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The environmental impacts of preparation for reuse: A case study of WEEE reuse in Germany

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Abstract

According to the European waste management hierarchy, preparation for reuse (PfR) is preferable to recycling. From an environmental point of view, reuse is beneficial, if the impacts that arise during a certain usage duration of a reused product are smaller than those of a new product. If this is not the case, reuse is not beneficial to recycling. This study explores potential benefits of PfR compared to other waste management options for four white goods (washing machine, refrigerator, range, freezer) and four small electric devices (PC, printer, monitor, laptop) by the use of Life Cycle Assessment. These eight devices account for 68% by weight of all the collected waste electrical and electronic equipment (WEEE) in Germany. The results show, that the assumption that reuse is preferable to recycling does not apply to every case. Especially the impact categories of global warming, water consumption and cumulative energy demand are strongly dominated by the use phase of white goods, therefore a reuse of inefficient devices should be avoided. The results show that a reuse of products with an European energy efficiency rating of D and C is not recommended for any of the analyzed products. For small electric devices, the use phase is less dominant in comparison to the production, therefore reuse leads to significant saving potentials in almost all impact categories. A comparison of energy efficiency classes allows for product-specific decisions, whereas the assessment approach based on average devices yields for generalizable recommendations. Therefore, the results support environmentally conscious consumer decisions about the acquisition of a new versus a second-hand product and enable End-of-Life decision making in terms of the separation of reusable devices at collection points.

Keywords

Preparation for reuse; Waste management; Life cycle assessment; WEEE; Environmental saving potential

1 Introduction

The aim of maximizing resource efficiency by keeping materials at their highest value at all times is a commonly agreed aim among various definitions of Circular Economy (CE) (Kalmykova et al., 2018). Kirchherr et al. (2017) analyze 114 definitions of CE and identify different End-of-Life (EoL) frameworks and the system perspective as the two core principles of CE. The framework of "reduce, reuse, recycle" (in hierarchical order) is the most prominent within a CE context (Prieto-Sandoval et al., 2018; Reike et al., 2018). The assumption that higher ranked EoL options put less pressure on the environment designate reuse as a major concept of the CE to achieve its goals (Ghisellini et al., 2016). The supposition that reuse leads to less impacts compared to lower ranked options needs to be validated for the entire life cycle of a product. Environmental impacts can be measured with advanced tools such as Life Cycle Assessment (LCA). In this article we conduct a LCA to investigate the prioritization of reuse for WEEE with reference to the waste hierarchy implemented by the European Waste Framework Directive (Directive, 2008/98/EC).

Waste prevention takes first priority in the waste hierarchy for all EU member states. When a consumer disposes of a product or expresses the will to dispose (KrWG §3), the product passes the waste threshold and turns into waste. Beyond the waste threshold, preparation for reuse is the preferred waste management option. Following the German Law on Closed Cycle Management and Waste (Kreislaufwirtschaftsgesetz, KrWG), preparation for reuse and recycling of municipal waste must account for 65% by January 1st, 2020 (KrWG §14). A recent case study quantifies the potential of wastes that could be spared from recycling and instead be prepared for reuse. The study states that 113.114 t of waste electrical and electronic equipment (WEEE) arise annually at Bavarian collection points alone, of which up to 87% are theoretically viable for reuse (Messmann et al., 2019). From an environmental point of view, the preferability of reuse compared to lower-ranked waste management options (recycling, energetic recovery, landfilling) is challenged in literature (Baxter, 2019). The impacts arising during the entire life-cycle of "unpowered" products are dominated by the production phase, whereas the energy efficiency during the use phase gains importance for Energy Using Products (EuPs), which include all types of electrical and electronic equipment (Cooper and Gutowski, 2015). Therefore, the assumption that reuse always results in lower impacts needs to be assessed in detail for (waste) electrical and electronic equipment. In this study we focus on preparation for reuse (PfR) of devices from private households arising at municipal collection points. According to a survey of the German Environment Agency, municipal collection points are the main disposal route with a share of 37% of the respondents using this return option, followed by an exchange with a new product at point of delivery (16%), curbside collection (13%), return to retailers (9%) and public collection containers (8%) (Schmiedel et al., 2018). Based on a primary data assessment at German collection points (Messmann et al., 2019), we select the most relevant white goods (washing machine, refrigerator, range, freezer) and small electric devices (PC, printer, monitor, laptop) to investigate the following research questions, considering different impact categories and changes in efficiency for new and reused devices:

Q1 What are the environmental **saving potentials** of reuse?
Q2 For **which products** can reuse be recommended?

In detail, this is examined for the impact categories *global warming* (GWP), *terrestrial ecotoxicity* (TE), *human carcinogenic toxicity* (HT(c)), *mineral resource scarcity* (MRS), *water consumption* (WC) and *cumulative energy demand* (CED). The study's structure is illustrated in Fig. 1. Our research approach follows seven subsequent steps in three phases (A-C). The first phase (A) clarifies our research aim and operationalizes the research question into two distinct fields of interest: environmental saving potentials of reuse and maximum usage duration for which reuse is environmentally beneficial.

A literature review in the field of environmental impact assessment of electrical and electronic equipment supports the development of an approach for the LCA of PfR (phase B). In the third research phase (C) and section 4 of this paper, we apply our approach to a selection of four white goods and four small electrical devices to compare the environmental impacts of reused and new products for the German market. This study concludes in section 5 with a discussion of results and recommendations for follow-up research.

2 State of the art

A current review in the context of waste electrical and electronic equipment (WEEE) recognizes an increasing interest in reuse-related issues from 2009 onwards (Pérez-Belis et al., 2015). We find a range of studies discussing potentials and barriers to reuse (Kissling et al., 2013; McMahon et al., 2019; Messmann et al., 2019), design for reusability (Bakker et al., 2014; Johnson et al., 2015; RREUSE, 2013) or economic and social implications of reuse activities (González et al., 2017; O'Connell et al., 2012; Pini et al., 2019). In the following, we focus on studies that assess the environmental impacts of (preparation for) reuse of WEEE, and transferable scenarios such as lifetime extension or early replacement. We searched the online catalogue of Google Scholar and Web of Science by the following search string: ("*Life Cycle Assessment*" OR "*LCA*" OR "*Life Cycle Analysis*" OR "*environmental impact*") AND ("*WEEE*" OR "*electrical*" OR "*electronic*" OR "*home appliances*") AND ("*reuse*" OR "*replacement*" OR "*durability*" OR "*remanufacturing*" OR "*product lifetime*") to identify publications that assess or compare the environmental impacts of new and reused products (step B1, Fig. 1). All of the 26 identified articles incorporate LCA in their method of environmental impact assessment. Appendix A shows the list of identified publications, the according scope and assessed devices. The findings from the analyzed studies are hardly comparable, due to strong variations in scope, definition of the functional unit, method of impact assessment, and impact categories. To determine the saving potential of reuse and answer the present research question, comparable LCA data for all eight analyzed products is required. No publication is available that assesses all of the required products and the assessment approaches differ too strongly to allow for a comparison of results among different studies. Additionally the present study aims to identify the reuse potential for the German market. Therefore it is important to use the German electricity mix to model the impacts of the use phase. This requirement is not met if literature data from different countries is taken. This demonstrates the need for a consistent LCA for all products in the German scope.

To derive a suitable method for the environmental impact assessment of new and reused products, we analyze the approaches in literature. Not all identified publications explicitly cover preparation for reuse, but a broad range of related topics. Most frequently analyzed are the environmental potentials of **product durability** or **extending the lifetime of products** (Ardente and Mathieux, 2014, 2012; Bobba et al., 2016; Devoldere et al., 2009; Downes et al., 2011; Iraldo et al., 2017; Prakash et al., 2016b; Tecchio et al., 2016). In their review, Ardente et al. (2012) define the assessment of product durability as "assessment of environmental benefits/drawbacks of extending the operating time of products that can be achieved due to specific design and maintenance actions, in comparison to their replacement with newer ones." The evaluation of trade-offs resulting from the replacement of products with more efficient ones is equivalent to the current case of PfR. The environmental assessment of lifetime-extension can also focus on the design phase, e.g. proposing eco-design strategies (Bobba et al., 2016). This target setting is different from the current perspective on EoL options. A related issue with similar objectives is the environmental assessment of **early replacement** of products with more efficient ones (Pérez-Belis et al., 2017; Prakash et al., 2012; Rüdenauer et al., 2005; Rüdenauer and Gensch, 2007a, b, 2005; Tasaki et al., 2013). In the case of PfR, WEEE are assumed to not have reached their maximum lifespan and to be viable for a second life. Therefore, the methodology for the evaluation of an early replacement is transferable to the PfR-case. Different studies propose methods for the assessment of a **remanufactured** product compared to a newly manufactured one from a life-cycle-perspective in terms of energy savings (Boustani et al., 2010; Gutowski et al., 2011; Quariguasi Frota Neto and Bloemhof, 2009, 2012). Other approaches include a broader range of impact categories (Ardente et al., 2018; Kerr and Ryan, 2001).

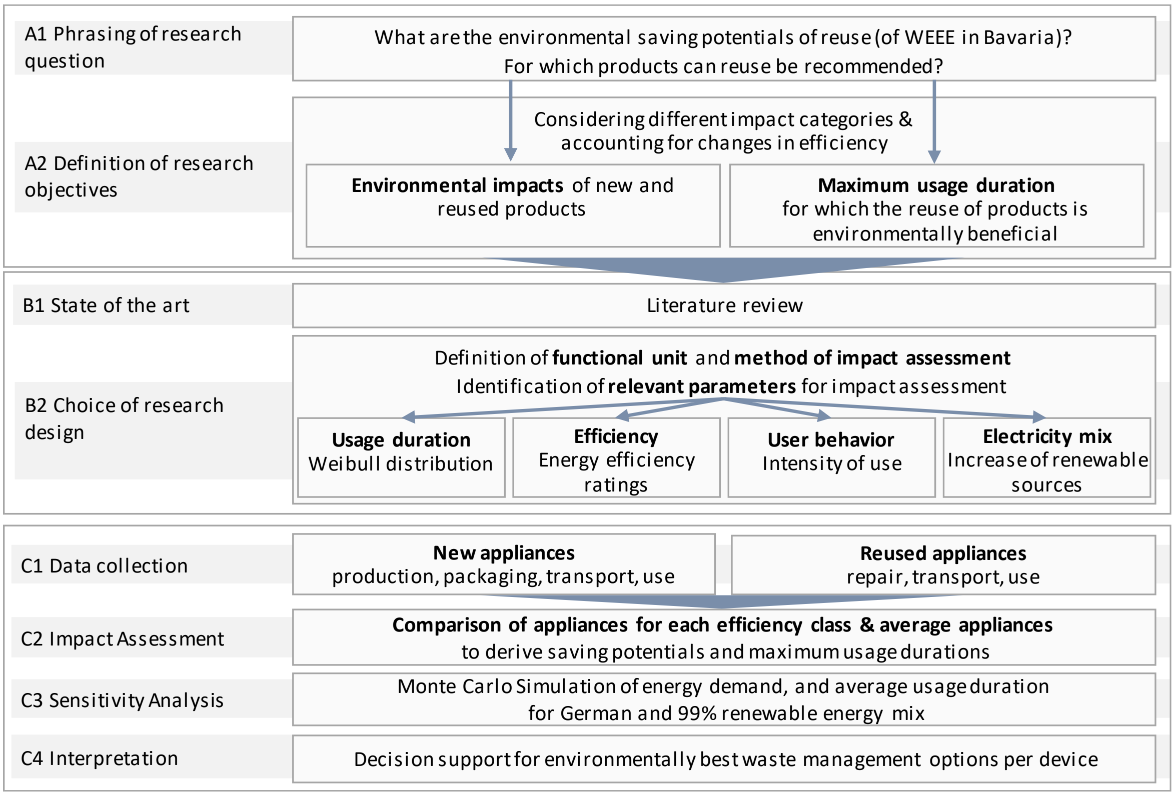


Figure 1. Research approach for the assessment of environmental impacts of new and reused products

Ardente et al. (2018) assess potential trade-offs between reusing components and therefore reducing the impacts of manufacturing and resulting changes in the electricity consumption during the use phase. The provided classification of types of reuse defines remanufacturing as a reuse activity, but clearly differentiates it from PfR, since the product is assumed to be functionally equivalent to a new product. Therefore, this model targets OEMs and requires adaption for the PfR-case. O'Connell and Fitzpatrick (2013), O'Connell et al. (2012) and O'Connell (2012) evaluate the impacts of reuse in terms of energy, the approaches of Baxter (2019) and WRAP (2011) account for a range of other impact categories. Baxter (2019) compares the environmental impact (EI) of **reuse and recycling** for domestic refrigerators. The approach targets the support of policy and decision making in the field of EoL handling options, we can therefore build on the proposed approach to answer the present research questions.

In the next section, we transfer the methodological approaches to the case of PfR of WEEE and derive system boundaries for the definition of the functional unit, a suitable method of impact assessment and parameters, which influence the EI of new and reused electrical and electronic devices during their life-cycle. We develop a structured approach for the assessment of environmental impacts that supports decision making on environmentally preferable waste management options of electrical appliances, which arrive at municipal collection points. The findings are especially relevant for policy and practitioners in the context of municipal collection points.

3 Research approach

From an environmental point of view, reuse is beneficial, if the impacts that arise during a certain usage duration of a reused product are smaller than those of a new product. If this is not the case, reuse is not beneficial to recycling. The performance of reuse is determined by the trade-off between the higher impacts during the second use of a (less efficient) PfR device versus the impacts resulting from the manufacturing and use of a new (more efficient) one. Our approach comprises comparative LCAs of new and reused devices and takes into account improvements in efficiency as well as changes in usage duration and electricity mix. Subsequent to the impact assessment of new and reused devices for each energy efficiency class, we quantify the average saving potentials of reuse and calculate the maximum advisable usage duration of reused devices. In the following, we outline the goal and scope of the LCAs, explain the selection of parameters that affect the EI, and describe our approach for the assessment of saving potentials and maximum usage duration (step B2, Fig. 1).

The EI are obtained by applying LCA. According to ISO 14040 and ISO 14044, an attributional LCA requires a clear and fair definition of the goal and scope of the study. The aim of this study is to compare the EI of all relevant life-cycle phases of a new product and a waste product undergoing PfR from a consumers point of view. Subsequently, the definition of the functional unit, the method of impact assessment as well as parameters that influence EIs during the use phase are described.

The literature review pointed out the relevance of considering multiple life-cycle aspects related to the reuse of products.

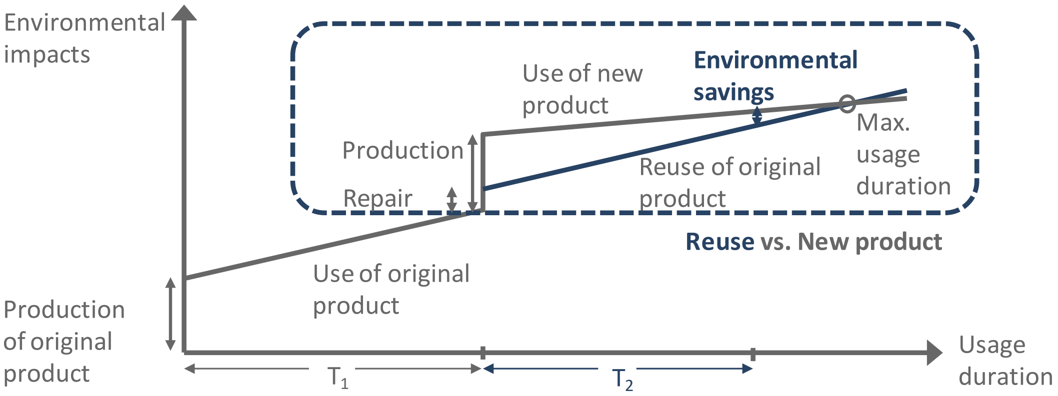


Figure 2. System boundaries for the comparison of new and reused products

On the supposition that both products are capable of fulfilling the same function, the functional unit of our study is the usage of each product for the same duration. Fig. 2 is adopted from Cooper and Gutowski (2015) and shows the system boundaries. The assessment of the new product comprises the production, distribution and use for the duration T_2. In the PfR-case, we include recovery operations required for the recirculation of waste into the use phase (examination, cleaning, and repairing) (KrWG §3), distribution and use for the identical duration T_2. Impacts of production and PfR depend on the material composition and mass of the product or spare parts and the electricity consumption of processing or repairing, respectively. At the beginning of T_2, more EI are attributed to the new product, due to higher impacts of production and distribution in comparison to the PfR-case. During T_2, the use of the reused product leads to higher impacts because it is less efficient than the new one. The higher gradient of the blue line in Fig. 2 results from higher EIs of a PfR device during the use phase. The break-even point (intersection of the two lines) marks the usage duration for which the use of the new and reused product result in the same EI (maximum usage duration). After this point, the saved impacts of production and distribution of the spared new product are set off by the inferior efficiency performance of the reused product. Then, it is more beneficial to produce and use a new product than to reuse a device. At the following EoL, products are recycled. If reuse takes place over a longer period of time, fewer products would be required and therefore recycling would occur less often. The exact time-shift of recycling depends on assumptions about the life time extension through reuse. Besides the timeshift, recycling processes are identical for both cases (Baxter, 2019). Since high quality data on recycling processes is not available for all products and since we assume the effect of the time shifted recycling marginal, the EoL phase is excluded.

The transferable scenarios analyzed in section 2 include a range of parameters that affect the EIs of EuPs. The majority of the existing studies assume impacts of production to be unchanged over time.

Bobba et al. (2016) model a factor to represent the variation of impacts to account for the use of different materials or new technologies during the production process. In the present case, we assume the same functionality of the products and consider changes in production processes as neglectable. Production impacts (IP_i) are allocated according to material composition and mass (Bovea et al., 2018). Variations in the extend of repair as in Ardente and Mathieux (2014), Baxter (2019) and Bobba et al. (2016) are modelled rather seldom, whereas repair of used products is commonly included (Bovea et al., 2018; Pérez-Belis et al., 2017). The same holds true for transport modes and distances in the distribution phase. To account for distribution of the new product, we model the average distance and mode of transport from the production facility to the consumer as impacts of transport (IT_i^{New}). In the case of PfR, we model the resulting impacts of the most common repair actions, as impacts of repair (IR_i). Average distances from municipal collection points to the consumer are taken for distribution (IT_i^{PfR}). For the modelling of the use phase, four parameters need to be considered (see Fig. 1, B2) as follows:

1. Usage duration,
2. Efficiency,
3. User behavior and
4. Electricity mix.

In contrast to the assessment of impacts during a fixed **usage duration** (n), a flexible usage duration enables the determination of the amortization period for manufacturing a new product (O'Connell and Fitzpatrick, 2013; Rüdenauer et al., 2005). Avoiding the assumption of a fixed usage duration, which equals the product lifetime, a Weibull distribution function is used in literature to define the lifetime of EuPs (Parajuly et al., 2017). Weibull distribution provides the best fits of lifespans for most products and yields higher analytical tractability compared to other statistical distributions (Wang et al., 2013). Wang et al. (2013) calculate lifespan profiles for various product groups in the Netherlands based on stock data and the age composition of products discarded from households. They publish data on product group specific shape and scale parameters. These parameters and the maximum lifetime, which is considered to be 35 years (Parajuly et al., 2017), define the product groups specific lifetime profile. The lifetime profiles derived for the Netherlands are transferable to Germany due to similar socioeconomic conditions (Magalini et al., 2016). Different studies agree that the product lifetime is time-dependent and may change due to social and technical development (Thiebaud Müller et al., 2017; Wang et al., 2013). The values published by Wang et al. (2013) indicate only marginal changes over time, therefore and for reasons of simplicity, we assume the given lifetime profiles for 2005 to be static. The expected usage duration in the base case results from the mean defined by the shape and scale parameters.

Literature shows different approaches to account for **changes in efficiency**. A common approach is the modelling with a fixed or variable parameter or a function, giving the performance of one product in relation to the other (Ardente et al., 2018; Ardente and Mathieux, 2014; Baxter, 2019). Perez-Belis et al. (2017) and Devoldere et al. (2009) refer to European energy efficiency classes, assigned to the product group of white goods. Commission Regulation (EU) 2017/1369 sets out the basis for labelling energyrelated products and repeals the Energy Labelling Directive, 2010/ 30/EU, which established the regulatory framework for providing end-user information about energy efficiency for energy-related products. Currently, the label shows the energy consumption of a product during its use on a scale from A+++ to G. With the latest Commission Regulation (EU) 2017/1369, a rescaling of energy labels to the former A to G scale is initiated to avoid the high population of top classes and allow for a better differentiation of products. For each energy class, an interval of annual electricity consumption (kWh/yr) is assigned. In accordance with Perez-Belis et al. (2017), we select the average for each interval as a white goods annual electricity consumption and calculate the electricity demand ($DE_{\alpha/\beta}$) for each energy efficiency class. This allows for a comparison of two specific products in practice. Since energy labels are attached to white goods arising at municipal collection points, the proposed approach enables a product-specific decision on the environmentally best waste management option. Changes in efficiency are not solely relevant for the electricity consumption, but also for other resources like water. Water consumption is not necessarily related to the energy efficiency labelling. Nevertheless, as newer products work more efficiently, a decrease in water consumption can be assumed. This is modelled as demand of water in relation to the assigned efficiency class ($DW_{\alpha/\beta}$). The interrelation between water demand energy efficiency class and age of the product needs to be assessed in detail for each product group. For small electric devices no equivalent energy labelling is available. To account for changes in efficiency we define reference periods and assign an average energy demand for new and PfR devices. For instance, the average energy demand of a product from 2012 to 2015 is defined as a PfR product's energy demand, and the average from 2016 to 2018 is that of a new product. If relevant, the approach is transferable to water consumption.

Depending on the product group, **usage behavior** (UB) may influence the EI during the use phase to a varying extend (Pérez- Belis et al., 2017). Whereas products always remaining in active use (e.g. refrigerators) are less dependent on user behavior, the impact is more significant for products that are not used constantly (e.g. vacuum cleaners, washing machines). Bovea et al. (2018) identify a significant influence of the frequency of use on the EI for a range of household appliances.

As shown by Baxter (2019), the country's **electricity mix** strongly influences the impacts of electricity use ($IE_{i,t,c}$). Since the use phase of the present study takes place in Germany, we select the electricity mix based on the German electricity generation. The German Government targets the share of power from renewable energy sources to reach at least 40% by 2025, 60% by 2035 and 80% by 2050 (EEG, 2017). With reference to Downes et al. (2011), we incorporate this trend in our model to account for a changing electricity mix during the lifetime of a product. To model the current situation, Ecoinvent data is adapted to the 2017 electricity mix (AGEB, 2018). For the future composition, predictions on the gross electricity generation by energy source for 2020, 2025, 2030, 2040 and 2050 are available (Schlesinger et al., 2014), data for other years is calculated by linear interpolation. Schlesinger et al. (2014) predict that the share of renewables does not reach the targets for 2035 and 2050. This conservative scenario is taken for the base case.

The environmental impacts of the new ($I^{New}_{i,n,\alpha,DE}$) and reused ($I^{PfR}_{i,n,\beta,DE}$) device can be expressed as follows:

$$I^{New}_{i,n,\alpha,DE} = \left(IP_i + IT^{New}_i\right) * \frac{n}{\bar{n}} + \sum_{t=1}^{n}\left[\left(IW_i * DW_\alpha\right) + \left(IE_{i,t,c} * DE_\alpha\right)\right] * UB \tag{1}$$

$$I^{PfR}_{i,n,\beta,c} = \left(IR_i + IT^{PfR}_i\right) + \sum_{t=1}^{n}\left[\left(IW_i * DW_\beta\right) + \left(IE_{i,t,c} * DE_\beta\right)\right] * UB \tag{2}$$

For each impact category (*i*), the environmental impacts of production (IP_i) are included for a new product, whereas impacts of repair (IR_i) are relevant for the PfR product. In both cases transportation (IT_i) is incorporated. The average usage duration of a new product is represented by $\bar{n}$. We included the multiplication with the factor $\frac{n}{\bar{n}}$ to consider that a reused product is most likely less durable ($n \leq \bar{n}$) than a new product. For a usage duration of a reused product of e.g. n = 5, the entire impacts of the initial repair are therefore allocated to the PfR product for these 5 years. In contrast, the new product is assumed to be functional until its average usage duration $\bar{n}$ is reached. To avoid an overestimation of the impacts of production and transport for short usage durations, these impacts are allocated to the entire service life. The real lifetime of a new product can differ from the average value. It is possible that a new product is very durable as well as it can fail early. For this case study we assign an average usage duration for each new product and assume a shorter usage duration for reused products. The assumption about the average usage duration will be part of the sensitivity analysis in section 4.1. The impacts of the use phase result from the use of water and electricity. The indices α and β represent the energy efficiency of the new product and the PfR product, respectively. The use of water is expressed as impacts of the use of 1 l water (IW_i) and the water demand ($DW_{\alpha/\beta}$) per use, dependent on the efficiency of each product. Analogously impacts of 1 kWh of electricity (IE_i) are multiplied with electricity demand ($DE_{\alpha/\beta}$) per use and efficiency. Impacts of electricity depend on country (c) and year, whereby a usage duration of t = 1 equals the year 2017. The index *c* is omitted in the following, since this study only focuses on Germany. UB is a scalar that represents the intensity of use. The impacts of use are summed up over the usage duration *t=1,…,n*. The impacts are calculated for each impact category (i). Bovea et al. (2018) conduct a literature review to obtain the most common LCIA methods and impact categories in the field of environmental assessment of EuPs. In accordance with their findings, we use the ReCiPe 2016 (H) midpoint method (V. 1.02) for impact assessment. Results are calculated for all 18 midpoint categories, the interpretation is focused on the categories *climate change* (GWP), *terrestrial ecotoxicity* (TE), *human carcinogenic toxicity* (HT(c)), *mineral resource scarcity* (MRS) and *water consumption* (WC). This set is complemented with the aggregated cumulative energy demand (CED). The CED includes six categories (each three non-renewable and renewable) and is calculated with the method Cumulative Energy Demand (V. 1.10). Impacts are assessed with the SimaPro 8.5 software.

The calculation of EI for each energy efficiency class of white goods enables device-specific decisions on the environmentally preferable waste management option for each impact category dependent on the expected usage duration. The modelling of average PfR and average new devices allows for general recommendations about waste management options of WEEE. To account for the changes in efficiency, market data, indicating the share of energy efficiency classes sold per year, and Weibull distribution, indicating the average age of a device are matched. **Saving potentials** ($S_{i,n,\alpha,\beta}$) of reuse result from the comparison of an average new device with an average reused device. Impacts of the new device equal 100% and impacts of the PfR device are expressed in relation to the new one. If impacts from PfR exceed impacts from a new device, a negative saving potential results. Negative values indicate a better performance of the new device over the considered usage duration, whereas positive values imply the preferability of reuse.

Environmental saving potential: $$S_{i,n,\alpha,\beta} = 1 - \frac{I_{i,n,\beta}^{PfR}}{I_{i,n,\alpha}^{New}} \quad (3)$$

In a first step we calculate the saving potential for the average PfR device arriving at municipal collection points and the average new device sold in 2017. Products are differentiated by their efficiency. For small electric devices, only one value for the energy demand is defined for old and PfR devices, respectively. Therefore these values already represent the average devices. For white goods, different energy demands can refer to a new or PfR product, depending on the assigned energy efficiency rating. The production or PfR phase is equivalent for products of all efficiency ratings. The shares of currently sold efficiency classes per product define the average new white good. To model the average PfR white good, we match historical market data on efficiency classes of product sales with the corresponding lifetime profile. The lifetime profile for different products is defined by Wang et al. (2013). The probabilities for a product coming to its EoL are weighted with the sales shares for each energy efficiency class per year and subsequently cumulated. This defines the expected shares of energy efficiency classes for an average PfR product arriving at collection points in 2017 (see Supplementary Material S3).

The saving potential depends on a fixed usage duration n. The next step is to determine the **maximum usage duration** ($T_{i,\alpha,\beta}^{max}$), which is defined as the point, for which the saving potential is still positive. $T_{i,\alpha,\beta}^{max}$ equals the maximum n for which this condition is fulfilled.

Maximum usage duration: $$T_{i,\alpha,\beta}^{max} = \max n \in N, \quad \forall n: S_{i,n,\alpha,\beta} > 0 \quad (4)$$

The calculation of saving potential and maximum usage duration delivers different results depending on the considered impact category. Both indicators support recommendations about the selection of products that should be reused. A reference value for the maximum usage duration can be defined to decide which products should be reused. If the maximum usage duration for a product with the efficiency rating D is below the reference value (e.g. ten years), reuse would not be recommended. In the following case study, we will use a threshold of $T_{i,\alpha,\beta}^{max} \geq 10$ as the limit for a favorization of PfR. Nevertheless, this value is subjective and needs to be validated individually for each decision-maker.

4 Case study

The case study explores potential benefits of PfR compared to other waste management options (phase C) for the four most relevant white goods and small electrical appliances by weight, based on the findings of primary data acquisition at German collection points (Messmann et al., 2019). With the selection of devices, the environmental impacts of PfR can be quantified for 68% by weight of all collected WEEE. Data collection (see Fig. 1, C1) is structured according to the life-cycle phases of the products (production/PfR, use). For new devices, data on production, packaging and transport is needed. In the case of PfR, repair and transport are included. In the use phase, the devices are differentiated by their efficiency. The specification of the base cases is summarized in Appendix B1-B8. In a first step, EI and the resulting saving potentials for the average new and reused device (section 4.1) are assessed (see Fig. 1, C2). To explore the effects the assumptions may have on the impacts, a sensitivity analysis is performed (see Fig. 1, C3). Subsequently, maximum usage durations for white goods are calculated for each combination of efficiency ratings (section 4.2).

4.1 Saving potential

In the base case scenario the EI for the average new and reused device are calculated for a usage duration of 5 years for white goods and 4 years for small electric devices (see Fig. 1, C2). The respective results for the EI are presented in the Supplementary Material (S5). Fig. 3 illustrates the environmental saving potentials that result from the reuse of an average PfR device in comparison to an average new one ($S_{i,n,\bar{\alpha}\bar{\beta}}$). The indices $\bar{\alpha}$ and $\bar{\beta}$ indicate the average efficiency of PfR and new devices. A positive saving potential indicates the preferability of reuse. Only in the category MRS reuse leads to savings for all products. In the category TE reuse leads to savings for three products, whereas it results in the same impacts for a new and reused freezer. The other impact categories are strongly dominated by the impacts of the use phase. The avoided impacts of production are set off by higher efficiencies in the use phase. Since the results vary strongly between different impact categories, the preferability of reuse can neither be confirmed nor denied on a general basis.

A different picture occurs for small electric devices (see Fig. 4). Positive saving potentials can be realized in all impact categories for a laptop, monitor and PC. The reuse of a printer results in savings in three categories and in the same impacts as a new one in the category CED. It causes slightly more impacts in the category GWP. In contrast to white goods, the functionality of small electric devices changes more rapidly. Therefore, the question arises if the functional unit needs to be defined differently. Currently the functional unit is defined as the use of a product for a certain amount of time. In the case of small electric appliances, it could also be defined more precisely as the use of a product with a certain performance (e.g. computing power, screen size). To account for these changes in service performance we scaled the total energy consumption to the average print speed (printer), average screen area (monitor) and average number of CPUs and average processor speed (laptop and PC). Appendix C shows the resulting figures. The saving potentials decrease for all products and all categories, but remain positive. This means that even if improvements in the performance of the products are factored in, PfR is still the preferable waste management option.

The previous analysis provides an assessment of the environmental saving potentials of WEEE reuse for the base case assumptions. As outlined in section 3, the parameters chosen for the average usage duration, efficiency, user behavior and electricity mix have significant impacts on the results. Therefore, a sensitivity analysis is conducted to test the robustness of the results to uncertainties in the underlying parameters (see Fig. 1, C3). As usage behavior can only be modelled for products that are not in permanent use and is already included in the energy demand for small devices, the sensitivity analysis is carried out for the remaining three parameters:

- Impacts of electricity consumption change with the underlying **energy mix**. Nitsch (2016) calculates how the energy mix needs to change in order to limit global warming to below 2.0°C, as agreed on by the United Nations Climate Change Conference (COP 21). For 2050, it is concluded that the energy mix is composed of 99% renewable sources. Here, we derive two scenarios: 1) the German electricity mix of 2017 and forecasted until 2050 (as in the base case), and 2) a “green scenario”, where the underlying energy mix is based on the assumption of 99% renewable sources (see Appendix D).

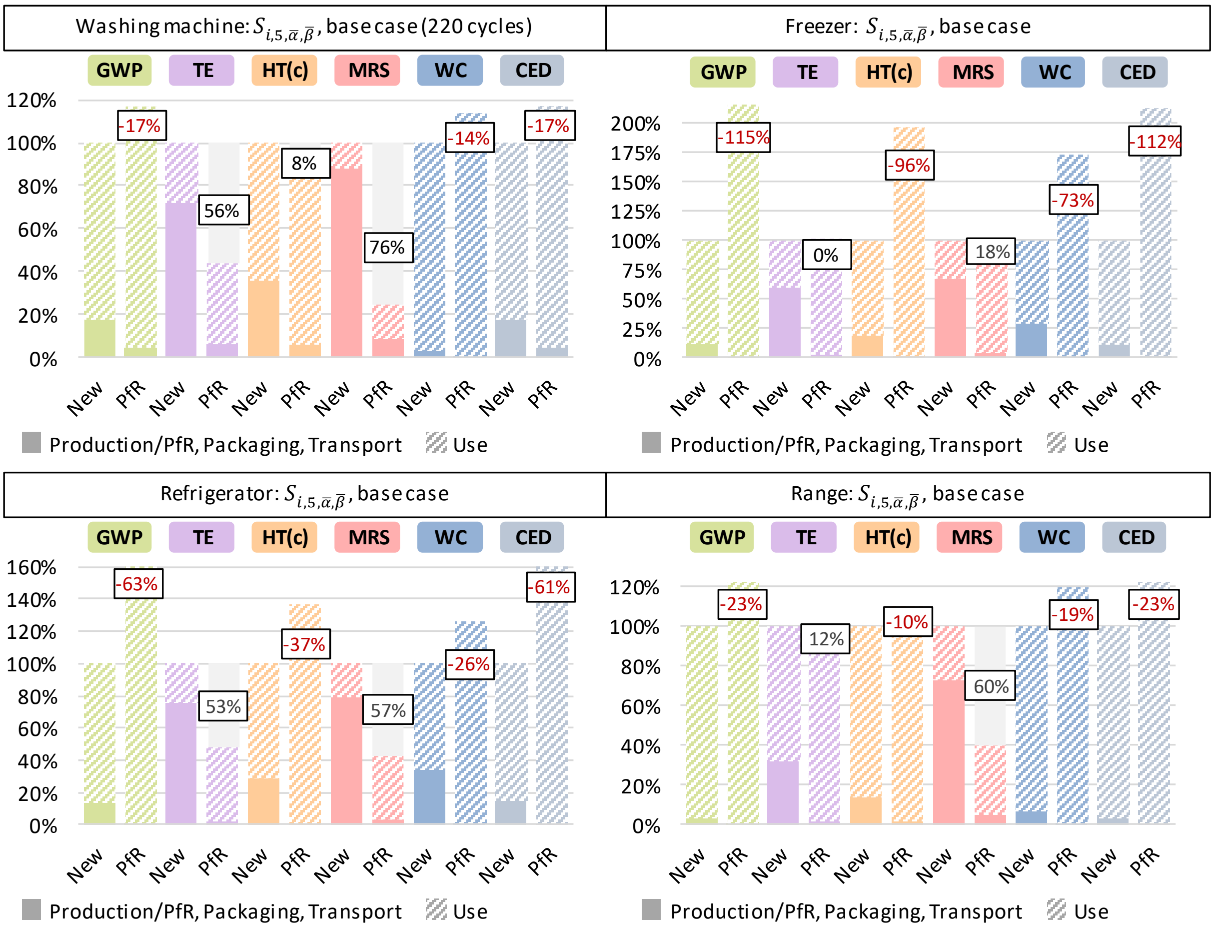
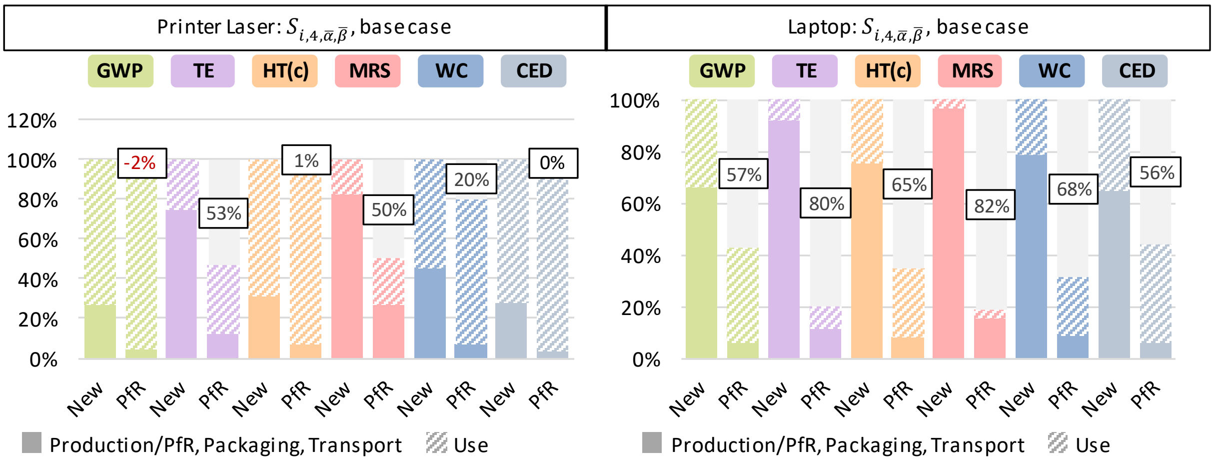


Figure 3. Saving potential of reuse for average white goods (base case)



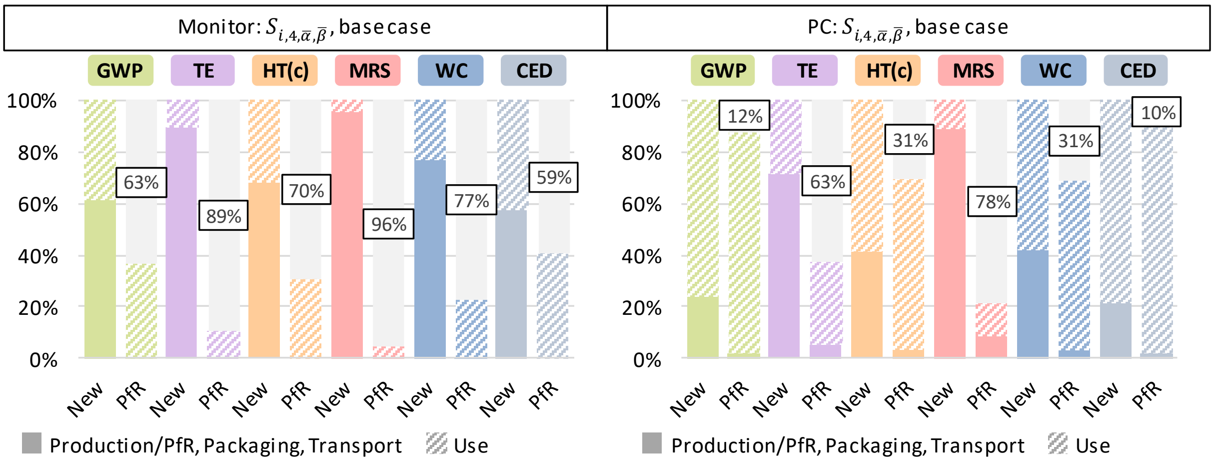


Figure 4. Saving potential of reuse for small electric devices (base case)

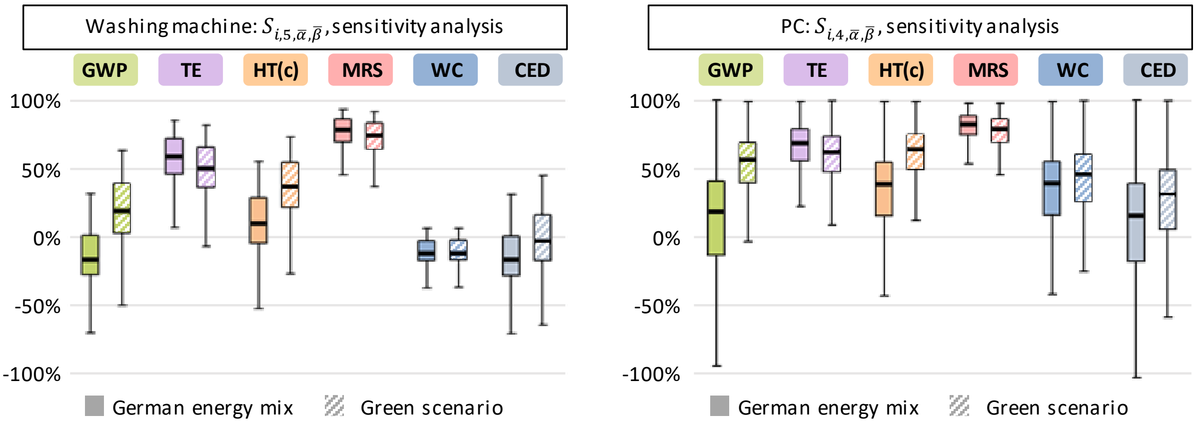


Figure 5. Results of Monte Carlo Simulation of saving potentials for washing machine and PC

For both scenarios, a Monte Carlo Simulation (MCS) with 10,000 runs is carried out in which the stochastic influence of the following two variables is tested:

- In the base case, the **average usage duration** is the mean resulting from the respective Weibull distribution. In the MCS, Weibull-distributed random variables are generated with respective shape and scale parameters for every product.
- The **energy demand** of small electric devices in the base case is defined as the average energy demand of products in the reference periods for new and PfR devices. The distribution of the primary energy demand data is fitted for every product. The resulting distributions are used for the simulation. The energy demand of white goods results from the matching of market data and electricity demand for each energy efficiency class. The average new white good is defined by the shares of currently sold efficiency classes and remains constant. Therefore, we simulate as only remaining free parameter the expected age of a PfR device and match it with the market data on efficiency classes of product sales.

An overview of the assumptions for the sensitivity analysis is given in Appendix D. Fig. 5 shows the results of the simulation of energy demand and average usage duration for the washing machine and PC for the two energy mix scenarios. The saving potentials are plotted as boxplots with a first quartile (25th percentile), median (50th percentile), third quartile (75th percentile), and whiskers. For reasons of a better legibility, we neglected the outliers. Graphs for the other products are shown in Appendix F. Detailed results are provided in the Supplementary Material S7.

The comparison of the two scenarios for the energy mix shows that the transition towards renewable energy sources does not lead to a reduction of the environmental impacts for all impact categories. The green scenario leads to a better performance of reuse in the categories GWP, HT,WC and CED, whereas the saving potentials decrease for the categories MRS and TE.

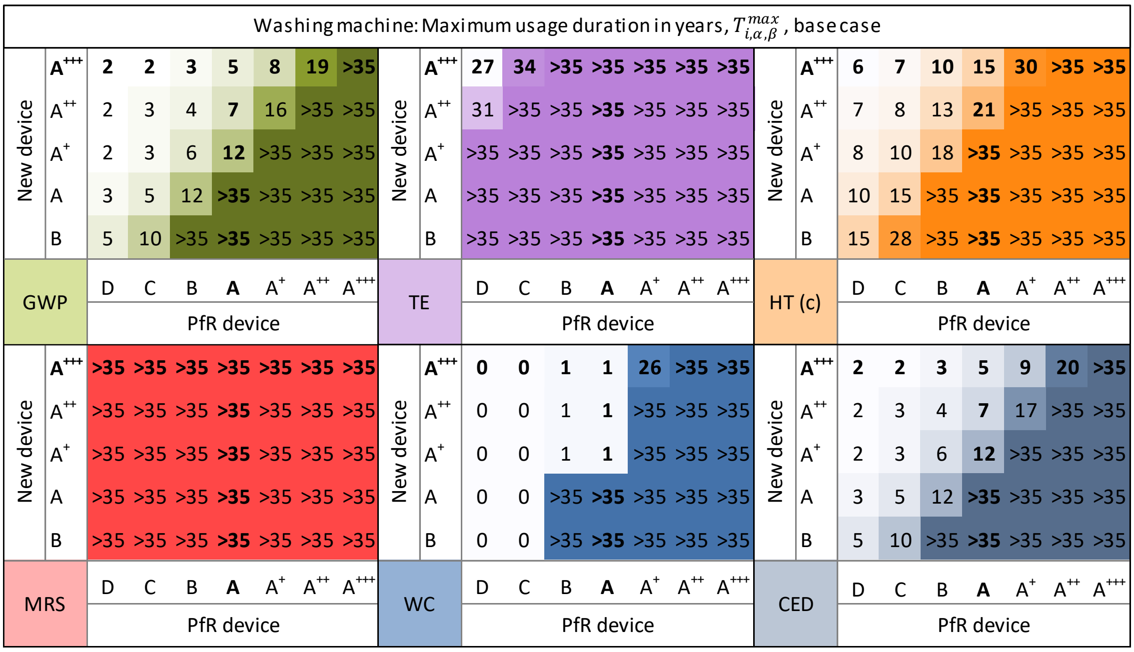
The median changes slightly (between 0% and +2% for different white goods and between 0% and +7% for different small devices), with the exception of the printer (between +6% and +16%). For laptop and monitor, no change in sign between the upper and lower quartile appears for any impact category, and in between 97% and 100% of the test runs, a positive saving potential is determined. This confirms the robustness of the results for varying energy demands and average usage durations for most devices. For the other products, a change in sign between the quartiles occurs for some impact categories (e.g. Fig. 5, GWP and CED of PC for the German energy mix). These impact categories are sensitive towards the assumptions for energy demand and average usage duration. Depending on these assumptions, a different waste management option is preferable for the categories GWP (printer, PC), HT (washing machine, refrigerator, range, printer), TE (freezer), MRS (freezer), WC (refrigerator), and CED (printer, PC). We can differentiate those cases in two groups. Those that have a positive saving potential and those that have a negative saving potential in the base. For those products with a positive saving potential in the base case and a change in sign between the quartiles in the MCS, we further investigate the probability that the saving potential remains positive. A positive saving potential for those products can be determined for at least

60% of the test runs. The MCS shows that the results of the laptop and monitor are most robust, whereas the results for the printer are most sensitive.

The separate simulation of energy demand with a fixed average lifetime, and vice versa, allows for a test towards the importance of each parameter. For most devices, the sole simulation of the energy demand leads to a broader range between the upper and lower quartile in the categories GWP, HT, WC and CED. This shows that those categories are more sensitive towards assumptions of energy demand, whereas the categories TE and MRS are more sensitive towards the expected lifetime.

4.2 Maximum usage duration

The maximum usage duration specifies the amount of years, for which the reuse of a product is environmentally beneficial compared to a new one. The heat maps depicted in Fig. 6 show the maximum usage duration for each combination of energy efficiency ratings for new and reused washing machines in the base case. Maximum usage durations vary strongly for the different impact categories. Nevertheless, the results can be used as decision support for consumers.



Washing machine: Maximum usage duration in years, $T^{max}_{i,\alpha,\beta}$, base case

GWP	PfR device						
New device	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	**2**	**2**	**3**	**5**	**8**	**19**	**>35**
A^{++}	2	3	4	**7**	16	>35	>35
A^{+}	2	3	6	**12**	>35	>35	>35
A	3	5	12	**>35**	>35	>35	>35
B	5	10	>35	**>35**	>35	>35	>35

TE	PfR device						
New device	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	**27**	**34**	**>35**	**>35**	**>35**	**>35**	**>35**
A^{++}	31	>35	>35	**>35**	>35	>35	>35
A^{+}	>35	>35	>35	**>35**	>35	>35	>35
A	>35	>35	>35	**>35**	>35	>35	>35
B	>35	>35	>35	**>35**	>35	>35	>35

HT (c)	PfR device						
New device	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	**6**	**7**	**10**	**15**	**30**	**>35**	**>35**
A^{++}	7	8	13	**21**	>35	>35	>35
A^{+}	8	10	18	**>35**	>35	>35	>35
A	10	15	>35	**>35**	>35	>35	>35
B	15	28	>35	**>35**	>35	>35	>35

MRS	PfR device						
New device	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	**>35**	**>35**	**>35**	**>35**	**>35**	**>35**	**>35**
A^{++}	>35	>35	>35	**>35**	>35	>35	>35
A^{+}	>35	>35	>35	**>35**	>35	>35	>35
A	>35	>35	>35	**>35**	>35	>35	>35
B	>35	>35	>35	**>35**	>35	>35	>35

WC	PfR device						
New device	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	**0**	**0**	**1**	**1**	**26**	**>35**	**>35**
A^{++}	0	0	1	**1**	>35	>35	>35
A^{+}	0	0	1	**1**	>35	>35	>35
A	0	0	>35	**>35**	>35	>35	>35
B	0	0	>35	**>35**	>35	>35	>35

CED	PfR device						
New device	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	**2**	**2**	**3**	**5**	**9**	**20**	**>35**
A^{++}	2	3	4	**7**	17	>35	>35
A^{+}	2	3	6	**12**	>35	>35	>35
A	3	5	12	**>35**	>35	>35	>35
B	5	10	>35	**>35**	>35	>35	>35

Figure 6. Maximum usage durations of reused washing machines per energy efficiency (base case)

Our previous findings show that the most common new device is rated A+++ whereas the most common PfR device is an A-rated model, these classes are highlighted in bold characters. The comparison of these devices leads to the conclusion that the reused device could be used for a longer period than the expected 12 years until the break-even point is reached in the categories TE, HT (c) and MRS. In the categories GWP and CED, a reuse of the A device would be beneficial up to a usage duration of five years, for WC only up to one year. Due to the high impacts of production, reuse is beneficial for all devices in the category MRS and TE. The heat maps for the other products are given in Appendix G and show similar results.

If a consumer needs to decide between the reuse of a product and the purchase of a new device with given efficiencies, the decision mainly depends on the expected usage duration and considered impact categories. PfR devices are always beneficial compared to new devices with the same rating. Taking $T_{i,\alpha,\beta}^{max} \geq 10$ as the limit for a favorization of PfR, general recommendations about reuse can be derived. The following recommendations are based on a comparison of the PfR products with the most common new products. The reuse of washing machines and ranges rated D and C is not recommended for the majority of impact categories. For the products freezer and refrigerator a reuse of products rated D, C and B is not recommended. B-rated washing machines and ranges should only be reused if not the best available technology would be purchased otherwise.

5 Discussion and conclusion

By quantifying the environmental savings for the preparation for reuse of WEEE, we support environmentally optimal decision making on end of life alternatives (see Fig. 1, C4). According to the European waste management hierarchy, preparation for reuse is preferable to recycling. From an environmental point of view, reuse is beneficial, if the life-cycle impacts for an expected usage duration are smaller than those of a new product. If this is not the case, reuse is not beneficial to recycling. The performance of reuse is determined by the trade-off between the higher impacts during the second use of a (less efficient) PfR device versus the impacts resulting from the manufacturing and use of a new (more efficient) one. This study shows that the assumption that reuse is preferable to recycling does not apply in every case. Comparative LCAs on eight products in the German market show that the decision mainly depends on the considered impact category, efficiency of the products, and the expected usage duration. The use phase dominates the impacts of white goods, therefore, reuse of inefficient devices (C and D) should be avoided. The present study calculates a negative saving potential for the reuse of average washing machines (mainly rated A and worse) for the categories GWP, WC and CED. Savings can be realized in three of the six categories. The results confirm the findings from WRAP (2011) and O'Connell and Fitzpatrick (2013). An earlier study of Devoldere et al. (2009) promotes reuse of washing machines rated A. This cannot be confirmed any more. Ardente and Mathieux (2012) and Tecchio et al. (2016) recommend reuse for most cases. We find that the reuse of an average freezer (mainly rated B and worse), refrigerator (mainly rated A and worse) and range (mainly rated B and worse) is unfavorable in comparison to the production and use of new devices for all categories but TE and MRS. Based on the catgeories CED and GWP, Rüdenauer and Gensch (2007a, b) recommend the reuse of freezers rated B and better. The present results update these findings and support a reuse of devices rated A and better. According to Iraldo et al. (2017), the reuse of a refrigerator and oven is already unfavorable, if the new device is more efficient by only one efficiency class. The present results show that the reuse of a refrigerator can be beneficial, even if the new device is better by more than one class. In contrast to the present results, Baxter (2019) determines benefits of reuse of 12-15% in 5 out of 6 impact categories. The results for the oven are not directly comparable, since the current study evaluates a combination of oven and cooktop. The impacts of small electric devices are dominated by the production phase and reuse leads to significant saving potentials in almost all impact categories. The present results for a laptop are in alignment with findings from literature (André et al., 2019; Gutowski et al., 2011; Prakash et al., 2016a; Sahni et al., 2010). No comparable studies are identified for a laser printer. Saving potentials for a monitor are slightly higher, and for a PC slightly lower than findings from literature suggest (Gutowski et al., 2011; Prakash et al., 2016a; Quariguasi Frota Neto and Bloemhof, 2012; Sahni et al., 2010). The functionality and performance of small electric devices changes more rapidly than those of white goods. New devices can even generate more environmental impacts than reused ones, as they are more powerful (e.g. laptops or PCs) or larger (e.g. monitor or TV). The question about reusability is therefore dominated more strongly not only by environmental performance, but also by consumer demands.

The discrepancy between present findings for the reuse of a refrigerator in Germany and the findings of Baxter (2019) for Norway demonstrates the influence of regional scope and energy mix. For the individual case, the decision about the environmentally best waste management option depends on numerous decision parameters. An intensified use favors the new and more efficient product, whereas a higher share of renewable energy sources decreases the relevance of the use phase and favors the reused product in most categories. The scenario analysis shows that a higher share of renewable energy sources leads to a better performance of reuse in the categories GWP, HT, WC and CED, whereas the saving potentials decrease for the categories MRS and TE. This means that it cannot be generally assumed that impacts from electricity consumption become less important, but impacts need to be validated for each category. The sensitivity analysis proves the results of laptop and monitor to be most robust towards uncertainties in the energy consumption and average usage duration, whereas the results for the printer are most sensitive. In the present study, we compare average old appliances arriving at municipal collection points and average new appliances sold in 2017. It can be argued that reuse is especially attractive for consumers with lower budgets. That implicates that those consumers would not buy the best and therefore most expensive, but rather the cheapest available technology (O'Connell et al., 2012). Cheaper white goods can be assumed less efficient than the best and newest ones. If reused products are not compared to the average available products (as in the calculation of the saving potential in the present study), but to the cheapest available ones, the results of the comparison would shift in favor of reuse. Furthermore, we exclude the recycling process, as it takes place in both cases, but with a time-shift in the case of PfR. A discussion and evaluation on environmental implications of the time-shifted benefits and burdens associated with recycling could be part of subsequent work. Follow up research could take the national perspective by combining this approach with the methodology of Material Flow Analysis. The comparison of specific energy efficiency classes could then allow aggregated decisions on product groups on national level. A combined model could incorporate more complex relations between WEEE and products that enter the market, in order to determine the best waste management options on a macroeconomic level.

Reuse is considered a major concept of the CE to achieve increased material efficiency. CE not only promotes closed loops, but also small loops as it is argued that "the smaller the loop (activity-wise and geographically) the more profitable and resource efficient it is" (Kalmykova et al., 2018). The PfR system as analyzed in this paper supports the idea of small (local) loops as products are returned at municipal collection points and regionally re-distributed. The high saving potential for all products in the category mineral resource scarcity confirms the positive effect of reuse on the CE's aim of maximizing resource efficiency. However, we cannot confirm the assumption that reuse is preferable to recycling for every impact category such as global warming or cumulative energy demand. The findings of this paper enable a differentiated perspective on the environmental implications of PfR. The comparison of specific energy efficiency classes allows for product-specific decisions, whereas the assessment approach based on average devices allows for more generalizable recommendations about PfR of product groups. Therefore the results yield three benefits. They support purchasing decisions of individual consumers, facilitate the separation of reusable devices at collection points and enable recommendations for policy in the field of EoL options, such as a PfR-target.

Author contributions section

Sandra Boldoczki: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writinge original Draft, Writing- Review and Editing, Visualization. **Andrea Thorenz**: Conceptualization, Methodology, Validation, Writing- Review and Editing, Project administration, Funding acquisition. **Axel Tuma**: Conceptualization, Methodology, Validation, Resources, WritingReview and Editing, Supervision, Funding acquisition.

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Declaration of competing interest

None.

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The environmental impacts of preparation for reuse:
A case study of WEEE reuse in Germany

Appendix A. Supplementary data

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1.1 Literature review on studies dealing with relevant aspects of reuse of products

Author	Year	Use of LCA	Comparison with new products	Life time extension	Early replacement	Durability	Remanufacturing	Reuse	Other scope	Dishwasher	Freezer	Refrigerator	Vacuum cleaner	Washing machine	Laptop	Mobile phone	PC	Printer/Copier	TV	Other product
Ardente & Mathieux	2014	x	-	x	-	x	-	-	-	-	-	-	-	x	-	-	-	-	-	-
Ardente & Mathieux	2012	x	x	x	-	x	-	-	-	-	-	-	-	x	-	-	-	x	x	-
Ardente et al.	2018	x	x	-	-	-	x	-	-	-	-	-	-	-	-	-	-	-	-	server
Baxter	2019	x	x	-	-	-	-	x	-	-	-	x	-	-	-	-	-	-	-	-
Bobba et al.	2016	x	x	x	-	-	-	-	-	-	-	-	x	-	-	-	-	-	-	-
Boustani et al.	2010	x	x	-	-	-	x	-	-	x	-	x	-	x	-	-	-	-	-	-
Bovea et al.	2018	x	-	-	-	-	-	-	environ. performance	-	-	-	-	-	-	-	-	-	-	small EEE
Devoldere et al.	2009	x	x	x	-	-	-	-	-	-	-	-	-	x	-	-	-	-	-	-
Downes et al.	2011	x	x	x	-	-	-	-	-	-	-	-	-	x	x	x	-	x	-	toaster
Gutowski et al.	2011	x	x	-	-	-	x	-	-	x	-	x	-	x	x	-	x	-	-	screen/monitor
Iraldo et al.	2017	x	-	x	-	x	-	-	-	-	x	x	-	-	-	-	-	-	-	oven
Kerr & Ryan	2001	x	x	-	-	-	x	-	-	-	-	-	-	-	-	-	-	x	-	-
O`Connell	2012	x	x	-	-	-	-	x	-	x	x	x	-	x	-	-	-	-	-	tumble dryer
O'Connell et al.	2012	x	x	-	-	-	-	x	-	-	-	-	-	x	-	-	-	-	-	-
O'Connell & Fitzpatrick	2013	x	-	-	-	-	-	x	-	-	-	-	-	x	-	-	-	-	-	-
Pérez-Belis et al.	2017	x	x	-	x	-	-	-	repair	-	-	-	x	-	-	-	-	-	-	-
Prakash et al.	2012	x	x	-	x	-	-	-	-	-	-	-	-	-	x	-	-	-	-	-
Prakash et al.	2016	x	x	x	-	-	-	-	-	-	-	-	-	-	x	-	-	-	-	-
Quariguasi & Bloemhof	2009	x	x	-	-	-	x	-	-	-	-	-	-	-	-	x	x	-	-	-
Quariguasi & Bloemhof	2012	x	x	-	-	-	x	-	-	-	-	-	-	-	-	x	x	-	-	-
Rüdenauer & Gensch	2005	x	-	-	x	-	-	-	-	-	-	-	-	x	-	-	-	-	-	-

Author	Year	Use of LCA	Comparison with new products	Life time extension	Early replacement	Durability	Remanufacturing	Reuse	Other scope	Dishwasher	Freezer	Refrigerator	Vacuum cleaner	Washing machine	Laptop	Mobile phone	PC	Printer/Copier	TV	Other product
Rüdenauer & Gensch	2007	x	x	-	x	-	-	-	-	-	x	x	-	-	-	-	-	-	-	-
Rüdenauer et al.	2005	x	-	-	x	-	-	-	-	-	-	-	-	x	-	-	-	-	-	-
Tasaki et al.	2013	x	-	-	x	-	-	-	-	-	-	x	-	-	-	-	-	-	x	air conditioner
Tecchio et al.	2016	x	x	x	-	x	-	-	-	x	-	-	-	x	-	-	-	-	-	-
WRAP	2011	x	x	-	-	-	-	x	refurbishment	-	-	-	-	x	-	-	-	-	-	-

1.2 Specification of base cases

Washing machine

Life-cycle phase	New device	Life-cycle phase	PfR device
Production	Inventory data of washing machine (Boyano Larriba et al., 2017) Capacity of 7.00 kg Weight of 70 kg	PfR	Average repair scenario (WRAP, 2011) Capacity of 7.00 kg Weight of 70 kg
Transport	Transport mode and distances adapted from WRAP, 2011 700 km (lorry), 20 km (light commercial vehicle)	Transport	Transport mode and distances adapted from WRAP, 2011 50 km (lorry), 20 km (light commercial vehicle)
Use	220 washing cycles per year (Boyano Larriba et al., 2017) Electricity and water consumption according to rating from A+++ to B Average usage duration of 12.3 years (Wang et al., 2013)	Use	220 washing cycles per year Electricity and water consumption according to rating from A+++ to D Average usage duration of 5 years

Freezer

Life-cycle phase	New device	Life-cycle phase	PfR device
Production	Inventory data of freezer (European Commission, 2007b) Capacity of 216 l Weight of 57 kg	PfR	Average repair scenario for refrigerators (European Commission, 2016) assumed to be equivalent for freezers Capacity of 216 l Weight of 57 kg
Transport	Transport mode and distances adapted from Rüdenauer & Gensch, 2007 400 km (lorry), 60 km (light commercial vehicle)	Transport	Transport mode and distances adapted from WRAP, 2011 50 km (lorry), 20 km (light commercial vehicle)
Use	Electricity consumption according to rating from A+++ to A Average usage duration of 20.6 years (Wang et al., 2013)	Use	Electricity consumption according to rating from A+++ to D Average usage duration of 5 years

Refrigerator

Life-cycle phase	New device	Life-cycle phase	PfR device
Production	Inventory data of refrigerator (European Commission, 2016) Net Volume of 247 dm^3 Weight of 50 kg	PfR	Average repair scenario for refrigerators (European Commission, 2016) Net Volume of 247 dm^3 Weight of 50 kg
Transport	Transport mode and distances adapted from Rüdenauer & Gensch, 2007 400 km (lorry), 60 km (light commercial vehicle)	Transport	Transport mode and distances adapted from WRAP, 2011 50 km (lorry), 20 km (light commercial vehicle)
Use	Electricity consumption according to rating from A+++ to D Average usage duration of 14.6 years (Wang et al., 2013)	Use	Electricity consumption according to rating from A+++ to A+ Average usage duration of 5 years

Range

Life-cycle phase	New device	Life-cycle phase	PfR device
Production	Inventory data of range composed of electric oven (European Commission, 2011a) and electric hob (European Commission, 2011b) Capacity of 54 l (oven) Weight of 31 kg (oven), 7 kg (hob)	PfR	Impacts of PfR are assumed to amount to a certain share[1] of the impacts of production Capacity of 54 l (oven) Weight of 31 kg (oven), 7 kg (hob)
Transport	Transport mode and distances adapted from WRAP, 2011 700 km (lorry), 20 km (light commercial vehicle)	Transport	Transport mode and distances adapted from WRAP, 2011 50 km (lorry), 20 km (light commercial vehicle)
Use	110 baking processes per year (European Commission, 2011a); 438 cooking cycles per year (European Commission, 2011b) Electricity consumption according to rating from A+++ to D Average usage duration of 16 years (Wang et al., 2013)	Use	110 baking processes per year (European Commission, 2011a); 438 cooking cycles per year (European Commission, 2011b) Electricity consumption according to rating from A+++ to B Average usage duration of 5 years

[1] No data for average failures of an oven or hob is available. Therefore the average share of the impacts of PfR from the products washing machine, refrigerator and freezer is used to calculate the impacts of PfR of a range per impact category.

Printer

Life-cycle phase	New device	Life-cycle phase	PfR device
Production	Inventory data of laser printer colour (Ecoinvent database) Weight of 4.61 kg	PfR	Average repair scenario for printers (Prakash et al., 2016c) Weight of 4.61 kg
Transport	Transport mode and distances adapted from Downes et al., 2011 750 km (lorry), 20,000 km (transoceanic ship), 25 km (light commercial vehicle)	Transport	Transport mode and distances adapted from WRAP, 2011 50 km (lorry), 20 km (light commercial vehicle)
Use	Annual electricity consumption of 33.23 kwh (Energy Star, 2018a) Average usage duration of 9 years (Wang et al., 2013)	Use	Annual electricity consumption of 44.62 kwh (Energy Star, 2018a) Average usage duration of 4 years

Monitor

Life-cycle phase	New device	Life-cycle phase	PfR device
Production	Inventory data of LCD monitor (Ecoinvent database) TFT LCD color screen, screen area of 419 in^2 (Energy Star, 2019) Weight of 6.00 kg	PfR	Average repair scenario for monitors (Prakash et al., 2016c) TFT LCD color screen, screen area of 289 in^2 (Energy Star, 2019) Weight of 6.00 kg
Transport	Transport mode and distances adapted from Ecoinvent database for German market; production facilities of main retailers located in Asia, north and south America. 70 km (lorry), 18.659 km (transoceanic ship), 500 km (light commercial vehicle)	Transport	Transport mode and distances adapted from WRAP, 2011 50 km (lorry), 20 km (light commercial vehicle)
Use	Annual electricity consumption of 56.15 kwh (Energy Star, 2019) Average usage duration of 6.7 years (Wang et al., 2013)	Use	Annual electricity consumption of 53.28 kwh (Energy Star, 2019) Average usage duration of 4 years

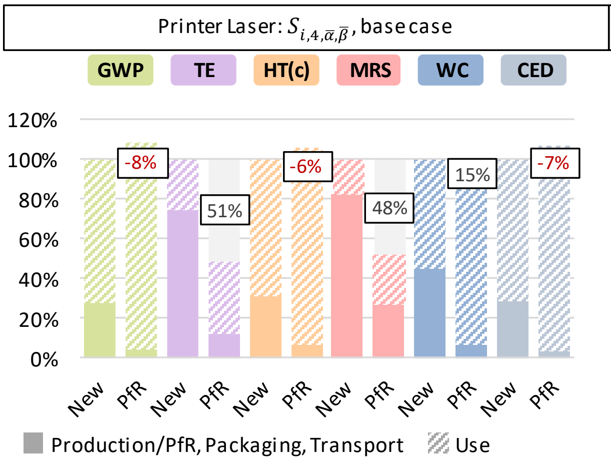
Desktop PC

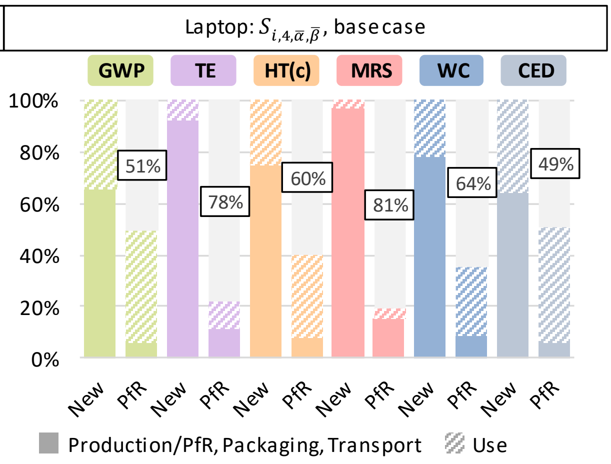
Life-cycle phase	New device	Life-cycle phase	PfR device
Production	Inventory data of desktop PC (Ecoinvent database) 3.36 CPU; 3.33 GHz (Energy Star 2018b) Weight of 6.37 kg	PfR	Common repair actions adapted from Prakash et al., 2016c and personal communication with regional repair and reuse centers 2.96 CPU; 3.23 GHz (Energy Star 2018b) Weight of 6.37 kg
Transport	Transport mode and distances adapted from Ecoinvent database for German market; production facilities of main retailers located in Asia, north and south America. 70 km (lorry), 18,659 km (transoceanic ship), 500 km (light commercial vehicle)	Transport	Transport mode and distances adapted from WRAP, 2011 50 km (lorry), 20 km (light commercial vehicle)
Use	Annual electricity consumption of 91.09 kwh (Energy Star 2018b) Average usage duration of 8.5 years (Wang et al., 2013)	Use	Annual electricity consumption of 102.30 kwh (Energy Star 2018b) Average usage duration of 4 years

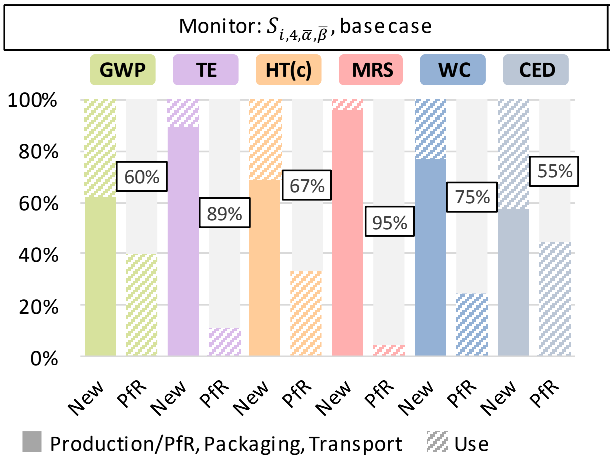
Laptop

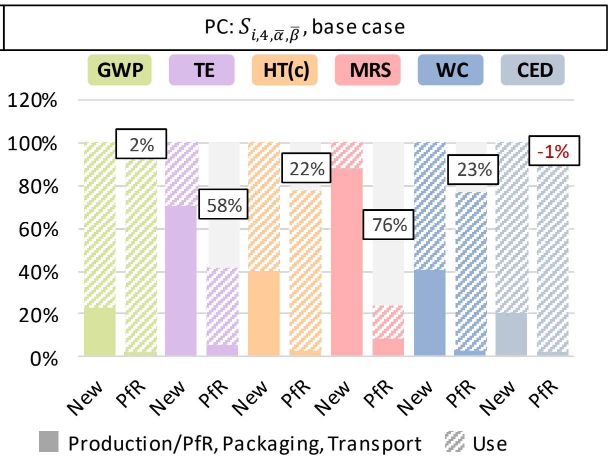
Life-cycle phase	New device	Life-cycle phase	PfR device
Production	Inventory data of Laptop (Ecoinvent database) 2.90 CPU; 2.27 GHz (Energy Star 2018b) Weight of 2.57 kg	PfR	Average repair scenario for laptops (Prakash et al., 2016c) 2.80 CPU; 2,09 GHz (Energy Star 2018b) Weight of 2.57 kg
Transport	Transport mode and distances adapted from Ecoinvent database for German market; production facilities of main retailers located in Asia, north and south America. 70 km (lorry), 18,659 km (transoceanic ship), 500 km (light commercial vehicle)	Transport	Transport mode and distances adapted from WRAP, 2011 50 km (lorry), 20 km (light commercial vehicle)
Use	Annual electricity consumption of 27.35 kwh (Energy Star 2018b) Average usage duration of 4.7 years (Wang et al., 2013)	Use	Annual electricity consumption of 29.84 kwh (Energy Star 2018b) Average usage duration of 4 years

1.3 Saving potential of reuse for small electric devices (normalized energy consumption)


Printer Laser: $S_{i,4,\bar{\alpha},\bar{\beta}}$, base case


Laptop: $S_{i,4,\bar{\alpha},\bar{\beta}}$, base case


Monitor: $S_{i,4,\bar{\alpha},\bar{\beta}}$, base case


PC: $S_{i,4,\bar{\alpha},\bar{\beta}}$, base case

1.4 Share of power from renewable energy sources, for German electricity mix, green scenario and targets

	Share of power from renewable energy sources [4]		
Year	German mix[1]	Green scenario[2]	Targets[3]
2020	0.37	0.99	
2025	0.45	0.99	0.40
2030	0.46	0.99	
2035	-	0.99	0.60
2040	0.51	0.99	
2050	0.65	0.99	0.80

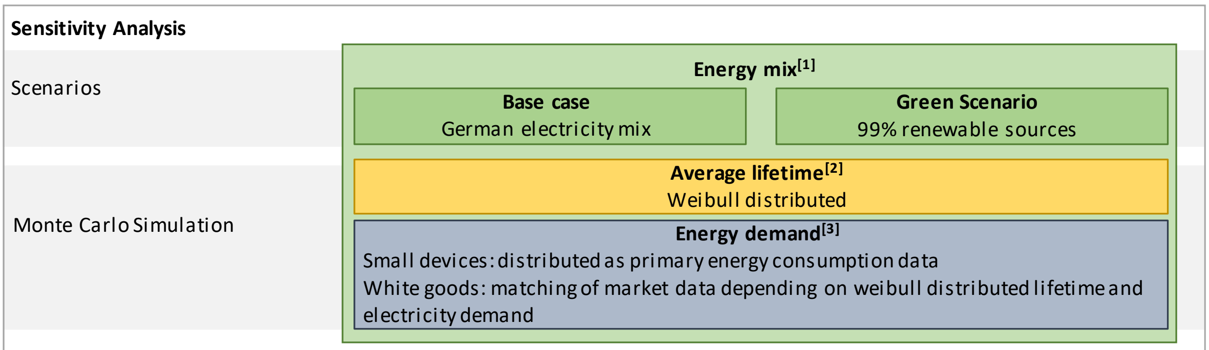
[1] Schlesinger, 2014

[2] Nitsch, 2016

[3] EEG, 2017

[4] The detailed composition of energy sources for both scenarios s listed in the supplementary material (S4)

1.5 Overview of assumptions for sensitivity analysis



Sensitivity Analysis

Scenarios

Monte Carlo Simulation

Energy mix[1]

Base case
German electricity mix

Green Scenario
99% renewable sources

Average lifetime[2]
Weibull distributed

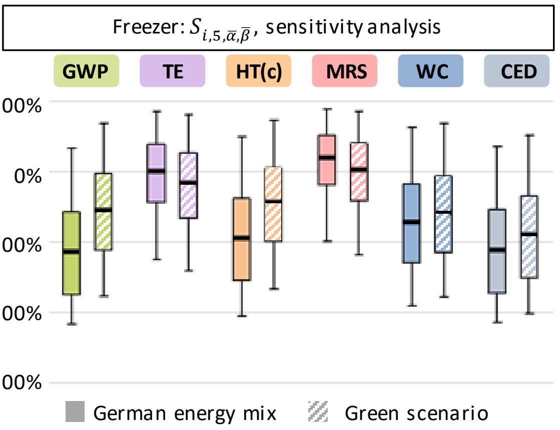
Energy demand[3]
Small devices: distributed as primary energy consumption data
White goods: matching of market data depending on weibull distributed lifetime and electricity demand

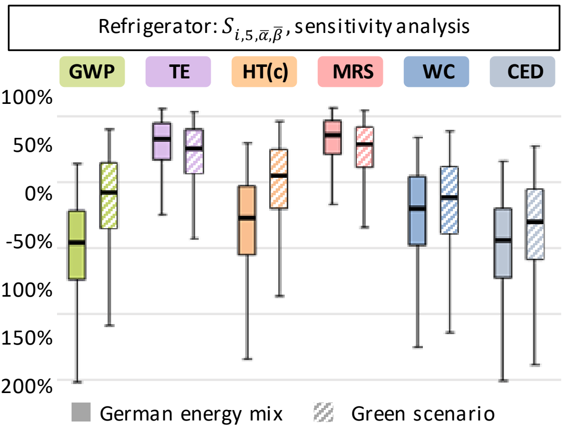
$$I_{i,n,\alpha,c}^{New} = (IP_i + IT_i^{New}) \cdot \boxed{\frac{n}{\bar{n}}} + \sum_{t=1}^{n} \left[(IW_i \cdot DW_\alpha) + \left(\boxed{IE_{i,t,c}} \cdot \boxed{DE_\alpha} \right) \right] \cdot UB$$

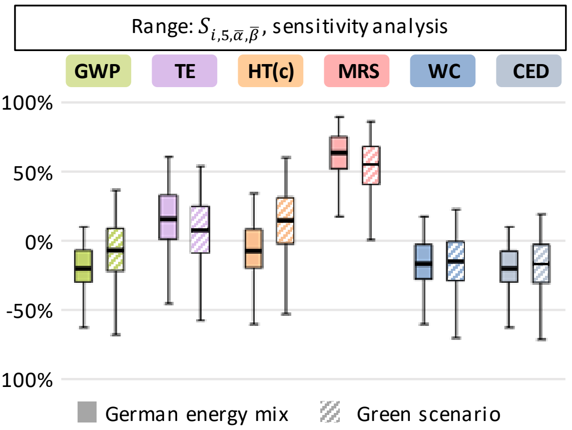
$$I_{i,n,\beta,c}^{PfR} = IR_i + IT_i^{PfR} + \sum_{t=1}^{n} \left[\left(IW_i \cdot DW_\beta \right) + \left(\boxed{IE_{i,t,c}} \cdot \boxed{DE_\beta} \right) \right] \cdot UB$$

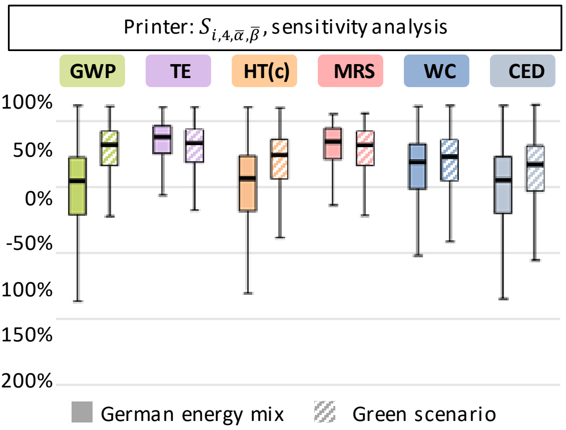
[1] For composition of electricity mix see supplementary material S4
[2] For distribution parameters see supplementary material S3
[3] For distribution parameters see supplementary material S6

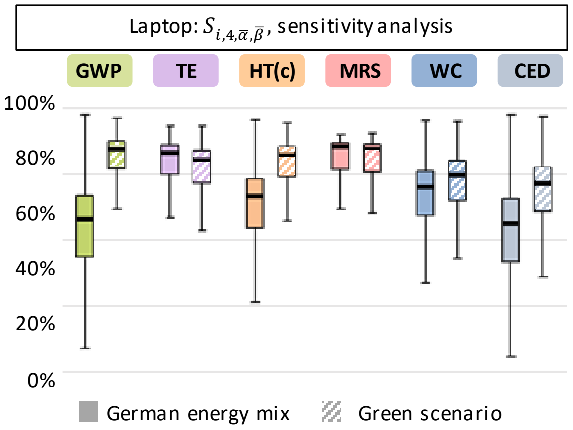
1.6 Results of Monte Carlo Simulation of saving potentials for freezer, refrigerator, range, printer, laptop and monitor

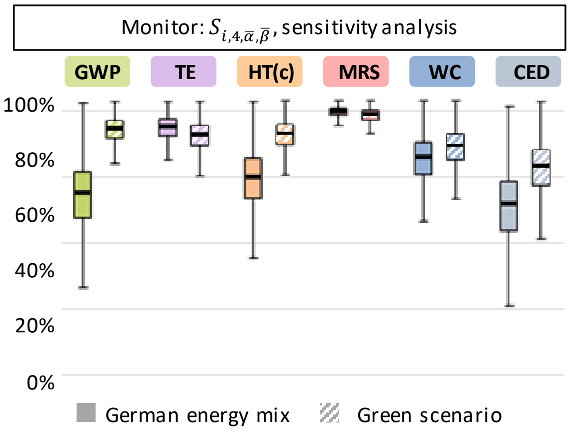




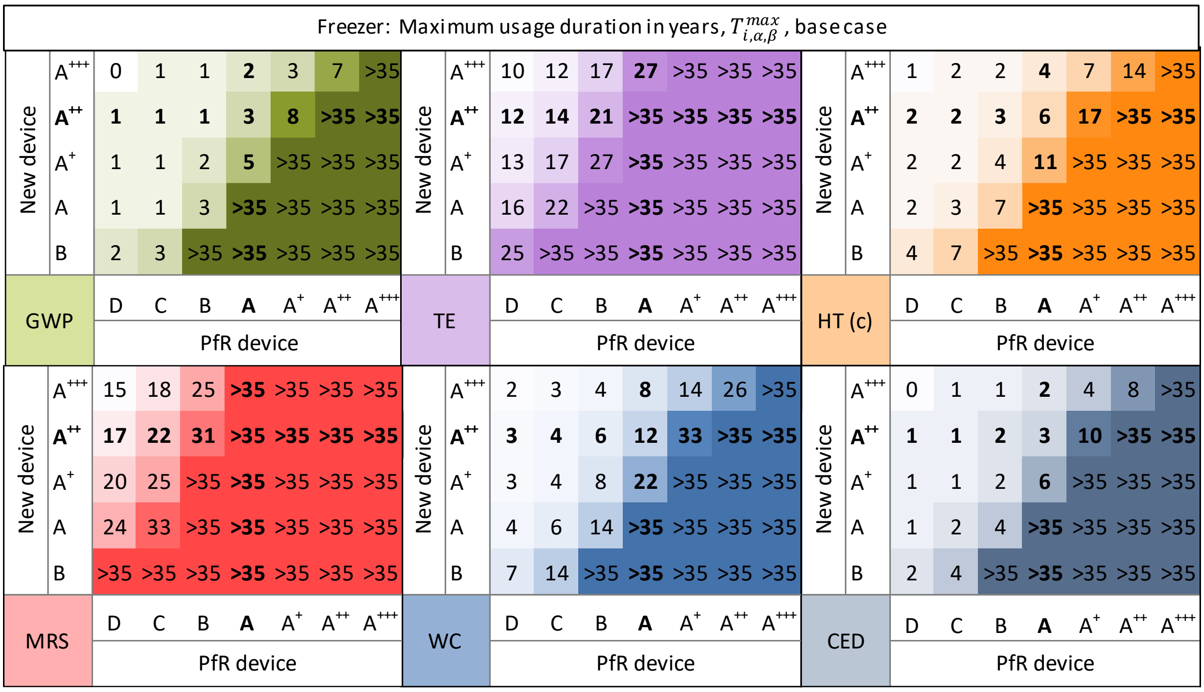








1.7 Maximum usage durations of reused freezer, refrigerator and range per energy efficiency class (base case)



Freezer: Maximum usage duration in years, $T_{i,\alpha,\beta}^{max}$, base case

GWP		D	C	B	**A**	A^{+}	A^{++}	A^{+++}
New device	A^{+++}	0	1	1	**2**	3	7	>35
	A^{++}	**1**	**1**	**1**	**3**	**8**	**>35**	**>35**
	A^{+}	1	1	2	**5**	>35	>35	>35
	A	1	1	3	**>35**	>35	>35	>35
	B	2	3	>35	**>35**	>35	>35	>35

PfR device

TE		D	C	B	**A**	A^{+}	A^{++}	A^{+++}
New device	A^{+++}	10	12	17	**27**	>35	>35	>35
	A^{++}	**12**	**14**	**21**	**>35**	**>35**	**>35**	**>35**
	A^{+}	13	17	27	**>35**	>35	>35	>35
	A	16	22	>35	**>35**	>35	>35	>35
	B	25	>35	>35	**>35**	>35	>35	>35

PfR device

HT (c)		D	C	B	**A**	A^{+}	A^{++}	A^{+++}
New device	A^{+++}	1	2	2	**4**	7	14	>35
	A^{++}	**2**	**2**	**3**	**6**	**17**	**>35**	**>35**
	A^{+}	2	2	4	**11**	>35	>35	>35
	A	2	3	7	**>35**	>35	>35	>35
	B	4	7	>35	**>35**	>35	>35	>35

PfR device

MRS		D	C	B	**A**	A^{+}	A^{++}	A^{+++}
New device	A^{+++}	15	18	25	**>35**	>35	>35	>35
	A^{++}	**17**	**22**	**31**	**>35**	**>35**	**>35**	**>35**
	A^{+}	20	25	>35	**>35**	>35	>35	>35
	A	24	33	>35	**>35**	>35	>35	>35
	B	>35	>35	>35	**>35**	>35	>35	>35

PfR device

WC		D	C	B	**A**	A^{+}	A^{++}	A^{+++}
New device	A^{+++}	2	3	4	**8**	14	26	>35
	A^{++}	**3**	**4**	**6**	**12**	**33**	**>35**	**>35**
	A^{+}	3	4	8	**22**	>35	>35	>35
	A	4	6	14	**>35**	>35	>35	>35
	B	7	14	>35	**>35**	>35	>35	>35

PfR device

CED		D	C	B	**A**	A^{+}	A^{++}	A^{+++}
New device	A^{+++}	0	1	1	**2**	4	8	>35
	A^{++}	**1**	**1**	**2**	**3**	**10**	**>35**	**>35**
	A^{+}	1	1	2	**6**	>35	>35	>35
	A	1	2	4	**>35**	>35	>35	>35
	B	2	4	>35	**>35**	>35	>35	>35

PfR device

Refrigerator: Maximum usage duration in years, $T^{max}_{i,\alpha,\beta}$, base case

New device / PfR device

GWP	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	0	1	1	**2**	3	7	>35
A^{++}	**1**	**1**	**1**	**3**	**8**	**>35**	**>35**
A^{+}	1	1	2	**6**	>35	>35	>35
A	1	1	3	**>35**	>35	>35	>35
B	2	3	>35	**>35**	>35	>35	>35

TE	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	16	20	27	**>35**	>35	>35	>35
A^{++}	**19**	**23**	**34**	**>35**	**>35**	**>35**	**>35**
A^{+}	21	27	>35	**>35**	>35	>35	>35
A	26	35	>35	**>35**	>35	>35	>35
B	>35	>35	>35	**>35**	>35	>35	>35

HT (c)	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	2	2	3	**5**	9	17	>35
A^{++}	**2**	**3**	**4**	**8**	**22**	**>35**	**>35**
A^{+}	2	3	5	**14**	>35	>35	>35
A	3	4	9	**>35**	>35	>35	>35
B	5	9	>35	**>35**	>35	>35	>35

MRS	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	20	24	33	**>35**	>35	>35	>35
A^{++}	**23**	**28**	**>35**	**>35**	**>35**	**>35**	**>35**
A^{+}	26	33	>35	**>35**	>35	>35	>35
A	32	>35	>35	**>35**	>35	>35	>35
B	>35	>35	>35	**>35**	>35	>35	>35

WC	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	2	3	4	**7**	13	25	>35
A^{++}	**3**	**4**	**6**	**12**	**32**	**>35**	**>35**
A^{+}	3	4	7	**21**	>35	>35	>35
A	4	6	13	**>35**	>35	>35	>35
B	7	13	>35	**>35**	>35	>35	>35

CED	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	0	1	1	**2**	4	8	>35
A^{++}	**1**	**1**	**2**	**3**	**9**	**>35**	**>35**
A^{+}	1	1	2	**6**	>35	>35	>35
A	1	2	4	**>35**	>35	>35	>35
B	2	4	>35	**>35**	>35	>35	>35

Range: Maximum usage duration in years, $T^{max}_{i,\alpha,\beta}$, base case

New device / PfR device

GWP	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	0	0	0	**0**	1	3	>35
A^{++}	0	0	0	**1**	2	>35	>35
A^{+}	0	0	1	**2**	>35	>35	>35
A	**0**	**1**	**2**	**>35**	**>35**	**>35**	**>35**
B	1	2	>35	**>35**	>35	>35	>35

TE	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	5	6	8	**12**	19	>35	>35
A^{++}	6	7	10	**16**	35	>35	>35
A^{+}	7	9	14	**28**	>35	>35	>35
A	**9**	**14**	**28**	**>35**	**>35**	**>35**	**>35**
B	13	26	>35	**>35**	>35	>35	>35

HT (c)	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	1	2	3	**4**	6	15	>35
A^{++}	2	2	3	**5**	13	>35	>35
A^{+}	2	3	5	**10**	>35	>35	>35
A	**3**	**4**	**10**	**>35**	**>35**	**>35**	**>35**
B	4	9	>35	**>35**	>35	>35	>35

MRS	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	29	35	>35	**>35**	>35	>35	>35
A^{++}	32	>35	>35	**>35**	>35	>35	>35
A^{+}	>35	>35	>35	**>35**	>35	>35	>35
A	**>35**	**>35**	**>35**	**>35**	**>35**	**>35**	**>35**
B	>35	>35	>35	**>35**	>35	>35	>35

WC	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	0	0	1	**1**	2	6	>35
A^{++}	0	1	1	**2**	5	>35	>35
A^{+}	1	1	2	**4**	>35	>35	>35
A	**1**	**2**	**4**	**>35**	**>35**	**>35**	**>35**
B	2	4	>35	**>35**	>35	>35	>35

CED	D	C	B	**A**	A^{+}	A^{++}	A^{+++}
A^{+++}	0	0	0	**0**	1	3	>35
A^{++}	0	0	0	**1**	2	>35	>35
A^{+}	0	0	1	**2**	>35	>35	>35
A	**0**	**1**	**2**	**>35**	**>35**	**>35**	**>35**
B	1	2	>35	**>35**	>35	>35	>35