Life cycle environmental impacts of vacuum cleaners and the effects of European regulation

DOI:
10.1016/j.scitotenv.2016.03.149

Science of the Total Environment 559 (2016) 192–203

Contents lists available at ScienceDirect

Science of the Total Environment

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

Life cycle environmental impacts of vacuum cleaners and the effects of European regulation

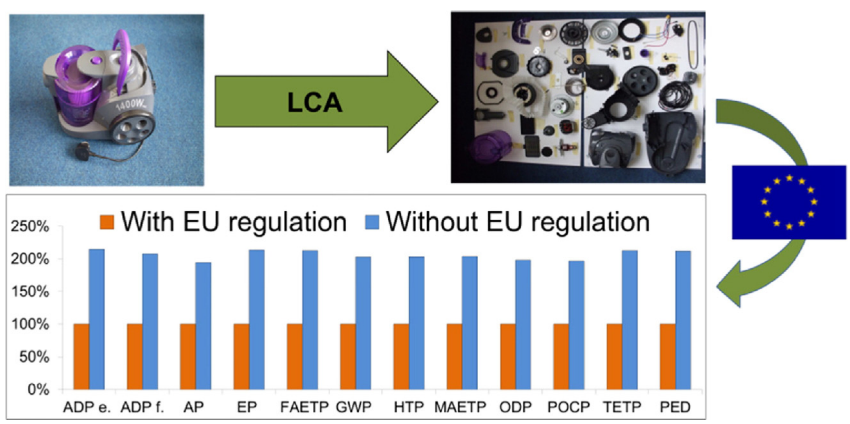
Alejandro Gallego-Schmid *, Joan Manuel F. Mendoza, Harish Kumar Jeswani, Adisa Azapagic

Sustainable Industrial Systems, School of Chemical Engineering and Analytical Science, The University of Manchester, The Mill, Sackville Street, Manchester M13 9PL, UK

HIGHLIGHTS

- Over 200 M domestic vacuum cleaners in the EU consume 18.5 TWh electricity annually.
- First comprehensive LCA of vacuum cleaners to estimate the effects of EU regulation
- The eco-design regulation will reduce the EU impacts by 37%–44% by 2020.
- The WEEE directive will have a moderate effect, reducing the impact by <1%.
- Decarbonisation of electricity would decrease most the impacts by 6%–20% by 2020.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 21 December 2015
Received in revised form 15 March 2016
Accepted 20 March 2016
Available online xxxx

Editor: Simon Pollard

Keywords:
Eco-design
Energy efficiency
Life cycle assessment (LCA)
Electricity decarbonisation
Waste electrical and electronic equipment (WEEE)

ABSTRACT

Energy efficiency of vacuum cleaners has been declining over the past decades while at the same time their number in Europe has been increasing. The European Commission has recently adopted an eco-design regulation to improve the environmental performance of vacuum cleaners. In addition to the existing directive on waste electrical and electronic equipment (WEEE), the regulation could potentially have significant effects on the environmental performance of vacuum cleaners. However, the scale of the effects is currently unknown, beyond scant information on greenhouse gas emissions. Thus, this paper considers for the first time life cycle environmental impacts of vacuum cleaners and the effects of the implementation of these regulations at the European level. The effects of electricity decarbonisation, product lifetime and end-of-life disposal options are also considered. The results suggest that the implementation of the eco-design regulation alone will reduce significantly the impacts from vacuum cleaners (37%–44%) by 2020 compared with current situation. If business as usual continued and the regulation was not implemented, the impacts would be 82%–109% higher by 2020 compared to the impacts with the implementation of the regulation. Improvements associated with the implementation of the WEEE directive will be much smaller (<1% in 2020). However, if the WEEE directive did not exist, then the impacts would be 2%–21% higher by 2020 relative to the impacts with the implementation of the directive. Further improvements in most impacts (6%–20%) could be achieved by decarbonising the electricity mix. Therefore, energy efficiency measures must be accompanied by appropriate actions to reduce the environmental impacts of electricity generation; otherwise, the benefits of improved energy efficiency could be limited. Moreover, because of expected lower life expectancy of vacuum cleaners and limited availability of some raw materials, the eco-

* Corresponding author.
E-mail address: alejandro.gallegoschmid@manchester.ac.uk (A. Gallego-Schmid).

http://dx.doi.org/10.1016/j.scitotenv.2016.03.149

design regulation should be broadened to reduce the impacts from raw materials, production and end-of-life management.

1. Introduction

Several studies have assessed life cycle environmental impacts of different electrical appliances and electronic products (Andrae and Andersen, 2010; Song and Li, 2015). The former include refrigerators (Monfared et al., 2014), dishwashers (Johansson and Björklund, 2010), ovens (Mudgal et al., 2011) and washing machines (Ardente and Mathieux, 2014). The impacts of electronic products studied in the literature include plasma TVs (Feng and Ma, 2009; Hischier and Baudin, 2010), computers (Choi et al., 2006; Duan et al., 2009; Teehan and Kandlikar, 2012) and monitors (Zhou and Schoenung, 2007), mobile phones (Andrae and Vaija, 2014) and e-books (Jeswani and Azapagic, 2015). However, the analysis of the life cycle environmental performance of vacuum cleaners has received little attention in literature with few studies available. For example, Lenau and Bey (2001) and Hur et al. (2005) proposed and tested different simplified life cycle assessment (LCA) methodologies using semi-quantitative inventory data of unspecified models of vacuum cleaners as examples. In both studies, the main objective was to compare the proposed methodologies and, therefore, these studies did not provide specific conclusions related to the environmental performance of these devices. A screening LCA on vacuum cleaners (AEA, 2009) was also performed as part of preparatory documents for the development of the European Union (EU) eco-design regulation for vacuum cleaners (European Commission, 2013a). The main objective of this study was to assess the environmental performance of different types of vacuum cleaner and to identify improvement opportunities. The study was performed with aggregated inventory data provided by manufacturers and specific data obtained by disassembly of certain elements (AEA, 2009). Only three environmental impacts were considered (global warming, eutrophication and acidification), in addition to some air emissions and heavy metals which were estimated at the inventory level only. The findings indicated that use of vacuum cleaners was the main hotspot and identified various alternatives to improve their energy efficiency and cleaning performance. However, as far as we are aware, a comprehensive LCA study of vacuum cleaners has not been carried out yet so that it is not known how the use stage affects other impacts and how much the other life cycle stages, such as raw materials and waste management, contribute to these. This is particularly pertinent in light of the European strategy on circular economy which promotes resource efficiency and waste minimisation (European Commission, 2014).

The power rating of vacuum cleaners has increased markedly since the 1960s, from 500 W to over 2500 W, persuading consumers that a “powerful” cleaner will perform better (AEA, 2009; Biček et al., 2014; Dyson, 2011). However, higher power does not necessarily lead to a better cleaning performance but does mean a lower energy efficiency, which dropped from 30–35% in the 1970s to below 25% in recent years without noticeable improvements in the cleaning performance (AEA, 2009).

More than 200 million of domestic vacuum cleaners are currently in use in the European Union (EU), with around 45 million sold annually and a market growth of 9% per year (European Commission, 2013b). The average annual electricity consumption by these devices in the EU was estimated at 18.5 TWh in 2010 (European Commission, 2013b), representing 0.6% of the total EU consumption (ENTSO-E, 2011) and equivalent to the annual electricity generation by five gas power plants (DECC, 2015). Vacuum cleaners, therefore, represent an important area of action to help reduce the environmental impacts from households. For that reason, the European Commission (EC) has recently developed an eco-design regulation to encourage manufacturers to produce more energy efficient vacuum cleaners without compromising product performance and economic feasibility (European Commission, 2013a). The regulation considers only most widely used domestic vacuum cleaners (i.e. upright and canister/cylinder) and excludes others, such as dry and/or wet, robot, battery-operated and floor-polishing devices.

Another important aspect considered by the EC to improve the environmental performance of household appliances is the recycling of waste electrical and electronic equipment (WEEE). The generation and treatment of WEEE is currently a rapidly growing environmental problem in many parts of the world. As the market continues to expand and product innovation cycles become shorter, the replacement of electric and electronic equipment accelerates, making electronic devices a fast-growing source of waste (Kiddee et al., 2013; Premalatha et al., 2014; Robinson, 2009; Song and Li, 2014; Widmer et al., 2005). To help address this problem, the WEEE directive aims to prevent, re-use, recycle and/or recover these types of waste (European Parliament, 2012). It also seeks to improve the environmental performance of all players involved in the life cycle of electrical and electronic equipment (producers, distributors and consumers) and, in particular, those involved directly in the collection and treatment of WEEE. Waste prevention and minimisation also contribute directly to improving resource efficiency which is at the core of the European 2020 strategy for creating a smart, sustainable and inclusive economy (European Commission, 2010).

Therefore, considering these policy drivers, the main objectives of this study are:

- to evaluate life cycle environmental impacts of vacuum cleaners and identify opportunities for improvements; and
- to assess the effects at the EU level of the implementation of the eco-design and WEEE regulations related to vacuum cleaners and provide recommendations for future research and policy.

As far as we are aware, this is the first study of its kind for vacuum cleaners internationally.

2. Methods

The LCA study has been conducted according to the guidelines in ISO 14040/44 (ISO, 2006a, 2006b), following the attributional approach. The assumptions and data are detailed in the following sections, first for the reference vacuum cleaner considered here and then for the study at the EU level.

2.1. Reference vacuum cleaner

2.1.1. System description and boundaries

Vacuum cleaners can be broadly categorised as upright and canister/cylinder type. In the upright design, the cleaning head is permanently connected to the cleaning housing, whereas in the cylinder type, the cleaning head is separated from the vacuum cleaner body, usually by means of a flexible hose. Cylinder vacuum cleaners represent 85% of the European market (AEA, 2009). Vacuum cleaners can have a disposable bag or they can be bagless with a reusable dust container. The European market shows an upward consumer trend towards low-cost bagless vacuum cleaners with high power rating, most of which are produced in China (AEA, 2009). Therefore, this study focuses on a conventional 1400 W bagless vacuum cleaner, which is representative of the European market for these products.

The scope of the study is from 'cradle to grave', with the following stages considered (Fig. 1):

- raw materials:
  - o metals: galvanized and stainless steel, aluminium, brass and copper;
  - o plastics: polyvinyl chloride (PVC), polypropylene (PP), acrylonitrile butadiene styrene (ABS), polyoxymethylene (POM), high density polyethylene (HDPE) and ethylene vinyl acetate (EVA); and
  - o cardboard (for packaging);
- production: metal stamping and plastic moulding (to obtain the desired shape), production of internal cables, power cord and plug, screen printing, product assembly and packaging;
- use: consumption of electricity and replacement of filters;
- end of life: disposal of post-consumer waste; and
- transport: raw materials and packaging to the production factory, vacuum cleaner to retailer, end-of-life waste to waste management facility. Consumer transport to and from retailer is not considered because of a large uncertainty related to consumer behaviour and allocation of impacts to a vacuum cleaner relative to other items purchased at the same time. A sensitivity analysis showed that this assumption is robust as the contribution of consumer transport (petrol or diesel car, average distance of 5 km) to the total impacts of a vacuum cleaner is negligible (<0.9%).

The functional unit is defined as the 'use of the vacuum cleaner for 50 h/year over a period of eight years (product lifetime) to clean a typical European household (87 m^2)'. This definition is based on the specifications provided by the eco-design regulation (European Commission, 2013a) to analyse the energy consumption of vacuum cleaners. In order to assess the effects of the application of the eco-design and WEEE regulations, the environmental impacts are calculated by considering the total number of vacuum cleaners used in the EU28 over a year.

2.1.2. Inventory data

The inventory data for the vacuum cleaner are detailed in Table 1 with an overview of the dismantled product displayed in Fig. 2. The contribution of the different components to the total weight (61% for plastics, 22% for metals and 17% for packaging) correspond well with the average values provided by the AEA (2009) for vacuum cleaners sold and used in the EU (50% plastics, 20–30% metals and 10–20% for packaging).

Primary production data, including the amount and type of raw and packaging materials and a detailed description of the vacuum cleaner production, have been obtained from a major vacuum cleaner producer. Background data have been sourced from the Ecoinvent v2.2 database (Ecoinvent Centre, 2010). Open literature sources and GaBi database (Thinkstep, 2015) have been used to fill data gaps if data were not available in Ecoinvent. Further details on the inventory data are provided in the next sections.

2.1.2.1. Raw materials, production and packaging. The dismantled components of the main body and accessories show in Fig. 2 have been individually weighed to estimate the material composition of the vacuum cleaner (Table 1). The total weight of the main body is 3.5 kg. The metallic components (1.2 kg) are made of aluminium (motor and screws), stainless and galvanized steel (motor), brass (plug) and copper (plug, power cord, wire cables and motor). The materials used for the plastic components of the main body (2.3 kg) are PP (external and motor structure), ABS (dust container and structure of air filters), HDPE (air filters) and PVC (plug, power cord and wire cables). Accessories (0.95 kg) are made of EVA (flexible hose, hose collar and handle), PP (floor brush and furniture tool) and HDPE (extension tube). Ecoinvent life cycle data have been used for these components, except for the production of POM, for which the data were not available and have been sourced from Plastics Europe (2014). As the materials are produced in China, Ecoinvent data for the electricity grid in China have been used for all production processes. Injection moulding is assumed for the production of

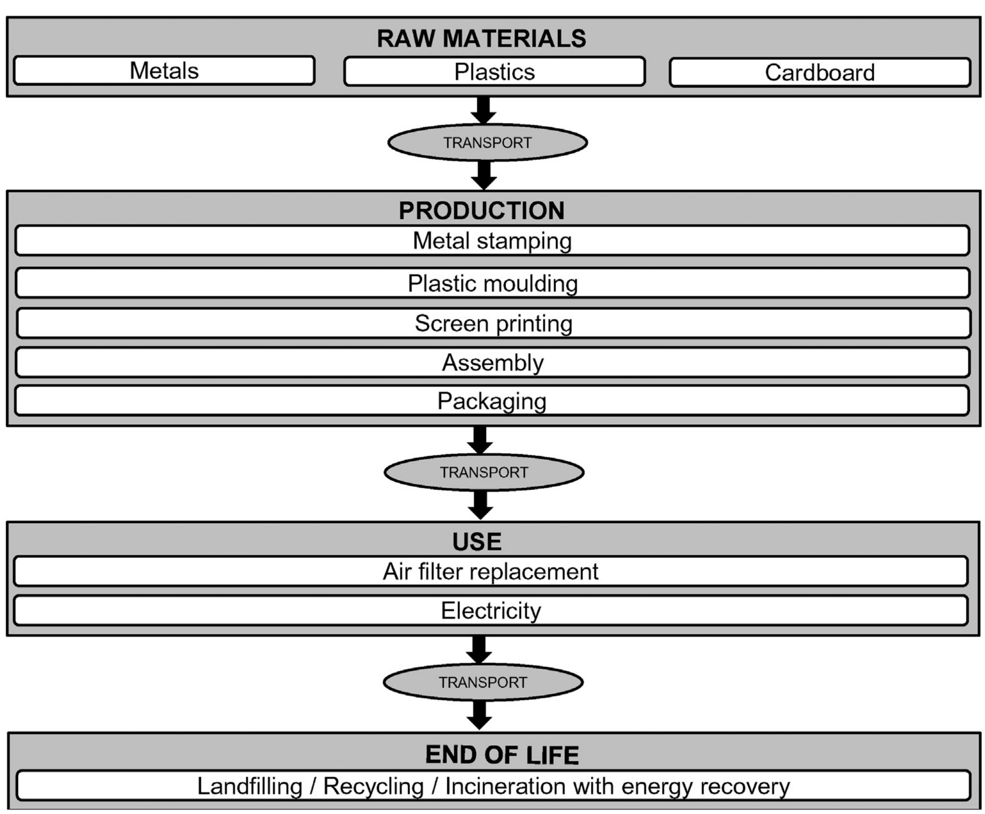


Fig. 1. System boundaries.

Table 1
Life cycle inventory data for the vacuum cleaner.

Life cycle stages		Data source[a]
Raw material (main body)		
Polyvinyl chloride	342 g	Own measurements[b]
Polypropylene	806 g	Own measurements[b]
Acrylonitrile butadiene styrene	1112 g	Own measurements[b]
Polyoxymethylene	23 g	Plastics Europe (2014) and own measurements
High density polyethylene	19 g	Own measurements[b]
Copper	177 g	Own measurements[b]
Brass	20 g	Own measurements[b]
Galvanized steel	234 g	Own measurements[b]
Stainless steel	408 g	Own measurements[b]
Aluminium	376 g	Own measurements[b]
Raw material (accessories)		
Ethylene vinyl acetate	415 g	Own measurements[b]
High density polyethylene	229 g	Own measurements[b]
Polypropylene	301 g	Own measurements[b]
Packaging		
Folding box	695 g	Own measurements[b]
Cardboard trays	176 g	Own measurements[b]
Protective cardboard	19 g	Own measurements[b]
Polyethylene bags	26 g	Own measurements[b]
Production		
Injection moulding (electricity)	17.3 MJ	Manufacturer[c]
Injection moulding (heat)	14.4 MJ	Manufacturer[c]
Metal stamping (electricity)	5.6 MJ	Manufacturer[c]
Metal stamping (heat)	2.5 MJ	Manufacturer[c]
Screen printing (electricity)	0.2 kJ	Manufacturer[c]
Power cord, plug and wire cables		
Electricity	2.1 MJ	Manufacturer[c]
Heat	0.3 MJ	Manufacturer[c]
Assembly and packaging		
Electricity	26.3 MJ	AEA (2009)
Water	13 l	AEA (2009)
Transport		
Raw materials (main body): transport to factory	0.3 t·km	Own assumption[d]
Raw materials (accessories): transport to factory	0.2 t·km	Own assumption[d]
Packaging: transport to factory	0.1 t·km	Own assumption[d]
Vacuum cleaner: factory to Shanghai port	0.8 t·km	Own assumption[d]
Vacuum cleaner: Shanghai port to Rotterdam port	104.6 t·km	Sea Distance (2016)
Vacuum cleaner: port (Rotherham) to Munich	4.4 t·km	Via Michellin (2016)
Vacuum cleaner: distribution centre (Munich) to retailer	0.8 t·km	Own assumption[d]
End of life: transport to waste treatment	0.4 t·km	Own assumption[e]
Use		
Electricity	560 kWh	ENTSO-E (2014a)
Three air filter replacements[f]	378 g	Own measurements[b] and manufacturer[c]
End of life[g]		
Recycling (metals)	1154 g	AEA (2009), Kemna et al. (2011)
Recycling (plastics)	943 g	Plastics Europe (2015), Schmidt (2012)
Recycling (packaging)	748 g	Eurostat (2015a)
Incineration with energy recovery (plastics)	1305 g	ENTSO-E (2014a), Plastics Europe (2015)
Incineration with energy recovery (packaging)	62 g	ENTSO-E (2014a), Eurostat (2015a)
Landfilling (metals)	61 g	AEA (2009), Kemna et al. (2011)
Landfilling (plastics)	1404 g	Plastics Europe (2015)
Landfilling (packaging)	80 g	Eurostat (2015a)

[a] Ecoinvent data (Ecoinvent Centre, 2010) have been used for the background data, except for the data incineration with energy recovery which are from GaBi (Thinkstep, 2015).
[b] Vacuum cleaner was disassembled and raw materials and packaging individually weighted.
[c] Confidential.
[d] 150 km.
[e] 50 km for landfilling and 100 km for incineration and recycling.
[f] 12% high density polyethylene and 88% acrylonitrile butadiene styrene.
[g] Plastics includes the main body, accessories, filter replacements and polyethylene bags. Packaging includes folding box, cardboard trays and protective cardboard.

different plastic parts. Steel stamping and aluminium cold impact extrusion are assumed for the production of steel and aluminium components, respectively. As no specific processes were available for copper shaping, Ecoinvent data for generic metal shaping have been considered.

The primary packaging of the vacuum cleaner consists of a folding cardboard box, two cardboard trays, one interior protective cardboard and several plastic (polyethylene) bags to protect the accessories (Fig. 3). Inventory data for the board folding and production of the box with offset printing have been used for the folding box. The trays and cardboard have been modelled using data for corrugated board (mixed fibre) and PE film has been used for the plastic bags. Data from Ecoinvent have been used for all packaging.

The following assumptions have been made to fill data gaps and adapt some datasets:

- For power cord and plug, Ecoinvent data for production of the computer cable have been adapted. The power cord H05VVH2-F 2×0.75 mm^2 has been assumed, with a weight of 14 g/m of copper instead of the 19.5 g/m in a regular computer cable, based on own measurements. For the plug, the Ecoinvent dataset has been modified

Fig. 2. Dismantled vacuum cleaner, including its accessories.

to reflect the actual mass of different materials (22 g of PVC, 20 g of brass and 3 g of copper).

- Data for electricity and water consumption for vacuum cleaner assembly and packaging have been obtained from AEA (2009).

2.1.2.2. Use. Based on an average use of 50 h/year and an expected life of eight years, the estimated electricity consumption during the lifetime of the vacuum cleaner with the power rating of 1400 W is equal to 560 kWh. The inventory data for electricity generation for the EU28 have been obtained from the European Network of Transmission System Operators for Electricity (ENTSO-E) to model the EU electricity mix (ENTSO-E, 2014a); see Table S1 in Supporting information. The data correspond to the year 2013, which is considered here as the base year. For filter replacements, it has been assumed that air filter is changed once every two years (or after 100 h of use), as recommended by manufacturers.

2.1.2.3. End of life. The following assumptions have been made for the end-of-life stage for the main body of the vacuum cleaner:

- For metal waste, 95% recycling rate has been assumed (AEA, 2009; Kemna et al., 2011) and Ecoinvent data have been used to model the recycling process. The system has been credited for recycling by subtracting the equivalent environmental impacts of virgin metals, while also including the impacts from the recycling process. Based on the 'net scrap' approach (Bergsma and Sevenster, 2013), the credits have only been considered for the percentage of recycled metals that exceeds the recycled content in the original raw material. For example, copper is made up of 44% recycled and 56% virgin metal so that the system has been credited for recycling 51% of copper (95% minus 44%) at the end of life. A similar approach has been applied for steel and aluminium.
- In the case of plastics (PVC, PP, ABS, POM and HPDE), plastic disposal data for Europe in 2012 have been assumed: 26% recycling, 36% incineration with energy recovery and 38% landfilling (Plastics Europe, 2015). The system has been credited for recycled materials using the approach described above. For recycling, data from Schmidt (2012) have been modelled, but using the EU28 electricity mix in 2013 (ENTSO-E, 2014a). The same electricity mix has been used to credit the avoided impacts for the recovered electricity from incineration of plastic waste. The GaBi database has been used for these purposes since these data are not available in Ecoinvent. All polyethylene bags are assumed to be landfilled, using life cycle inventory data from Ecoinvent.
- For the cardboard packaging, the latest available packaging disposal data (for the EU27 in 2012) have been assumed as follows: 84% recycling, 7% incineration with energy recovery and 9% landfilling (Eurostat, 2015a). Since the cardboard packaging is mostly made from recycled material, no credits for the avoided material have been considered.

The WEEE directive established that for small household appliances, including vacuum cleaners, the rate of recovery should be 70% and at least 50% of the weight of appliance shall be recycled (European Parliament, 2012). Considering the assumptions made in this study, 73% of the weight of the vacuum cleaner is recovered at the end of life (50% is recycled and 23% incinerated with energy recovery), which is in compliance with the directive.

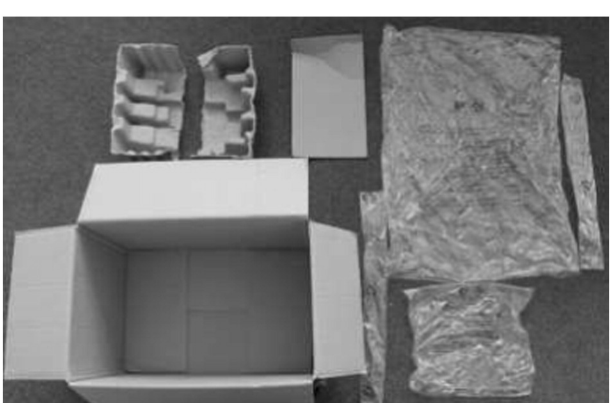


Fig. 3. Primary packaging of the vacuum cleaner.

2.1.2.4. Transport. The transport details can be found in Table 1. If not specified in databases, the raw materials and the packaging are assumed to travel for a distance of 150 km to the factory in 16–32 t Euro 3 truck. After the production and packaging in China, the vacuum cleaner is shipped to Europe. The transport distances have been estimated considering shipping by a transoceanic tanker (19,500 km) between major container ports in China (Shanghai) and Europe (Rotterdam) (Sea Distance, 2016; World Ship Council, 2013) and then road transport by a 16–32 t Euro 5 truck to a distribution centre in Munich (830 km), representing geographically a central point of the EU. Generic distances of 150 km have been used for transport from production factory to port of Shanghai (16–32 t Euro 3 truck) and from distribution centre to retailer (16–32 t Euro 5 truck). For the transportation of waste to final disposal, a distance of 50 km (for landfilling) and 100 km (for incineration and recycling) in a 16–32 t Euro 5 truck have been assumed. The Ecoinvent database has been used for the background transport data.

Table 2
Parameters considered for the current situation and a future scenario.

Parameter	Current situation (2013)	Future scenario (2020)	Sensitivity analysis for future scenario (2020)
Functional unit	213.84 million units	229.26 million units	229.26 million units
Power	1873 W	1060 W	2337 W
Lifetime expectancy	8 years	8 years	5 years
Electricity mix	EU28 (year 2013)	EU28 (year 2020)	Poland, Ireland, France, Denmark (year 2020)[a]
End-of-life options	80% recovery (70% recycling)	70% recovery (50% recycling)	100% landfilling

[a] Sensitivity analysis for one vacuum cleaner.

2.2. The EU level: current situation and a future scenario

This section gives an overview of the assumptions for the study at the EU28 level, carried out to evaluate possible implications of the implementation of the eco-design regulation (European Commission, 2013a) and the WEEE directive (European Parliament, 2012). Two timelines are considered for these purposes: i) current situation (2013) and ii) a future scenario for the year 2020. In both cases, the impacts have been estimated for all vacuum cleaners in use in the EU28 countries over a year.

As shown in Table 2, a number of different parameters have been considered, including power ratings and end-of-life options for vacuum cleaners as they are affected by both regulations. Furthermore, since electricity consumption is the main hotspot in the life cycle of vacuum cleaners, different electricity mixes are considered, assuming a lower carbon intensity in 2020 than at present (European Parliament and Council of European Union, 2009). Finally, a different number of vacuum cleaners in use have also been considered. These assumptions are explained in more detail in the next two sections.

2.2.1. Current situation

The following assumptions have been made for the key parameters for the current situation:

- Average power rating: according to the European Commission (2013b), the average power rating of vacuum cleaners in the EU was 1739 W in 2010, with an average annual increase of 2.5%. Thus, the average power rating of 1873 W has been assumed for 2013.
- Electricity mix: 2013 electricity mix for the EU28 countries as described in Section 2.1.2.2 has been considered.
- Number of vacuum cleaners in use: based on the number of households in the EU28 countries in 2013 (Eurostat, 2015b) and assuming one vacuum cleaner per household (Huisman et al., 2008), it is estimated that 213.84 million cleaners were in use that year.
- End-of-life disposal: waste options described in Section 2.1.2.3 have been used.

2.2.2. A future scenario

By 2020, both the eco-design and the WEEE regulations will be fully implemented, therefore, the future scenario has been modelled for the year 2020. The key parameters for this scenario are estimated as below:

- Average power rating: The eco-design regulation establishes that new vacuum cleaners marketed after 1 September 2014 should have a power rating below 1600 W and those marketed after 1 September of 2017 should be below 900 W. Given that the mix of new and old vacuum cleaners will be in use in 2020, an average power rating of 1060 W has been assumed, based on the following: i) an average power value of 1400 W for vacuum cleaners produced between 2014 and 2016 and 800 W for 2017–2020; ii) an expected lifespan of eight years, equivalent to the annual substitution rate of 12.5% (European Commission, 2013b) and iii) 9% increase in sales each year (European Commission, 2013b).
- Electricity mix: the most feasible scenario for decarbonising the EU28 electricity mix by 2020 projected by ENTSO-E (2014b) has been considered (see Table S1 in Supporting information).
- Number of vacuum cleaners in use: to estimate the total amount of vacuum cleaners in use in 2020, the same approach has been used as for the current situation. Considering the number of households in the EU28 countries in 2013 (Eurostat, 2015b) and 1% annual growth (European Commission, 2013b), it is estimated that 229.26 million of vacuum cleaners will be in use in 2020.
- End-of-life disposal: If the WEEE directive is fully implemented by 2020, small appliances such as vacuum cleaners should have a rate of recovery of 80% and, at least, 70% shall be recycled. To achieve these rates, and considering that the actual recycling ratio of metals is already high (95%), future changes in recovery and recycling will be focused mainly on plastic components. Thus, to achieve the above rates, a minimum of 57% of plastics must be recycled and 15% incinerated with energy recovery, with the rest being landfilled. These rates have been applied to the plastic materials making up the main body of the vacuum cleaner (PVC, PP, ABS, POM and HPDE). Note that the WEEE directive affects only the electronic section of products, hence the consideration of the plastics in the main body. For the other parts, (accessories, filters and packaging), no changes in waste treatment have been considered because of the lack of specific data or regulation on recycling. To evaluate the effects of the WEEE directive, a scenario with 100% landfilling of the main body and accessories has been used as a reference case for comparison.

2.2.3. Other assumptions

The other assumptions for the current situation and the future scenario are as follows:

- The same inventory data for the raw materials, packaging, production and transport presented in Section 2.1.2 have been used for both the current situation and the future scenario. The vacuum cleaner is representative of the actual European vacuum cleaners and, therefore, its inventory data are considered to be accurate for the current situation. However, development of new technologies to achieve the same cleaning efficiencies with less power can have environmental implications, especially in the manufacturing of future vacuum cleaner models. These developments do not necessarily imply an increase of environmental impacts, because, for example, a tendency to use less material has been observed in recently developed vacuum cleaners according to new regulations (Biček et al., 2014; European Commission, 2013b). Taking this tendency into account, the assumption made here for the same amount of materials used in the future as today can be considered as a worst case scenario.
- For both the current situation and the future scenario, the lifetime of eight years has been assumed for the vacuum cleaners. However, the European Commission (2013b) stated that it is possible that the life expectancy of the average vacuum cleaner in 2020 would be reduced to five years. The effect of this assumption has been tested through a sensitivity analysis.
- For end of life, the same assumptions have been made for all vacuum cleaners. However, it can be argued that the recyclability can vary from one model to another. To explore the significance of this assumption, a sensitivity analysis considers an extreme situation with all the waste landfilled by 2020.

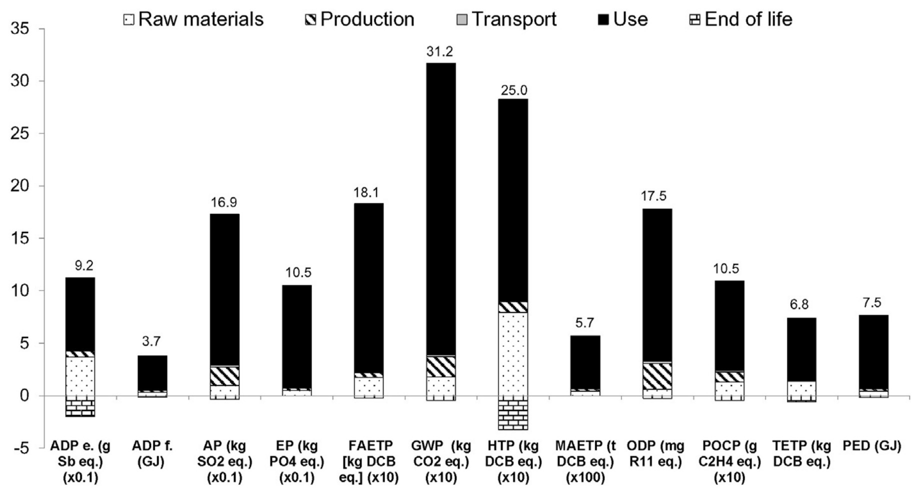


Fig. 4. Life cycle environmental impacts of the vacuum cleaner over the eight-year lifetime. [The values shown on top of each bar represent the total impact after the system credits have been applied and should be multiplied by the factor shown in brackets for some impacts to obtain the original values. Raw materials include the packaging. $ADP_{e.}$: abiotic depletion potential of elements, $ADP_{f.}$: abiotic depletion potential of fossil resources, AP: acidification potential, EP: eutrophication potential, GWP: global warming potential, HTP: human toxicity potential, MAETP: marine aquatic ecotoxicity potential, FAETP: freshwater aquatic ecotoxicity potential, ODP: ozone layer depletion potential, POCP: photochemical oxidants creation potential, TETP: terrestrial ecotoxicity potential, PED: primary energy demand. DCB: dichlorobenzene].

- The EU average electricity mix has been considered in the analysis; however, the electricity profile can vary highly from one country to another. Therefore, a sensitivity analysis has been conducted considering country-specific electricity mixes in 2020 for different countries.

2.3. Environmental impact assessment

GaBi 6.5 software (Thinkstep, 2015) has been used to model the system and the CML 2001 (April 2013 version) mid-point impact assessment method (Guinee et al., 2001) has been applied to calculate the environmental impacts of the vacuum cleaner. The following impacts are considered: abiotic depletion potential of elements ($ADP_{elements}$), abiotic depletion potential of fossil resources (ADP_{fossil}), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), freshwater aquatic ecotoxicity potential (FAETP), ozone depletion potential (ODP), photochemical oxidants creation potential (POCP) and terrestrial ecotoxicity potential (TETP). In addition to the CML impact categories, primary energy demand (PED) has also been calculated.

3. Results and discussion

The results are first discussed for the reference vacuum cleaner, followed by the impacts at the EU28 level.

3.1. Reference vacuum cleaner

The environmental impacts of the reference vacuum cleaner and the contribution of different life cycle stages are shown in Fig. 4 and Table S2 (Supporting information), respectively. For example, over its lifetime the vacuum cleaner will use 7.5 GJ of primary energy and emit 312 kg CO_2 eq. The use stage is the major contributor (>78%) to most impact categories, except for the $ADP_{elements}$ and HTP to which it contributes 62% and 68%, respectively. The impacts are almost entirely due to the consumption of electricity by the vacuum cleaner, partly because of the high energy usage over its lifetime and partly because of the dominance of fossil fuels in the electricity mix (Table S1 in Supporting

Table 3
Comparison of annual environmental impacts of vacuum cleaners in EU28 for the current situation and the future scenario.

Impacts[a]	Total value for the current situation (2013)	Future scenario (2020)				
		Variation due to the implementation of the eco-design regulation	Variation due to implementation of the WEEE directive	Variation due to the decarbonisation of the electricity mix	Variation due to the increase in the number of vacuum cleaners	Total[b]
$ADP_{elements}$ (t Sb eq./year)	30.9	−11.5 (−37.2%)	−0.07 (−0.2%)	10.5 (+34.0%)	2.2 (+7.2%)	32.1 (+3.8%)
ADP_{fossil} (PJ/year)	127.6	−53.8 (−42.2%)	−1.1 (−0.9%)	−6.3 (−4.9%)	9.2 (+7.2%)	75.7 (−40.7%)
AP (kt SO_2 eq./year)	58.1	−23.7 (−40.8%)	−0.20 (−0.3%)	−8.2 (−14.1%)	4.2 (+7.2%)	30.2 (−48.1%)
EP (kt PO_4^{3-} eq./year)	36.8	−16.1(−43.8%)	−0.07 (−0.2%)	−7.4 (−20.1%)	2.7 (+7.2%)	15.9 (−56.7%)
FAETP [Mt DCB eq./year)	6.3	−2.7 (−42.9%)	−0.02 (−0.3%)	−1.2 (−19.0%)	0.5 (+7.2%)	2.8 (−54.6%)
GWP (kt CO_2 eq./year)	10,874	−4626 (−42.5%)	−76 (−0.7%)	−983 (−9.0%)	784 (+7.2%)	6050 (−44.4%)
HTP (Mt DCB eq./year)	8.4	−3.2 (−38.1%)	−0.03 (−0.4%)	−0.7 (−8.3%)	0.6 (+7.2%)	5.1 (−39.6%)
MAETP (Gt DCB eq./year)	19.8	−8.4 (−42.4%)	−0.2 (−1.0%)	−3.7 (−18.7%)	1.4 (+7.2%)	8.9 (−54.9%)
ODP (kg R11 eq./year)	597.8	−236.9 (−39.6%)	−0.3 (−0.1%)	72.8 (+12.2%)	43.1 (+7.2%)	477.0 (−20.2%)
POCP (kt C_2H_4 eq./year)	3.6	−1.4 (−38.9%)	−0.04 (−1.1%)	−0.3 (−8.3%)	0.3 (+7.2%)	2.1 (−40.4%)
TETP (kt DCB eq./year)	235.0	−98.6 (−42.0%)	−0.1 (−0.1%)	0.5 (+0.2%)	17.0 (+7.2%)	153.8 (−34.6%)
PED (PJ/year)	263.7	−115.8 (−43.9%)	−1.1 (−0.4%)	−22.4 (−8.5%)	19.0 (+7.2%)	143.5 (−45.6%)

[a] For impacts nomenclature, see Fig. 4.
[b] The total value for each impact represents the sum of the current impact and all the variations in the impact due to different parameters. The values in brackets represents the percentage increase (+ve) or decrease (−ve) on the 2013 values.

information), particularly coal which is the main contributor to the ADP_{fossil}, AP, GWP, EP, FAETP, HTP, MAETP and POCP (Table S2 in Supporting information).

As can also be seen in Fig. 4, the raw materials used to manufacture the vacuum cleaner are important contributors to the $ADP_{elements}$ (32%), HTP (28%) and TETP (18%). Most of these impacts are associated with the use of copper and stainless steel. The manufacturing process for vacuum cleaners has significant contribution only for the ODP (15%), mainly owing to the emissions of halogen organic compounds (Freon 12) from the solvents used in the moulding of plastic components. The contribution of manufacturing to some other categories, such as the AP, POCP and GWP, is relatively small (11%, 10% and 7%, respectively) and even lower for the rest of the impacts. Transportation has no significant influence in any of the categories considered, with contributions below 1.5% for all indicators. The end-of-life disposal of the vacuum cleaner has an overall positive effect on the impacts because of the recycling credits, particularly for copper and stainless steel which affect the $ADP_{elements}$, HTP and TETP most significantly.

3.2. Current situation and the future scenario

The potential environmental impacts of vacuum cleaners in 2013 and 2020 across the EU28 are compared in Table 3. The results for the future scenario also show the variations related to the implementation of the eco-design and WEEE regulations, the assumed changes in the European electricity mix and the projected increase in the number of units in use.

As can be seen from Table 3, all the impacts would decrease by 2020 under the assumptions made here. The only exception to this is the $ADP_{elements}$ which is expected to increase by around 4%. Even though the implementation of the eco-design regulation will result in a significant reduction of this impact (by 37% compared to the current situation), this is offset by the increase associated with the change in the electricity mix (34%) and the expected rise in the number of vacuum cleaners in 2020 (7%) The expected improvements to the $ADP_{elements}$ related to the WEEE directive are negligible. The increase in the impact associated with the electricity mix change is mainly due to the assumed increase in the number of solar photovoltaic panels which are manufactured using scarce elements, such as tellurium and silver.

As also indicated in Table 3, the other environmental impacts would be reduced by 20%–57% in 2020 as compared to 2013. For example, the GWP is expected to be 44% lower than at present, saving 4824 kt CO_2 eq./year. To put these results in context, based on the data from the EU Joint Research Centre (2014), this reduction in CO_2 eq. is equivalent to the annual GHG emissions of Bahamas (4865 kt CO_2 in 2012) and 2.5 times the emissions of Malta (1921 kt CO_2/year). This is mainly due to the improvements in the energy efficiency related to the implementation of the eco-design regulation (4626 kt CO_2 eq./year) and to a lesser extent due to the decarbonisation of the electricity mix (983 kt CO_2 eq./year). Compared to these reductions, the decrease in the GWP associated with the implementation of the WEEE directive is small (76 kt CO_2 eq.). On the other hand, the expected rise in the number of vacuum cleaners would increase the GWP by 784 kt CO_2 eq./year. Therefore, the implementation of the eco-design regulation and decarbonisation of the EU electricity mix could compensate the annual GHG emissions of a whole country like Bahamas.

Similar to the GWP, the most substantial reduction in the other impacts is due to the improvements in the energy efficiency of vacuum cleaners. Further notable improvements would be achieved through the decrease in the share of coal and increase of renewable electricity in the European electricity mix by 2020, particularly for the AP, EP, FAETP and MAETP. However, as shown in Table S3 in Supporting information, the change in the electricity mix would increase the ODP of electricity generation by 24%. This is due to the higher use of natural gas (related to emissions of halogenated gases used as fire suppressants in gas pipelines). Therefore, the expected reduction for this impact in 2020 is lower than for the others (20%). The reduction in the TETP is also lower (35%) because the impact rise for the 2020 electricity mix associated with the increased share of wind power (related to the chromium emissions in the production of stainless steel) is offset by the lower contribution of lignite and hard coal (less heavy metals emitted during burning) and nuclear energy (decrease of air emissions of arsenic associated with uranium mining tailings). This means that the TETP from electricity remains largely unchanged in 2020 (Table S3 in Supporting information). Therefore, the improvements in this impact category are only affected by the increase in energy efficiency associated with the eco-design regulation.

The following sections discuss in more detail the variation in the impacts associated with the eco-design regulation and the WEEE directive.

3.2.1. Effects of the implementation of the eco-design regulation

As discussed in the introduction, a tendency to increase the power rating of vacuum cleaners has been observed in European countries in recent years. In the absence of the EU eco-design regulation, this trend would likely continue so that by 2020 the average power of vacuum cleaners would be 2337 W (European Commission, 2013b). Consequently, the environmental impacts of vacuum cleaners in the EU28 would be 82%–109% higher by 2020 as compared to the impacts with the implementation of this regulation (Fig. 5). To put this in context, for the example of the GWP, the implementation of this regulation

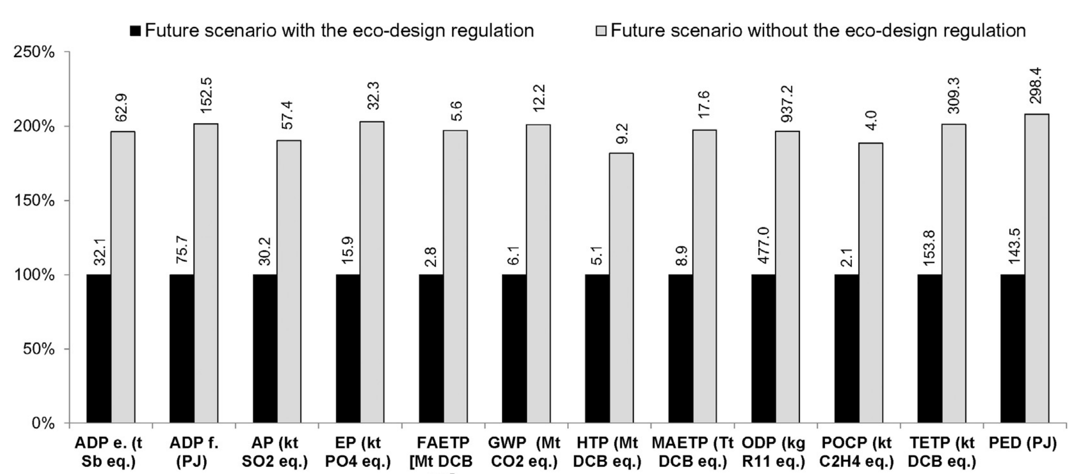


Fig. 5. Comparison of annual environmental impacts of all vacuum cleaners in EU28 in 2020 with and without the implementation of the eco-design regulation (Basis: 229.25 million units. For impacts nomenclature, see Fig. 4).

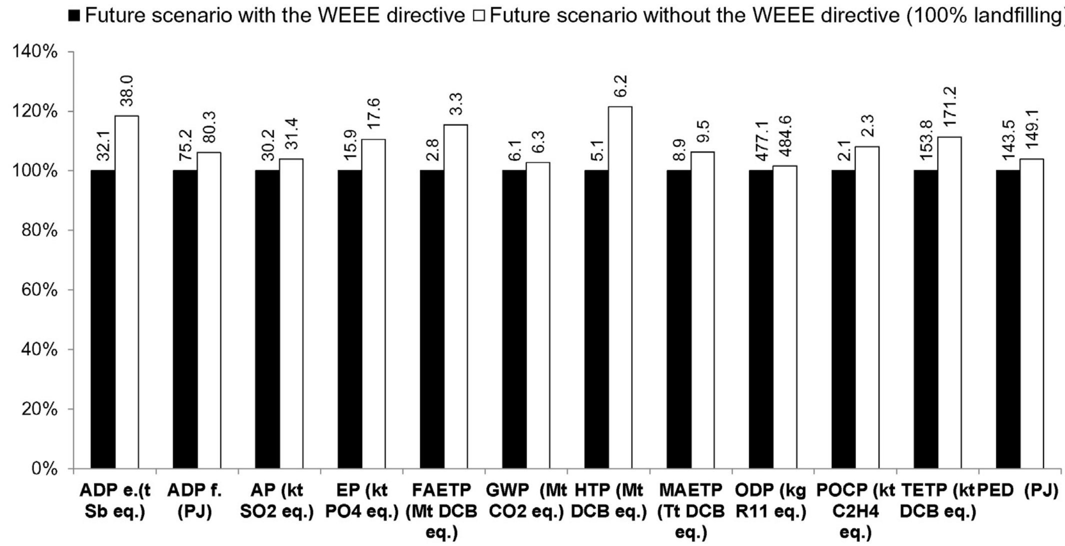


Fig. 6. Comparison of annual environmental impacts of all vacuum cleaners in EU28 in 2020 with and without the implementation of the WEEE directive (Basis: 229.25 million units. For impacts nomenclature, see Fig. 4).

would lead to a reduction in GHG emissions of 6100 kt CO_2 eq./year which is equivalent to the emissions of the whole country of Guyana in 2012 (Joint Research Centre, 2014).

3.2.2. Effects of the implementation of the WEEE directive

As mentioned in Section 3.2, the implementation of the WEEE directive would also reduce the environmental impacts of vacuum cleaners by 2020; however, the reductions are small in comparison to the reductions related to the eco-design regulation. Nevertheless, similar to the discussion on the absence of the eco-design regulation in the previous section, it is important to find out how the impacts would change if there was no WEEE directive. For these purposes, it is assumed that there is no recycling of vacuum cleaners or their incineration to recover energy, with the main body and the accessories being landfilled.

These impacts are compared in Fig. 6 to those with the WEEE directive being implemented for the year 2020. Although this is an extreme scenario, only four of the 12 impacts ($ADP_{elements}$, FAETP, HTP and TETP) would increase by >10% as compared to the expected situation in 2020 with the implementation of the directive. All other impacts would increase by 2%–9%. Although these reductions appear minor, considering the large number of vacuum cleaners expected to be in operation in the EU in 2020 (229.26 million), the overall environmental benefits would still be considerable. For example, the implementation of the WEEE directive across the EU28 countries would save 76 kt CO_2 eq. (relative to 2013) and 220 kt CO_2 eq. (compared to no WEEE directive). This is equivalent to the GHG emissions generated annually by around 67,500 and 195,500 light duty vehicles, respectively, assuming an average CO_2 emission of 90 g/km and a distance of 12,500 km/year (Winkler et al., 2014). Furthermore, possible future trends, such as lower lifetime expectancy, reduced availability of some raw materials or even greater improvements in energy efficiency or the electricity mix, can increase the relative environmental importance of recycling the vacuum cleaners.

3.3. Sensitivity analysis

3.3.1. Country specific electricity mix

The analysis so far has been based on the average EU28 electricity mix. To explore the effect this assumption may have on the impacts, four EU countries with very different electricity mix are considered as part of the sensitivity analysis: i) Poland (mainly coal, 70.5%), ii) France (mainly nuclear, 47.4%), iii) Denmark (mainly renewables,

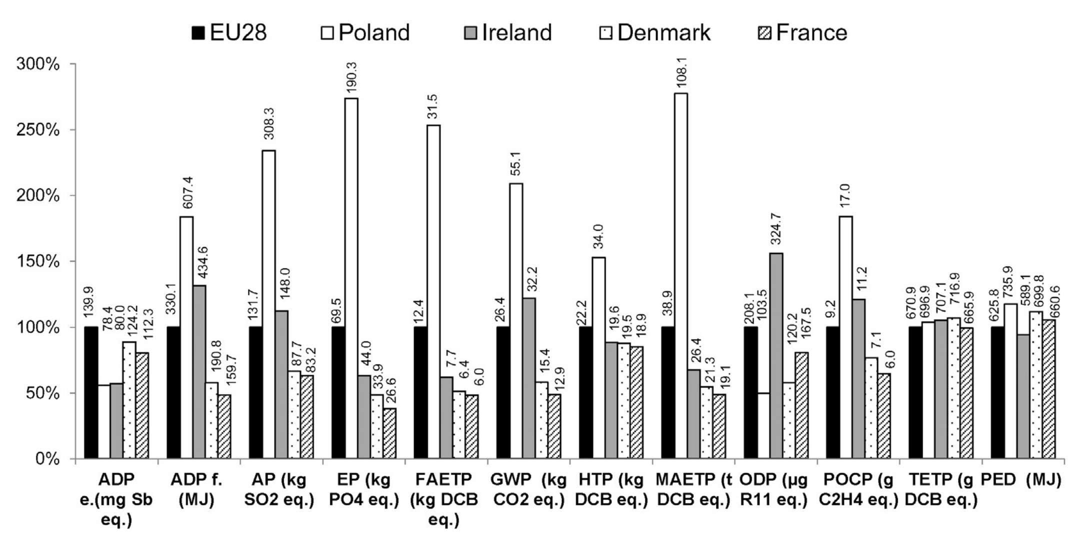


Fig. 7. Comparison of annual environmental impacts of an average vacuum cleaner in 2020 used in different EU countries with the EU28 average [Basis: a 1060 W vacuum cleaner used 50 h/year. For impacts nomenclature, see Fig. 4].

81.5%, of which 53% is wind) and iv) Ireland (mainly natural gas, 37.7%); for details, see Table S1 in Supporting information. As previously, 2020 is taken as the reference year and the annual impacts are estimated considering the use of a vacuum cleaner for 50 h/year. Owing to a lack of data on the average power of vacuum cleaners at national levels, the average power of the vacuum cleaner (1060 W) is assumed. All other assumptions are the same as for the reference vacuum cleaner.

The results in Fig. 7 suggest that in countries where electricity is dominated by coal (as in Poland), 10 out of 12 impacts of the vacuum cleaner are higher compared to the EU28 average. The greatest increase (>110%) is found for the AP, EP, FAETP, GWP, MAETP and POCP. On the other hand, a higher share of natural gas in the electricity mix (like in Ireland), results in six impacts ($ADP_{elements}$, EP, FAETP, HTP, MAETP and PED) being lower relative to the EU28 average; however, the other impacts are higher. Finally, the use of renewable or nuclear-dominated electricity (Denmark and France, respectively) leads to significantly lower impacts for 10 out of the 12 analysed categories. This is due to the reduced use of fossil fuels, with the largest reductions in the ADP_{fossil}, EP, FAETP, GWP and MAETP. This demonstrates that the effect of energy efficiency measures, such as those in the eco-design regulation, can be greater if accompanied by electricity decarbonisation. On the other hand, for countries which already have a low-carbon grid, the environmental benefits of energy efficiency are lower, but nevertheless still significant.

3.3.2. Reduced lifetime expectancy

In the above analyses, an estimated lifetime of eight years has been considered for the vacuum cleaners. However, as mentioned earlier, the life expectancy of an average vacuum cleaner could be reduced to five years by 2020 (European Commission, 2013b) Therefore, the effect of this reduction on the environmental impacts is considered here.

The results suggest that a decrease in the service life of vacuum cleaners would cause a modest increase in impacts, 10%–20% for seven categories and <10% in the other five. As shown in Fig. 8, the highest increase would occur for the HTP, which would rise by 19% and the smallest for the PED (6%). These findings are perhaps not surprising as the impacts are dominated by the use stage. However, as the energy efficiency measures take hold and future electricity mix becomes less carbon intensive, the importance of the lifetime of vacuum cleaners as well as the other life cycle stages may increase. To illustrate the point, we consider the contribution of different life cycle stages to the impacts of vacuum cleaners with the life expectancy of five years.

As can be observed in Table 4, the raw materials and vacuum cleaner production are jointly responsible for over 19% of the impact for each category considered. For the $ADP_{elements}$ and HTP, the combined contribution of these two stages is twice as high (>40%). Similarly, for these two categories, the contribution of waste management related to the improved end-of-life waste management (in line with the WEEE directive) is important, reducing the total impacts by over 20%. This suggests that the possible reduction in the lifespan of vacuum cleaners, along with the increased energy efficiency and future electricity decarbonisation, could increase the relative importance of the raw materials, production and waste management stages. Therefore, even though further energy efficiency improvements will be necessary, optimising the use of raw materials, production processes and disposal of waste should also be considered to help achieve greater environmental improvements in the life cycle of vacuum cleaners (and other devices).

Table 4
Annual environmental impacts by life cycle stage for all EU28 vacuum cleaners in 2020 considering a lifetime of five years.

Impact cat. ind.[a]	Raw materials	Production	Use	End of life	Transport
$ADP_{elements}$ (t Sb eq.)	16.9	2.6	25.7	−9.4	0.1
ADP_{fossil} (PJ)	14.2	9.8	65.1	−7.4	1.1
AP (kt SO_2 eq.)	4.0	8.8	23.0	−1.9	0.8
EP (kt PO_3^{4-} eq.)	2.2	1.2	13.7	0.1	0.2
FAETP (Mt DCB eq.)	0.8	0.2	2.3	−0.1	0.0
GWP (Mt CO_2 eq.)	0.7	1.0	5.1	−0.3	0.1
HTP (Mt DCB eq.)	3.6	0.4	3.5	−1.5	0.0
MAETP (Tt DCB eq.)	1.9	1.1	7.2	−0.3	0.0
ODP (kg R11 eq.)	19.5	123.6	391.3	−11.8	11.5
POCD (kt C_2H_4 eq.)	0.6	0.5	1.6	−0.3	0.1
TETP (kt DCB eq.)	61.5	5.4	129.2	−27.8	0.2
PED (PJ)	16.5	13.5	130.1	−8.9	1.3

[a] For impacts nomenclature, see Fig. 4.

4. Conclusions and recommendations

This paper has presented for the first time a comprehensive study of life cycle environmental impacts of vacuum cleaners and discussed the implications in the EU context. Electricity consumption during the use stage is currently the main contributor to all impact categories in the life cycle of a vacuum cleaner. However, the raw materials (especially copper and stainless steel) and end-of-life disposal can be considered hotspots for the depletion of scarce elements, human toxicity and terrestrial ecotoxicity, and the production stage for the depletion of the ozone layer. These results demonstrate that environmental impact studies of vacuum cleaners and other energy-using products must consider all stages in the life cycle and not just their use, to avoid solving one environmental problem at the expense of others.

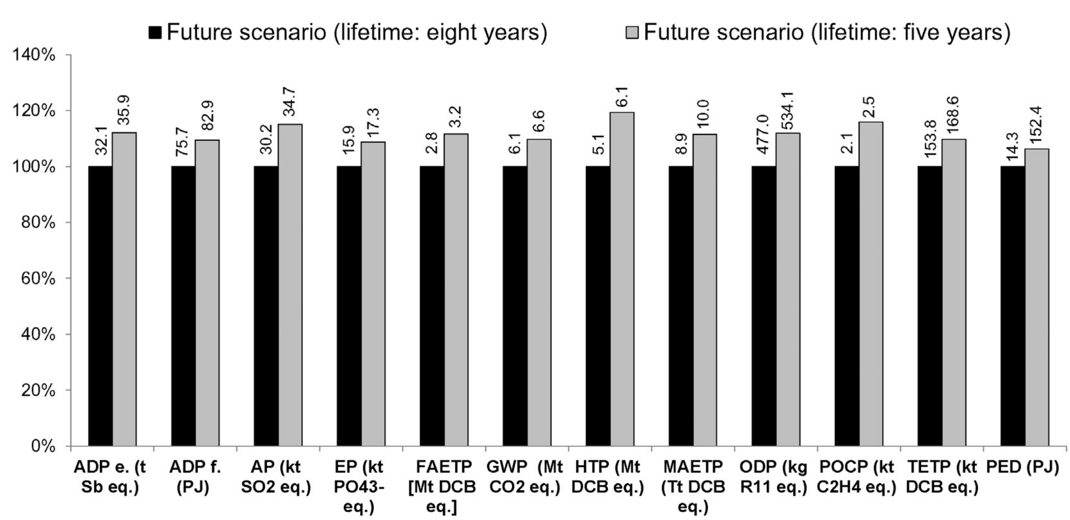


Fig. 8. Comparison of annual environmental impacts of all EU28 vacuum cleaners in 2020 for the lifetimes of eight and five years (Basis: 229.25 million units. Indicators, see Fig. 4).

This study has also considered the impacts of vacuum cleaners at the European level (EU28) taking into account the effects of two EU laws (the eco-design regulation and the WEEE directive) as well as the expected decarbonisation of electricity and the projected increase in the number of units in use. By 2020, the combined effect of these parameters could amount to a 20%–57% reduction in the environmental impacts as compared to the current situation, with the global warming potential being 44% lower than today. The exception to this is depletion of elements, which will increase by around 4% on the present value.

The implementation of the eco-design regulation alone would improve significantly the environmental performance of vacuum cleaners by 2020 compared with current situation, with all the impacts reduced from 37% for the depletion of elements to 44% for eutrophication and primary energy demand. On the other hand, if the regulation was not implemented and business as usual continued, the impacts would be 82%–109% higher by 2020 compared to the impacts with the implementation of the regulation. This would, for example, mean the additional emissions of GHG equivalent to 6100 kt CO_2 eq./year.

Improvements associated with the implementation of the WEEE directive are much smaller (<1%) compared to the current situation than those achievable by the eco-design regulation. However, if the WEEE directive did not exist, then the impacts would be 2%–21% higher. Although this increase may sound small, it is still significant given the number of vacuum cleaners in use; for instance, the global warming would increase by 220 kt CO_2 eq./year.

Electricity decarbonisation would help to reduce the impacts of vacuum cleaners for all of the categories considered, except for the depletion of elements and the ozone layer. The former would increase because of the use of scarce metals for solar photovoltaics and the latter because of a higher share of natural gas in the electricity mix. Related to this, the environmental impacts of vacuum cleaners at a country level depend on the national electricity mix, with those based on renewable and nuclear power having lower impacts than those with fossil fuels. Therefore, policy measures addressing energy efficiency (such as the eco-design regulation) must be accompanied by appropriate actions to reduce the impacts of electricity generation, otherwise their benefits could be limited.

Because of possible future trends, such as shorter lifetime of vacuum cleaners, reduced availability of some raw materials or greater improvements in energy efficiency or electricity generation, in addition to the use stage, it will be important to focus future efforts on understanding the impacts from other parts of the life cycle, including raw materials, manufacture and waste treatment. As the results of this study demonstrate, any improvements in these stages will result in significant environmental benefits, as the number of vacuum cleaners in use in Europe is expected to increase in the future. Further studies of possible improvements in these life cycle stages based on eco-design principles are recommended for future research. Furthermore, reuse and refurbishing of vacuum cleaners could be evaluated to identify opportunities for environmental improvements. Finally, the impacts of other types of vacuum cleaner (e.g. battery operated, robot, industrial, etc.) currently not covered by any specific EU regulation should be considered in future studies to help inform policy development.

Acknowledgments

This work has been funded by the Sustainable Consumption Institute at the University of Manchester and the UK Engineering and Physical Sciences Research Council (EPSRC, Gr. no. EP/F007132/1). The authors gratefully acknowledge this funding. The authors are also grateful to Roy Kershaw at the University of Manchester for his help with the disassembly of the vacuum cleaner.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.03.149.

References

AEA, 2009. Work on Preparatory Studies for Eco-Design Requirements of EuPs (II) (TREN/D3/390-2006). Lot 17 Vacuum CleanersAEA Energy & Environment final report to European Commission, Oxfordshire (United Kingdom) 118 pp.

Andrae, A.S.G., Andersen, O., 2010. Life cycle assessments of consumer electronics—are they consistent? Int. J. Life Cycle Assess. 15 (8), 827–836.

Andrae, A.S.G., Vaija, M.S., 2014. To which degree does sector specific standardization make life cycle assessments comparable?—the case of global warming potential of smartphones. Challenges 5, 409–429.

Ardente, F., Mathieux, F., 2014. Environmental assessment of the durability of energy-using products: Method and application. J. Clean. Prod. 74, 62–73.

Bergsma, G., Sevenster, M., 2013. End-of-life Best Approach for Allocating Recycling Benefits in LCAs of Metal Packaging. CE Delft, Delft (The Netherlands), p. 26 pp.

Biček, A., I. Markič, J. Rihtaršič, J. Rejec and M. Čudina (2014). Vacuum Cleaner Suction Unit Performance and Noise Characterization- an Overview. 6th Congress of Alps-Adria Acoustics Association, 16–17 October 2014, Graz (Austria).

Choi, B.C., Shin, H.S., Lee, S.Y., Hur, T., 2006. Life cycle assessment of a personal computer and its effective recycling rate. Int. J. Life Cycle Assess. 11 (2), 122–128.

DECC, 2015. Chapter 5: Electricity. Digest of UK Energy Statistics. Department of Energy and Climate Change, London 43 pp.

Duan, H., Eugster, M., Hischier, R., Streicher-Porte, M., Li, J., 2009. Life cycle assessment study of a Chinese desktop personal computer. Sci. Total Environ. 407 (5), 1755–1764.

Dyson, 2011. Dyson Position Paper: Eco Design and Energy Labelling Cleaners. Dyson, Wiltshire (United Kingdom) 12 pp.

Ecoinvent Centre, 2010. Ecoinvent v.2.2 Database. Swiss Centre for Life Cycle Inventories, Dübendorf (Switzerland).

ENTSO-E, 2011. Statistical Yearbook 2010. European Network of Transmission System Operators for Electricity, Brussels (Belgium) 68 pp.

ENTSO-E, 2014a. ENTSO-E Yearly Statistics & Adequacy Retrospect 2013. European Network of Transmission System Operators for Electricity, Brussels (Belgium) 68 pp.

ENTSO-E, 2014b. In: 146 pp (Ed.), Scenario Outlook and Adequacy Forecast (SO&AF) 2014–2030 Dataset. European Network of Transmission System Operators for Electricity, Brussels (Belgium).

European Commission, 2010. EUROPE 2020 a strategy for smart, sustainable and inclusive growth. Communication of European Commission (COM (2010) 2020 Final), Brussels (Belgium) 35 pp.

European Commission, 2013a. Commission regulation (EU) No 666/2013 of 8 July 2013 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for vacuum cleaners. Off. J. Eur. Union L 192, 24–34 13.7.2013.

European Commission, 2013b. Impact Assessment Accompanying the Documents: Commission Regulation Implementing Directive 2009/125/EC of the European Parliament and of the Council with Regard to Ecodesign Requirements for Vacuum Cleaners and Commission Delegated Regulation Supplementing Directive 2010/30/EU of the European Parliament and of the Council with Regard to Energy Labelling of Vacuum Cleaners. European Commission staff working document, Brussels (Belgium) 57 pp.

European Commission, 2014. Towards a circular economy: a zero waste programme for Europe. Communication of European Commission (COM (2014) 398 final), Brussels (Belgium) 14 pp.

European Parliament, 2012. Directive 2012/19EU of the European parliament and of the council of 4 July 2012 on waste electrical and electronic equipment (WEEE). Off. J. Eur. Union L 197, 38–71 24.7.2012.

European Parliament and Council of European Union, 2009. Decision No 406/2009/EC of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020. Off. J. Eur. Union L 140, 136–148 5.6.2009.

Eurostat (2015a). Packaging waste statistics. Available at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_waspac&lang=en (Lastaccess: 22-09-2015).

Eurostat (2015b). Number of private households by household composition, number of children and working status within households. Available at: http://ec.europa.eu/eurostat/web/products-datasets/-/lfst_hhnhwhtc (Last access: 22-05-2015).

Feng, C., Ma, X.Q., 2009. The energy consumption and environmental impacts of a colour TV set in China. J. Clean. Prod. 17 (1), 13–25.

Guinee, J.B., Gorrèe, M., Heijungs, R., Huppes, G., Kleijn, G.R., van Oers, R.L., Wegener, L., Sleeswijk, A., Suh, S., de Haes, H.A. Udo, de Bruijn, H., van Duin, H.R., Huijbregts, M.A.J., 2001. Life Cycle Assessment, an Operational Guide to the ISO Standards. Part 2a: Guide. Kluwer Academic Publishers, Dordrecht (the Netherlands) 101 pp.

Hischier, R., Baudin, I., 2010. LCA study of a plasma television device. Int. J. Life Cycle Assess. 15 (5), 428–438.

Huisman, J., Kuehr, M.F., Maurer, C., Ogilvie, S., Poll, J., Delgado, C., Artim, E., Szlezak, J., Stevels, A., 2008. Part 1 Review of Directive 2002/96 on Waste Electrical and Electronic Equipment (WEEE). United Nations University Final Report, Bonn (Germany) 129 pp.

Hur, T., Lee, J., Ryu, J., Kwon, E., 2005. Simplified LCA and matrix methods in identifying the environmental aspects of a product system. J. Environ. Manag. 75 (3), 229–237.

ISO, 2006a. ISO14040:2006. Environmental Management – Life Cycle Assessment – Principles and Framework.ISO Standards, Geneva (Switzerland) 20 pp.

ISO, 2006b. ISO14044:2006 Environmental management - Life Cycle Assessment – Requirements and Guidelines. ISO standards, Geneva (Switzerland) 46 pp.

Jeswani, H.K., Azapagic, A., 2015. Is e-reading environmentally more sustainable than conventional reading? Clean Techn. Environ. Policy 17 (3), 803–809.

Johansson, J.G., Björklund, A.E., 2010. Reducing life cycle environmental impacts of waste electrical and electronic equipment recycling. J. Ind. Ecol. 14 (2), 258–269.

Joint Research Centre (2014). Emission Database for Global Atmospheric Research (EDGAR), version 4.2. Available at: http://edgar.jrc.ec.europa.eu/overview.php?v=CO2ts 1990–2011&sort = des9 (last access: 04/12/2015).

Kemna, R., Azaïs, N., van Elburg, M., van der Voort, M., Li, W., 2011. Part 2: Environmental Policies & Data. Methodology for Ecodesign of Energy-related Products. Final Report Developed From VHK Consulters for European Commission, Brussels (Belgium) 200 pp.

Kiddee, P., Naidu, R., Wong, M.H., 2013. Electronic waste management approaches: an overview. Waste Manag. 33 (5), 1237–1250.

Lenau, T., Bey, N., 2001. Design of environmentally friendly products using indicators. Proc. Inst. Mech. Eng. 215 (Part B), 637–645.

Monfared, B., Furberg, R., Palm, B., 2014. Magnetic vs. vapor-compression household refrigerators: a preliminary comparative life cycle assessment. Int. J. Refrig. 42, 69–76.

Mudgal, S., Tinetti, B., Hoa, E., Audard, G., Robertson, C., Goodman, P., Pitman, S., 2011. Preparatory studies for ecodesign requirements from EuPs (III) (Tender TREN/D3/91–2007). Task 5: Definition of Base-case. Lot 22: Domestic and Commercial Ovens (Electric, Gas, Microwave), Including When Incorporated in Cookers. Final Report From Bio Intelligence Service and ERA Technology to European Commission (DG ENER), Paris (France) 60 pp.

Plastics Europe, 2014. Polyoxymethylene (POM). Eco-profiles and Environmental Product Declarations of the European Plastics Manufacturers. Plastics Europe, Brussels (Belgium) 28 pp.

Plastics Europe, 2015. Plastics – the Facts 2014/2015: an Analysis of European Plastics Production, Demand and Waste Data. Plastics Europe, Brussels (Belgium) 34 pp.

Premalatha, M., Tabassum-Abbasi, Abbasi, Abbasi, T., Abbasi, S.A., 2014. The generation, impact, and management of E-waste: state of the art. Crit. Rev. Environ. Sci. Technol. 44 (14), 1577–1678.

Robinson, B.H., 2009. E-waste: an assessment of global production and environmental impacts. Sci. Total Environ. 408 (2), 183–191.

Schmidt, J.H., 2012. Plastberegner.dk-LCA Tool for Plastics Converters in Denmark. Documentation of the Tool and Database. 2.-0 LCA Consultants, Aalborg (Denmark) 126 pp.

Sea distance, 2016. Distance from Shanghai port to Rotterdam port. Available at: http://www.sea-distances.org (last access: 22/02/2016).

Song, Q., Li, J., 2014. A systematic review of the human body burden of e-waste exposure in China. Environ. Int. 68, 82–93.

Song, Q., Li, J., 2015. Greenhouse gas emissions from the usage of typical e-products by households: a case study of China. Clim. Chang. 132, 615–629.

Teehan, P., Kandlikar, M., 2012. Sources of variation in life cycle assessments of desktop computers. J. Ind. Ecol. 16 (1), 182–194.

Thinkstep, 2015. GaBi 6.5 database. Thinkstep, Leinfelden-Echterdingen (Germany).

Via Michellin, 2016. Maps and route planner. Available at: http://www.viamichelin.co.uk/ (last access: 22/2/2016).

Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., Boni, H., 2005. Global perspectives on e-waste. Environ. Impact Assess. Rev. 25 (5), 436–458.

Winkler, S.L., Wallington, T.J., Maas, H., Hass, H., 2014. Light-duty vehicle CO_2 targets consistent with 450 ppm CO_2 stabilization. Environ. Sci. Technol. 48 (11), 6453–6460.

World Ship Council (2013). Top 50 world containers ports. Available at: http://www.worldshipping.org/about-the-industry/global-trade/top-50-world-container-ports (last access: 04/12/2015).

Zhou, X., Schoenung, J.M., 2007. An integrated impact assessment and weighting methodology: evaluation of the environmental consequences of computer display technology substitution. J. Environ. Manag. 83 (1), 1–2.