Carbon Footprint of a pale lager packed in different formats: assessment and sensitivity analysis based on transparent data

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Abstract

Energy and water consumption, waste generation, and emissions to air are the main environmental issues of the brewing industry. Several strategies have been so far proposed to reduce its impact on the global climate. This study assessed the environmental impact of the industrial production and distribution of 1 hL of a pale lager, as packed in different formats by the Italian brewery *Birra Peroni* Srl (Rome, Italy) over the period April 2012-March 2013, in compliance with the Publicly Available Specification 2050 standard method. The estimated carbon footprint of 1 hL of lager beer packaged in 66-cL glass bottles, 33-cL glass bottles assembled in cardboards or cluster packs, 33-cL aluminum cans, or 30-L steel kegs was of the order of 57, 67, 74, 69, or 25 kg CO_{2e}, respectively. Such a difference in the overall carbon footprint values was due to the diverse contributions of packaging materials and transportation. In particular, the impact of packaging materials was minimum in the case of kegs, in virtue of the high reuse coefficient, and maximum in the case of the 33-cL glass bottle cluster packs. The estimated carbon footprint values were considerably lower than those reported in the most recent literature, probably because of the large production scale and short distribution chain of *Birra Peroni* brewery, utilization of beer co-products as feed and anaerobic digestion of liquid wastewaters. Owing to the linearity of the mathematical model of the carbon footprint, its sensitivity to the change of one-emission factor-at-a-time allowed the main hot spots in the life cycle of beer (i.e., glass bottle production and barley cultivation) to be identified and targeted for mitigating the carbon footprint of any pale lager, both of them being not related to the brewery production scale examined here. The scientific value of this work relies on the choice of estimating the carbon footprint using wholly transparent data in order to allow its direct comparison to other estimates, as well as its straightforward re-calculation using better quality data, as available.

1. Introduction

In spite of the main commitments to reduce the current greenhouse gas (GHG) emissions in the Earth atmosphere and mitigate climate change under the Kyoto Protocol targets, the GHG emissions associated to the food supply chain are significantly contributing to the Earth global warming. For instance, Tukker et al. (2006) estimated that the food, drink, tobacco, and narcotics area of consumption accounted for 22-31% of the so called Global Warming Potential (GWP) impact category referred to a series of products (i.e., cars, food, heating, and house building) consumed in the EU-25. Within this area of consumption, meat and meat products had the greatest environmental impact with an estimated contribution to GWP in the range of 4-12 % of all products, whereas the soft-drinks and alcoholic beverages accounted for the 0.9 and 0.6% of the GWP of total products, respectively. Thus, the beverage sector has started implementing strategies to reduce its impact on the global climate, as focused for instance by the Beverage Industry Environmental Roundtable on the basis of the sensitivity of the beer GWP to variations in material or process practice aspects (such as packaging material selection, distribution logistics, recycling rates, etc.) in either Europe or North America (BIER, 2012). Despite its ancient tradition, the brewing industry is currently pushed to perform within the constraints of product quality, process safety, economic viability, and limited environmental damage.

The main environmental issues associated with brewing include material, water, and energy consumption, as well as waste production. Brewery processes are intensive users not only of both electrical and thermal energy, but also of good-quality water. By referring to some European breweries, their corresponding specific consumption yields ranged from 8 to 12 kWh, from 100 to 200 MJ, and from 4 to 7 hL per hL of beer produced, respectively (Olajire, 2012). Additionally, wastewater generation ranges from 1 to 5 % of total beer production. Several studies have been so far carried out to understand and verify the environmental impact generated through the entire life cycle of some lager beers in Chile (Muñoz et al., 2012), Denmark (Frees and Pedersen Weidema, 1998), Estonia (Talve, 2001), Greece (Koroneos et al., 2005), Italy (Cordella et al., 2008), Japan (Takamoto et al., 2004), and Spain (Hospido et al., 2005). Also a few environmental product declarations (EPD, 2010, 2011ab) provided reliable quantification and certification of the environmental performance of lager-type beers packed in disposable 33-cL glass bottles, 25-L steel kegs, or 20-L plastic drums, according to the Life Cycle Assessment methodology (ISO, 2006).

By accounting for the beer life cycle, Hospido et al. (2005) and Talve (2001) assessed that the most relevant environmental impact of the agricultural subsystem regarded the eutrophication impact category, owing to the leakage of nitrogen- and phosphorous-rich compounds from agricultural fields, production of fertilizers, etc. The packaging system used greatly affected the GHG emissions, these ranging from about 106 or 149 kg CO_{2e} hL^{-1} of beer barreled in plastic or steel kegs, up to 190 kg CO_{2e} hL^{-1} of beer bottled in glass bottles (EPD, 2011a). Whereas the GHG emissions associated with the production process represented as little as 14.8 to 17.7 % of the overall ones, those issued from the upstream production or downstream processes were the greatest ones when including glass bottle production or steel keg distribution, respectively (EPD, 2011a).

Another study was performed by the Climate Conservancy (2008) in cooperation with New Belgium Brewing Company to assess the GHG emissions across the full life cycle of Fat Tire® Amber Ale (FT) using the British Standard Publicly Available

Specification (PAS 2050) standard method (BSI, 2008a), as detailed in the Guide to PAS 2050 (BSI, 2008b). The system boundaries of the life cycle study included acquisition and transport of raw materials, brewing operations, business travel, employee commuting, transport and storage during distribution and retail, use and disposal of waste. The estimated carbon footprint (CF) was about 150 kg CO_{2e} per hL of beer packaged in glass bottles of 12-fluid ounce capacity (1 fl ounce ≈ 29.57 mL) in a 6-bottle selling unit, this figure being quite smaller than the values mentioned above (EPD, 2011a).

Owing to the numerous factors, assumptions, and performance variables that can impact the above calculated carbon footprints, current carbon quantification exercises cannot in principle be used to compare not only different beverages, but also the same category of beverages. Despite several comparative LCA studies of beer production have been published over the last decade, the use of qualitative, often incomplete, data and, what is more, unknown emission factors allow no direct comparison among the environmental scores reported.

Among the numerous international standards (i.e., PAS 2050; *Bilan Carbone*®; *Environmental Product Declaration*, EPD®; *Greenhouse Gas Protocol; Australian Wine Carbon Calculator*, AWCC) currently available to assess product and service environmental impact, the great majority of them, except the EPD® procedure, focuses on the single impact category of climate change only, and does not assess other potential social, economic and environmental impacts (Moresi, 2014). Despite the carbon footprint is a "reduced scope" tool, which does not provide an indicator of the overall environmental impact for the activity examined, it appears to be an opportunity for small and medium enterprises to make their activities more sustainable, as well as to satisfy the interest of the market towards eco-labeling initiatives.

To calculate the carbon footprint, it is crucial to rely on appropriate emission factors. Similarly, the estimation of all the environmental impact categories, considered for instance by the Eco-indicator 99 method, asks for an impressive number of prefixed parameters in order to reduce the 11 impact categories to just three damage categories (Goedkoop and Spriensma, 2001). Even the use of a well known LCA software, such as Simaprò (PRé Consultants, Amersfoort, NL), does not help to understand concealed material, energy, and emission interrelationships. In the circumstances, it is difficult to make comparisons among the CF studies reported in the literature, the typical weakness of which being their nontransparent nature regarding the use of data sources and limitations. Only the Bilan Carbone® and AWCC procedures refer to manuals reporting a series of emission factors (ADEME, 2007; NGA, 2013), and thus make the GHG emissions estimated by different companies for a given food or drink not only comparable, but also transparent. On the contrary, the quite numerous EPD® studies openly available at <http://www.environdec.com> provide no information about the emission factors used, this making such environmental assessment exercises no way repeatable and, thus, ineffective from a scientific point of view.

The first aim of this study was to develop a life-cycle assessment model to estimate the carbon footprint (CF) of the industrial production and distribution of 1 hL of lager beer in different packaging formats (i.e., 66- or 33-cL glass bottles, 33-cL aluminum cans, 30-L stainless steel kegs) and selling units (i.e., carton, tray, or cluster-multipack), by indicating clearly not only all the processing and packaging consumption yields, but also all the emission factors used. The second aim of this study was to carry out a sensitivity analysis of CF to assess the influence of different parameters (such as, origin of raw materials and their cultivation methods, GHG emissions per kWh of electric energy generated by fossil and/or renewable sources, transportation by road or railway, etc.) by changing one-emission factor-at-a-time and keeping the others at their nominal values in order to identify the most promising strategy to mitigate the GHG emissions associated to the production and distribution of the pale lager of concern.

2. Methods

The life-cycle analysis was performed in compliance with the PAS 2050 standard method (BSI, 2008a, 2008b), the stages of which being the following: goal and scope definition, inventory analysis, impact assessment, and interpretation of results. The scope of this study was to assess the environmental impact from cradle to beer distribution centers, this complying with a business-to-business study in accordance with PAS 2050.

2.1. Goal and scope

The goal for this study was to develop an LCA model to assess the carbon footprint of a pale lager beer, made of malted barley, maize grits and hop pellets, and produced from the Italian brewery *Birra Peroni* Srl (Rome, Italy), and consumed in Italy, as well as to identify its life-cycle hot spots. The purpose of the study was also to provide information for carbon labeling so as to inform the consumer on the total carbon footprint of lager beer, as well as to aid environmentally conscious decision-making.

2.2. *Functional unit*

The analysis was based on a *functional unit* defined as 1 hL of lager beer packaged in different packaging formats and selling units.

2.3. *System boundary*

The system boundary for this study was not restricted to the brewing process; and, in accordance with the LCA approach, it also included the upstream and downstream phases. The whole system is represented in Fig. 1 and included:

i) the agricultural processes of barley, corn, and hop cultivation;

ii) the production of malt, maize grits, and beer;

iii) the production of the packaging materials (glass bottles; aluminum cans; stainless steel kegs; closures; labels; cardboard cartons, trays or cluster-multipacks; wrap films; etc.), as well as the auxiliary ones (oxygen; carbon dioxide; phosphoric acid; calcium chloride; diatomaceous earth, DE; polyvynil-polypirrolidone, PVPP; cleaning products);

iv) the transport of raw, process, and packaging materials from their production sites to the brewery gate, as well as that of packaged beer to the distribution centers;

v) the disposal of packaging material waste generated in the brewery;

vi) the treatment of wastewaters, including the production of methane by anaerobic digestion, and

vii) the production of heat, as well as electricity utilization from the Italian grid.

All identification items used in Fig. 1 are given in the List of Symbols.

Since roots, spent grains, and yeast surplus are by-products that occur during malting and brewing processes, they were considered as an avoided production of cattle feed. This effect was accounted for in the life cycle assessment by means of CO_2 credits.

Contrary to PCR (2013), this case study neglected the beer consumption phase (i.e., beer refrigeration, dispensing, and losses; consumer displacement and wastewater treatment). Use phase scenarios are indeed extremely variable and a precise determination would have required an onerous investigation. Consequently, the waste generation in the consumption stage was not included; while the distribution stage was limited to the distribution centers, the consumer transport to and from the retail shop being excluded by the PAS 2050 standard method (see Section 6.5). As stipulated by PAS 2050, the production of capital goods (machinery, equipment and energy wares) was also excluded from the system boundary. Finally, all CO_2 credits from recycling of renewable and non-renewable materials were included.

2.4. Data gathering and data quality

According to PAS 2050 (Section 7.2), the following was stated:

i) <u>*Geographic scope*</u>: this LCA study focused on the production, and distribution of *Peroni* lager differently packaged in Italy. Fig. 2 shows the maps of raw materials purchased and *Peroni* lager sales distributed by the *Birra Peroni* brewery (Rome, Italy).

ii) <u>*Time scope*</u>: the reference time period for assessing the Carbon Footprint values was April 2012-March 2013. According to Assobirra (2013), the overall beer production by the three breweries owned by *Birra Peroni* Srl in Rome, Bari and

Padoa (Italy) in the years 2009 to 2013 was approximately constant and equal to 329,460 ± 6,736 m^3. Thus, the beer production was regarded as about steady over the above quinquennium, the change in beer demand being of the order of 2%.

iii) *Technical reference*: the process technology underlying the datasets used in this study reflects process configurations, as well as technical and environmental levels, which are typical for industrial-scale lager beer processing in the reference period.

iv) *Primary data* for this PAS 2050-compliant study were collected from the Italian brewery *Birra Peroni* Srl (Rome, Italy).

v) *Secondary data* were sourced from the Italian Institute for Environmental Protection and Research as concerning the GHG emissions associated to the Italian electric energy production by renewable and non-renewable sources (ISPRA, 2012), an LCA software (i.e., Simapro 7.2 v.2, Prè Consultants, Amersfoort, NL), and several databases (such as BUWAL 250, Ecoinvent, ETH-ESU 96, Franklin USA 98, Idemat 2001, LCA Food-DK) using the method developed by IPCC (2007), as well other technical reports (ADEME, 2007; BIER, 2012; BSI, 2008b; Chicago Manufacturing Center, 2009; Cimini and Moresi, 2015; Climate Conservancy, 2008; Coca Cola, 2010; Field To Market, 2012; International Aluminium Institute, 2013; ISPRA, 2012; Kanokkantapong et al., 2009; Ma et al., 2012; Manfredi et al., 2009).

Table 1 summarizes the emission factors, expressed in kg CO_{2e} emitted over a time horizon of 100 years, associated to the manufacture of the raw and packaging materials, ingredients and processing aids, as well as to the delivery of the main energy sources, aforementioned materials, final product in the tertiary packages of concern, and solid wastes generated during the brewing process under study. Since the final carbon footprint values are heavily dependent on the values chosen for such factors, these were carefully checked to provide perspectives on the key drivers to the product environmental impact and were deliberately shown to make transparent the CF estimation.

2.5. Inventory analysis

In this stage of the LCA procedure all the inputs of resources and energy and yield outputs for raw material production; beer processing, packaging, and transportation; waste management; and refrigerant losses were gathered as reported below.

2.5.1 Raw materials

The agricultural stage included barley, maize, and hop cultivation and postharvest operations (i.e., cleaning; de-stoning; grain germination; bran, grit and germ separation; drying; storage). Barley cultivation gives rise to several GHG emissions (as due to seed production, farm machinery operations, irrigation, use of fertilizers, pesticides, and soil amendments, as well as emissions from the soil) totaling ~0.638 kg CO_{2e} kg^{-1} of barley (Climate Conservancy, 2008). Malting consists of barley steeping in water and germination, followed by malt drying and roasting. Each of these steps requires both electric and thermal energy. According to the Chicago Manufacturing Center (2009), the GHG emissions associated to malting amounted to (0.292 ± 0.084) kg CO_{2e} kg^{-1} of malted barley, while the average ratio of barley-to-malt was approximately equal to 4:3 (Climate Conservancy, 2008). Thus, the default emission factor for malted barley was estimated as 1.143 kg CO_{2e} kg^{-1}. In this study, malted barley was produced at the malthouse *Saplo Spa* (Pomezia, Rome, Italy) from barley cultivated in Central and South Italy, the overall cultivation area being about 16,880 ha (Birra Peroni, 2012). Fig. 2a shows the cultivation map of barley purchased by *Birra Peroni* Srl. By accounting for the amounts of barley supplied by the regions of Italy differently colored in the map, it was possible to estimate the kilometric distance travelled by any lot of barley from its cultivation site to the *Saplo* processing plant (Pomezia, Italy) and then to the brewery using the web site http://www.viamichelin.it, these average distances being about 236 and 33 km, respectively.

As concerning the maize grits, two hybrid varieties of corn (that is, *Nostrano Peroni PR* and *ME*) were used as raw materials (Birra Peroni, 2012). Such varieties were cultivated in the provinces of Parma and Messina (Italy), respectively, as shown by the areas marked in yellow in Fig. 2a. Thus, their average transport distance was of about 608 km. Based on the USA GHG emissions per bushel of corn for grain from 1980 to 2011 (Field to Market, 2012), corn growth and harvesting would result in ~0.227 kg CO_{2e} kg^{-1} of grain corn, its moisture mass fraction being generally 0.155. Grain corn conversion into maize grits at an average moisture content of 12 % is of the order of 0.5 kg per kg of raw corn (Gresser, 2010; Mejía, 2003) and involves several operations, such as grain conditioning, degermination, drying, grading, and milling (Mejía, 2003). By assuming that such a process would take almost the same energy of malting, the GHG emissions associated to corn grit production may be roughly estimated as 0.746 kg CO_{2e} kg^{-1} maize grits.

In accordance with Climate Conservancy (2008), hop agriculture was regarded as characterized by the same impact categories accounted for barley, this leading to an estimated value of GHG emissions of about 2 kg CO_{2e} kg^{-1} hops processed. In the major hop growing regions, harvest is generally targeted when cones reach approximately 23% dry matter, while hops are dried down to 8-12% moisture for packaging and storage (Madden and Darby, 2012), this yielding further 0.391 kg CO_{2e} per kg of hops processed. In this case, hop pellets were sourced in Germany, this resulting in an average distance of 1,509 km.

It was also assumed that barley and corn were cultivated on land which had been used for agricultural purposes for longer than 20 years (PAS 2050: Section 5.5); therefore, the GHG emissions arising from land use change were not considered.

2.5.2. Processing

There are several steps in the brewing process, these including mashing, lautering, boiling, cooling, oxygenation, fermentation, conditioning, yeast removal, kieselguhr filtering, PVPP stabilization, and packaging. The lager beer under study was obtained with the high-gravity brewing method (Eßlinger, 2009). To arrest biological contamination, the chill haze-free lager beer was pasteurized using the conventional tunnel pasteurization method to heat progressively either glass bottles or aluminum cans up to 60 °C for 10-20 min, or the flash pasteurization method to heat the product up to circa 70 °C for 60-90 s before its aseptic filling in steel kegs.

In the schematic brewing process flow sheet shown in Fig. 1, all input materials and solid waste generated, as well as the needs for electric energy (EE) to drive all process equipment, machines, and refrigeration system (i.e., malted barley and corn grit conveyors, millers, mixers, filter, pumps, compressors, etc.) and for thermal energy (Q) during the mashing and wort boiling phases, were pointed out.

By referring to the overall production of 1,160,835 hL of *Birra Peroni* Srl in the reference time period examined, Table 2 shows the specific consumption yields for raw materials (malted barley, maize grits, hop pellets); brewing coadjutants and processing aids (i.e., oxygen; compressed air; calcium chloride and sulfate; phosphoric acid at a mass fraction of 0.75; DE; PVPP); chemicals for plant cleaning and PVPP regeneration (30 % caustic soda, 53% nitric acid, Oxonia active, etc.); and refrigerants (ammonia and ethylene glycol). Table 2 also lists the specific formation yields for spent grains and surplus yeast, i.e., the main by-products that occur during brewing, these being regarded as an avoided production of cattle feed. In particular, hop pellet consumption was estimated on the basis of an average iso-α–acid mass fraction of 0.055, whereas the average raw protein mass fraction of spent grains was assumed as equal to 0.08 (Platto Feeding Company, 2014). Moreover, *Oxonia active* (Ecolab Inc., St. Paul, MN, USA) is an acidic colorless liquid sanitizer for food processing equipment, composed of hydrogen peroxide (mass fraction: 0.275) and peracetic acid (CH_3-CO-O-OH, mass fraction: 0.058). No information about the lubricant consumption was available, thus their consumption per each functional unit was regarded as negligible in agreement with other CF estimates (Moresi and Paone, 2012). The weak wort, resulting from the final rinsing of spent grains with hot water and having a low sugar content of 1-2 °P (degrees Plato), and hot trub, separated from the hopped wort in the centre of the whirlpool tank, represented about the 6.7% and 4.0% by volume of any wort batch (i.e., 1,200 hL), respectively. The wastewaters had an average COD value of about 6,000 ppm (mg O_2 L^{-1}) and were firstly submitted to anaerobic digestion, the resulting liquid digestate being aerobically treated up to a final COD value of 69 ppm and then disposed of in the municipal sewer system. The resulting sludge was firstly anaerobically treated and finally composted.

All the other materials used in minimum quantities (that is, yeast starter cultures, minor chemicals and wastes, etc.) were not included in the system boundaries since their potential influence on the analysis results was assumed as negligible, being smaller than 1% (PAS 2050: Section 6.3).

2.5.3. Packaging

Beer packaging varied with the format selected. In the reference time period examined, the 88.9% of the overall *Peroni* beer was packaged in glass bottles (the 66.6% of which having a volume of 66 cL and the remainder 22.3% of 33 cL), the 6.9% in 33-cL aluminum cans and the residual 4.2% in 30-L steel kegs. Moreover, the 56% of the lager beer packaged in 33-cL glass bottles was assembled in cartons, each one containing 24 x 33-cL bottles; while the remainder in 3-packs and then in cartons, each one containing 8 clusters. Fig 3 shows the block diagrams for their primary, secondary and tertiary packaging processes in order to identify all the packaging materials and aids needed, the solid waste generated, as well as the electric and thermal energy needs.

Beer packaging is carried out using counter-pressure fillers, where any beer package is purged with CO_2 before being filled with beer. The gaseous stream used by *Birra Peroni Srl* was mainly that leaving the beer fermentors, while as little as the 5% of the overall amount needed was of fossil origin. This fraction was assumed to be totally dispersed in the Earth atmosphere. The utilization of the carbon dioxide exiting the beer fermentors guarantees perfect quality control, since residual oxygen in the commercial carbon dioxide has a detrimental effect on beer flavor stability. The gaseous streams leaving the fermentation tanks are firstly fed to a foam separator and then stored in low-pressure gas storage balloons. From these, the gas is firstly cleaned in a scrubber by counter flow of water, compressed to one sixteenth of its original volume, dried via molecular sieves, deodorized by activated carbon, and finally condensed at -20 °C and 18 bar.

Table 3 lists all the packaging materials and aids (i.e., glass bottles, aluminum cans, steel kegs, crown and can open closures, ball lock keg couplers, labels, adhesive, ink, cartons, cluster packs, trays, stretch and shrink film, pallet, etc.) used to prepare the beer primary, secondary and tertiary packages. Particularly, the primary packages consisted of 33- or 66-cL amber glass bottles, 33-cL aluminum cans, or 30-L stainless steel kegs. The secondary packages were made of cartons, each one containing 15 x 66-cL bottles, 24 x 33-cL bottles, or 8 clusters (any of the latter assembling 3 x 33-cL bottles), or trays of 24 x 33-cL cans.

Table 4 shows the specific consumption of the packaging materials used to package 1 hL of lager beer in the different formats examined.

2.5.4. Waste management

Fig. 4 shows the block flow diagram of solid waste and gaseous effluent formation during the *Birra Peroni* packaging and pallet management in the distribution centers. In particular, all wastes arising from the beer making were disposed of as follows:

- glass bottles, aluminum cans, or stainless steel kegs rejected during cleansing, sterilization and filling steps were collected and recycled to glass, aluminum, or steel manufacturing, respectively;

- body, neck and bar code labels discarded during primary packaging, as well as pallet tapes and labels rejected during tertiary packaging, were gathered and used as feedstock for recycled paper;
- cartons and trays refused during secondary packaging were amassed for recycling and reusing;
- stretch wrap films discarded during the secondary packaging of cans or tertiary one of bottles and cans, as well as keg valves during the primary packaging of kegs, were collected and recycled to make other polyethylene products;
- wooden pallets, either discarded during tertiary packaging or gathered for collection at the distribution centers, were repaired and reused.

On the contrary, the fossil carbon dioxide used to pilot the beer filling machines was assumed as totally released in the air.

Table 5 lists the different solid wastes formed during the manufacturing process as referred to the functional unit. Each packaging material waste can be extracted from the data listed in Table 4.

2.5.5. Transport

The only transport modality for raw materials, processing aids and detergents from their production sites to the *Birra Peroni* factory gate in Rome (Italy) was by road via the means of transport listed in Table 6. Their corresponding emission factors were dependent on the European emission standards and were sourced from the software Simaprò 2 (PRé Consultants, Amersfoort, NL). According to Birra Peroni (2012), the average emission factor for any means of transport was estimated by assuming that the

30% of all materials was transported by using Euro 5 means, while the remainder 70% by Euro 3 ones.

The average distance travelled from any production site to the brewery gate by all raw and packaging materials, processing aids, and detergents, as well as any transport modality, is shown in Tables 2 and 4.

As regarding the final product packaged in the formats under study, such packages were generally delivered to numerous distribution centers located in quite all the provinces of Italy (see Fig. 2). According to Birra Peroni (2012), about the 30% of the overall production was delivered by means of heavy rigid trucks (HRT), while the remainder 70% by articulated trucks (AT), their average emission factors being listed in Table 6. Thus, the average emission factor resulted to be equal to:

[0.3 x (0.3 x 0.268 + 0.7 x 0.291) +0.7 x (0.3 x 0.154+ 0.7 x 0.168)]

≈ 0.2 kg CO_{2e} (Mg km)$^{-1}$.

Moreover, since 2009 *Birra Peroni* Srl has rationalized its distribution network so as to increase the average truck loading rate and minimize the distance travelled by any format. According to the data sourced by the Sales Office of *Birra Peroni* Srl, it was possible to identify the sales volume of *Birra Peroni* in any of the formats under study, as well as the average distance travelled to reach each distribution center using the web site http://www.viamichelin.it, as shown in Table 7. These data referred to an overall sales volume of 950,163 hL and were regarded as valid for all the production capacity registered in the reference time period of this study. In particular, for any tertiary package the GHG emissions were calculated by accounting for the transport of a single pallet and, then, referred to 1 hL of the final product packaged in the formats examined (Table 3).

According to Birra Peroni (2012), the 30-L stainless steel kegs are generally reused 3.6 times per year for as long as 20 years. Thus, the GHG emissions associated to their transport were estimated by splitting the transport contribution of the new kegs from that of the reused ones. The former was assessed by accounting for the average distance travelled from the manufacturer to the brewery gate (i.e., 1,500 km) and the amount of kegs yearly replaced, this being equal to 1/(3.6 x 20) = 1/72-th of the keg consumption yield listed in Table 4. This was line with the LCA report by the Chicago Manufacturing Center (2009), having any steel keg an expected life of 100 uses. On the contrary, the keg return system contribution was estimated by referring to the average distance travelled by the filled kegs, that is 143.6 km (Table 7).

Once the lager beer had been delivered on wooden pallets, the distributor or trader collected the empty pallets to allocate them back to the original producer, where defected pallets were repaired according to specification and made available again to the brewery. Since the pallet operators serving *Birra Peroni* Srl were located at distances in the range of 25 to 335 km, the average distance travelled by the repaired pallets was estimated as equal to about 150 km by accounting for both the mass of pallets transported and relative transport distance. Altogether, the average distance travelled by the empty pallets was fixed at circa 300 km, the average distance travelled by the final product independently of its primary packaging being of about 153 km (Table 7).

The impact of solid waste transportation was assessed on the basis of an average distance between the brewery gate and each disposal site of about 400 km, in agreement with previous assessment (Moresi and Paone, 2012) by means of light-medium rigid trucks, the average emission factor of which being equal to 0.65 kg CO_{2e} (Mg km)$^{-1}$, as shown in Table 6. Finally, the main byproducts of brewing, that is spent grains and surplus yeast (Table 2), were used as cattle feed and transported to about 150 km from the brewery.

2.5.6. *Energy sources*

The energy sources used by *Birra Peroni* Srl to manufacture the pale lager packed in the aforementioned formats were of the electric or thermal (i.e., methane and diesel) type.

Electric energy was used to pilot process machines and equipment, to refrigerate process streams and final product during the production and packaging phases, as well as to run plant utilities and electric forklifts. Their specific consumption needs were collected from the industrial brewery *Birra Peroni* Srl (Rome, Italy), and listed in Table 8. By referring to the Italian thermoelectric production in 2011, the overall electric energy dissipation rate was about 3% (ISPRA, 2012); thus, the overall consumption of electric energy was assumed as equal to the 97% of that effectively absorbed by the grid network.

Methane-fired boilers were used to generate either the steam or hot water needed during the phases of mashing, lautering, and wort boiling, or sanitization of pipes, equipment and filling machines. A fraction of the methane required consisted of digester methane gas. All thermal energy consumption needs, expressed in MJ hL^{-1}, are shown in Table 8. The overall thermal energy requirements during the brewing process were estimated on the basis of an average steam boiler efficiency of 88%, whereas the overall volumetric consumption of methane was guessed on account of its lower heating value of 37.76 MJ m^{-3} (STP). Thus, the only GHG emissions deriving from the burning of fossil methane were accounted for.

Two out of the nine forklifts dedicated to pallet transport within the brewery were of the diesel type, the other 7 forklifts being of the electric one. No information about their diesel oil consumption was available, thus such consumption per each functional unit was regarded as negligible, in agreement with previous estimates (Moresi and Paone, 2012).

2.5.7. Refrigerant losses

Refrigerant losses in the life cycle of beer take place during the manufacturing process and use phase (i.e., refrigerated storage of beer at pubs, bars, and home), the latter being disregarded in this study. In the brewery examined a safety refrigerant as ammonia, known as R 717, was used. Although it is synthetically produced, ammonia is considered a natural refrigerant because it occurs in nature's material cycles. Moreover, such a colorless gas has no ozone depletion potential (ODP = 0) and no direct global warming potential (GWP = 0). Its indirect greenhouse effect contribution is also very limited owing to its high energy efficiency (its latent heat of evaporation being equal to 1262 J g^{-1}) (Eurammon, 2011). Its characteristic odor makes its leakage in the air easy to detect, thus no leakage was accounted for.

An aqueous solution of ethylene glycol was used as secondary refrigerant, this being cooled via the primary refrigerant system and circulated for use during wort fermentation and beer filtration in the temperature range of 0-12 °C. The loss of such refrigerant per each hL of beer is given in Table 2 and was assumed to contribute to the organic load of wastewaters, these being disposed off in accordance with the antipollution norms by combining anaerobic pre-treatment and aerobic post-treatment.

2.5.8. Life-cycle impact assessment

To assess the C*arbon Footprint* of the functional unit chosen (1 hL of packed beer), all GHG emissions associated to the production of raw and packaging materials, processing aids and detergents, to their transportation and that of the final product and processing wastes, to the consumption of thermal and electric energy sources, were estimated by multiplying the entity Ψ_i of any activity parameter (expressed in mass, energy, mass-km basis) by its corresponding emission factor EF_i:

$$CF = \sum_i (\Psi_i \, EF_i) \tag{1}$$

Since all activity data were referred to the aforementioned functional unit, the resulting carbon footprint was expressed as kg CO_{2e} hL^{-1}.

3. Results

By referring to the default option for the emission factors listed in Table 1, the *impact assessment phase* resulted in the calculation of the carbon footprint (CF) of 1 hL of lager beer packaged in 66-cL glass bottles (~57 kg CO_{2e}), 33-cL glass bottles assembled in either cardboards (~67 kg CO_{2e}) or cluster packs (74 kg CO_{2e}), 33-cL aluminum cans (~69 kg CO_{2e}), or 30-L stainless steel kegs (~25 kg CO_{2e}), as shown in Fig. 5.

The percentage contribution of the different life cycle phases to CF is illustrated in Fig. 6 and depends on the packaging format of choice. According to the data shown in Table 9, minimum and maximum percentage impacts of raw materials and processing aids (RPM), as well as brewing processing (BRP) and packaging (PP), were associated to the beer packaged in a 3-pack of 33-cL glass bottles and 30-L stainless steel kegs, respectively. As concerning the packaging materials (PM) or transportation (TR), the corresponding contribution varied from 48 to 58 or from 10 to 14 % of CF for the beer bottled or canned to as little as 5 or 25 % of CF in the case of kegs, owing to their high reuse coefficient. The contribution of wastes generated in the brewery was of the order of 1-2 % of CF for all the formats examined (Table 9).

The GHG emissions associated to raw materials, brewing processing and packaging amounted to ~25.3 kg CO_{2e} hL^{-1} independently of the package used (Table 9). On the contrary, the contribution of packaging materials was minimum in the case of kegs (~1.86 kg CO_{2e} hL^{-1}), in virtue of their expected life of 72 uses, and maximum in the case of the 33-cL glass bottle cluster packs (~48.3 kg CO_{2e} hL^{-1}). The latter was slightly greater than that of 33-cL Al cans (~47.6 kg CO_{2e} hL^{-1}). In the case of beer packed in 33-cL aluminum cans, the contribution of packaging materials to the overall

CF was about the double of that of raw materials, processing aids and brewing, and not comparable to the aforementioned items, as estimated by Pasqualino et al. (2011). The contribution of transportation varied from as low as ~8.1 kg CO_{2e} hL^{-1} to as high as ~12.4 kg CO_{2e} hL^{-1} in the case of Al cans or 3-packs, respectively. As shown in Table 9, utilization of beer co-products (i.e., spent grains, and surplus yeast) as feed definitively reduced the overall GHG emissions by ~12.1 kg CO_{2e} hL^{-1}.

By accounting for the sales volumes of the different formats examined, it was also assessed an overall CF value of ~59.2 kg CO_{2e} per hL of lager beer allocated to any *Birra Peroni* distribution center in any of the formats accounted for.

3.1 *Sensitivity analysis*

Owing to the numerous assumptions, the above calculated carbon footprints cannot in principle be directly compared to those of other lager beers, the latter differing one from another not only for production methods and recipes, but also for the use of unknown emission factors. To improve the scientific value of this CF assessment exercise, it was decided to resort to transparent data, such as those shown in Tables 1- 8, and to study how the uncertainty in the output of the LCA model of CF, defined by Eq. (1), can be apportioned to different sources of uncertainty in its input variables, especially in the emission factors EF_i of any activity parameter.

Sensitivity may be measured by monitoring changes in the dependent variable of choice (i.e., CF in this specific case) by differentiating CF with respect to the generic i-th independent variable (EF_i) while keeping all the other emission factors (EF_j) constant for $j \neq i$. Alternatively, it would be possible to change one-emission factor-at-a-time (EF_i), while keeping all the others ($EF_{j \neq i}$) at their baseline (nominal) values, to observe what effect this would produce on CF. In this way, it is possible to compare the results, having been all effects computed with reference to the same central point in space, and to identify the model inputs having no or limited effect on CF. Despite its simplicity, such approach does not fully explore the input space, since it does not account for the simultaneous variation of the input variables. According to Saltelli et al. (2006), this approach is illicit and unjustified, unless the model under study is proved to be linear, as the simple linear model described by Eq. (1).

Therefore, to provide perspectives on the key drivers to the CF of the pale lager under study, the sensitivity of the overall CF of 1 hL of pale lager packed in all the formats examined was assessed by changing the emission factor (EF_i) of a given activity by ±50% with respect to the default condition (Table 1). More specifically, the following activities were taken into account: (i) barley or corn grown locally or globally using (ii) an organic or a conventional agriculture method; (iii) glass bottles or aluminum cans with different recycled contents; (iv) electricity generated by more or less renewable sources; (v) thermal energy from methane deriving from different combination of fossil and biogenic sources; (vi) differently combined modes of final product transportation by road and railway. The main results of such a sensitivity analysis are shown in Fig. 7.

The range of variation for CF appeared to be smaller than ±3% within a ±50% range of variation for the distance travelled by barley, differently-recycled aluminum cans, electricity generated by differently combined fossil and renewable sources, and corn of different agriculture methods. The variation of CF was of the order of ±4% provided that the emission factors for the means of transport used to dispatch the final product to the distribution centers, as well as for methane of more or less fossil origin, exhibited a ±50% variation with respect to the default case. CF was more sensitive to changes in the emission factors for glass bottles and barley. In particular, if they were reduced by 50%, CF accordingly exhibited about a 20 or 10% reduction with respect to the basic case, respectively.

More specifically, as shown in Table 10, the use of Italy-grown organic barley instead of conventional one (their emission factors being equal to 0.545 or 1.345 kg CO_{2e} kg^{-1}, as listed in Table 1) would lessen CF by about -11 %, while the use of barley, organically or conventionally cultivated at an average distance from the malthouse of 1,500 km, would lower or increase CF by about -6 or +9 %, respectively. The use of electricity produced only by fossil fuels or photovoltaic sources (their corresponding emission factors reducing from 0.545 to 0.055 kg CO_{2e} kWh^{-1}) affected the overall CF of the pale lager beer under study by approximately +2 or -5 % with respect to the corresponding default value, respectively. Finally, the change in the final product transportation mode from road to railway (their relative emission factors reducing from 0.2 to 0.0393 kg CO_{2e} Mg^{-1} km^{-1}) would lessen CF by about -6 %.

Thus, glass bottle production and barley cultivation resulted to be the controlling life cycle phases of the pale lager examined.

4. Discussion of results

Table 11 summarizes the main material, water, and energy consumption yields, as well as waste production ones, relative to the operation of the *Birra Peroni* Srl brewery, as compared to the typical and average (within brackets) ones for some European breweries (Donoghue et al., 2012; IFC, 2007; Olajire, 2012; Sturm et al., 2013; UNEP, 1996).

According to Olajire (2012), a well-run brewery would use from 8 to 12 kWh electricity, ~5 hL water, and ~150 MJ fuel energy per hL of beer produced. In the circumstances, the *Birra Peroni* brewery may be classified as a brewery with low consumption figures, also because the process effluent is firstly submitted to anaerobic digestion, the recovered biogas being used for process heating. The registered entity of ~10 MJ hL^{-1} represented the (13-16) % of the overall brewery thermal energy needs. Water consumption was near to 4 L per L of beer produced, this being less that the figure issued by SAB Miller (4.56 L L^{-1}) and InBev (4.32 L L^{-1}) (SAB Miller, 2011). Actually, water consumption for modern breweries varies from 3.5 to 10 L L^{-1} of beer produced, but in old micro-breweries it can be as high as 19 L L^{-1} (Sturm et al., 2013). The recovery of spent yeast as a feeding supplement appeared to be less than that usually registered, probably because of its re-use as production yeast for at least 4 fermentation cycles. The greatly reduced specific PVPP consumption yield was attributed to the brewery choice of using the regenerable PVPP type. Even, the hop pellet consumption yield was quite low, but this was related to the recipe formulation used by *Birra Peroni Srl*.

As concerning the carbon footprint of beer, it depends on how much of the life cycle is included. According to Saxe (2010), the value for the total life cycle varies from

80 to 150 kg CO_{2e} per hL of beer; but, excluding the user phase, it lessens to as low as 40 kg CO_{2e} hL^{-1}. Recently, Lalonde et al. (2013) provide an Environmental Product Declaration for a few ales packaged in 12-oz glass bottles. In particular, the estimated CF values ranged from 48 to 116 or from 144 to 175 kg CO_{2e} hL^{-1} provided that the use phase was excluded or included. By referring to a Chilean small-sized brewery (1,500 hL/year), the CF of a lager beer packed in 33-cL glass bottles from cradle to retail was equal to 178 ± 49 kg CO_{2e} hL^{-1} (Muñoz et al., 2012). On the contrary, Berners-Lee (2010) estimated a CF of 53 or 88 kg CO_{2e} per hL of beer produced locally or imported from abroad, if consumed in a pub. These data are quite lower than those assessed for Tuborg® beer (EPD, 2011a), that amounted to 106 or 149 kg CO_{2e} per hL of beer barreled in plastic or steel kegs, and to 190 kg CO_{2e} per hL of beer kept in glass bottles. By referring to the different GHG burden of the main commercial *Birra Peroni* formats (Table 9), the allocation of 1 hL of beer packed in 66-or 33-cL glass bottles (the latter assembled loosely in cardboards or in cluster packs), 33-cL cans or 30-L steel kegs resulted in the emission of ~57, 67, 74, 69 or 25 kg CO_{2e}, respectively. Such CF values were smaller than the aforementioned ones (EPD, 2011a), probably because of the greater production scale and shorter distribution chain of *Birra Peroni* brewery, as well as for the slighter glass bottles used (190 vs. 200 g, respectively).

According to the CF values estimated here, the overall impact of beer consumption in Italy, equaling 29.2 L per capita in 2013 (Assobirra, 2013), would represent from 0.1 to 0.3 % of the overall Italian direct GHG emissions (458.2 Tg CO_{2e}), including net GHG emissions adsorbed from land use, land-use change and forestry, in 2011 (ISPRA, 2013).

The sensitivity analysis on CF pointed out the primary effects of glass bottle production and then barley cultivation in agreement with previous studies by Cordella et al. (2008), Koroneos et al. (2005), and Talve (2001). In particular, the packaging materials represented from 48 to 58% of the GHG burden in the case of glass bottles and aluminum cans, respectively; while the use of stainless steel kegs, owing to their high reusing coefficient, limited its impact to as little as the 5% of CF. On the contrary, the high mass of the empty keg (i.e., 9.6 kg) enhanced the contribution of its transport to the 25% of CF, this being instead limited to 14% or 10% in the case of glass bottles or Al cans.

The environmental impact of different reuse percentages for glass beer bottles was assessed by Mata and Costa (2001). The advantages of the use of returnable bottles over that of non-returnable ones increase with the number of cycles performed by the returnable bottles. In the case of a 50% reuse (i.e. the same number of returnable and non-returnable bottles), the contribution of returnable bottles to global warming, acidification, photochemical ozone creation, critical air and water volume, human toxicity, energy and raw-material consumption was found to be smaller than that of the non-returnable bottles after the second reuse. On the contrary, the contribution of returnable bottles to eutrophication, ozone depletion, solid waste, water and auxiliary material consumption was larger even after several reuses (Mata and Costa, 2001). Thus, the optimal reuse percentage should be identified by accounting not only for the environmental, but also for the economic, technological and social implications of the different alternative distributions of beer in returnable or non-returnable bottles.

The use of the novel PET bottles enriched with nanoclays, manufactured by Nanocor® (Lan, 2007), would not only extend the beer shelf-life up to 30 weeks thanks to their high barriers to CO_2 and O_2 migration (Senturk et al., 2013; Smith, 2008), but it would also reduce either the primary packaging mass from 185-290 g, typical of a generic glass bottle, to ~30 g, or the packaging material emission factor from ~9 kg CO_{2e} kg^{-1} for aluminum cans to 3-4 kg CO_{2e} kg^{-1}. The now commercially available polymer-clay nanocomposite (PCNC) bottles have become popular with beverage manufacturers, such as Miller Brewing Company (Senturk et al., 2013). Moreover, in the case of Tuborg® beer the use of plastic drums (having a unitary mass of 290 g; and a capacity of 20 L) resulted in about 70% less GHG emissions (EPD, 2011a).

The possibility of resorting to a novel enzymatic technique to replace conventional malting in beer production, its climate benefits amounting to ~8.4 g CO_{2e} per 33-cL can of beer (Kløverpris et al., 2009), would save ~3.6 % of the carbon footprint of the *Peroni* lager packaged in Al-cans, this equaling to about one third of the savings achievable by resorting to local organic barley.

It would also possible to reduce by ~70% the global warming potential for the current industrial beer DE-filtration, regenerable PVPP stabilization and pasteurization procedures by resorting to a novel combined pale lager precentrifugation, PVPP stabilization, cartridge filtration and final ceramic tubular crossflow microfiltration procedure, as reported by Cimini and Moresi (2015).

Finally, there is a growing interest towards the social sustainability of beverage consumption (Ali et al., 2010). According to the product category rules for beer from malt (PCR, 2013), the use phase scenario should be included in the life-cycle analysis of the product. For instance, Watson (2008) assessed that the highest environmental impact of beer life cycle was due to the use phase, this being mainly affected by energy consumption for refrigeration and dispensing, consumer displacement, as well as disposal of solid wastes and wastewaters generated by the consumer itself. In particular, consumer displacement, mainly attributed to car use, seemed to be the hottest spot, being strongly linked to fossil fuel combustion, both as resource consumption and combustion. Effective action to reduce environmental burden should be considered at consumer level and a few suggestions, such drinking draught beer instead of bottled one, or reducing car use to reach dispensing location, were given by Normand et al. (2012) and Watson (2008). In fact, by comparing the different GHG burden of the main commercial *Peroni* pale formats, consuming 33 cL of beer from a glass bottle, a can, or a keg in a pub would involve the emission of 246, 229 or 82 g CO_{2e}, respectively. Such CF values were by far smaller than that (589 ± 161 g CO_{2e}) estimated by Muñoz et al. (2012) for a small-scale brewery. Altogether, such data still suggest that consumers might choose a more responsible consumption of draught beer in a local pub. Furthermore, draught beer might be dispensed from beer pipelines (linking the pub to the storage tanks of a brewery in close proximity) rather than from steel or plastic kegs. The distribution of the latter severely affects local traffic, especially in historic sites, such as Bruges in Belgium (AFP, 2014), or during beer festivals, such as the Oktoberfest in Munich in Germany (Becker, 2014). Unfortunately, the present-day major consumption of beer is by far from glass bottles. Indeed, the sales for *Peroni* lager barreled in steel kegs were as little as the 3.2% of the overall ones (Table 7).

5. Conclusions

By referring to fully transparent primary and secondary data, the estimated carbon footprint (CF) of *Peroni* pale lager significantly varied with the package used. In particular, it was equal to ~57, 67, 74, 69 or 25 kg CO_{2e} per hL of lager beer packed in 66-cL glass bottles, 33-cL glass bottles assembled in cardboards or cluster packs, 33-cL aluminum cans or 30-L stainless steel kegs, respectively. Such a difference in CF was due to the different contribution of packaging materials and transportation. The former was minimum in the case of kegs (~1.86 kg CO_{2e} hL^{-1}) and maximum in the case of the 33-cL glass bottle cluster packs (~48.3 kg CO_{2e} hL^{-1}), while the latter ranged from as low as ~8.1 kg CO_{2e} hL^{-1} in the case of aluminum cans to as high as ~12.4 kg CO_{2e} hL^{-1} for three 33-cL bottle packs.

The CF values for the packages examined here were considerably lower than those recently reported in the literature, probably because of the larger production scale and shorter distribution chain of *Birra Peroni* brewery. Also, the CO_2 credits from the anaerobic digestion of wastewaters and utilization of beer co-products as feed partly offset the higher energy-related emissions in the product chain.

The one-factor-a-time sensitivity analysis revealed that two promising strategies might be applied to reduce the overall GHG emissions. Firstly, the replacement of glass bottles and steel kegs with plastic bottles and drums; and, secondly, use of organic barley grown locally were, in descending order, the options yielding the greatest reduction in the carbon footprint of pale lager. Both these strategies might be generally applied, being not specifically related to the brewery production scale examined here.

Contrary to the quite numerous environmental assessment exercises openly available, the choice of resorting to wholly transparent data allows the present CF model to be reproduced by any researcher, this being one of the main principles of the scientific method. Thus, despite further work is needed to collect primary data for barley and corn agriculture, consumption of equipment lubricant and forklift diesel oil, as well as post-consumer waste management, this CF model relying on transparent data may serve as an example for similar studies in other countries, as well as it may generate other CF estimates as soon as better quality data are available. Also the effect of the beer production scale on the carbon footprint should be quantified, especially because of the current market growth of the microbrewery phenomenon in Europe and North America.

LIST OF SYMBOLS

AA	Tap water
AC	Compressed air
ALC	33-cL aluminum can
AP	Well water
APR	Process water
AT	Articulated truck
B33	33-cL glass bottles
B66	66-cL glass bottles
BCI	Primary-packaged *Peroni* lager
BCII	Secondary-packaged *Peroni* lager
BCIII	Tertiary-packaged *Peroni* lager
BP	Chill haze-free *Peroni* lager ready-to-be packaged

BPC	Byproduct credits
BRP	Brewing processing
BS	Beer sales
C	Multipack
CA	Cartons
CF	Carbon footprint of a functional unit (kg CO_{2e} hL^{-1}), as defined by Eq. (1)
CL	Cardboard multipack
CO	Can open closures
CO_2	Carbon dioxide
COC	Carton or tray adhesive
COE	Label adhesive
COL	Neck labels
CSK	Plastic keg ball locker
DE	Diatomaceous earth
E	Body labels
EBC	Bar code labels
EE	Electric energy
EF_i	Emission factor for the generic i-th activity
EO	Keg holographic label
EP	Pallet label
F	30-L stainless steel keg
FP	Pallet wrap stretch film
FV	Tray wrap stretch film
GB	Glass bottle

GHG	Greenhouse gas
GWP	Global Warming Potential
HRT	Heavy rigid truck
ID	Ink and diluent
i, j	dummy indexes
LCA	life-cycle assessment
ME	related to the Messina province of Italy
NP	Pallet tape
ODP	Ozone depletion potential
P	Wooden pallet
PCNC	Polymer–clay nanocomposite
PM	Packaging materials
PP	Packaging
PR	related to the Parma province of Italy
PVPP	Polyvynilpolypyrrolidone
Q	Thermal energy
RPM	Raw materials and processing aids
RT	Light-medium rigid truck
SAC	Carbon dioxide waste
SB	Beer waste
SB33	33-cL glass bottle waste
SB66	66-cL glass bottle waste
SC	Can waste
SCA	Carton waste

SCO	Can open closure waste
SCOL	Neck label waste
SCSK	Keg ball locker waste
SE	Body label waste
SEBC	Bar code label waste
SEO	Keg holographic label waste
SEP	Pallet label waste
SF	Keg waste
SFP	Pallet wrap film waste
SFV	Tray wrap film waste
SNP	Pallet tape waste
SSK	Stainless steel keg
STC	Crown closure waste
STP	Standard temperature (273.15 K) and pressure (1 bar)
SV	Tray waste
TC	Crown closure
TR	Transportation
UCY	Utility consumption yield
V	Cardboard tray.
WD	Waste disposal.
Ψ_i	Entity of the i-th activity, expressed in kg, J or Mg km.

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Table 1

Minimum, maximum and default values of the GHG emission factors for the energy sources; means of transport; raw and packaging materials, detergents, and processing aids; refrigeration fluids; waste disposal; and byproduct uses, applied in this carbon footprint exercise, as extracted from several databases (i.e., BUWAL250, Ecoinvent, ETH-ESU 96, Franklin USA 98, Idemat 2001, Industry data 2.0, LCA Food-DK, USA Input Output database 98) of the LCA software Simapro 7.2 v.2 (Prè Consultants, Amersfoort, NL) and technical references.

Emission Factor	Min-Max Values	Default Value	Unit	Ref.
Energy source				
Electricity, medium voltage, at grid/IT	0.582-0.818	0.3931	kg CO_{2e} kWh^{-1}	BUWAL 250; ISPRA (2012)
Electricity, fossil fuels, at grid/IT		0.545	kg CO_{2e} kWh^{-1}	ISPRA(2012)
Photovoltaic electricity		0.055	kg CO_{2e} kWh^{-1}	ADEME (2007)
Diesel oil (upstream+combustion)		3.487	kg CO_{2e} kg^{-1}	ADEME (2007)
Natural gas (upstream+combustion)		0.064	kg CO_{2e} MJ^{-1}	ADEME (2007)
Means of transport				
Transport, lorry >32 Mg, EURO5-3	0.104-0.117		kg CO_{2e} Mg^{-1} km^{-1}	Ecoinvent
Transport, lorry 16-32 Mg, EURO5-3	0.154-0.168		kg CO_{2e} Mg^{-1} km^{-1}	Ecoinvent
Transport, lorry 7.5-16 Mg, EURO5-3	0.268-0.291		kg CO_{2e} Mg^{-1} km^{-1}	Ecoinvent
Transport, lorry 3.5-7.5 Mg, EURO5-3	0.657-0.635		kg CO_{2e} Mg^{-1} km^{-1}	Ecoinvent
Transport, freight, rail/RER S	0.0393-0.0577	0.0393	kg CO_{2e} Mg^{-1} km^{-1}	Ecoinvent; ETH-ESU 96
Raw Materials, Ingredients, Detergents, Processing Aids				
Barley (produced in Europe, or	0.19-0.62	0.26	kg CO_{2e} kg^{-1}	BIER (2012)
in the USA, transport not included)	0.53-0.79	0.66		
Barley Malting	0.199-0.362	0.292±0.084	kg CO_{2e} kg^{-1}	Chicago Manufacturing Center (2009)
Italy-grown malted barley		1.143	kg CO_{2e} kg^{-1}	This work
Foreign malted barley	0.545-1.345		kg CO_{2e} kg^{-1}	This work
Corn grain	0.20-0.55	0.227	kg CO_{2e} kg^{-1}	Ma et al. (2012); Field to Market (2012)
Maize grits		0.746	kg CO_{2e} kg^{-1}	This work
Hop Pellets (transport not included)		2.39	kg CO_{2e} kg^{-1}	Climate Conservancy (2008)

PVPP		2.41	kg CO_{2e} kg^{-1}	Cimini and Moresi (2015)
Compressed air (>30 kW, 8 bar)		0.0627	kg CO_{2e} m^{-3}	Ecoinvent
Oxygen		0.228	kg CO_{2e} kg^{-1}	BUWAL250
Water, deionised, at plant/CH S		1.03	kg CO_{2e} m^{-3}	Ecoinvent
Tap water, at user/CH S		0.154	kg CO_{2e} m^{-3}	Ecoinvent
Lime (burnt) ETH S, equiv. to DE		1.39	kg CO_{2e} kg^{-1}	LCA Food-DK
Gypsum		0.27	kg CO_{2e} kg^{-1}	ETH-ESU 96
$CalCl_2$		0.931	kg CO_{2e} kg^{-1}	Ecoinvent
$ZnSO_4.H_2O$		1.85	kg CO_{2e} kg^{-1}	Ecoinvent
H_3PO_4, 85% in H_2O		1.46	kg CO_{2e} kg^{-1}	Ecoinvent
HNO_3, 50% in H_2O	0.308-3.20	3.2	kg CO_{2e} kg^{-1}	Ecoinvent
NaOH 50% in H_2O		1.12	kg CO_{2e} kg^{-1}	Ecoinvent
Acetic acid, 98% in H_2O		1.58	kg CO_{2e} kg^{-1}	Ecoinvent
H_2O_2, 50% in H_2O		1.21	kg CO_{2e} kg^{-1}	Ecoinvent
CO_2		0.266	kg CO_{2e} kg^{-1}	BUWAL 250
Refrigeration Fluids				
Ethylene glycol		1.61	kg CO_{2e} kg^{-1}	Ecoinvent
Ammonia liquid		2.12	kg CO_{2e} kg^{-1}	Ecoinvent
Packaging Materials				
Glass bottles, 100% recycled - virgin	0.546- 0.936		kg CO_{2e} kg^{-1}	Franklin USA 98
Glass bottles, 10% recycled		0.57		Climate Conservancy (2008)
Al cans, 50% recycled		8.96	kg CO_{2e} kg^{-1}	International Aluminium Institute (2013)
Al cans, unspecified recycling rate	9.38		kg CO_{2e} kg^{-1}	Coca Cola (2010)
Aluminum, 99% purity	11.5		kg CO_{2e} kg^{-1}	Idemat 2001
Stainless steel AISI 316		4.02	kg CO_{2e} kg^{-1}	Idemat 2001
Stainless steel kegs	1.70		kg CO_{2e} kg^{-1}	Chicago Manufacturing Center(2009)
Steel crowns, 28% recycled		2.81	kg CO_{2e} kg^{-1}	Climate Conservancy (2008)
PVC injection moulding		2.87	kg CO_{2e} kg^{-1}	Industry data 2.0
Paper Labels	0.306-4.86	1.17	kg CO_{2e} kg^{-1}	Ecoinvent; Climate Conservancy

				(2008)
Adhesive		2.35	kg CO_{2e} kg^{-1}	Climate Conservancy (2008)
Solvents, organic, unspecified		2.31	kg CO_{2e} kg^{-1}	Ecoinvent
Printing ink		1.45	kg CO_{2e} kg^{-1}	USA Input Output database 98
Packaging LDPE film	1.74-2.6	2.6	kg CO_{2e} kg^{-1}	Ecoinvent
Kraft unbleached 100% rec.FAL	1.76-4.86	2.33	kg CO_{2e} kg^{-1}	Franklin USA 98
Waste disposal				
Landfill				
PE packaging waste	0.113-0.491	0.113	kg CO_{2e} kg^{-1}	Ecoinvent; BUWAL 250
Paper packaging waste	0.021-1.34	1.34	kg CO_{2e} kg^{-1}	BUWAL 250; Ecoinvent
Cardboard packaging waste	0.02-1.73	1.73	kg CO_{2e} kg^{-1}	BUWAL 250; Ecoinvent
Wood untreated	0.0857	0.086	kg CO_{2e} kg^{-1}	Ecoinvent
Urban and biological wastes	0.561-0.786	0.8	kg CO_{2e} kg^{-1}	Manfredi et al. (2009); BSI (2008b)
Disposal, zeolite or concrete, 5% water		0.00708	kg CO_{2e} kg^{-1}	Ecoinvent
Copper (inert)		0.000557	kg CO_{2e} kg^{-1}	ETH-ESU 96
Incineration				
Digester sludges		0.0695	kg CO_{2e} kg^{-1}	Ecoinvent
Used lubricating oils or fuel wastes	3.4-3.76	3.5	kg CO_{2e} kg^{-1}	ADEME (2007); Kanokkantapong et al. (2009)
Waste oil		2.88	kg CO_{2e} kg^{-1}	ETH-ESU 96
Recycling				
paper	-0.0635-0	-0.0635	kg CO_{2e} kg^{-1}	BUWAL 250; Ecoinvent
Plastics (incl. PE and excl. PVC)	-0.332-0	-0.332	kg CO_{2e} kg^{-1}	BUWAL 250; Ecoinvent
Wood		0	kg CO_{2e} kg^{-1}	Ecoinvent
glass		-0.376	kg CO_{2e} kg^{-1}	BUWAL 250
aluminium		-10.6	kg CO_{2e} kg^{-1}	BUWAL 250
steel		-1.69	kg CO_{2e} kg^{-1}	BUWAL 250
Byproduct uses				
Animal feed production (low protein)≡ equiv. spent grains + surplus yeast		-0.637	kg CO_{2e} kg^{-1}	LCA Food-DK

Table 2 Specific consumption yields of raw materials, processing aids, brewing coadjutants, detergents, refrigerants, and by-products per hL of *Peroni* lager together with the transport means used (see Table 6) and average distance travelled from their production site to the brewery gate.

Inventory	**Consumption Yield**	**Unit**	**Means of Transport**	**Distance** [km]
Raw materials and Processing Aids				
Barley	14.36	kg hL^{-1}	AT	236
Malted Barley	10.77	kg hL^{-1}	AT	33
Maize Grits	4.71	kg hL^{-1}	AT	608
Hop Pellets	91.60	g hL^{-1}	HRT	1509
Oxygen	1.43	g hL^{-1}	RT	91
Compressed Air	2.58	M^3 hL^{-1}	-	-
Calcium Chloride	24.78	g hL^{-1}	RT	210
Calcium Sulfate	19.91	g hL^{-1}	RT	210
Brewing coadjutants				
Diatomaceous Earth	0.112	kg hL^{-1}	RT	110
PVPP	0.110	g hL^{-1}	RT	445
Phosphoric Acid (75% w/w)	14.21	g hL^{-1}	RT	445
Detergents				
Nitric Acid (53% w/w)	17.22	g hL^{-1}	RT	445
Caustic Soda (30% w/w)	0.606	kg hL^{-1}	RT	445
Oxonia active	17.055	g hL^{-1}	RT	589
Trimeta LPC	40.256	g hL^{-1}	RT	589
Refrigerants				
Ammonia	0.052	g hL^{-1}	RT	175
Ethylene Glycol	0.956	g hL^{-1}	RT	62
Byproducts				
Spent Grains	17.44	kg hL^{-1}	RT	150

Surplus Yeast	1.45	kg hL^{-1}	RT	150

Table 3
Mass of any component of primary, secondary and tertiary packages together with their corresponding overall masses and GHG emissions associated to the transport of a pallet or a functional unit (FU) of beer packaged in different formats.

Format	Amber Glass Bottle			Aluminum Can	Stainless Steel keg	Unit
Primary Packaging						
Volume	0.66	0.33		0.33	30	L
Mass	290	185		12.3	9600	g
Diameter x Height	74.8 x 267.6	61 x 213.2		66.2 x 115.2	408 x 510	mm
Adhesive for Labels	0.293	0.154		-	-	g
Ink diluent	0.0015	0.0007		0.0000	0.0023	g
Ink	0.0002	0.0001		0.0000	0.0017	g
Crown Closure	1.99	1.99		-	-	g
Can Open Closure	-	-		3.8	-	g
Plastic Liner for Crowns	0.11	0.11		-	-	g
Body Label	0.63	0.29		-	-	g
Neck Label	0.48	0.40		-	-	g
Plastic Ball Lock Keg Coupler	-	-		-	5	g
Primary Packaging Overall Mass	0.9568	0.5196		0.3478	39.755	g
Secondary Packaging	Carton	Carton	Cluster Pack	Tray	-	
No. of Primary Packages	15	24	8	24	-	-
Length x Width x Depth	383x227x273	369x253x218	369x253x218	287x523x58	-	mm
Carton or Tray Mass	282.76	254.5	240.5	91.08	-	g
3-bottle Cluster Mass	-	-	27.91	-	-	g
Adhesive for Cartons or Trays	16	15	15	-	-	g
Stretch and Shrink Film	-	-	-	20	-	g
Beer Volume per Carton	9.9	7.92	7.92	7.92	-	L

Secondary Packaging Overall Mass	14.651	12.740	12.934	8.472	-	kg
Tertiary Packaging						
No. Secondary or Primary Packages	11	9	9	9	6	-
No. Layer per Pallet	6	8	8	13	4	-
Height of Pallet	1.782	1.888	1.888	1.640	2.290	m
Bar code Label	1 x 1.08	1 x 1.08	1 x 1.08	1 x 1.08	5 x 1.08	g
Pallet Label	2 x 3.108	2 x 3.108	2 x 3.108	2 x 3.108	-	g
Pallet Tape	2 x 0.29	2 x 0.29	2 x 0.29	2 x 0.29	2 x 0.29	g
Stretch & Shrink Film	483	385	385	555.6	-	g
Pallet Mass	18	18	18	18	4 x 22	kg
Beer Volume per Pallet	653.4	570.2	570.2	926.6	720	L
Tertiary Packaging Overall Mass	985.4	935.7	949.6	1009.8	1042.1	kg
GHG emissioni per pallet	28.9	28.2	37.0	34.8	29.9	kg CO_{2e}
GHG Emissions per FU	**4.42**	**4.94**	**6.48**	**3.76**	**4.16**	**kg CO_{2e} hL^{-1}**

Table 4
Specific consumption yield for all the packaging materials used to package 1 hL of *Peroni* lager in the different formats examined together with their transport modality and average distance travelled from their production site to the brewery gate, as well as the overall GHG emissions associated to the transport of the packaging materials allocated in the functional unit (FU).

Packaging Materials	**Packaging Formats**					**Unit**	**Means of Transport**	**Distance [km]**
Primary Packaging	66-cL GB	33-cL GB	33-cL GB	33-cL ALC	30-L SSK			
Secondary Packaging	Carton	Carton	Cluster+Carton	Tray	-			
Beer volume used	1.022	1.022	1.022	1.022	1.022	$hL\ hL^{-1}$		
No. of bar code labels	0.162	0.189	0.189	0.189	0.667	hL^{-1}		
Mass of bar code labels	0.17	0.20	0.20	0.12	3.6	$g\ hL^{-1}$	RT	608
Carton adhesive	37.37	45.45	45.45	22.73	0.0	$g\ hL^{-1}$	RT	599
Label adhesive	44.44	46.72	46.72	0.0	0.0	$g\ hL^{-1}$	RT	599
Ink diluent	0.23	0.20	0.20	0.71	0.0	$g\ hL^{-1}$	RT	577
Ink	0.03	0.03	0.03	0.51	0.0	$g\ hL^{-1}$	RT	577
No. of bottles, cans or kegs	152.12	305.76	305.76	304.24	3.33	hL^{-1}		
Mass of bottles	44.12	56.57	56.57	-	-	$kg\ hL^{-1}$	AT	166
Mass of cans	-	-	-	3.74	-	$kg\ hL^{-1}$	AT	470
Mass of new kegs	-	-	-	-	0.44	$kg\ hL^{-1}$	AT	1500
Mass of reused kegs	-	-	-	-	32.00	$kg\ hL^{-1}$	AT	144
No. of crowns or can open closures	152.73	305.45	305.45	306.67	-	hL^{-1}		
Mass of crowns	320.7	641.5	641.5	-	-	$g\ hL^{-1}$	HRT	300
Mass of can open closures	-	-	-	1.17	0	$kg\ hL^{-1}$	HRT	470
No. of plastic ball log keg coupler	-	-	-	-	3.33	hL^{-1}		
Mass of plastic ball log keg coupler	-	-	-		16.67	$g\ hL^{-1}$	RT	1500
No. of paper body and neck labels	152.27	304.24	304.24	-	-	hL^{-1}		
Mass of paper body labels	95.93	70.58	70.58	-	-	$g\ hL^{-1}$	HRT	1370
Mass of paper neck labels	73.09	121.70	121.70	-	-	$g\ hL^{-1}$	RT	1370

No. of cluster multi-packs	-	-	101.01	-	-	hL^{-1}		
Mass of cluster multi-packs	-	-	2.82	-	-	kg hL^{-1}	AT	380
No. of cartons and trays	10.16	12.69	12.69	12.69	-	hL^{-1}		
Mass of cartons	2.87	3.23	3.052	-	-	kg hL^{-1}	AT	380
Mass of trays	-	-	-	1.16	0.00	kg hL^{-1}	AT	421
Stretch and Shrink Film per trays	-	-	-	252.5	0	g hL^{-1}	RT	502
No of pallets	0.15	0.16	0.16	0.11	0.57	hL^{-1}		
Mass of pallets	2.73	2.95	2.95	2.05	12.47	kg hL^{-1}	AT	300
Mass of pallet labels	2.01	2.35	2.35	1.41	-	g hL^{-1}	RT	608
Pallet tape	0.09	0.10	0.10	0.07	0.33	g hL^{-1}	RT	608
Wrap film per pallet	73.23	63.13	63.13	63.13	-	g hL^{-1}	HRT	502
Carbon dioxide*	0.63	0.62	0.62	0.48	1.32	kg hL^{-1}	RT	85
Overall GHG Emissions per FU	**1.69**	**2.12**	**2.29**	**0.73**	**1.50**	kg CO_{2e} hL^{-1}		

* It refers to the CO_2 of fossil origin used to package the clarified and stabilized beer; it represents just the 5% of the overall amount needed, the remainder being recovered from the gaseous streams leaving the beer fermentors.

Table 5
Specific formation of solid wastes associated to the production of a functional unit (FU) of *Peroni* lager, and overall GHG emissions associated to their transport under the assumptions reported in the text.

Solid Waste type	**Consumption Yield** [g hL^{-1}]	**Specific GHG Emissions** [kg CO_{2e} hL^{-1}]
Urban Wastes	19.2	0.0050
Spent DE sludges	336.0	0.0874
Digester Sludges	183.7	0.0478
Waste Fuels	202.1	0.0526
Paper and carboard packaging waste	218.9	0.0569
Plastic packaging waste	169.4	0.0441
Wood packaging waste	39.5	0.0103
Waste toner and printer cartridges	159.2	0.0414
Glass packaging waste	143.2	0.0373
Hydrocarbon-rich wastes	13.3	0.0035
Concrete structures to be demolished	5.2	0.0014
Aluminium waste	7.4	0.0019
Iron and steel waste	15.4	0.0040
Waste copper wire	7.0	0.0018
Spent grains	17442.6	1.7017
Surplus yeast	1449.1	0.1433
Overall GHG Emissions per FU		**2.2420**

Table 6
Means of transport used to delivery all the materials involved in the brewing process under study together with their corresponding European GHG emission standards on a km-mass basis as sourced from Simaprò 7.2 v.2 (Prè Consultants, Amersfoort, NL).

Means of Transport	**Load Capacity** [Mg]	**European emission standards** [kg CO_{2e} (Mg km)$^{-1}$] EURO 5	EURO 4	EURO 3	**Average Emission Factor** [kg CO_{2e} (Mg km)$^{-1}$]
Articulated truck (AT)	16 – 32	0.154	0.152	0.168	0.164
Heavy Rigid truck (HRT)	7.5 – 16	0.268	0.265	0.291	0.284
Light-Medium Rigid truck (RT)	3.5 - 7.5	0.635	0.626	0.657	0.650

Table 7
Sales volume of *Peroni* lager sold in different formats in the time period examined (i.e., glass bottles, GB; aluminium cans, ALC; stainless steel kegs, SSK) and corresponding average distance travelled from the brewery gate to the distribution centers.

Primay Package	**Secondary Package**	**Volume** [hL]	**Average Distance travelled** [km]
66-cL GB	15 pieces per carton	672,178	146.5
33-cL GB	24 pieces per carton	128,998	150.6
33-cL GB	8 clusters per carton	100,968	194.6
33-cL ALC	24 pieces per tray	17,972	172.5
30-L SSK	-	30,047	143.6
Overall Packages		**950,163**	**152.6**

Table 8
Consumption yields for electric (EE) and thermal (Q) energy; well (AP), tap (AA) and process (APR) water referred to 1 hL of *Peroni* lager produced and packed in the formats examined, together with the partial and overall utility consumption yield (UCY) per hL of beer produced.

Utility Consumption Yield (UCY)	**EE** [kWh hL^{-1}]	**Q** [MJ hL^{-1}]	**AP** [L hL^{-1}]	**APR** [L hL^{-1}]	**AA** [L hL^{-1}]
Beer processing (BRP)					
Well water distribution	0.021	-	-	-	-
Process water production	-	-	-	-	242.3
Thermal energy generation	0.093	-	2.9	-	-
Refrigeration	2.237	-	116	-	-
Compressed air	0.602	-	2.1	-	-
CO_2	0.676	-	10.5	-	-
Wort production	0.638	24.5	0.0	128.2	-
Beer making	1.359	8.9	50.2	53.2	12.5
Forklifts	0.158	-	-	-	-
General Plant Utilities	0.739	3.0	-	0.30	8.8
Biogas	-	10.0	-	-	-
Energy dissipation	0.202	6.3	-	-	-
Subtotal UCY referred to BRP	**6.73**	**52.72**	**77.2**	**181.6**	**263.7**
Beer Packaging (PP)					
Packaging Line for 0.66-cL GBs	1.317	24.9	43.8	28.5	-
Packaging Line for 0.33-cL GBs	2.516	17.7	66.2	6.8	-
Packaging Line for 0.33-cL ALCs	3.035	11.7	5.5	122.0	7.7
Packaging Line for 30-L SSKs	1.604	20.9	-	177.4	-
Overall UCY referred to BRP and PP	**8.61**	**73.7**	**118.7**	**226.9**	**264.5**

Table 9
Percentage contribution of the different life cycle phases to the carbon footprint of a functional unit (1 hL) of *Peroni* pale lager packed in 66- or 33-cL glass bottles (GB), the latter being assembled either loose or in cluster (C), 33-cL Al cans (ALC), or 30-L stainless steel kegs (SSK).

Life Cycle Phases		**Carbon Footprint for Different Packaging Formats**								
		[kg CO_{2e} hL^{-1}]	[%]	[kg CO_{2e} hL^{-1}]	[%]	[kg CO_{2e} hL^{-1}]	[%]	[kg CO_{2e} hL^{-1}]	[%]	[kg CO_{2e} hL^{-1}]	[%]
Final Product Primary Packaging		**66-cL GB**		**33-cL GB**		**33-cL GBC**		**33-cL ALC**		**30-L SSK**	
Raw materials & processing aids	(RPM)	16.88	24	16.88	21	16.88	20	16.88	21	16.88	46
Brewing processing	(BRP)	6.26	9	6.26	8	6.26	7	6.26	8	6.26	17
Packaging materials	(PM)	33.33	48	42.19	54	48.34	56	47.55	58	1.86	5
Packaging	(PP)	2.15	3	2.14	3	2.14	2	2.07	3	2.15	6
Transportation	(TR)	9.71	14	10.67	14	12.37	14	8.09	10	9.26	25
Waste disposal	(WD)	0.58	1	0.58	1	0.58	1	0.57	1	0.61	2
Beer production excluding byproducts credits		**68.91**	100	**78.71**	100	**86.57**	100	**81.42**	100	**37.02**	100
Byproduct credits	(BPC)	-12.16		-12.16		-12.16		-12.16		-12.16	
Beer production including byproducts credits		**56.76**		**66.55**		**74.41**		**69.26**		**24.86**	

Table 10
Effect of different parameters on the carbon footprint (CF) of a functional unit (1 hL) of *Peroni* lager packed in 66- or 33-cL glass bottles (GB), the latter being assembled either loose or in cluster (C), 33-cL Al cans (ALC), or 30-L stainless steel kegs (SSK).

Parameter / **CF**	**66-cL GB** [kg CO_{2e} hL^{-1}]	**33-cL GB** [kg CO_{2e} hL^{-1}]	**33-cL GBC** [kg CO_{2e} hL^{-1}]	**33-cL ALC** [kg CO_{2e} hL^{-1}]	**30-L SSK** [kg CO_{2e} hL^{-1}]	**All formats** [kg CO_{2e} hL^{-1}]
Italy-grown barley	56.76	66.55	74.41	69.26	24.86	59.23
Low impact barley grown in Italy	50.32	60.12	67.98	62.83	18.43	52.80
Low impact barley grown abroad	53.30	63.09	70.95	65.80	21.40	55.77
High impact barley grown abroad	61.91	71.71	79.57	74.42	30.02	64.39
Electric energy from fossil fuels	57.98	67.96	75.81	70.74	26.13	60.52
Photovoltaic electric energy	54.04	63.43	71.29	65.96	22.05	56.38
Rail Transportation	53.21	62.58	69.20	66.24	21.52	55.51

Table 11
Specific consumption yields of raw materials, processing aids, thermal and electric energy, detergents, and water, as well as generation of byproducts and methane, relative to the *Birra Peroni* brewery (Rome, Italy) and main European breweries. The data within brackets refer to the average values.

Specific consumption yield	***Birra Peroni* Srl**	**European Breweries**	**UdM**	**Ref.**
Malted barley	10.8	15-18	kg hL^{-1}	UNEP (1996)
Corn Grits	4.7	-	kg hL^{-1}	This work
Hop Pellets	91.6	260	g hL^{-1}	Assobirra (2012)
Diatomaceous Earth	112	80 – 570 (255)	g hL^{-1}	IFC (2007); UNEP (1996)
PVPP	0.1	20-40	g hL^{-1}	Gopal and Rehmanji (2000)
Caustic Soda (30% w/w)	0.6	0.39 – 1.07 (0.7)	kg hL^{-1}	UNEP (1996)
Carbon Dioxide	619-1320	830– 3060 (1830)	g hL^{-1}	UNEP (1996)
Thermal energy	64-78	150-350 (110)	MJ hL^{-1}	Olajire (2012); Sturm et al. (2013); UNEP (1996)
Biogas generated	10	3.0-3.3	MJ hL^{-1}	Donoghue et al. (2012); IFC 2007)
Electric energy	8.3-9.8	8-20 (12.7)	kWh hL^{-1}	IFC (2007); Olajire (2012); Sturm et al. (2013); UNEP (1996)
Water	3.4-4.03	5-20 (4.9)	hL hL^{-1}	Olajire (2012); Sturm et al. (2013); UNEP (1996)
Spent Grains	17.4	14-19 (17)	kg hL^{-1}	IFC (2007); UNEP (1996)
Surplus Yeast	1.4	2-4 (3)	kg hL^{-1}	IFC (2007); UNEP (1996)

FIGURE 1

Beer system boundary (TR = transport).

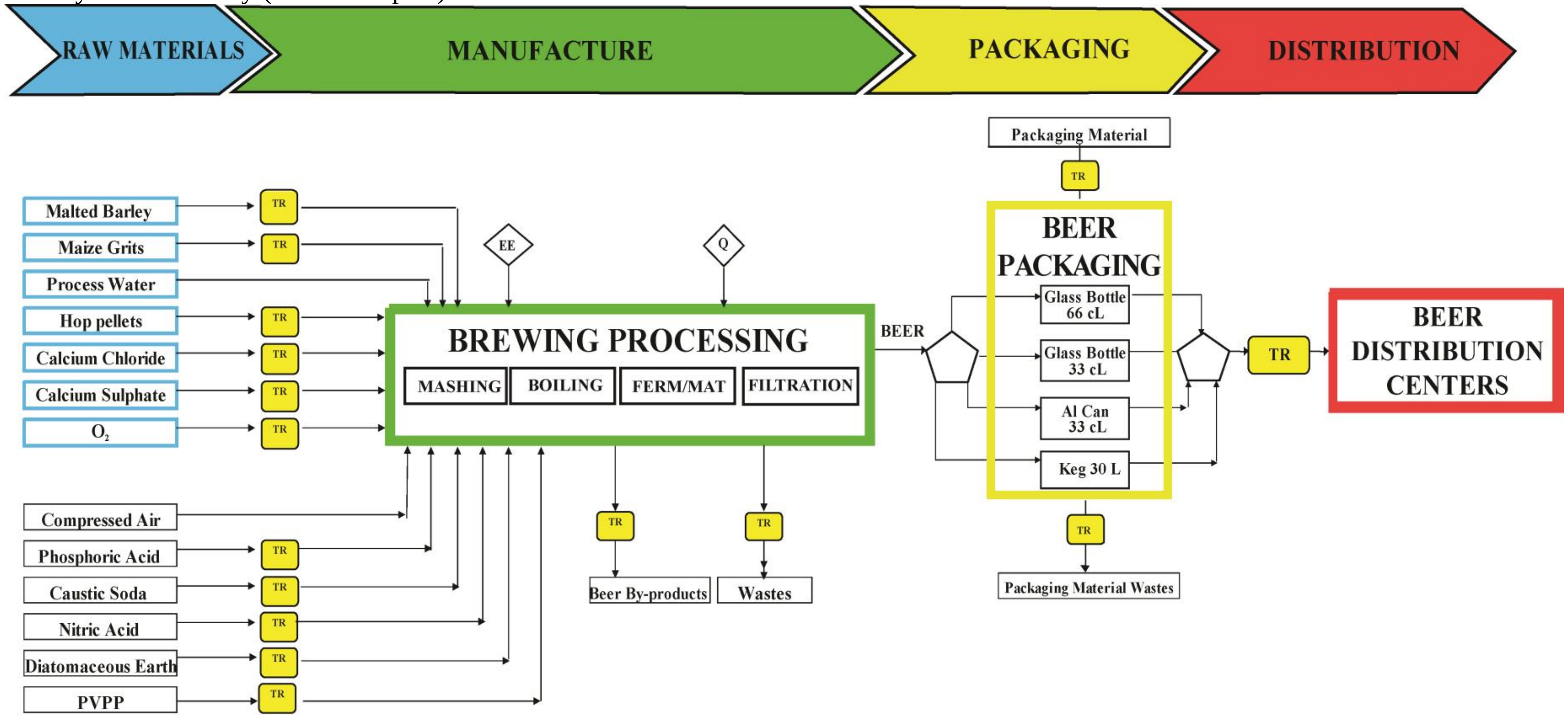
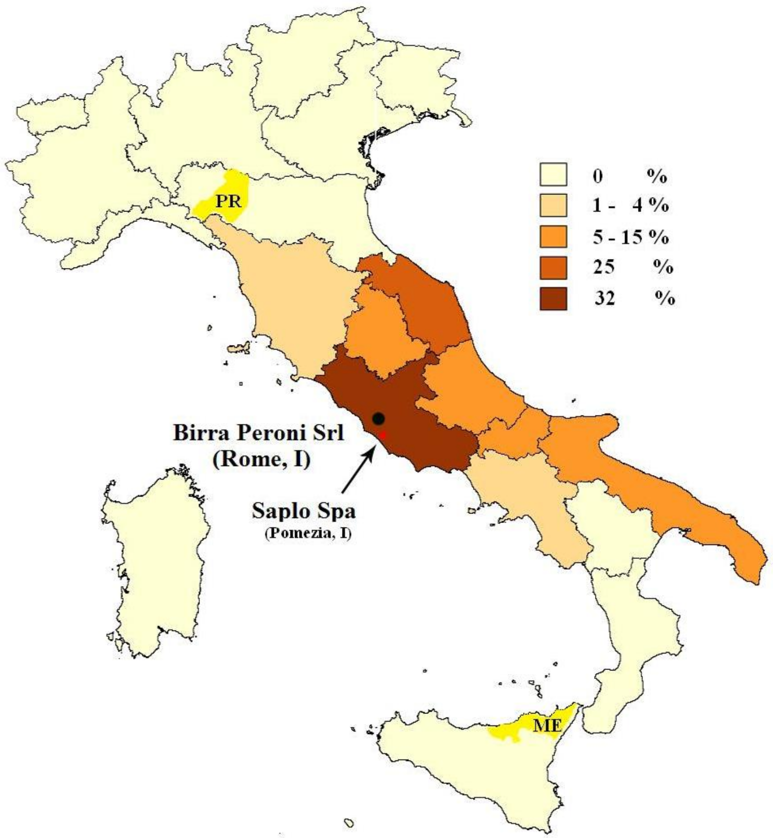


FIGURE 2

Maps of (**a**) barley and maize grits supply and (**b**) all-format *Peroni* beer sales distribution, both referred to the brewery examined in this work. The different colors used to mark the regions of Italy refer to the mass fraction percentages of barley supplied to the malthouse Saplo Spa (Pomezia, Italy) in order to be converted into malt and then transported to the brewery Birra Peroni Srl (Rome, Italy), or to the beer sales volume (BS) expressed in m^3, respectively.

a)



b

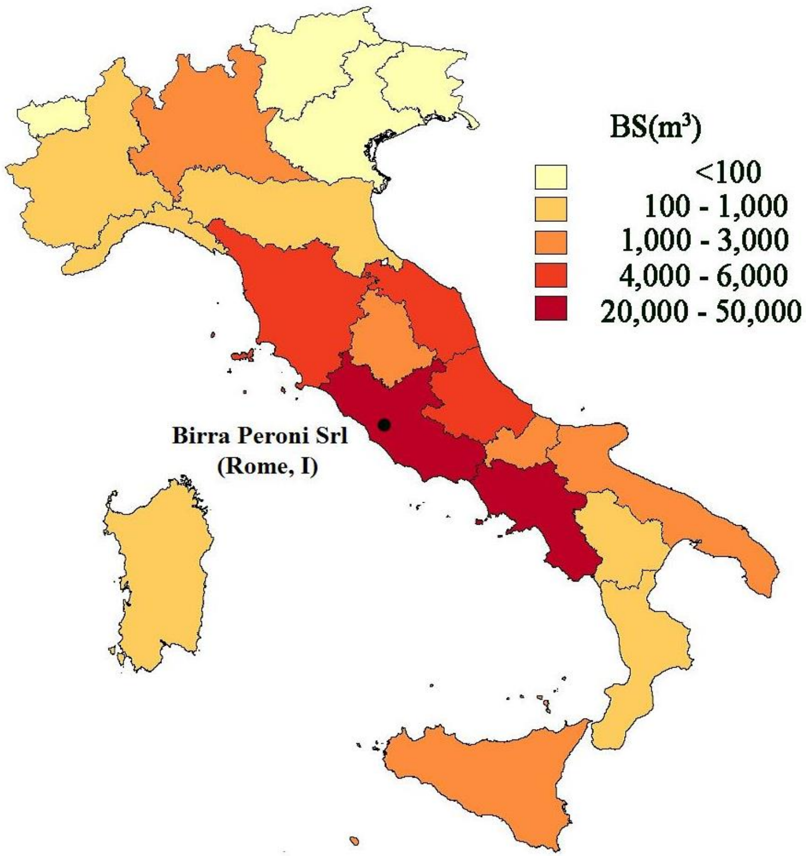
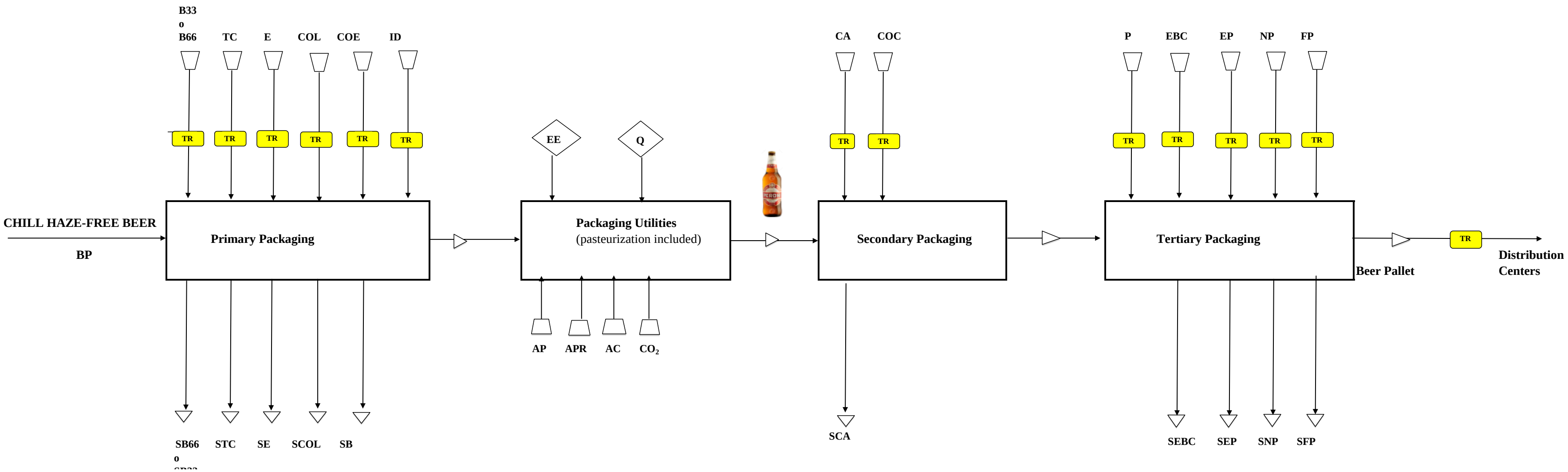


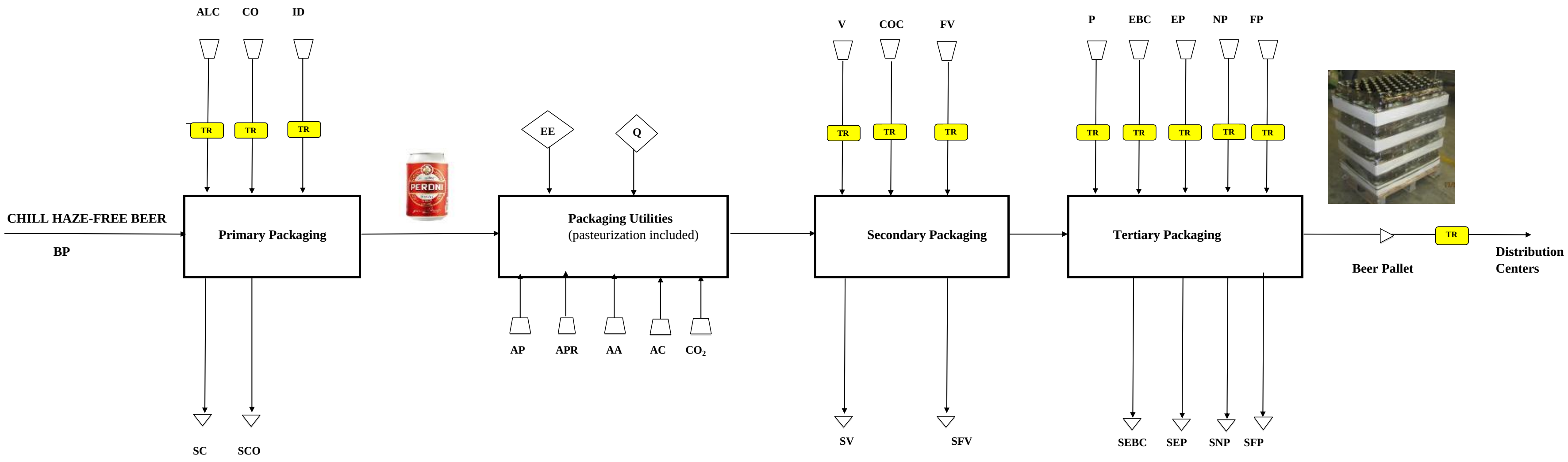
FIGURE 3

Schematic diagram of the packaging process for *Peroni* lager in (**a**) 33- or 66-cL amber glass bottles; (**b**) 33-cL aluminum cans; (**c**) 30-L stainless steel kegs. All the identification items for the input and output materials are reported in the List of Symbols.

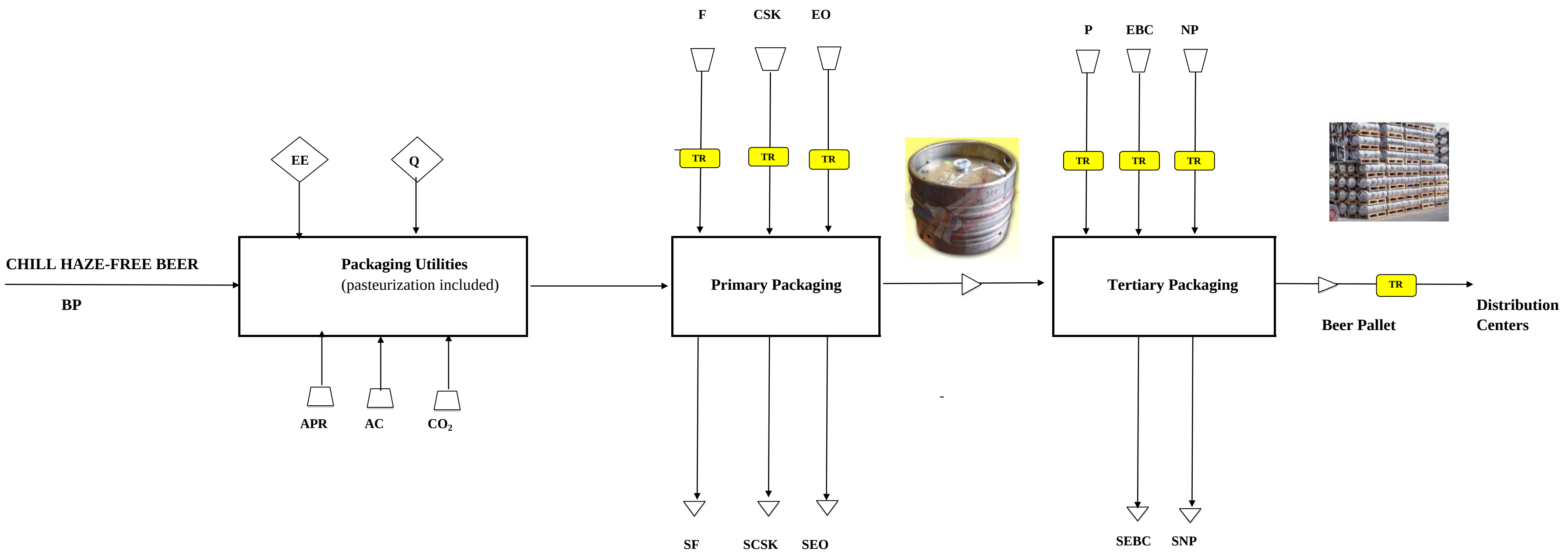
a)



b)


ALC
CO
ID
TR
TR
TR
CHILL HAZE-FREE BEER
BP
Primary Packaging
SC
SCO
PERONI
EE
Q
Packaging Utilities
(pasteurization included)
AP
APR
AA
AC
CO_2
V
COC
FV
TR
TR
TR
Secondary Packaging
SV
SFV
P
EBC
EP
NP
FP
TR
TR
TR
TR
TR
Tertiary Packaging
SEBC
SEP
SNP
SFP
Beer Pallet
TR
Distribution
Centers

c)


F
CSK
EO
P
EBC
NP
EE
Q
TR
CHILL HAZE-FREE BEER
BP
Packaging Utilities
(pasteurization included)
Primary Packaging
Tertiary Packaging
Beer Pallet
Distribution Centers
APR
AC
CO_2
SF
SCSK
SEO
SEBC
SNP

Figure

Figure 4
Block flow diagram of solid waste and gaseous effluent formation during *Peroni* lager packaging and pallet management in tertiary packaging and distribution centers. All symbols used are reported in the List of Symbols.

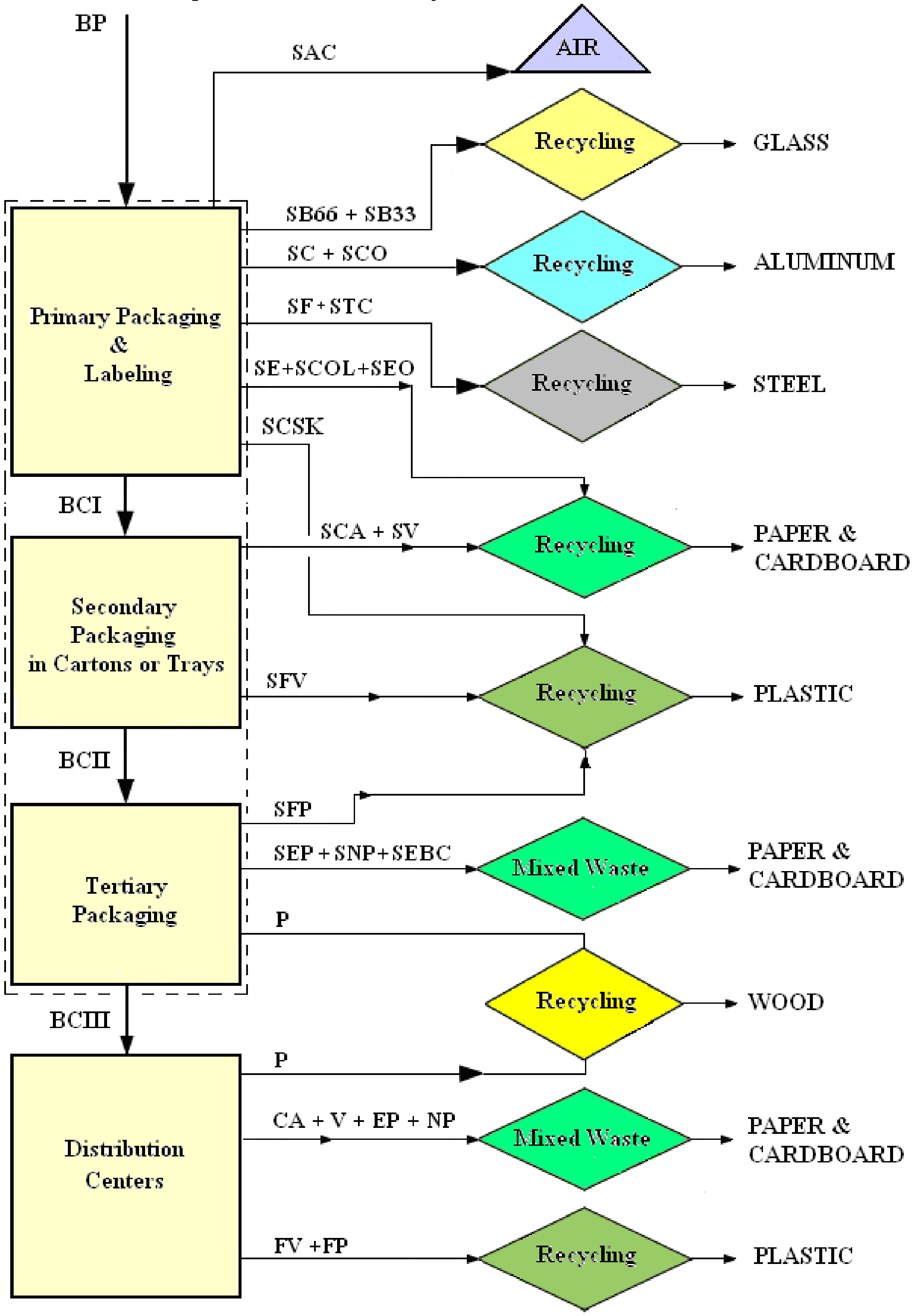


Figure 5

Carbon footprint (CF) of a functional unit (1 hL) of *Peroni* lager packed in 66- or 33-cL glass bottles (GB), assembled in cartons either as loose or multipack (C) bottles, 33-cL Al cans (ALC), or 30-L stainless steel kegs (SSK).

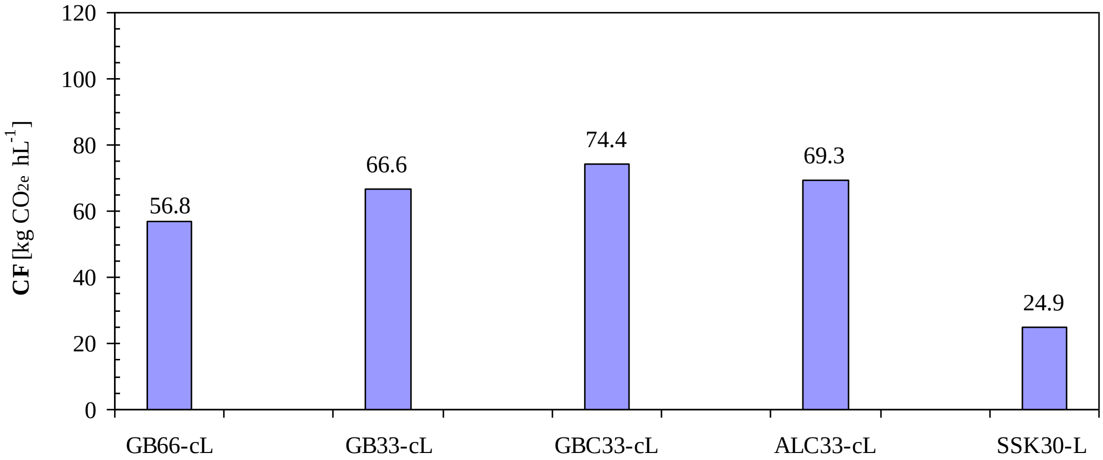


Figura 6
Percentage contribution of the different life cycle phases to the carbon footprint of a functional unit (1 hL) of *Peroni* lager packed in 66- or 33-cL glass bottles (GB), assembled in cartons either as loose or multipack (C) bottles, 33-cL Al cans (ALC), or 30-L stainless steel kegs (SSK): RPM, raw materials and processing aids; BPR, brewing processing; PM, packaging materials; PP, packaging; TR, transportation; WD, waste disposal.

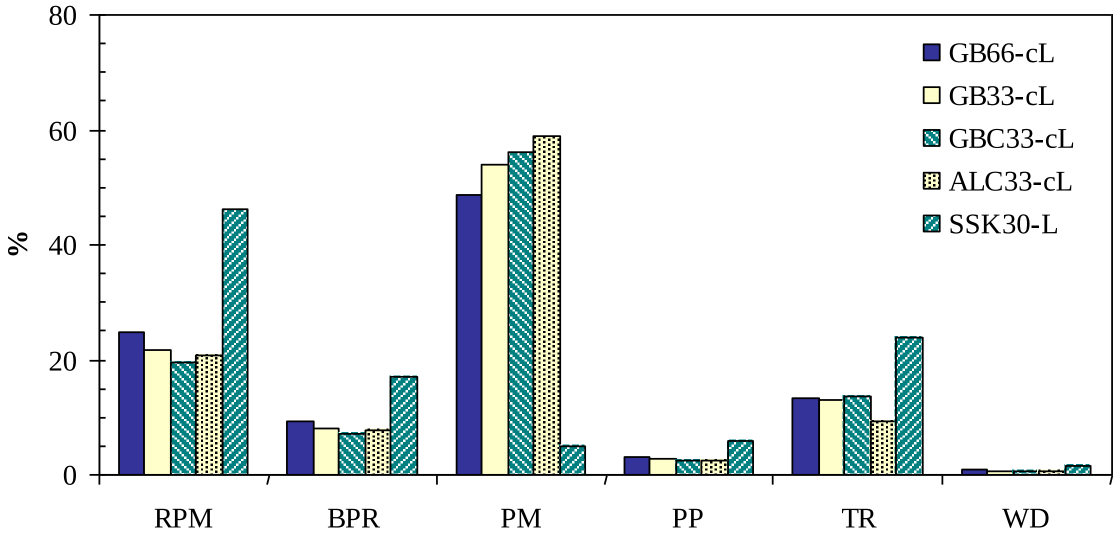


Figure 7

Effect of the percentage variation of the emission factor (EF_i) for malted barley (■), barley production site (▲), maize grits (△), glass bottles (○), aluminum cans (□), electric (●) and thermal (◆) energy, or means of transport of final product (◊) on the percentage variation of the carbon footprint of a functional unit (1 hL) of *Peroni* lager packed in all the formats examined with respect to the basic case.