Journal of Cleaner Production 267 (2020) 121952

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Environmental impacts of household appliances in Europe and scenarios for their impact reduction

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A R T I C L E I N F O

Article history:
Received 1 April 2019
Received in revised form
14 February 2020
Accepted 27 April 2020
Available online 12 May 2020

Handling editor: Tomas B. Ramos

Keywords:
Life cycle assessment
Consumer footprint
Household appliances
Ecoinnovation
Scenarios
Policy impact

A B S T R A C T

Assessing the environmental impact due to consumption of goods and services is a pivotal step towards achieving the sustainable development goal related to responsible production and consumption (i.e. SDG 12). Household appliances plays a crucial role and should be assessed in a systemic manner, namely considering all life cycle stages, technological efficiency, and affluence aspects. The present study assess the impact of such household appliances used in Europe, and tests scenarios of potential impact reduction at various scales. Life cycle assessment is applied to 14 different household appliances (ranging from dishwashers to television devices) selected to build a set of representative products, based on their economic value and diffusion in households in Europe. Related impacts are calculated with the Environmental Footprint method for calculating a Consumer Footprint "appliances" for the baseline year 2010. A number of scenarios encompassing eco-solutions on a technical level, changes in consumption pattern, behavioral changes, as well as the combination of all these aspects are run to estimate the Consumer Footprint related to household appliances for the year 2030, compared against this baseline scenario. The baseline Consumer Footprint is confirming the importance of the use phase in leading the impacts in almost all impact categories. Testing different scenarios concludes that there is a reduction of the impact for most of the categories (with up to 67% for the ozone depletion potential, and still around 35% for the global warming potential), while two of the here examined impact categories (i.e. land-use and mineral resource depletion) show an overall potential that is even negative – i.e. the results of all scenarios are higher than the ones of the 2010 baseline scenario. The increase in purchase and use of such appliances may offset energy efficiency benefits in some of the examined categories. Hence, the assessment of sustainability of appliances consumption should always include several scales, from the efficiency of the products (micro scale), to the improvement of the energy mix (meso scale), up to accounting for socio-economic drivers and patterns of consumption affecting the overall appliances stock (macro scale).

1. Introduction

Household appliances are currently a core area of consumption in developed and developing countries and projections related to increase in population and in welfare forecast that more and more people will use such household appliances in the future. This implies an increasing energy consumption in order to respond to several needs, from basic to luxury ones. Global statistics show that a 37% increase in appliances is expected by 2020, compared to the year 2013 (Statista.com, 2018). Given the increase dependency of energy consumption and resources needed to produce and use all these appliances, they are considered one of the relevant area of intervention to ensure sustainable production and consumption. Indeed, considering United Nations' Sustainable Development Goals (SGDs) (UN, 2015), household appliances may bring both benefits and impacts. Then promoting "sustainable consumption and production" (i.e. SDG12) aims at bringing positive effects on other SDGs such as SDG13 on "climate action" or SDG7 on "affordable and clean energy". On the other side, a growing of the consumption system size associated to emerging or increasing needs could limit such benefit and/or even have (negative) effects

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https://doi.org/10.1016/j.jclepro.2020.121952

on other environmentally relevant SDGs, such as SDG14 about “life below water” or SDG15 about “life on land”. The sustainable development goals are putting a new challenge on the way sustainable production and consumption should be assessed, namely there is the need of a system perspective in which solutions towards reaching one goal should be assessed in light of potential trade-offs with other goals and objective. For this kind of assessment a systematic approach is needed.

Life cycle thinking, embracing all life cycle stages from the extraction of resource to the final disposal, is considered a pivotal approach to assess impacts and benefits associated to products and product systems in a systematic manner and in relation to SDGs (Sala, 2019). The main method to quantify those impacts is life cycle assessment (LCA) according to the ISO 14040 series (ISO, 2006, b). For what concerns the area household appliances, the method has been applied since the end of the 90’s already in the assessment of electric and electronic devices, investigating most of the time specific types of appliances (see review paper of Subramanian and Yung, 2016, or studies such as Tekawa et al., 1997, Atlantic Consulting and IPU, 1998, Hischier and Baudin, 2010, Lee and Tansel, 2012, Javani et al., 2013, Elduque et al., 2014, Xiao et al., 2015, Subramanian and Yung, 2017, Favi et al., 2018, or Zhang et al., 2019). On a more comprehensive and thus device-independent level, to the best of author’s knowledge, only few studies have been published so far. A US-study from Ryen and coworkers (Ryen et al., 2015) presents a consumption-weighted LCA approach, applied to a group of interrelated electronics devices in the area of information, communication, and entertainment services only, over one year in an average household of the United States of America. Most other such overarching studies focused on the end-of-life phase (see e.g. Barba-Gutiérrez et al., 2008; Wäger et al., 2011; Biganzoli et al., 2015; Fiore et al., 2019; Boldoczki et al., 2019).

LCA and its underlying concept of life cycle thinking affected policy development in the past decades. The Ecodesign Directive in Europe (European Union, 2009) can been considered one of the first policy examples applying life cycle thinking while addressing product performance. In 2010, the energy-related products covered by this directive represented approximately 38,700 PJ (925 Mtoe) of direct and indirect primary energy consumption, corresponding to 53% of total EU-28 gross energy consumption in 2010, the latter being 1759 Mtoe (VHK, 2016). Energy-related products are defined in the Directive as products that are using energy during the use phase or have a significant impact on the energy consumption of products that are using energy. More in detail, the Directive targets those products which (i) represent a relevant volume of sales and trade, (ii) have a significant environmental impact considering the quantities put into service or placed on the market, and (iii) show an important improvement potential at not excessive cost. The Directive establishes a framework for the setting of ecodesign requirements for these products with the aim of reducing their environmental impacts. Household appliances are in the scope of the Directive. Results of a broad monitoring of the effects of this Directive have been published in 2016 (VHK, 2016), applying a life cycle approach as defined in the so-called MEErP methodology (i.e. Methodology for Ecodesign of Energy-related Products) (Kemna, 2011). The past few years saw therefore popping-up several LCA studies on the quantification of the potential impact reduction coming from energy efficiency measures (e.g. Ardente and Mathieux, 2014; Amienyo et al., 2016, or Tao et al., 2014). But so far, those studies focused on one product group or one type of innovation only. However, looking at the product performance only it is not enough, because sustainability is posing systemic challenges which means that the entire system of production and consumption (both in terms of product choice and user behavior) should be modelled and assessed.

In this context, and especially in view of SDG12 (“responsible consumption and production”), the European Commission’s Joint Research Centre (EC-JRC) has been developing an assessment framework to monitor the evolution of environmental impacts associated to the consumption within Europe (Sala et al., 2019). This framework allows the support of a wide array of different policy objectives, such as resource efficiency, eco-innovation and a circular economy through the calculation of a so-called Consumer footprint indicator. This Consumer footprint aims at assessing the potential environmental impacts of the consumption of an average European citizen with the support of life cycle assessment (LCA) calculations of a Basket of representative Products (BoP), purchased and used in one year by this average citizen. Five key areas of consumption have been investigated, i.e. housing (see Baldassarri et al., 2017; Lavagna et al., 2018), mobility (see Castellani et al., 2017), food (see Notarnicola et al., 2017; Castellani et al., 2017), household goods (Castellani et al., 2019) as well as household appliances (Reale et al., 2019).

The present study is focusing on the latter area, i.e. the area of household appliances, aiming at providing a systemic overview with different types of devices and a large choice of eco-innovation options which is so far, according to the authors’ knowledge, lacking in literature. The aim of the present study is therefore to apply a full set of LCA indicators to a basket of different devices of household appliances (called hereinafter “BoP appliances”), representative for the consumption by an average European citizen towards the assessment of the Consumer Footprint for household appliances. For this, the on-hand manuscript is structured in the following way: section 2 explains briefly the applied method; section 3 describes the data collection process for the calculations of the various scenarios examined within this study, including the resulting life cycle inventory data for these scenarios; section 4 presents/discusses the results of all the LCA calculations for the various scenarios; and last but not least, section 5 concludes by summarizing the main conclusions across all these calculations.

2. Method and data

Assessments of the environmental impacts generated by consumption and, more generally, by citizens’ lifestyle can be found more and more in scientific literature – allocating the impacts on the consumer or on the producer (see e.g. Hertwich and Peters, 2009 or Wiedmann et al., 2013). Various methods for estimating the footprint of households and governments have been developed over the last years, being top-down (by applying Environmentally Extended Input-Output tables (EEIOTs) combined with households’ expenditure statistics), bottom-up (in applying LCA on representative products that are up-scaled) or hybrid approaches (being a combination of the former two), and having all their pros and cons (for a more detailed discussion see e.g. Huppes et al., 2006). Within this study, the Consumer Footprint approach, developed by EC-JRC and described in Sala et al., (2019), is applied. Therefore, a process-based life cycle inventory of a basket of devices, representative of the appliances’ stock owned by European citizens, is developed and assessed. Being based on LCA’s of specific products in combination with European consumption statistics, the method allows a realistic and more detailed as well as more comprehensive picture of the environmental impacts of the examined area of household appliances, than applying e.g. current Input-Output tables (such as Exiobase). For example, European consumption statistics allows calculating the import share (from extra-EU) for a product sold in Europe in a reference year, detailing it by extra-EU country of production, and in turn to represent such information in the manufacturing stage (e.g. by modelling the country-specific electricity mix) and in the transport of the stock units from the production country to Europe, in the reference year.

At the same, some limitations are present. With specific reference to the previous example, stock data reported in the EU statistics (or other consulted product-related studies) do not include the age of stock units and all of them are assumed to be produced in the same (reference) year.

2.1. Method description

In a first step of the Consumer Footprint approach, the BoP appliances of a so-called “baseline scenario” is specified. The objective of this baseline scenario is to assess the impacts associated to the consumption of household appliances in Europe, covered by the Ecodesign directive (European Union, 2009), in the reference year 2010, by an average European citizen. Three main types of household appliances are taken into account for this BoP: (i) white goods, (ii) appliances for basic functions related to housing (e.g. space cooling), and (iii) entertainment and leisure. In parallel to this general principle, the selection of products categories has taken into account that the final goal of the project was to assess the impacts from an average European citizen considering the all five mentioned key areas (Sala and Castellani, 2019),Thus, in order to avoid potential double counting, appliances fully covered in any of the former Consumer Footprint studies are not included again here. This is the case of the heating infrastructure which is fully represented in the study about housing.

As reference flow, the “amount of household appliances consumed by an average EU-27[1] citizen and their use in the reference year 2010″ is used.

The executed calculations cover the entire life cycle of the various household appliances being part of the BoP – starting from the extraction of the various materials, up to the recycling and end-of-life options at the end of the lifetime of the various household appliances. This baseline scenario for the year 2010 allows for identifying the environmental hotspots along the entire lifecycle of these devices (i.e. allowing to identify which actor could influence how much these impacts), but also within the examined BoP appliances (i.e. allowing to identify the environmental relevance of the various household appliances included in this basket).

For the second step, the results of this hotspot analysis of the baseline scenario are then used as starting point for the selection of possible actions in order to reduce the environmental burdens – i.e. in order to define what is called in the on-hand manuscript the various “future scenarios”. For this, the study examined the environmental implications of a number of different eco-innovations applied to the household appliances system in the year 2030, covering the implementation of eco-solutions on a technical level, changes in consumption pattern, behavioral changes, as well as the combination of all these aspects. In practice, this has been translated into a thorough literature review in order to identify the different areas of (potential) improvement and their related eco-innovation aspects. Guiding principles for the choice of these future scenarios have been the following three aspects: (i) the most relevant environmental hotspots identified in the baseline, (ii) effects due to European policies, and (iii) innovations that at present are a niche, but are foreseen to become relevant in the future. Overall, the objective of this second step is the identification of the potential environmental benefits associated to each of these examined actions as well as to unveil possible trade-offs, e.g. due to the reduction of impacts in one impact category (e.g. climate change) while increasing impacts in another one (e.g. ecotoxicity).

All the LCA calculations in the frame of this study have been executed with the software tool SimaPro 8, using data from ecoinvent version 3.2 (ecoinventCentre, 2015) in the background and applying the Environmental Footprint (EF) method (European Commission, 2018), in the life cycle impact assessment (LCIA) step in order to get a comprehensive overview of the resulting environmental impacts. The method builds upon the list of recommended impact factors (European Commission - Joint Research Centre, 2011) in EC-JRC’s ILCD (International Reference Life Cycle Data System) handbook, updating these recommendations for a number of impact categories, namely: water use, land use, particulate matter, resource use, and the toxicity-related ones (ecotoxicity, human toxicity cancer and non-cancer). The here applied characterisation factors refers to the EF package 3.0 (EF 3.0) (European Commission - Joint Research Centre, 2019), and an overview of them is reported in Fazio et al., (2018).

2.2. Definition of scenarios

2.2.1. Baseline scenario for the year 2010

For the quantification of the baseline scenario of this BoP appliances a quantitative and qualitative analysis of the structure of EU-27 household consumption was performed including the analysis of related international trade flows (Eurostat, 2017). As these appliances have a service life longer than one year, including only the mere apparent consumption (i.e. production + imports - exports) is not enough to capture the effective environmental impacts due to the annual consumption and use of such appliances by an average citizen. Instead, stock information is used for each of the included product categories. For most of the product categories the stock data were retrieved from related Ecodesign preparatory studies. Exceptions are the tumble dryer and refrigerator, for which stock data were retrieved from the overview report of the Ecodesign Impact Accounting (VHK, 2016), as well as room air conditioners (RAC) and lighting, whose stocks are estimated as below described:

- **RAC.** Stock of RAC units in EU-27 households is calculated by multiplying the EU-27 dwelling stock (as modelled in Baldassarri et al., 2017 for the BoP Housing) and the penetration rate of air conditioning systems in the residential sector, assuming one unit installed for each dwelling. This was done by reworking data from the database of the project “ODYSSEE” (ODYSSEE, 2014), for the reference year 2010;
- **Lighting.** Starting point for the stock calculation for the representative products in the area of lighting is the overall electricity consumption for lighting of the residential sector in 2010 (based on respective data in ODYSSEE, 2014). This electricity consumption is then distributed among the various lamp technologies used in households proportionally to the average installed power for each of them (i.e. incandescent lamps, compact fluorescent lamps, halogen lamps, etc.) in a dwelling. This installed power of each lamp technology in the residential area is derived from the latest Ecodesign preparatory study in this area (VITO, 2015) with reference to the year 2010. In a subsequent step, this annual electricity consumption per lamp technology was then divided by the related average annual operating hours (giving the overall kWh per light source) and then further divided for the average power of each light source in order to get the total stock of lamps.

Table 1 summarizes the resulting stock data for the year 2010 (i.e. for the baseline scenario), together with the average lifetime

[1] European in the context of this study means the European Union (EU) before the adherence of Croatia, also commonly called “EU-27" (due to its 27 member states) in 2010.

Table 1
Stock data, average lifetime, average consumption, and share of stock covered by the representative products of the selected household appliances in the 2010 baseline scenario.

Product group	Representative product	Stock 2010 [units]	Lifetime [years]	Annual consumption [units per person]	Share of EU stock covered (%)
Dishwashing	Dishwasher 10 ps Dishwasher 13 ps	82,799,000	12.5	0.0132	100%
Washing and drying machines	Washing Machine (7 kg capacity)	185,828,000	12.5	0.0296	100%
	Electric condenser tumble dryer (3.4 kg capacity)	63,037,000	13	0.0058	60%
Refrigerators	Combined refrigerators-freezers	299,289,000	15	0.0222	56%
Air conditioning	Room Air conditioner (RAC) (3.5 kW, reversible single split)	28,077,000	15	0.0037	100%
Cooking appliances	Electric oven (built-in)	216,000,000	19	0.0102	45%
Lighting	Compact fluorescent lamp	1,485,936,000	12	0.2464	100%
	Halogen lamp, low voltage	902,902,000	4.4	0.4084	100%
	Halogen lamp, mains voltage	1,058,346,000	3.3	0.6382	100%
	Incandescent lamp	1,575,695,000	2.2	1.4254	100%
	LED[a]	0	34.2	0.000	100%
Computer	Notebook	211,039,000	5	0.0284	40%
Television	LCD TV screen 32“	332,254,000	6	0.0584	53%

[a] LED are mentioned as used in scenarios but not part of the 2010 BoP.

(i.e. the real use phase of these appliances) and the resulting average consumption of the various household appliances by an average European citizen.

2.2.2. Future scenarios

Building upon the data and the results of this Baseline Scenario 2010, a total of twelve different future scenarios have been examined in the frame of this study dealing with a reduction of the impact in the use phase, with changes in the stock characteristics, and with changes of the user behavior respectively. The selection of the scenarios encompassed several scales, from the improvement of the efficiency of the products (i.e. the micro scale), to the improvement of the energy mix (representing the meso scale), up to the accounting for behaviors as well as to patterns of consumption affecting the overall appliances stock (i.e. the macro scale). This choice is made along the line of unveiling the role of the different interventions in terms of eco-efficiency and eco-effectiveness (Hauschild, 2015). Table 2 gives an overview of the here analysed scenarios.

2.3. Life cycle inventory data

Life cycle inventory (LCI) data for the representative products (for the baseline scenario 2010) of these different product categories have been gathered for their entire life cycle – starting from the extraction of the required raw materials, up to the end-of-life treatment (i.e. recycling, disposal) of the used product. A detailed overview of all covered processes and activities along all life cycle stages is given in Table 3.

The compilation of these LCI data started - whenever available - from the respective Ecodesign preparatory study (e.g. from Boyano et al., 2017b for the Dishwasher) and was completed - if necessary - with further data sources. If no such preparatory study has been available or when those data haven't been judged as being up-to-date for the year 2010, other data sources have been used. Table S1 (in the supplementary materials) summarizes the various sources used for the LCI datasets of all here examined, representative products. More detailed information of all these inventories can be found also in Reale et al., (2019). Table 4 summarizes the key elements (i.e. composition data, energy consumption, specification of maintenance and End of Life (EoL) treatment) of the modelled, representative products being part of the BoP appliances, and used for the calculation of the baseline scenario for 2010. Within these materials composition data listed in Table 4, covering the devices as well as their packaging, the category “electronics” is not modelled in a similar manner for all the examined devices; as for some of the devices this amount represents only the actual electronic components (i.e. printed wiring boards - PWBs - with the various, mounted components), while in other devices this share contains also cables, motors and further elements. For the television and the notebook, the PWBs are modelled with the respective dataset for a laptop computer, available in the background database (ecoinvent v3.2), while the PWBs of all other devices are modelled with the market dataset for unspecified, surface mounted, lead-free PWBs. In all cases, the modelling is done in a way that no materials is omitted or counted twice. More detailed information about the material compositions (including e.g. a detailed split of the packaging materials) can be found in section 1 of the supplementary materials.

For the manufacturing of each device, the European electricity mix[2] is used for the share of production that is known to happen in Europe. For the share of production known to happen outside Europe, a specific electricity mix was created, representing the real conditions of the production sites (according to the share of imports coming from extra-EU countries). The modelling of distribution and retail again takes into account the share of products that is imported from outside Europe, modelling the related transportation efforts (i.e. means of transport and distances), based on the different exporting countries (identified in respective statistical data (Eurostat, 2017). For the share of consumed products produced in Europe, the transport is modelled according to the “local supply chain” defined within the Product Environmental Footprint Category rules (PEFCR) guidance (European Commission, 2018). The transport from distribution centre/retail to the final consumer is part of the use stage. A transport for 250 km by VAN, Euro 3 is considered for all products.

3. Results and discussion

Results of the baseline scenario for 2010 and the tested future scenarios are reported in the next sections, complemented with a discussion on the overall environmental impact reduction potential associated with the different interventions. A comparison with other studies is hardly possible – as indicated in section 1, past

[2] Dataset “Market group for electricity, medium voltage (Europe without Switzerland)” from ecoinvent v3.2 (recycled-content model).

Table 2
Ecoinnovation scenarios examined in this study.

Area of intervention	Possible kind of action	Scenario analysed	Assumptions
Reduction impacts of the use phase	Production of energy with less impacts	[1] Use of a more renewable electricity mix (European Electricity Mix 2030)	Based on data in (European Commission, 2016), an electricity mix with 42.9% of renewables is assumed (8% biomass-waste; 10.7% hydro; 17.3% wind; 6.6% photovoltaic; and 0.3% geothermal). More details can be found in Table S5
	Use of more energy efficient devices	[2] Improved efficiency of Dishwasher	Scenario with most favorable combined results for energy savings and life cycle costs reported in Boyano et al., 2017b is used, taking into account all related changes of the BOM (bill of materials).
		[3] Improved efficiency of Washing Machine	Scenario with most favorable combined results for energy savings and life cycle costs reported in Boyano et al., 2017a is used, taking into account changes for the amount of detergents. This scenario requests no changes of the BOM. No increase of machine capacity is taken into account neither.
		[4] Improved efficiency of Refrigerator	Best available technology (BAT) scenario according to VHK, 2016 is used – including all consequences on the level of materials (i.e. thicker insulation layer and larger outside dimensions in order to keep storage volume constant) along the complete life cycle of the device.
		[5] Improved efficiency of Television Device	BAT scenario, based on Götz, 2015, assuming an average screen size of 46 inches and a (constant) lifetime of 6 years with a constant BOM of the device.
Reduction of ozone depleting substances	Less emission	[6] Reduction of refrigerant leakages during the use of air conditioners	Release limit of 1% per year from Germany's "Chemikalien-Klimaschutzverordnung" for HFC-containing devices with more than 100 kg of refrigerant is applied here.
	Less harmful substance(s)	[7] Substitution of current refrigerants	R600a (i.e. isobutene) as substance with zero ODP and low GWP (VHK, 2016) used instead of R134a (used in baseline scenario) in a 1:1 replacement (due to a similar COP, coefficient of performance, according to Heinrich et al. 2015).
Changes of stock characteristics	Introduction of new technology	[8] Increased share of LED lighting sources	Based on VHK 2016, a split of 70% LED lamps and 30% compact fluorescent lamps is assumed for 2030 – assuming same amount of lamps as used in the baseline scenario.
Changes of User behavior	Density devices in society	[9] Amount of devices per inhabitant	Increases (and few decreases) of specific appliances based on 2030 projections (e.g. a 305% increase in air conditioning and a phasing out from the market of incandescent and halogen lamps). Details are provided in Table S6.
	Increase of reusability	[10] Increase of remanufacturing and reuse	No reuse for lighting, laptop and LCD television; for all other reuse of the high-quality models is assumed – i.e. 10% (washing machine, refrigerator, electric oven), 15% (dishwasher), 20% (tumbler dryer); The life-time of a reused devices is assumed to be 1/3 of the first life; impacts of repairing are multiplied by a factor of 2 in order to count for the preparation of these devices for the 2nd life.
		[11] Increase of the collection rate	A uniform 90% collection rate for all product groups others than halogen and incandescent lamp is assumed here
		[12] Increase of the recycling rate	Increased recycling rates based on recycling potentials reported in (Seyring et al., 2015) (e.g. 98% for all metals or 95% for PWB from TV and laptops). The complete list is available in Reale et al., (2019).

Table 3
System boundaries (i.e. covered life cycle stages and included activities/processes) for the baseline scenario of the BoP appliances.

Covered Life Cycle Stages	Included Activities/Processes
Manufacturing components	• Production of raw materials • Processing of raw materials • Transport of components to factory where manufacturing takes place
Manufacturing of product	• Assembly of components
Packaging	• Manufacture packaging • Transport of packaging to factory • Final disposal packaging (landfill, incineration, energy recovery, recycling)
Distribution and retail	• Transport packaged product from factory to Retail/Distribution Centre
Use phase	• Transport of product from Retail/Distribution Centre to final consumer • Consumption of energy and water from the use of the product • Use of detergents and salt, if any (detergents, salt and additives (rinse off) for Dishwashers and detergents and additives – e.g. softeners, bleaching agents, etc. - for Washing machines) • Waste management, if any (e.g. wastewater treatment of product used).
Maintenance and repair	• Manufacturing of components to be substituted (production and processing of raw materials, transport of materials to factory) • Waste management of substituted components
EoL of the product	• Sorting of materials/components • Recycling • Incineration and energy recovery • Landfill

studies investigated specific types of appliances (see e.g. air conditioning -Ross and Cheah, 2017; fridges - Dekoninck, and Barbaccia, 2019; cooking ovens -Landi et al., 2019 just to name a few) and applied a focused set of scenarios (e.g. on end of life only, as in Pérez-Belis et al., 2017). The available studies went much more into the details on a technical level, whereas our study looked at the effect at macro scale. Hence, no similar work has been published so far. Adopting a different angle, Input output LCA based studies exist and recent studies tried to find a match between bottom-up and top down approaches (see e.g. Castellani et al., 2019 comparing

Table 4
Key data and assumptions considered for the modelling of the representative products included in the BoP appliances (as used in the baseline scenario).

	DishWasher 13ps	DishWasher 10ps	Washing machine	Tumble dryer	Combined refrigerator-freezer	Electric oven (BI)	Notebook	LCD TV screen	RAC	Compact fluorescent lamp	Incandescent lamp	Halogen lamp low voltage	Halogen lamp medium voltage	LED
(i) Product Composition														
Total Weight (in kg)	*47.8*	*41.5*	*66.7*	*42.2*	*69.6*	*28.4*	*2.1*	*10.9*	*44.8*	*0.06*	*0.03*	*0.03*	*0.02*	*0.15*
Plastics	22.7%	20.3%	17.7%	32.0%	34.0%	2.3%	21.6%	47.6%	18.0%	23.0%	5.2%	–	–	19.7%
Glass	–	–	2.8%	4.4%	10.0%	14.5%	0.4%	–	–	45.3%	89.2%	96.9%	86.1%	10.7%
Metals	57.3%	59.6%	48.9%	58.9%	54.6%	82.8%	22.2%	35.5%	75.5%	3.7%	4.2%	1.8%	6.6%	51.6%
Electronics	2.9%	2.9%	0.3%	4.7%	0.5%	0.4%	55.8%	16.5%	3.3%	24.8%	0.6%	0.3%	0.8%	18.0%
Other materials	17.1%	17.2%	30.3%	–	0.8%	–	–	0.4%	0.5%	3.2%	0.8%	1.0%	6.5%	–
Refrigerant					0.1%				2.7%					
(ii) Packaging Composition														
Total Weight (in kg)	*1.33*	*1.07*	*2.92*	*2.90*	*4.65*	*2.39*	*0.19*	*0.90*	*3.92*	*0.06*	*0.06*	*0.03*	*0.06*	*0.04*
Cardboard and paper	30.5%	28.4%	78.1%	77.0%	63.29%	54.8%	77.0%	76.9%	77.0%	90.0%	90.0%	90.0%	90.0%	90.0%
Plastics	69.5%	71.6%	21.9%	23.0%	36.71%		23.0%	22.9%	23.0%	10.0%	10.0%	10.0%	10.0%	10.0%
(iii) Use characteristics														
Energy (kWh/a)	398	398	140.4	450	290	164	52	237	384	5.6	24.3	16.4	16.4	0
Water (L/a)	5,180	5'180	11,000	–	–	–	–	–	–	–	–	–	–	–
Lifetime (a)	12.5	12.5	12.5	13	15	19	5	6	15	12	2.2	4.4	3.3	34.2

More detailed information can be found in Tables S2 and S3 of the supplementary materials.

Table 5
Results for the BoP appliances in EU in 2010 (Baseline Scenario – i.e. annual consumption and use of household appliances by average EU-27 citizen), expressed with the Environmental Footprint method (i.e. the EF 3.0 method).

Impact category		Unit	Baseline Result
Climate change	GWP	kg CO_2 eq	3.48E+02
Ozone depletion	ODP	kg CFC-11 eq	8.85E-05
Particulate matter	PMFP	kg $PM_{2.5}$ eq	1.04E-05
Ionizing radiation	IRP	kBq U^{235} eq	1.27E+02
Photochemical ozone formation	POFP	kg NMVOC eq	8.95E-01
Acidification	AP	molc H^+ eq	2.10E+00
Terrestrial eutrophication	TEP	molc N eq	3.01E+00
Freshwater eutrophication	FEP	kg P eq	3.70E-01
Marine eutrophication	MEP	kg N eq	4.42E-01
Human toxicity, cancer effects	HTPc	CTUh	2.17E-07
Human toxicity, non-cancer effects	HTPnc	CTUh	6.53E-06
Freshwater ecotoxicity	FETP	CTUe	7.06E+03
Land use	LUC	kg C deficit	1.95E+03
Water resource depletion	WDP	m^3 water eq	1.55E+02
Fossil Resource depletion	FRD	MJ	7.01E+03
Mineral Resource Depletion	MRD	kg Sb eq	1.27E-02

bottom up with Exiobase). However, a matching between the product categories (e.g. among the 167 product categories of Exiobase, the closest is "furnishing, household equipment and maintenance") and the products selected as representative in the BoP Appliances is not possible.

An overview of the characterized results per functional unit (i.e. for an annual consumption and use of household appliances by an average EU-27 citizen) is shown in Table 5. Table 6 gives an overview of the resulting benefits and/or additional burdens from the different (future) scenarios investigated. Further numerical results in relation to the below figures can be found in Tables S7–S9 of the supplementary materials.

3.1. Baseline scenario for the year 2010

In order to be able to get a comprehensive overview of the most relevant elements in terms of lifecycle stages as well as contributing appliances of the situation in 2010 (i.e. the baseline scenario), the related LCA results have been calculated and analysed in two different directions – each time applying the functional unit "annual consumption and use of household appliances by an average EU-27 citizen". These two directions are (i) an analysis of the contributions of the different categories of household appliances, and (ii) an analysis of the contributions of the various lifecycle stages of all the household appliances that an average citizen owns nowadays. Figs. 1 and 2 summarize the results of these two different view angles.

The results in Fig. 1 show dishwasher, washing machine, refrigerator and television as the most relevant appliances. This is partially due to their specific impact per unit and partially to the high number of those appliances owned by European households. Mainly due to the latter reasons, lighting shows also a rather high contribution in this scenario. Air conditioners dominate the factor ODP due to the losses of refrigerant into the environment, while in all other impact categories, these devices are of minor relevance only. Finally, the factor MRD is dominated by the LCD Televisions due to their high amount of electronic components.

When investigating the various lifecycle stages as shown in Fig. 2, the actual use of the devices dominates the impacts, followed by the materials used for their production. The latter dominate by more than 90% the factor MRD. All other lifecycle stages distinguished within this study show a rather limited contribution to the overall impacts, except in case of the factor ODP, where the maintenance step shows a contribution in the order of almost 20%. The

Table 6
Results for the future scenarios of the BoP appliances. Shown are the changes, expressed in % compared to the overall 2010 Baseline Scenario (Scenarios 1 and 9 to 12), and in % compared to 2010 baseline scenario of the respective category (Scenarios 2 to 8), with the chosen Baseline result set each time as 100%. A negative value represents a reduction of the impacts compared to the baseline. For the acronyms of the impact categories, see Table 5.

	Use of electricity mix with higher share of >renewable sources (Scenario 1)	Use of more efficient and less harmful device (Scenario 2 to 8): Reported are changes in comparison to the 2010 baseline scenario of the respective category (set as 100%)						Changes of User behavior (Scenario 9 to 12) Reported are changes in comparison to the overall 2010 Baseline Scenario (set as 100%)			
		Dishwasher	Washing Machine	Refrige-rator	Air Conditioner	Lighting	LCD Television	More Devices	Increased reuse	Increased collection	Increased recycling
GWP	−24.3%	−39.6%	−37.2%	−50.9%	−24.0%	−71.8%	−38.5%	37%	−2.2%	−0.56%	−0.12%
ODP	−1.2%	−34.8%	−33.0%	−78.2%	−97.0%	−73.0%	−40.5%	181%	−1.2%	0.78%	0.31%
PMFP	−21.5%	−26.5%	−25.8%	−34.4%	−1.8%	−56.1%	−18.9%	38%	−2.2%	−1.33%	−0.25%
IRP	−23.9%	−46.9%	−53.8%	−59.0%	−0.1%	−77.0%	−56.6%	31%	−2.2%	0.28%	0.10%
POFP	−32.4%	−33.1%	−27.7%	−43.8%	0.4%	−65.2%	−29.2%	35%	−2.3%	−0.76%	−0.18%
AP	−47.2%	−34.9%	−36.1%	−48.1%	−0.7%	−69.6%	−34.1%	36%	−2.2%	−1.01%	−0.36%
TEP	−31.4%	−33.2%	−33.6%	−45.1%	−0.7%	−67.3%	−28.8%	36%	−2.2%	−0.48%	−0.14%
FEP	−21.1%	−34.0%	−41.6%	−51.7%	−0.1%	−60.2%	−19.9%	40%	−1.9%	−0.96%	−0.38%
MEP	−21.9%	−35.8%	−41.5%	−45.1%	−0.5%	−68.8%	−31.0%	33%	−2.5%	−0.84%	−0.22%
HTP c	−13.5%	−20.2%	−18.2%	−28.7%	−4.9%	−59.5%	−26.2%	33%	−2.6%	−2.08%	−0.24%
HTP nc	−13.3%	−12.5%	−33.7%	−28.1%	−0.7%	−34.6%	−15.3%	48%	−2.5%	−3.55%	−0.93%
FETP	−11.3%	−25.1%	−38.4%	−34.2%	−0.6%	−49.8%	−14.2%	39%	−2.3%	−1.76%	−0.99%
LUC	36.5%	−39.2%	−39.3%	−53.2%	−0.1%	−73.8%	−42.7%	34%	−2.3%	0.99%	0.36%
WDP	−11.8%	−19.9%	−34.2%	−40.3%	−1.1%	−65.2%	−37.9%	38%	−2.8%	0.26%	0.09%
FRD	−20.5%	−42.4%	−41.9%	−53.0%	−0.2%	−74.0%	−44.7%	33%	−2.2%	−0.14%	−0.02%
MRD	0.7%	−3.1%	−8.7%	−8.5%	−0.2%	82.3%	−0.7%	55%	−1.3%	−0.76%	−0.41%

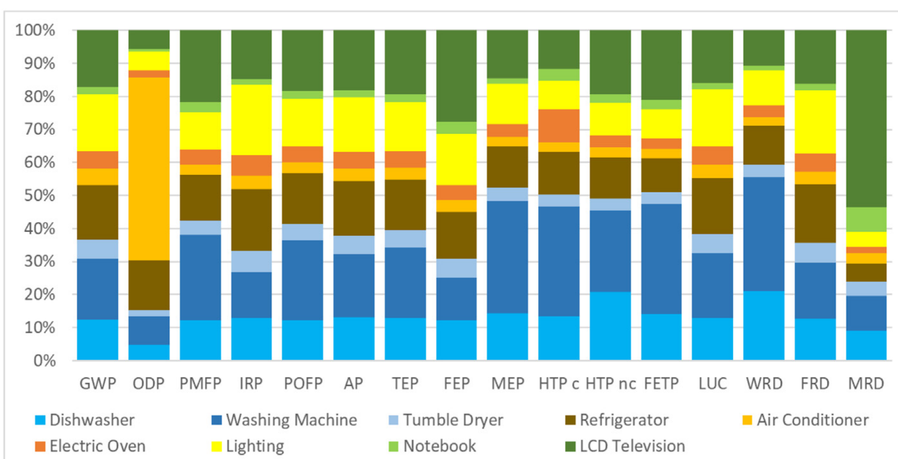

Fig. 1. Contribution analysis per type of household appliances of the environmental impacts (according to the EF 3.0 method) of the annual use of such devices by an average European citizen in 2010 (i.e. baseline scenario). For list of shown impact categories see Table 5.

dominance of the use phase is not a surprise – the BoP here is composed by energy-related products, which were selected as object of the Ecodesign directive in relation to their energy intensity in the use phase. Consequently, electricity production in the applied EU electricity mix results as the most contributing process to a relevant number of impact categories, namely photochemical ozone formation, acidification, terrestrial and marine eutrophication.

3.2. Future scenarios

An overview of the reduction potential of the various tested scenarios is listed in Table 6. Hereinafter, there are the details of the results of each scenario.

Use of a more renewable electricity mix (Scenario 1). This first scenario is taking up the main issue from the analysis of the baseline, i.e. the use phase being the most relevant lifecycle stage among almost all impact categories. There, one issue is clearly dominating: the electricity consumption. With a first scenario, the influence of a change of the electricity mix towards a more sustainable mix on the overall results is investigated. For this, the forecasted mix of gross electricity generation by source in the year 2030 from the report "EU Reference Scenario 2016 – Energy, transport and GHG emissions Trends to 2050" (European Commission, 2016) is used here in order to model the future, more renewable European electricity mix for the year 2030. More detailed information how these statistical data have been translated into an LCA dataset in the frame of this study here can be found in section 2.1 of the supporting materials. This (future) electricity mix has then been applied on the use phase of the original BoP and Fig. 3 summarizes the resulting impacts, taking as reference (set to 100%) the impacts from the 2010 baseline scenario.

All changes (i.e. deviations from 100%) in this figure are caused by the use phase, as this is the only element that has been modified. The resulting pattern shows that such a more renewable electricity mix is not automatically resulting in lower emissions and thus

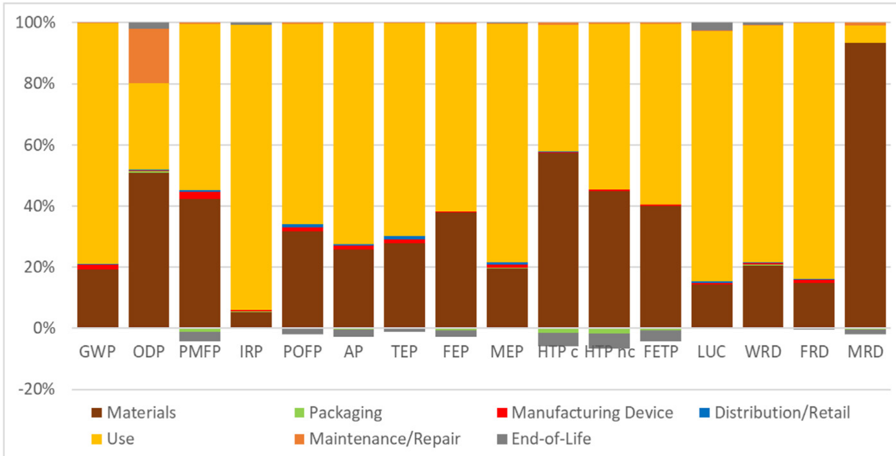

Fig. 2. Contribution analysis by lifecycle stages of the environmental impacts (according to the EF 3.0 method) of the annual use of such devices by an average European citizen in 2010 (i.e. baseline scenario). For list of shown impact categories see Table 5.

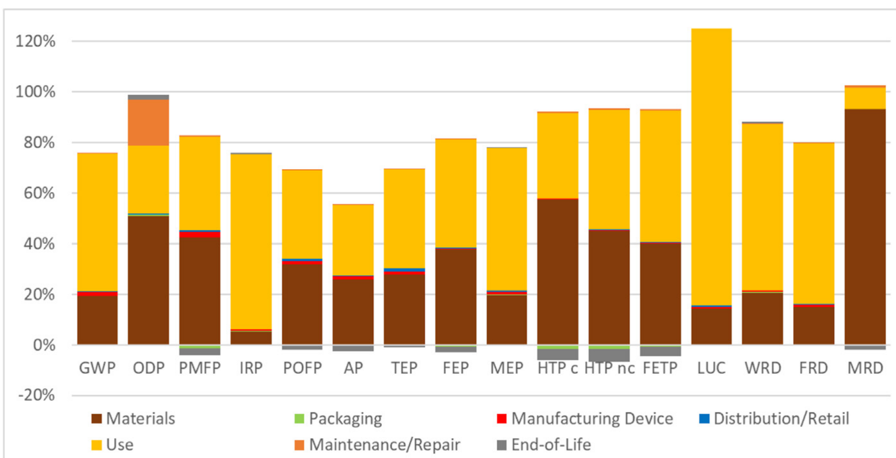

Fig. 3. Influence of the changes in the electricity mix on the impacts (according to the EF 3.0 method) of the annual use of household appliances by an average European citizen in 2030. For list of shown impact categories see Table 5.

impacts. While there are some categories that show a considerable reduction (e.g. AP with more than 40% reduction), two categories (e.g. ODP and MRD) show almost no changes, and there is even one category (LUC) with increasing results. In the area of global warming, the application of this more renewable electricity mix leads to a reduction of almost one quarter of the respective impact, with the use phase remaining by far the most relevant contributor to GWP.

Use of more efficient and less harmful devices (Scenario 2 to 8). In a second step, several scenarios that are dealing with making the actual service that the client gets from these devices more efficient and less harmful have been analysed. Table 2 above summarizes the cornerstones of these scenarios towards more efficient and less harmful devices for the six product categories showing the highest contribution in the baseline scenario (i.e. dishwasher, washing machine, refrigerator, television, lighting and air conditioner). Calculating these various scenarios results in the in Fig. 4 shown reduction potential for each of these product categories – with 100% representing the baseline result of the respective category.

The highest reduction potentials could be observed for the category ODP in case of air conditioners – the change of the cooling substance together with a lower leakage rate can result in a reduction potential bigger than a factor of 20. For GWP, these changes result also in a reduction of the impacts in the order of 20%, while all other categories show hardly any changes in case of the air conditioners.

From the remaining five categories, lighting shows clearly the highest reduction potential – ranging from about 75% (e.g. for ODP or IRP) to at least 33% (for FEP and FETP, respectively). In the same time, lighting is also the only category that shows an impact that increases (MRD) to almost twice the value from the baseline scenario; being the result from the technology change (towards LED – consuming much more high-impacting resources). The reduction for all other categories is the result mainly from the considerable reduction of the energy consumption in its use by almost a factor of 7 (i.e. from 404 kWh/year down to 61 kWh/year in a single dwelling); representing the by far highest energy saving potential of all here examined product categories.

For the four remaining, bulky devices (dishwasher, washing machine, refrigerator and television), the applied efficiency measures – mainly in the area of energy consumption in the use phase – results in most of the here examined impact categories in a reduction potential of 20–40% compared to the respective baseline.

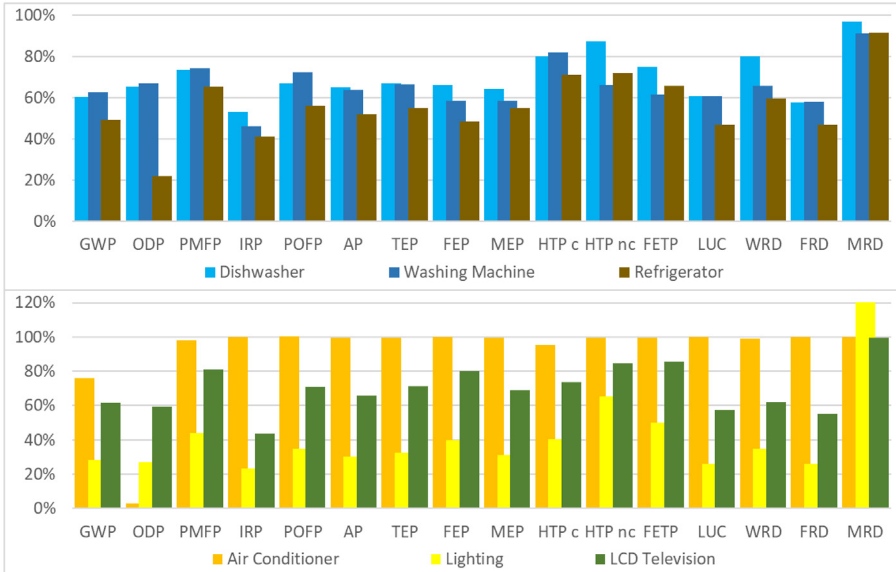

Fig. 4. Reduction potential due to their increasing efficiency of the annual use of the most relevant household appliances by an average European citizen in 2030. Shown is the resulting impacts (according to the EF 3.0 method) for the here modelled, most efficient devices in comparison to the 2010 baseline scenario of the respective category. For list of shown impact categories see Table 5.

Due to the change of the refrigerant (from R134a to R600a), the refrigerator shows for ODP and GWP a further reduction potential compared to the other bulky devices – leading for ODP to about 5 times less impacts than in the baseline calculation.

Influences from changes in the user behavior (Scenario 9 to 12). Within the user behavior, two different view angles have been investigated - a high-level view looking on the number of devices that each individual European citizen owns, and a more detailed, device-specific view looking on the way, how such devices are actually used. In the latter case (as listed in Table 2 above), the aspects of an increasing reuse, an increasing collection and an increasing recycling rate are distinguished and analysed individually. All these aspects have however only a minor influence on the overall impacts – their reduction potential never exceeds 3%; while the first one (i.e. the reuse of devices) shows a reduction potential of 2–2.5% for all factors (except ODP), an increase of the collection and/or the recycling activities hardly influences the overall results (see also Fig. S1 in the supplementary materials).

Changing the view angle towards the above mentioned, high-level view (looking on the number of devices that an individual citizen owns), leads to a considerable different result – result shown in Fig. 5. Here, all the examined impact categories show a more or less uniform increase of the impact in the order of 35–40% for the annual use of household appliances of an average citizen – except for ODP, where the increase is in the order of 180%. The latter is due to the expected much higher increase of air conditioners in the coming two decades (more than 3 times more such devices are expected per citizen in 2030, compared to the situation in 2010); this is thehighest increase compared to all other product categories, as can be seen from the data in Table S6 in the supplementary materials.

Overall potential (combining scenarios 1 to 12). Last but not least, the overall potential, when combining all these individual ecoinnovation scenarios together, has been calculated. This calculation is established in four subsequent steps, adding up the intermediate results each time, in order to allow a more easy identification of the relevance of each type of ecoinnovation. The four individual steps distinguished in this final calculation – going from the micro up to the macro scale – are the following:

- "Efficiency of the Devices" – being a first part of the micro scale and representing the total of the scenarios 2 to 8 (dealing with the use of more efficient and less harmful devices);
- "Increased Usability" – being the second part of the micro scale and representing the total of the scenarios 10 to 12 (dealing with an increasing reuse, increasing collection and increasing recycling of these different devices);
- "Changed Electricity Mix" – representing the meso scale with the application of the in Scenario 1 specified future, more sustainable European electricity mix for the use phase of all examined product categories;
- and "Increased Amount" – representing the macro scale in this study by applying the forecasted increase of amount of household appliances per average European citizen identified within scenario 9.

Fig. 6 shows the results of this stepwise calculation of the overall potential that lays in the sum of all here examined ecoinnovation scenarios, illustrating the relative importance of interventions at the three here distinguished scales (as summarized in the list of bullet points above).

The overall potential of all the examined ecoinnovation scenarios is a mix of measures on three scales (micro – meso – macro) and it results in a significant reduction of the impact for most of the categories (with up to 67% for ODP, and still around 35% for GWP). However, two of the examined impact categories (i.e. LUC and MRD) show an overall potential that is negative – i.e. the sum of all these future scenarios together results in a higher impact compared to the impact of the 2010 baseline scenario.

The stepwise projection in Fig. 6 shows clearly that the scenarios on "Increased Usability" influence the overall results the least; only in case of HTPnc and MRD these three scenarios lead to changes of 10% or more; in all other categories their induced changes are clearly lower. Hence, the overall reduction on the micro scale – ranging from 14% (MRD) to 77% (ODP), with an average of 39% – is mainly due to the scenarios summed in "Efficiency Devices". This

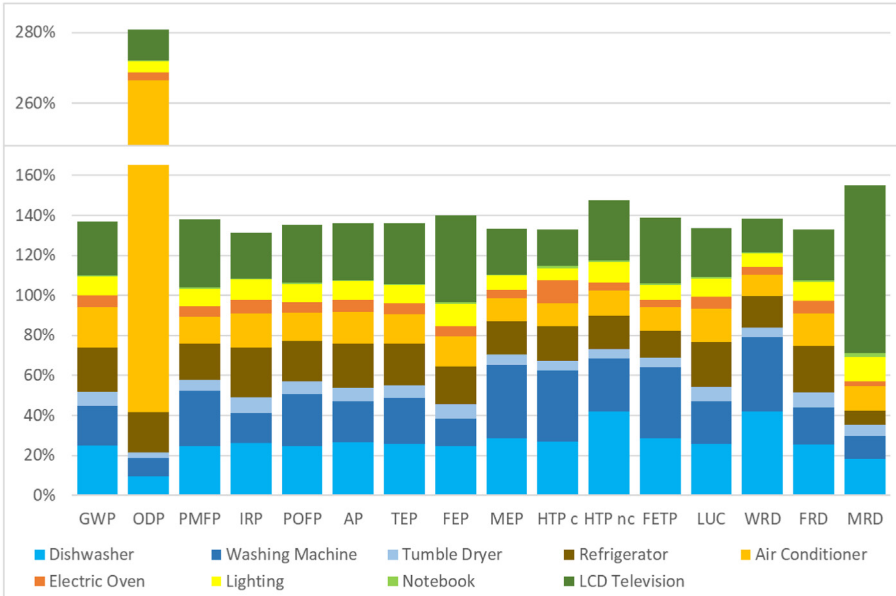

Fig. 5. Impacts (according to the EF 3.0 method) of the annual use of household appliances by an average European citizen in 2030, taking into account the increasing amount of devices per household. For list of shown impact categories see Table 5.

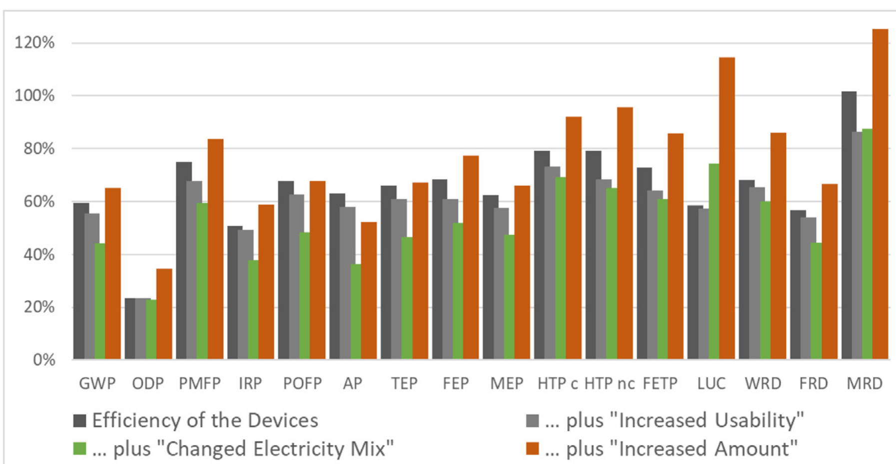

Fig. 6. Overall (reduction) potential for the annual use of the household appliances by an average European citizen in 2030 when applying all ecoinnovation scenarios. Shown is the resulting impacts (according to the EF 3.0 method) stepwise (details see text) in comparison to the 2010 baseline scenario. For list of shown impact categories see Table 5.

scale represents the main portion of the overall reduction potential – the two other scales (i.e. meso, macro) show a much lower impact. While the first allows for most of the impact categories a small, further reduction, ranging from less than 1% (ODP) to about 20% (AP) – with two categories (LUC and MRD) showing an increase of the impacts on this scale. The macro scale shows for all factors an increase of the impacts – ranging from 12% (ODP) to about 40% (LUC, MRD) – with an average increase on the macro scale of 22.5%. All in all, the results show that the latter scale counterbalances clearly all reduction effects coming from the lower scales.

4. Conclusion

With the Consumer Footprint, the European Commission has created an approach that allows for the first time a comprehensive evaluation of the environmental impacts related to the consumption behavior of an average European citizen. The here examined BoP appliances represents the most relevant product groups of household appliances in terms of energy consumption and market share, in line with the Ecodesign directive (European Union, 2009) as the most relevant regulatory framework related to these types of products. Using an average product per product group leads to a sort of bottom-up approach, allowing analyzing improvement options on the product level. The approach does not allow to examine the influence of individual parameters of the covered product categories (e.g. the energy efficiency of different types of products in the market or the differences in material composition of products from different brands or technologies). The calculation results for the 2010 baseline scenario confirm the high relevance of the use phase over all the other life cycle phases considered, due to electricity use. Within the use phase, the energy efficiency of the products as well as the consumer behavior (i.e. intensity of use) are the two main factors that determine the resulting impacts. Across the examined BoP, large appliances such as washing machines, dishwashers and refrigerators, together with the TV screen and the lighting are those product groups that contribute the most to the overall impacts. This is partially due to their high impacts per unit, but partially also due to the high number of those appliances owned by the average European citizen.

As in all LCA studies, all the results are affected by uncertainties and limitations related to the representativeness of the set of selected products together with the assumptions used in the respective life cycle models, the completeness and representativeness of the used LCI datasets, as well as known limitations in the LCIA method used (like e.g. those ones concerning the impact assessment models addressing resources or toxicity). Nevertheless, the main conclusions out of the results obtained here seem nevertheless rather reliable and they can be considered relevant in order to support several policies acting at the product level, such as the already several times mentioned Ecodesign directive (European Union, 2009) or the WEEE directive (European Union, 2002). But also for policies with a broader scope, related to resource efficiency, critical raw materials and circular economy, this study here gives valuable hints and inputs. Last but not least, the BoP of this study has been established in a way that it can be easily adjusted and/or adapted in order to examine scenarios acting on different user behaviors in light of the current increasing interest in behavior-oriented policies, which may affect both the selection and the use of products.

According to the figures from the present study, the assessment of the environmental sustainability of appliances should always include several scales. The expected improvement in efficiency of the products (micro scale), should be assessed together with the improvement of the energy mix (meso scale), while accounting for the socio-economic drivers and patterns of consumption affecting the overall appliances stock (macro scale).

Declaration of competing interest

None.

CRediT authorship contribution statement

Roland Hischier: Conceptualization, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Francesca Reale:** Conceptualization, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Valentina Castellani:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Serenella Sala:** Conceptualization, Methodology, Validation, Writing - original draft, Writing - review & editing.

Acknowledgements

The present work is based on the research performed by the authors within the JRC and/or for the JRC, and was financially supported by the Directorate General for the Environment (DG ENV) of the European Commission in the context of two Administrative Arrangement "Ecodesign 4 Circularity" (N° 070201/20157SI2.719458/ENV.A.1) and "Indicators and assessment of the environmental impact of EU consumption" (N° 070201/2015/SI2.705230/SER/ENV.A1).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.121952.

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