 2493–2508, 20 January 2017.
Xiao, Rufeng, Zhang, You, Liu, Xin, Yuan, Zengwei, 2015. A life-cycle assessment of household refrigerators in China. J. Clean. Prod. 95, 301–310, 15 May 2015.