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The link between product service lifetime and GHG emissions

A comparative study for different consumer products

Simon Glöser-Chahoud[1] | Matthias Pfaff[2] | Frank Schultmann[1,3]

[1] Institute for Industrial Production (IIP) at Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

[2] Fraunhofer-Institute for Systems and Innovation Research (ISI), Karlsruhe, Germany

[3] Adelaide Business School, University of Adelaide, Adelaide, South Australia, Australia

Correspondence
Simon Glöser-Chahoud, Institute for Industrial Production (IIP) at Karlsruhe Institute of Technology (KIT), Hertzstr. 16, 76187 Karlsruhe, Germany.
Email:simon.gloeser-chahoud@kit.edu.

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Abstract

The production, use, and final disposal of goods are directly linked to various environmental impacts caused along their supply chains and over their entire life cycles. When assessing these impacts for energy-consuming products such as consumer electronics, not only the emissions caused during production but also the energy consumption during the use phase need to be taken into account in order to provide a holistic view on environmental impacts. However, the interplay between a product's lifetime, reduction of demand through higher durability, energy consumption, and related greenhouse gas (GHG) emissions cannot be generalized but requires very specific analyses, which take into account product-related aspects and their temporal changes as well as the (changing) properties of the energy and use system. This contribution provides a quantitative assessment of the interrelation between product lifetime and environmental impacts, particularly GHG emissions, using refrigerators and mobile phones as exemplary products with differing characteristics. Whereas in the case of refrigerators, the strongest impact is caused during the use phase because of high energy consumption and related emissions, mobile phones as representatives of classical consumer electronics have their highest environmental impact during production. To assess impacts for both product categories, two simulation models of product life cycles based on methods from dynamic material flow analysis (MFA) are linked with life cycle inventory (LCI) data and LCA results for the respective products, focusing on the impact category of global warming potential (GWP). By systematically evaluating different scenarios, we show major influences on the overall GHG emissions over a product's lifetime capturing temporal developments and modifications within the target system at European scale. In the case of refrigerators, we show that there is a trend towards increasing optimum lifetimes and that current energy efficiency improvements of new devices do not justify early replacement of older devices and, hence, a reduction of service lifetime. This is also because the GHG emissions of electricity production have continuously decreased with an increasing share of renewable energy sources. Regarding mobile phones, we emphasize the counterproductive effect of unused storage time (hibernation) when taking efforts for increasing the service lifetimes aiming at a reduction of demand for new, resource-consuming devices.

KEYWORDS
cascade simulation, durability, global warming potential (GWP), greenhouse gas (GHG) emissions, product lifetime extension, scenario analysis

1 | INTRODUCTION

It is becoming increasingly clear that the goals of the Paris Agreement cannot be reached through measures that exclusively focus on the reduction of greenhouse gas (GHG) emissions through energy efficiency and renewable energy. According to a recent study by the Ellen MacArthur Foundation, 45% of current emissions stem from the production of goods and services as well as the management of land. In order to address these emissions, a more efficient use of resources and a more circular way of organizing economies are required. The circular economy concept envisions the decoupling of material consumption from environmental impacts by keeping materials inside the loop through various measures ranging from product lifetime extensions to efficient recycling systems (Stahel, 2016). This contribution will focus on the specific case of the effect of product lifetime on environmental impacts of consumer products over their entire life cycle.

In the case of energy consuming products, such as consumer electronics, not only the emissions caused during production (embodied emissions) but also the emissions during the use phase need to be taken into account. The energy consumption during the use phase strongly differs between different product categories and may change over time even within one product group, for example, through energy efficiency improvements. This situation represents a trade-off between the spreading of embodied emissions over longer product lifetimes and efficiency improvements of products that reduce the specific use phase emissions (Skelton & Allwood, 2013). Both embodied and use phase emissions further depend on the respective local electricity mixes (of the places of production and use), which might also change over time. In contrast, measures for increasing product durability, for example, through product design, might be counteracted by the behavior of consumers who seek the newest products and therefore replace well-functioning ones with new devices prematurely (Glöser-Chahoud et al., 2019). Used products are often kept in households without providing any additional service, which is also referred to as hibernation[1] (Oswald & Reller, 2011). Hence, the interplay between a product's lifetime, energy consumption and related GHG emissions cannot be generalized but requires very specific analyses, which take into account product related aspects and their temporal changes as well as the properties of the energy system (Kagawa et al., 2011).

This paper provides a quantitative assessment of the interrelation between lifetime extension and environmental impacts, particularly GHG emissions, for selected consumer products. We chose refrigerators as an example of a product group with high energy consumption during the use phase and mobile phones as representatives for classical consumer electronics with high GHG emissions during production, particularly caused by the provision of various high-tech metals (cf. Figure 1b).

Current average European electricity consumption per household is around 4000 kWh (Enerdata, 2020), while the average refrigerator in use consumes approximately 250 kWh/a (Michel et al., 2015). This results in a significant share of at least 6% of overall household electricity consumption and associated GHG emissions caused by refrigerators (assuming one device per household). The overall lifetime GHG emissions of mobile phones in comparison to refrigerators are comparatively small (cf. Figure 1b). However, with annual sales numbers of around 200 million devices in Europe and in use stocks of over 600 million devices (see simulation results in this paper), mobile phones are among the most common consumer electronic components and therefore form an important reference case. Beside the differing distribution of impacts over the respective life cycle stages, consumers' perceptions vary between the considered products as depicted in Figure 1a. In the case of mobile phones, aesthetic characteristics, specific functionalities and technological innovation are of high importance for most consumers, often leading to early replacements of devices even though they are still functioning. This is not necessarily the case for white goods, such as refrigerators, since basic functionality and costs generally play a more important role in purchasing decisions than emotional influences (European Commission, 2009; Oeko-Institut, 2018). Even though this may be partially changing due to the emergence of fridges with special designs and premium features, these characteristics generally lead to comparatively longer use phases despite potentially outdated energy efficiency levels. Anecdotal evidence also suggests that consumers may have a higher propensity to swap functioning fridges with new ones because they desire new features or existing features stopped working (e.g., ice dispensers), or so that the old fridges can be used in other parts of their houses, for example, as extra refrigeration capacity in the garage or basement. In addition, there may be regional differences in consumers' valuation of these characteristics. Hence, each product group has its specific

[1] This is not to be confused with a low power mode of electronic devices, which is sometimes also referred to as hibernation.

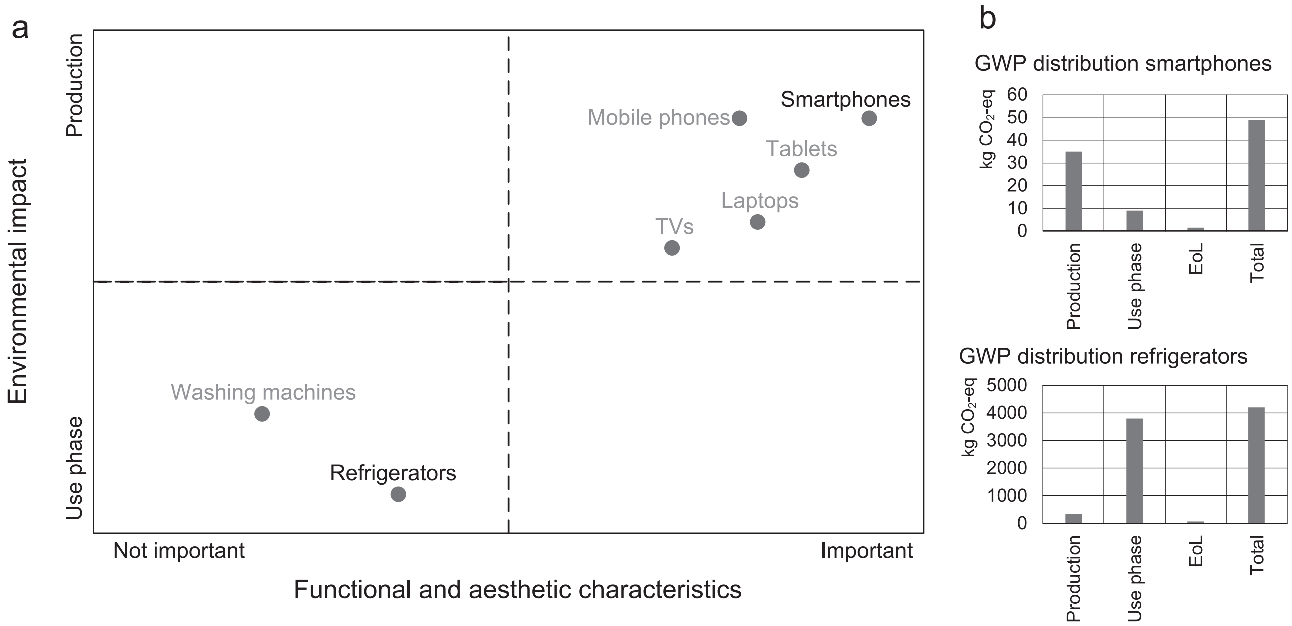

FIGURE 1 Characterization of different consumer products. (a) Classification regarding environmental impacts and functional and aesthetic aspects (European Commission, 2009; Glöser-Chahoud et al., 2019; Oeko-Institut, 2018). (b) Contribution of different life phases to overall GHG emissions regarding the two product types in focus. GWP data based on average literature results of LCAs according to Suckling and Lee (2015) for mobile phones and JEMA (2014) for refrigerators. See Supporting Information S2 for underlying data

characteristics, which have to be considered in analyses of their overall environmental impacts (cf. Figure 1a for a general clustering of different consumer products regarding functional and aesthetic characteristics on the one side and distribution of environmental impacts over the product life cycle on the other side).

In this study, we link simulation models of product life cycles based on a methodology which is regularly applied in the field of dynamic material flow analysis (Müller et al., 2014) with life cycle inventory (LCI) data and results of LCA studies for the respective products. Through the evaluation of different scenarios, we show major influences on the overall GHG emissions over a product's lifetime. The analysis is conducted at the European level in order to have a clear target system regarding sales numbers and energy provision. However, the findings are generally transferrable to other product groups and geographical regions.

By merging an individual life cycle simulation model for both product groups with environmental impact assessment, we demonstrate the complexity and versatility of influences of product lifetime extension on the environmental performance particularly regarding GHG emissions and the impact category of GWP. Product lifetimes have been discussed from various angles both qualitatively and quantitatively (Bakker & Schuit, 2017; Box, 1983; Rivera & Lallmahomed, 2016; Thiébaud-Müller et al., 2018), though often without systematically discussing the aforementioned trade-offs between embodied and use phase emissions in the context of lifetime extensions. Some studies have addressed these trade-offs with different scopes and levels of detail (Allwood et al., 2011; Bakker et al., 2014; Cooper et al., 2014; Kagawa et al., 2008). Skelton and Allwood (2013), for instance, present a systematic assessment of optimal lifetimes of different product categories with respect to GHG emissions. However, they focus on the steel content and the associated emissions of individual products without reference to the geographical setting. In contrast, we adopt a "systems perspective" (Babbitt, 2017) for the analysis of overall emissions. Furthermore, most existing assessments of lifetime influences exclude temporal changes in the electricity mix and the energy efficiency of the considered products, even though this may have a large impact on use phase emissions. Dynamic life cycle assessments usually address temporal changes, such as emissions from energy provision (Boldoczki et al., 2020). However, they are product centered without quantifying effects on the entire use system, such as adjustment of demand in case of modified lifetimes in order to retain the desired in-use stock level (Müller, 2006). This paper extends these analyses by conducting simulations of lifetime extensions of refrigerators and mobile phones from a systemic perspective, taking into account stock dynamics and changes in the demand for new devices, which is a key aspect when assessing both embodied impacts and impacts during the use phase. These simulations are conducted at the European level, taking into account changes in product attributes and the underlying energy system.

The paper is structured as follows: After presenting basic principles of the dynamic stock and flow simulation approach and the model structure for the two product groups in the methods part, we present the results of different scenarios regarding lifetime modifications and further variations of model settings. We then summarize major findings in the discussions section and we subsequently draw conclusion and give an outlook on further applications and future modifications of the simulation approach.

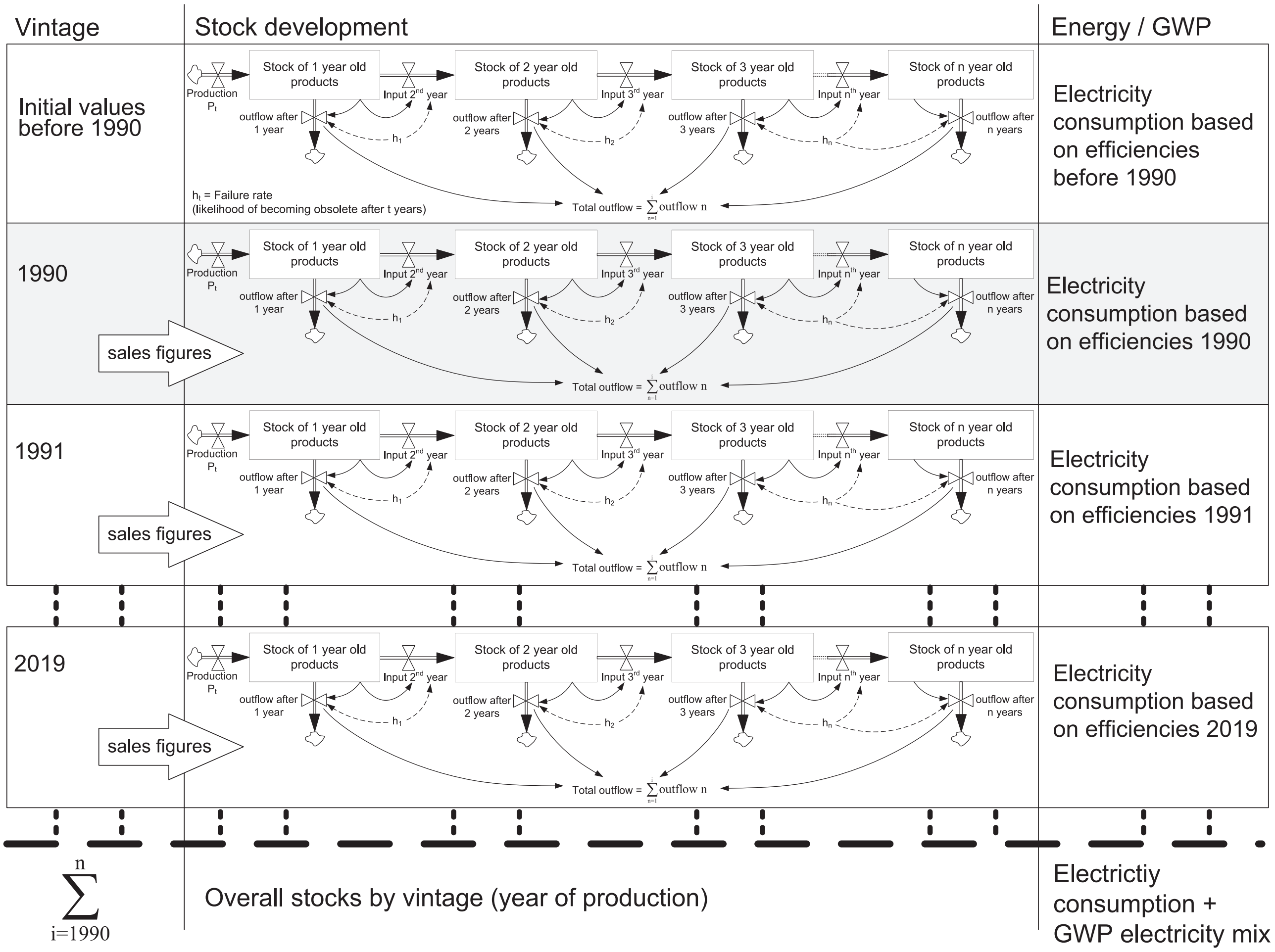

FIGURE 2 Basic structure of the life cycle simulation model for refrigerators simulating each vintage separately as energy consumption (average efficiency level) depends on the year of production and electricity mix changes over time. In addition, this simulation approach allows for adjustment of failure rates based on the age of specific devices

2 | METHODS

The goal of this contribution is to emphasize the differences in life cycle characteristics of the two product categories in focus and to derive related strategies for decreasing environmental impacts in the form of global warming potential (GWP). Our approach combines aspects of dynamic MFA and LCA, which are both common methodological approaches in Industrial Ecology research. We do not conduct a separate LCA in this contribution but focus on the mid-point impact category of GWP from existing studies, regarding both the impacts caused by the production of the considered goods and average GHG emissions for the provision of energy during their use phase. We then apply these static results from product-based LCA approaches to system-wide dynamic life cycle simulation. For the analysis, not only knowledge of the overall stocks of appliances in use and EoL material flows but also a detailed assessment of the age and vintage of products in use is necessary. Especially for refrigerators, there has been a continuous improvement in energy efficiency leading to lower impacts of younger devices during the use phase (Hollander & Roser, 2015). However, some studies suggest that these efficiency gains have slowed down in the recent past and will not continue forever due to physical limits (cf. Hollander & Roser, 2015; Wieser et al., 2015). The simulation approach thus needs to be capable of accounting for such efficiency gains by simulating a product's aging process in detail. At the same time, the approach must be capable of taking changes in the overall system into account, for instance, the continuing decarbonization of the European electricity system and the corresponding reduction in use phase emissions of electric and electronic goods. In recent years, a variety of tools for conducting dynamic MFA have been developed (Pauliuk et al., 2015). In this study, we used a system dynamics (SD) approach because the stock and flow structure of SD allows for a detailed simulation of aging chains and material/product accumulation in use as depicted for the respective vintages in Figure 2. The aging chain consists of a cascade stock and flow system in which each year of life is represented by one stock variable (boxes in the aging chain in Figure 2) while after each year the respective probabilities of entering the next age cohort or of being scrapped are calculated from the underlying lifetime distributions. A more detailed description of the aging chain and the simulation method is provided in the Supporting Information S1.

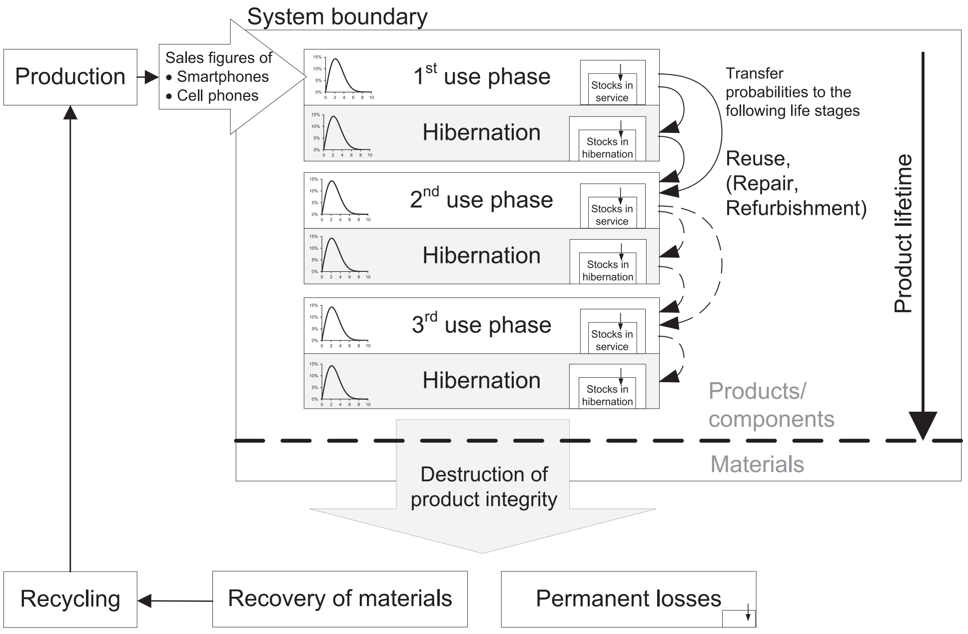

FIGURE 3 Basic structure of the life cycle model for mobile phones including different use phases and hibernation times representing a cascade use system

Based on this simulation approach, we have developed two separate models (cf. Figure 2 and 3) capturing the life cycles of refrigerators and mobile phones, respectively. While in the case of mobile phones, the production of new devices causes the highest impacts and, hence, a reduction of demand for new products by increasing the service lifetime appears to be a promising strategy, refrigerators are among those products that consume large quantities of energy during their use phase (cf. Figure 1). In this case, the effect of an increase in energy efficiency of new devices and the question of the best point in time for the replacement of an old refrigerator from the perspective of overall GHG emissions is of interest for the simulation approach. Both aspects are addressed with the simulation models presented here. As each model structure is different, we provide a basic description of each model in the following section.

2.1 | Refrigerators

For refrigerators, it is necessary to simulate the stock in use for each vintage depending on the year of production separately. This is because the energy efficiency of average devices has strongly increased over the previous decades (Hollander & Roser, 2015). In order to capture these effects and to balance efficiency gains on the one side and energy consumption for the production of new devices on the other side, a detailed approach that accounts for each year of production separately (as shown in Figure 2) is necessary. The model requires the distinction of stock composition by age, which enables the modeling of temporal modifications in energy consumption and embodied emissions. At the same time, the energy mix and GHG emissions related to electricity generation need to be addressed for a holistic analysis. This is achieved by a separate implementation of the aging process for each vintage, while overall stocks in use and energy consumption are calculated from the summation of each individual aging chain. The resulting model structure for refrigerators is illustrated in Figure 2.

While we discuss the most relevant input data in the context of the assessed scenarios, more detailed information regarding model implementation, assumptions and additional illustrative figures are provided in the Supporting Information S1.

2.2 | Mobile phones

As illustrated in Figure 3, in the case of mobile phones, we simulate different life stages (service lifetime and hibernation) in a cascade use system as first described by Thiébaud et al. (2017) and adapted by Glöser-Chahoud et al. (2019). However, these previous publications focus on the product use phase itself and the materials contained in these products, whereas herein, we assess environmental impacts associated with different product lifetimes and replacement strategies. As illustrated in Figure 3, the overall lifetime of a mobile phone consists of service phases in which the phone is actually in use and unused storage phases to which we refer as hibernation. This hibernation time is counterproductive when developing strategies

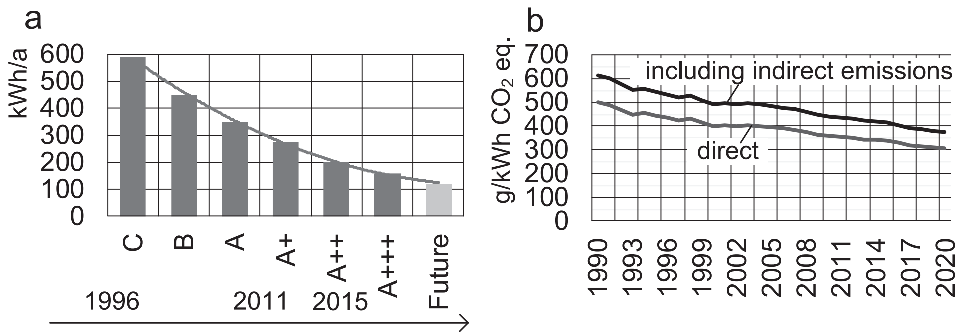

FIGURE 4 (a) Development of energy efficiency levels of household refrigerators according to EU labeling (Hollander & Roser, 2015) (b) direct and indirect GHG emissions of average European electricity generation (Moro & Lonza, 2018). Underlying data of both figures are included in the Supporting Information S2

towards higher use intensity and therefore needs to be addressed in simulation models capturing the entire product life cycle. After each use or storage phase, transfer probabilities regulate the flows to the following stage of life or subsequent disposal (including exports of used goods). While Figure 3 provides a sufficient understanding of the model structure for the purpose of the following scenario analysis, we provide more detailed information on the model structure, data and assumptions in the Supporting Information S1.

3 | RESULTS

In the following section, we present exemplary scenarios from the two simulation models aimed at highlighting differences between the product types regarding GHG emissions and related GWP over the entire life cycle. We start with the lifetime simulation of refrigerators, as this is more relevant for emissions during the use phase and the question of the best replacement date of old devices. In the case of mobile phones, we mainly quantify the potential of GWP reduction through increasing service lifetimes and decreasing hibernation, the latter of which counteracts efforts towards higher use intensity. Hence, in the case of mobile phones the emissions during production of new devices and the potential of reducing environmental impacts through decreasing demand for new products is in the focus of the presented scenarios.

3.1 | Lifetime simulation of refrigerators and related GHG emissions

The lifetime simulation model for refrigerators as depicted in Figure 2 is capable of following refrigerators for each production year (vintage) over the entire lifespan and of calculating the corresponding GWP by considering both the production phase and the energy consumption during the use phase. This enables the simulation of different lifetime scenarios and corresponding GHG emissions. While the simulation approach provides information on the GWP of the overall life cycle and yearly system-wide emissions, it does not directly derive a theoretical optimum lifetime. However, the model allows for the comparison of lifetime scenarios. In order to assess potential improvements of GHG emissions through lifetime adjustment, we primarily compare different scenarios using sales figures for refrigerators, resulting product stocks in use, energy efficiency development of refrigerators (from 1990–2020) and the yearly average GHG emissions per kWh of electricity production as major input data. Most relevant for the understanding of the following scenarios is the development of the energy efficiency of refrigerators over time (Figure 4a) and the average GWP of electricity provision in Europe (Figure 4b), which serves as the basis for this study. Of course, there are large differences in GHG emission for electricity supply among different member states and within different regions (Moro & Lonza, 2018). However, for the more general conclusions and analyses conducted in this study, average figures are sufficient.

The first scenario shown in Figure 5a is supposed to be the state of the art reference scenario in which each refrigerator is used on average for 13 years. This is the reference lifetime for household refrigerators from literature (Michel et al., 2015; Xiao et al., 2015). Hence, for each vintage from 1990 to 2020, which is the timeframe of the scenarios analyzed here, an expected value of 13 years using Weibull distributions is implemented in the simulation model, as depicted in Figure 2. This leads to a stock accumulation of around 190 million devices and serves as the reference stock for the second scenario in which the effect of decreasing product lifetimes on overall GHG emissions is analyzed. To this end, the average lifetime (expected value of the underlying distribution) is reduced to 8 years. At the same time, the reference stock from the baseline scenario needs to be met, which leads to a significant increase of new purchases and related embodied emissions. The resulting higher overall emissions, particularly at the beginning of the time horizon, are well observable in Figure 5b. On the other side, an increase of average lifetime by a similar range (+5 years resulting in an expected value of 18 years for the underlying distributions) shows very little variation as compared to the baseline

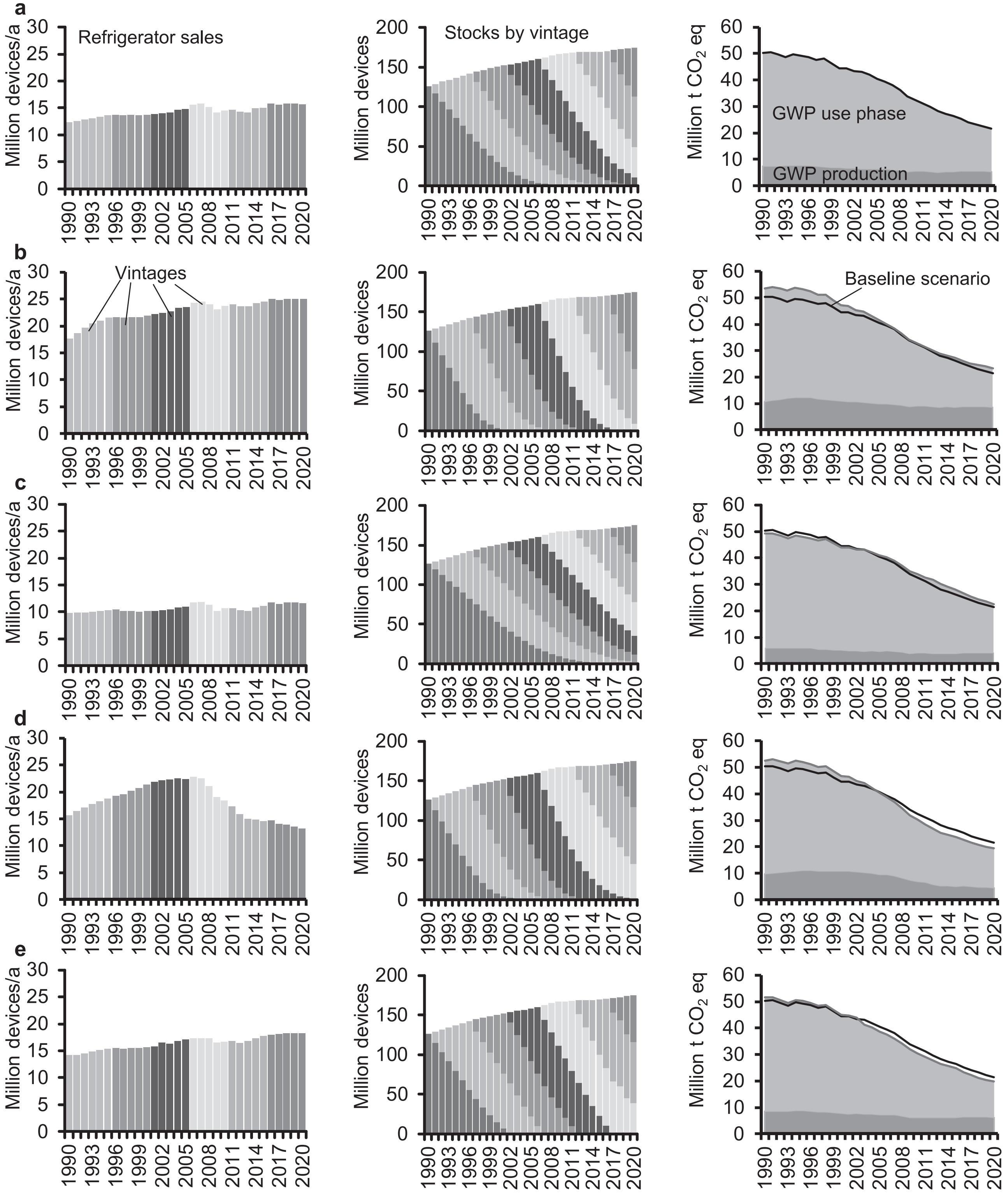

FIGURE 5 Selected scenarios regarding GHG emissions from refrigerators in Europe (EU28) from a systemic perspective. In all scenarios, the overall stock in use is equal to the baseline scenario (a) in order to keep the service from stock at a constant level. (a) Baseline scenario according to real data at EU28 level (average lifetime of 13 years). (b) Scenario with decreased average lifetime of 8 years (expected value of the underlying distribution). (c) Scenario with increased average lifetime of 18 years. (d) Scenario with an adjustment to optimum lifetimes based on the expected values of the distributions. (e) Baseline scenario with a direct replacement after reaching the optimum lifetime (adjustment of failure rates). Underlying data used to create this figure can be found in the Supporting Information S2

TABLE 1 Optimum use phase duration calculated according to Equation (1) and implemented in the scenarios in Figure 5d,e

Vintage	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Optimum use phase	9	9	9	8	8	8	8	8	8	8
Vintage	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Optimum use phase	8	8	8	9	9	10	11	11	12	13
Vintage	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Optimum use phase	14	14	15	15	15	15	15	15	15	15

scenario (Figure 5c). This already is an interesting result, as it clearly shows that the effect of energy savings through early replacement of older devices with lower energy efficiency is rather small. In the subsequent scenarios (Figure 5d,e), we assess the effect of an optimized lifetime on the overall GHG emissions from refrigerator use in Europe. The basic idea is that due to higher energy efficiency of new devices (clear temporal trend in Figure 4a), the emissions caused during production of a new refrigerator might be overcompensated by energy savings and related GHG emission during the use phase leading to an improvement of overall GWP. To assess this effect, we use an intuitive heuristic for the determination of the optimum lifetime for each vintage based on the year of production and the related average energy efficiency level for refrigerators from that time. According to this heuristic, a refrigerator should get replaced as soon as the sum of potential yearly energy savings compared to a new device and related GWP reduction is higher than the GHG emissions for the production of a new device. Hence, this heuristic seeks to minimize the overall GWP taking into account both expected yearly impacts during the use phase and impacts due to the production of new devices.

The abort criterion for increasing the lifetime n of a device according to this concept is summarized in Equation (1).

$$n \cdot \left(\mathrm{GWP}_{y\_old} - \mathrm{GWP}_{\mathrm{y\_new}}\right) > \mathrm{GWP}_{\mathrm{p\_new}} \tag{1}$$

where GWP_p is the impact of production, GWP_y is the yearly impact during use at the time of replacement, n is the service lifetime and the subscripts "new" and "old" refer to the devices being replaced or installed, respectively. A graphical illustration of this heuristic algorithm to determine the optimum lifetime from a systems perspective is provided in the supplementary material to this paper.

An advantage of this simple abort criterion is that there is no need for optimization within a given timeframe as discussed further below. Instead, we have a simple continuous concept for determining the time for replacing an old device. This approach only makes sense if there is a continuous improvement of new devices regarding energy efficiency and accompanied GHG emissions. This is true for refrigerators in the previous decades, making this approach suitable for determining improved lifetimes in this simulation approach. The results of the application of this concept to the determination of optimum lifetimes for different refrigerator vintages are summarized in Table 1 for each year of production. The calculations take into account the specific energy consumption of each refrigerator vintage, including observed average efficiency gains, and the respective European electricity mix at each point in time (see Supporting Information S1 for a depiction of the heuristic approach and influencing factors).

The calculated optimum lifetimes in Table 1 clearly show an increasing trend, which also indicates that early replacement of older devices particularly in the future does not seem reasonable. This is mainly caused by two major influences: first, the additional efficiency gains of new devices are decreasing (cf. Figure 4a); second, the GHG emissions of electricity production are decreasing (cf. Figure 4b), which directly results in decreasing use phase impacts of refrigerators (see baseline scenario in Figure 5a). This leads to a continuously increasing optimum lifetime according to the abort criterion in Equation (1) (see also illustrative example in the Supporting Information S1).

In order to assess the effect of optimized use phases on GWP, we have implemented these values (Table 1) in the lifetime distributions of the simulation model for each vintage in the subsequent two scenarios. The replacement with new devices is then modeled with a stock driven approach, which ensures that the baseline stock is kept at the desired level as described before (cf. Müller, 2006).

There are two possibilities of implementing the optimum lifetimes in Table 1 into the model: first, the expected values of the underlying lifetime distribution can be adjusted (scenario in Figure 5d). Second, using the distributions from the baseline scenarios, the survival rates (transfer probability to the next higher age cohort) can be set to 0 after having reached the optimum lifetime (scenario in Figure 5e).

As illustrated in the subsequent two scenarios (Figure 5d,e), the effects of adjusting the lifetime on overall emissions are comparatively small. In fact, the higher demand for new devices in Figure 5d even increases overall emissions at the beginning of the time horizon, while a small payoff is observable after 2005 (Figure 5d right). The last scenario, in which the failure rates are adjusted after having reached the optimum lifetime (Figure 5e) does not show high additional demand for new devices and related additional embodied emissions at the beginning of the time frame, however, also in this scenario, the emission reduction as compared to the baseline is comparatively small (Figure 5e right).

Hence, when considering the increased demand for new devices and associated additional environmental impacts during production but also for EoL treatment and waste management, general strategies for decreasing product lifetimes through, for example, planned obsolescence or early replacement of functioning older devices seem counterproductive, even for refrigerators with comparatively high energy consumption during the use phase. This is an interesting result as one could have expected a clearer effect regarding GHG reduction in the respective scenarios. However, the increasing share of renewables in electricity supply, decelerating efficiency improvements of new devices and average lifetimes that do not lead to significant differences in energy efficiency classes in use (see, e.g., the different generations (vintages) of refrigerators in the stock accumulation in Figure 5) minimize the effect of lifetime optimization on overall emissions.

3.2 | Lifetime simulation of mobile phones and related GHG emissions

For mobile phones, beside the baseline scenario, which mainly serves as a reference for the in-use stocks, two different scenarios were simulated with the setup shown in Figure 3. The intention of these two scenarios is to quantify the possible reduction of demand for new devices and accompanied embodied emissions through modifications in the system structure, particularly regarding the use intensity. With these scenarios, we do not attempt to represent real future developments but to provide a basic understanding of the system behavior and of the main drivers of emission reductions. As depicted in Figure 3 and described in the methods section, a mobile phone spends long periods of its overall lifetime in hibernation without providing any service. Therefore, we analyze the effect of hibernation time reduction of mobile phones on the demand for new devices and related environmental impacts in comparison with simple lifetime extensions without changing consumer behavior. Additional data regarding transfer probabilities between different life stages and duration of respective use and hibernation are available in the Supporting Information S1. The simulation model for mobile phones is mainly useful as a tool to assess theoretical future scenarios. Therefore, we refer to a timeframe from 2000 to 2030 with a continuous transition from historical data to future scenarios. For the stock accumulation in the reference scenario, we use historical sales figures until 2018 (cf. Supporting Information S1), while for future developments, sales figures were kept at a constant level, which is a continuation of stagnating sales within the EU28 of around 200 million devices per year. Note that the model distinguishes between classical cell phones and smartphones. While historical use was dominated by classical cell phones, nowadays the market for mobile phones consists almost entirely of smartphones with touchscreens and internet capabilities, which influences the resource intensity and associated environmental impacts of the devices (Clément et al., 2020). As the future scenarios mainly refer to smartphones and for the sake of simplicity, we do not distinguish between historical cell phones and modern smartphones in the stock accumulation and sales numbers shown in Figure 6. However, we provide more detailed information on stock composition in the Supporting Information S1.

The first scenario (Figure 6b) assumes technical improvements, for example, regarding product design, durability of specific components or software update services reducing technical obsolescence. In this scenario, the underlying transfer probabilities to unused storage phases resulting in hibernation of mobile phones are kept at a constant level compared to the baseline scenario. As we do not assume modifications in consumer behavior in this scenario, the increased product durability is unlikely to directly affect the duration of the first service lifetime (first 2 years of the overall lifetime) as the product's functionality in this use phase remains relatively equal compared to the baseline scenario. Only the second and third service lifetimes—because the products are likely to reach technical or functional obsolescence in these phases—are increased by these technical improvements. However, as clearly shown in the simulation results, such technical measures are counteracted by the unused storage phases and the imperfect cascade use structure in the form of second hand products. The majority of European mobile phones do not even enter the second and third service lifetime but end up in hibernation and subsequent disposal or export without providing any additional service (cf. stock composition in the reference scenario). Hence, the effectiveness of these technical improvements is relatively low as long as there is no change in consumer behavior, such as an increased willingness to purchase used devices. Similar to the case of refrigerators, we use a stock driven approach to enable a comparison of the scenarios: From the baseline scenario, the overall stock of mobile phones in service until 2030 is extracted. This is the reference number of mobile devices used in Europe. By increasing the second and third service lifetime, the theoretical stock of devices in use would increase. This theoretical increase is balanced by reducing the demand for new devices. Hence, the longer service time leads to a certain reduction of demand and a shift from first to second and third service lifetimes. However, this effect is moderate as only a mere fraction of overall mobile phones really reaches the second and third service lifetime. In the scenario shown in Figure 6b, we assumed an increase of second service lifetime by half a year and an increase of third service lifetime by one year (see Supporting Information S1 for all distributions within the model).

In the second scenario, we assess the effect of a reduction of hibernation to a level of zero until 2030, which is achieved by successively reducing the transfer probabilities to hibernation. Such an effect—even though highly theoretical—could, for example,, be achieved through product oriented product service systems (PSS) in which the consumer no longer owns the device and simply returns it after the use phase. The potential reduction of demand for new devices and associated emission reductions during the production phase in this scenario is shown in Figure 6c. In the scenarios illustrated in Figure 6, the potential reduction of GHG emissions is quantified in the form of GWP reduction using data from LCA studies of mobile phones (Suckling & Lee, 2015). As addressed in the discussion section, these impacts vary among different studies (due to varying system boundaries, different assumptions and different types of mobile phones under investigation, see particularly Clément et al. (2020)) while in the simulation model, we only included average numbers depicted in Figure 1b (around 40 kg CO_2 eq. per average device). However, for the purpose of the systemic simulation-based scenario analysis presented here, this level of detail seems sufficient.

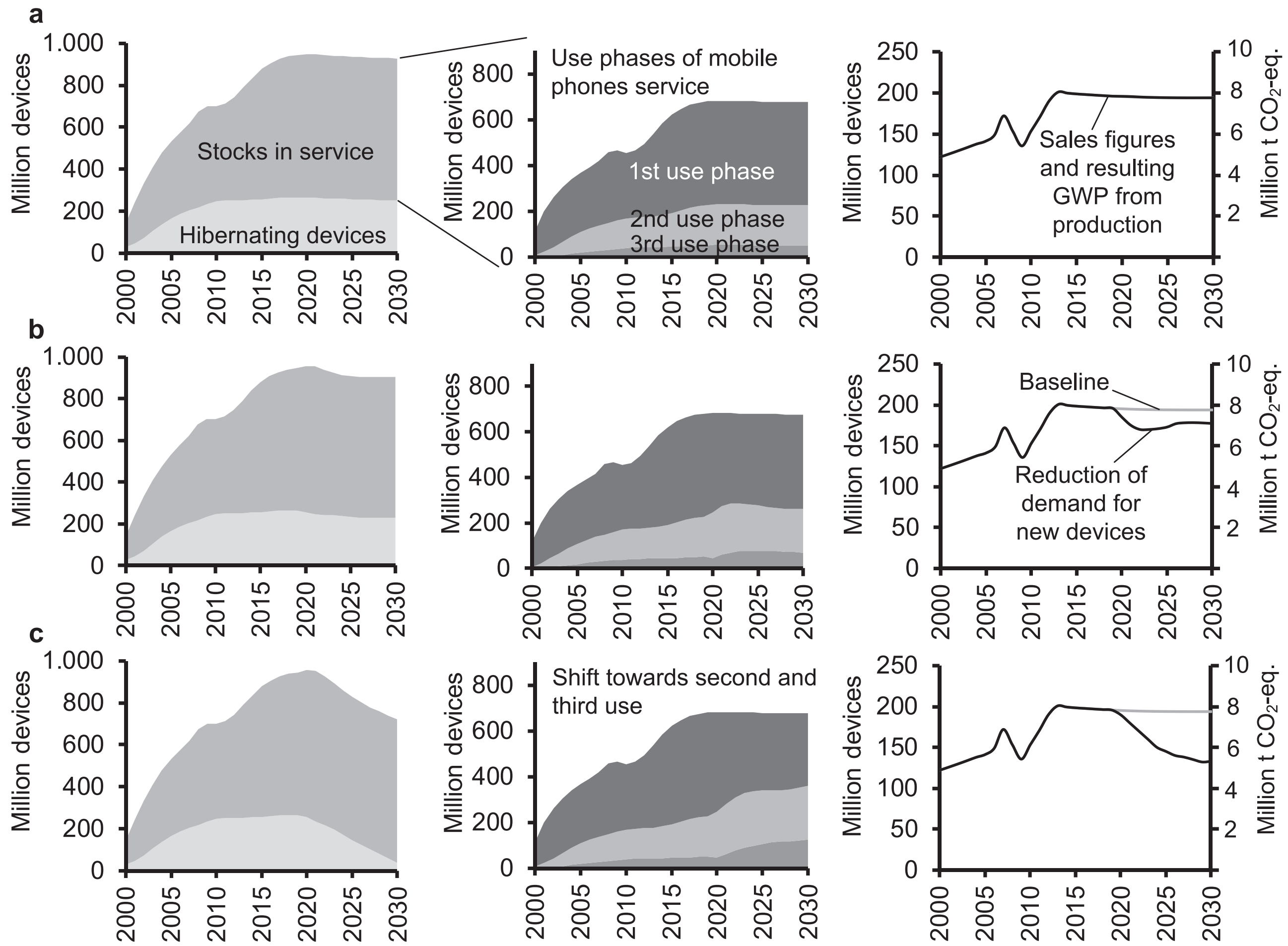

FIGURE 6 Selected scenarios regarding mobile phone stock dynamics and modifications in lifetime and use structure. (a) Baseline scenario with past real sales figures and constant sales in future. (b) Scenario regarding technical lifetime extension. c) Scenario with systematic reduction of transfer probabilities to hibernation phase. For the link between sales figures and GWP, average data from literature (around 40 kg CO_2 eq. per mobile phone, (cf. Suckling & Lee, 2015) are implemented into the model. (a) Baseline scenario as a reference for in service stocks and sales figures. (b) Scenario regarding lifetime extension through technical measures. (c) Scenario regarding avoidance of hibernation. Underlying data used to create this figure can be found in the Supporting Information S2

4 | DISCUSSION

The difference in use structure and related consumer behavior of the two product groups presented here made the analysis in two individual models necessary, which are both based on merging dynamic stock and flow modeling with specific impact categories from LCA studies. The intention of the simulation based approach was to emphasize the need for systemic but product group specific models that are capable of identifying key drivers and their effects regarding modifications of product lifetimes. The models focus on two different product groups and Europe as the system boundary. However, both the modeling concept and the simulation results are transferrable to further research. From a methodological perspective, besides linking aspects of dynamic MFA with results from LCAs, the stock driven approach applied both to refrigerators and mobile phones might become relevant for future work. Most dynamic MFAs are flow driven, accumulating input flows over time (Müller et al., 2014), while when comparing scenarios of lifetime variation in this study, reference stocks from the baseline scenario formed the driver for adjusted flows (purchases of new devices). This is necessary, as a product's service is provided from in-use stocks and a comparison of scenarios in this context is only possible when maintaining the same service level (Müller, 2006; Pauliuk & Müller, 2014).

Regarding replacement strategies of refrigerators due to efficiency gains of new devices, we applied a simple heuristic to get a basic understanding of optimized lifetimes (Equation 1). For the systemic simulation based approach presented here, this procedure seems to be a suitable method while there is the need for a clear distinction from discrete mathematical optimization. Discrete optimization is especially useful for individual decision-making and could be formulated as a linear program within a clear timeframe (e.g., 1990–2020) and solved with combinatorial algorithms from the field of operations research (Kim et al., 2006). A comparable approach has been presented by Skelton and Allwood (2013) in the context of lifetime optimization of different product groups from an environmental perspective. However, this goes beyond the scope of the systemic simulation approach in this study but constitutes a field of research that needs more investigation and that could be linked to simulation based models as presented here. In such optimization approaches, trade-offs between different impact categories could additionally be assessed, for example, regarding the reduction of GWP due to efficiency gains on the one side and further impact categories for production of new devices on the other side.

The key findings from the scenarios presented here also need specific interpretation for each product group. As refrigerators have their highest environmental impact during the use phase and there have been significant improvements in energy efficiency over the previous years, it is ex ante unclear whether an earlier replacement of old refrigerators does in fact reduce GHG emissions over the entire life cycle. This question needs a systemic assessment such as the one presented here, since overall stocks need to be kept at the desired level. Furthermore, temporal changes such as the decreasing carbon intensity of electricity supply also need to be considered. However, as demonstrated with the scenarios presented here, an overall reduction of expected lifetimes shows minimal effects regarding GHG emissions. In addition, when keeping in mind that the production of new devices is accompanied by further environmental impacts, a reduction of lifetime expectancy due to reasons of energy efficiency does not make sense from an ecological perspective. This does not mean the individual replacement of outliers regarding age and related energy efficiency is infeasible from an ecological perspective.

In the case of mobile phones, the scenarios show that hibernation is counterproductive regarding measures to increase service lifetime, and that a reduction of hibernation could significantly contribute to reducing the demand for new carbon-intensive products. The stock driven approach presented here also shows that in a functioning cascade system, the share of second hand products can increase significantly, assuming that consumers readily use refurbished products. Recent research suggests that circular economy measures such as second hand markets can have adverse effects since they provide contrary incentives with respect to purchasing decisions of new devices (Makov & Font Vivanco, 2018; Zink & Geyer, 2017). However, these effects are not explicitly covered in our analysis.

Regarding transferability and data uncertainty of the simulation study presented here, it is clear that this systemic approach builds upon average values for example, energy efficiency (cf. Figure 4) or average GWP during the production phases of respective products. This is of sufficient detail to show general effects from a systems perspective. However, it is necessary to keep in mind variations of results from case-specific studies, including changes of production processes in global supply chains. LCAs of mobile phones for instance clearly show uniform trends regarding the share of impacts during the life cycle (see additional data in the supplementary material), while there are clear variations due to product specifics, system boundaries, impact allocation methods, and so forth. (Clément et al., 2020). We focused on the GWP as environmental impact because this is the most important category for the global issue of climate change. However, particularly for mobile phones, a consideration of further impact categories, which are also mainly restricted to the production phase, would be useful and could be performed in the same manner as in the case of GWP presented here. GHG emissions for both the production and the use phase are directly linked to the consumption of fossil-based energy. Beside the embodied GWP, some studies explicitly address the embodied energy. As we build upon existing LCA studies that aggregate upstream emissions in the form of CO_2 equivalents, it is not directly possible to extract the embodied energy from the input data used for the simulation models. However, several studies explicitly quantify the embodied energy, also referred to as "emergy" (Raghavan & Ma, 2011). This embodied energy is around 5–7 GJ for refrigerators (Ciceri et al., 2010; Gonzalez et al., 2012) and 1 GJ for smartphones (Raghavan & Ma, 2011). While the GWP enables a direct comparison of embodied and use phase GHG emissions and hence the impact on climate change, it seems reasonable to also keep the related energy consumption in mind.

The approach presented here focuses on individual products and strategies to reduce their aggregate emissions at the European level. However, as Ryen et al. (2014) have described, products are not purchased and used by households individually, but form so called product communities with shared functionalities. Contrasting trends of increased/multifunctionality and rising numbers of household electronics have led to steady or increasing environmental impacts of these products at the household level (Kasulaitis et al., 2019; Ryen et al., 2015). This makes measures aimed at specific products potentially futile since they may not affect overall household emissions. However, this perspective at the same time opens up opportunities for further research in which a stock driven approach as suggested in this paper can be combined with a product community perspective. In this case, not the stocks of individual products are considered to provide services to households but "functional" stocks based on product communities. For instance, separate products in the form of compact cameras and dedicated navigation devices have traditionally performed the functions of spontaneous still image recording and GPS navigation. These functions can now be easily performed by smartphones, which have increasing degrees of multifunctionality. However, the increased use of multifunctional products only results in environmental benefits if existing products are in fact replaced. Kasulaitis et al. (2020) have found consumer preferences to point towards the retention of existing products and therefore call for coupled strategies of multifunctionality and product-level reduction of environmental footprints.

5 | CONCLUSIONS

The goal of this contribution was to assess the effect of modifications in service lifetimes and use structures of selected products on their environmental performance regarding GHG emissions over the entire life cycle from a systems perspective, taking into account both embodied emissions and use phase emissions. To this end, we have linked a dynamic stock and flow modeling approach of product life cycles with the impact category of GWP regarding the production phase and temporal developments in energy supply and energy efficiency. We chose refrigerators and mobile phones as exemplary product groups due to their differing impacts over the life cycle and the differences in use structure and associated consumers' perception and behavior. From a methodological perspective, particularly the stock driven simulation might be of interest for further research as this enables an analysis of lifetime modifications from a systems perspective, which is contrast to most previous studies applying a product-centric approach. Concerning simulation results, we demonstrated the status quo regarding the life cycles of both product types at a European level in baseline scenarios and assessed the effect of modifications of lifetimes and use structure. For refrigerators, we showed that a reduction of expected service lifetime due to efficiency gains of new devices has minimal effects on the overall GHG emissions and leads to a significant increase of demand for new devices in order to maintain the overall stock in service as compared to the baseline reference. This does not mean that the replacement of outliers regarding age and efficiency level is not reasonable. However, decreasing the overall expected lifetime, for example, through planned obsolescence, is not useful concerning overall emissions. Additionally, the increasing share of renewable power generation and the resulting decreasing GHG emissions from electricity consumption have led to a continuously increasing optimum lifetime of refrigerators in recent years from an environmental perspective. This is because the impact of less efficient older devices is reduced leading to a longer environmental amortization period of new devices with higher efficiencies. For mobile phones, we demonstrated the effect of increased service lifetime through technical measures and decreased hibernation on the potential reduction of demand for new devices. These scenarios mainly rely on the shift from new devices within the first service lifetime to second hand products within a functioning cascade use system. This, however, requires the willingness of consumers to use refurbished products. While we focused on Europe as a system boundary, both the method applied in this study and the generic scenarios are transferrable to other systems and product groups. However, due to the specifics of each product life cycle and related use structures, individual systemic simulation approaches will be necessary.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Simon Glöser-Chahoud https://orcid.org/0000-0002-2198-7751

Matthias Pfaff https://orcid.org/0000-0002-5838-4807

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