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DOI:
10.1016/j.scitotenv.2017.11.064

Document Version
Accepted author manuscript

Citation for published version (APA):
Gallego-Schmid, A., Mendoza, J. M. F., & Azapagic, A. (2018). Environmental assessment of microwaves and the effect of European energy efficiency and waste management legislation. *Science of the Total Environment*, *618*, 487-499. https://doi.org/10.1016/j.scitotenv.2017.11.064

Published in:
Science of the Total Environment

Accepted for publication in Science of The Total Environment 618: 487-499.
doi: 10.1016/j.scitotenv.2017.11.064

Environmental assessment of microwaves and the effect of European energy efficiency and waste management legislation

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Abstract

More than 130 million microwaves are affected by European Union (EU) legislation which is aimed at reducing the consumption of electricity in the standby mode ('Standby Regulation') and at more sustainable management of end-of-life electrical and electronic waste ('WEEE Directive'). While legislation focuses on these two life cycle stages, there is little information on the environmental impacts of the entire life cycle of microwaves. To address this gap, this paper presents a comprehensive life cycle assessment of microwaves and assesses the environmental implications of the Standby Regulation and the WEEE Directive at the EU level. The impacts are first considered at the level of individual appliances and then at the EU level, with the aim of evaluating the potential environmental implications of the full implementation of the above two EU regulations by 2020. The effects of the electricity decarbonisation and the expected increase in the number of microwaves in use have also been considered. The results suggest that implementation of the EU regulation by 2020 will reduce the environmental impacts considered by 4%-9% compared to the current situation. The majority of these reductions is due to the Standby Regulation, with the contribution of the WEEE Directive being small (~0.3%). However, the expected decarbonisation of electricity will result in much higher reductions (6%-24%) for most impact categories. The results also show that materials used to manufacture the microwaves, the manufacturing process and end-of-life disposal are environmental hot-spots for several impacts, including depletion of abiotic elements. Therefore, efforts to reduce the environmental impacts of future electricity mix should be combined with the development of specific eco-design regulations for microwaves that stipulate optimisation of resource consumption. Possible future trends, such as shorter lifetimes and limited availability of some resources, make the development of such product regulations more critical.

Keywords: climate change; circular economy; life cycle assessment (LCA); resource consumption; standby regulation; waste of electrical and electronic equipment (WEEE)

1. Introduction

Rapid technological developments and falling prices are driving the purchase of electrical and electronic (EE) appliances in Europe (EEA 2014). Consumers also tend to buy new EE appliances before the existing ones reach the end of their useful life as electronic goods have become fashionable and 'status' items (Mansfield 2013). As a result, discarded EE goods are one of the fastest growing waste streams worldwide (EEA 2014). A further issue associated with their growing consumption is the increase of household electricity consumption in most EU countries over the last decade, despite many appliances being more energy efficient (Eurostat, 2016).

EE goods generate environmental impacts in all stages of their life cycle (Andrae and Andersen 2010). This has been demonstrated by many authors who have analysed life cycle impacts of different devices using life cycle assessment (LCA) as a tool. Some examples include LCA studies of plasma TVs carried out by Feng and Ma (2009), Hischier (2015) and Hischier and Baudin (2010). Life cycle impacts of computers have been evaluated by Choi et al. (2006), Duan et al. (2009) and Jönbrink (2007). Examples of studies of electrical devices include an LCA of refrigerators (Monfared et al. 2014), dishwashers (Johansson and Björklund 2010), washing machines (Presutto et al. 2007b) and vacuum cleaners (Gallego-Schmid et al. 2016).

However, for microwaves, only screening LCA studies have been carried out so far, with most being based on generic or outdated data and assumptions. For instance, Jungbluth (1997) assessed the life cycle environmental performance of different cooking devices, including microwaves, in Switzerland and Germany. The study published generic aggregated inventory data for microwaves, but no specific results were given for the microwaves as the analysis focused on the comparison of electric, gas and wood ovens. Moreover, the inventory data are now 20 years old and can be considered outdated. Another study (Devuono et al. 2000) compared environmental performance of cooktops, ovens and microwaves, but focused only on CO_2, SO_2 and NO_x emissions from electricity consumption in the use stage. In 2002, the National Environmental Technology Information Centre of Korea published the product category rules for microwaves with the aim of developing Environmental Product Declarations (EPDs) from a life-cycle perspective (APEC-VC Korea 2002). A set of general rules were established to make EPDs comparable, but no specific inventory data or guidelines for data collection were included, except for the definition of a standard scenario to calculate the environmental impacts of the use stage. Finally, the Bio Intelligence Service in association with ERA Technology (Mudgal et al. 2011a) performed a technical, environmental and economic analysis of domestic and commercial ovens, as a preparatory study for the development of EU eco-design and energy labelling regulations, both of which aim to improve energy efficiency of energy-using products. In their study, Mudgal et al. (2011a) carried out screening LCA studies for 10 types of electrical oven, including microwaves. Although this work represents the most complete LCA study of microwaves so far, it relied on aggregated inventory data and general assumptions on the consumption of materials and product manufacture. Furthermore, only five environmental impacts were considered (eutrophication, acidification, global warming, ozone layer depletion and primary energy demand), in addition to some air emissions and heavy metals, which were estimated at the inventory level only. The authors concluded that use of microwaves was the only environmentally relevant life cycle stage, suggesting that minimising power consumption in the standby mode was the only cost effective alternative to improving their energy efficiency, as they are a mature product with limited room for additional improvements (Mudgal et al. 2011a). Based on these conclusions, and given that microwaves were already included in the EU regulation (No. 1275/2008) to reduce power consumption in the standby mode (European Commission 2008), they were excluded from the eco-design and energy labelling regulations (Nos. 66/2014 and 65/2014, respectively) for domestic ovens, hobs and range hoods (European Commission 2014a,b)[1].

However, some other authors have argued that it is likely that the importance of the use stage for the environmental impacts has been overestimated in the European eco-design regulations for some devices, such as televisions, monitors and computers (WRAP 2010; van Rossem and Dalhammar 2010; Huulgaard et al. 2013). As a result, this has obscured the relative importance of other life cycle stages, particularly the production process and the materials used for the manufacture of electrical and electronic devices. To address this issue, WRAP (2010) specifically recommended that life cycle inventory (LCI) for microwaves should be improved for these two life cycle stages. According to the authors, the available LCI data were limited, incomplete or insufficient, preventing a reliable characterisation of the environmental footprint of these appliances.

The raw materials extraction and processing stages have been gaining importance in recent years in terms of their contribution to the environmental impacts of microwaves. This is due

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[1] Microwave ovens are only included when associated with an electric or gas domestic oven (i.e. appliances which have ‘microwave heating’ as a primary cooking function are not included).

to their lower life expectancy, which decreased from 10-15 years in the late 90s to 6.5-8 years nowadays (Dindarian and Gibson 2011; Huisman et al. 2008; Mudgal et al. 2011a). The main reasons for this trend are faster product innovation cycles and the recent EU 'Standby Regulation' to reduce standby electricity consumption in the use stage (European Commission 2008). Given that microwaves account for the largest percentage of sales of all type of ovens in the EU, with a stock of 125 million units in 2007 and a predicted stock of nearly 135 million units by 2020 (Mudgal et al. 2011a), it is increasingly important to start addressing their impact on resource use and end-of-life waste.

The latter is increasing rapidly in many parts of the world. In the EU, 184,000 tonnes of waste electrical and electronic equipment (WEEE) were generated in 2005 from microwave ovens (Huisman et al. 2008) with more than 195,000 tonnes (16 million units) expected to be sent for disposal in 2025 (Mudgal et al. 2011a). To cope with the problem of the growing EE waste, the WEEE Directive provides the European regulatory framework to prevent, re-use, recycle and/or recover this type of waste (European Parliament 2012). It also aims to improve the environmental performance of operators in the supply chain of EE equipment, including producers, distributors and consumers and, in particular, those collecting and treating WEEE. Thus, any achievements in waste prevention and minimisation would contribute directly to improving resource efficiency. The latter underpins the *Europe 2020* strategy, which aims to contribute to Europe's smart, sustainable and inclusive economy (European Commission 2010).

However, so far, there has been no comprehensive study of environmental impacts of microwaves over their whole life cycle and hence their environmental impacts beyond the use stage remain largely unknown. Similarly, there is a lack of knowledge about the effects on the impacts of the EU regulation related to reducing energy use in the standby mode and end-of-life waste. To address these gaps, the main goals of this study are:

- to estimate the environmental impacts of the whole life cycle of a microwave, identify life cycle stages that contribute most to the impacts ('hot-spots') and suggest possible improvement options; and
- to assess the implications at the EU level of the implementation of the Standby Regulation (European Commission 2008a) and the WEEE Directive (European Parliament 2012) and provide guidance on future research and policy making.

To our knowledge, this is the first study of its kind internationally.

2. **Methods**

The environmental impacts of microwaves have been evaluated through LCA, following the guidelines specified in the ISO 14040/44 standards (2006a,b). In compliance with these standards, the study followed the four LCA phases: i) goal and scope definition; ii) inventory analysis; iii) impact assessment and iv) interpretation of the results. These stages are described in the next sections.

2.1. Goal and scope of the study

In accordance with the goals of the study defined in the introduction (and hence not repeated here), two functional units are considered, one at the product level and another at the EU level:

i) Product level: 'use of a microwave for 1200 use cycles per year consuming 0.056 kWh per cycle over its lifetime of eight years'. This definition corresponds to the EU market specifications provided by Mudgal et al. (2011a) and it has been used to calculate the environmental impacts presented in section 3.1.
ii) The EU level: 'use of all microwaves in the EU28 over one year'. This functional unit is used to assess the implications of the Standby and the WEEE regulations at the EU level, with the results discussed in sections 3.2 and 3.3. The impacts for this functional unit have been estimated by dividing the impacts for the first functional unit by 8 (as the analysis is over one year rather than over the lifetime of the microwave) and multiplying by the total microwave stock in use in the EU28.

For both functional units, a reference microwave representative of the EU market has been used as described below.

Microwaves can be broadly classified into three categories: conventional, with grill and combined ovens (with conventional and microwave cooking). The European market shows a trend towards the purchase of low-cost conventional microwaves, with a power rating of 1150 W, capacity of around 18 L, with most being produced in South-East Asia (Mudgal et al. 2011a). Therefore, in congruence with the market trends, the focus in this study is on a conventional microwave. The specific model selected for consideration has a rating of 1150 W, capacity of 17 L and is produced in China.

The system boundaries of the study are from ‘cradle to grave’ (Fig. 1), comprising the following stages and specific activities considered in the study**:**

- Production of materials:
    - metals: galvanized steel, aluminium, brass, copper, ferrite, tin, lead, gold, nickel, silver, zinc, and palladium;
    - plastics: acrylonitrile butadiene styrene (ABS), polyethylene terephthalate (PBT), polyvinyl chloride (PVC), polypropylene (PP), glass fibre reinforced nylon, polystyrene (PS) and polyoxymethylene (POM);
    - tempered glass;
    - ceramics; and
    - cardboard (for packaging).
- Manufacturing of microwaves: metal cold impact extrusion and plastic moulding (in order to obtain the desire shape), production of electronic components (power cord, plug, magnetron, capacitor, transformer, wire cables, lamp and printed control board (PCB)), steel powder painting and curing, product assembly and packaging.
- Use of microwaves: consumption of electricity.
- End-of-life waste management: disposal of post-consumer wastes.
- Distribution: transport of microwave materials and packaging to the manufacturing facility, microwave to retailer and end-of-life waste to the waste management plant. Transport of consumers to purchase the appliance is excluded to avoid the uncertainty associated with allocation of impacts between the microwave and other items that may be purchased at the same time. This also is congruent with the PAS 2050 standard (BSI, 2011) and other recent LCA studies (e.g. Amienyo et al. 2014).

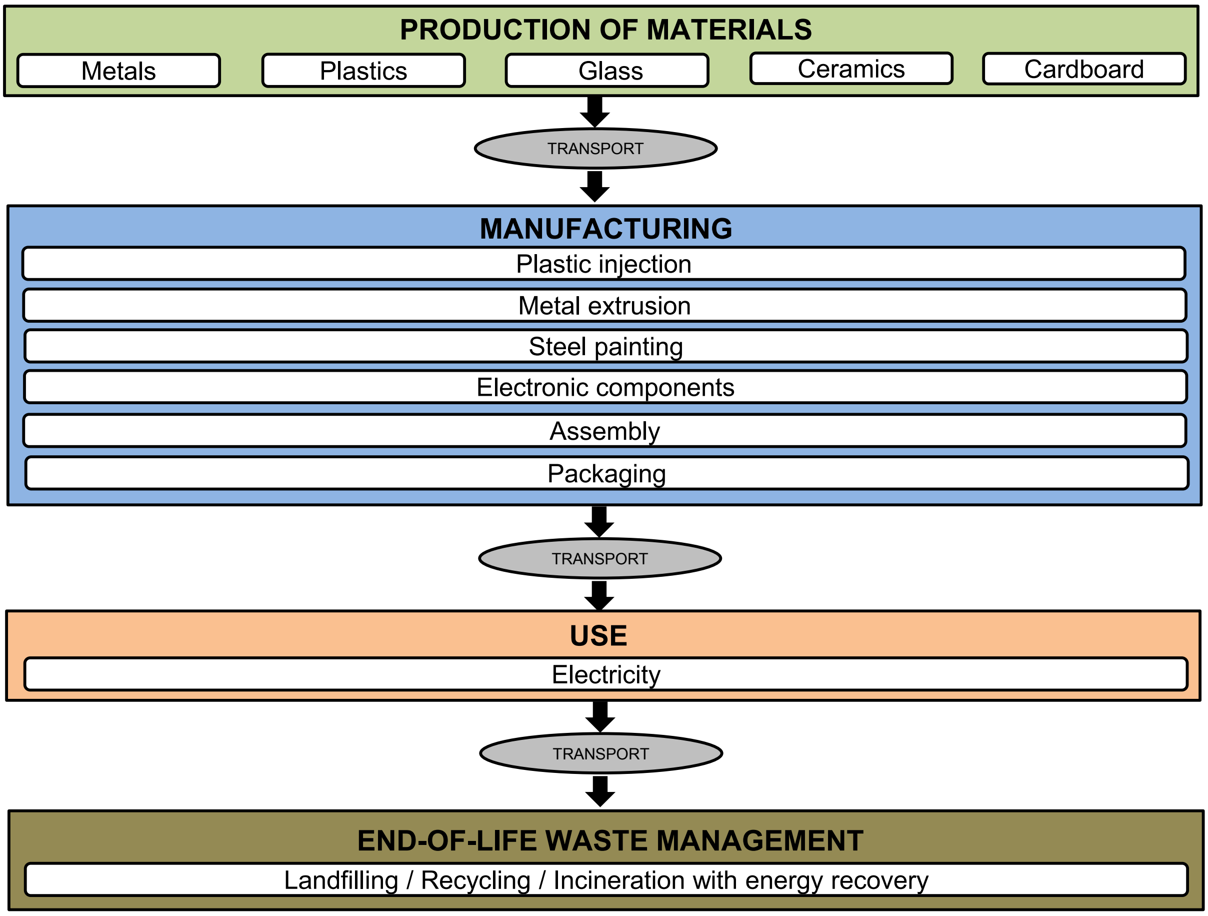

Fig. 1. System boundaries considered in the study

2.2. Life cycle inventory

Primary data, including the amount and type of microwave materials and packaging, as well as a detailed description of the manufacturing process, have been obtained from a main microwave supplier. The data on the type and amount of materials used to produce the microwave have been obtained by dismantling the microwave (see Fig. 2). Ecoinvent v2.2 database (Ecoinvent Centre 2010) has been used for the background LCI data for production of materials and packaging, energy generation, transport and waste management. Any data gaps in Ecoinvent have been filled using open literature sources and the GaBi database (Thinkstep 2015). The inventory data are detailed in Table 1 and discussed in the next sections.

2.2.1. Production of materials and microwaves

The material composition of the microwave (Table 1) has been determined by weighing the components of the microwave shown in Fig. 2. The metallic components (8.6 kg) are made of galvanised steel (casing, transformer, magnetron and screws), copper (plug, power cord, wire cables, magnetron, transformer, capacitor), brass (plug), aluminium (magnetron, transformer, capacitor), ferrite (magnets in magnetron) and small amounts of tin, lead, gold, nickel, silver, zinc and platinum (as part of the PCB). The following components are made of plastics (0.8 kg): door and control frame (ABS), control mechanism (PBT), power cord and wires (PVC), door frame and fan (PP), printed circuit board (nylon reinforced with glass fibre), turntable moving system (PS) and door locker (POM). Electrical ceramics (0.07 kg) are used in the magnetron and tempered glass (1.1 kg), mainly in the door and turntable as well as in the lamp. The background data for these components are from Ecoinvent, with the exception of POM, for which the data are from Plastics Europe (2014) as they are not available in Ecoinvent. To account for the manufacture and assembly of the microwave in China, the Ecoinvent data for Chinese electricity have been used for all production processes. Likewise, specific data for manufacturing of materials in China have been used where available; otherwise, worldwide data have been used. Plastic parts are assumed to be produced by injection moulding. Steel and aluminium cold-impact extrusion are considered for shaping these metals and powder painting is used for colouring the casing. Due to a lack of specific data for copper shaping, Ecoinvent data for generic metal shaping have been assumed instead.

The primary packaging of the microwave consists of a folding box, two interior protective cardboards (turntable and main body), four polystyrene foam trays to protect the corners and one polyethylene bag to protect the whole device (Fig. 3). The production of the box has been modelled using inventory data for the folding board and offset printing. Corrugated board data have been assumed for the cardboard. The board protecting the turntable is a double-wall cardboard with mixed fibre and the board protecting the main body is a single-wall cardboard with recycled fibre. Expandable polystyrene has been used to model the polystyrene foam and LDPE film for the plastic bags. The background LCI data for packaging are from the Ecoinvent database.

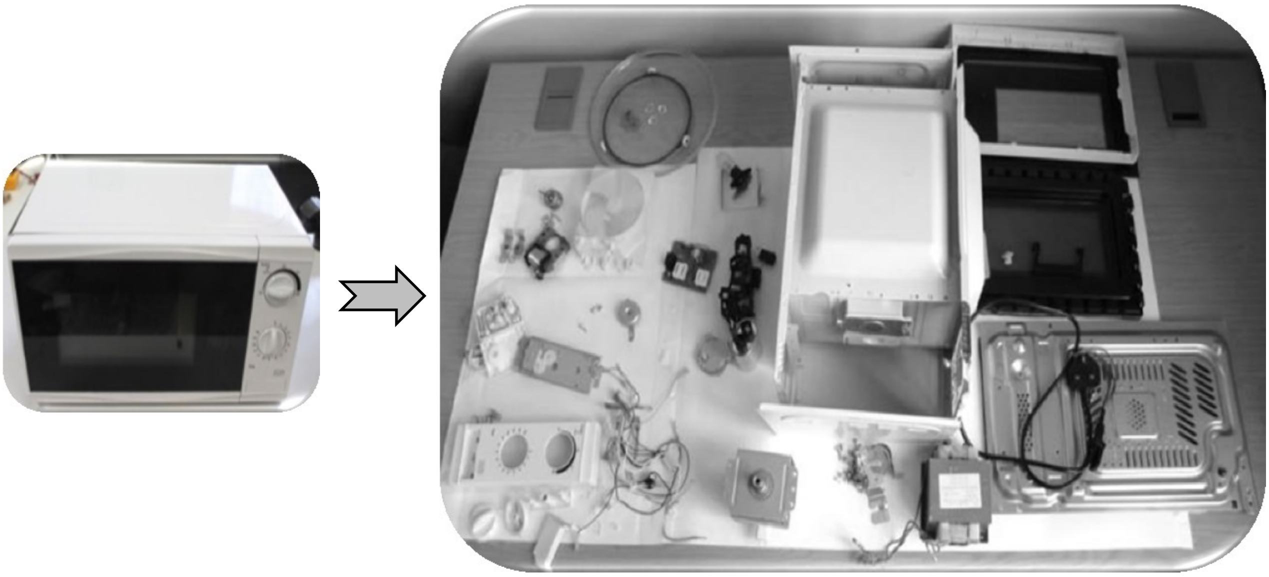

Fig. 2. The microwave and its component parts

Fig. 3. Primary packaging used for the microwave

Table 1. Life cycle inventory data for the reference microwave[a]

Life cycle stages			
Production of materials		**Manufacturing of microwaves**	
Galvanised steel	7040 g	Plastics injection moulding (electricity)	4.2 MJ
Copper	645 g	Plastics injection moulding (heat)	3.5 MJ
Aluminium	618 g	Metal extrusion (electricity)	11.1 MJ
Ferrite	280 g	Metal extrusion (heat)	5.3 MJ
Brass	20 g	Steel powder painting (electricity)	6.3 MJ
Other metals[b]	4.2 g	Steel powder painting (heat)	46.7 MJ
Acrylonitrile butadiene styrene	241 g	Production electronic components (electricity)	41.1 MJ
Polyethylene terephthalate	167 g	Production electronic components (heat)	7.7 MJ
Polyvinyl chloride	162 g	Assembly and packaging (electricity)	36.3 MJ
Polypropylene	141 g	Assembly and packaging (water)	20.2 L
Nylon	40 g	**Distribution**	
Polystyrene	24 g	Materials: transport to factory	0.5 t·km
Polyoxymethylene	11 g	Packaging: transport to manufacturing plant	0.1 t·km
Glass	1139 g	Microwave: factory to Shanghai port	1.8 t·km
Ceramics	67 g	Microwave: Shanghai port to Rotterdam port	227.6 t·km
Packaging		Microwave: Rotterdam port to Munich	9.7 t·km
Folding box	665 g	Microwave: distribution centre Munich-retailer	1.8 t·km
Protective carton board (single wall)	157 g	End of life: transport to waste treatment facility	1.1 t·km
Protective carton board (double wall)	75 g	**Use**	
Polystyrene foam trays	165 g	Electricity	573 kWh
Polyethylene bag	12 g	**End-of- life waste treatment**	
		Recycling (metals)	8177 g
		Recycling (plastics)	204 g
		Recycling (paper and plastic packaging)	753 g
		Incineration with energy recovery (plastics)	283 g
		Incineration with energy recovery (paper and plastic packaging)	63 g
		Landfilling (metals)	430 g
		Landfilling (plastics)	299 g
		Landfilling (paper and plastic packaging)	258 g
		Landfilling (glass)	1139 g
		Landfilling (ceramics)	67 g

[a] All life cycle inventory data are from Ecoinvent 2.2 (Ecoinvent Centre 2010), except for the data for POM (Plastics Europe (2014), for light bulb (Elijošiutė et al. 2012), for metal content in printed control board (Park and Fray 2009), for incineration with energy recovery (Thinkstep 2015) and for plastic recycling (Schmidt 2012)

[b] Tin (1.8 g), lead (1.2 g), gold (0.015 g), nickel (0.6 g), silver (0.06 g), zinc (0.6 g) and palladium (0.006 g).

To fill data gaps, the following assumptions have been made:

- No specific data were found for PBT production so that data for polyethylene terephthalate have been used instead.
- For the power cord and plug, Ecoinvent data computer cables have been modified as follows. The power cord H05VVH2-F 2 x 0.75 mm^2 has been assumed but, based on own measurements, the amount of copper has been reduced from 19 g/m to 14 g/m. The data for the plug have also been adapted using the actual mass of materials used (22 g of PVC, 20 g of brass and 3 g of copper).
- Data for the light bulb have been obtained from Elijošiutė et al. (2012).
- For the magnetron, only raw materials extraction and metal-shaping processes have been considered due to a lack of data.
- Data for the metal content in PCB have been obtained from Park and Fray (2009).
- Data for electricity and water consumption during microwave assembly and packing have been sourced from Mudgal et al. (2011a).
- Data for the waste generated in the manufacturing process were not available so the default values from Ecoinvent have been used instead.

2.2.2. *Use of microwaves*

Based on the functional unit defined in 2.1, using the microwave would consume 537.6 kWh of electricity over its lifetime of eight years (1200 cycles/yr at 0.056 kWh/cycle). A similar average value (563 kWh) was used by APEC-VC Korea (2002) in their standard scenario to characterise the use stage of a conventional microwave. This excludes consumption of electricity in the standby mode. For the latter, the EU Standby Regulation establishes that the maximum standby power rating for microwaves without a digital display, such as the one considered here, should not exceed 0.5 W for units produced after 2013 (Table 2). Based on this and assuming that the appliance is plugged in over the entire lifetime, the electricity consumption in the standby mode would equal 35 kWh. Therefore, a conventional microwave would consume in total 573 kWh during its lifespan. The ENTSO-E (2014a) data have been used for the electricity mix in the EU28 (Table A1 in the Supporting Information). The year 2013 is considered as the base year.

Table 2. Maximum power rating of microwaves in the standby mode depending on the year of manufacture (European Commission 2008)

Type of microwave	2010-2012	2013 onwards
Without digital display	1 W	0.5 W
With digital display	2 W	1 W

2.2.3. *End of life waste management*

The following outlines the assumptions for the end–of-life management of the microwave:

- All metals are assumed to be recycled at a rate of 95% at the end of microwave's lifetime (Kemna et al. 2011; Mudgal et al. 2011a; Xue et al. 2015). Systems expansion has been applied to credit the system for the recycling by subtracting the impacts of the displaced virgin metals and adding the impacts from the recycling process. Congruent with the 'net scrap' method (Bergsma and Sevenster 2013), the system has been credited only for the amount of recycled materials that exceeds the recycled content in the original material. For instance, copper has 56% and 44% of virgin and recycled material, respectively, so that the system has been credited for recycling 51% of the metal (95%–44%). The same method has been used for the other metals. Due to a lack of information on the recycled content in the original materials used to manufacture the microwaves, the recycled content at the global scale has been considered for the different metals as specified in Ecoinvent.
- The waste management data for the plastic materials (PVC, PP, ABS, POM and HDPE) are based on the 2012 data for disposal of plastics in Europe, with 38% landfilled, 36% incinerated with energy recovery and 26% recycled (Plastics Europe 2015). The same approach described above for the metals has been used to credited the system for the recycled plastics. Data from Schmidt (2012) have been used for recycling, assuming that 1.12 kg of recycled plastic is needed to substitute 1 kg of virgin plastic, but adapted for the EU28 electricity mix in 2013 (ENTSO-E 2014a). This electricity mix has also been used to credit the system for the recovered electricity from the incineration of plastic waste. The incineration process has been modelled using the GaBi database (which provides data for integrated electricity and heat recovery, as opposed to Ecoinvent where no energy recovery is considered, with the impacts fully allocated to the waste disposal function). Ecoinvent data have been used for landfilling. Polystyrene foam trays and polyethylene bag have been assumed to be landfilled.
- The type of glass used in the door and turntable is flat glass. The flat glass industry, unlike the container glass sector, uses only internal flat glass cullet generated during the production process (to avoid defects) and therefore external cullet (pre- and post-consumer) is not normally consumed (Neagu-Cogălniceanu and Neagu-Cogălniceanu 2014). Thus, it has been assumed that flat glass is landfilled, which is also in agreement with the current situation described by the association for Europe's manufacturers of flat glass (Glass for Europe 2013).
- For ceramic components, landfilling of inert material has been considered.

- For cardboard packaging, 2012 packaging disposal data for the EU28 have been assumed (Eurostat 2014): 84% recycled, 9% landfilled and 7% incinerated with energy recovery. Given that the cardboard is produced mainly from recycled material, no environmental credit for the avoided material has been considered in this case.

The WEEE Directive established that the rate of recovery of waste microwaves should be 80% and at least 75% of the weight per appliance should be recycled (European Parliament 2012). Based on the assumptions given above on the recycling rates of different materials and their respective weights in the microwave, 82% of the weight of the microwave is recovered at the end of life, of which 79% is recycled and 3% incinerated with energy recovery, in compliance with the Directive.

2.2.4. Transport

The transport data are summarised in Table 1. If not specified in the LCA databases, the microwave materials and packaging are assumed to be transported to a distance of 150 km from the processing plant to the product manufacturing facility by a 16-32 t Euro 3 truck. Production of components from individual microwave materials and the assembly take place at the same location so no transport of the components is considered. A distance of 19,500 km has been estimated for shipping the microwave by a transoceanic tanker from China (Shanghai) to Europe (Rotterdam). The product is then transported by 16-32 t Euro 5 truck for 830 km to a distribution centre in Munich (geographically, the central point in the EU). A distance of 150 km is assumed for road transport (16-32 t Euro 3 truck) from the manufacturing facility to the port in Shanghai and from the distribution centre to the retailer (16-32 t Euro 5 truck). End-of-life waste destined for landfilling is transported by a 16-32 t Euro 5 truck for 50 km and 100 km to incineration and recycling facilities. Life cycle inventory data for transport have been sourced from the Ecoinvent database.

2.2.5. Data and assumptions at the EU level

This section provides a summary of the data and assumptions used to assess implications of the implementation of the Standby Regulation (European Commission 2008) and the WEEE Directive (European Commission 2012). First, the current situation is considered, taking the year 2013 as a baseline, followed by a future scenario in 2020, representing the year when both regulations are fully implemented. In both cases, the LCI of the reference microwave has been considered as it is representative of the EU28 market (see section 2.1.), with slight differences in the standby and end-of-life considerations as discussed below. The impacts have been estimated based on the total number of microwaves used over one year in the EU28 countries.

2.2.5.1. Current situation

The key parameters for the current situation, based on the year 2013, have been estimated as follows:

- Average electricity consumption in the standby mode: Mudgal et al. (2011a) estimated an average value of 2.2 Wh for the standby consumption of a microwave in 2010 at the European level. The maximum power rating set by the Standby Regulation for new microwaves with a digital display sold in the period 2010-2012 is 2 W (Table 2). In the absence of data on the number of units with and without a digital display, a conservative approach has been taken assuming that all the microwaves have a digital display. Therefore, taking the value estimated by Mudgal et al. and the maximum value prescribed by the Standby Regulation, the average consumption of electricity in the standby mode over an hour assumed here for the base year is equal to 2.1 Wh. Microwaves have been considered to be in the standby mode for 24 hours every day over the year (8760 h/yr). Therefore, each microwave consumed, on average, 18.4 kWh/yr in standby in the base year.

- Electricity mix: The baseline electricity mix in 2013 in the EU28 countries has been considered, as described in section 2.2.2.
- Number of microwaves in use: 131.34 million units (Mudgal et al. 2011a) were available for use in the EU28 in 2013 (Table A2 in the Supporting Information).
- Waste disposal: waste scenarios described in section 2.2.3 have been considered.

2.2.5.2. Future scenario

The following has been assumed for the 2020 scenario:

- Average standby electricity consumption: The maximum power rating in the standby mode set by the Standby Regulation for new devices launched after January 2013 is 1 W (Table 2). Following the same conservative approach as for the current situation, it has been assumed that all the microwaves sold between 2013-2020 have a digital display; therefore, a power rating of 1 W in the standby mode. Considering the average value for the standby electricity consumption of 2.1 Wh for the 2013 stock and the rate of substitution of microwaves between 2013-2020 (see Table A2 in the Supporting Information), the average standby consumption over one hour in 2020 is equivalent to 1.06 Wh. Therefore, considering that microwaves are in the standby mode for 24 hours every day over the year (8760 h/yr), each microwave will consume on average 9.3 kWh/yr in the standby mode.
- Use stage: As the energy efficiency of microwaves is not likely to improve in the foreseeable future (Mudgal et al. 2011a), the use stage data defined in section 2.2.2 have been considered for the year 2020. Also, the most feasible scenario predicted by ENTSO-E (2014b) for EU28 electricity generation in 2020 has been considered for the electricity mix (Table A1 in the Supporting Information).
- Number of microwaves in use: Based on projections by Mudgal et al. (2011a), 134.66 million microwaves will be in use by 2020 in the EU28 countries (Table A2 in the Supporting Information).
- Waste disposal: If the WEEE Directive is fully implemented by 2020, end-of-life recovery rate of appliances like microwaves should be 85% and at least 80% of the total number of microwaves should be recycled. These are higher than the current recovery and recycling rates of 80% and 75%, respectively (see section 2.2.3). Given that recycling of metals is already high (95%) and no imminent recycling improvements are expected for flat glass (Glass for Europe 2013), the new recycling targets can only be achieved by focusing on plastic components. In that case, a minimum of 52% of plastics would have to be recycled and 40% incinerated with energy recovery. The rest would be landfilled. These rates have been assumed for the plastic materials used for the main body of the microwave (ABS, PBT, PVC, PP, Nylon, PS and POM). The reason for considering the main body only is that the WEEE Directive applies only to the electronic parts of equipment. Waste treatment of packaging is assumed to remain the same in 2020 as at present due to a lack of data and regulation on packaging recycling. A 100% landfilling of the microwaves is also considered to explore the effects of the WEEE Directive on the environmental impacts.

2.2.5.3. Common assumptions for the current situation and the future scenario

A number of additional assumptions have also been made for the current situation (2013) and the future scenario (2020), as given below:

- The same inventory data for the microwave materials, manufacture, packaging and transportation given in the previous sections have been used to analyse the environmental impacts at the EU level, both for the current situation and in 2020. The inventory data are considered to be accurate for the current situation as the reference microwave is representative of the actual European market. Changes in the design of microwaves to represent the current average standby consumption in 2013 (2.1 Wh) or achieve lower standby consumption by 2020 (1.06 Wh) are minor and hence the corresponding changes in the environmental impacts from manufacture, distribution and disposal are considered negligible.

- The same service lifetime (eight years) has been considered for the microwaves for both the current situation and the future scenario. However, as mentioned in the introduction, there has been a trend of reducing the life expectancy of microwaves in recent years (Dindarian and Gibson 2011; Huisman et al. 2008; Mudgal et al. 2011a) that may continue in the future. The effect of this trend has been explored in a sensitivity analysis, by considering a life expectancy of six years in 2020. This is the same lifetime considered by Mudgal et al. (2011a) in their study.
- For end-of-life waste management, the same assumptions are made for all microwaves (see section 2.2.3), with the only difference being the microwave recycling rates at present (75%) and in 2020 (80%). However, their recyclability can vary for different models and countries. To determine the effect of this assumption on the results, the extreme situation of landfilling all waste microwaves in 2020 has been assessed through the sensitivity analysis.
- The study is based on the EU average electricity mix. As the electricity mix varies widely across the EU countries, the effect of this assumption is also explored through the sensitivity analysis by considering electricity mixes in different countries in 2020. Due to a lack of data on the number of microwaves in use in different countries, the impacts in this part of the sensitivity analysis have been calculated for a single (reference) microwave rather than at the EU level, but considering the electricity mix in each country.

2.3. Life cycle impact assessment

The microwave system has been modelled using GaBi 6.5 software (Thinkstep 2015) and the impacts have been estimated according to the CML 2001 (April 2015 version) method (Guinee et al. 2001). The following impacts are considered: primary energy demand (PED), abiotic depletion potential of elements ($ADP_{elements}$), abiotic depletion potential of fossils (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), terrestrial ecotoxicity potential (TETP), ozone depletion potential (ODP) and photochemical oxidants creation potential (POCP).

3. Results and discussion

This section presents first the results for the reference microwave, followed by the impacts estimated at the EU28 level.

3.1. Reference microwave

Fig. 4 shows the total environmental impacts of the reference microwave. For example, the microwave will use 8.9 GJ of primary energy and contribute around 416 kg CO_2 eq. over its service life. The results in Fig. 4 also indicate that the use stage is the main contributor (over 54%) to all impacts categories, except the $ADP_{elements}$ to which it contributes only 23%. The consumption of electricity in the standby mode contributes 6% to the impacts from the use stage or 3%-5% to the overall life cycle impacts (except for $ADP_{elements}$ to which it contributes <2%). The use stage is most significant environmentally due to the high energy consumption over its lifetime relative to the other stages. A further reason is the dominance of fossil fuels and particularly coal in the EU electricity mix (Table A1 in the Supporting Information), which is the major contributor to ADP_{fossil}, AP, EP, GWP, FAETP, HTP, MAETP and POCP (see Table A3 in the Supporting Information).

The materials used in the manufacture of the microwave are important contributors to $ADP_{elements}$ (67%); they are also relevant for HTP (27%), FAETP (14%), MAETP and POCP (13% each). Most of these impacts are due to the copper used in the electrical cables and electronic parts, except for the $ADP_{elements}$ and POCP, where gold and galvanised steel also play a major role. The consumption of scarce elements, such as copper and gold, are the main contributors to ADP$_{elements}$ (64%) while emissions to water of heavy metals (e.g. beryllium) during copper mining contribute significantly to FAETP and MAETP (8% and 7%, respectively). Finally, emissions of heavy metals to air (such as arsenic) in the refining process after copper mining and of carbon monoxide during iron sintering (used for galvanised steel) are among the main contributors for HTP and POCP, respectively.

The microwave manufacturing process contributes more than 15% for 10 out of 12 impact categories, and for AP, ODP and POCP it exceeds 30%. The production of PCB plays an important role owing to the consumption of electricity in the assembly and the production of the wafer. For the latter, the wastewater from the production process increases the EP while the emission of R22 (chlorodifluoromethane), used in the production of Teflon (polytetrafluoroethylene) for coating the wafer, raises the ODP. During the production of capacitors, methyl ethyl ketone (butanone) is released, which contributes significantly towards POCP.

The overall contribution of transport to the impacts is small (<2%). Finally, the end-of-life disposal of the microwaves has a positive effect on most impacts because of the recycling credits, particularly for copper and gold, which affect the ADP$_{elements}$ and HTP most significantly (Fig. 4).

3.1.1. Comparison with literature

As far as we are aware, there are no other comprehensive LCAs studies of microwaves so that like-for-like comparison with literature is not possible. As mentioned in the introduction, there are only three studies of microwaves, two of which (Jungbluth 1997; Devuono et al. 2000) had a different scope to the current study and are based on outdated data; hence, the comparison is not appropriate. The third study (Mudgal et al. 2011a) used recent EU data but also had a different scope and considered only five impact categories. Nevertheless, these are compared in Fig. 5 for four impacts, as the fifth (ODP) was not reported as a numerical value but as "negligible".

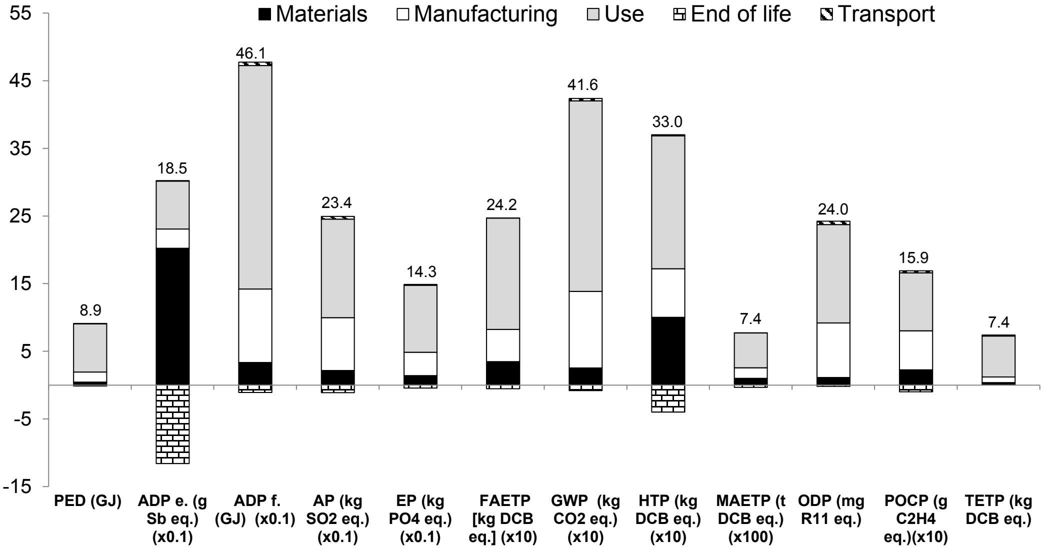

Fig. 4. Life cycle environmental impacts of the reference microwave over the eight-year lifespan
[The values given in the graph represent the total impact after the system credits. Some values have been scaled to fit. To obtain the original values, relevant values should be multiplied by the factor shown in brackets. Materials include the packaging. PED: primary energy demand, 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. DCB: dichlorobenzene.].

As can be observed from Fig. 5, there is a good agreement of the results for PED, AP and GWP. This is despite Mudgal et al. (2011a) focusing mainly on the use stage and using general assumptions related to the consumption of materials and product manufacturing. However, the agreement with the results for these three impacts is not surprising after all, because they are dominated by the consumption of electricity in the use stage (see section above). Furthermore, both studies considered the microwave with the same power rating (1150 W), a lifetime expectancy of eight years and an EU electricity mix. On the other hand, a significant difference can be observed for eutrophication. This is because Mudgal et al. only considered direct water emissions of nutrients, while in the present study, the effect of air emissions (mainly NO_x from the burning of fossil fuels) is also included.

3.1.2. Comparison with other EE equipment

To contextualise the results, this section discusses the environmental impacts of microwaves in relation to those associated with some other types of EE equipment, such as fridges, dishwashers, TVs and computers. Although they all serve a different function, this contextualisation is useful from both the policy-maker and consumer point of view as they are commonly used in households and contribute to the overall impacts in the EU.

The results are summarised in Fig. 6, showing three impacts for which the data were available in the literature: PED, AP and GWP. As can be seen, the microwave has similar impacts to other medium-to-small household devices, such as coffee machines, laptops or vacuum cleaners. The larger devices with longer lifetime expectancies (e.g. refrigerators, dishwasher or washing machines) or with a more intensive use stage (e.g. television) have significantly higher impacts. It can be noted that out of all the EE equipment considered in Fig. 6, microwave is the only device not currently regulated by a specific EU eco-design regulation for energy-related products, because it has the least potential for reducing energy use. However, as the results of this work show, materials are an important contributor to the environmental impacts of microwaves and should be considered in future regulations to minimise resource consumption and increase their circularity. This is discussed further in the next section.

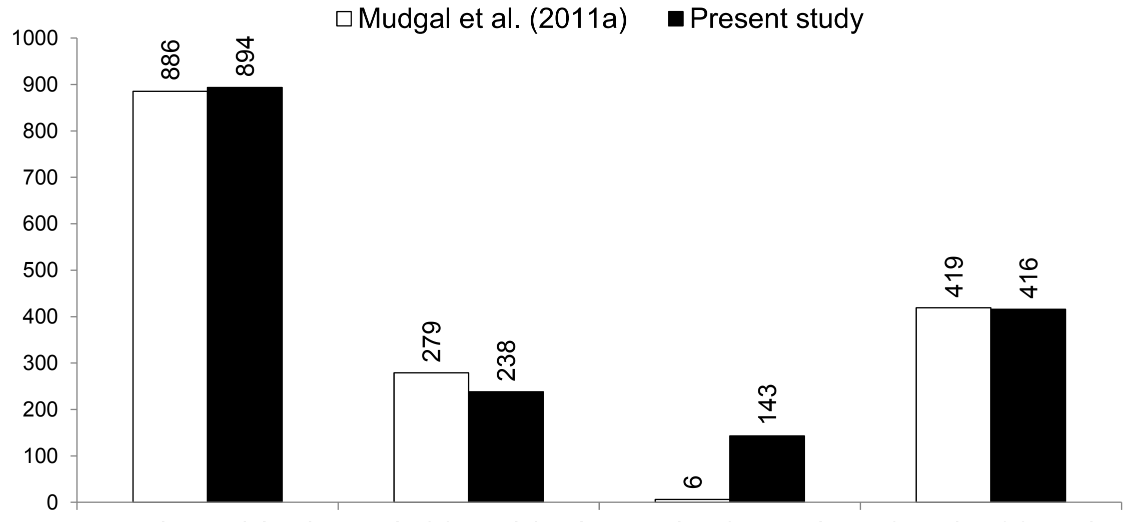

Fig. 5. Comparison of results with the literature. [All impacts refer to the microwave over its eight-year lifespan. The values should be multiplied by the factor shown in brackets for relevant impacts to obtain the original values. For impacts nomenclature, see Fig. 4.]

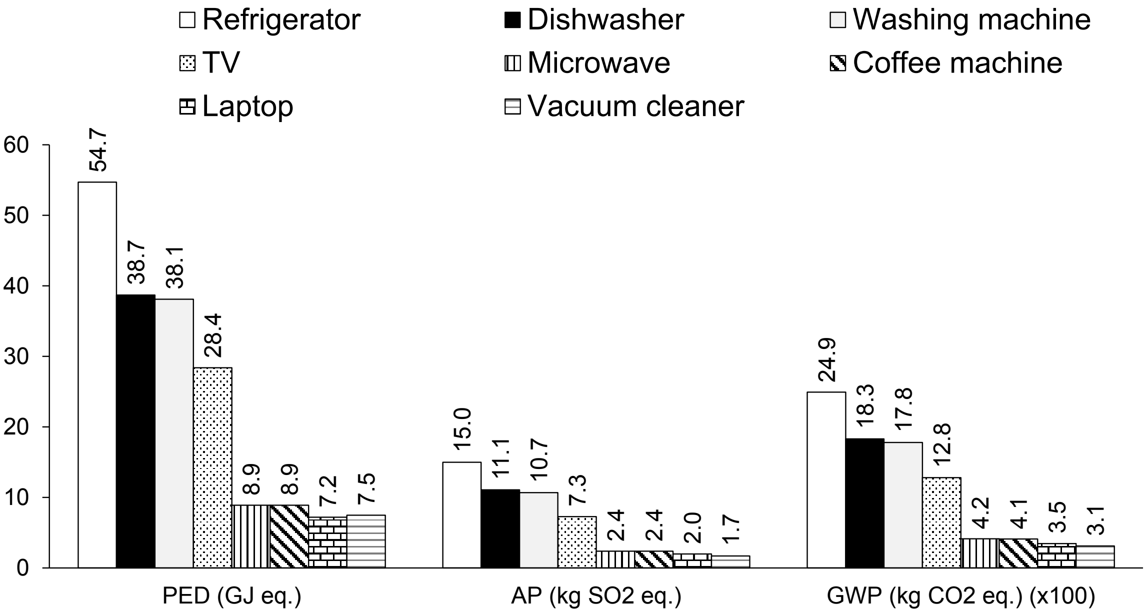

Fig. 6. Environmental impacts of different electronic and electrical equipment. [All impacts from 'cradle to grave'. The values for GWP scaled to fit – to obtain the original value, multiply by 100. For impacts nomenclature, see Fig. 4. Data sources - Refrigerator, freezer, dishwasher and washing machine: Presutto et al. (2007a,b); TV (LCD): Stobbe (2007); Microwave: present study; Espresso coffee machine (hard cap): Mudgal et al. (2011b); Laptop: Jönbrink (2007); Vacuum cleaner: Gallego-Schmid et al. (2016).]

3.2. Impacts at the EU level

Table 3 presents the potential environmental impacts of microwaves used in 2013 and 2020 at the EU28 level. For the latter, the differences in the impacts related to the following four aspects have been considered: the implementation of the Standby and WEEE legislation, the expected changes in the EU electricity mix and the assumed increase in the number of microwaves in use (134.66 million units in 2020 vs 131.34 million in 2013). The results indicate that the reduction in environmental impacts by 2020 related to the application of both EU regulations would be moderate. With the implementation of the Standby Regulation, the environmental impacts would be reduced by 4% ($ADP_{elements}$) to 9% (TETP). The environmental savings related to the implementation of the WEEE Directive would account for only ~0.3% across all the impact categories. If on the other hand, the expected decarbonisation of EU electricity is achieved by 2020, much greater reductions in the impacts would be achieved in nine out of the 12 categories (6%-24%), compared to the combined effect of both regulations. However, these reductions would be somewhat countered by the expected increase in the number of units in use of 2.5%.

Nevertheless, the net effect of all of the above four aspects is still positive (the last column of Table 3), with 10 out of 12 impacts decreasing by 6% (TETP) to 29% (EP) by 2020. The GWP is expected to be 15% lower, saving 1.17 Mt CO_2 eq./yr compared to the present situation. This is equivalent roughly to the annual GHG emissions of the Seychelles (JRC, 2014) with 1.25 Mt CO_2 eq. in 2012. These savings are due to the decarbonisation of the electricity mix (789.6 kt CO_2 eq./yr) and the reduction of the standby energy consumption (566.4 kt CO_2 eq./yr) related to the implementation of the corresponding EU regulation. Compared with these reductions, the decrease in the GWP related to the implementation of the WEEE directive is small (11 kt CO_2 eq./yr) because end-of-life waste management does not contribute much to this impact (see Fig. 4). On the other hand, the expected rise in the number of microwaves would increase the GWP by 2.5% (195.3 kt CO_2 eq./yr).

The exceptions to these trends are $ADP_{elements}$ and ODP, which increase by around 25% and 10%, respectively by 2020 compared to today's values. Although the implementation of the

Standby Regulation reduces $ADP_{elements}$ by 4% compared to the current situation, this is countered by the increase in resource depletion associated with the decarbonisation of the electricity mix (27%) and the growth in the number of microwaves in 2020 (2.5%). The increase associated with the electricity decarbonisation is due to the higher share of electricity from solar PV, as the PV panels require the use of rare elements, such as tellurium and silver. The decarbonisation of electricity also worsens ODP (14%), mainly because of a higher relative contribution of natural gas and associated emissions of halons 1211 and 1301, which are used as fire suppressants in the gas pipelines. For further details on the effects of decarbonisation on the impacts see Table A4 in the Supporting Information. The expected improvements in $ADP_{elements}$ and ODP related to the implementation of the WEEE Directive are negligible (0.1% in both cases).

3.3. Sensitivity analysis

The following aspects are considered in the sensitivity analysis at the European level to gauge their effect on the environmental impacts:

i) landfilling of microwaves instead of recycling stipulated by the WEEE Directive;
ii) the electricity mix of different EU countries instead of the average EU28 mix; and
iii) reduced lifetime expectancy of microwaves.

3.3.1. Landfill disposal

As discussed in the previous section, the implementation of the WEEE Directive would reduce the environmental impacts of microwaves by 2020, but the reductions would be small compared to those related to the Standby Regulation or the decarbonisation of the electricity mix. Nevertheless, it is also important to analyse the potential effect on the environmental impacts if the WEEE Directive was not implemented. Therefore, it is assumed here that all the microwaves are landfilled instead of recycled..

Table 3. Influence of different factors on the annual impacts of all microwaves in use at the EU28 level in 2020 relative to the current situation[a].

		Future scenario (year 2020)				
Impact[b]	**Current situation (2013)**	**Differences due to the Standby Regulation[c]**	**Differences due to the WEEE Directive[c]**	**Differences due to Electricity decarbonisation[c]**	**Differences due to the increase in the number of microwaves[c]**	**Total[c,d]**
PED (PJ/yr)	170.2	-14.3 (-8.4%)	-0.25 (-0.1%)	-19.5 (-11.4%)	4.3 (+2.5%)	140.5 (-17.5%)
ADP$_e$. (t Sb eq./yr)	32.8	-1.4 (-4.3%)	-0.03 (-0.1%)	9.0 (+27.3%)	0.8 (+2.5%)	41.2 (+25.4%)
ADP$_f$. (PJ/yr)	87.2	-6.6 (-7.6%)	-0.22 (-0.3%)	-5.6 (-6.4%)	2.2 (+2.5%)	77.0 (-11.7%)
AP (kt SO_2 eq./yr)	43.8	-2.9 (-6.7%)	-0.04 (-0.1%)	-7.1(-16.3%)	1.1 (+2.5%)	34.8 (-20.5%)
EP (kt PO_4^{3-} eq./yr)	26.9	-2.0 (-7.4%)	-0.07 (-0.2%)	-6.3 (-23.6%)	0.7 (+2.5%)	19.1 (-28.7%)
FAETP (Mt DCB eq./yr)	4.5	-0.3 (-7.4%)	-0.01 (-0.2%)	-1.0 (-22.8%)	0.1 (+2.5%)	3.2 (-27.8%)
GWP (kt CO_2 eq./yr)	7730.8	-566.4 (-7.3%)	-10.96 (-0.1%)	-789.6 (-10.2%)	195.3 (+2.5%)	6559.2 (-15.2%)
HTP (Mt DCB eq./yr)	6.1	-0.4 (-6.5%)	-0.01 (-0.1%)	-0.6 (-10.3%)	0.2 (+2.5%)	5.2 (-14.4%)
MAETP (Gt DCB eq./yr)	13.8	-1.0 (-7.5%)	-0.01 (-0.1%)	-3.2 (-23.3%)	0.3 (+2.5%)	9.9 (-28.4%)
ODP (kg R11 eq./yr)	441.5	-29.3 (-6.6%)	-0.18 (-0.1%)	61.5 (+13.9%)	11.2 (+2.5%)	484.7 (+9.8%)
POCP (kt C_2H_4 eq./yr)	2.9	-0.2 (-6.0%)	-0.01 (-0.3%)	-0.2 (-7.9%)	0.1 (+2.5%)	2.6 (-11.6%)
TETP (kt DCB eq./yr)	140.3	-12.2 (-8.7%)	-0.04 (-0.1%)	0.1 (+0.1%)	3.5 (+2.5%)	131.8 (-6.1%)

[a] Current umber of microwaves: 131.34 million. Assumed number of microwaves in 2020: 134.66 million.

[b] For the impacts nomenclature, see Fig. 4.

[c] The values in brackets represent the increase (+) or decrease (–) relative to the 2013 values.

[d] The total value represents the sum of the current impacts and the differences in the impacts due to the different parameters given in the table.

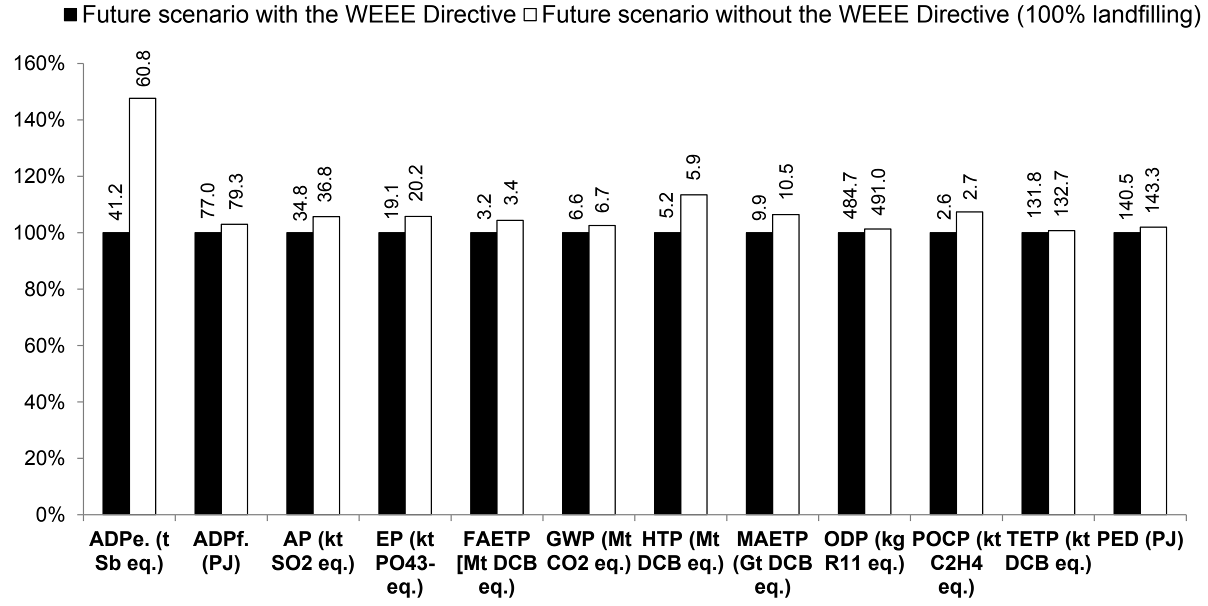

Fig. 7. Annual environmental impacts of all microwaves in 2020 at the EU28 level with and without the WEEE Directive [Basis: 134.66 million units. The values on top of the bars represent the total annual impacts. For the impacts nomenclature, see Fig. 4.]

The results in Fig. 7 suggest that the impacts would increase from 1% (TETP and ODP) to 48% ($ADP_{elements}$). Although the reductions for most impacts but $ADP_{elements}$ may seem relatively small, the environmental savings at the EU level would be considerable, given the large number of microwaves expected to be in operation by 2020 (134.66 million units). For instance, implementing the WEEE Directive in the EU28 by 2020 would save 11 kt CO_2 eq. relative to 2013 but if there was no WEEE Directive, the impact would increase by 167 kt CO_2 eq. (see Fig. 7). The latter is equal to the annual GWP of around 148,000 light-duty vehicles, assuming average CO_2 emissions of 90 g/km and distance travelled of 12,500 km/yr (Winkler et al. 2014). For context, the saving of 11 kt CO_2 eq. equates to the annual emissions from 10,000 light-duty vehicles.

The above-mentioned increase in $ADP_{elements}$ of almost 50% suggests that the relative environmental importance of microwave recycling would increase further in the future, particularly if their expected lifespan is reduced, the availability of some resources becomes constrained and a greater decarbonisation of the electricity mix is achieved.

3.3.2. Country specific electricity mix

In the analysis so far, the average EU28 electricity mix has been assumed. Here we explore the effect of the assumed electricity mix on the environmental impacts of microwaves by considering four EU countries with quite different electricity mixes (in 2020):

a) Ireland, where the electricity is dominated by natural gas (37.7%);
b) Poland, with mainly coal on the grid (70.5%);
c) Denmark, which uses mainly renewables (81.5%, of which 53% is wind); and
d) France, where almost half of the electricity (47.4%) is from nuclear power plants.

For further details on the above electricity mixes, see Table A1 in the Supporting Information. As mentioned earlier (see section 2.2.5.3), due to a lack of data on the number of microwaves in use in different countries, the impacts have been estimated for one (reference) microwave in year 2020 rather than for the total number of microwaves in the EU. This is deemed appropriate as the aim here is to consider the effect of different electricity mixes rather than the total impacts of microwaves.

The results indicate that in countries with coal-dominated electricity (e.g. Poland), 10 out of 12 impacts from the microwave are higher than for the EU28 average electricity (Fig. 8). The impacts that increase most (>110%) are AP, EP, FAETP, GWP and MAETP. In the case of Ireland, which has a greater contribution of natural gas, six impacts are lower in comparison to the EU28 average (ADP$_{\text{elements}}$, EP, FAETP, HTP, MAETP and PED), while the remaining impacts are higher. The electricity profiles of Denmark and France, which are dominated by renewable and nuclear sources, respectively, have significantly lower impacts for 10 impact categories. In both cases, the lower impacts are due to the reduction in the use of fossil fuels, with largest reductions in ADP$_{\text{fossil}}$, EP, FAETP, GWP, MAETP and ODP. This shows that combining energy efficiency measures, such as those in the Standby Regulation, with electricity decarbonisation can lead to greater overall environmental improvements. It also suggests that countries which are well on the path to decarbonise would benefit less from such regulation.

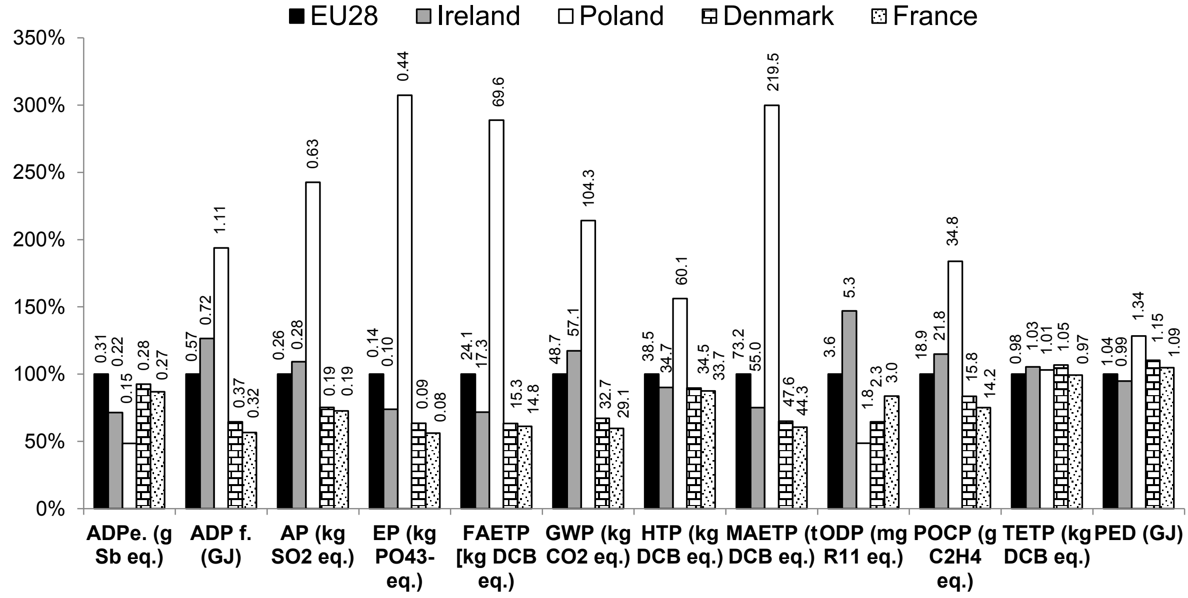

Fig. 8. Annual environmental impacts of an average microwave used in different EU countries in 2020 compared with the EU28 average [Basis: 1150 W microwave with 1200 cycles/yr, consumption of 0.056 kWh/cycle and standby consumption of 9.3 kWh/yr. The values on top of the bars represent the total impacts. For the impacts nomenclature, see Fig. 4].

3.3.3. Lower lifetime expectancy

As mentioned earlier, there has been a continuous decline in the lifespan of microwaves since the 1990s and this trend may continue in the future. The effect of this trend on the environmental impacts is analysed in this section, assuming a reduction in the lifetime from the current eight to six years in 2020. The results are summarised in Fig. 9 which shows that a decrease in the lifespan would lead to a modest increase in impacts, with the highest increase found for POCP and ADP$_{\text{elements}}$ (16%) and the lowest for PED (7%). Given that the impacts are largely dominated by the use stage, these findings may not be surprising. Nevertheless, with the implementation of the energy efficiency measures and electricity decarbonisation, the lifetime of microwaves may become a more influencing factor, together with the other life cycle stages.

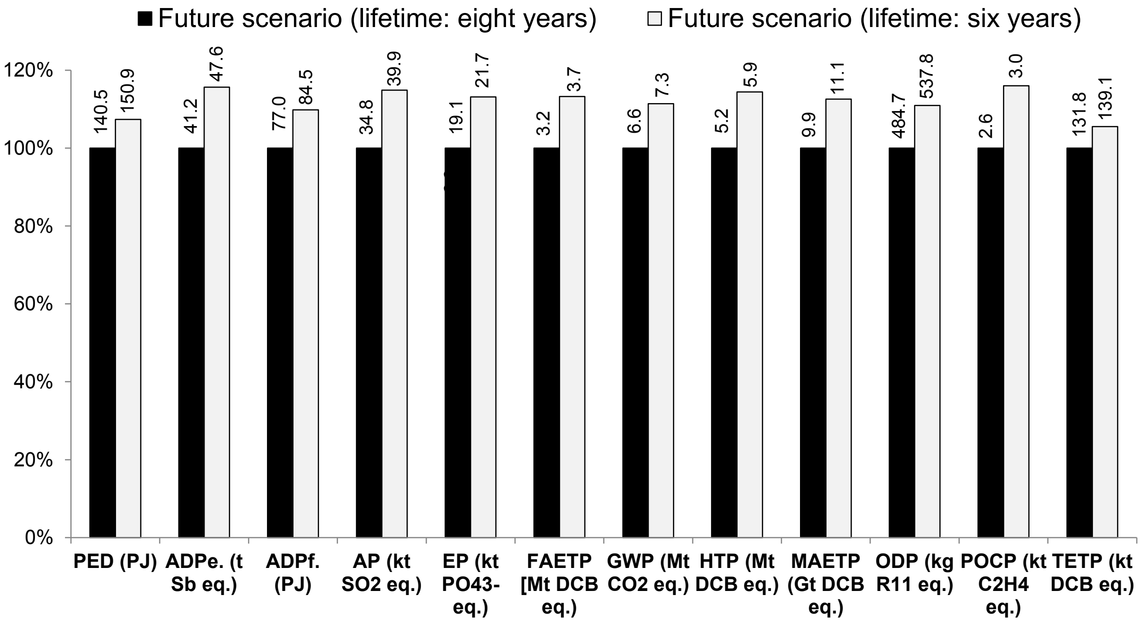

Fig. 9. Influence of the microwave lifespan on the annual environmental impacts at the EU28 level in 2020 [Basis: 134.66 million units. The values on top of the bars represent the total impacts. For the impacts nomenclature, see Fig. 4].

The effect of the latter is considered in

Fig.10 which shows that the materials and microwave manufacture contribute significantly (>45%) to seven impacts ($\mathrm{ADP_{elements}}$, AP, EP, FAETP, HTP, MAETP and POCP). The positive contribution of improved end-of-life waste management related to the WEEE Directive is also significant, reducing in particular $\mathrm{ADP_{elements}}$ by 35% and HTP by 13%. Therefore, reductions in the lifetime of microwaves and lower carbon intensity of electricity could increase the relative importance of materials, manufacture and end-of-life management. Thus, optimisation of these stages should be an integral part of a strategy for reducing environmental impacts across the life cycle of microwaves (and other EE devices).

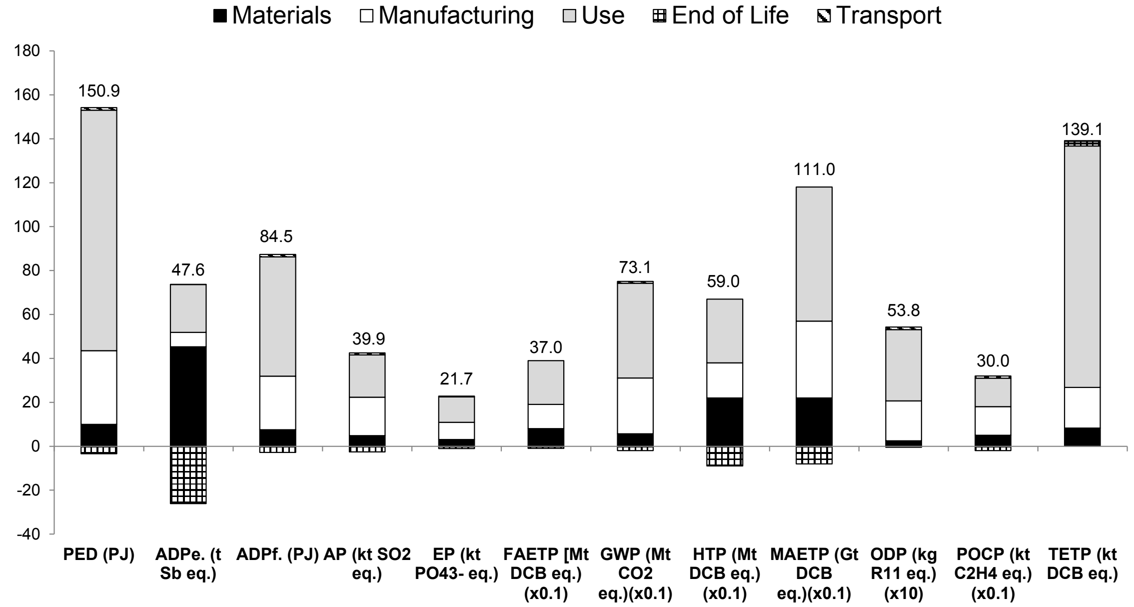

Fig.10. Contribution of different life cycle stage to the annual impacts of the microwaves at the EU28 level in 2020, assuming a lifespan of six years [Basis: 134.66 million units. The values on top of the bars represent the

total impacts and should be multiplied by the factor shown in brackets for relevant impacts to obtain the original values. For the impacts nomenclature, see Fig. 4].

4. Conclusions

This paper has presented the results of the first comprehensive environmental evaluation of microwaves across the whole life cycle. It has also assessed the environmental implications at the EU level of the implementation of the Standby and WEEE regulations. The results suggest that electricity consumption in the use stage is the main contributor to the environmental impacts. However, the resources used to manufacture the microwaves are the major contributors to the depletion of abiotic elements (67%) and play an important role for human and aquatic toxicities as well as for photochemical oxidants creation (13%-27%). Furthermore, manufacturing of microwaves also has a relevant contribution to 10 out of the 12 impact categories considered, especially photochemical oxidants (34%), ozone layer depletion (33%) and acidification (31%). End-of-life disposal has an overall positive effect on the environmental impacts due to the credits for recycling, in particular, for depletion of elements and human toxicity. These results demonstrate the need to consider other life cycle stages beyond the use, which has been the focus of the existing studies and policy so far.

At the EU level, the results suggest that all but two environmental impacts ($ADP_{elements}$ and ODP) would be reduced by 6%-29% by 2020 relative to the current situation. Global warming potential is estimated to be lower by 15%. The contribution of the Standby Regulation to these reductions will be modest, ranging from 4% to 9%. Microwaves are mature products from the energy-efficiency perspective and, therefore, efforts to reduce energy consumption should focus on improving consumer behaviour to use them more efficiently; for example, by adjusting the time of heating to each type of food. The provision of best practices and guidelines by microwave manufactures could help consumers to integrate these into daily practices.

The environmental savings related to the WEEE Directive are much smaller (~0.3%) than those from the Standby Regulation. However, without the WEEE Directive, assuming that 100% of the microwaves are landfilled instead, all impacts would increase. For example, depletion of elements would be higher by 48%, human toxicity by 14% and creation of photochemical oxidants by 7%. Given the number of microwaves in use, these increases are significant; for instance, global warming potential would be higher by 167,000 t CO_2 eq./yr.

The greatest potential for improving the environmental performance of microwaves is related to the expected decarbonisation of the electricity mix in the EU, which would reduce the impacts by 6%-24%. The only impacts that would increase because of decarbonisation are depletion of elements (27%) and the ozone layer (14%). Thus, policy instruments related to energy efficiency (such as the Standby Regulation) should be complemented by appropriate measures to reduce the impacts from electricity generation. Otherwise, their benefits could be limited.

To improve the environmental footprint of microwaves further, it is also necessary to develop specific regulations for these devices, considering other life cycle stages apart from the use. Possible future trends, such as shorter microwave lifetime, electricity decarbonisation and reduced availability of some materials, will make it even more critical to understand better the effect on the impacts of other life cycle stages, such as production of materials, microwave manufacture and waste treatment. As this study demonstrates, improvements in these parts of the supply chain will result in significant environmental benefits, particularly as the number of microwaves is expected to increase in the future. Therefore, the development of a specific eco-design regulation for microwaves, focused on all the life cycle stages, should be an objective for European authorities in the near future. Related to this, further research should be centred on analysing the potential for eco-design of microwaves.

Improvements in product resource efficiency through eco-design could contribute to achieving relevant additional environmental savings, together with the energy-efficiency measures. Decoupling resource consumption and environmental impacts from the economic growth is essential to pursuing and shaping a circular economy in Europe and the EE equipment is a key product category that can contribute to it.

Acknowledgments

This research has been funded by UK Engineering and Physical Sciences Research Council (EPSRC; grant no. EP/K011820/1) and the Sustainable Consumption Institute at the University of Manchester. This funding is gratefully acknowledged. The authors are also grateful to Mr Roy Kershaw for his support in disassembling the microwave.

Appendix A. Supporting information

The Supporting Information includes data on the electricity mixes in the EU28 and some Member States; stocks and sales of microwaves; environmental hot-spot analysis by life cycle stage; and the environmental profile of the average EU28 electricity.

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Accepted for publication in Science of The Total Environment 618: 487-499.
doi: 10.1016/j.scitotenv.2017.11.064

Environmental assessment of microwaves and the effect of European energy efficiency and waste management legislation

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Supporting information

Table A1. EU electricity mix in 2013 and in 2020

Source of electricity	EU28 (2013)[a]	EU28 (2020)[b]	Poland (2020)[b]	France (2020)[b]	Denmark (2020)[b]	Ireland (2020)[b]
Nuclear	29.1%	11.8%	0.0%	47.4%	0.0%	0.0%
Lignite	10.3%	5.7%	18.8%	0.0%	0.0%	1.3%
Hard coal	17.3%	10.8%	51.7%	4.2%	7.7%	9.3%
Natural gas	14.0%	20.7%	6.1%	5.6%	10.6%	37.7%
Oil	1.5%	2.2%	0.0%	4.2%	0.1%	10.0%
Wind	7.8%	18.6%	15.1%	12.0%	53.0%	34.6%
Solar	2.8%	11.0%	0.0%	6.0%	7.6%	0.9%
Biomass	4.0%	3.6%	2.2%	1.5%	20.9%	1.9%
Hydropower (renewable)	12.2%	11.3%	1.4%	15.9%	0.1%	2.4%
Hydropower (others)	1.1%	4.4%	1.0%	3.1%	0.0%	2.9%

[a] Measured (ENTSO-E, 2014a).
[b] Based on net generation capacity (ENTSO-E, 2014b).

Table A2. Stock and sales for microwave for period 2008/2020 (Mudgal et al. 2011)

Year	Stock in use (units)	Sales (units)
2008	126,342,972	14,176,712
2009	127,858,076	14,488,600
2010	129,392,373	14,807,349
2011	130,039,335	14,970,230
2012	130,689,532	15,134,903
2013	131,342,979	15,301,386
2014	131,999,694	15,569,702
2015	132,659,693	15,639,868
2016	133,057,672	15,764,985
2017	133,456,845	15,891,107
2018	133,857,215	16,018,236
2019	134,258,787	16,146,382
2020	134,661,563	16,275,553

Table A3. Hot-spots in the life cycle assessment of a microwave

Life cycle stage	Impact[a]	Contribution to the total (%)	Main contributor	Contribution to life cycle stage (%)
Raw materials: copper	$ADP_{elements}$	38.7	Cu consumption	83.4
	FAETP	8.6	Be (Cu mining)	31.9
	HTP	16.2	As (Cu refining after mining)	41.1
	MAETP	7.4	Be (Cu mining)	67.9
Raw materials: gold	$ADP_{elements}$	19.9	Gold consumption	99.9
Raw materials: galvanized steel	POCP	5.9	CO (sintered iron)	49.7
Production: PCB[b]	ADP_{fossil}	9.6	Fossil fuels (electricity for assembly)	51.9
	EP	16.3	TOC (wastewater wafer production)	21.8
	AP	7.4	SO_2 (coal burning)	34.7
	FAETP	10.3	Ni (mining of coal used in electricity mix for the assembly)	18.2
	GWP	11.4	CO_2 (fossil fuels electricity for assembly)	41.3
	MAETP	8.4	Be (coal mining)	18.7
	OLD	22.0	R22 (Teflon coating)	21.5
	PED	8.1	U (nuclear energy)	22.9
Production: capacitor	POCP	9.1	Butanone (production capacitors)	44.7

Table A3. Continued.

Life cycle stage	Impact[a]	Contribution to the total (%)	Main contributor	Contribution to life cycle stage (%)
Use: electricity consumption	ADP$_{\text{elements}}$	23.4	Cu (electricity distribution)	48.7
	ADP$_{\text{fossil}}$	69.2	Fossil fuels consumption	96.7
	AP	58.4	SO_2 (coal burning)	81.6
	EP	66.6	PO_4^{3-} (coal mining)	71.7
	FAETP	66.6	Ni (coal mining)	41.8
	GWP	66.5	CO_2 (combustion of fossil fuels)	82.0
	HTP	53.1	Se (coal mining)	20.1
	MAETP	66.9	Be (coal mining)	34.9
	ODP	60.1	Halon 1211 (natural gas distribution)	55.9
	POCP	50.7	SO_2 (coal burning)	46.4
	TETP	83.4	Cr (electricity distribution)	83.0
	PED	78.1	U (nuclear energy)	33.4
Disposal: copper recycling	ADP$_{\text{elements}}$	-19.3	Cu consumption (avoided)	-80.2
Disposal: gold recycling	ADP$_{\text{elements}}$	-16.6	Gold consumption (avoided)	-99.9

[a] ADP$_{\text{elements}}$: abiotic depletion potential of elements, ADP$_{\text{fossil}}$: abiotic depletion potential of fossil resources, AP: acidification potential, EP: eutrophication potential, GWP: global warming potential, HTTP: human toxicity potential, MAETP: marine aquatic ecotoxicity potential, FAETP: freshwater aquatic ecotoxicity potential, ODP: ozone layer depletion potential, POCP: photochemical ozone creation potential, TETP: terrestrial ecotoxicity potential, PED: primary energy demand.

[b] PCB: printed circuit board

Table A4. Environmental impacts of low-voltage electricity consumed in the EU28 countries in 2013 and 2020

Impact categories[a]	Unit[b]	Year 2013	Year 2020	Variation[c]
ADP$_{\text{elements}}$	mg Sb eq./kWh	1.2	2.1	+70.4%
ADP$_{\text{fossil}}$	MJ/kWh	5.77	5.25	-9.1%
AP	g SO_2 eq./kWh	2.5	1.9	-26.8%
EP	g PO_3^{4-} eq./kWh	1.7	1.1	-35.2%
FAETP	kg DCB eq./kWh	0.29	0.19	-34.2%
GWP	kg CO_2 eq./kWh	0.49	0.42	-15.2%
HTP	kg DCB eq./kWh	0.34	0.28	-17.2%
MAETP	kg DCB eq./kWh	900.89	593.60	-34.1%
ODP	µg R11 eq./kWh	250	310	+23.7%
POCP	g C_2H_4 eq./kWh	0.15	0.13	-14.4%
TETP	g DCB eq./kWh	10.58	10.62	0.4%
PED	MJ/kWh	12.43	10.58	-14.9%

[a]. For impacts nomenclature, see Table A3.

[b] DCB: dichlorobenzene.

[c] Variation in 2020 relative to 2013. Positive/negative values indicate an increase/decrease of impacts.

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