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Reimagining the milk supply chain: Reusable vessels for bulk delivery

Tomasz Blazejewski[a], Stuart Walker[a,b,c], Rukayya Ibrahim Muazu[b,d], Rachael H Rothman[a,b*]

[a]Department of Chemical and Biological Engineering, University of Sheffield, Sheffield. S1 3JD UK

[b]Grantham Centre for Sustainable Futures, University of Sheffield, Sheffield. S3 7RD UK

[c]College of Engineering, Maths and Physical Sciences, University of Exeter, Penryn TR10 9FE

[d]Department of Animal and Plant Sciences, University of Sheffield, Sheffield. S10 2TN

*Corresponding author r.rothman@sheffield.ac.uk

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Abstract

Milk packaging has been analysed multiple times in pursuit of finding the most appropriate vessel from an environmental point of view. Research has concentrated on commercially available containers of 0.5 – 2.5 litres, usually made from High-Density Polyethylene (HDPE), Polyethylene Terephtalate (PET), paper-based cartons, or glass, with some studies considering a reuse scheme for glass bottles. Whilst applicable for household delivery, such a reuse scheme is not practical for delivery to cafés where large volumes of milk are used every day; little information is known about transportation of bulk volumes of milk in bigger vessels such as steel churns. This study compares a proposed milk supply chain using a mix of reusable stainless steel churns and reusable glass bottles with the current supply chain that uses single-use HDPE bottles, for transportation of milk to 10 cafés belonging to The University of Sheffield. A cradle-to-grave life cycle assessment (LCA) is conducted using data obtained from the university and Our Cow Molly, a local dairy farm which delivers milk to the university. Sensitivity analysis was performed around the recycling rate of plastic bottles, water consumption for churn cleaning, the reuse rate of glass bottles and churns and the source of the on-farm electricity. The study suggests that the greenhouse gas emission can be lowered by approx. 6.5 tons of CO_2 equivalent annually if the reuse scheme is applied (this equates to a 65% reduction for the processes analysed). Considerable savings are also reported in categories such as water consumption, fossil resources depletion and cumulative energy demand. The reuse scheme is, however, likely to induce a similar or higher mineral resource use and higher environmental damage in the marine eutrophication category due to water treatment. Production of plastic bottles in the plastic scenario and maintenance and transport on the reusable side are the main contributors to the environmental impact. Further improvements in the reuse scenario could be achieved by reducing the amount of water used for cleaning and hence the electricity demand for water heating. The reuse scheme could also benefit environmentally from using an electric refrigerated van instead of a diesel vehicle.

1 Introduction

In 2020, globally over 189 million tons of dairy milk were consumed (USDA Foreign Agricultural Service, 2020); if all this milk was packaged in 2 litre plastic bottles, over 4 million tons of single-use plastic packaging would be used each year. This figure is likely to be an underestimate as milk is often packaged in bottles smaller than 2 litres, thereby requiring more plastic per litre of milk. To move towards a circular economy, a reusable packaging system for milk delivery is important.

Milk is commonly packaged in single-use HDPE (high density polyethylene), PET (polyethylene terephthalate), paper board (e.g. Tetrapak) or glass. Reusable bottles ranging in size from 500 ml to 2 litres have been used for domestic milk delivery. In the UK, the prevalent reusable milk bottle is the 1 pint (568 ml) glass bottle. In 1975, pint glass bottles had a 94% market share for UK milk packaging, but in the 1990s HDPE bottles became the prevalent means for milk transportation and by 2016 the market share of milk in glass bottles was only 10% (Vaughan et al. 2007; Greenwood et al. 2020).

Glass bottles are not suitable for bulk delivery of milk to cafés due to the volumes of milk involved and the limitations on size of glass bottle. For example, Starbucks alone, with over 31000 stores worldwide, uses over 500 million litres of milk each year (Starbucks, 2020). Milk churns (a churn is a large metal container, often approximately cylindrical, used for milk) were used 150 years ago for bulk delivery of milk from farm to market, however their use declined dramatically as more convenient and lighter weight containers, such as glass and plastic bottles, came into use. A milk packaging solution for bulk delivery of milk to cafés is urgently needed to reduce the volumes of single-use plastic waste.

Reusable steel vessels are regularly used for liquids other than milk, however the environmental impacts have mostly been described from the point of view of transporting chemicals in large steel drums (Biganzoli et al. 2019; Rietveld & Hegger 2014) in a centralised supply chain. This study sought to determine whether substitution of single-use plastic packaging with reusable bulk steel packaging has environmental benefit for the distributed (local) milk supply chain. Life cycle assessment was used to determine the environmental impacts of the single-use plastic packaging scenario and the reusable packaging scenario. In a café setting, the reusable metal churn would be connected directly to a milk pump, in a similar way to systems used for dispensing beer. The study analyses and balances the relative impacts of type of vessel: larger volumes of raw material, lower recycled content and variable recycling rate for plastic bottles versus an increased payload for transport and potentially elevated water usage for reusable vessels. This study will be of use to academics, farmers, milk suppliers and those working in the milk supply chain.

2 Literature Review

A number of studies have been conducted on the environmental consequences of substituting the single-use HDPE bottles most commonly used for milk delivery with an alternative. The conclusions, as well as the results of the comparisons, are very case-dependent.

One of the most popular substitutions for plastic in milk packaging is paper-based cartons, although both are single-use. Bertolini et. at (2016) found lower environmental impacts associated with single-use multilayer cartons for extended shelf-life milk packaging, compared to single-use PET and HDPE containers, based on Italian market data. The biggest contribution to the impacts was the manufacturing of the container itself. Despite long assumed distances for the transport of raw materials (some of which were imported from other countries) and products, transport did not contribute greatly to the environmental impacts, apart from in a few impact categories for the carton scenario. The study analyses only the end-of-life scenario reflecting Italian data from 2010, with relatively low recycling rates. A study considering 100% recycling, 100% incineration and 100% landfill for each of aseptic cartons, PET and HDPE bottles was performed by Meneses et al. (2012). Aseptic cartons showed the lowest global warming impact and acidification potential, irrespective of end-of-life scenario. The study assumed only local transport of milk (distance of 100 km). Thus, the impact of the transportation proves to be negligible, especially when it is compared with the impact of milk production, which is an order of magnitude greater.

A wider, multidimensional analysis was conducted by Burek et al. (2017) who compared single-use PET, HDPE, and cartons and pouches for milk packaging, taking into account different sizes and both ambient and chilled delivery systems, on a national scale. The study also considered aspects such as milk loss which is dependent on the supply chain used. Lightweighting and recycling generally decrease the environmental impacts of the vessels, however the systems considered showed similar tendencies across their environmental impacts, associated for example with the electricity market and combustion of fossil fuels, and there was no obvious “best” packaging choice.

Franklin Associates (2008) compared Polylactic Acid (PLA), carton, HDPE and glass vessels for milk packaging, with the glass bottles either single-use, or used eight times in a reuse scheme. The reuse data was based on information provided by local milk producers. The HDPE container showed the lowest emission of carbon-dioxide equivalent of the four options considered. Increasing the return rate of glass bottles from 8 to 11.9 uses made the glass bottles more comparable, but they still showed higher impacts. Transport accounted for 25% of the total energy use for the glass bottle scenario. This is due to glass being considerably heavier than the plastic alternatives, where transport only accounted for around 5% of the energy use.

Similar conclusions were drawn by Stefanini et al. (2020), who compared PET (recycled and not recycled) and glass (returnable and nonreturnable) for pasteurised milk packaging. The authors chose the number of uses to be 8, relying on the assumption that the benefit of reuse does not increase significantly after further reuses. The non-returnable glass bottle had the greatest impact on the environment in all 6 categories considered and in the proposed marine litter indicator. Returnable glass bottles have the smallest score in the marine litter indicator but overall present poorer performance than R-PET bottles, even at 30 use cycles. Overall, non-returnable glass bottles suffer from being energy-inefficient, requiring more secondary and tertiary packaging and more transport. Applying the reuse scheme reduces the impact of the production, but still induces environmental impacts due to the single-use cap, distribution and the reuse activities themselves. The scenario considered was centralised distribution with long transport distances (250 – 400 km), which disadvantages the heavier packaging types such as glass. R-PET bottles benefit from small mass and being energy-efficient.

The Waste and Resources Action Programme (WRAP) considered both doorstep (Meyhoff Fry et al. 2010a) and retail (Meyhoff Fry et al. 2010b) milk delivery. Where reuse was considered for glass bottles, a use rate of 17.5 was assumed. A distinction is made between various End-of-Life options (including recycling in the UK and China), recycled content and recycling rate for HDPE bottles. Recycling of the bottles in the UK proves to be the most beneficial way to treat HDPE bottles in almost all categories. Compared to municipal incineration, climate change potential is reduced by almost a half in this scenario. A similar comparison for returnable glass bottles shows a smaller difference between different disposal methods, but still overall shows that recycling is the most beneficial. The biggest contributions were associated with material production.

Humbert et al. (2009) compared single-use plastic pots and glass jars as baby food packaging. With equal transport distances, plastic containers showed lower environmental impacts in almost all impact categories considered, including about 30% smaller global warming potential, in most part due to their lighter weight.

The reviewed studies show that the material, transport distances and end-of-life pathway are all significant when calculating the environmental impacts of milk packaging, and that the relative impacts depend on the specific scenario considered e.g. local or centralised supply chain. Glass, being usually the heaviest of the options, is at a disadvantage both for initial production and transport. Inclusion of recycled glass content is important and reuse is crucial – without reuse the environmental impacts are significantly higher than for other packaging choices. In this regard, the number of times the glass packaging is reused is critical. The end-of-life considerations vary across the studies, with some considering national mixes, whereby glass and cardboard have higher recycling rates than plastic, whilst some compare packaging assuming the same end-of-life approach for each type. Reuse and recycling do not directly alleviate the high impact of heavier materials due to transport and a local supply chain is therefore likely to show considerably different results to nationwide distribution.

All the studies discussed above analysed supply chains where a reasonably small volume of vessel (up to 4 litres) is employed. Most of the studies take into account centralised supply chains concerning country-level delivery and hence use country-level averages for distances and waste treatment mix. Whilst this method is applicable for averaged doorstep delivery and averaged household consumption, cafés have a large milk consumption and can therefore benefit from economy of scale; consideration of localised bulk delivery is important in this case. To the authors' knowledge no studies have considered the most appropriate packaging for bulk milk delivery in a local supply chain. This study analyses such bulk delivery in order to improve the already existing knowledge about the environmental impacts associated with the milk supply chain.

Biganzoli et al. (2019) assessed the benefits of reusable steel drums (volume 210-220 l), for transportation of chemicals, with the initial production of the drums found to be the main contributor to environmental impacts. The environmental impacts fall with each use of a drum, with around a 25% fall in environmental impacts after two uses, compared to a single-use scenario. Rietveld and Hegger (2014), assessed the environmental benefits of reconditioning intermediate bulk containers (IBCs), as well as plastic and steel drums (volume 55 US gallons), finding the reconditioning reduced the global warming impact of all containers considered. Although new steel drums showed greater greenhouse gas emissions than their plastic equivalents, reconditioned drums made from steel presented similar or lower impact than plastic drums, depending on the design.

Boesen et al. (2019) conducted a comparison of Danish perception of sustainability of packaging. In the case of milk, most respondents identified glass bottles with steel caps to be the most sustainable solution (the other options were plastic jug, laminated carton, laminated carton with a cap, plastic bag), however, there was poor awareness of the end-of-life options for glass. This highlights the need for good public engagement for a reuse scenario to be successful.

To enable reuse, the new supply chain needs not only to be sustainable environmentally, but also economically. Accorsi et al. (2014) compared single use packaging (wood, plastic and cardboard) and multi-use plastic packaging, in a local supply chain of fruit and vegetables, finding decreased costs for vendors and farmers, but higher costs borne by distribution centres and customers. There was an overall global cost increase of about 60 euro per tonne of delivered goods. It is therefore important to consider economic feasibility, to obtain a multidimensional picture of consequences of enabling the reuse.

3 Methods

A Life Cycle Assessment includes goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and interpretation of the results, in compliance with ISO14040 and ISO14044 (International Organization for Standardization, 2006a, 2006b). This work has also been carried out in accordance with the Product Environmental Footprint (Manfredi et al. 2010).

3.1 Goal and scope

The goal of the study is to evaluate and compare the environmental impacts of single-use and reusable milk packaging, from cradle to grave, for bulk delivery to cafés. For the case study considered here, the dairy farm is Our Cow Molly, situated in Dungworth just outside Sheffield, UK, and the cafés are situated at The University of Sheffield. The two scenarios considered are the “plastic” scenario (single-use HDPE bottles) and the “reuse” scenario (a combination of reusable metal churns and reusable glass bottles depending on volume of milk delivered), as detailed in sections 3.1.1 and 3.1.2. Raw material extraction, material production and upstream processes necessary to obtain products present in the life cycle, as well as the end-of-life, are included. The study does not include the use of the milk or production of the milk by the cows. The packaging scenarios are compared based on the following functional unit: “The delivery of 1 litre of milk from Our Cow Molly to The University of Sheffield Cafés, calculated as the average of a yearly delivery of 1896 l of whole and 280 l skimmed milk over a period of 15 years, using a 4 ton refrigerated van”. In total, over 15 years, that equals almost 1.7 million litres of milk. This functional unit is based on an example weekly delivery from Our Cow Molly from the week ending 20th October 2019 (E. Andrew 2019, personal communication, 6th December). The functional unit is set as the average over 15 years as this is the longest vessel lifetime. Results are presented per average litre of milk in this functional unit for ease of understanding.

Figure 1 shows the system boundaries for the plastic scenario and reuse scenario and Table 1 shows the number of vessels and cleaning activities required to fulfil the functional unit, along with the transport km.

Table 1: Amounts necessary to fulfil the functional unit across the full 15 years

Material/process	Plastic scenario	Reuse scenario		
		Steel churns	Glass bottles	Aluminium caps
Number of units	848640	104	1421	404040
Transport allocated [t km]	73416	93188		
Cleaning activities required	0	105300	404040	N/A

The following elements are excluded from the analysis:

a) Production of labels and adhesive for plastic bottles. Their mass is about 2% of the mass of the whole bottle and therefore their environmental effect is judged to be negligible. The cap is treated as a part of a bottle. The glass bottle cap is however included for completeness as it constitutes a much bigger fraction of the materials used in the reuse scenario, since a new cap is used every time a bottle is filled.
b) Electricity needed to pump the milk while bottling. This is because the bottling of multiple types of vessels can happen simultaneously and therefore the pump is almost never running to supply the milk for one type of vessel only. It is therefore difficult to fully allocate or expand the system to account for the possible difference in the usage of electricity for different vessels, and this difference is assumed to be very small.
c) Necessary inputs for milk production such as water, food for cows and their maintenance – since they are identical for both scenarios. This analysis considers the life cycle of the milk packaging only.
d) Additional equipment that would have been needed to use any type of vessels in the cafés, for example dispensing equipment to get milk out of a churn. The lifetime of the equipment is likely to be longer than that of the churns; additionally, some cafés would not need any new equipment.
e) Any auxiliary refrigeration equipment needed both in farm and in the cafés. There is no correlation between a type of vessel and the time it is refrigerated. Refrigeration of the van used for transport is taken into account.
f) Any additional crates needed to carry the bottles. Existing versions are assumed to remain in use, as their life and durability is high. Moreover, they are used both for glass and plastic bottles.
g) Any additional milk losses that would be dependent on the type of vessel used, since this is assumed to be negligible.
h) Wear of the bottling machines and tanks as this is assumed to have negligible impact and does not vary significantly with vessel type.

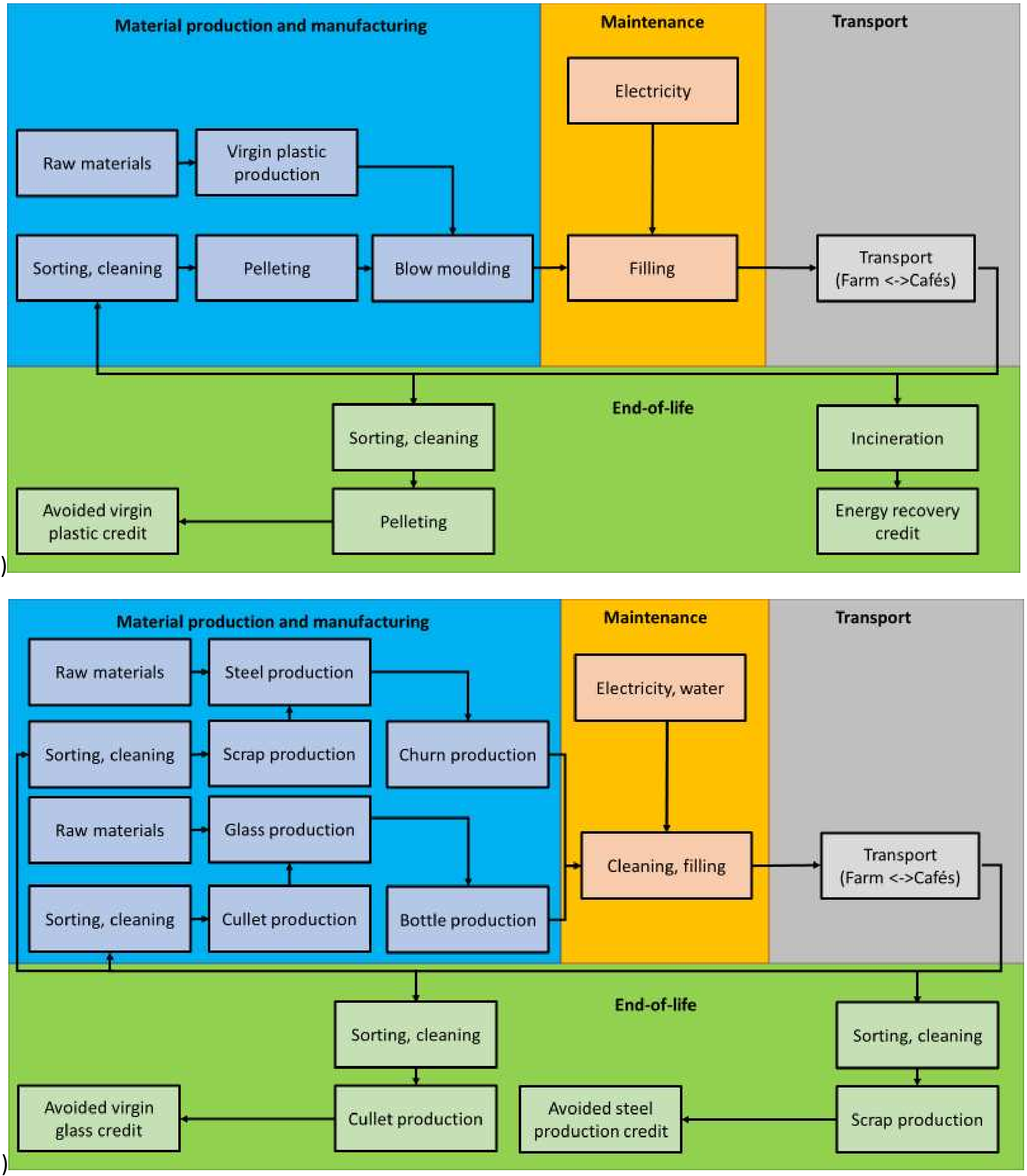

Figure 1: System Description for a) the plastic scenario and b) the reuse scenario

For the purpose of analysis, the process is split into four subsections, as shown in Figure 1: Material production and manufacturing, Maintenance, Transport and End-of-life. The colours used in Figure 1 map the colours used in Figures 5-6 and 8-10 in the results section i.e. all processes in blue in the "Material Production and Manufacturing" are also coloured blue in the results graphs. All transport processes are considered in the analysis, including those during manufacturing and end-of-life, however, for clarity only transport from farm to café (and back) is included as a separate subsection. The remaining transport processes are included in the respective subsections they refer to. Transport between farm and café has been differentiated as it is a foreground process with a potentially significant contribution to the overall impact of both solutions.

3.1.1 "Plastic" scenario

In the plastic scenario considered, single use high density polyethylene (HDPE) plastic milk bottles are used for the milk packaging. According to Dairy UK, (2018) most HDPE milk bottles have a 30% recycled plastic content. In this study, HDPE bottles are produced by a company based in Sheffield and are supplied to Our Cow Molly approximately every 6 weeks (E. Andrew 2020, personal communication, 1st July), along with bottle caps from which are also produced locally. Polypropylene labels are printed in Sheffield. The effect on the environment of the adhesive used, and production of labels from paper and polypropylene resin is considered negligible due to their relatively small mass. Milk is pumped from a tank and bottled using an electric filling machine, which is powered directly by electricity generated by rooftop photovoltaic panels at Our Cow Molly (E. Andrew 2020, personal communication, 1st July 2020).

The University of Sheffield has two waste collection streams: one for mixed recyclables (paper, glass, metal and plastic) and one for general waste, which is then burnt in an Energy Recovery Facility (ERF) in which electricity and heat are co-generated. The mixed recyclables go to a sorting facility where they are separated by waste type, baled, and sent to recycling sites. Labels separated during this stage are incinerated. In this model, it is assumed 1 kg of used bottles yields 0.86 kg of granulate (Wernet et al., 2016). Based on interviews with café staff, it is assumed that 50% of the bottles are recycled and 50% are sent to the ERF.

3.1.2 "Reuse" scenario

In the reuse scenario, a combination of reusable steel churns and reusable glass bottles are used to contain milk delivered to the cafés. The choice of metal churn or glass bottle depends on the volume of milk required. 16 litre stainless steel churns are used to transport whole milk as, when full of milk, a churn of this volume is close to the maximum allowable weight for safe manual handling. Churns are estimated to have a minimum expected lifetime of 15 years. Every day, Our Cow Molly staff would deliver fresh milk and collect empty churns from the previous delivery. In total, there must be enough churns for 3 days of deliveries to each café, in order to account for the filling-delivery-use-return-washing-filling cycle time. The frequent delivery schedule means that milk will not be wasted despite the significant increase in vessel volume as cafés order the amount they require. Filling of the churns is done mechanically, using the same pump as in the plastic bottle scenario. The electricity needed to power the pump is excluded from consideration as it would be of similar value in every scenario and is assumed to be negligible compared to other energy requirements. For the delivery to cafés with smaller milk demand, glass bottles are used for skimmed milk instead of steel churns to avoid waste. Glass bottles are estimated to have an average lifetime of 5 years. Whilst churns and glass bottles travel between café and dairy, they are ultimately owned by Our Cow Molly and at the end of their life a near-ideal recycling rate can be achieved. This rate is therefore assumed to be 100%.

The number of metal churns and glass bottles is calculated based on the delivery schedule using plastic bottles. The delivery schedule is the same for the reusable scenario as the plastic scenario and there has been no attempt to consider a different delivery schedule. The number of vessels is rounded up for each day for each café separately. There are enough churns and bottles to make the largest three consecutive deliveries, irrespective of which days of the week these deliveries occur. This ensures a stable flow of churns – there is always one set ready for the next delivery, one ready to come back from the café and one awaiting cleaning and filling for the next day. 15% additional bottles and churns, on top of those required for delivery, are included in the analysis to account for losses, breakages and the chance of a larger required delivery on any day. Based on those calculated values, churns would be reused on average 1012 times and bottles 283 times. These numbers appear realistic, as Our Cow Molly have glass bottles in circulation that have been used for delivery for more than 20 years (E. Andrew 2020, personal communication, 1st July).

3.2 Life Cycle Inventory

The life cycle inventory data are given in Table 2 and Table 3. Raw data was collected through direct measurement and production data was obtained from Our Cow Molly Farm and other relevant suppliers. Ecoinvent 3.6 (Wernet et al. 2016) is used as the default database and the processes described come from this database unless otherwise stated and referenced. The GaBi database (Thinkstep, 2016) and literature are used where data is not available in Ecoinvent. In particular, GaBi is used for the inventory for stainless steel as it includes up-to-date data for the type of steel used for making churns and is approved by Eurofer.

Multifunctionality is solved by a mix of system expansion and allocation, using the former method whenever possible. Thus, virgin material that would have been used is replaced by recovered material from recycling. To account for the burden associated with the transport of the milk to the cafés, allocation by mass (milk plus vessels) is used.

Table 2: Summary of the packaging inventory data by vessel type

Property	Type of vessel		
	Plastic bottle	Glass bottle	Steel churn
Volume [l]	2	0.568	16
Mass of one vessel [g]	45	272	3800
Material of construction	High-Density Polyethylene	Glass	304 grade stainless steel
Recycled content [%]	30	60	62
Percent of material going to recycling/incineration	50/50	100/0	100/0

Table 3: Life cycle inventory data for milk packaging, including reference to processes used from Ecoinvent and other databases

Activity	Amount	Process used	Comments
Material production			
Virgin plastic production	31.5 g/vessel	Polyethylene, high density, granulate {RER}| production	
Recycled plastic production – sorting, cleaning, pelleting	13.5 g/vessel	Polyethylene, high density, granulate {Europe without Switzerland}| polyethylene, high density, granulate, recycled to generic market for high density PE granulate	
Blow moulding	45 g/vessel	Blow moulding {RER}| blow moulding	The intrinsic additional input of LDPE changed to HDPE with 30% recycled content. Assumption of 3% additional plastic input retained.
Transport from the plastic bottle producer to Our Cow Molly	15 km 0.675 kgkm/vessel	Transport, freight, lorry 7.5-16 metric ton, EURO6 {GLO}| market for | APOS, U	Distance of 15 km estimated based on Google Maps
Stainless steel production (along with associated inputs)	3.8 kg/vessel	Stainless steel cold rolled coil (304)	Taken from GaBi
Churn manufacturing	3.8 kg/vessel	Metal working, average for steel product manufacturing {RER}| processing	The additional input of steel is changed as in section 2.3.1
Glass bottle production (along with associated inputs)	272 g/vessel	Packaging glass, white {RER w/o CH+DE}| production	The transport processes for the market for packaging glass are retained, but changed to the European versions for land (freight, train) transport.
Aluminium production	0.25 g/glass bottle (1 pint of milk)	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for	
Production of caps from aluminium	0.25 g/glass bottle (1 pint of milk)	Sheet rolling, aluminium {RER}| processing	
Transport			

Transport between the farm and the cafés	43.3 kgkm/l of transported milk for plastic scenario 54.9 kgkm/l of transported milk for reuse scenario		See section 3.2.2 for details of Transport calculations
Maintenance			
Filling of a glass bottle	4 Wh/bottle	Electricity, low voltage {GB}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted	
Filling of a plastic bottle	4 Wh/bottle	Electricity, low voltage {GB}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted	
Water consumption for vessel cleaning	0.5875 kg/bottle 8 kg/churn	Tap water {Europe without Switzerland}| market for	Data for glass bottles measured on farm; data for churns estimated
Electricity use for water heating for cleaning	40 Wh/bottle 545 Wh/churn	Electricity, low voltage {GB}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted	
Sodium hypochlorite used for cleaning	0.01 g/glass bottle 0.14 g/churn	Sodium hypochlorite, without water, in 15% solution state {RER}| market for sodium hypochlorite, without water, in 15% solution state	
Sodium hydroxide used for cleaning	2.9 g/glass bottle 40 g/churn	Sodium hydroxide, without water, in 50% solution state {GLO}| market for	
Wastewater treatment for the maintenance step	0.5875 l/glass bottle 8 l/churn	Wastewater, average {Europe without Switzerland}| market for wastewater, average	
End-of-life			
Recycling of aluminium caps	0.125 g/pint of milk transported	Aluminium scrap, post-consumer {RER}| treatment of, by collecting, sorting, cleaning, pressing	The waste treatment flow “Aluminium scrap, post-consumer, prepared for melting {GLO}| market for” has been changed to consider only European markets.
Avoided burden of aluminium recycling	0.9488 kg/kg of aluminium at the refiner/remelter	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for	The avoided burden as suggested by (Wernet et. al 2016)

Incineration of aluminium	0.125 g/pint of milk transported in a glass bottle	Scrap aluminium {Europe without Switzerland}| treatment of scrap aluminium, municipal incineration	The waste treatment flow (for the aluminium which is recovered from incineration and sent to recycling) “Aluminium scrap, post-consumer, prepared for melting {GLO}| market for” has been changed to consider only European markets.
Plastic recycling – sorting, cleaning, pelleting	15% of the waste plastic mass	Polyethylene, high density, granulate, recycled {Europe without Switzerland}| polyethylene production, high density, granulate, recycled	This, based on the net scarp approach, is the net scrap generated for 50% recycling case. The recycling of the remaining mass included in Material production stage
Avoided burden for plastic	0.86 kg/1kg of waste plastic	Polyethylene, high density, granulate {RER}| production	The amount based on losses associated with the previous process
Transport from the Cafés to ERF	3 kgkm/kg of waste of any type	Transport, freight, lorry 7.5-16 metric ton, EURO6 {GLO}| market for | APOS, U	Distance of 3km estimated based on Google Maps
Incineration of plastics	50% of the waste plastic mass	Waste polyethylene {RoW}| treatment of waste polyethylene, municipal incineration	The credits for electricity and heat added to the process, as explained in section 3.2.4
Transport of glass and steel to recycling facility	50 kgkm/kg of waste material of any type	Transport, freight, lorry 7.5-16 metric ton, EURO6 {GLO}| market for | APOS, U	Assumption
Glass recycling into cullet	35% of the waste glass mass	Glass cullet, sorted {RER}| treatment of waste glass from unsorted public collection, sorting	Based on the amount of net scrap generated. The recycling of the remaining mass included in Material production stage
Producing glass bottles from cullet obtained in the process	1.65 kg/kg of cullet	Packaging glass, white {RER w/o CH+DE}| production	The input of cullet is deleted, as the cullet is provided by the recycling process. The amount of this process is adjusted according to the amount of cullet.
Avoided burden credit for glass	1 kg/kg of glass produced from the cullet	Packaging glass, white {GLO}| packaging glass production, white, without cullet	
Avoided electricity burden	1.54 kWh/kg waste plastic	Electricity, high voltage {GB}| market for	As explained in section 2.3.4

Avoided heat burden	10MJ/kg waste plastic	Heat, district or industrial, natural gas {RER}| market group for	As explained in section 2.3.4
GB energy mix in sensitivity analysis around the farm's electricity	1 kWh of GB mix substitutes 1 kWh of electricity from PV panels	Electricity, low voltage {GB}| market for	
Stainless steel recycling and credits (sorting, cleaning, scrap production and avoided burden credit)	38% of the waste steel obtained	Stainless steel product (304) - value of scrap	Taken from GaBi, the amount based on net scrap approach. The recycling of the remaining mass included in Material production stage

3.2.1 Material production and manufacturing

Details of the processes used in the model are included in Table 3. Plastic bottles are assumed to be made of 30% recycled granulate and 70% virgin granulate (as is standard in HDPE milk bottle production (Dairy UK,2018)). The upstream transport has been kept the same as for the global market for plastic and the mass of a plastic cap is included in a mass of a bottle.

Underlying assumptions have been retained for the production of glass bottles, i.e. 60% glass cullet input. As suggested by Alufoil European Aluminium Foil Association (n.d.), 0% recycled content is assumed for the aluminium foil tops, and by the net scrap approach, credit is given at end-of-life for content that could be recycled. This gives the same net result as including recycled content at the start and having less scrap at the end for which to get credit.

The metal churns are to be manufactured from 304 grade stainless steel. An inventory for 304 stainless steel and its scrap, assuming 62% scrap input, is used (World Steel Association, 2017). The amount of steel required is increased by 14% to account for losses. This value is based on the losses for drums and barrels from (Flint et al., 2020) and changed from 22.7% as suggested in process "Metal working, average for steel product manufacturing {RER}"). This amount of steel is credited to the system as scrap during end-of-life.

The masses of the plastic and glass bottles that are in use have been measured, while for churns, the mass has been estimated based on Pharma Hygiene Products Ltd (2017).

3.2.2 Transport

As day-to-day transport of milk to cafés is a potential differentiating factor for all the scenarios, it is considered a foreground process and therefore attention has been paid to model this part of the life cycle separately and as accurately as possible. The transport process built in to Ecoinvent ("transport, freight, lorry with refrigeration machine, 3.5-7.5 ton, EURO6, R134a") has been modified to account for payload and return trip according to data from Our Cow Molly. The main assumption is that the van's payload decreases linearly with distance. The same emissions and contributions as in Ecoinvent 3.6 (Wernet et al. 2016) are considered, using the uploaded versions of the same sources (Infras 2019; Ntziachristos et al. 2019) to model the "Emissions to air" category, and fuel demand, taking into account the decreasing payload along the way. The brake, road and tyre wear are adjusted, considering the actual average payload. The remaining entries are scaled using average payload and total trip length. The emission factors have been modified to account for a driving pattern described as "Saturated" (Infras 2019) and the data is taken for an urban area of Germany at a speed limit of 60 km/h. This is the scenario that best resembles the characteristics of the trip: speed limit of 30 mph along the majority of the road and 60mph in the area near the farm, the trip is during morning hours when the traffic is saturated. The van's payload by default is 2700 kg, but it increases to about 2800 kg when plastic bottles (that go to the university cafés) are substituted with reusable vessels. Allocation by mass is used to solve the multifunctionality in transport. The default route that the Our Cow Molly van travels is used (E. Andrew 2019, personal communication, 1st July 2020). These modifications have been applied only to the transport on route from Our Cow Molly to the customer cafés and back. Transport in the remaining parts of the life cycle is modelled using the default assumptions and processes made by Ecoinvent.

The density of milk used to calculate the total payload of the van is taken to be 1.03kg/l (Anton Paar, 2017). To account for refrigeration, the energy needed for the vehicle is increased by 20% as in the Ecoinvent database (Lévová, 2015), which results in a proportional increase in emissions resulting from an increased fuel use. The increased percentage of fuel consumption due to refrigeration estimated by Meyhoff Fry et al. (2010b) is 15%, therefore the 20% used here is a conservative estimate.

3.2.3 Maintenance

Maintenance is defined as everything that happens to a vessel that has just arrived or returned to the farm until it is put in the van ready for delivery. For plastic bottles this is filling the bottles, whereas for glass bottles it involves cleaning and filling, and for churns involves cleaning only, as they are filled mechanically. The reusable vessels are cleaned even before the first use whereas plastic bottles are delivered in a sterile form to the farm. This category is differentiated from other stages as it is crucial to determine the environmental effect the intrinsic properties of the vessels have. Pumping of the milk and on-farm refrigeration are excluded from the analysis.

The process of cleaning the glass bottles is modelled on the practice employed at Our Cow Molly: a bottle washing machine cleans by spinning crates of glass bottles. Sodium hydroxide and sodium hypochlorite are used as chemicals. Electricity used for the maintenance on the farm comes from on-site solar panels. The electricity generated by the solar panels each year is far greater than that used by the maintenance stage, therefore the default model assumes 100% solar electricity. Sensitivity analysis is performed on this to consider the impact if grid electricity were to be used. The electricity demand has been calculated using heat capacity, the desired temperatures of water used for cleaning and assuming the temperature of the water from the network to be 15 °C. The final value is rounded up in order to give a conservative value and to account for losses. The water goes down the drain at the end of cleaning and is treated in a wastewater treatment plant. The processes used for water and its treatment are: "Tap water {Europe without Switzerland}| market for | APOS, U" and "Wastewater, average {Europe without Switzerland}| market for wastewater, average | APOS, U". The water treatment is part of the "Maintenance" section, not the "End-of-life" as this activity is strictly connected with cleaning and there is no decision making connected with this activity.

The precise auxiliaries needed to clean a milk churn used for delivery as proposed here are unknown and there is very little information in the literature. The initial practise will involve manual cleaning of churns, using a hose and solutions similar to those used for glass bottles. Cleaning of kegs and casks in the brewing industry is a much better described activity. Cask washing machines (Hugh Crane (Cleaning Equipment) Ltd, 2020) exist which provide an estimate of about 15 l water per cask of bigger volume than the churns used in this analysis. Hence, as an initial estimate, 8 l of water per churn is used. The sensitivity analysis considers a range of water requirements for churn washing. The electricity and chemical usage for churns is scaled by the amount of water used based on the cleaning of glass bottles.

The electricity demand of the filling lines for plastic and glass bottles could not be determined. Table 4 presents values found in literature regarding this process. As can be seen, the electricity demand varies considerably between the sources and no conclusion can be made about the relative demand between glass and HDPE bottles. As the capacity of both machines is similar, in this analysis, the energy is assumed to be 4 kWh per 1000 bottles, regardless of bottle size and material. The importance of this assumption is analysed in the discussion section.

Table 4: Electricity demand during filling stage found in literature

Bottle material	Volume	Beverage	Electricity per 1000 vessels [kWh]	Source	Comments
Glass	0.33 l	Beer	2.5	(De Marco et al. 2016)	
Glass	0.52 l	Beer	9.1	(Koroneos et al. 2005)	
PET	1 l	milk	3.3	(Stefanini et al. 2020)	Includes blowing, filling, packaging
PET	1 l	milk	3.9	(Stefanini et al. 2020)	Includes blowing, filling, packaging
Glass	1 l	milk	0.6	(Stefanini et al. 2020)	Includes filling and packaging
Multilayer carton	1 l	milk	4	(Bertolini et al. 2016)	
HDPE, PET	1 l	milk	28	(Bertolini et al. 2016)	Ultra clean filler, includes decontamination, filling and capping

The maintenance stage is not a "reuse" burden even though it involves cleaning. The inputs associated with this stage are independent of the number of times a particular vessel is reused as even new reusable vessels are cleaned. Instead, the inputs are associated with a certain amount of churn and bottle deliveries, which are the number of instances where a churn or a bottle is cleaned and then filled, as defined in the functional unit.

3.2.4 End-of-life

Since the glass bottles and metal churns are to be reused, it is the farm's responsibility to collect them and transport them to the recycling facilities at their end-of-life. Therefore, 100% of vessels are assumed to be recycled. The responsibility for end-of-life treatment of the plastic bottles falls to the user, meaning that plastic bottles can be recycled or incinerated in an ERF. As mentioned previously, 50 % recycling rate is assumed as default.

To account for recycling activities, a 'net scrap' approach is used. This means that each system, at the end-of-life, is credited for the net scrap produced (the difference between scrap produced at the end-of-life and the scrap input, taking losses into account). In the case of the plastic, the process "Polyethylene, high density, granulate, recycled {Europe without Switzerland}| polyethylene production, high density, granulate, recycled" is used to account for auxiliaries needed to convert waste plastic into granulate. The amount of net secondary plastic granulate produced (after having accounted for the losses) is equal to the amount of the avoided virgin plastic granulate production, so this approach should be treated as a best-case scenario for plastic bottles, where recycled granulate is qualitatively equal to the virgin one. The same approach is used for glass bottles: "Glass cullet, sorted {RER}| treatment of waste glass from unsorted public collection, sorting" is used to transform waste glass into glass cullet; "Packaging glass, white {RER w/o CH+DE}| production" is then used to convert the cullet into glass bottles again. The input of glass cullet present in the packaging process is removed to avoid double counting as the cullet is obtained from the recycling process. The glass bottles prepared from the recovered glass are assumed to be a substitution for virgin glass bottles. The avoided product is hence “Packaging glass, white {GLO}| packaging glass production, white, without cullet”.

The process of recycling of aluminium is based on “Aluminium scrap, post-consumer {RER}| treatment of, by collecting, sorting, cleaning, pressing”, with an avoided burden, after refining and remelting being “Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for”. Since the aluminium lids would be disposed of in the cafés, the same recycling rate as for plastic bottles is assumed (50%). The remaining 50% is assumed to go to the ERF. The approach used to model the recycling of churns is in line with the modelling used for plastic and glass and is taken from World Steel Association (2017). Thus, the approach used for recycling is consistent throughout. The scrap flow is described in Table 5.

Table 5: ‘Scrap’ inputs and outputs in the system

	Plastic bottles	Glass bottles	Stainless steel churns*	Aluminium caps
Secondary material produced in total, kg/kg of vessel/lid	0.43	0.92	1	0.53
Scrap material input fraction	0.30	0.60	0.62	0
The net scrap fraction	0.13	0.32	0.38	0.53

*The metal inventory is designed in a manner that does not require the user to directly calculate the losses, hence at 100% recycling rate the mass of a churn is shown to be the mass of waste steel.

The incineration of plastic is modelled using Waste polyethylene {CH}| treatment of, municipal incineration with fly ash extraction. Since the Sheffield Energy Recovery Facility generates both electricity and heat which is used to supply heat to buildings in the city via a district heating network (Veolia, n.d.), both the credit for production of electricity (1.54 kWh per 1 kg of waste plastic) and heat (10 MJ per 1 kg of waste plastic)(Wernet et al. 2016) are accounted for. This has been done using “Electricity, high voltage {GB}| market for” and “Heat, central or small-scale, natural gas {RER}| market group for” as the avoided burdens, respectively.

The process of disposing of aluminium caps in the general waste bin has been modelled using “Scrap aluminium {Europe without Switzerland}| treatment of scrap aluminium, municipal incineration”. The assumption of recovery of 31% of aluminium from the incineration and sending it to recycling has been kept.

3.3 Life Cycle Impact Assessment

SimaPro 9.1 was used to model the system. The ReCiPe 2016 Midpoint (H) impact assessment method is used as the impact assessment method. The method contains 13 out of 14 impact categories recommended for the Product Environmental Footprint by Manfredi et al. (2010). The remaining category “Eutrophication – terrestrial” is assumed to be covered by Marine eutrophication, Terrestrial acidification, Freshwater eutrophication and Terrestrial ecotoxicity. The Midpoint version has been used as it provides results of lower uncertainty (National Institute for Public Health and the Environment 2017), while the Hierarchist version was used as it is based on a moderate timeframe (100 years) (National Institute for Public Health and the Environment 2017).

The inventories taken from the GaBi software were analysed using the same ReCiPe method as that used in SimaPro. To calculate the total energy demand, the "Cumulative Energy Demand" method in SimaPro was used and "Primary energy demand from renewable and non-renewable resources" from GaBi, with both using higher heating values. No weighting has been applied.

3.4 Break-even calculations

In the default scenario discussed in sections 3.2 and 3.3, the metal churns are reused approximately 1000 times and glass bottles 280 times. It is useful to understand the number of reuses required, for each of churns and glass bottles, for the reuse scenario to have lower impact than the single-use plastic option. Here the break-even for global warming potential and water consumption are calculated (as defined by the ReCiPe method).

The number of churns needed for break-even is calculated based on the equation:

$$\frac{Cd}{y+1} * m_c * (P_c + E_c) + \frac{Bd}{x+1} * m_b * (P_b + E_b) + M_r + T_r = S_{pl} \tag{1}$$

Where:

Cd is the amount of churn-deliveries, the total number of times all churns are used

Bd is the amount of bottle-deliveries, the total number of times all bottles are used

y is the average number of reuses of churns

x is the average number of reuses of glass bottles

m_c and m_b are a mass of a single churn and a single glass bottle, respectively

P_c and P_b are the specific life cycle results for production of a churn and a bottle, respectively

E_c and E_b are the specific life cycle results of the end-of-life of churns and bottles, respectively

M_r is the total score of a maintenance stage of the reusable scenario. It is constant since the churns and the bottles need to be cleaned and filled the same number of times regardless of the number of reuses

T_r is the total score of a transport stage. It is constant as it concerns only the transportation between the farm and the cafés.

S_{pl} is the total life cycle result for the whole plastic scenario

Inputs such as transport of churns or bottles from the production facility or to the recycling facility are included in the production and end-of-life specific impact scores, respectively.

3.5 Economic Evaluation

Table 6 presents costs of products considered in the economic analysis. The amount of diesel used is taken from the transport process described in section 2.3.2. The density of diesel is taken as 0.84 kg/l (Frischknecht et al., 2007). The price of any labour other than the additional labour for churn handling is disregarded. It should be noted that in accordance with Wernet et al. (2016), using reusable churns induces a slightly larger tyre, brake, road and vehicle wear (due to the larger payload). This has been judged to be negligible. The milk use stage, as for environmental analysis, is not considered. The default end-of-life as described earlier in the report and the default water consumption for churn cleaning were used. Waste treatment of reusable vessels is excluded. Any fuel expense due to transportation other than from the farm to the cafés is excluded.

Table 6: Inventory for economic analysis of packaging choice, including unit prices. Unit numbers are average per annum

Product	Unit	Cost per unit	Number of units		Source
			Plastic	Reuse	
Our Cow Molly costs					
Materials production					
Plastic bottle, a bottle cap and a label	a piece	£0.14	56576	0	E. Andrew 2020, personal communication, 8th September
Glass bottle	a piece	£0.35	0	95	E. Andrew 2020, personal communication, 8th September
Metal churn	a piece	£60	0	7	AB-Handling 2020, personal communication, 20th August
Glass bottle caps	a piece	£0.0005	0	26936	E. Andrew 2020, personal communication, 8th September
Transport					
Diesel	l	£1.18	440	550	RAC (n.d.)
Maintenance					
Photovoltaic electricity	kWh	£0.25	200	5200	Dong et al. (2020)
Water	m^3	£1.39	0	72	E. Andrew 2020, personal communication, 8th September
Sodium hypochlorite solution	l	£0.60	0	15	E. Andrew 2020, personal communication, 8th September
Sodium hydroxide	kg	£3.41	0	360	E. Andrew 2020, personal communication, 8th September
University costs					
Waste Management					
Disposal, mixed recycling	kg	£0.18	1300	3.4	The University of Sheffield
Disposal, general waste	kg	£0.26	1300	3.4	The University of Sheffield
Milk purchase					
Purchase of 2l plastic bottle of milk	a piece	£1.57	56576		E. Andrew 2020, personal communication, 8th September
Purchase of a pint glass bottle of milk	a piece	£0.63		26936	E. Andrew 2020, personal communication, 8th September
Purchase of a 16l churn of milk	a piece	£12.56		6162	E. Andrew 2020, personal communication, 8th September

4 Results

The life cycle impact assessment of all scenarios (including the sensitivity analysis scenarios), broken down into stages, is available in the supplementary information.

4.1 Life cycle environmental impacts

Figure 2 presents the impacts of the reusable and the plastic scenario, across the full range of impact categories. In each case the set of bars are normalised such that the highest value is set to 100. In all but two criteria, the reuse scenario has significantly lower impact than the plastic scenario. The higher score in marine eutrophication category could be attributed to the water treatment in the maintenance section. Even though the plastic option uses more water, most of it undergoes a “Wastewater, unpolluted” treatment process, which has significantly less impact than the “Wastewater, average” process used by the reuse case. The very similar scores for mineral resource scarcity can be attributed to the Maintenance section as well, as the photovoltaic panels prove to require large amounts of metals such as zinc and silver.

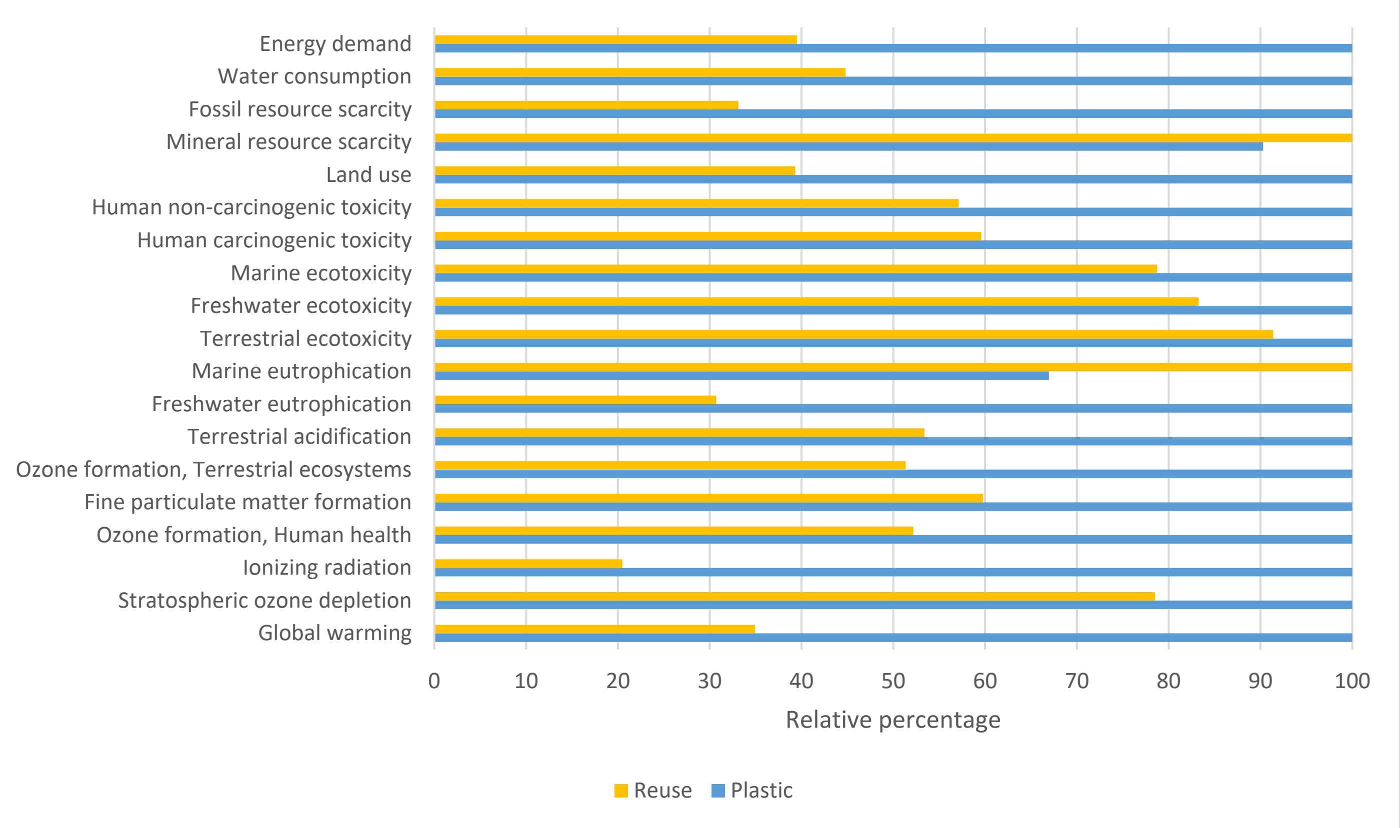

Figure 2: Relative impacts of the single-use plastic and reusable scenarios using ReCiPe Midpoint (H) criteria and cumulative energy demand

4.2 Detailed results

Figure 3 and Figure 4 present the breakdown of the environmental results into the sub-categories, with respect to the global warming potential and water consumption. The production of plastic bottles proves to be a major contributor to the environmental damage of the plastic scenario (approximately 57 g of CO_2 equivalent emitted and 0.9 l of water consumed per litre of milk) while the production of the reusable vessel is almost negligible. The reverse is observed for the maintenance stage, whereby the maintenance of the reusable vessels has a much higher environmental damage score than plastic bottles. The maintenance, a stage which uses significant amounts of water, poses a smaller threat to the environment in terms of water consumption than the production of the bottles. As far as maintenance is concerned, the parts mainly responsible for the damage are sodium hydroxide consumption and the electricity needed for water heating, even though it is of photovoltaic source. This part of maintenance accounts for 40% or more of the total maintenance impact in the reusable scenario in 16 out of 18 criteria analysed by the ReCiPe method. From an environmental point of view, on-roof water heating panels could be considered for water heating, instead of photovoltaic panels and electrical heating of water, as that would reduce the energy conversion needed to heat the water and potentially increase the efficiency. The solar intensity at the Our Cow Molly site should be considered in evaluating this option. Another possible solution to reduce the electricity demand is reducing the amount of water used for cleaning vessels. As bottles are already washed by a machine, it is the process of cleaning of churns which can more easily be optimised, see section 4.3.2. As predicted, transportation represents a considerable fraction of the damage and in some criteria (for example fossil resources depletion) it is the main damage contributor on the reusable side. As the van transporting the milk is a EURO 6 standard, a potential way to reduce to reduce the environmental damage of this stage could be employing an electric van instead of a diesel one, however electric refrigerated vans with the desired payload are not yet commercially available.

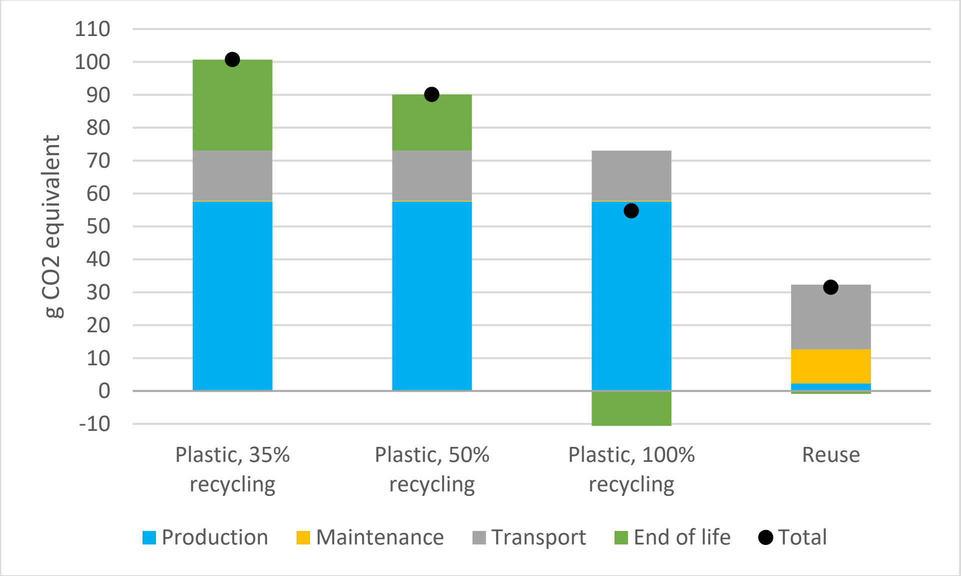

Figure 3: Global warming potential per litre of milk including sensitivity analysis on the percentage of plastic bottles recycled

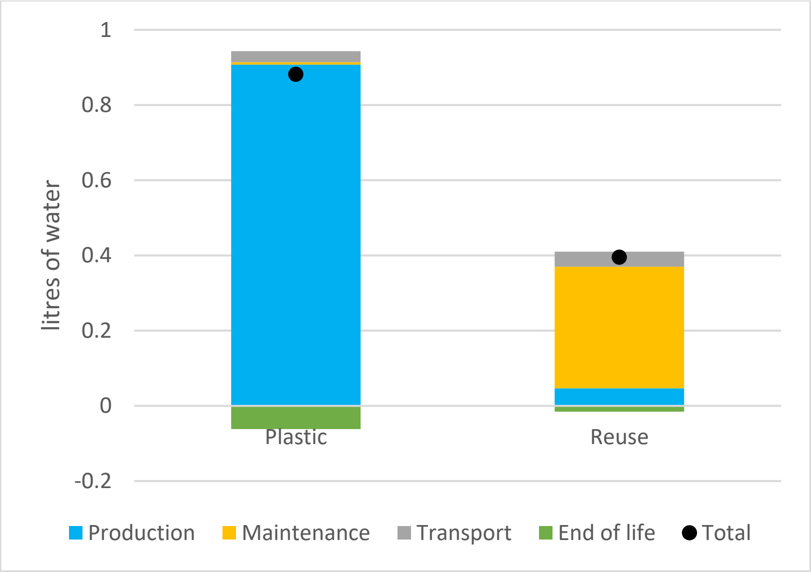

Figure 4: Water consumption per litre of milk

Assuming that all churns and a third of glass bottles needed are bought in the first week of operation, it takes 19 weeks for the reuse scenario to break-even with the plastic scenario on global warming potential. After the 19 weeks the reuse scenario is always favourable. This highlights the short amount of time the reuse scenario needs to be employed for in order for it to be beneficial.

4.3 Sensitivity Analysis

4.3.1 Recycled fraction of bottles

Figure 3 shows that under the assumptions made here, the end-of-life of the plastic bottles can constitute both a considerable burden and a considerable positive factor for the environment, based on the recycling rate. The end-of-life of plastic bottles causes carbon emissions when a 50% recycling rate is used, however, with a 100% recycling rate, the end-of-life is a carbon sink; the end-of-life as modelled here therefore becomes carbon-neutral at a recycling rate between 50% and 100%. This is due to the additional recycled plastic produced that cannot be used in milk bottles (as bottles contain only 30% recycled content) for which credit is given through the net scrap approach.

Figure 5 shows the impact of plastic recycling rate across all impact categories considered. Increasing the recycling rate substantially reduces the impact of the plastic option on global warming, water and fossil resources depletion, because of the higher avoided burden credit. Despite this reduction, the reuse scenario still performs better in these categories due to the significantly lower number (and therefore mass) of vessels produced. Furthermore, in some categories a higher recycling rate induces greater environmental damage. This is reported for marine eutrophication (31% higher than the default scenario), land use (25% increase) and mineral resource scarcity (18% increase). For simplicity of comparison, only the categories with the most interesting trends have been shown and the default of 50% plastic recycling has been set to 100% in all criteria. In the extreme case of 100% recycling, the plastic option is more environmentally friendly in 4 out of 19 criteria considered. The 100% recycling for plastic bottles represents a best-case scenario for the end-of-life of plastic, however, based on the interviews with café staff, this level of recycling would be difficult to achieve in reality. The analysis does not take into account the risk that plastic bottles become litter, or the environmental impacts of that litter. This is hard to quantify, but nonetheless an important consideration as plastic litter can have serious impact on wildlife and aquatic life. Development of an effect factor taking into account the impact of litter on marine life (Woods et al., 2019; MarILCA, 2020; Stefanini et. al., 2020) and of an indicator to quantify the impact of littering more generally (Civancik-Uslu et al., 2019) is ongoing.

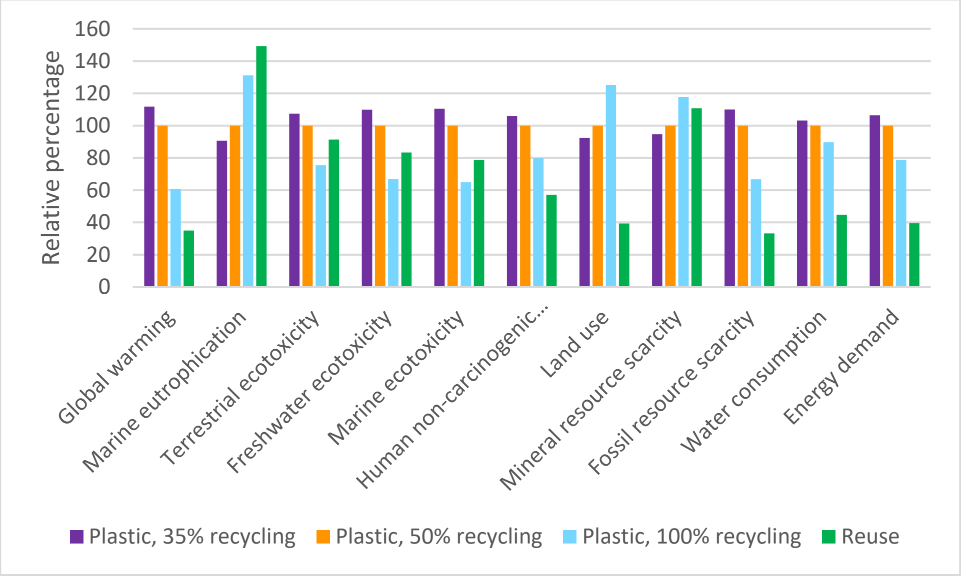

Figure 5: Sensitivity analysis around the recycled fraction of the bottles in chosen categories

4.3.2 Water usage for churn cleaning

Figure 6 shows that the amount of water used for churn cleaning can influence considerably the damage caused by the whole reusable life cycle. In categories where the maintenance stage is a key contributor, such as marine eutrophication, the difference between the minimum assumed water demand per churn cleaning (5 l) and the maximum one (15 l) is 130% of the total plastic scenario's score in this category. The water consumption of the reusable option is between 34% and 70% of the default plastic scenario's score. Global warming potential of the churns and glass bottles is a weaker function of the water usage for churn cleaning, being between 32% and 43% of the current scenario's score in this category. At maximum predicted water usage, the proposed supply chain induces a greater impact to the environment in 5 out of 19 categories. Again, for clarity, the default plastic scenario score in each category has been set to 100% and only some categories are shown.

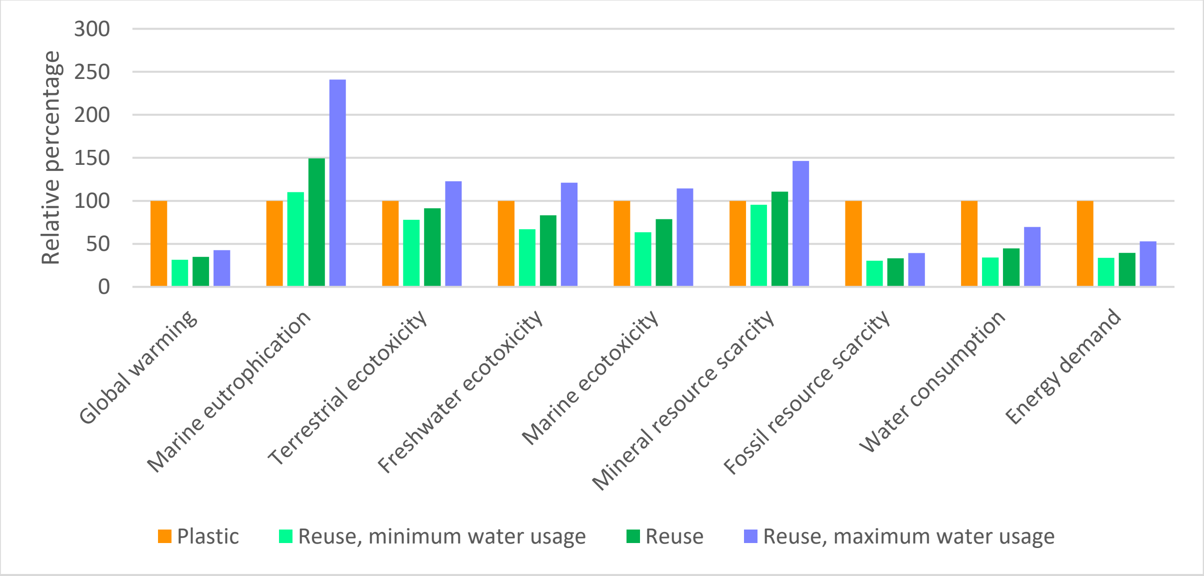

Figure 6: Sensitivity analysis around the water usage for churn cleaning for chosen categories. A 50% recycling rate of plastic bottles is used.

4.3.3 Source of electricity used for maintenance

It is likely that the farm will not be powered fully by photovoltaic electricity during less sunny months, especially in winter. Whilst the total amount of solar electricity produced through the year is easily sufficient for the full year of maintenance activites, in winter months electricity is bought from the grid and in summer months electricity is sold to the grid. A sensitivity analysis has been therefore performed on the electricity source for the on-farm activities (cleaning, filling and bottling), see Figure 7. As the on-farm electricity demand for the plastic scenario is considerably lower than that for the reuse scenario, the electricity source makes negligible difference in all impact categories for the plastics case, therefore only the default plastic case is included. Figure 7 includes impact categories where the impact changes by more than 5%. To model the GB grid electricity mix, “Electricity, low voltage {GB}| market for” is used. This sensitivity analysis therefore considers the “best case” and “worst case” scenarios for the electricity source on the farm.

Switching from photovoltaic electricity to GB grid electricity has varying impact on the result of the reuse scenario. Global warming potential increases by 13% and ionising radiation by 117%, with respect to the plastic scenario, which is predominantly a consequence of fossil-fuel and nuclear electricity, respectively. On the other hand, mineral resource depletion decreases at the expense of fossil resource depletion as materials used for making the panels are substituted with a greater fossil fuel consumption. Water consumption decreases by 7%, due to the manufacture of silicon being water-consuming. This is also reflected in other water-related categories – Freshwater and marine ecotoxicity.

In general, the source of electricity on the farm has limited effect on most impact categories. It is likely that, as the greenhouse gas intensity of the UK grid reduces, the difference in impact between PV panels and the overall country mix will decrease. The impact of this element can again be minimised by optimising the amount of water used for cleaning, which is the prevalent electricity consumer on the farm.

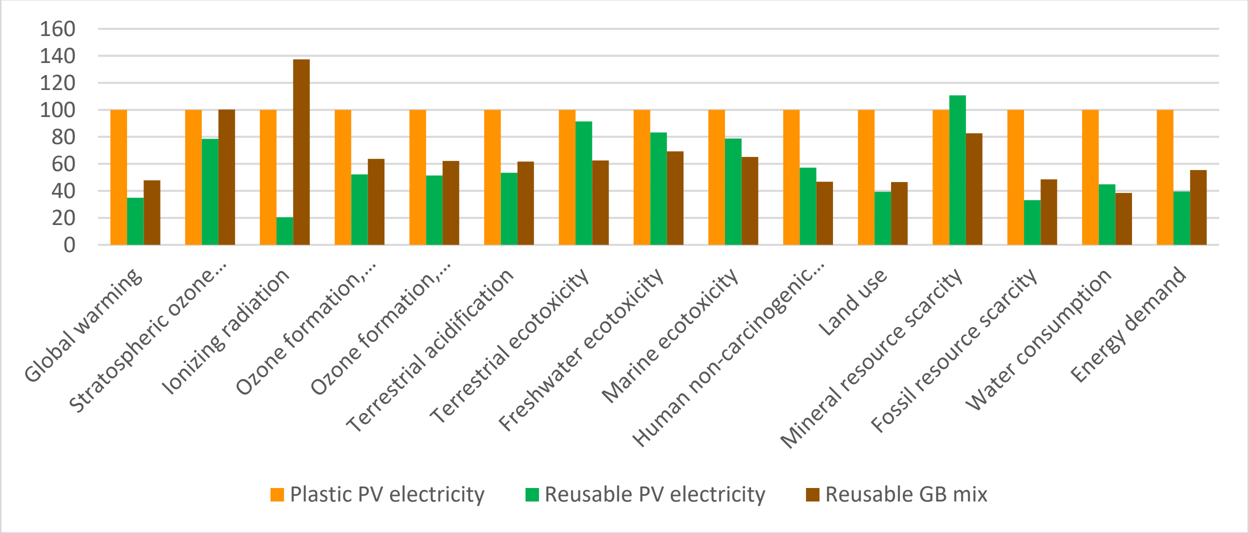

Figure 7: Sensitivity analysis on the source of electricity used on the farm.

4.3.4 Number of reuses

For the results presented in Figures 2 – 7, the metal churns are reused approximately 1000 times and glass bottles 280 times. Figure 8 and Figure 9 show the number of reuses of metal churns and glass bottles required for the reuse scenario to have a lower environmental impact than the plastic scenario (global warming potential and water consumption as calculated using the ReCiPe method). As can be seen, even with a much more conservative number of reuses, the reuse option contributes less to global warming and water consumption than the plastic scenario. At approximately 15 reuses of churns for global warming and 40 reuses of churns for water consumption, the reusable option is almost certain to be more beneficial, provided the bottles are reused at least 8 times.

Substitution of single-use plastic bottles with single-use metal churns or glass bottles (i.e. number of reuses = 0) would not bring benefit from an environmental point of view. This highlights the importance of developing a system that encourages and ensures reuse. This conclusion is in accordance with Kouloumpis et al. (2020) and Stefanini et al. (2020).

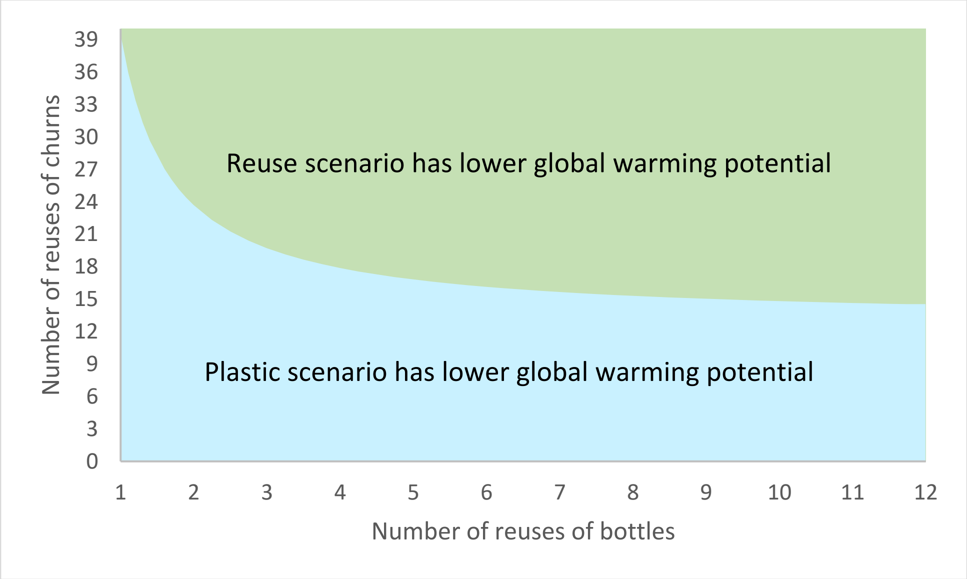

Figure 8: Global warming potential based on the number of reuses of glass bottles (x axis) and metal churns (y axis), showing the number of reuses of each reusable vessel required for the Reuse scenario to have a lower global warming potential (green) compared to the single-use plastic scenario

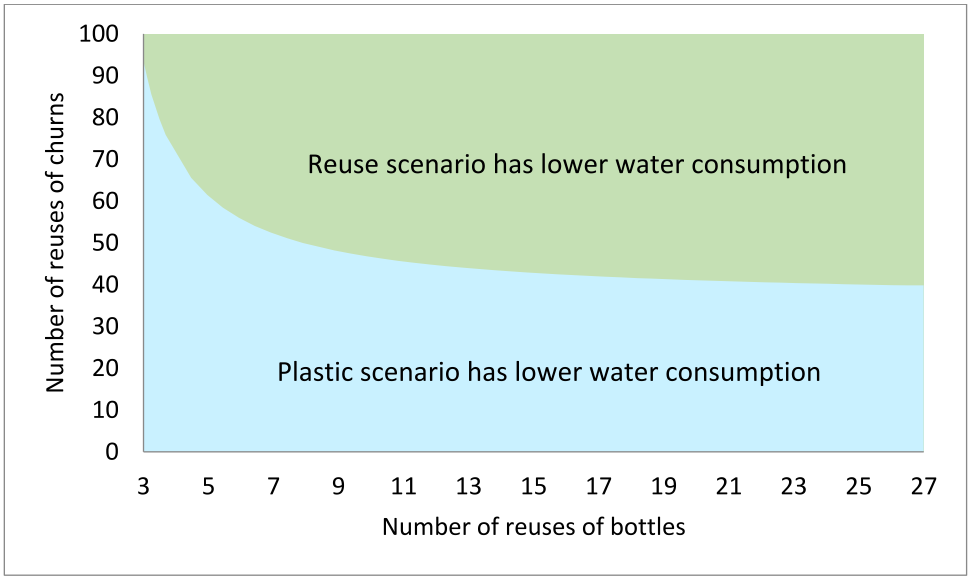

Figure 9: Water consumption based on the number of reuses of glass bottles (x axis) and metal churns (y axis), showing the number of reuses of each reusable vessel required for the Reuse scenario to use less water (green) compared to the single-use plastic scenario

4.4 Economic Evaluation

Table 7 shows the differential costs for the farm and the cafés. Considerable savings are recorded on the farm side, with the purchase of plastic bottles being the most significant (£8000/year). A slightly higher cost is induced by the higher diesel consumption, but the increase in cost due to the necessary auxiliaries for reusable vessels cleaning (£2600) is more significant. The difference in transport expenses is negligible. As this figure used allocation by mass of the vessels to solve multifunctionality and uses the price of fuel from a certain date, this number is not of utmost precision, however, overall, this part of the cost is of lesser impact.

Table 7: Annual differential costs associated with switching from plastic to reuse

Dairy Farm (Our Cow Molly)		The University of Sheffield Cafés	
Item/Process	Differential cost per year [£]	Item/Process	Differential cost per year [£]
Non-reusable packaging purchase: bottles, lids, labels	-8000	Change in waste disposal amounts: less plastic, more aluminium	-560
Reusable packaging purchase: glass bottles, aluminium lids, metal churns	460	Not buying milk in plastic anymore	-89000
Transport from the farm to the cafés	130	Buying milk in reusable vessels	94000
Maintenance of reusable vessels	2600		
Total	-4900	Total	5000

The cost of delivering milk in reusable vessels proves to be higher than the cost of delivering the same amount of milk in plastic bottles by about 6% (£94,000 per year to £89,000 per year). This is due to the fact that delivery in glass bottles is more expensive per unit volume than the delivery in plastic bottles or metal churns and partly because the number of glass bottles of milk is rounded up therefore slightly extra milk (0.5% total) is purchased in the reusable case. Small savings are made on waste disposal, due to the smaller amount of material being disposed of by the university. Overall, considering the factors presented in the table, Our Cow Molly would need to pay about £5,000 less and the university about £5,000 more yearly if the reusable vessels system was to be introduced. Additional labour costs on the farm (due to reusable vessel cleaning) are not included here.

4.5 Data quality

Table 8 presents a pedigree matrix of values and inventories used in the analysis. It considers criteria and recommendation suggested by Weidema & Wesnæs (1996). Rows coloured in orange represent data that is of improvable quality, however it proved not to have a major impact on the results of the study. Filling electricity requirements input represents at most 2.2% of the total life cycle impact in all categories, either on the plastic or reusable side. The input of metal churns represents 3% or less in the majority of the categories in the reusable scenario.

The rows in yellow show data that is of improvable quality, however sensitivity checks have been performed to provide a possible range of values and “worst-case estimates” as suggested by Weidema & Wesnæs (1996) for cleaning of churns water demand and recycling rate of plastic bottles. Lifespan of a glass bottle churn are analysed indirectly through reuse-reuse diagrams to see the number of reuses required to equalise the environmental impact of the two scenarios.

Table 8: Pedigree matrix of data used in the analysis (scored 1 – 5). 1 indicates case specific and highly reliable data.

Data	Basic uncertainty	Reliability	Completeness	Temporal correlation	Geographical correlation	Further technological correlation	Source
Plastic impacts	2	2	3	1	2	2	(Wernet et al., 2016)
Glass bottles impacts	2	2	3	1	2	3	(Wernet et al., 2016)
Plastic bottles production impacts	2	2	3	1	2	2	(Wernet et al., 2016)
Steel production impacts	2	2	3	1	2	2	(World Steel Association 2017)
Mass of a churn	3	3	4	1	1	2	Assumption, (Pharma Hygiene Products Ltd 2017)
Masses of a plastic and glass bottle	1	1	1	1	1	1	Our Cow Molly
Churn production impacts	2	2	3	1	2	2	(Wernet et al., 2016)
Steel losses	2	1	2	1	2	2	(Flint et al. 2020)
Aluminium caps production impacts	2	2	3	1	2	2	(Wernet et al., 2016)
Weight of an aluminium cap	1	1	1	1	1	1	Our Cow Molly
Distance: Our Cow Molly to the cafés	1	1	1	1	1	1	Our Cow Molly
Transport: Our Cow Molly to the cafés	1	3	3	2	2	2	(Wernet et al., 2016), (Infras 2019)
Filling electricity requirements	3	3	4	1	2	2	Our Cow Molly
Cleaning of glass bottles inputs	1	1	1	1	1	1	Our Cow Molly
Cleaning of churns data	3	1	1	1	1	1	Our Cow Molly
Water	2	2	3	1	2	2	(Wernet et al., 2016)

Electricity	2	2	3	1	1	2	(Wernet et al., 2016)
Hypochlorite	2	2	3	1	2	2	(Wernet et al., 2016)
Sodium hydroxide	2	2	3	1	3	2	(Wernet et al., 2016)
Recycling impacts of plastic	2	2	3	1	2	2	(Wernet et al., 2016)
Recycing impacts of glass	2	2	3	1	2	2	(Wernet et al., 2016)
Recycling impacts of steel	2	2	3	1	2	2	(World Steel Association 2017)
Recycling rate of plastic	3	2	3	1	1	2	Interviews with cafés and assumptions
Recycling rate of glass	2	2	1	1	1	1	Our Cow Molly
Recyling rate of steel	2	2	1	1	1	1	Our Cow Molly
Incineration of plastic	2	2	3	1	3	2	(Wernet et al., 2016)
End-of-life of aluminium caps	2	2	4	1	2	2	(Wernet et al., 2016)
Other transport	2	2	3	2	3	2	(Wernet et al., 2016)
Lifespan of glass bottle and a churn	3	2	1	1	1	1	Our Cow Molly, assumption

5 Discussion

To compare the results of this analysis quantitatively, the number of reuses assumed must be mentioned, along with the specific emissions of a given vessel. Table 9 presents relevant global warming potential impacts from literature along with those obtained in this study (highlighted in blue). Global warming potential (GWP) has been chosen for comparison as it is the most popular criterion as well as one of the best defined. To divide the total impact of the reuse scenario in this study between the steel churns and glass bottles, allocation by volume of milk transported has been applied to the transport stage. The remaining elements are separate and hence no multifunctionality occurs.

It should be noted that while the number of reuses has been adjusted for the purpose of comparison, this is not the case for the remaining assumptions and transport distances and hence this should be taken into account when comparing the values. Additionally, the system boundaries and the approach to recycling and incineration credits in the described publications may be similar but by no means identical to those explained here.

In general, obtained values are of the same order of magnitude as those found in literature. The overall GWP scores of both plastic and glass bottles are particularly similar to Meyhoff Fry et al. (2010a) and

Meyhoff Fry et al. (2010b). As in other sources, end-of-life has a considerable effect on the overall environmental impact, wherein a higher recycling rate of the vessels induces lower greenhouse gas emissions. In this study the net scrap approach has been used, meaning the end-of-life credit and production impact will be higher than studies that employ a different approach, but the net total results are comparable. Furthermore, similar conclusions are reached with regards to the HDPE supply chain, acknowledging that the production of bottles is the predominant contributor to the overall environmental damage in the plastic scenario and that the filling, packing, secondary and transit packaging impacts are of negligible importance. Additionally, Meyhoff Fry et al. (2010a) concluded that the Maintenance and Transport stages are of major environmental importance for a reusable scenario.

Table 9: Comparison of global warming potential impact of different containers per litre of milk obtained in this study (blue) and from literature

Container material	Recycled content	Container volume	Number of reuses	% Recycling/ incineration/ landfill	GWP [g CO_2 eq/ l milk]	Source	Comments
HDPE	30%	2 l	N/A	100/0/0	55	This study	
HDPE	30%	2 pints	N/A	100/0/0	60	(Meyhoff Fry et al. 2010b)	Bottle to bottle recycling in UK
HDPE	30%	2 pints	N/A	100/0/0	55	(Meyhoff Fry et al. 2010a)	Bottle to bottle recycling in UK
HDPE	Not mentioned	1 l	N/A	100/0/0	57	(Meneses, Pasqualino & Castellsa 2012)	
HDPE	30%	2 l	N/A	50/50/0	90	This study	
HDPE	0%	1/2 US gallon	N/A	29/57/14	94	(Franklin Associates, 2008)	
HDPE	30%	2 l	N/A	35/65/0	101	This study	
HDPE	30%	2 pints	N/A	0/100/0	108	(Meyhoff Fry et al. 2010b)	
HDPE	30%	2 pints	N/A	0/100/0	103	(Meyhoff Fry et al. 2010a)	
HDPE	Not mentioned	1 l	N/A	0/100/0	179	(Meneses, Pasqualino & Castellsa 2012)	
Glass	60%	1 pint	7	100/0/0	117	This study	
Glass	62.50%	1 l	7	76.2/0/23.8	207	(Stefanini et al. 2020)	
Glass	60%	1 pint	8	100/0/0	108	This study	
Glass	35%	1/2 US gallon	8	15/17/68	131	(Franklin Associates, 2008)	
Glass	60%	1 pint	17.5	100/0/0	74	This study	
Glass	60%	1 pint	17.5	100/0/0	64	(Meyhoff Fry et al. 2010a)	Recycling in UK

Glass	60%	1 pint	283 (default)	100/0/0	43	This study	No relevant studies found to compare
Churn	62%	16 l	1012 (default)	100/0/0	30	This study	No relevant studies found to compare

In the study by Stefanini et al. (2020), an impact of 207 g CO_2 eq. per 1 l of milk was reported for a glass bottles reused 7 times. In the present study, if the same number of reuses is assumed, an impact of about 117 g CO2 eq. would be obtained. The source of this difference in impact is different system boundaries (considering secondary and tertiary packaging of different type) between the studies, much longer transport distances in the Stefanini et al. model, and different end-of-life assumptions. Significantly higher impacts are also reported by Stefanini et al. for plastic alternatives: PET and R-PET, 186 and 152 g per 1 l of milk, respectively. Furthermore, positive scores for all types of vessels are reported for the end-of-life impact, meaning a different approach/assumption of allocation is likely to have been made.

Some of the studies in Table 9 considered “lightweighting” of the packaging as a possible way to reduce the environmental damage. This term describes the reduction of the packaging weight to reduce impacts related to materials and transport. The reduction would mainly concern the production and transportation stage. This has not been considered in the present work as the aim was to compare the current supply chain and the hypothetical bulk supply chain, using as much actual data as possible. Furthermore, as the lifetime of reusable vessels has been established empirically, it would be difficult to estimate the impact of lightweighting of the reusable vessels on their functionality and hence lifespan.

The study has a number of assumptions and limitations that could be improved in future, however the trend shown by the results is not expected to change. The study used assumptions and default, average transport values, particularly for early stages of material production. Ideally, those values should be substituted with actual values when known to increase the precision of the study. As plastic bottle caps are produced in a different facility than the plastic bottles, they could be treated as separate inputs in the future. The same applies to labels and adhesives that are put on the bottles.

The sensitivity analysis showed that the amount of water used to clean a churn could influence considerably the overall impact of the whole life cycle. The actual amount of water could be determined once the system is running and could change throughout as a potential increase in demand for milk in churns could encourage Our Cow Molly to invest in an automated system for churn cleaning. This is likely to decrease the water usage and increase the electricity usage, compared with manual washing.

The analysis is a case study that aims to support a concrete decision around the supply chain change and as such estimates accurately the difference in environmental impacts between the two scenarios in the described conditions. The results, and particularly the reuse-reuse sensitivity analysis explained in section 3.3.3 are applicable to this particular functional unit, but the trends are also relevant for other distributed local supply chains. The usage of different types of vessels is dictated by practicality reasons. Furthermore, the usage of electricity from photovoltaic source on the farm should be appreciated since it is used to heat significant amounts of water in the farm. Hence, to be able to draw the same conclusions about the maintenance stage given a different electricity source, another analysis would need to be performed.

The cooperation between the café and the milk producer is crucial here: it is thanks to good communication and cooperation that the vessels can be collected and reused so that the amount of materials needed is minimised.

On the reuse side, the milk dispensing system will have to be cleaned daily however that value should be much smaller than the amount of water used for cleaning the vessels. The same applies to electricity demand for dispensing the milk – the amount of electricity should be small compared to the energy needed to heat the water for cleaning on the farm, additionally, the electricity at the University is also of renewable source, namely from solar, wind and hydro sources.

6 Conclusions

The study concludes that the modelled reusable system of milk delivery is more environmentally friendly in most impact categories than the current plastic scenario. Within the presented system boundaries, significant savings in greenhouse gas emissions (by at least 55%), water consumption (by at least 45%) and fossil resources depletion (by at least 60%) can be achieved at the expense of e.g. mineral resource scarcity (increased by up to 45%) and marine eutrophication (increased by up to 140%).

The production of the vessels has been identified to have the biggest impact in the plastic scenario. Although an increased recycling rate can alleviate the damage in some categories (global warming, water and energy demand), the reuse scheme still proves to be of lower environmental burden in most categories due to a significant difference in the masses of material needed for the vessels.

As expected, because of the increased weight and necessity to clean the vessels, transport and maintenance play a key role part in the damage assigned to the reuse scheme. Increased water usage renders the metal churns and glass bottles' scenario considerably worse in the Marine eutrophication category. The lack of precise data for water usage in cleaning of churns is of minor importance in categories such as global warming potential and fossil resources scarcity, although might be a decisive factor in categories such as Terrestrial or Freshwater Ecotoxicity.

At the assumed reuse rate (about 280 times for glass bottles and 1000 for churns), the production of reusable vessels has a minor contribution to the total environmental impact of the reusable system, although it must be noted that metal churns and glass bottles prove not to reduce water usage or greenhouse gas emissions if they are not reused a sufficient amount of times. At 8 reuses of glass bottles, churns need to be reused at least 15 and 40 times for the reusable system to be equal in greenhouse gas emission and water consumption respectively, compared to the plastic scenario.

Transport and maintenance prove to be the impact hotspots of the reuse scheme; however, it is maintenance that has the greatest potential for improvement. Further research should be conducted on the cleaning of both steel churns and glass bottles, with a view to minimising the water and energy usage per vessel cleaned. Reduction of water may be achieved by automating the cleaning of the steel churns. Research on the use of on-roof water heating (in addition or instead of the current photovoltaic panels) should be carried out as this may reduce the energy input required for vessel cleaning. As electric refrigerated vans are currently not offered in sizes appropriate for dairy delivery, switching to delivery powered by electricity might not yet be a possible option, however this should be investigated once the option is available. Further options for decarbonising energy use would also benefit the maintenance stage for reuse vessels.

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