



# Life cycle engineering of production, use and recovery of self-chilling beverage cans



Noemi Arena<sup>\*</sup>, Philip Sinclair, Jacquetta Lee, Roland Clift

Centre for Environment and Sustainability, University of Surrey, Guildford, United Kingdom

## ARTICLE INFO

### Article history:

Received 15 June 2016

Accepted 23 November 2016

Available online 24 November 2016

### Keywords:

Self-chilling systems

Activated carbon

Sustainable manufacturing

Life cycle engineering

Beverage cans

Closed loop use

## ABSTRACT

The chill-on-demand system is a new technology designed to provide cooled products on demand, thereby avoiding chilled storage. It uses the cooling effect provided by endothermic desorption of carbon dioxide previously adsorbed onto a bed of activated carbon and has the potential to be applied to any type of product that needs to be cold at the point of consumption. The principles of life cycle engineering have been utilized to evaluate the overall environmental performance of one possible application of this technology: a self-chilling beverage can, with a steel outer can to contain the beverage and an inner aluminium can to contain the adsorbent.

An attributional life cycle assessment has been undertaken considering all the life cycle stages of a self-chilling can: manufacture of each part of the beverage container, its utilization, collection of the used can, and management of the waste by reuse, recycling and landfilling. Activated carbon production is included in detail, to assess its contribution to the overall life cycle. The results are compared with those for conventional aluminium and steel beverage cans stored in two types of retail chiller: a single door refrigerator and a large open-front cooler. A sensitivity analysis explores alternative scenarios for activated carbon production and for recovery of the can components post-use for reuse or recycling. The results highlight the importance of using activated carbon produced from biomass by a process with efficient use of low-carbon electrical energy, energy recovery from waste streams and appropriate air pollution control, and of achieving high rates of recovery, re-use and recycling of the cans after use. The results suggest limited markets into which the product might be introduced, particularly where it would displace inefficient chilled storage in an electricity system with a high proportion of coal-fired generation.

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## 1. Introduction

The chill-on-demand system is a new technology to provide rapid cooling on demand. This paper considers its application to chilling a canned beverage, i.e. to cool it to the desired temperature at the point of consumption. This technology could have the potential to disrupt the beverage market: for instance, it might be possible to reduce or even eliminate chilled storage with a consequent revolution in the whole supply chain of beverages. Thus the chill-on-demand system could possibly make a significant contribution to reducing emissions of greenhouse gases (GHGs),

particularly if it displaces inefficient and poorly maintained refrigerated beverage storage cabinets or dispensers. These are common in low-income countries, frequently utilized in middle-income countries and encountered under some circumstances even in wealthy countries (Calm, 2002). This work was undertaken to explore these possibilities.

The system provides the chilling-on-demand effect by endothermic desorption of carbon dioxide previously adsorbed onto a bed of activated carbon (AC); for the beverage system, this is contained in an inner component of the can. The essential features of the device are shown schematically in Fig. 1. An outer can of tinned steel contains the beverage and an inner aluminium can, called the Heat Exchange Unit (HEU); only the HEU is made of aluminium because otherwise the combined can would be too expensive. The HEU contains the AC with adsorbed carbon dioxide and prevents contact between the beverage and the activated carbon. The presence of the HEU requires the self-chilling can to be

<sup>\*</sup> Corresponding author. Centre for Environment and Sustainability, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey, GU2 7XH, United Kingdom.

E-mail address: [noemi.arena@surrey.ac.uk](mailto:noemi.arena@surrey.ac.uk) (N. Arena).

### List of acronyms

AC	Activated Carbon
ADP	Abiotic Depletion Potential
AP	Acidification Potential
BOF	Blast Oxygen Furnace
EAf	Electric Arc Furnace
EP	Eutrophication Potential
FAETP	Freshwater Aquatic Ecotoxicity Potential
GWP	Global Warming Potential
HEU	Heat Exchange Unit
HTP	Human Toxicity Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
ODP	Ozone Layer Depletion Potential
OFC	Open Front Cooler
SDC	Single Door Cooler
TETP	Terrestrial Ecotoxicity Potential
WMS	Waste Management System
WMS	Waste Management System

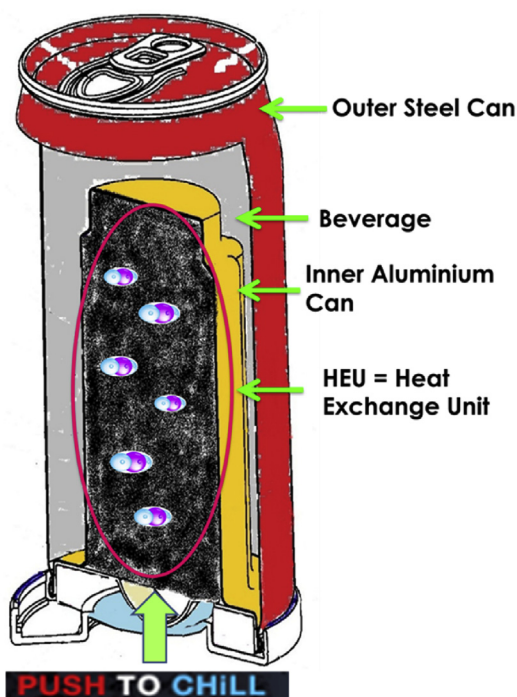


Fig. 1. Sketch of the self-chilling beverage can.

correspondingly larger than a conventional can for the same beverage volume (see Table 1). A button in the base of the can activates a valve to release the pressure inside the HEU by venting the carbon dioxide to the atmosphere; the desorption of carbon dioxide is endothermic and therefore provides a cooling action that ideally cools the beverage by about 15 °C.

The overall objective of the analysis is to devise a way to ensure the best cooling performance with minimal environmental impact at reasonable cost. An industrial ecology approach has been

adopted, “considering the ecological aspect when dealing with the interaction and inter-relationship both within industrial systems and between industrial and natural systems” (Despeisse et al., 2012; Graedel and Lifset, 2015; Leigh and Li, 2015). Because of the additional materials and components, management of the self-chilling cans after use is even more important than for conventional beverage containers. Fig. 2 shows the re-use and recycling system examined here according to the principles of life cycle engineering (Peças et al., 2009; Ribeiro et al., 2008). It is assumed that the cans will be recovered after use as a separate stream; the aluminium HEU can be separated from the outer steel can and re-used while the steel can is sent to the existing steel recycling chain.

Collection, recovery, reuse, and recycling of metals and AC pellets are considered explicitly. A detailed analysis of the environmental impacts of activated carbon production from coconut shells has been developed (Arena et al., 2016) and the results, together with suggestions for possible improvements, have been incorporated in this study.

## 2. Methods

### 2.1. Product system and assessment

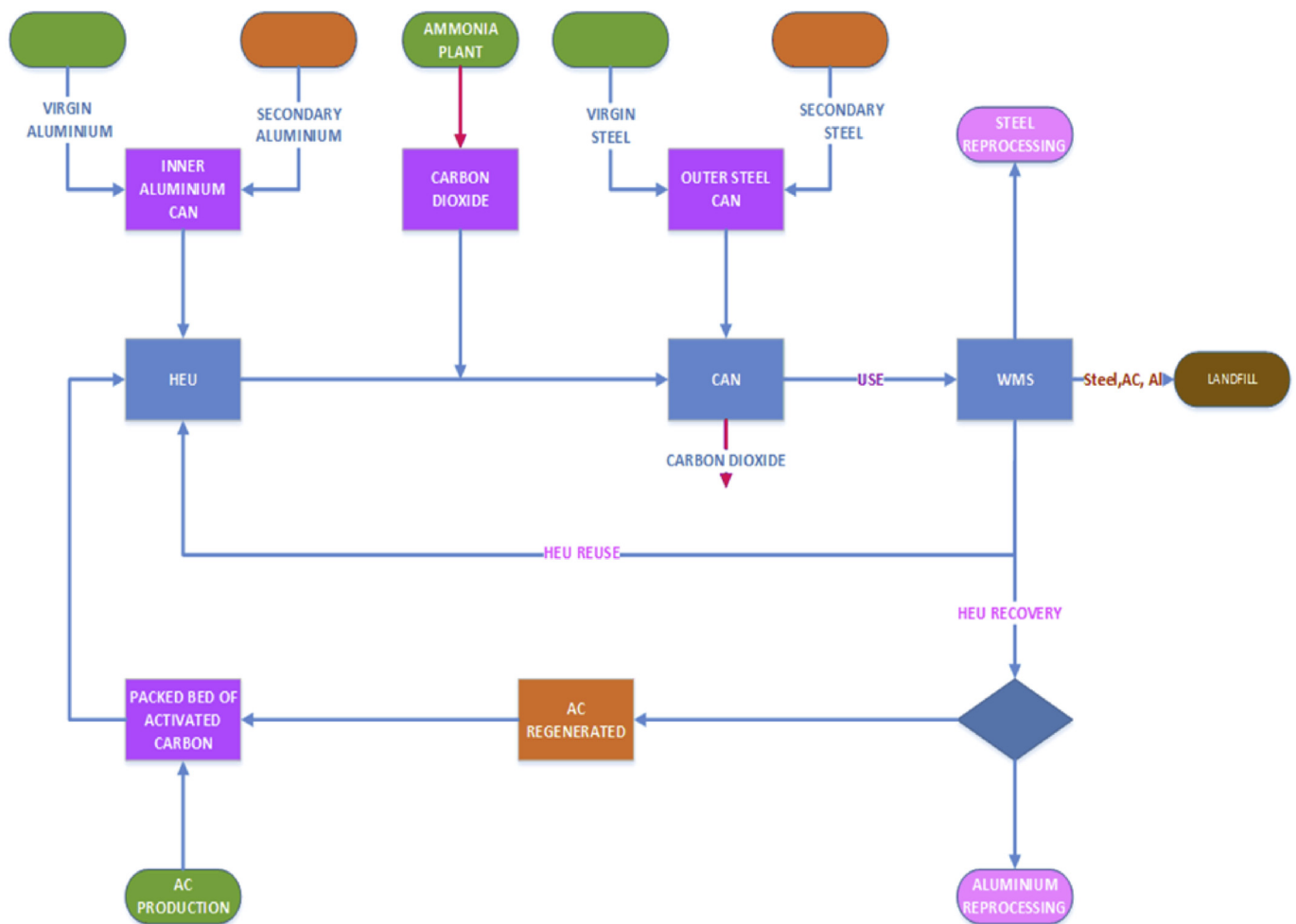
The goal of the study was to compare, by means of a life cycle assessment (LCA), the potential environmental impacts of the overall self-chilling beverage can system with those of the conventional approach to delivering cold beverages from chilled retail storage. The analysis aims in particular to identify scenarios in which the self-chilling system can show advantages over the conventional system, to guide product and market development. The system includes the production, use, and end-of-life phases of the cans, which are assumed to be manufactured and filled in California (USA). For the self-chilling can, the AC is assumed to be produced in Indonesia and transported to California (Arena et al., 2016). It is particularly important, from environmental and economic points of view, to design the supply system for the self-chilling can to approach “closed-loop” use of materials and, in particular, the heat exchange units: a large proportion of the cans must be recovered after use, so that the outer steel can and the inner aluminium HEU can be separated for re-use and/or recycling. The importance of recovery is explored in detail in Section 3. It is assumed that can disassembly is carried out close to the location of can manufacture and filling.

The LCA was carried out according to ISO standards (ISO-14040, 2006; ISO-14044, 2006). The functional unit is the delivery of one unit of 300 mL of chilled beverage. Since the purpose of the study is to compare self-chilling against conventional cans, an attributional approach has been adopted (Brander et al., 2009; Finnveden et al., 2009; Kua and Kamath, 2014; Thomassen et al., 2008). If the technology does prove to be successful, it will be appropriate to follow up with a consequential LCA but, at this stage, such an analysis would be too speculative to be meaningful. The life cycle environmental impacts were assessed using the CML-2001 methodology developed at the University of Leiden (Guinée et al., 2002). The following midpoint potential impacts were considered: Abiotic Depletion, Acidification, Eutrophication, Freshwater Aquatic Ecotoxicity, Terrestrial Ecotoxicity, Human Toxicity, Global Warming, Ozone Layer Depletion and Photochemical Ozone Creation. In accordance with the ISO standard 14044 (2006), normalization has been used to identify the impact categories most significant for the system under analysis. The software Gabi 6.0 was used to model the system.

**Table 1**

Input to inventory analysis for the Self-Chilling Can and Conventional Cans. In bold is reported the total amount for each component.

Direct burdens, for 300 mL of beverage	Self-chilling can	Aluminium conventional can	Steel conventional can
<b>Overall Volume, mL</b>	<b>510</b>	<b>330</b>	<b>330</b>
<b>Carbon dioxide, kg</b>	<b>0.055</b>	-	-
<b>Steel (tinplate), kg</b>	<b>0.029</b>	-	<b>0.025</b>
<b>Aluminium, kg</b>	<b>0.039</b>	<b>0.012</b>	-
<b>Activated Carbon, kg</b>	<b>0.110</b>	-	-
Virgin Aluminium, kg	0.0103	0.0064	-
Recycled Aluminium, kg	0.0095	0.0059	-
Virgin Steel (tinplate), kg	0.0180	-	0.0147
Recycled Steel (tinplate), kg	0.0120	-	0.0098
Energy for CO <sub>2</sub> processing, MJ	0.0613	-	-
Energy for CO <sub>2</sub> pressurizing in HEU, MJ	~0	-	-
Energy for AC pressurizing in HEU, MJ	0.0864	-	-
Energy for AC regeneration, MJ	83.2	-	-
Energy for can chilling in a single door cooler, MJ	0	15	15
Energy for can chilling in an open front cooler, MJ	0	343	343
Transport (Return journey to Store, 30 km), kgCO <sub>2eq</sub>	1.54E-08	1.06E-09	2.12E-09

**Fig. 2.** Flow-sheet of the self-chilling beverage can system.

## 2.2. Can components and recovery

The principal components of the self-chilling can and two types of conventional can are listed in Table 1, along with the other key inputs to the inventory analysis.

As mentioned above, the activated carbon adsorbent is assumed to be produced in Indonesia from coconut shells and then

transported to California. Coconut shells are often utilized as raw materials for activated carbon production, due to their abundant supply (which allows the economic viability of their manufacture) and high density and high purity (Yahya et al., 2015). Coconut shell could be regarded as the waste from a food crop but the information received from AC producers indicated that nothing of the coconut is actually wasted: the meat is used in food; the coconut milk

**Table 2**

Main assumptions for the Base case and the alternative scenario with high HEU recovery (reported in bold).

Material quantities	Base case	Best HEU recovery and reuse
Pre-use fraction of recycled steel, -	0.4	0.4
Pre-use fraction of virgin steel, -	0.6	0.6
Post-use fraction of steel recovered, -	0.7	0.7
Post-use fraction of steel to landfill, -	0.3	0.3
Pre-use fraction of recycled aluminium, -	0.48	0.48
Pre-use fraction of virgin aluminium, -	0.52	0.52
Post-use fraction of HEUs recovered, -	0.7	<b>0.9</b>
Post-use fraction of HEUs to landfill, -	0.3	<b>0.1</b>
Fraction of recovered aluminium reused, -	0.7	<b>1</b>
Fraction of recovered aluminium recycled, -	0.3	<b>0</b>
Fraction of recovered carbon re-used, -	0.7	<b>1</b>

and water are used in beverages and pharmaceuticals; and the coconut shell, if not used for production of activated carbon or other materials such as barbecue brickettes, is typically used locally as a biofuel. Therefore, the analysis here follows the scenario developed by [Arena et al. \(2016\)](#) in which the coconut shells used in producing AC are diverted from use as fuel and the resulting use of fossil fuel instead is included. The energy for loading and compressing the activated carbon in the HEU is also taken into account.

The analysis allows for the larger quantities of metals used in the self-chilling can. Minor materials – primarily plastic components – contribute much less to the life cycle environmental impacts and have therefore been omitted from this study. Re-use of recovered HEUs is a closed-loop system (see [Fig. 2](#)). However, the metals themselves are not necessarily used in a closed loop system, so that the proportions of recycled metal used and recovered for post-use recycling are not necessarily the same and must therefore be specified separately. The following assumptions have been made, as summarized in [Table 2](#), together with those describing an alternative scenario (Scenario “Best HEU Recovery” – see below) with higher recovery and re-use of the HEUs:

- The conventional aluminium can, which represents 90% of current beverage cans worldwide ([Rexam, 2016](#)), is assumed to follow current European practice ([European Aluminium Association, 2013](#)), comprising 52% virgin and 48% recycled material.
- The tinplate can, representing 10% of beverage cans worldwide ([Rexam, 2016](#)), comprises 60% virgin and 40% recycled material ([World Steel Association, 2011](#)).
- For all three types of can, recovery and re-use are assumed to follow current European patterns: 70% are recovered post-use with the remaining 30% lost to landfill.
- In the absence of any empirical evidence, it is assumed for the purposes of this preliminary assessment that 70% of the HEUs recovered can be reused by recharging the activated carbon with carbon dioxide
- For the remaining 30% of the recovered HEUs (i.e. 21% of the total post-use HEUs in the base case), the activated carbon is regenerated in an energy efficient furnace (Minfurn™), with an energy consumption estimated to be 1 kWh/kg ([Mintek, 2014](#)). The aluminium in these HEUs is reprocessed.

The steel forming the outer can of the self-chilling device and the aluminium and steel in the recovered conventional cans are reprocessed. The impacts related to the recycling of steel and aluminium have been treated according to the method recently proposed by [Gala \(Gala et al., 2015\)](#), already used in carbon foot-printing ([Clift et al., 2009](#)): the impacts of reprocessing are

allocated to the next use while, to estimate the avoided burdens, recycled materials are assumed to replace not virgin material but the average mix of virgin and recycled material actually used in the market.

Following common practice in the carbonated beverage industry, the carbon dioxide in the HEU is recovered from a waste stream from other industrial processes, in this case from the vent gases from an ammonia plant. Since the gas is ultimately emitted to the atmosphere whether or not it is used for chilling, it is not included in the comparison. However, the additional energy and materials required to recover this carbon dioxide, compress it into cylinders and supply it to the chill cans have been included (see [Table 1](#)). The associated GHG emissions are of the same order of magnitude as those associated with producing CO<sub>2</sub> from fossil fuel ([Rice, 1997](#)).

### 2.3. Transport and storage

Because of their different sizes, the self-chilling and conventional cans have different transport requirements. Details of the logistic system modelled are given in [Table 1](#). It is assumed that diesel trucks of the “Euro 4” type, with payload capacity 27 tonnes, are used to transport both filled and post-use cans. However, different vehicles are used to transport the full and empty cans so that all trucks are assumed to be empty on their return journeys.

Beverages in the two types of conventional can are assumed to be dispensed from two types of retail refrigerator: a single door (SDC: model FV 650; [Frigoglass, 2015](#)) and a large open front cooler (OFC: model Chicago multi-deck 1.8; [Bibalou et al., 2014](#)). Both coolers have a direct expansion system (DX), associated with a leakage of refrigerant of about 2% per year ([Frigoglass, 2015](#)). [Table 3](#) reports the inputs to the inventory analysis for storage in both types of cooler, obtained from data from literature and refrigerator retailers ([Bibalou et al., 2014](#); [Bovea et al., 2007](#); [Frigoglass, 2015](#)). The life cycle impacts of the energy consumed by refrigeration has been analysed for three different energy mixes, corresponding to Europe and USA (intermediate carbon intensity), Indonesia (high carbon intensity) and New Zealand (low carbon intensity). The cans are assumed to be kept in refrigerated storage for only one day ([Bibalou et al., 2014](#); [Frigoglass, 2015](#)): for both types of cooler, the impacts from energy consumption and refrigeration leakage were scaled for one can of 300 mL stored for one day.

## 3. Results

The positive or negative contributions from all the stages of the beverage delivery systems are reported here in terms of the impact categories listed in [Section 2](#), normalized in terms of person equivalent units, where one person equivalent represents the

**Table 3**

Basis of Life Cycle Inventory for 300 mL conventional cans in single door and open front coolers.

Refrigerator	Open front	Single door
Capacity, cans	770	528
Energy Use, MJ/can*day	3.43E-01	1.49E-02
Type of refrigerant	R404a	R134a
Quantity of refrigerant in chiller for the whole life span, kg	5.40E-01	2.96E-01
Refrigerant per can, kg	1.02E-03	3.84E-04
Leakages, kg/can*day	5.60E-08	2.10E-08
GWP of refrigerant leakage, kgCO <sub>2</sub> eq/can*day	1.13E-11	1.47E-11

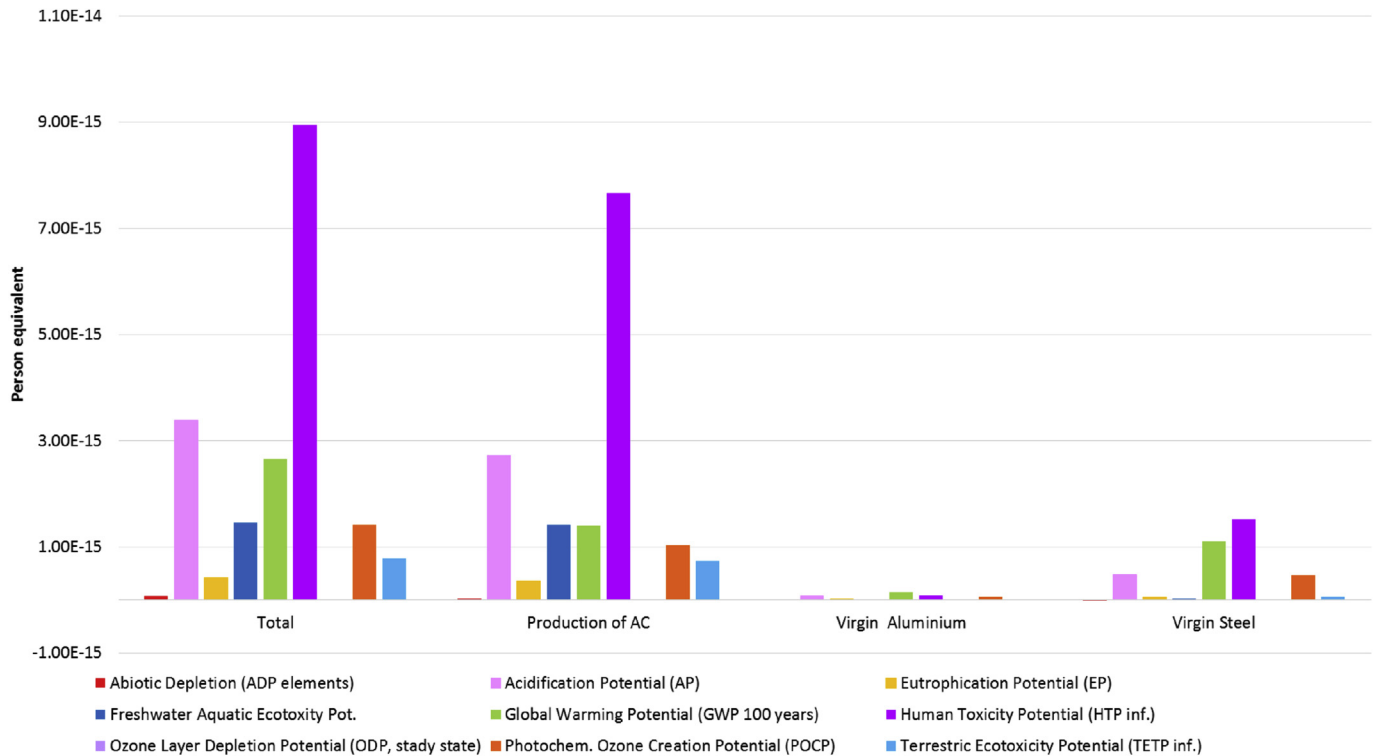


Fig. 3. Comparison of LCIA results of the overall self-chilling beverage can system and those of the productions of fresh AC and virgin metals (normalization: world, year 2013 CML-2001 person equivalents).

global average impact in the specific category associated with one person during one year.

### 3.1. Self-chilling system

Fig. 3 shows the impact results for the chill-on-demand system, including production of the principal material inputs; more details on individual processes are given in Figs. A1–A4 of the Supplementary Information. Normalization reveals Global Warming Potential, Human Toxicity Potential and Acidification Potential as the most significant global and localized impacts categories. Results for these three categories for the self-chilling and conventional cans are shown in Table 4; the results for all categories are given in Table A1 of the Supplementary Information.

The dominant role of activated carbon production for the self-chilling can is evident from Fig. 3, with production of virgin steel for the outer can also significant. A specific study on AC production (Arena et al., 2016) highlighted the dominant contributions of crushing and tumbling of the coconut shells or activated carbon to obtain powdered or granulated material and of heat recovery and steam generation. This results primarily from the associated consumptions of electrical energy, which in the Indonesian energy mix is produced mainly from hard coal (Arena et al., 2016). This also explains the dominance of the midpoint categories of HTP, AP and GWP.

A sensitivity analysis has been carried out by defining alternative scenarios, as suggested by (Clavreul et al., 2012). In the first alternative scenario (see Table 2), called “best HEU recovery”, a higher percentage recovery of HEU (90% rather than 70%) has been assumed, together with complete recovery and reutilization of aluminum components and, above all, activated carbon, as detailed in Table 2. The results for this scenario are shown in Fig. 4 and Table 5. Increased reuse of HEUs, and of AC contained in these units,

leads to substantial reduction in all the relevant impact categories, particularly AP and GWP.

The dominant contribution of the activated carbon production to the overall performance of the system suggested three further alternative scenarios, specifically focused on this stage. The related results are reported in Table 5 and Fig. 5.

Scenario 1 considers AC production in a different country, sufficiently close to Indonesia but with an energy mix

Table 4  
Principal normalized impacts for self-chilling and conventional cans.

	AP	GWP	HTP
<b>Self-chilling Can</b>			
Base case	3.39E-15	2.66E-15	8.95E-15
Best HEU recovery	1.50E-15	1.59E-15	3.75E-15
<b>Aluminum can</b>			
<b>Single door cooler</b>			
EU	6.40E-17	9.73E-17	7.02E-17
NZ	5.53E-17	6.93E-17	3.45E-17
IN	2.38E-16	1.88E-16	7.95E-16
USA	6.22E-17	1.17E-16	8.76E-17
<b>Open front cooler</b>			
EU	9.68E-16	1.12E-15	1.10E-15
NZ	7.72E-16	4.76E-16	2.73E-16
IN	4.96E-15	3.21E-15	1.78E-14
USA	9.27E-16	1.59E-15	1.49E-15
<b>Tin-plate steel can</b>			
<b>Single door cooler</b>			
EU	1.87E-16	3.80E-16	4.84E-16
NZ	1.79E-16	3.52E-16	4.49E-16
IN	3.61E-16	4.71E-16	1.21E-15
USA	1.85E-16	4.00E-16	5.02E-16
<b>Open front cooler</b>			
EU	1.09E-15	1.41E-15	1.51E-15
NZ	8.94E-16	7.59E-16	6.87E-16
IN	7.68E-15	3.49E-15	1.82E-14
USA	1.05E-15	1.87E-15	1.91E-15



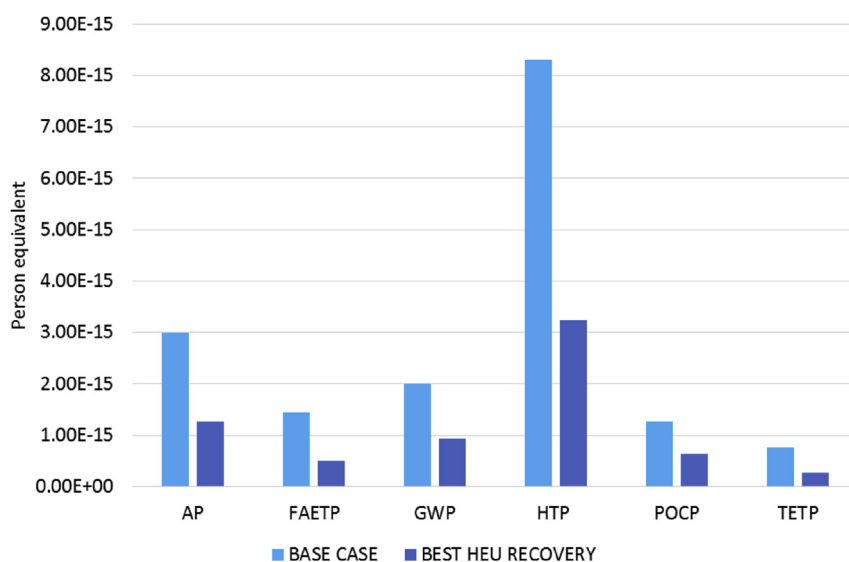


Fig. 4. Results of the sensitivity analysis of the self-chilling beverage can system, Best HEU Scenario.

characterised by predominantly renewable sources: in the specific case considered here, it has been assumed that the coconut shells are shipped from Indonesia to New Zealand for processing (Arena et al., 2016). The results indicate lower impacts compared with those of the base case in all categories. However, compared with the best HEU recovery scenario, this change only leads to better performance in HTP, underlining the crucial importance of recovery and re-use.

Scenario 2 assumes that the company producing AC avoids the use of electricity generated from hard coal by using coconut shells as biofuel for production of the electrical energy used and also as the feedstock for the manufacturing process. In this scenario. It is assumed that the biofuel is burned in a power station of small-to-medium size with overall net efficiency of electrical energy conversion of 16% (Arena et al., 2016). The results for this scenario indicate lower impacts than the base case in all categories but, again, higher impacts compared with the best HEU recovery scenario.

Finally, Scenario 3, which represents the “Optimal scenario”, combines Scenarios 1 and the “best HEU Recovery” by assuming that the AC production is located in New Zealand and that a HEU recovery of 90% is obtained. The results (Table 5 and Fig. 5) show that this scenario provides the best environmental performance thanks to the high HEU recovery, which implies reduced production of activated carbon, and to the electricity mix in New Zealand characterised by predominantly renewable sources.

### 3.2. Comparison with conventional cans

The environmental impacts for the self-chilling can, used according to the base case scenario, are compared with the

conventional aluminium can in Fig. 6 and with the steel can in Fig. 7 in terms of contribution to the three dominant impact categories. Results are shown for the two types of retail chiller, used in electrical supply systems characterised by intermediate carbon intensity (exemplified by the EU and USA), high (exemplified by Indonesia) and low (exemplified by New Zealand). For the conventional cans, the environmental impacts are dominated by electricity consumption because the refrigerants used (R144a in the single-door cooler and R404 in the open-fronted cooler; Frigoglass, 2015) have very low ODP and GDP. Of course the comparisons will be different if, contrary to the Montreal protocol, the chillers use CFC refrigerants.

Even with a high carbon electricity system, both types of conventional can refrigerated in a single door cooler show better environmental performance than the self-chilling beverage can. Open-front coolers are less thermally efficient and therefore have higher energy demands. Even so, the conventional cans show lower impact than the self-chilling can in countries with low (New Zealand) and medium (Europe and USA) carbon electricity systems. The only instance in which the self-chilling can, used according to the base case scenario, is environmentally preferable in all categories is when it displaces open-front coolers in countries with a high carbon electricity system, such as Indonesia.

In view of this comparison with the base case scenario, the other scenarios introduced above are compared with the conventional cans. Fig. 8 shows the comparisons across the three dominant impact categories for the specific case of the US electricity mix. Details of the other comparisons are given in the additional documentation (See Figs. A5–A7 and Tables A2–A3). For the very high recovery rates in the “Best HEU Recovery” scenario and the US

Table 5  
Normalized impacts in base case and three alternative scenarios.

Category	Base case	Best HEU Recovery	Scenario 1	Scenario 2	Scenario 3 “optimal scenario”
AP	3.39E-15	1.50E-15	3.13E-15	2.22E-15	1.41E-15
EP	4.18E-16	1.73E-16	4.73E-16	4.53E-16	1.92E-16
FAETP	1.46E-15	5.08E-16	1.43E-15	1.45E-15	5.08E-16
GWP	2.66E-15	1.59E-15	1.80E-15	1.58E-15	1.33E-15
HTP	8.95E-15	3.75E-15	1.89E-15	4.10E-15	1.67E-15
POCP	1.42E-15	6.85E-16	1.38E-15	1.62E-15	6.01E-16
TETP	7.80E-16	2.83E-16	6.61E-16	8.63E-16	2.47E-16

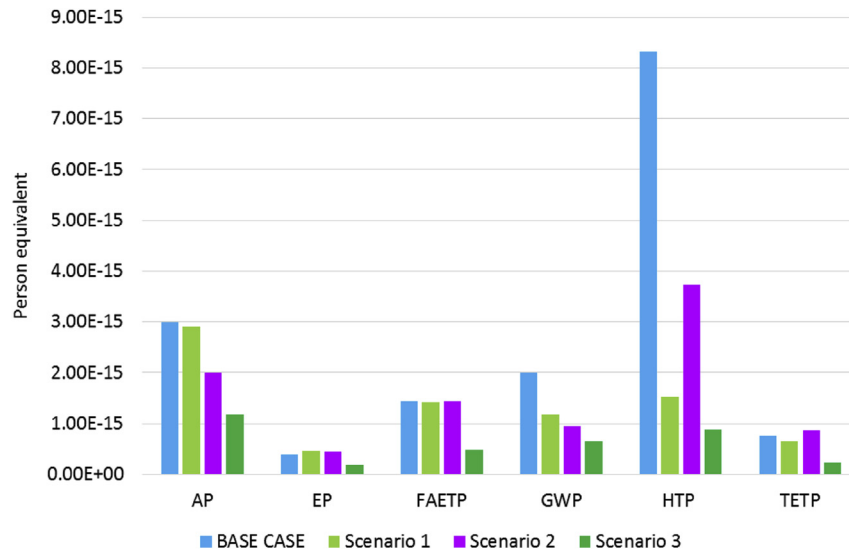


Fig. 5. Results of the sensitivity analysis of the self-chilling beverage can system, scenario 1, scenario 2 and scenario 3.

electricity grid, the self-chilling can contributes less to GWP than either type of conventional can but is still worse in the other categories (see Fig. 8). For the most optimistic “Optimal Scenario”, in which the activated carbon is produced in a country with a very low carbon electricity supply (New Zealand) and with very high rates of recovery of cans and re-use of the HEUs, the self-chilling can shows environmental performance comparable with the conventional cans from single-door coolers in countries with high-carbon

electricity and from open-front coolers in all the electricity systems considered.

#### 4. Discussion

The environmental impacts of producing the additional components required for the self-chilling can, particularly the activated carbon used in the Heat Exchange Units, are so large that the new



Fig. 6. Comparison of the self-chilling beverage can system with the base case and a conventional beverage aluminium can in Europe, USA, Indonesia and New Zealand.

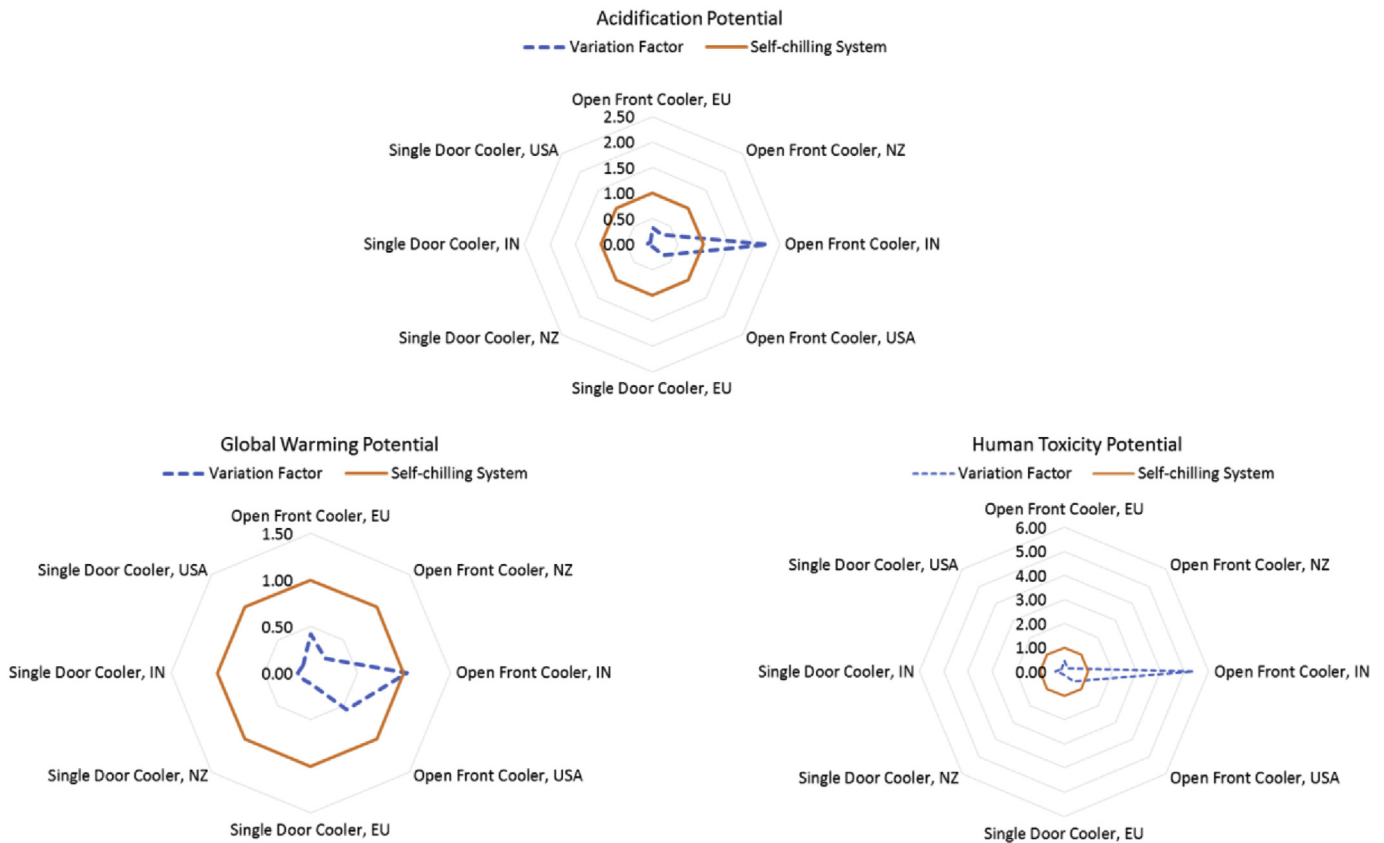


Fig. 7. Comparison of the self-chilling beverage can system with the base case and a conventional beverage tinplate steel can in Europe, USA, Indonesia and New Zealand.

system would only represent an environmental improvement over conventional beverage cans under very specific circumstances: inefficient chilled storage with an electricity system using a high proportion of coal-fired generation. The impacts can be reduced to some extent by improving the efficiency of activated carbon production and locating that production in countries with a low carbon electricity supply. More substantial environmental improvements would depend on finding adsorbents with much larger capacity and developing a system with very high rates of recovery and re-use.

With the system and can design foreseen at present, unrealistically high rates of recovery, re-use and recycling of post-use cans are needed to offset the impacts of the additional material inputs, amplifying the additional cost of the self-chilling system over conventional cans. The self-chilling system does offer environmental advantages where it can displace storage with a high carbon footprint. Therefore it appears to be essentially a 'niche' product, to be marketed where it would displace low-efficiency chilled retail storage, particularly where the electricity supply has a high carbon intensity, and

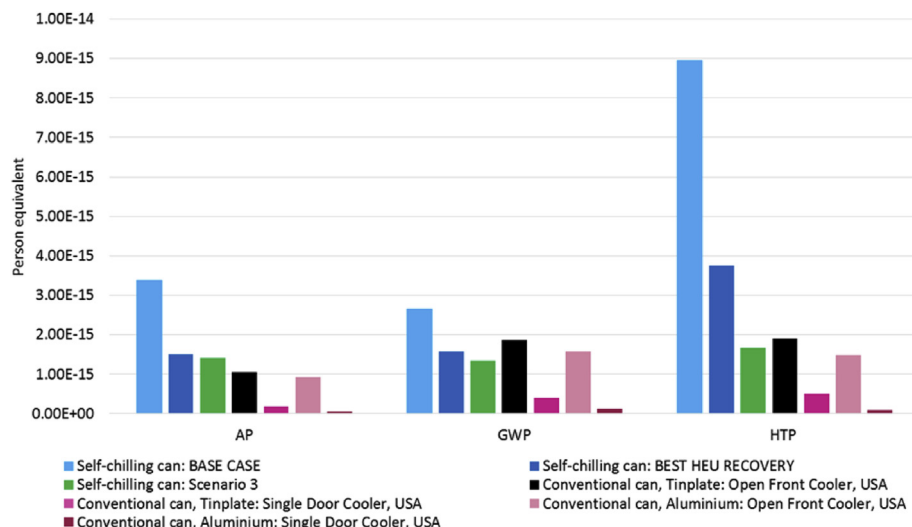


Fig. 8. Comparison of the self-chilling beverage can system with a conventional beverage cans made of aluminium and steel in USA.



where refrigerated cabinets and dispensers are poorly maintained so that they have relatively high refrigerant leakage rates. This suggests a prime market including vacation resorts, particularly in the 'Global South', especially where it has additional convenience value because consumers are reluctant to use ice cubes to cool their drinks due to fear of microbiological contamination. Whether high rates of recovery and re-use can be achieved in these markets is an open question. The self-chilling can also has a role as a convenience product where refrigerators are not available (for example, drivers on long journeys) and where drinks would otherwise be chilled inefficiently in portable devices such as ice-boxes (e.g. picnics and camping trips, or drinks with sandwiches on the sea shore).

Thus the self-chilling beverage system appears not to represent a truly disruptive technology. Even if its environmental performance can be improved to the point where it is fully competitive with conventional beverage cans, it would not completely displace retail or domestic refrigerators which will still be needed for products which must be kept chilled during storage. A specific experimental investigation on carbon dioxide adsorption on and desorption from AC has been carried out, leading to a model to describe heat transfer between the HEU and its surroundings (Arena, 2016) as a basis for exploring other possible applications of the chill-on-demand technology.

In view of the restricted market potential for self-chilling beverage cans, the assumptions made in the attributional analysis are appropriate: the new technology would represent a marginal increase in demand for coconut shells as the feedstock for production of activated carbon and a marginal reduction in the use of chilled storage. These assumptions can be revisited if the self-chilling technology is ever developed to the point where it appears likely to achieve a substantial market share.

## 5. Conclusions

Life Cycle Assessment of a novel system for supplying self-chilling beverages shows that the most significant environmental impact categories are Global Warming Potential, Human Toxicity Potential and Acidification Potential. Production of the activated carbon (AC) adsorbent for the Heat Exchange Units (HEUs) dominates the overall environmental impacts. Sustainability of AC production, and consequently that of the whole self-chilling system, can be improved by reducing the electrical energy consumption in the process units of crushing and tumbling, by using an efficient integrated process and by locating the production where the carbon intensity of the electricity supply is low, or by using energy produced *in situ* from renewable sources such as biomass. Off-setting the additional impacts of producing the additional components of the self-chilling can would require unrealistically high rates of recovery and re-use, particularly of the HEUs.

The environmental analysis provides a perspective which limits any expectation that chilling on demand represents a disruptive technology. It shows that the new product should be marketed where it would displace inefficient refrigerated storage using electrical power with high carbon intensity.

## Acknowledgements

The authors gratefully acknowledge Chemviron Carbon Ltd and Frigoglass SAIC for help in compiling the inventory data, and the EPSRC (grant number: EP/G037612/1) for supporting this research.

## Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jclepro.2016.11.148>.

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