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Optimum operational lifespan of household appliances considering manufacturing and use stage improvements *via* life cycle assessment

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ABSTRACT

To lessen the residential sector environmental burdens from the energy consumption of household appliances, notable efforts have been directed to replace existing energy-consuming appliances by new energy-efficient equipment. However, less attention has focused to understand the optimum operating period of households so reduced greenhouse gas emissions can be achieved. Conventional household appliances should be preferably replaced with new designs featuring improved energy efficient models, along with reduced environmental burdens associated with the manufacturing of the new products. Such studies, to the best of our knowledge, have not been extensively investigated. To address this gap, the global warming potential during the life cycle of three representative household appliances, a microwave oven, a dishwasher and a washing machine is analyzed using a *cradle-to-grave* life cycle assessment. To provide guidelines towards impact reduction, the current situation and four new scenarios focused on material efficiency, recycled material, renewable electricity and responsible consumption are analyzed. Depending on the scenario, impacts of 84–261, 317–1330, and 533–1375 kg·CO_2 eq/lifetime are obtained for a microwave, a dishwasher and a washing machine, respectively. Balancing energy efficiency and life-time when replacing a class A appliance, operating periods of 3.4–30, 2.7–26.2 and 4.6–33.9 years for microwaves, dishwashers, and washing machines, render the lowest CO_2 footprint. These results may assist manufacturers, policymakers and citizens to promote environmentally sustainable production and consumption patterns.

1. Introduction

Ensuring environmentally sustainable production and consumption patterns is becoming an increasingly relevant need for most of the societal actors including primary industries, citizens, businesses, policymakers and third sector organisations (Figueiredo Nascimento et al., 2016). Environmental sustainability is now considered as a key driver from innovation in many corporate strategies (Grigorescu et al., 2020), while citizens seek additional sustainability metrics of products to make informed decisions (Sauermann et al., 2020). These new trends are coupled with the push-pull effect arising from the implementation of environmental policy instruments (Horbach et al., 2012). The transition towards more sustainable production and consumption patterns (Sustainable Development Goal 12) inevitably passes through the implementation of a Circular Economy model, where wastes and pollution are ideally eliminated, resources (in terms of materials and products) are circulated, and natural systems are regenerated (Ellen MacArthur Foundation, 2017). The reuse of goods and components is considered the key Circular Economy action to reduce the consumption of virgin resources and avoid the generation of new waste streams such as CO_2 emissions (Foster, 2020; Sandin and Peters, 2018). Therefore, much work has been devoted during the last decade to prioritize reuse over other inner loop strategies such as repair, refurbish, remanufacture, and finally recycling.

However, when it comes to energy related products, the energy consumption upon use plays a predominant role defining the CO_2 emissions of the whole life cycle (Omer, 2009). With a worldwide 37% increase in the 2013–2020 period, household appliances represent a core area of consumption and their use is expected to grow notably over the coming years (Statista Research Department, 2014). The energy consumption of residential buildings represented the 27.2% of the aggregate energy consumption in the European Union during 2017 (Damigos et al., 2020), which increased up to 40% in countries such as Ghana (Sakah et al., 2019). Although these appliances generate CO_2

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emissions in all of their life cycle stages, the use phase represents a major environmental burden in energy related products such as microwaves (Hischier et al., 2020), dishwashers (Gallego-Schmid et al., 2018), or washing machines (Yuan et al., 2016). In this framework, the European Commission defined in its Ecodesign Directive (Directive 2009/125/EC) an energy-related product as any energy-using product or energy-saving product having an impact on energy consumption during use (Directive 2009/125/EC, 2009). This directive establishes common baselines for specific implementing measures regarding energy-related products being sold within the European Union, covering more than 40 product groups including air conditioning, TVs, microwaves or fridges. Products that comply with this directive bear the CE marking and can be commercialized.

Energy saving and management in the residential sector is becoming of increasing relevance in the fields of energy systems and smart grids (Aiad and Lee, 2018). With the aim of reducing energy consumption, 2009/125/EC framework directive, together with the Energy Label Directive (2010/30/EU), relate the energy consumption according to its energy efficiency, and rank the energy efficiency of products on an A (green) to G (red) scale. It is commonly argued that notable energy saving could be achieved upon the replacement of existing electrical appliances by energy-efficient appliances (Damigos et al., 2020). Accordingly, several programs have been implemented to encourage businesses and citizens to replace their existing electric appliances by more efficient equipment as a way to transition towards more sustainable consumption schemes that reduce the impact on the environment (Nishijima et al., 2019). New circular business models focused on appliance leasing or pay-per-use are being established as a way to obtain material use benefits (Sigüenza et al., 2021a; Sigüenza et al., 2021b). In this sense, A to G energy label has been a success as nearly 85% of the European consumers recognize and use this system when purchasing, while it has also boosted innovative industry development. Energy efficiency measures are expected to result in annual energy savings of 38 TWh by 2030 in Europe (note that new labels have been launched in stores and on-line from March 1st 2021) (New Energy Efficiency Labels ExplainedAvailable at2019accessed on march, 2019).

However, the trade-offs between the direct energy savings arising from the increased efficiency of a product and the material and energy inputs required to manufacture a new product remain open to debate. Under certain conditions and environmentally speaking, it may be preferable to continue using high energy-consuming equipment rather than replacing them by new energy-efficient equipment (Ardente and Mathieux, 2014; Iraldo et al., 2017). In this sense, the questions that arise are: *For how long an appliance could be used under a certain energy efficiency context, before it becomes an environmental burden? How energy efficient an appliance should be to provide environmental benefits when replacing an existing energy related product?*

Accordingly, there is an urgent need to evaluate the greenhouse gas emissions of electric appliances through their operation lifespan so well-informed decisions regarding the optimum working period can be made. This would boost the implementation of sustainable business models where electrical and electronic equipment are used and replaced at the adequate moment (Young, 2008). This information could promote environmentally sustainable and resilient societies guiding consumers and policymakers when considering energy-saving and durability. Accordingly, life cycle assessment (LCA) emerges as a preferred methodology to determine the environmental impacts of a product, process or service throughout its life cycle. LCA enables the assessment of *"the potential environmental impacts and resources used throughout a product's life cycle, i.e. from raw material acquisition, via production and use stages, to waste management"* (Dufossé et al., 2017). Its potential to evaluate the environmental sustainability of different materials, processes and technologies is demonstrated by its gaining relevance in examples as varied as waste electrical and electronic equipment repurposing (Pérez-Martínez et al., 2021), batteries (Iturrondobeitia et al., 2021), or bio-waste valorisation (Sillero et al., 2021).

The quantification of electric appliances can provide light on the most environmentally efficient lifespan of electric appliances. Table 1 summarizes the reference literature and shows the average lifespan values. Based on this information, this work uses lifetime values of 10, 12.5 and 8 years for a washing machine, a dishwasher and a microwave, respectively. Further details on each appliance are given as follows. In Germany, 90% of washing machines last for less than 7 years, rendering an average lifespan of 12 years (Hennies and Stamminger, 2016). This estimated lifetime is similar to the 11.6 years reported by Tecchio, Ardente, & Mathieux (Tecchio et al., 2019). Regarding the Dutch market, a decrease in the average lifetime of washing machines is seen from the 12.1 years in 2000 and to the 11.7 years in 2005. Considering technical data from an Austrian professional repair operator, an average lifetime of 12.6 years is reported for washing machines (Tecchio et al., 2019). For a non-European market such as the Chinese one, the average lifetime of a washing machine is 10 years (Yuan et al., 2016). These results are considered relevant because they serve to construct the Ecoinvent database, used in this work.

When it comes to the dishwasher case, the data obtained from the Swedish market establishes an average lifetime ranging from 10 to 15 years (Johansson and Luttropp, 2009), whereas average values of 12.4 years are reported for Germany (Tecchio et al., 2019), and 10.5 years for the Netherlands (Bakker et al., 2014). A study based on technical data from the Austrian Reparatur-und Service-Zentrum, a professional repair operator, establishes the average lifetime of a non-repaired dishwasher in 12 years (Tecchio et al., 2019). For the dishwasher, the Ecoinvent database uses the average European market values (12.5 years) (Ardente and Talens Peiro, 2015). Finally, an optimistic average lifespan for microwaves estimates a lifespan of 13-to-15 years, with a 30% power loss after 10 years (Cooper, 2020). Data obtained from the Dutch market shows a decrease in the average lifetime, from 10.9 years in 2000 to 9.7 years in 2005 (Tecchio et al., 2019). When taking into account the European market, the average lifetime of a microwave is established in solely 8 years (reference for the Ecoinvent database) (Gallego-Schmid et al., 2018).

The lifespan reduction is often defined as planned obsolescence (Bakker et al., 2014; Hennies and Stamminger, 2016). Several subcategories of obsolescence could be found, being the most representative ones the quality obsolescence (a material decreases its quality), the functional obsolescence (caused by new products with enhanced features), and the psychological or desirability obsolescence (caused by social trends, heavily influenced by advertisement and mass media) (Hennies and Stamminger, 2016). Recent studies have

Table 1
Comparative appliance lifespan (in years) for three home appliances.

Appliance	Hennies and Stamminger (2016)	Prakash et al. (2016)	Bakker et al. (2014)	Tecchio et al. (2019)	Johansson and Luttropp (2009)	Cooper (2020)	Yuan et al. (2016) Ecoinvent 3.7	Ardente and Talens Peiro (2015) Ecoinvent 3.7	Gallego-Schmid et al. (2018) Ecoinvent 3.7	Average values
Microwave oven	–	–	9.7–10.9	–	–	13–15	–	–	8	10.77
Dishwasher	–	12.4	10.5–10.7	12	10–15	–	–	12.5	–	12.00
Washing machine	12	11.6	11.7–12.1	12.6	–	–	10	–	–	11.62

differentiated the absolute obsolescence with entails a total failure of the product, and the relative obsolescence, which refers to a product which is replaced but it could be still used (Cooper, 2004). In any case, the importance of obsolescence lies in the fact that it involves a notable shortening of the operating lifespan of appliances.

The last decade has witnessed several campaigns (with economic incentives) aimed at the replacement of existing appliances by new energy-efficient ones (Wang and Matsumoto, 2021). Some of these initiatives as those in Madrid's community (Spain) do not require a certain age of the old appliance, but just to purchase a new Class A, B or C appliance (Boletín Oficial de la Comunidad de Madrid, 2020). Following the guidelines provided by the Spanish public organization IDAE (Institute for Diversification and Saving of Energy), other Spanish regions such as Galicia are encouraging the substitution of electric appliances (Diario Oficial de Galicia, 2022). Upon buying an A, B or C Class new washing machine, the 25% of the cost (up to 70 €) is granted in Madrid, while 100 € are granted in Galicia and 150 € in La Rioja. For a dishwasher, the economic bonus reaches 110 € in Madrid, 100 € in Galicia and 150 € in La Rioja. Upon the combination of these initiatives, the Spanish energy consumption is expected to be reduced by 16.9 Mtoe (million tonne of oil equivalent) (Galarraga et al., 2013). In other countries of the European Union, such as Romania, the renewal of household appliances is boosted by national programmes, reaching amounts of 400 lei (~80 €) for the purchase of a washing machine (>C-class) or for the purchase of a dishwasher (>D-class) (Administraţia Fondului pentru Mediu, 2022). However, it should be noted that these plans do not integrate a Life Cycle perspective, so the environmental impacts associated with the fabrication of the new appliances are ignored.

In this context where the obsolescence is increasingly present and replacing plans for sustainable purposes are also gaining relevance, two main objectives have driven in this research. The first aim is the determination of the required energy efficiency a new appliance should have to obtain balanced CO_2 emissions considering the average lifespan of three representative household appliances: a washing machine, a microwave and a dishwasher. To that end, CO_2-eq emissions during the whole life cycle are studied. The second goal is the calculation of the optimum working lifespan (replacement year) of selected household appliances in a scenario where the working electric appliances are substituted by a Class A appliance. Especial attention is paid to manufacturing environmental affections of new appliances and the results are compared with the improved efficiency during the use phase of the new appliances. In all the cases, the current and four additional scenarios have been modelled. Overall, this study offers new information that can guide the decision-making process concerning the adequate substitution of household appliances, not only useful for the scientific community but also to policymakers, industrial manufacturing agents and end-consumers.

This work quantifies the life cycle CO_2 emissions of three representative household appliances. To the best of our knowledge, this work represents the first effort to address the optimum appliance operating lifespan (environmentally speaking) considering the trade-offs between manufacturing and use phases. To simulate different lifespan realities the current scenario and other 4 hypothetic scenarios have been modelled. These new scenarios offer further insights to explore novel sustainable strategies in electric appliance design. This research brings quantitative information to avoid the current electrical appliance replacement campaigns which are, in most of the cases, not based on scientific data.

2. Methods

2.1. Scope and Boundaries

As summarized in Fig. 1, in this work the *cradle-to-grave* greenhouse gas emissions of three household appliances are quantified. Life cycle assessment studies are conducted for the current scenario (with current average efficiencies) and additional 4 hypothetical production consumption patterns involving material resource efficiency during manufacturing (Scenario 1 and 2) or the implementation of a 100% renewable energy grid and low energy use patterns during use (Scenario 3 and 4). A microwave oven (MO), a dishwasher (DW), and a washing machine (WM) have been selected to conduct the research as

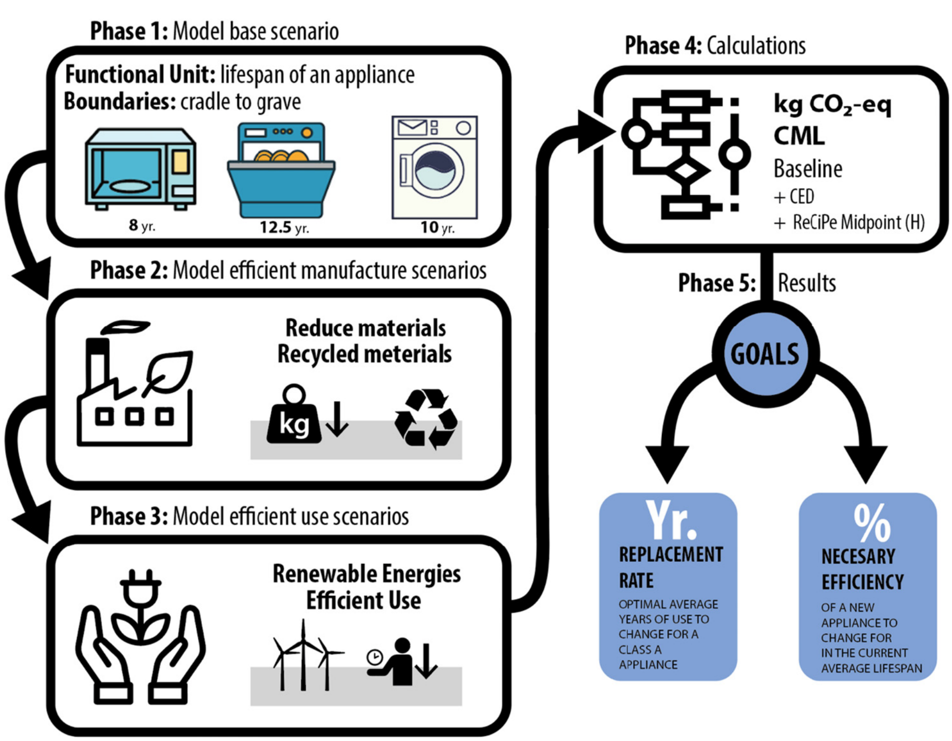

Fig. 1. Followed phases and procedures to perform the LCA analysis. Goals, scope and boundaries for the studied household appliances are also defined in the illustration.

representative product groups of energy-related products considered within the European Union's Ecodesign Directive (Directive 2009/125/EC). These three home electric appliances have been chosen due to their notable economic value and common presence (Golmohamadi et al., 2019; Khan et al., 2018). Although microwaves are excluded from the eco-design and energy labelling regulations for domestic ovens, hobs and range hoods, they represent an important group of household appliances (Gallego-Schmid et al., 2018). Consequently, these appliances have been included in this study.

The CO_2-equivalent emissions of household appliances throughout their whole life cycle are firstly computed to facilitate comparison and draw meaningful conclusions (working with multi-dimensional impact categories can make challenging to draw clear and comparable conclusions), although LCA enables the quantification of additional impact categories. Subsequently, the necessary efficiency improvements and the time required to improve each specific appliance until converting them to class A has been investigated. In essence, the time span at which the CO_2-equivalent emissions arising from the fabrication of a new household are compensated is analyzed. Thus, as shown in Fig. 1**,** the Functional Unit (FU) of the performed calculations is the operating lifespan of each electric appliance (the item itself). This way, the life cycle emission reduction for each modelled scenario could be estimated. Specifically, the FU involves the manufacture (including the corresponding end of life affection as part of the design of the object) and use phase impacts. Fig. 1 also illustrates the phases of the research, divided in 5 steps: modeling the base scenario, creation of manufacturing scenarios, creation of use scenarios, calculation and result interpretation. The main used methodology has been CML-IA Baseline 2016 (v4.7), an updated version of the CML 2 baseline 2000. In the baseline scenario, Cumulative Energy Demand (CED) and ReCiPe Midpoint Hierarchist (H) methodologies have been also used to provide a quantitative reference of the environmental burdens in the selected 7 categories. CED has been used to provide differences between direct energy and energy footprint consumption levels. The Global Warming Potential (GWP) indicator has been calculated using CML-IA Baseline 2016 and ReCiPe Midpoint Hierarchist (H) computing methods, this second method was used for comparison with CML results.

2.2. Designed Scenarios

The base scenario (defined as *Scenario 0*) has been firstly modelled according to Ecoinvent 3.7 database for household appliances. To calculate the whole life cycle impacts, the energy and water use have been estimated according to Table 1. Four additional scenarios have been modelled to understand how different strategies affect the *cradle-to-grave* CO_2-equivalent emissions. The optimum operating lifespan of household appliances (in years, and schematically summarized in Fig. 2) and the required efficiency to replace the appliance at the current average lifespan has been investigated. Scenarios 1 and 2 reflect possible improvements in manufacturing processes; while scenarios 3 and 4 simulate sustainable actions during the use. These five scenarios enable the comparison of different sustainable strategies (advantages and disadvantages) during the complete life cycle. The modelled scenarios are described below:

- *Scenario 1* considers a 10% reduction of the materials required for the production of a new appliance.
- *Scenario 2* estimates that, in addition to the 10% material's reduction, half of the material originates from recycled resources.
- *Scenario 3* hypothesises a 100% renewable energy during the use phase. The base scenario used the electric mix of Spain in 2016 according to the International Energy Agency (IEA). This mix is converted into a renewable mix preserving the current proportions in the grid of solar (4.7%), wind (54.1%), hydro (38.3%) and biomass (2.9%) as summarized in the Supplementary Information, **Table S4** and **S5**. It should be noted that additional 0.03723 kWh are needed as inputs to generate 1 kWh output as a result of the losses.
- *Scenario 4* not only uses 100% renewable energy but also reduces a 10% the consumption during use as a result of a responsible operation of the appliance (lower temperature programs or shorter operating times).

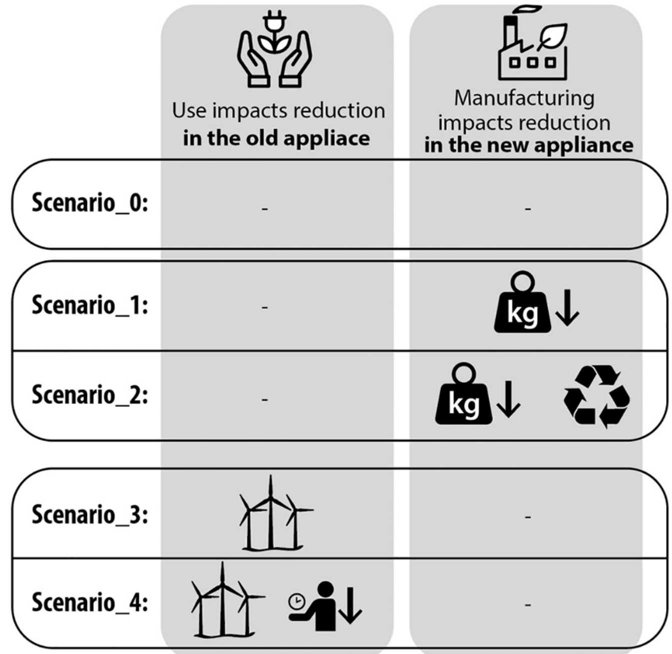

Fig. 2. Modelled scenarios where CO_2-eq emissions are quantified. Summary depicting proposed new four scenarios. To reduce the environmental impacts during use of the existing appliances the implementation of a 100% renewable power supply and a responsible consumption pattern are considered. To reduce the environmental impacts during from the replacement of the existing appliance by a new one, an improved material efficiency (10% weight loss) and recycled materials are considered.

Eq. (1) is applied to account for how energy-efficient (during use) a new appliance should be to balance the CO_2-equivalent emissions of an old appliance.

$$Requiered\ efficiency\ during\ USE_{NEW}\ (\%) = \frac{Manufacture\ (and\ End\ of\ life)_{NEW}}{Use_{OLD}} \quad (1)$$

This equation allows the estimation of the required efficiency (in use phase) for the new appliance, considering the impacts originating from the manufacturing phase of the new appliance and the use-related impacts generated by the existing appliance. The manufacture of the old appliance has been excluded from the equation as we consider it is not further possible to eliminate the impacts that have already occurred.

2.3. Life Cycle Interpretation and Inventory

LCA studies were performed using OpenLCA software and Ecoinvent 3.7 was used to extract data for the manufacturing phase. For the use phase, a literature review has been performed to gather average data of energy and water consumption for each appliance (Table 1). Energy consumption data for each appliance has been extracted from IDAE. The water consumed by the dishwasher and the washing machine is computed according to (Richter, 2011), and (Pakula and Stamminger, 2010), respectively. The detergent use has not been considered with the aim of avoiding impact distribution changes originating from aspects not merely related to the manufacturing phase or the energy

Table 2
Parameters of use phase in each selected household appliance.

	Electrical consumption (kWh/year)	Water consumption (L/year)	Further details
Microwave oven	67.2	Not required	10.6 kg, 17 L capacity, manufactured in China
Dishwasher	245	3780	50 kg, manufactured in Europe
Washing machine	254	9900	75 kg, manufactured in China

consumption during use. The manufacturing of the appliances has been obtained from the version 3.7 of the Ecoinvent database. It considers the transport of materials to the factory, metal and plastic processing, electronic component production (including lamps, wires, transformers or the printed control board), external painting and part assembly (Gallego-Schmid et al., 2018). Packaging has not been included. The material inputs from technosphere and the energy required to produce an average microwave oven, dishwasher and washing machine are taken from (Gallego-Schmid et al., 2018), (Ardente and Talens Peiro, 2015) and (Yuan et al., 2016), respectively (the manufacturing phase is considered starting from the reception of materials at the factory). Relevant information for the base scenario, hereafter referred to as *Scenario 0*, is disclosed in Table 1. Additional details regarding the flow diagrams, material and energy input inventory for the microwave oven, the dishwasher and the washing machine are given in the Appendix-Supplementary materials as **Scheme S1** and **Table S1**, **S2** and **S3**, respectively. This inventory also accounts for disposal of all materials.

A *cradle-to-grave* perspective has been followed to cover the CO_2-eq emissions during manufacturing, use and end-of-life phases. The appliance lifespan is considered as a FU so it is possible to compare the performance of appliance performance throughout their life cycle. The system model was based in a *cut-off* method, where wastes are producer's responsibility and recycled materials are available burden-free to recycling processes (Ecoinvent, 2022). Accordingly, recyclable products are preferred so mining or forestry activities required for the extraction of the new materials are avoided. Regarding the impact calculation, a *unit* approach is followed, where the sub-processes included in the main process are studied observing the contribution-tree.

Product Category Rules (PCRs) enable more comparable LCA results for products having a similar functionality (Del Borghi et al., 2020), even though an LCA does not necessarily requires a PCR to be followed. As a result, obtained information can be contrasted with related products. Accordingly, our study has been performed following available PCRs as far as possible. Although some countries such as the Republic of Korea have their own PCR for microwaves (Gallego-Schmid et al., 2018), we were unable to find an appropriate European-level PCR for the microwave oven, so no PCR was followed in this case. No PCR available for dishwashers is found. In fact, the only reference to dishwashers is based on the detergent use, establishing the EU Ecolabel criteria for dishwasher detergents (European Commission, 2017). Finally, a complete PCR in accordance with the ISO 14025 standard was followed for the washing machine (Environment and Development Foundation, 2008).

Five scenarios are considered to analyze the CO_2-equivalent emissions of household appliances. Firstly, the current market situation is simulated to get information of a base scenario (*Scenario 0*, Table 2). Scenarios 1 to 4 analyze the effect of energy efficiency and the reduction of the material consumption (see Table 3). Specifically, the effect of a weight reduction in metals and plastics consumed during the manufacturing of a new appliance is considered in *Scenario 1*. *Scenario 2* also incorporates recycled materials (50% for aluminium and steel). The implementation of a renewable energy mix during use phase of the existing appliance is considered in *Scenario 3*, and *Scenario 4* incorporates a reduced 10% energy consumption during use due to responsible use patterns. These scenarios should *a priori* show reduced CO_2 emissions as the implementation of renewable energy efficiently improves the environmental performance of household appliances during the use phase (Hischier et al., 2020). As a matter of fact, the greatest benefits in terms of CO_2 emissions during the life cycle of a washing machine (Dutch market) have been related to an efficient transition towards renewable energy (Sigüenza et al., 2021a). This pivotal role of renewable energy has been observed regardless of the business model adopted.

3. Results

3.1. Cradle-to-Grave CO_2-eq Emissions of Household Appliances under Current Scenario

The *cradle-to*-grave CO_2-eq emissions under current market scenario are summarized in Fig. 3. The dishwasher and the washing machine show larger CO_2 emissions in comparison with the microwave oven. Specifically, with a value of 1375–1398 kg CO_2-eq, the washing machine presents the largest contribution to the global warming

Table 3
Characteristics of five modelled scenarios for the *cradle-to-grave* CO_2-eq emissions of a microwave oven (MO), a dishwasher (DW) and a washing machine (WM).

		Weight of materials	Nature of materials	Electrical energy		Energy consumption in use phase	
				Manuf.	Use	Electricity (kWh/year)	Water (L/year)
Scenario 0	MO DW WM	Conventional	Conventional	Conventional	Conventional	67.20 245.00 254.00	– 3780 9900
Changes in manufacture of the new appliance							
Scenario 1	MO DW WM	90% of *Scenario 0* (10% saving)	Conventional	Conventional	Conventional	67.20 245.00 254.00	– 3780 9900
Scenario 2	MO DW WM	90% of *Scenario 0* (10% saving)	50% recycled aluminium & steel	Conventional	Conventional	67.20 245.00 254.00	– 3780 9900
Changes in use of the existing appliances							
Scenario 3	MO DW WM	Conventional	Conventional	Conventional	100% renewable	67.20 245.00 254.00	– 3780 9900
Scenario 4	MO DW WM	Conventional	Conventional	Conventional	100% renewable, 10% reduction (*responsible use*)	60.48 220.50 228.60	– 3402.00 8910.00

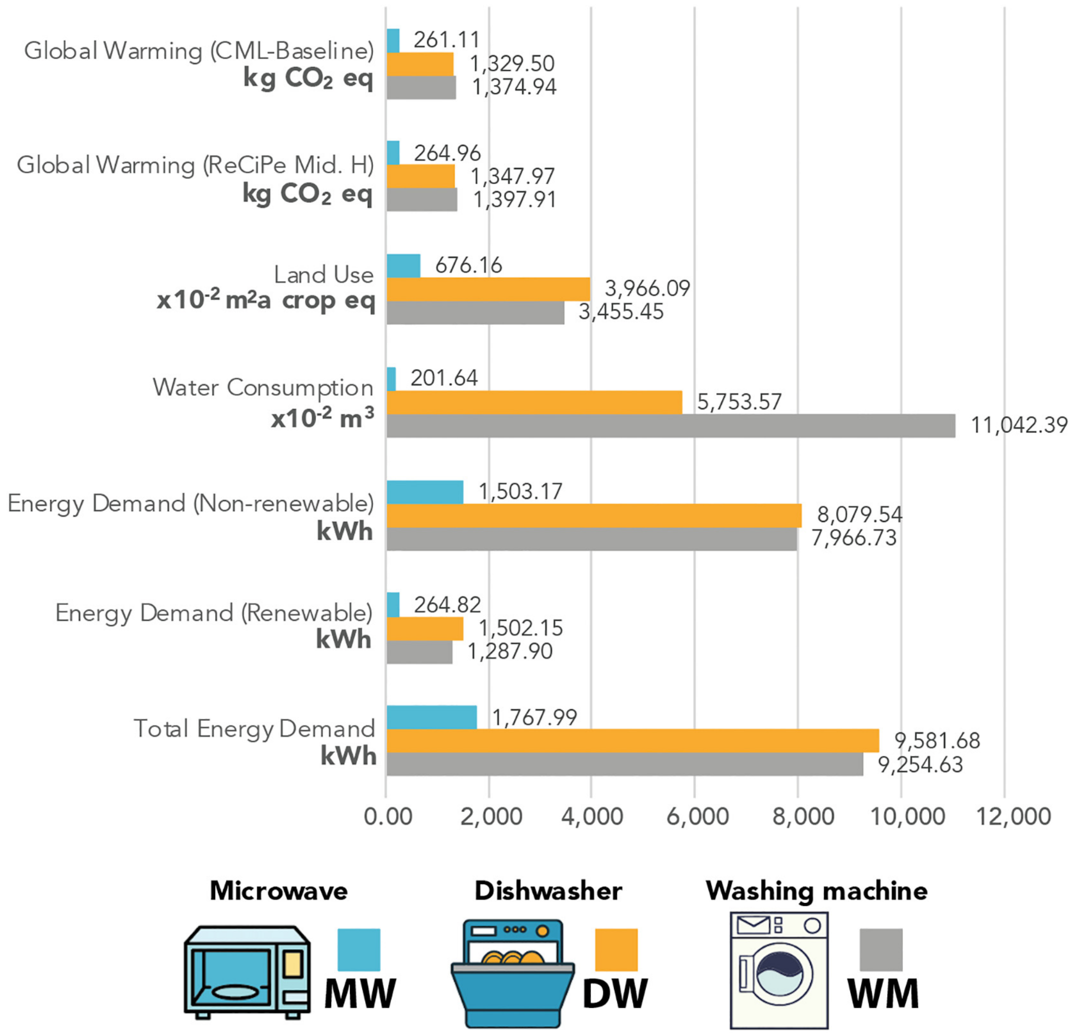

Fig. 3. *Cradle-to-grave* CO_2-eq emissions for *Scenario 0* (or base scenario).

potential. This value is similar to the 1066 CO_2–eq reported for the life-time impacts of a 5 kg semi-automatic washing machine (Garg et al., 2018). In comparison to ReCiPe Midpoint (H), 1.91% lower CO_2-eq (in average) are obtained when the CO_2 footprint is accounted using CML-IA Baseline 2016. Water use is another relevant impact driver as such information is often needed by city planners to ensure financial, ecological, and social sustainability, even in the regions with no water shortage risk (Bich-Ngoc et al., 2021). In this context, the washing machine shows a water consumption of 110.42 m^3 during its life cycle (being 99 m^3 consumed in a direct way during its use phase) which represents a 1.9 and 55-fold increase in comparison to the dishwasher and the microwave oven, respectively. On the contrary, the dishwasher has the largest contribution to land use (notable contributions from natural land transformation are expected as a result of the metals required during manufacturing) and energy demand (in the manufacturing, end of life and also during the washing programs rely on relatively high temperatures and large times). This result can be explained in terms of the longer lifetime of 12.5 years of the dishwasher in comparison to the lifetime of 8 and 10 years for the microwave oven and washing machine, respectively. According to the total energy footprint in Figs. 3, 1768, 9582 and 9255 kWh is consumed during the whole lifetime of the MW, DW and WM, respectively. The direct energy consumption during the use phase represents the 30, 32 and 33% for these appliances (see Supplementary Information, **Table S6**).

To analyze how the environmental impacts of household appliances could be reduced, we focus our attention to the global warming indicator quantified in the form of a carbon dioxide equivalent or CO_2–eq. This indicator is commonly applied to compare the emissions originating from different greenhouse gases on the basis of their global-warming potential (GWP) after the conversion of amounts of other gases to the equivalent amount of CO_2 with the same global warming potential. As a result, it is possible to make informed choices regarding strategies to reduce the emissions, moving from emission targets to temperature goals established in the Paris Agreement (Cain et al., 2019). Fig. 4 shows CO_2-eq emissions of each appliance throughout their lifetimes for each of the 5 scenarios analyzed. Although the goal of the research is not to compare the emissions of the appliances between them, having these values for the current market situation (*Scenario 0*,) can help to understand the energy consumption and CO_2 emissions of appliances. It is seen that the washing machine has the largest contribution to the GWP with a value of 1374.94 kg CO_2-eq (over its whole lifetime). This value is similar to that of the dishwasher (1329.50 kg CO_2-eq) but notably higher than the 261.11 kg CO_2-eq obtained for the microwave oven. The manufacturing phase of the washing machine presents a 3 times larger GWP in comparison to that of the dishwasher (356.10 kg CO_2-eq *vs.* 125.18 kg CO_2 eq), which is translated into a notably larger share in the total impact contribution (26% *vs.* 6%). The slightly larger contribution of the use phase for the dishwasher over the washing machine (1204.32 kg CO_2-eq *vs.* 1018.84 kg CO_2-eq) arises from its

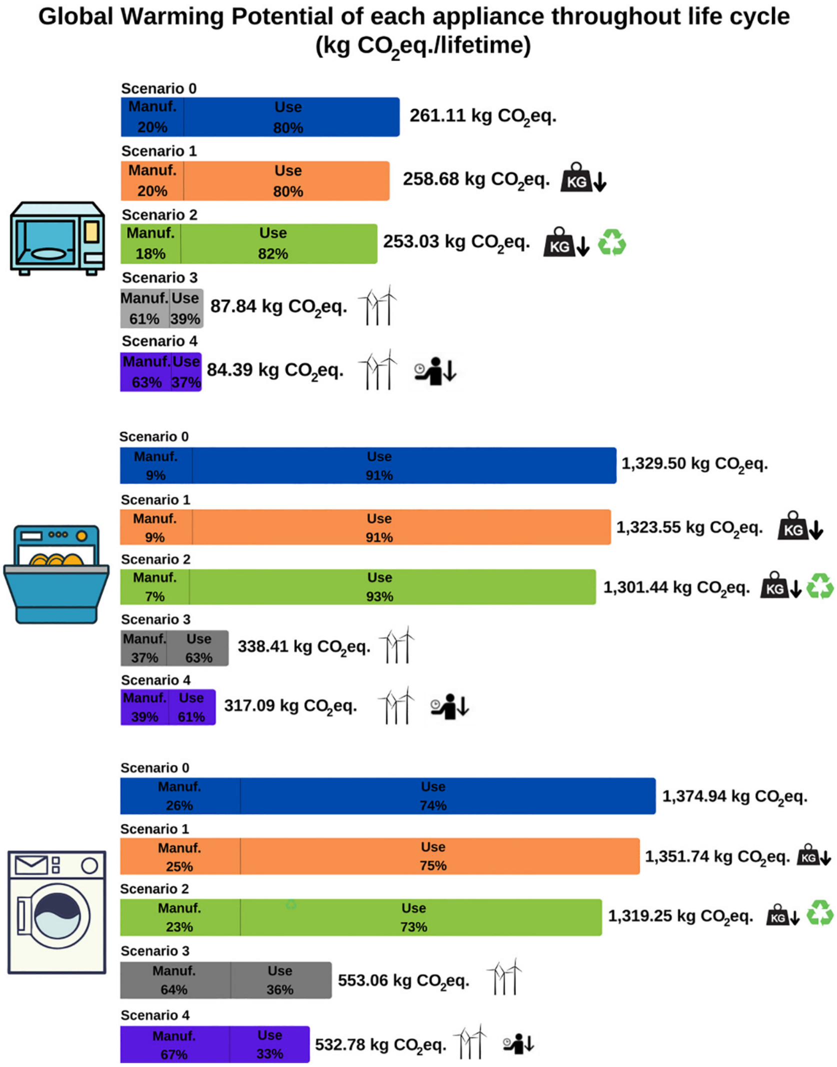

Fig. 4. Global warming potential (CML-Baseline) measured in carbon dioxide equivalent (CO_2-eq) of a microwave oven (top), a dishwasher (middle) and a washing machine (bottom) throughout their whole life cycle. 5 scenarios have been modelled (see further details in Fig. 2 and Table 2). The percentage of emissions during manufacture (including end of life) and use are defined.

longer operation lifespan (12.5 *vs.* 10 years) as the washing machine presents a 6% larger contribution per operating year. Our results are in line with the use-phase CO_2 footprint of 835 and 937 kg CO_2-eq obtained for two different washing machines (Bourrier et al., 2011). A predominant role of the use phase is observed when accounting for the life cycle impacts of household appliances as also reported by previous works (Gallego-Schmid et al., 2018; Hischier et al., 2020; Yuan et al., 2016).

It can be observed in Fig. 4 that all of the 4 alternative scenarios proposed to reduce the life cycle CO_2 emissions of household appliances provide environmental benefits as suggested by the lower GWP values. As regards to *Scenario 1* (10% material reduction during production), mitigations of 0.93% for the microwave, 0.48% for the dishwasher and 1.69% for the washing machine are obtained. Although material efficiency is regarded as a key opportunity to cut CO_2 emissions and move towards the 1.5 °C target in the Paris Agreement (United Nations Environmental Programme, 2022), Fig. 4 shows that the reduction potential of greenhouse gas emissions from material efficiency strategies in the household appliance sector is of limited effectiveness. In addition to the considerations of *Scenario 1*, when half of the material used in the production stage originates from recycled resources (*Scenario 2*) larger environmental benefits are obtained. In combination with the 10% material reduction, CO_2-eq savings of 3.09% for the microwave, 2.11% for the dishwasher and 4.05% for the washing machine are reached. As producing goods from recycled materials is generally less energy intensive over manufacturing from primary materials (Damgaard et al., 2009), recycled materials present an interesting potential to reduce the carbon emissions in the appliance sector. Similarly to the base case, the washing machine still has the largest GPW value in *Scenario 1* and *2*, being the emissions produced in the use phase responsible of it.

Scenario 3 considers a 100% renewable energy during the use phase as shifting from a fossil-based to a renewable-energy mix efficiently reduces the environmental impacts (CO_2 eq, freshwater ecotoxicity, eutrophication, particulate-matter exposure) of manufactured goods (de Lapuente Díaz de Otazu et al., 2021; Hertwich et al., 2015). Importantly, reductions on life cycle CO_2 emissions of 66.36% for the microwave, 74.55% for the dishwasher and 59.78% for the washing machine are observed in Fig. 4. It is worthy to note that the relative contribution of the manufacturing and use phases is reversed. In other words, manufacturing life cycle stage has the largest environmental burden when a renewable energy mix is implemented in its use. Coupled with a 10% reduction of the energy consumption as a result of responsible operation procedures (lower temperature programs and shorter operating times), the life cycle CO_2 emissions reach up to 67.68% for the microwave, 76.15% for the dishwasher and 61.25% for the washing machine. As in previous scenarios, the washing machine is the appliance with the greatest contribution to the CO_2.

Altogether, these results confirm that a preferential consideration should be given to the implementation of renewable energy to power household appliances to effectively mitigate the carbon footprint in the residential sector. However, the use of recycled materials or weight reduction present additional attractive as they can lessen the need for primary raw material extraction (increasing the security of supply) (Dussaux and Glachant, 2019), and reduce waste streams that end into landfills, incineration plants or lost into marine/land environments (Schyns and Shaver, 2021).

3.2. Determination of the Required Efficiency in Use to Compensate CO_2-eq Emissions from Building a New Appliance

To design environmentally sustainable consumption patterns, the trade-offs between the direct energy savings during the use of energy-efficient household appliances and the material-energy inputs needed to manufacture a new appliance should be understood. In other words, the determination of how efficient a new appliance should be to compensate the CO_2 generated during its manufacturing can guide policymakers and consumers during the decision-making process. Accordingly, Fig. 5 displays the energy-efficiency required (for a new appliance) for the replacement of a microwave following the five scenarios above-described (see **Table S7** for further details). Efficiencies of 25.67% for *Scenario 0*, 24.50% for *Scenario 1*, 21.78% for *Scenario 2*, 154.62% for *Scenario 3*, and 171.80% for *Scenario 4* are achieved. It is seen that a greater efficiency is need in new appliances when old appliances are powered by renewable energy. Furthermore, efficiencies above 100% are identified with situations where it is not possible to manufacture a new appliance which improves the environmental performance of the existing appliance. Accordingly, in the presence of a renewable-energy grid and environmentally speaking, extending the operation lifespan of the existing appliance (*via* repair, for example) is preferred.

As shown in Fig. 6, in the case of a dishwasher, required efficiencies of 10.39%, 9.90%, 8.06%, 58.71%, and 65.23% are obtained for *Scenarios 0-to-4*, respectively. In this case, the replacement results environmentally beneficial for all of the studied scenarios. Nevertheless, it can be seen that for *Scenarios 0-to-2*, notably low improvement efficiencies are needed (equivalent to a change from E to C class, 14.7% of improvement). Instead, notably larger improvements are required for *Scenario 3* and *4* (equivalent change from G to B class, 63.1% in *Scenario* 3, and 65.5% of improvement from G to A in *Scenario 4*).

Finally, Fig. 7 summarizes the energy-efficiency needed for the replacement of a washing machine. Efficiencies of 34.95% for *Scenario 0*, 32.67% for *Scenario 1*, 29.49% for *Scenario 2*, 180.80% for *Scenario 3*, and 201.55% for *Scenario 4* are achieved. Similarly to the case of the microwave, efficiencies above 100% are obtained when the appliance is powered by a renewable-energy mix (*Scenario* 3 and 4). In the case of the washing machine it remains clear that its replacement is not accompanied by environmental benefits (according to CO_2-eq emissions) when renewable energy or responsible use are applied. Instead, if no renewable energy can be used to power the appliance, the change from a Class G to a new Class D is recommended (with a minimum efficiency improvement G to D of 44.0% for *Scenarios 0, 1* and *2*).

3.3. Determination of the Optimum Operation Lifespan for Household Appliances

Considering obtained results, the optimum operation lifespan for an existing appliance to be replaced by a class A appliance is proposed in Fig. 8 and **Table S7**. Even though no regulation could be found for microwave ovens, a similar methodology to that followed for dishwashers and washing machines has been applied. Overall, longer operating times are needed in the cases where the existing appliances are already energy efficient. For current market circumstances (*Scenario 0*), 4.04, 3.42 and 5.50 years are set as the optimum operation lifespan for microwaves, dishwashers and washing machines, respectively. Namely, if the

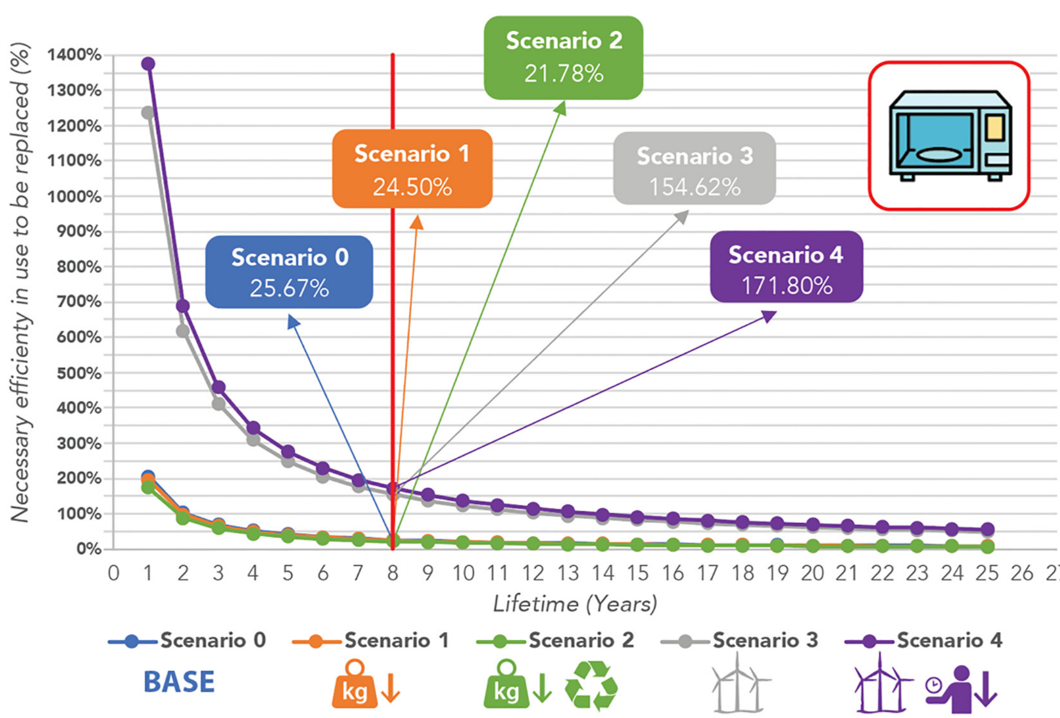

Fig. 5. Efficiency required over operating years of a microwave for five scenarios considering the Global Warming Potential (CML-baseline IA method) category. The red line represents the estimated lifetime for an average microwave (see scenario details in Fig. 2 and Table 3).

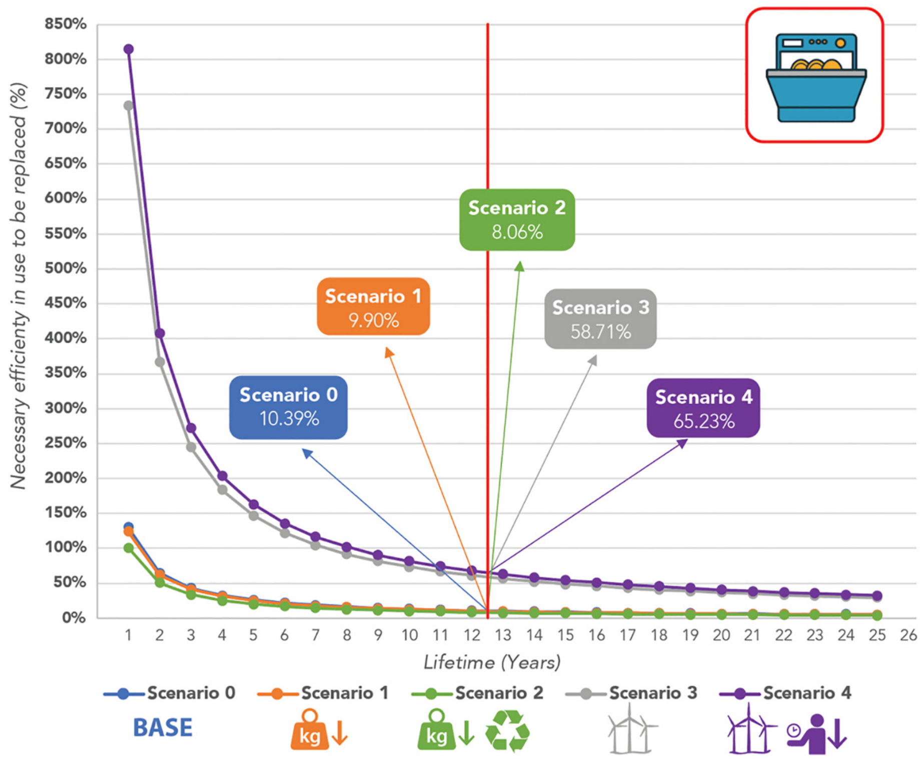

Fig. 6. Efficiency required over operating years of a dishwasher for five scenarios considering the Global Warming Potential (CML-baseline IA method) category. The red line represents the estimated lifetime for an average dishwasher (see scenario details in Fig. 2 and Table 3).

existing appliances are replaced by new equipment before this preferred time, increased environmental burdens will be obtained as a result of the manufacturing of new appliances. On the contrary, when the substitution is carried out after this preferred time, larger impacts are expected due to the less energy-efficient character of the existing appliance.

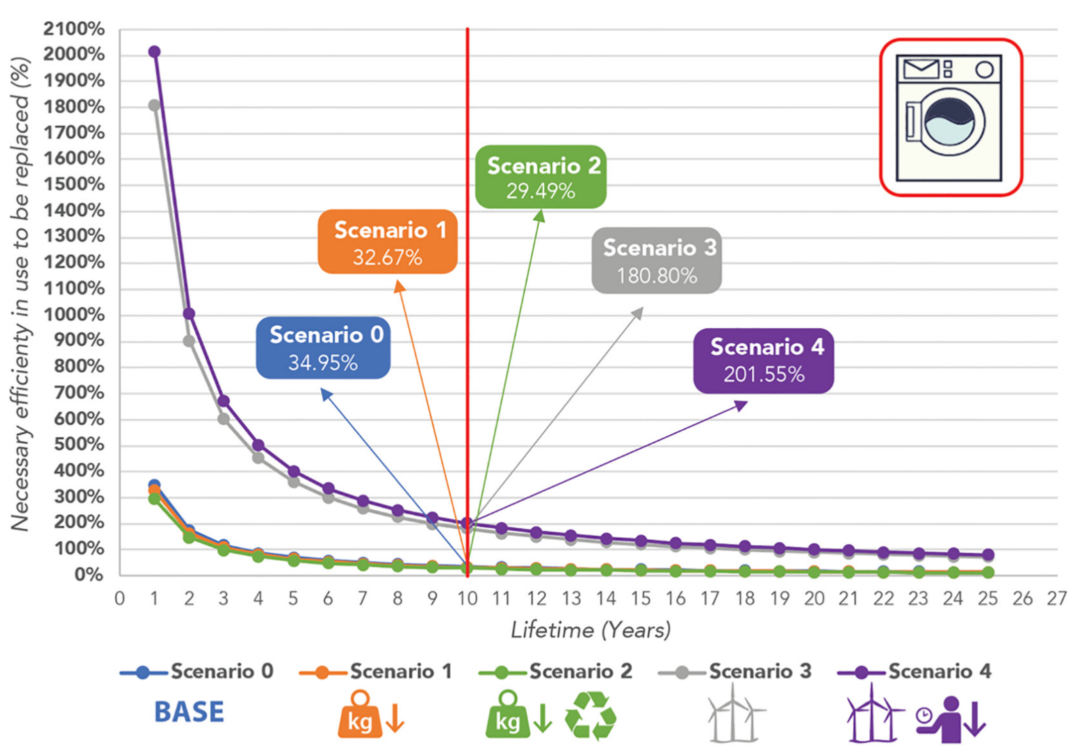

Fig. 7. Efficiency required over operating years of a washing machine for five scenarios considering the Global Warming Potential (CML-baseline IA method) category. The red line represents the estimated lifetime for an average washing machine (see scenario details in Fig. 2 and Table 3).

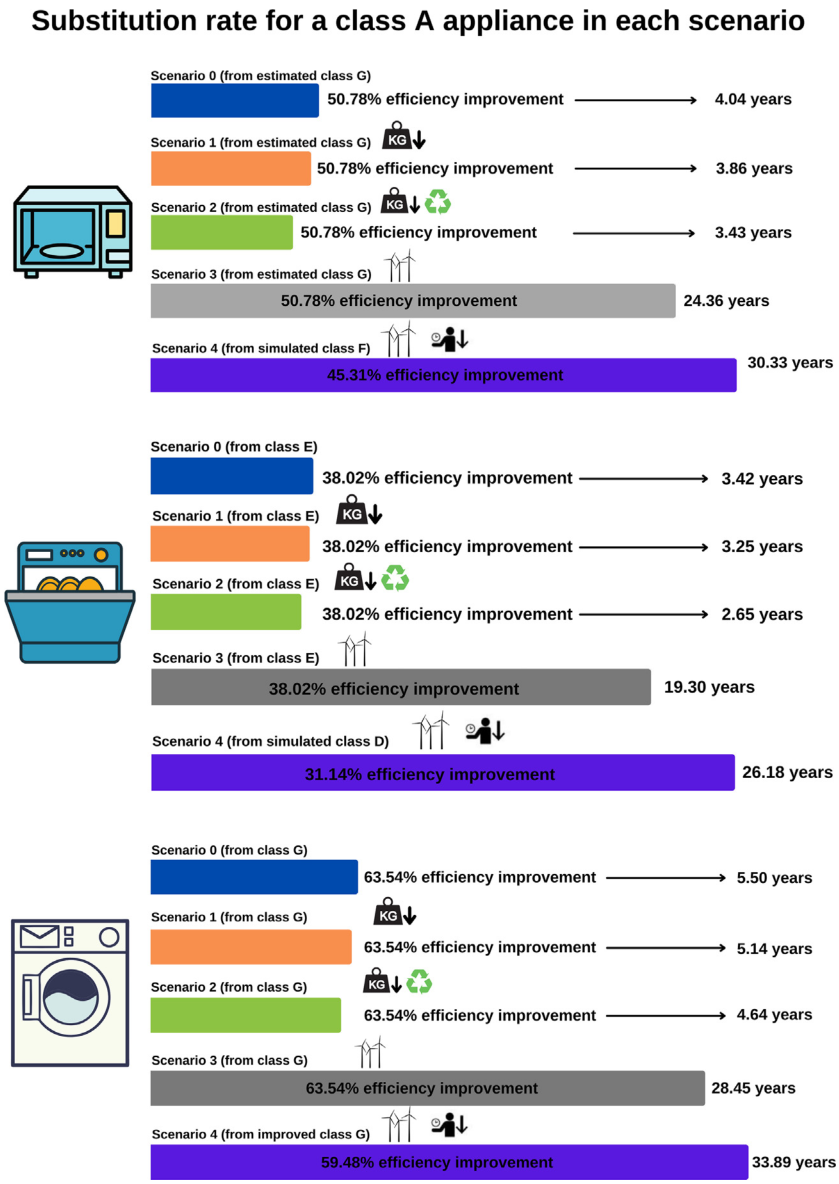

Fig. 8. The optimum operation lifespan for an existing appliance to be replaced by a class A appliance under five different scenarios (see scenario details in Fig. 2, Table 3 and **Table S8**).

In this way, a shorter operating lifespan is preferred for the *Scenario 1*, where a lower CO_2 contribution during manufacturing is expected as a result of the 10% material reduction. This trend is further evidenced in *Scenario 2*, lowering the optimum operating lifespan to 3.43, 2.65 and 4.64 years for microwaves, dishwashers and washing machines, respectively. On the contrary, a notably longer operation lifespan is preferred for *Scenario 3* and *4*, which rely on the use of renewable-energy. In this way, a maximum of 30.33 working years are preferred to replace a class A microwave oven, 26.18 years for a dishwasher and 33.89 years for a washing machine. The results from *Scenario 3* and *4*, when a renewable-energy mix powers household appliances, indicate that the selection of the appropriate operation lifespan plays a pivotal role towards reducing the CO_2 emissions originating from residential appliances. In addition, *Scenario 4* underlines the relevant role of energy-efficiency awareness and practice to ensure a responsible operation of the appliance. The combination of these measures should be considered in the short-term for energy-saving policy interventions specifically targeted at households. Overall, those results are in line with the conclusions drawn by (Sigüenza et al., 2021b), who recommended reconsidering extending the minimum standard lifetime for domestic washing machines by at least 25% over the current average of 12.5 years.

These results challenge the widely held idea that the replacement of the existing household appliances by new ones results an efficient approach to lower the greenhouse gas emissions in the residential sector. Fig. 9 displays the GWP reduction for the studies alternative scenarios. It is seen that *Scenario 1* and *2* offer low improvement rates (from 0.4 to 4.1% in total CO_2–eq emissions). Instead, *Scenario 3* and *4* can lower the GWP by 59.8–76.2%. In fact, the trade-offs between the savings provided by energy efficient appliances and the added burdens arising from the manufacturing of new appliances should be considered. It is important to note that the environmentally preferred lifespan obtained when renewable energy is used notably surpasses the average lifetime of selected appliances. As progress is being made regarding the decarbonisation of the energy mix and the implementation of energy originating from renewable sources within the current scenario to reach the climate objectives, policymakers and manufacturers should focus on the extension of the lifetime rather than developing new technologies which reduce the energy consumption.

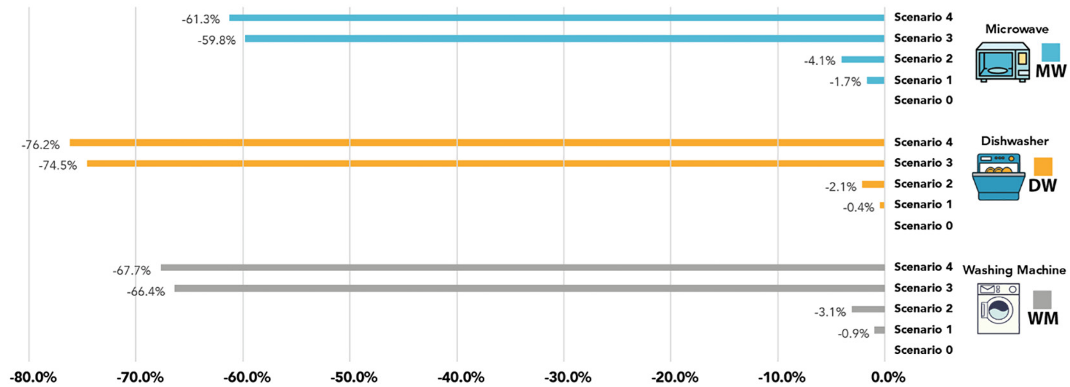

Fig. 9. Reductions in GWP according to CML-Baseline for each household appliance (see **Table S9**).

4. Discussion

Policymakers now face the challenge of implementing effective measures in the current scenario where technology is giving signs of maturity, that is, energy-efficiency can be hardly improved (Sakah et al., 2019). In this sense, to promote environmentally sustainable societies it becomes fundamental to face the issues related to the household appliance obsolescence by failure (also known as absolute obsolescence). As a cornerstone of Circular Economy, product durability, defined as "the characteristic of those objects or materials that maintain their properties over time" (Peris Mora, 2007), can slow down resource loops and promote the implementation of circular approaches into the residential sector (Yamamoto and Murakami, 2021). The design for easy repair and maintenance can lead to environmental benefits by avoiding the manufacturing phase, supply chain impacts, and delaying the end-of-life (Ardente and Mathieux, 2014).

This work demonstrates that current lifespans (Table 1) should be enlarged when appliances are feed with renewable energy. As summarized in Fig. 10, lifespans need to be extended up to 30, 26 and 34 years (from current average of 8, 12.5 and 10) for MW, DW and WM, respectively (increasing current operating lifespans by 375%, 208% and 340%). Once this working period is reached, the existing appliance should be replaced to reduce CO_2-eq emissions, even for the most optimistic hypothetical scenario (Scenario 4). Accordingly, policy makers and households can have a clear reference of the environmentally preferred scenario are replaced after the working years shown in Fig. 10. Furthermore, replacing the selected appliances under current scenario does not reduce CO_2 emission since the GHG emission associated with the fabrication of a new appliance should be considered. Instead, when renewable energy and responsible use practices are adopted, a replacement during the current lifespan seems to be feasible. Thus, when new "renove plans" are designed, it is clear that, first of all, the electric mix

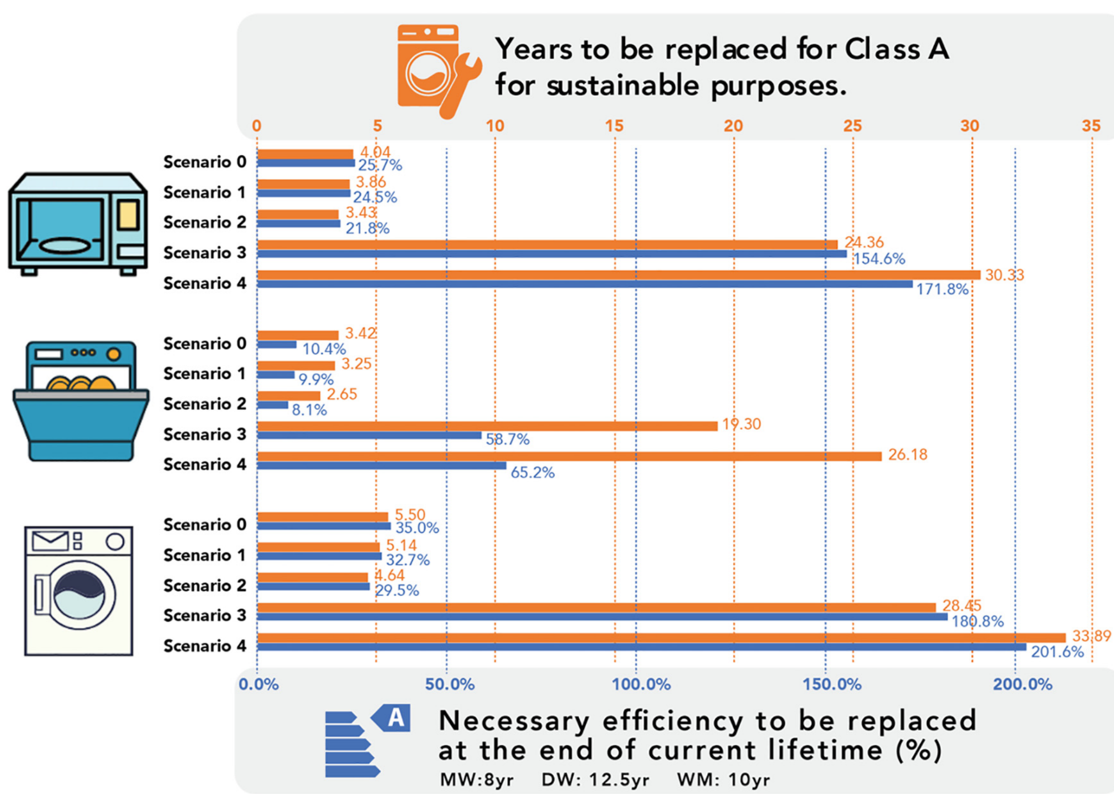

Fig. 10. Estimated optimum lifespan and substitution rates.

of private houses needs to be shifted into renewable sources, and later, the industries need to build efficient appliances with adequate efficiencies during use to lower the overall carbon emission values.

The European Commission's new plans for "right to repair" rules covering smartphones, tablets and laptops in 2021 can be seen as part of wider efforts (that will soon cover household appliances) to help Europe on its path to achieve climate-neutrality by 2050. Upgradability by the replacement of electronic components or updating installed software is also an interesting option as it may enable the improvement of the energy-efficiency of the existing appliance with no need of a complete replacement. To compensate the potentially lower profits from reduced production and sale rates, private sector can focus on circular business models based on product-service systems (Zamfir et al., 2017), such as those aimed at developing access and subscription-based business models. Following the lessons learned upon the implementation of the European Union Ecodesign Directive, policy measures such as the implementation of a minimum guaranteed lifetime, modular design or establishing a minimum availability time for spare parts are also worthy of analysis. Importantly, long-lasting products help to save resources, minimize waste and encompass lower life cycle cost for the consumer (Iraldo et al., 2017).

The results here shown are subjected to uncertainties and limitations arising from how representative the selected examples are. Based on previously published works, several assumptions were made during the life cycle inventory. Thus, their accuracy can also affect the results. However, this work provides findings in 3 levels:

- LCA calculations with indirect (manufacture and end of life) and direct (use) impact proportions to provide new analysis scenarios for environmental scientists. For the current scenario GWP values of 84–261, 317–1330, and 533–1375 kg·CO_2 eq/lifetime for a microwave, a dishwasher and a washing machine are obtained. For all the appliances, the use phase accounts for 73–93% of the lifecycle CO_2 emissions in the current situation and in scenarios aimed at material resource efficiency. When shifted to a 100% renewable energy mix, the contribution of the use phase is lowered to 33–63%.
- information to support policymakers and business-to-business transactions where clear action to boost renewable energy must be enhanced before supporting "renove" replacement campaigns. Before the replacement, the appliances should ideally function for the period summarized in Fig. 10. Furthermore, companies can serve from additional references to target the energy efficiency of new appliance designs, not only for the use phase but also fir the manufacturing (including end of life) phase.
- information to support final consumers in their way towards sustainable consumption patterns so clear and well-informed choices could be made. Consumers can understand the environmentally optimal replacement period (years) of an existing appliance considering the whole life cycle.

The environmental footprint of appliances plays a pivotal role to monitor the Sustainable Development Goal 12 (responsible production and consumption) and is also being considered in novel indicators such as "Consumer Footprint", which assess the potential environmental impact originating from household consumption according to a process-based LCA (Sala and Castellani, 2019).

5. Conclusions

The comparative analysis carried out demonstrates that the electricity consumption during the use stage is the main *cradle-to-grave* contributor to the greenhouse gas emissions of household appliances. The implementation of measures framed within the Circular Economy have can potentially reduce the greenhouse gas emissions of household appliances. Specifically, reductions in CO_2-eq emissions up to 68% for a microwave oven, 76% for a dishwasher and 61% for a washing machine can be achieved. Such improvements are obtained thanks to a combination of a renewable energy mix during the use phase and an energy consumption reduction of 10% due to a responsible use, underlining the key role of a decarbonised electricity mix for the future sustainable development. However, achieved environmental improvements are accompanied with increases in the number of years that the existing appliance has to be used before its replacement by a new energy-efficient appliance. In fact, when a 100% renewable energy mix is applied during the use phase, the replacement with a "class A" microwave oven, dishwasher and washing machine would be solely environmentally preferred after 24.36, 19.30 and 28.45 years, respectively. If the energy consumed during use is reduced by a 10% as a result of responsible consumption patterns, this time period spans up to 30.33, 26.18 and 33.89 years, respectively.

It is important to note that among the studied appliances, a single PCR focused on washing machines was found. Therefore, further efforts are encouraged to develop Product Category Rules for the most relevant household appliances so comprehensive and comparable *cradle-to-grave* CO_2-eq emissions can be obtained. Considering the quantitative LCA results, the measures here proposed are aimed at reducing the impacts associated with home appliances and contribute towards the achievement of energy efficient communities. Although the idea of replacing an electric appliance by energetically more efficient equipment is *a priori* seem as an environmentally responsible measure, it could be environmentally counterproductive if not performed under well-informed scenarios. These results here shown could guide manufacturers when designing household appliances, citizens when deciding the appropriate household replacement period and policymakers when implementing funding programmes. Importantly, the use of a renewable electricity mix is a determinant factor to achieve effective reductions in CO_2 emissions, rather than continuing with current policies largely focused on the replacement of household appliances by energetically-efficient ones. Interestingly, further efforts to support renewable energy to power existing electrical appliances could boost additional Circular Economy actions such as the *"right to repair"* rule for electronics, so the life cycle of products can be extended.

In the near future indirectly produced impacts during the life cycle should be analyzed. In addition, LCA databases should be extended and consequential type calculation methodologies (Cut-off) should be improved to standardize the calculations. Academia should transfer the knowledge to companies so it is possible to integrate a new labelling for environmental impacts that not only integrates the current direct affections (already reflected with the energy consumption class: A, B, C…) but also the indirectly ones such as manufacturing and end of life. The establishment of more complex scenarios of LCA can provide more realistic results to guide the transition into sustainable policies in the household industry.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2022.04.007.

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