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Research article

Evaluation of the environmental impact of plastic cap production, packaging, and disposal

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ABSTRACT

This study analysed the impact of the production of high-density polyethylene (HDPE) caps on the environment. To determine the environmental impact of injection moulding production, a life-cycle assessment was performed. The life-cycle assessment results showed that, in the injection moulding tool manufacturing process, the largest amount of environmental loading is attributable to electricity and steel consumption. Additionally, the HDPE cap production phase had the largest environmental impact associated with electricity consumption. However, scenario analysis showed that the environmental impact from electricity consumption can be reduced by up to ten times if cleaner sources of electricity are used. Large differences related to electricity sourcing should help developing countries to better understand the need to increase the use of cleaner sources of electricity.

1. Introduction

One of the most common plastic materials used in injection moulding is high-density polyethylene (HDPE), which is primarily used as a packaging material because of its good properties, such as hardness, inexpensiveness, resistance to moisture and chemicals, flexibility, electrical insulation and recyclability. The injection moulding manufacturing process for plastic products is known to consume electrical energy, and therefore significantly impact the environment (Madan et al., 2015). Matarrese et al. (2017) proposed a guideline for reliable and sensitive energy estimation of the injection moulding process in order to create an environmentally driven mould design. Mianehrow and Abbasian (2017) measured the specific energy consumption of six hydraulic injection moulding machines and the profile of their energy consumption over one cycle of the injection moulding process. Their results showed that the throughput and total cycle time most significantly impact energy consumption, and that each hydraulic injection moulding machine has a unique profile of energy consumption. Tranter et al. (2017) determined the direct energy consumption of injection moulding equipment and the quality of the moulded parts in order to optimise the sustainability of the process. Other approaches involve optimisation of the plastic injection moulding process through the use of a multi-criteria environmental impact assessment (Pun et al., 2003).

A standardised life-cycle assessment (LCA) is a scientifically sound and comprehensive approach that can be used to determine the environmental impact of various processes (Agarski et al., 2017; Arias et al., 2018; Zhou et al., 2018) and products (Cellura et al., 2012; Soode-Schimonsky et al., 2017). Life-cycle thinking and LCA allow for sustainable evaluation; thus, environmental and social LCA, in addition to life-cycle cost evaluation, have been widely employed to evaluate various human activities (Grubert, 2017). Elduque et al. (2015) analysed the processing of HDPE parts, placing emphasis on electricity consumption measurement. The conclusion was that electricity consumption represents the largest environmental load of the injection moulding process. In a later study by Elduque et al. (2018), the authors investigated the influence of the material and type of injection moulding machine on electricity consumption. Evaluation of their sample with 36 plastic parts confirmed that the electricity consumption needed to be further analysed in depth, preferably by measuring the consumption in an actual factory. Hesser et al. (2017) performed an LCA to investigate the environmental impact of various polypropylene composites fabricated via injection moulding; they found energy consumption to vary between 1.6 and 3.5 MJ/kg. In addition to injection moulding, plastic extrusion is another widely employed production process to which LCA can be applied to determine its environmental impact (Arnold and Alston, 2012).

Although the process of producing packaging products such as plastic caps via injection moulding consumes a lot of electricity, the next life-cycle stage at which the caps are assembled on the bottle is

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also significant from the perspective of electricity consumption. Osterroth et al. (2017) presented an enhanced modelling and simulation approach to meet the electrical power demands of beverage bottling plants. Before a plastic cap is produced, it has to be designed. The design phase is a very important phase in the life cycle of a product since it significantly influences the succeeding life-cycle phases. Silva et al. (2015) evaluated two variations of PET bottle cap designs; their results showed that the cap design may have influenced the applied opening forces, but not the temperature measured at the evaluated points on the hands of the subject. Nakatani and Hirao (2011) developed a multi-criteria design for plastic recycling, where CO_2 emissions and fossil resource consumption were used as evaluation criteria. Park and Gupta (2015) estimated the total environmental impact of post-consumer plastic bottles by performing an LCA; they found that their results may be relevant to communities interested in sustainable urban design and, in particular, urban waste management.

A promising HDPE production approach is bio-based HDPE production. Belboom and Léonard (2016) compared fossil-based HDPE and bio-based HDPE produced from sugar beet and wheat; they showed bio-based HDPE to reduce climate change and fossil fuel depletion categories by approximately 60%. Chen et al. (2016) compared fossil and bio-based PET bottles by performing a cradle-to-factory-gate LCA; their results indicated that woody-biomass-based PET bottles had 21% less global warming potential, and required 22% less fossil fuel than their fossil-based counterparts. Alternatively, Vidal et al. (2018) evaluated four novel aircraft interior panels made from renewable or recyclable polymers. According to their results, all of the sustainable panels exhibited better environmental performance than the conventional panels.

Applying environmental management tools such as LCA in plastic product production allows environmental hotspots to be determined, and can help a company to improve their environmental profile. Cossu et al. (2017) performed an LCA to investigate the environmental performance of end-of-life management options for plastic materials. Sangwan and Bhakar (2017) performed an LCA to analyse the HDPE pipe manufacturing process; they found the raw material phase to have the largest environmental impact. Civancik-Uslu et al. (2018) provided a literature review of LCA studies on plastics with functional fillers; they concluded that the use of fillers in the plastics industry may help to reduce environmental pollution. Although there are numerous environmental management options for end-of-life products, the reuse and recycling of waste plastic caps continues to garner the most attention. Oliveira et al. (2017) used disposed plastic bottle caps to develop a sustainable and low-cost sandwich composite structure. Unal et al. (2017) evaluated used PET bottle caps as an energy resource; they concluded that the heating value of PET is 3.5 times higher than that of lignite. In a review on PET bottle recycling by Welle (2011), sophisticated decontamination processes such as density separation were reported to be used to separate and remove the bottle caps in order to produce PET pellets. Bernardo et al. (2016) used LCA and life-cycle cost evaluation methods to evaluate polymers and polymer composites; they found the global warming potential and total energy use to be generally lower than those of alternative materials. Czaplicka-Kolarz et al., (2013) applied LCA and exergy analysis in order to evaluate polyethylene, polypropylene, polyvinylchloride, polystyrene and PET polymers. Alternatively, Gu et al. (2017) performed an LCA to assess the potential of a mechanical recycling process for waste plastics from various sources; they concluded that the impact of virgin composite production is nearly four times higher than that of recycled composite production. Hohenschuh et al. (2014) performed an economic and cradle-to-gate LCA of poly-3-hydroxybutyrate production from hybrid poplar leaves. Their results showed that irrigated poplar production generates 248.8% more greenhouse gases than the production of displaced polypropylene, whereas non-irrigated poplar production produces 76.1% less greenhouse gas. Hoppe et al. (2018) analysed polymer production via an LCA; they concluded that the decision about whether to recycle CO_2 into hydrocarbons is largely dependent on the source and amount of energy used to produce hydrogen. Nguyen et al. (2017) performed cost analysis and an LCA to evaluate various HDPE polymers; they found that recycled HDPE can be a better substitute for pristine HDPE owing to its low energy requirements and production costs. Although the generation of waste HDPE occurs in all life-cycle phases, it is most significant in the production and packaging stages (Usapein and Chavalparit, 2014). The amount of generated waste HDPE can be reduced by implementing sustainable waste management options that eliminate the need for landfills. A comparative LCA and life-cycle cost evaluation study by Simoes et al. (2013) showed that there is an overall environmental and economic benefit of using recycled HDPE instead of virgin HDPE. A review on the thermal and catalytic pyrolysis of plastic solid waste by Al-Salem et al. (2017) indicated that HDPE is suitable for pyrolysis, and that it is more environmentally friendly than combustion or gasification. Alternatively, HDPE plastic bags have been shown to withstand an 850 °C maximum mass reduction thermal treatment (Alam et al., 2018).

Although the injection moulding of plastic products is a process that has been extensively investigated from various perspectives, the environmental impact of each operation in the HDPE injection moulding process has yet to be considered in detail. No existing literature has provided a comprehensive analysis of the material and energy flows for the injection moulding tool manufacturing process, or an LCA of the HDPE cap production injection moulding process. In this study, a detailed life-cycle inventory (LCI) assessment was performed for the injection moulding tool manufacturing and HDPE cap production injection moulding processes. Furthermore, two different plastic cap designs intended for the same function were compared. The obtained LCI was used as input data for a life-cycle impact assessment (LCIA). The remainder of the paper is organised as follows. Section 2 describes the goal, scope, and LCI of this study. Section 3 presents the LCIA results for plastic caps production, packaging and disposal. Section 4 provides an interpretation of the results, and demonstrates the scenario analysis results. Section 5 includes a summary in the form of conclusions, limitations and future research directions.

2. Materials and methods

According to international standards ISO 14040 (ISO 14040, 2006) and ISO 14044 (ISO 14044, 2006), an LCA consists of the following: definition of the goal and scope, LCI analysis, an LCIA and interpretation. The following subsections have been organised according to these four standardised LCA phases.

2.1. Goal and scope

The plastic products investigated in this study were obtained from a small European producer of plastic products with a just-in-time production concept. The goal of this study was to assess and compare the environmental impacts of the production, packaging, and disposal processes of two designs of plastic caps that are intended for use in beverage packaging. The functional unit is one HDPE plastic cap that has been produced via injection moulding, packed in a corrugated box, and is ready for distribution. An attributional LCA was performed to analyse two different plastic cap designs: blue (blue-coloured cap) and red (red coloured cap) (Fig. 1). The differences between the cap designs are as follows: the height of the safety ring of the red cap design is lower, and the radius of the edge at the upper part of the red cap is wider. Both caps have the same morphology and functional properties, and there is no difference in performance. The blue cap design was used in past production, and the red cap design is the new and improved version. The red cap was designed to require less material without compromising the functional properties or performance. An appropriate reduction of the mass and volume of a product is a simple and direct way to reduce its environmental impact. The cap redesign has reduced

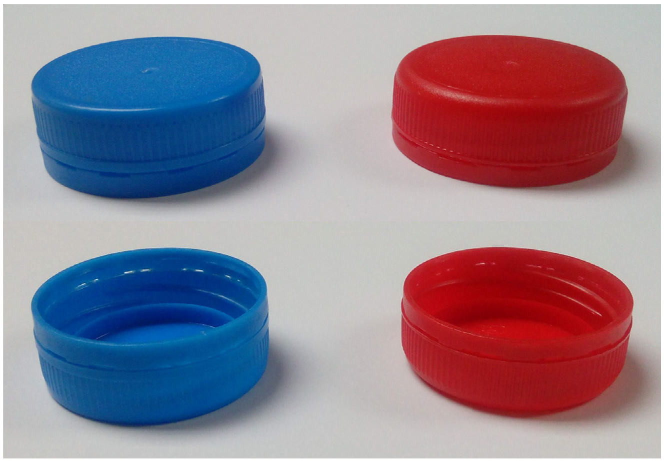

Fig. 1. Blue and red cap designs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the total mass of cap from 3.4 to 2.9 g, i.e. a 15% mass reduction, and both cap designs entail the use of HDPE. To evaluate the impact on the environment, the CML baseline (Guinée, 2002) LCIA method was applied in order to quantitatively characterise the LCA results. Specifically, the 100-yr global warming potential (GWP) in kg·CO_2 equivalents, photochemical oxygen-creation potential (POCP) in kg·C_2H_4 equivalents, acidifying potential (AP) in kg·SO_2 equivalents, and eutrophication potential (EP) in kg·PO_4^{3-} equivalents were selected to characterise the LCA results. According to the product category rules for plastic products and bottled water (EPD International, 2017; EPD International, 2018), presentation of the LCA results in terms of these four impact categories is recommended.

The system boundaries include the following life-cycle phases (Fig. 2): injection moulding tool manufacture, plastic cap production and packaging and disposal of the end-of-life plastic caps. The use phase, which corresponds to the packaging required for transport, and the transport and beverage consumption phases, was not considered, as the environmental impact of this phase was fully allocated to the beverage product in this study. The assumptions and limitations that were adopted for the LCA model of plastic caps are presented in Table 1.

2.2. Life-cycle inventory

The material and energy flow LCI results for previously defined life-cycle phases are respectively provided in Tables 2–5. The background data were obtained from the Ecoinvent 3.4 LCI database with cut-off system model, and the foreground data were obtained from the plastic cap manufacturer. The plastic cap manufacturer has a workshop dedicated to the manufacture of injection moulding tools and subsequent production of various plastic parts. The inventory for injection moulding tool manufacturing is provided in Table 2. The first step in the injection moulding tool manufacturing process is the transport of steel plates by a truck. The injection moulding tool machining inventory considers the amount of electricity consumed by the milling, turning, honing, hardening, grinding and thread grinding processes occurring in the workshop. After the injection moulding tool is completed, plastic cap production can proceed on the injection moulding machine. In the plastic cap production process, the injection moulding machine consumes electricity, HDPE granulate and, in smaller quantities, other auxiliary consumables (Table 3). The next life-cycle phase entails packaging the plastic caps; in this phase, the product is placed in polyethylene (PE) bags and a cardboard box (Table 4). The boxes containing plastic caps are then closed with duct tape and placed on a wood pallet. Finally, the boxes containing plastic caps are wrapped with stretch foil to secure safe transport. The packaging of beverages that have a plastic cap, distribution and beverage consumption were not included as system boundaries, and were therefore not considered in this study owing to insufficient information. The final life-cycle phase, i.e. plastic cap disposal, includes the transport, recycling and landfilling of waste plastic caps (Table 5). Because the specific data on plastic cap waste management were unavailable, the recycling rate for the plastic caps is determined according to the waste PET bottles (Table 1, assumption A17 and A18). The recycling rate for the plastic caps is calculated as the amount of PET bottles collected for recycling divided by the total amount of PET bottles on the market. Landfilling is assumed for the rest of the waste plastic caps (72%). All of the collected LCI data correspond to one functional unit, with the exception of the data presented in Table 2, which corresponds to the manufacture of one injection moulding tool.

3. Life-cycle impact assessment results

The characterised LCA results for GWP, POCP, AP and EP were obtained after the CML method was applied to the LCI data by using openLCA 1.7 software (Table 6, Figs. 3–6). All of the calculated results correspond to one functional unit, with the exception of the results illustrated in Fig. 3, which corresponds to the manufacture of one injection moulding tool.

4. Interpretation and discussion

Because the height of the safety ring is lower and the radius of the edge at the upper part of the cap is wider, the red cap design has smaller dimensions and a smaller volume; this corresponds to a smaller mass than the blue cap design. Therefore, a reduced mass is directly related to the reduced environmental impact of the red cap design. LCA characterisation does not allow comparison of impact category results. However, unlike the normalization results, which are dimensionless, the characterisation results permit quantitative interpretation of the LCA results (Table 6). In the production phase, the difference between the GWP of the blue and red caps was calculated as 0.11E-02 kg·CO_2, which may seem to be irrelevant. However, this difference is not negligible on the scale of mass production; for example, for 100,000 caps, this difference becomes 1.10E + 03 kg CO_2. Although the disposal phase does have some positive impact on the environment, in terms of impact, the production phase is dominant.

The characterised LCA results show that, in the tool manufacturing phase (Fig. 3), the largest environmental load is generated by the electricity consumed to manufacture the tool and perform the following machining operations: milling, turning, honing, hardening and grinding. In addition to electricity consumption, the production of the steel used to manufacture the tool significantly impacts the environment. Alternatively, in all impact categories, activities such as thread grinding, transport of the manufacturing steel, chips collection and the recycling of chips (labelled as "Other (< 5%)" on Fig. 3) each have less than a 5% impact on the environment.

The LCIA results for the blue and red cap design production phase (Fig. 4) are identical for all materials and processes, with the exception of the consumption and transport of HDPE granulate. The environmental impact of the HDPE granulate consumption and transport processes for the red cap design is smaller because of the smaller mass. As in the case of tool manufacturing, in the production phase, electricity consumption related to injection moulding machine and the heating and cooling of the tool were found to most significantly impact the environment. Aside from electricity consumption, the consumption of HDPE granulates significantly impacts the environment. The tool for plastic injection, the oil required for machine operation, the transport of HDPE granulates, the recycling of waste plastic and oil disposal negligibly impact the environment (labelled as "Other (< 5%)" on Fig. 4). Note that, because both the HDPE granulate supplier and plastic cap manufacturer commissioned in this study are located in Europe, the impact from transport was small. Alternatively, if the supplier of HDPE

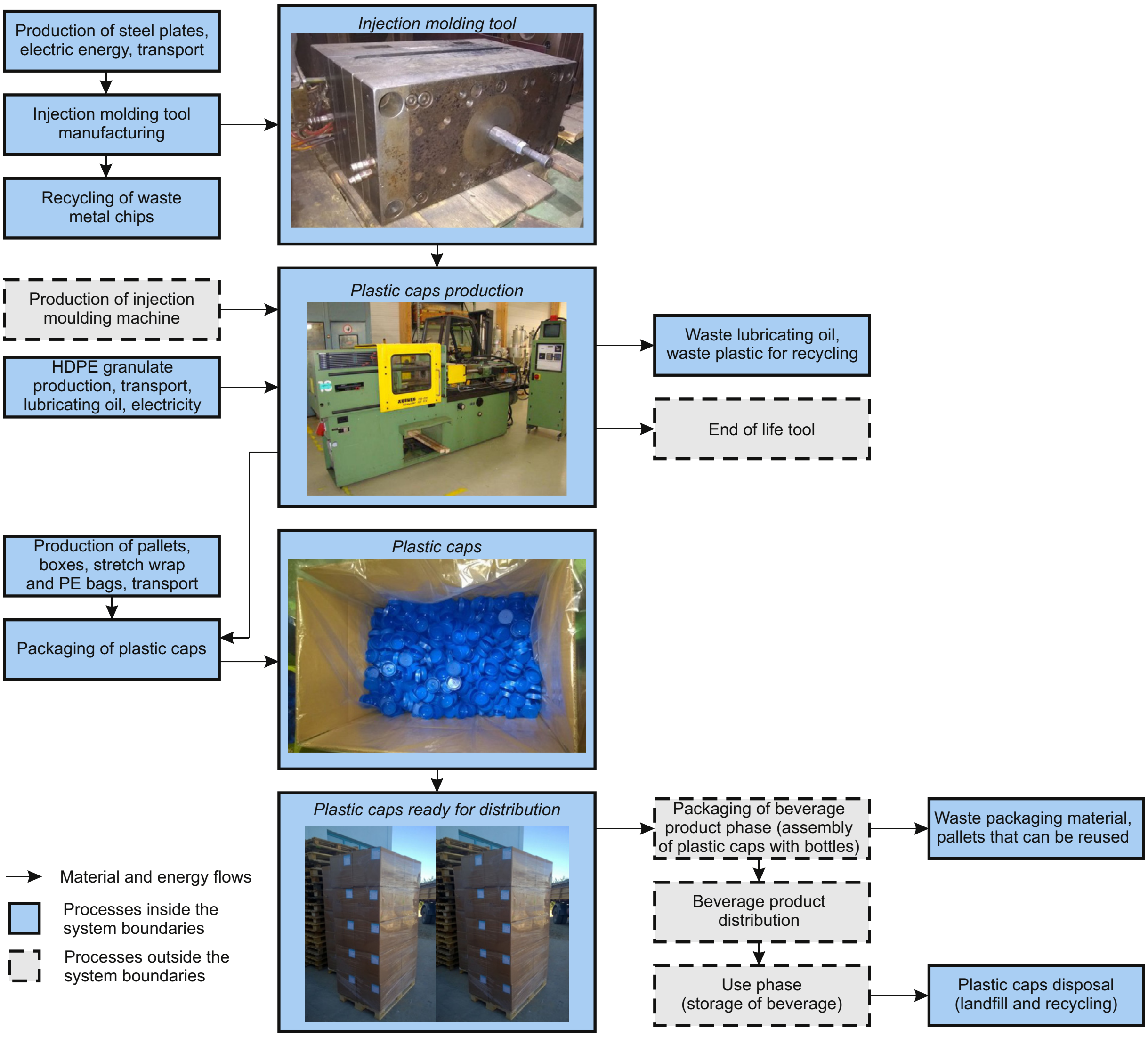

Fig. 2. System boundaries and considered life-cycle phases for the blue and red cap designs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

was from Asia, the transporting distance would be longer, the cost would be higher and the environmental impact would be larger.

The LCIA results for the packaging phase (Fig. 5) show that the use of corrugated cardboard (3.52E-04 kg·CO_2 eq) and stretch wrap (2.33E-04 kg·CO_2 eq) have the largest environmental impact. Conversely, Euro pallet and PE bag use have a small environmental impact (2.81E-05 and 1.67E-04 kg CO_2 eq, respectively). Avoided production of HDPE granulate in waste cap recycling allows the cap disposal phase to positively impact the environment, as can be seen in Fig. 6. For the POCP impact category, the positive impact due to waste material recycling was found to be much more significant than the negative impact on the environment due to transportation and landfilling. The results for POCP stand out because, for other impact categories, GWP, AP, and EP, the negative impact on the environment prevails in the disposal phase. Negative impact on the environment due to landfilling of waste plastic caps is especially high for GWP impact category results. Note that, the positive impact from the avoided production of HDPE granulate in waste cap recycling prevails only for GWP and POCP impact categories, while for AP and EP it is vice versa.

A comparison of the three considered life-cycle phases (production, packaging and disposal) for the blue and red cap designs (Table 6) show that, for all considered impact categories, the production phase most significantly impacts the environment. For AP, the largest environmental impact associated with the production phase was found to range from 3.53E-04 kg·SO_2 eq for the red cap design, to 3.56E-04 kg·SO_2 eq for the blue cap design. Conversely, the environmental impact of the packaging and disposal phases together was found to be approximately 150–200 times smaller (−1.70E-06 to −2,22E-06 kg·SO_2 eq combined) than that of the production phase. Recommendations for electricity consumption reduction can include the use of more efficient heating and cooling systems in plastic cap production, as well as the use of injection moulding machines with lower electricity consumption. As previously mentioned, the environmental impact of the red cap design is smaller than of the blue cap design.

4.1. *Use of biopolymers instead of the conventional HDPE*

In this section, the use of alternative materials, such as biopolymers, is discussed as an alternative to HDPE, i.e. the conventional material for cap production. Biopolymers are typically developed with the aim of reducing the environmental impact, and have been commercially available for three decades. Biopolymers tend to replace the conventional fossil fuel-based plastic materials; however, owing to differences in the mechanical, chemical and environmental properties, only a few biopolymers can effectively replace HDPE. Starch plastic, Bio-Polyethylene (Bio-PE), polylactide acid (PLA) and

Table 1
Assumptions and limitations for plastic cap life-cycle phases.

Life-cycle phase	Abbreviation	Assumptions and limitations
Injection moulding tool manufacturing	A01	The environmental impact of the land occupation of the injection moulding tool manufacturing workshop is considered as negligible and irrelevant.
	A02	The injection moulding tools for blue and red cap design production are very similar, and are thus considered to be the same tool.
	A03	The injection moulding tool comprises five steel types. Because the difference in environmental impact is small, only one type of steel from the LCI Ecoinvent database is considered.
	A04	The process "Pig iron, at plant/GLO S" is implemented as an avoided product in the LCA in order to account for the environmental benefits of chip recycling. The amount is equal to the mass of all material removed by the cutting processes, i.e. 6% of the total mass of the injection moulding tool.
Plastic cap production	A05	The environmental impact of the land occupation of the plastic cap workshop is considered as negligible and irrelevant.
	A06	It is assumed that the injection moulding tool for plastic cap production will be used to produce 19,008,000 caps or different HDPE plastic products, and will only undergo slight changes. After 19,008,000 caps have been produced, the end-of-life tool can be slightly modified for continued use in the production of the same product, used for another product or recycled. The post-production environmental impact of the 19,008,000 caps and benefits of recycling are not considered. The injection moulding machine produces 16 caps per min.; the production process runs 22 h per d, 25 days per mo., and the injection moulding tool lifetime is 36 mo, which corresponds to 19,008,000 caps.
	A07	Transport of the oil required for the injection moulding machine is not considered to be a system boundary because this process has a negligible impact on the environment.
	A08	Accidents and other problems that may arise in the plastic cap production process are not considered in order to minimise unpredictability and uncertainty.
	A09	The environmental impact of plastic production via an injection moulding machine is not considered, as it is very small impact and irrelevant.
	A10	70,000 of plastic caps are produced per production cycle.
Packaging	A11	The duct tape used to package the plastic caps placed in boxes is not considered, because the environmental impact is small and thus negligible. 3 m of duct tape is spent on one corrugated box. 0.857 mm of duct tape is used to package one cap.
	A12	The wood pallet has dimensions of 80 × 120 cm, and a mass of 20 kg.
	A13	Transport of the wood pallet, PE bag and stretch wrap is not considered.
	A14	3500 caps can be placed in one corrugated box; one box weighs 1 kg. Since 20 boxes can be placed on one Euro pallet, 70,000 caps can be placed on one pallet.
Use	A15	The use phase is not considered, because the environmental impact is fully allocated to the beverage product.
Disposal	A16	All end-of-life plastic caps are transported to a landfill that separates plastic for recycling. The transport distance is 20 km.
	A17	Approximately 28% of plastic caps will be recycled. The recycling rate for the plastic caps is determined as the amount of PET bottles collected for recycling divided by the total amount of PET bottles on the market (Radovanovic and Redzic, 2018).
	A18	Approximately 72% of plastic caps will be sent to a landfill. Although some percentage of waste plastic cap go to incineration, this percentage is unknown in Serbia, and thus for the rest of the plastic caps (72%) landfilling is assumed.

Table 2
Input and output flows for injection moulding tool manufacture.

Input of material and energy	Process described in the Ecoinvent LCI database	Amount	Note
Steel	Steel, low-alloyed - RER	2.33E+02 kg	220-kg total tool mass +13.2-kg chips removed via cutting (6%). (Table 1, A01, A02, and A03)
Consumption of electricity for milling	Electricity, low voltage - RS	2.84E+02 kWh	Operation time: 71 h; the machine tool consumes 4 kW per h.
Consumption of electricity for turning	Electricity, low voltage - RS	1.28E+02 kWh	Operation time: 32 h; the machine tool consumes 4 kW per h.
Consumption of electricity for honing	Electricity, low voltage - RS	8.60E+01 kWh	Operation time: 43 h; the machine tool consumes 2 kW per h.
Consumption of electricity for hardening	Electricity, low voltage - RS	1.80E+02 kWh	Operation time: 30 h; the machine tool consumes 6 kW per h.
Consumption of electricity for grinding	Electricity, low voltage - RS	1.88E+02 kWh	Operation time: 94 h; the machine tool consumes 2 kW per h.
Consumption of electricity for thread grinding	Electricity, low voltage - RS	5.20E+01 kWh	Operation time: 40 h; the machine tool consumes 1.3 kW per h.
Cutting fluid	Lubricating oil - RER	5.00E-02 kg	According to the metal machining processes described in the Ecoinvent LCI database, 3.82E-03 kg of lubrication oil is consumed per 1 kg of chips.
Transport of steel by truck	Transport, freight, lorry > 32 metric ton, EURO5 - RER	2.49E+02 t km	Transport from the steel plate manufacturer to the tool manufacturing workshop (total distance of 1070 km) × 233.2 kg.
Collection of waste chips	Iron scrap, unsorted - GLO	1.32E+01 kg	The process "Iron scrap, at plant/RER S" is used to account for the environmental burdens associated with chip collection. The amount is equal to the mass of all material removed during the cutting processes. Equates to 6% of the total mass of the injection moulding tool.
Output of material and energy	**Process described in the Ecoinvent LCI database**	**Amount**	**Note**
Tool for injection moulding	–	1 piece	The completed injection moulding tool has four cores and weighs 220 kg. A06, Table 1.
Recycling of waste chips	Pig iron - GLO	1.32E+01 kg	A04, Table 1

Table 3
Production-phase input and output flows for a single functional unit.

Input of material and energy	Process described in the Ecoinvent LCI database	Amount	Note
Tool for injection moulding	–	5.26E-08 piece	During its life cycle, the tool can produce 19.008E + 06 plastic caps (A06, Table 1). Therefore, 1/19.008E + 06 of the tool is needed to produce one plastic cap. The LCI for the tool is available in Table 2.
HDPE[a]	Polyethylene, high density, granulate - RER	3.41E + 00 g	White granulate mass + colour granulate mass + waste plastic mass = 3.4 + 0.009 (The colour granulate is also HDPE, and is 2% mass of the white granulate mass.)
HDPE[b]	Polyethylene, high density, granulate - RER	2.91E + 00 g	White granulate mass + colour granulate mass + waste plastic mass = 2.9 + 0.009 (The colour granulate is also HDPE, and is 2% mass of the total white granulate mass.)
Lubrication oil for the machine (CastrolHyspin AWS 46)	Lubricating oil - RER	3.38E-02 g	After 5000 working hours, the oil in the injection moulding machine has to be changed. 180 L of oil is changed in one service. The machine operates 22 h per day with 2-h-per-day delays, and produces 16 pieces/min. This means that 1/16[a]60 = 10.42E-04 h is needed for one piece. (180 L × 10.42E-04 h)/5000 h = 3.75E-02 ml. The oil has a density of 900 kg/m^3 = 3.38E-02 g
Tool heating	Electricity, low voltage - RS	2.67E-03 kWh	4 × 800 W × 0.8 (tool is heated for 80% of the total working hours) × 10.42E-04 h
Machine for injection moulding	Electricity, low voltage - RS	1.03E-02 kWh	18 kW × 0.55 × 1 (machine operates at 55% of full capacity 100% of the total working time) × 10.42E-04 h
Machine heating	Electricity, low voltage - RS	2.67E-03 kWh	4 × 800 W × 0.8 (tool is heated for 80% of the total working hours) × 10.42E-04 h
Cooling of the tool and machine	Electricity, low voltage - RS	3.04E-03 kWh	A chiller with a power of 2 × 31 kW × 0.8 (chiller operates for 80% of the total working time) × 0.00104166 h/17 (there are 17 machines dedicated to production)
Transport for HDPE[a]	Transport, freight, lorry 7.5–16 metric ton, EURO5 - RER	4.09E + 00 kg km[a]	The transport distance in Europe by road between the granulate and cap manufacturers is 1200 km × 3.409 g.
Transport for HDPE[b]	Transport, freight, lorry 7.5–16 metric ton, EURO5 - RER	3.49E + 00 kg km[a]	The transport distance in Europe by road between the granulate and cap manufacturers is 1200 km × 2.909 g
Output of material and energy	Process described in the Ecoinvent LCI database	Amount	Note
Blue cap design[a]	–	1 piece	The blue cap mass is 3.4 g.
Red cap design[b]	–	1 piece	The red cap mass is 2.9 g.
Waste oil	Hazardous waste, for incineration - GLO	3.38E-02 g	Burning of end-of-life oil.
Waste plastics	–	4.29E-08 g	Approximately 3 kg of waste plastic is generated by each production series. This waste plastic is a mixture of old and new products in the injection moulding machine and goes to recycling process (Table 5). 3 kg × 1/70,000

[a] Blue cap design.
[b] Red cap design.

polyhydroxyalkanoates/polyhydroxybutyrate (PHA/PHB) have the potential to replace the conventional HDPE material (Table 7). Among these four biopolymers, Bio-PE stands out as the best technical substitute (Shen et al., 2009, Spierling et al., 2018). However, the mechanical and chemical properties and market price determine the limitations of biopolymer applicability. A comparison of the mechanical properties has yielded the following results (Tipelin, 2018): starch plastic is the weakest, and PLA and Bio-PE have mechanical properties similar to those of HDPE (Shen et al., 2009). Unlike Bio-PE, various starch plastics, PLA and PHA/PHB are fully biodegradable. The GWP of starch plastic (1.9 kg·CO$_2$ eq/kg) and Bio-PE (1.6–2.1 kg·CO$_2$ eq/kg) is similar to that of HDPE (1.95 kg·CO$_2$ eq/kg) (Spierling et al., 2018). Conversely, owing to the wet milling of corn and PHB fermentation and recovery processes that enable utilization of fermentation residues as fuel, PHA/PHB positively impacts the environment (−2.3 to −1.4 kg·CO$_2$ eq/kg) through renewable feedstock and energy (Kim and Dale, 2008). A major disincentive for the wider use of biopolymers is their high price. In general, biopolymers are more expensive than HDPE, as their price can vary from 1.5 to 5 €/kg, whereas the price of conventional HDPE is 1.2–1.5 €/kg (Van den Oever et al., 2017).

4.2. Variability of electricity consumption in the production phase: scenario analysis

In addition to the default scenario for the Serbian electricity mix, the following scenarios were investigated in order to evaluate the total environmental impact of the electricity consumed by the manufacturing of an injection moulding tool and the production of plastic caps:

- S + 20SRB - 20% increased electricity consumption for Serbian country mix,
- S + 10SRB - 10% increased electricity consumption for Serbian

Table 4
Packaging-phase input and output flows for a single functional unit.

Input of material and energy	Process described in the Ecoinvent LCI database	Amount	Note
Corrugated box	Corrugated board box - GLO	2.86E-01 g	A14, Table 1
Pallet	EUR-flat pallet - RER	2.86E-06 piece	A12, A13, Table 1
PE bag	Packaging film, low density polyethylene - RER	5.71E + 01 mg	200 g of the PE bag are used to package one box.
Stretch wrap	Packaging film, low density polyethylene - RER	7.94E + 01 mg	Stretch wrap is rolled by hand on corrugated boxes placed on a pallet. The stretch wrap is on a roll that weighs 5 kg. One stretch roll can be used to package nine pallets with boxes.
Output of material and energy	Process described in the Ecoinvent LCI database	Amount	Note
One functional unit	–	1 piece	One plastic cap is packed in corrugated board and placed on a pallet.

Table 5
Disposal-phase input and output flows for a single functional unit.

Input of material and energy	Process described in the Ecoinvent LCI database	Amount[a]	Amount[b]	Note
End-of-life cap	–	1 piece	1 piece	End-of-life cap
Transport of waste	Municipal waste collection by 21 metric ton lorry - CH	6.80E-02 kg km	5.80E-02 kg km	A16, Table 1
Landfilling of waste caps	Waste polyethylene - GLO	2.45E + 00 g	2.09E + 00 g	A18, Table 1
Recycling of waste caps – avoided production of HDPE	Polyethylene, high density, granulate - RER	9.52E-01 g	8.12E-01 g	A17, Table 1
Recycling of waste caps – electricity consumption	Electricity, low voltage - RS	1.39E-04 kWh	1.18E-04 kWh	A17, Table 1 (Khoo, 2019)
Recycling of waste caps – natural gas consumption	Natural gas, high pressure – RoW	1.29E-05 m^3	1.10E-05 m^3	A17, Table 1 (Khoo, 2019)
Recycling of waste caps – diesel consumption	Diesel – Europe without Switzerland	1.78 E-06 kg	1.52E-06 kg	A17, Table 1 (Khoo, 2019)
Recycling of waste caps – solid waste disposal	Municipal solid waste - RoW	1.45E-04 kg	1.23E-04 kg	A17, Table 1 (Khoo, 2019)
Recycling of waste caps – CO_2 emission to air	Carbon dioxide	4.93E-05 kg	4.26E-05 kg	A17, Table 1 (Khoo, 2019)

[a] Blue cap design.
[b] Red cap design.

Table 6
Plastic cap life-cycle phase CML results for a single functional unit.

Impact category	Unit	Production[a]	Production[b]	Packaging[a]	Packaging[b]	Disposal[a]	Disposal[b]
GWP	kg·CO_2 eq	2.79E-02	2.68E-02	7.81E-04	7.81E-04	6.29E-03	5.37E-03
POCP	kg·C_2H_4 eq	1.27E-05	1.24E-05	1.79E-07	1.79E-07	− 2.33E-07	− 1.98E-07
AP	kg·SO_2 eq	2.94E-04	2.90E-04	3.30E-06	3.30E-06	2.63E-06	2.24E-06
EP	kg·PO_4^{3-} eq	1.61E-04	1.61E-04	1.00E-06	1.00E-06	4.20E-06	3.58E-06

[a] Blue cap design.
[b] Red cap design.

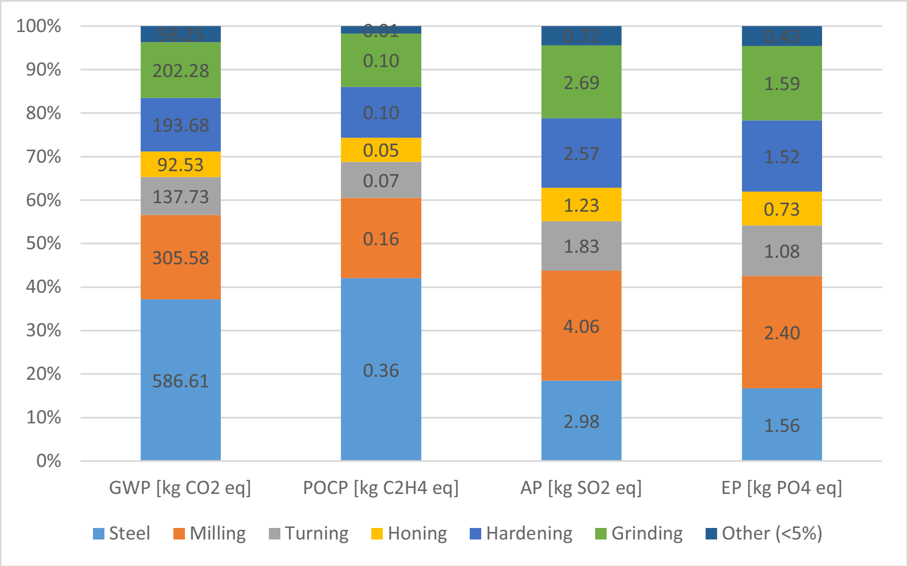

Fig. 3. CML results corresponding to the manufacture of one injection moulding tool.

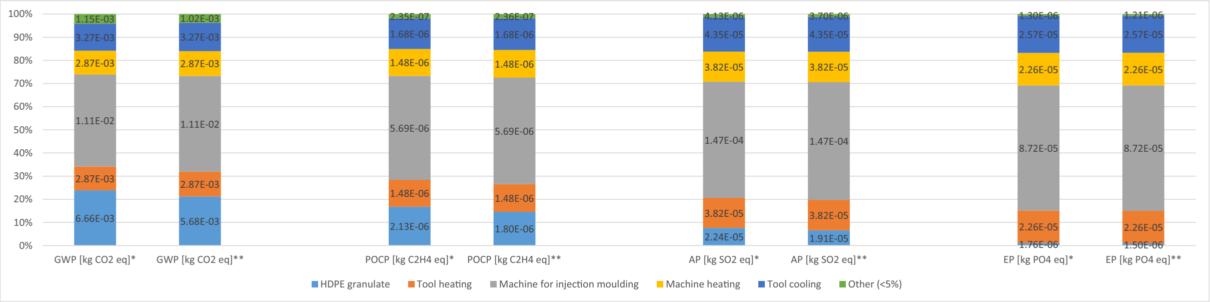

Fig. 4. CML results for the production phase of a single functional unit.

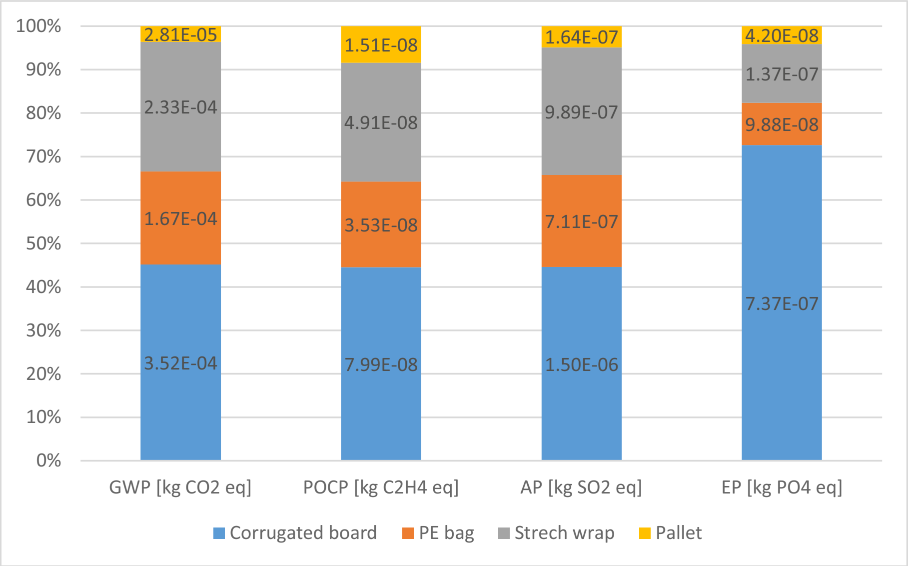

Fig. 5. CML results for the packaging phase of a single functional unit.

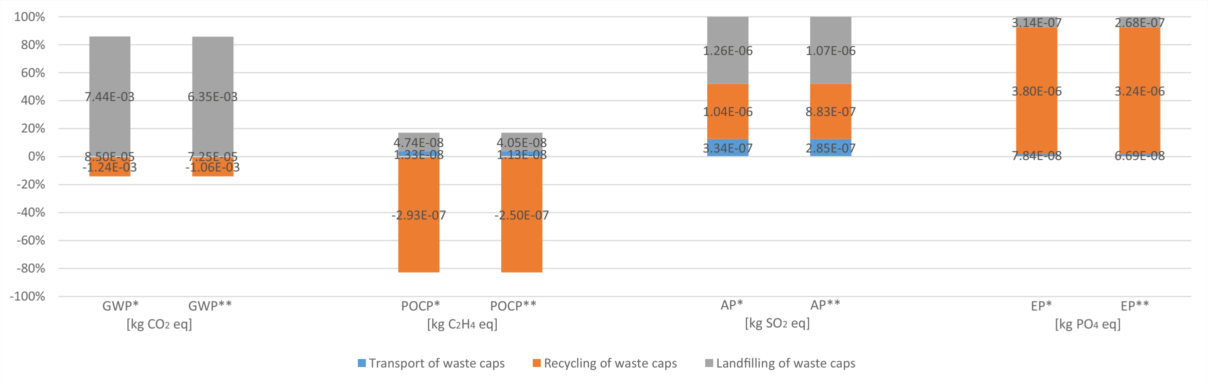

Fig. 6. CML results for the disposal phase of a single functional unit.

Table 7
Comparison between biopolymers and HDPE.

	Melt Mass-Flow Rate[a)] (190°/2.16 kg)	Density[a)]	Tensile strength at break[a)]	Flexural modulus[a)]	Technical substitution rate[a)]	Global warming potential production[b)]	Biodegradable[a)]	Price[c)]
Unit	g/10 min	g/cm^3	MPa	MPa	–	kg·CO2 eq/kg	–	€/kg
Starch plastic	3[d)]–8 [e)]	1.04[d)]–1.34[e)]	–	965[d)]–1700[e)]	Partial	1.9	No[d)]/Yes[e)]	2–4
PLA	10–25	1.25	48	3828	Partial	6.0E-01	Yes	2
PHA/PHB	5–25	0.92–1.39	10–40	800–3200	Partial	−2.3 to −1.4	Yes	5
Bio-PE	5–ss7.5	0.92–0.96	11–26	1200	Full	1.6–2.1	No	1.5–2
HDPE[f)]	4	0.95	13	1100	Full	1.95[g)]	No	1.2–1.5

[a] Shen et al., 2009.
[b] Spierling et al., 2018.
[c] van den Oever et al., 2017.
[d] Mater-Bi Y101U (Shen et al., 2009).
[e] Cereplast Hybrid resin (Shen et al., 2009).
[f] Tipelin, 2018.
[g] Results from Ecoinvent database with CML LCIA method).

country mix,
- S-10SRB - 10% decreased electricity consumption for Serbian country mix,
- S-20SRB - 20% decreased electricity consumption for Serbian country mix,
- SBA - electricity consumption for Bosnia and Hercegovina country mix,
- SPL - electricity consumption for Polish country mix,
- SHU - electricity consumption for Hungarian country mix,
- SDE - electricity consumption for Germany country mix,
- SHR - electricity consumption for Croatian country mix, and
- SCH - electricity consumption for Swiss country mix.

The scenario analysis results are shown on Fig. 7 for injection moulding tool manufacturing, and in Fig. 8 for plastic cap production. The scenario analysis results were calculated in terms of the GWP.

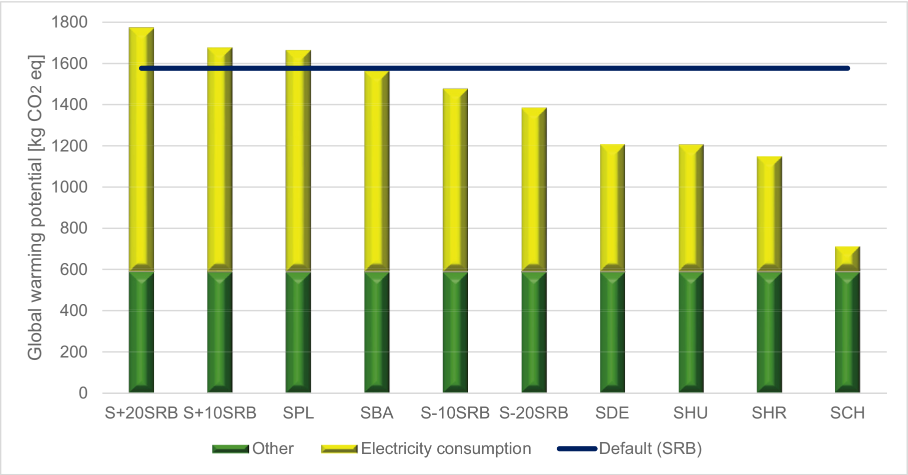

Fig. 7. Scenario analysis results for injection moulding tool manufacturing.

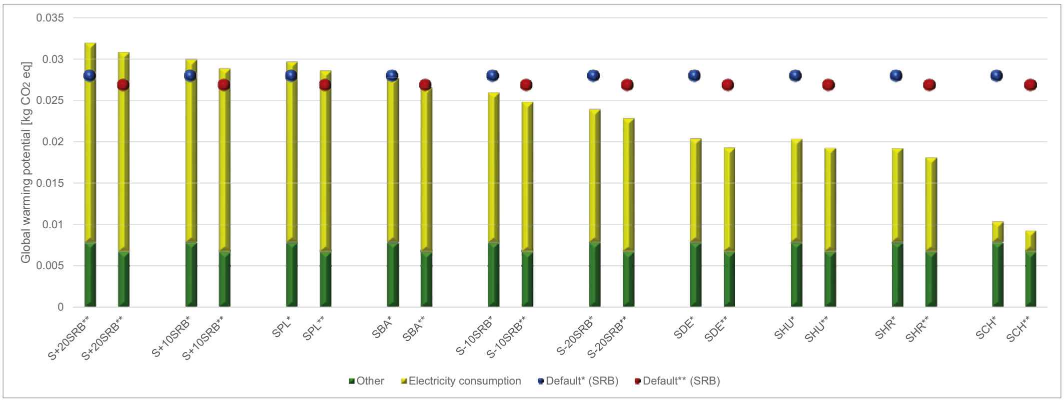

Fig. 8. Scenario analysis results for plastic cap production (*Blue cap design, **Red cap design). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Serbia, Bosnia and Hercegovina, and Poland have electricity mixes in which the main supply of electricity is coal that is burned in power plants (Table 8). The majority of the electricity mixes of Serbia and Bosnia and Hercegovina are sourced from lignite and hard coal burned in power plants and hydropower. The predominant supply of Polish electricity is coal burned in power plants: 54% hard coal and 37% lignite. The main difference between the German and Hungarian electricity mix is related to the use of hard coal and natural gas. Croatia sources an amount of hydropower that is similar to that of Bosnia and Hercegovina and Switzerland. The main sources of Switzerland's electricity are hydropower (49%) and nuclear power plants (43%).

The GWP of plastic cap production is strongly related to the inter-country variation of electricity sourcing (Figs. 7 and 8). The GWP results show that Polish electricity has the largest environmental impact of all countries considered in this study; it is followed by Serbian and Bosnian electricity scenarios. If the Polish electricity mix is disregarded, an electricity consumption increase and decrease of ± 10% and ± 20% (default) would mean that the electricity consumption of Serbia impacts the environment significantly more than the other considered counties. The GWP for Croatian electricity consumption was found to be approximately two times smaller than that for the Serbian default scenario. Analysis of the electricity mixes of Hungary and Germany show that their environmental impact is approximately 400 kg·CO_2 eq smaller than that of the Serbian default scenario. The Switzerland electricity mix scenario has the lowest GWP of all scenarios, as it is approximately eight times smaller than that of the Serbian electricity mix. The reason for the minimal environmental impact is Switzerland's cleaner electrical energy production method. Thus, burning lignite and hard coal to generate electricity largely impacts the environment, whereas hydropower, nuclear power and other alternative sources of electricity are more sustainable.

Table 8
Electricity consumption scenarios for various country mixes.

Scenario	Country mix	Lignite	Hard coal	Hydropower	Nuclear power	Natural gas	Other
Default, SRB	Serbia	67%	–	29%	–	1	3%
SBA	Bosnia and Hercegovina	23%	39%	37%	–	–	1%
SPL	Poland	37%	54%	2%	–	2%	5%
SHU	Hungary	16%	1%	–	39%	37%	7%
SDE	Germany	24%	20%	4%	24%	13%	15%
SHR	Croatia	7%	12%	45%	–	19%	17%
SCH	Switzerland	–	–	49%	43%	–	8%

5. Conclusion

Although the process of manufacturing an injection moulding tool significantly impacts the environment, this impact can be neglected when it is considered on a scale of single-cap production. The midpoint-level LCA characterisation results show that the environmental impact of injection moulding tool and plastic cap manufacturing is largely determined by the amount of electricity consumption. In the production phase, use of HDPE granulate in plastic cap production corresponds to the second-largest impact. In terms of the employed material, biopolymers can reduce the environmental impact; however, biopolymers that are capable of replacing HDPE tend to have less desirable mechanical properties, are more expensive and are not all biodegradable.

Scenario analyses for various countries confirmed that the Polish and Serbian electricity mixes most significantly impact the environment. Since the primary source of Polish and Serbian electricity is hard coal and lignite, it can be concluded that the use of cleaner sources can significantly reduce the environmental impact. This study also demonstrates the need of developing countries to increase the use of cleaner sources of electricity.

The limitations of this research are related to the following activities and their variations that were not covered by the system boundaries applied in this study: different suppliers and logistics for raw material, the use of biopolymers instead of conventional HDPE, the use of different injection moulding tools, machines and auxiliary equipment, evaluation of the end-of-life injection moulding tool, the use phase not being considered, and no universally applied end-of-life standard for waste caps. In this study, a European supplier was selected instead of a major HDPE producer from Asia or the Middle-East because of the low transporting costs. Although the environmental impact of HDPE transport represents a very small share of the total environmental impact of the production phase, the supplier of HDPE granulate and related logistics can affect the environmental impact. The use of an injection moulding tool with a larger number of cap moulds or a more energy-efficient injection moulding machine could also reduce the environmental impact. The use phase, which includes the packaging, transport and use of the beverage, could reveal details about the consumption of electricity in the beverage packaging phase. The logistics related to the collection of waste caps and end-of-life options are additional points of interest that are strongly dependent on the related countries' and municipalities' waste management systems.

Future research could focus on optimisation of the plastic cap production process and development of a more eco-friendly design. Another point of interest is optimisation of the injection moulding tool life-cycle management scheme, especially the end-of-life phase, since these tools have great potential for reuse and recycling. Sensitivity analysis can be extended to consider variations of other multiple factors, such as variations in the production process, injection moulding tool and machine variability, different supply material and waste management logistics, and different end-of-life options.

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