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Research article

Circular business models of washing machines in the Netherlands: Material and climate change implications toward 2050

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ABSTRACT

Among European countries, The Netherlands is boosting the transformation to a circular economy creating and deploying circular business models across different sectors, including the home appliances sector. Although in recent years shared access-based business models have attracted the attention of the scientific community from a sustainability perspective, a very different family of circular business models are in fact being deployed in other markets and have not yet been studied from a sustainability perspective. These circular business models are product lease and pay-per-use, which are now offered by more than ten companies in the Dutch market. However, whether these business models represent environmental and material benefits is still in question. In this article, we apply a dynamic life cycle assessment modelling framework to study the material use and climate change impact implications of the long-term and potentially large-scale adoption of these two circular business models in the Dutch market of washing machines towards 2050, considering the energy transition of three regions: The Dutch, European, and global regions. Of nine scenarios modelled, the large scale and quick adoption of product leasing will represent the largest material use benefits, followed by the pay-per-wash model, both comparable to the material benefits obtained by other well studied shared-access business models. In climate change impact mitigation, the benefits of the circular business models are dwarfed by the benefits of a decarbonized electricity. Yet, with a successful energy transition, we could expect a re-prioritization of the life cycle of energy intensive appliances regarding climate change impacts in the future, from the use phase to the use and production phase, equally.

1. Introduction

Amid current environmental pressures and fear of material scarcity and development within planetary boundaries, the circular economy has gained tremendous momentum as a model that could potentially achieve sustainable production and consumption (Kirchherr et al., 2017) . In recent years across the globe, countries and regions have set circular economy policies and initiatives and circularity targets (McDowall et al., 2017; Mhatre et al., 2021). Europe, particularly, has developed an Action Plan for the development of the Circular Economy (European Commission, 2020), while country members countries have developed specific roadmaps. The Netherlands, for instance, is one of the countries considered to be at the forefront of the circular economy transformation and has released a government-wide circular economy and implementation programs, setting the ambitious target of reducing primary material use by 50% by 2030 and transforming the economy to 100% circular by 2050 (Rijksoverheid, 2016, 2019). Such ambitious transformation will require the participation of multiple stakeholders including businesses and the deployment of circular business models (Stahel, 2012).

In the Netherlands, circular business models are being developed and deployed. Among other circular business models, access-based and performance business models are gaining acceptance. In these business models, which are also classified as product service systems, the consumers have access to the use of a product without owning the product (Bocken et al., 2016). The service providers usually charge a fixed recurrent fee and may include repair services or the eventual replacement of a faulty product without extra costs, enhancing the convenience to the customers and providing a worry-free lifestyle. The aim of these business models is to

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ACRONYMS AND NOMENCLATURE USED IN THIS ARTICLE

ACRONYMS

CBM-PLE	Circular Business Model Product Lease with Lifetime Extension
CBM-PPW	Circular Business Model Pay Per Wash
IBM	Incumbent business model
LCA	Life cycle assessment
LCC	Life cycle costing
BL	Baseline Scenario
ET	Energy Transition Scenario
HD	Halving Detergent Scenario
HDET	Halving Detergent with Energy Transition Scenario
HDET+	Halving Detergent with Energy Transition plus Washing Machine Improvements Scenario
CT-PLEf	Circular Transition Scenario with Circular Business Model Product Lease with Lifetime Extension – Fast Diffusion Variant
CT-PLEs	Circular Transition Scenario with Circular Business Model Product Lease with Lifetime Extension – Slow Diffusion Variant
CT-PPWf	Circular Transition Scenario with Circular Business Model Pay Per Wash – Fast Diffusion Variant
CT-PPWs	Circular Transition Scenario with Circular Business Model Pay Per Wash – Slow Diffusion Variant

VARIABLES

AR	Adoption rate
O	Obsolescence rate
U	Stock of products in use
S	Bass diffusion model sales
p	Bass diffusion model innovation coefficient
q	Bass diffusion model imitation coefficient
t	Time
m	Market size
k	Business model
l	Life cycle phase
v	Product vintage
a	Life cycle process
$\mathbf{A}$	Life cycle technology matrix
$\mathbf{S}$	Scaling factors matrix
$\mathbf{F}$	Final demand matrix
$\mathbf{B}$	Impact intensity matrix
$\mathbf{H}$	Impacts matrix
$\mathbf{M}$	Materials matrix
$\mathbf{I}$	Identity matrix
$\mathbf{X}$	Output matrix

SUBSCRIPTS AND SUPERSCRIPTS

CBM	Circular business model
IBM	Incumbent business model
ff	Foreground to foreground
fb	Foreground to background
bf	Background to foreground
bb	Background to background
$*$	Normalized to 1 unit of output
M	Materials
b	Background

intensify the use of products while extending their life spans in their best state possible by maintenance and repair, and disposing of them appropriately when they can no longer be restored, thus maximizing economic and material efficiency (Moreno et al., 2016; Stahel, 2016).

However, there is no agreement in whether this type of circular business models will result in real material and environmental gains. While, extending the life of products can result in lower environmental impacts and material use reductions (Pauliuk & Müller, 2014), extending the life of energy intensive products might as well result in higher environmental impacts (Ardente & Mathieux, 2014). Therefore, we see the need of analyzing the potential benefits and trade-offs of the long-term implementation of these circular business models, especially in a market where they are gaining acceptance to further develop strategies to secure their possible environmental and material benefits.

In this paper, we study two circular business models on washing machines that are currently being adopted by consumers and deployed by at least 10 companies in the Netherlands (2018) with a market-wide perspective. These business models are product leasing with lifetime extension and pay-per-wash. We analyze the climate change impacts and the material uses of these business models under different scenarios of adoption in the Dutch market, while we include our analysis critical technological component: the energy transition. We chose washing machines for four main reasons: first, they are often used to test environmental assessment methods (Cullen & Allwood, 2009), second, they contribute to about one fifth of the impacts of household appliances in use (Hischier et al., 2020), third, the demand of materials for appliances is expected to double by 2050 (Deetman et al., 2018), and fourth, the business models in this analysis have not yet been addressed in the existing scientific literature.

In the following section we present a literature review on circular business models, laundering activities and environmental assessments, where we depict the main conclusions of the most relevant scientific work and knowledge gaps. In section 3 we describe the methods used, in section 4 we discuss our results, and in section 5 we finalize with our conclusions.

2. Literature Review

2.1. Circular Business Models and Sustainability

The role of product-service-systems in sustainability has been present and discussed for several decades and while some may not regard these business models as the “sustainability panacea” (Tukker, 2015), some case studies confirm striking environmental benefits. For instance, Lindahl et al. (2014) analyzed three product-service offerings using life cycle assessment (LCA) and life cycle costing (LCC) of three different case studies: core plugs for paper mills, cleaning of building exteriors, and compacting soil. Depending on the product-service offering, they calculated environmental benefits between 5 and 90%.

Khumboon et al. (2009) performed a LCA of rental services of a photocopier that included reconditioning, and calculated that this business model achieved 25% less environmental impacts than the traditional product selling. Similarly, Kerr & Ryan (2001) calculated that extending the life of photocopiers by remanufacturing strategies could reduce material use threefold.

In cases of durable and energy intensive products, (Smidt Dreijer et al. (2013)) used LCA to compare the impacts of a product-service offering of temporary buildings with those of the conventional temporary building. According to their calculations, the product-service-system resulted in 27% less life cycle impacts including energy use, and 37% less impacts without considering energy use. However, environmental impact trade-offs can exist when extending the life of products. For example, Carrano et al. (2015) explored the environmental impacts of different business models of wooden pallets: selling expendable pallets, sell and buy-back pallets, and leasing pallets. They calculated that leasing pallets provided the lowest CO2 emissions for pallet manufacturing per functional unit, but this business model also yielded the smallest benefits at the end of life, as less pallets were incinerated for energy recovery due to their longer lifespans.

Extending the life of products can be controversial. Ardente & Mathieux (2014) developed a life cycle assessment-based method to analyze the benefits of extending the life of products. They applied their method to two different washing machines. Using their method, they observed that a reduced energy consumption in washing machines resulted in a smaller climate change benefit when their lifespans were extended, but the smaller benefits were also related to the higher impacts of the production of a more durable appliance. Moreover, the authors observed different trade-offs across different impact categories and product lifetime extension. In a similar work, Iraldo et al. (2017) proposed a method to calculate the economic and environmental cost of more durable products with a life cycle assessment perspective. They studied an energy intensive product and discovered that a durable product represented a better cost/benefit ratio to the consumer, but in detriment of the environment because of the inferior energy efficiency of the more durable product.

From these examples in the literature, one cannot generalize that these business models will always result in environmental benefits. At the same time, extending the lifetime of products with lower energy efficiency is a concerning point.

2.2. Impacts of Laundering

Environmental assessments of laundering and other laundering-related aspects are found in different instances of scientific literature, such as the impacts of washing machines (Hischier et al., 2020; Yuan et al., 2016), the durability of washing machines (Stamminger et al., 2020), the impacts of detergents (Hoof et al., 2002; Saouter et al., 2002), the impacts of washing in different regions (Kim et al., 2015), the impacts of garments including washing (Hoffmann et al., 2020; Zhang et al., 2015), and the impacts of washing different types of fibers (Moazzem et al., 2018).

Yuan et al. (2016) performed a LCA of a horizontal axis washing machine of China. They found that the LCA hotspots of the production of washing machines were electronics, plastic mold injection, and metal components, while the hotspots of the use phase were electricity and detergent use. Similarly, Zhang et al. (2015) performed a LCA on t-shirts in China, and like Yuan and colleagues, they found that the hotspots of the use phase of the t-shirt was due to washing, and identified electricity and detergent use as hotspots, while Kim et al. (2015) found that compared to China, South Korea, and the United States, Europe consumes more energy for washing, while China emits more GHG emissions due to a carbon-based electricity. In a more recent study, Hischier et al. (2020) took into account some hardware improvements as well as energy mix changes, and the stock size of appliances to assess the impacts of different home appliances for the average European resident (EU27) for 2030. For washing machines, they calculated that improvements in washing machine efficiency could decrease climate change impacts by more than 20% and up to 37% in combination with a cleaner energy mix. However, Hischier and colleagues disclaim that the age of the appliances was not considered for the 2030 scenario and that the stocks of appliances were considered to be built in the same year. Thus, such benefits might be smaller when the age of products is considered due to the presence of older and less efficient appliances in the European appliance stocks.

2.3. Impacts of Circular Business Models of Laundering

The scientific literature on circular business models of laundering activities is more homogeneous. A business model type that has caught the eye of the scientific community in recent years is the shared access business model, also known as or laundromats or launderettes. This business model reduces significantly the number of washing machines needed per user, as several users or entire households have access to the same washing machine or facilities of washing machines. We have identified a few environmental impact assessment studies of this business model.

Amasawa et al. (2018) for example, explored the potential environmental benefits of shared laundry facilities in a hypothetical community in Japan and calculated that climate change impacts could be reduced by 1.8% and resource use by 16%. In another study, Wasserbaur et al. (2020) explored with system dynamics modelling the climate change impact implications of Sweden and Europe shifting to this business model towards 2050 with 50 and 100% penetration rate targets. With a 50% penetration rate of the launderettes, they found that the cumulative climate change impacts of washing activities in Sweden could be reduced by 16% and 29% if the whole market is captured. For Europe, a full adoption would reduce impacts by 35%. These reductions are regarded to the longer lifespans of the washing machines as well as a series of technological improvements such as energy efficiency and electricity decarbonization. The laundromat case is particularly relevant for Sweden, where laundromats have been used for decades and are considered in dwelling design and construction regulations (Borg & Högberg, 2014). However, in other regions, the acceptance of such business model is debatable. In their own study, Amasawa and colleagues found that 39% of the surveyed population considered owning a washing machine at home as essential, a clear barrier for the adoption of shared-access laundry services.

Another circular business model of laundering is a type of access-based model: the pay-per-wash model. In this business model, users are subscribed to a service in which the service supplier installs a washing machine in the home of the subscriber and the subscriber pays only for each time the washing machine is used. In a longitudinal study with 56 subscribers, Bocken et al., (2018) found that subscribers of the pay-per-wash business model adopted different washing patterns to. The subscribers reduced the average temperature of the washing cycles by 5% and the monthly number of cycles by 20% compared with standard levels, which can in turn reduce the environmental impacts of the use phase.

In spite of the increasing interest in the assessment of circular business models for laundering activities, no impact assessments were found about pay-per-wash business models or product lease business models. This is concerning since it is not clear if extending the lifetime of energy intensive products such as washing machines is environmentally beneficial, while extending the life of products is one of the principles of the circular economy. Moreover, while the energy transition has been considered in some studies to some extent (see Hischier et al. (2020) and Wasserbaur et al. (2020)), the implications of the energy transition in the whole life cycle of washing machines and the possible re-prioritization of life cycle phases due to this transition has not yet been addressed.

In this paper, we perform a simultaneous dynamic material flow and climate change impact assessment of the adoption of two circular business models of washing machines in the Netherlands, a market where 99% of households have a washing machine (NIPO, 2017). We will aim to answer the following research questions: What are the environmental and material gains of the adoption of these circular business models in the Dutch market? What levels of penetration rates are necessary to achieve such benefits? How long will such adoption take? What is the role of the energy transition in the impacts of the Dutch washing machine market? And, how do these business models perform compared with alternative strategies?

Table 1
Technical parameters of the business models

		Incumbent Business Model		Circular Business Model Pay-Per-Was		Circular Business Model Product Lease with Lifetime Extension	
Parameter	*units*	*Value*	*Source, comments*	*Value*	*Source, comments*	*Value*	*Source, comments*
Washing machine weight	kg	70	Boyano et al. (2017); CECED (2018))	70	Boyano et al. (2017); CECED 2018)	77	Based on manufacturers and service providers information: (Bosch n.d.-a; Bosch n.d.-b); Bundles, 2020;Miele, n.d.)
Cycles per year	cycles/year	220	Boyano et al. (2017); CECED (2018)	198	Based on Bocken et al. (2018)	220	Boyano et al. (2017); CECED (2018)
Energy use per cycle*	kwh/wash	0.84	Boyano et al. (2017)	0.68	Based on Bocken et al. (2018) and Boyano et al. (2017)	0.76	Based on Boyano et al. (2017)
Lifetime (mean)	years or cycles	12.5 years or 2750 cycles	Boyano et al. (2017); CECED (2018)	15 years or 3000 cycles	calculated: 3000 cycles divided by 198 cycles/year	16 years or 3500 cycles	estimation
Lifetime Standard deviation	years	4	estimation	3	estimation	3	estimation
Detergent use*	kg/year	16.5	Boyano et al. (2017); CECED (2018)	8.9	40% less per cycle than IBM, based on (Bosch, 2020) and (Electrolux, 2020)	9.9	40% less per cycle than IBM, based on (Bosch, 2020) and (Electrolux, 2020)
Water consumption	m^3/year	11.7	Boyano et al. (2017); CECED (2018)	10.5	Calculated. Based on Bocken et al. (2018)	10.5	calculation
Maintenance	% in replacement parts	5%	Boyano et al. (2017); CECED (2018)	5%	based on Boyano et al. (2017) and Arriola (2019)	7.50%	estimation, based on longer lifetimes an increased maintenance.

**2020 values. The values of 2021 to 2050 are available in Appendix A2.*

3. Methods

We used the framework for circular transitions proposed by Sigüenza et al. (2020) to study the circular business models for washing machines in the Dutch market. This framework allows modelling and measuring both business- and technical-related aspects of a transition to circular business models. Business related aspects include the adoption rates, sales, and installed bases. The technical aspects are production, and obsolescence rates, material uses, material stocks, emissions, and impacts. The framework allows also to model technological changes that affect directly and indirectly the business models, such as the composition and energy use of products in the value proposition, manufacturing and end-of-life processes, as well as energy mixes with a dynamic approach. Incorporating these changes can be very important in prospective studies. The framework is divided in two modules. The first module combines diffusion of technologies with stock-flow dynamics, since the obsolescence rates of products can influence or limit the adoption of circular business models. The second module utilizes the outcomes of the first module and combines them with a dynamic time-vintage LCA model to assess material uses, material stocks, emissions, and environmental impacts.

3.1. Business Models

We included three business models in our study: the incumbent model (IBM), the circular business model-pay-per-wash (CBM-PPW), and the circular business model-product-lease-with-lifetime-extension (CBM-PLE). In this sub-section, we describe briefly each business model and in Table 1 we describe their main technical parameters.

The IBM is the reference business model, it represents the current situation of the market. This business model is a traditional ownership model, in which users purchase a washing machine, use it for a number of years, and then they discard it at will due to failure or perceived obsolescence, after 12.5 years in average (Boyano et al., 2017). Users in this business model will wash with average habits: 220 washes per year, 75g of detergent per wash, and energy use of 0.84kWh per wash. To simulate maintenance, we assumed that 5% of the parts of the washing machine could be replaced in all their lifetime.

The CBM-PPW is characterized by charging the user a monthly fee plus an extra fee for every extra wash depending on the water temperature of the cycle. In this business model, the users do not own the washing machine. Subscribers to this business model wash 20% less and they wash at lower temperatures (Bocken et al., 2018). Due to the reduced number of cycles per year and included maintenance services, we assumed that these washing machines can last 2.5 years longer than the average. In addition, these washing machines can save up to 50% of detergent use thanks to the auto-dosing system feature of washing machines as claimed by washing machine manufacturers (see Table 1).

The CBM-PLE characterizes by charging a monthly fee to customers without restriction to the number of washes. The washing machines in this business model are often highly efficient, top of the line models with a heavier build known to last longer (see TABLE 1). Like the CBM-PPW, these washing machines usually have an auto-dosing system, with the same gains in detergent use. Because there is no incentive to wash less, we assumed subscribers to this business model wash as much as the average, but use less energy because of highly efficient washing machines. In turn, we assumed that the washing machines of this business model require more maintenance due to their extended lives, summing to a total of 7.5% replaced parts in all their life span.

3.2. Scenarios

We modeled and analyzed 9 different scenarios. The first five scenarios explore the implications of the current trajectory of the market as well as the effects of detergent, the energy transition, and washing machine improvements. These scenarios are: Baseline (BL), Halving Detergent Use (HD), Energy Transition (ET), and Energy Transition with Halving Detergent Use (ETHD), and ETHD with washing machine improvements (HDET+). The last four scenarios explore the additional effects of the slow and fast adoption of circular business models CBM-PPW and CBM-PLE, which we named circular transitions: CT-PPW and CT-PLE, each with one fast diffusion and one slow diffusion variant of the circular business models, noted with the suffixes f for fast diffusion and s for slow diffusion. For each scenario, we calculated the product flows, stocks, material uses, and climate change impacts of each scenario with observable changes from 2015 to 2020 and projections until 2050 using the modelling framework proposed by Sigüenza et. al. (2020). In this section we briefly describe these scenarios with their main assumptions.

- BL: This scenario is the point of reference for the other scenarios. It represents that the incumbent business model persists until 2050, and that the main change is represented by the growing demand of washing machines until 2050 in relation with the growing number of households. The assumption is that there will be no technology and efficiency improvements after 2020 in foreground systems for the production and use of washing machines, nor improvements in background systems like energy production.
- ET: This scenario includes changes in the electricity mix of three different regions in the world toward 2050: The Netherlands, Europe, and rest of World. We considered these three regions because the use phase of washing machines in the Netherlands use local electricity, while the production of WMs for this market takes place mostly in Europe (Home Appliance Europe (APPLIA) 2020), for which we used the most representative energy mixes when modelling in in life cycle inventories. No other technological changes are included in this scenario.
- HD: In this scenario we modeled the progressive reduction of detergent use year by year, until reaching 50% of detergent use per WM until 2050. This is an exploratory scenario designed to measure the environmental benefits of the reduction of detergent use, as a simple, adoptable strategy.
- HDET: This scenario combines the attributes of the ET and the HD scenarios.
- HDET+: This scenario has the attributes of the HDET scenario plus the following progressive improvements reached by 2050: 20% in energy use, 10% in water use, and 10% in detergent dosage.
- CT-PPWf: In this scenario, the CBM-PPW competes with the incumbent business model and is continuously quickly adopted until 2050. The adoption rate of the pay-per-wash model is constrained by the obsolescence rate of washing machines of customers of the incumbent business model. In addition, we assume changes in the background energy mix as in the ET scenario, detergent use reductions in the IBM as in the HD scenario, as well as the technological improvements in washing machines as in the HDET+ scenario.
- CT-PPWs: This scenario has the same characteristics as the CT-PPWf, except that the circular business model is adopted at a slower rate.
- CT-PLEf: In this scenario, the CBM-PLE competes with the incumbent business model and is continuously and quickly adopted until 2050. The adoption rate of the CBM-PLE is constrained by the obsolescence rate of washing machines of customers of the IBM. Additionally, we assume changes in the background energy mix as in the ET scenario, detergent use reductions in the IBM as in the HD scenario, as well as the technological improvements in washing machines as in the HDET+ scenario
- CT-PLEs: This scenario has the same characteristics as the CT-PLEf, except that the circular business model is adopted at a slower rate.

In summary, Figure 1 maps the scenarios in this study against the depth of the assumptions of technological changes such as the energy mix and washing machine improvements, and user behavior changes, such as subscribing to a circular business model, using less detergent or the auto-dosing systems, and wash less or at lower temperatures.

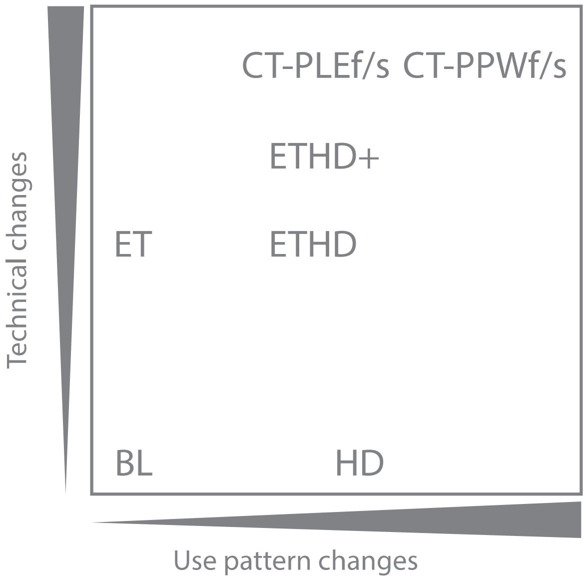

Figure 1. Mapping scenarios in this study according to the depth of the assumptions of technological changes and use pattern changes. BL: Baseline, HD: Halving Detergent use, ET: Energy Transition, ETHD: Energy transition and halving detergent use, ETHD+: ETHD with washing machine improvements, CT-PPWf/s: circular transition with pay-per wash model (fast and slow diffusion variants), CT-PLEf/s: circular transition with product lease and lifetime extension model (fast and slow diffusion variants).

3.3. Adoption of Circular Business Models and Washing Machine Stock Dynamics

For the scenarios BL, ET, ETHD, and ETHD+, where there is only one business model, the IBM, we used a vintage stock flow model (Müller, 2006; Vásquez et al., 2016) to determine the production rates, obsolescence rates, and installed bases of washing machines until 2050. The obsolescence rates were calculated as a probability of failure with a normal distribution according the lifespan and year of fabrication (vintage) of the washing machines (see Appendix A.1). We further calibrated the model so that it yielded the number of newly produced washing machines with less than 3% deviation from the statistics of sales of washing machine in the Dutch market for 2019, which were 669 thousand units in the same year according to Statista (2020).

To calculate the stock dynamics of washing machines for the four circular transition scenarios CT-PPWf/s and CT-PLEf/s we followed the framework proposed by Sigüenza and colleagues. We combined the forementioned vintage stock flow model with a modified diffusion Bass model (Bass, 1969). The Bass model is a sales growth model used to define the adoption rate and the installed base of a product based on the potential market size, an innovation coefficient, and an imitation coefficient, which together describe how quickly a product is adopted. The modified Bass diffusion model we used to calculate the unconstrained adoption rates of the circular business models is:

$$S(t) = m(t)\frac{(p+q)^2}{p}\,\frac{e^{-(p+q)t}}{(1+\frac{q}{p}e^{-(p+q)t})^2} \quad (1)$$

In Eq. 1, $S(t)$ is the unconstrained adoption rate, which is equivalent to the first-time purchases, $m(t)$ is the market size in function of time, p is the innovation coefficient, and q is the imitation coefficient. To simulate the fast diffusion variants of the circular transition scenarios, we used an imitation coefficient of 0.3, close

Table 2
Diffusion parameters and calibration for the adoption of circular business models in the circular transition scenarios.

	Fast diffusion of Circular Business Models	Slow diffusion of Circular Business Models
Innovation coefficient p	9.16×10^{-5}	1.7×10^{-5}
Imitation coefficient q	0.3	0.15
Simulated installed base of circular business models in 2020	13 992	13 989

to the imitation coefficient of clothes dryers and lower that the imitation coefficient of the diffusion of color television (Bass et al., 1994). For the slow diffusion variants, we halved the imitation coefficient to 0.15. Due to the lack of historic adoption data of the circular business models, we calibrated the innovation coefficient to obtain the same installed base of circular business models (approximately 14 thousand units) for 2020 in all variants as described in Table 2, considering that one of the leader companies in this market accumulated 1720 subscriptions in 2015 (de Thouars, 2018).

The combination of the diffusion and stock dynamics models is necessary because the adoption of the circular business models affects the installed bases of the competition and thus their production demand. We assumed that adoption of the circular business models is constrained by the obsolescence rate of washing machines of the incumbent business model. In other words, in a saturated market, users can only shift to a circular business model when their current washing machine becomes obsolete. Within this limit, the circular business models are adopted freely, even in a growing market.

The constrained adoption of the circular business models is described in the following equation:

$$AR^{*}_{CBM}(t) = \begin{cases} S_{CBM}(t), & S_{CBM}(t) < O_{IBM}(t) \\ O_{IBM}(t), & otherwise \end{cases} \tag{2}$$

In Eq.2, $AR^{*}_{CBM}(t)$ is the constrained adoption rate, $S_{CBM}(t)$ is the adoption rate calculated by the modified Bass diffusion model in Eq.2, and $O_{IBM}(t)$ is the obsolesce rate of washing machines of the IBM. With the constrained adoption of the circular business models, we then calculated the adoption the yearly production rates, obsolescence rates, and installed bases of each business model throughout every time step of the transition.

3.4. Electricity Mix Improvements and Data

As found in previous literature, the impacts of washing and washing machines are directly related to the electricity mix that powers the washing machines. To further study the implications of the energy transition in the different life cycle phases of the washing machines of the business models, we modeled the energy mixes of the future for milestone years based on present data as well as publications of experts in the energy transition of different regions. For the use phase, we modelled different electricity mixes for the Netherlands and for the production of materials, manufacture, and waste treatment phases we modelled different European and Global electricity mixes. We included these assumptions to compare the benefits of the circular business models with those of the energy transition to identify the long-term relevance of the circular business models in climate change impact mitigation.

For the baseline year, 2014, we used the electricity production data in ecoinvent v.3.4 (Wernet et al., 2016). For the Netherlands, for 2018, we used statistical data of the International Energy Agency (International Energy Agency IEA, 2020) and for 2050 we derived the electricity mixes of the Transform Scenario by TNO (2020). The Transform Scenario is one of two scenarios that explores changes in the Dutch energy system to achieve a 95% reduction in direct emissions for The Netherlands by 2050 compared with 1990 levels (TNO, 2020). For the European and global regions, we based our electricity mixes based on the results of the IMAGE Model of the Shared Sustainability Pathways SSP1-Baseline-Scenario by Riahi et al. (2017), using the results of the region composed by the members the Organization for Economic Co-operation and Development (OECD) as a proxy for the European region. We calculated the life-cycle impacts of the electricity production of the mixes of each region and milestone years until 2050 as indicated in Table 3. The life cycle inventories of the energy mixes for different years and regions are available in Appendix A.3.

3.5. Life Cycle Impacts, Material Stocks and Material Uses

We constructed a 2015 baseline life cycle inventory for each life cycle stage of the washing machines of each business model based on the bills of materials and life cycle inventories from Boyano et al. (2017), CECED (2018), and Yuan et al. (2016). We transformed these bills of materials into technology inventories compatible with the time-vintage LCA model of Sigüenza et. al. (2020). This model is described in Eq. 3.

$$\mathbf{S}(k,l,a,v,t) = \begin{bmatrix} \mathbf{I} & \mathbf{A}^{fb} \\ \mathbf{A}^{bf}(t) & \mathbf{A}^{bb}(t) \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{A}^{*ff}(k,v)^{-1}\,\mathbf{F}(k,l,a,v,t) \\ 0\cdots 0 \\ \vdots\ \ddots\ \vdots \\ 0\cdots 0 \end{bmatrix} \tag{3}$$

In Eq. 3, $\mathbf{S}(k,l,v,t)$ is the scaling factors by business model, life cycle stage, vintage and time, $\mathbf{I}$ is an identity matrix**,** $\mathbf{A}^{bf}(t)$ is the time-variable background to foreground technology matrix, $\mathbf{A}^{bb}(t)$, is the background to background technology matrix, $\mathbf{A}^{*ff}(k,v)$ are the vintage-variable foreground to foreground technology inventories by business model, and $\mathbf{F}(k,l,a,v,t)$ are the final demands by business model, life cycle stage, process, vintage, and time.

To calculate the impacts of each scenario, we first constructed two impact intensity datasets. One for the BL and HD scenarios, and one for the remaining scenarios. Each dataset contains the impact intensities of the materials and life cycle processes of the life cycle inventories for the years 2014 until 2050. To assemble this data, we first calculated the impacts of the milestone years 2014, 2020, and 2050. For all milestone years, we used the software Open LCA-v. 1.10.3 (Ciroth, 2007) and the CML-baseline impact assessment method in the Open LCA Impact Assessment package v.1.5.7 (Rodríguez et al., 2017). For the milestone years 2020 and 2050, we used modified versions of ecoinvent v.3.4 that included the changes of the electricity mixes of the regions described in section 3.4 to obtain the impact intensities of all processes. Lastly, we interpolated the impact intensities for the years in between and calculated the total impacts by multiplying the scaling factors in Eq. 3 with the impact intensity dataset, so that:

$$\mathbf{H}(h,l,k,a,v,t) = \mathbf{B}(h,a,t)\,\mathbf{S}(k,l,v,t) \tag{4}$$

In Eq. 4, $\mathbf{H}(h,l,k,a,v,t)$ is the impacts by impact category, life cycle stage, business model, process, vintage, and year, and $\mathbf{B}(h,a,t)$ is the impact intensity dataset, that contains the impact intensities for each life cycle process for each year from 2015 to 2050.

To calculate the material stocks, we multiplied the installed bases of washing machines of each business model with vintage detail by their correspondent material inventories described in their technology matrices $\mathbf{A}^{*ff}$, so that:

$$\mathbf{M}(k,a,\ use,v,t) = \ \mathbf{A}^{*}\widehat{^{ff}(k,v)}\,\mathbf{A}^{*ff}(k,v)^{-1}\mathbf{F}_{M}(k,use,v,t) \tag{5}$$

In Eq. 5, $\mathbf{M}(k,a,\ use,v,t)$ is the materials of the washing machines in use by business model, according to the size of the stock

Table 3
Electricity generation mixes for the Netherlands, OECD, and world regions for 2018/2020 and 2050. SSP1: Shared Sustainability Pathways SSP1-Baseline-Scenario by Riahi et al. (2017).

Energy Source	*Netherlands 2018* Based on IEA (2020)	*Netherlands 2050* *Based on* TNO (2020)	*OECD SSP1 2020* Based on Riahi et al. (2017)	*OECD SSP1 2050* Based on Riahi et al. (2017)	*World 2020 SSP1* Based on Riahi et al. (2017)	*World 2050 SSP1* Based on Riahi et al. (2017)
Other	*1%*	*8% (imports)*	-	-	-	-
Wind	*9%*	*Off-shore 65%* *On-shore 10%*	*7.5%*	*22%*	*4.4%*	*12%*
Solar	*3%*	*15%*	*3%*	*11%*	*1.6%*	*15%*
Nuclear	*3%*	-	*21%*	*3%*	*10.7%*	*2%*
Waste	*4%*	-	-	-	-	-
Biofuels	*2%*	-	*1.50%*	*0%*	*1%*	*0%*
Gas	*51%*	*2%*	*22%*	*33%*	*24.4%*	*28%*
Oil	*1%*	-	*2%*	*0%*	*3.6%*	*0%*
Coal	*26%*	-	*30%*	*19%*	*37.5%*	*32%*
Hydro	*0%*	-	*14%*	*12%*	*16.8%*	*11%*

of each vintage, and $\mathbf{F}_M(k, use, v, t)$ is the stocks of washing machines in use by business model, vintage, and time.

Lastly, we calculated the material uses for each year of each scenario, including the materials necessary for the production of the washing machines for each business model as well as the materials needed to make replacement parts for their maintenance, so that:

$$\mathbf{X}^b(k,l,v,t) = \begin{bmatrix} \mathbf{I} & \widehat{\text{zeroes}} \\ \mathbf{A}^{bf}(t) & \mathbf{I} \end{bmatrix} \mathbf{S}(k,l,v,t) \tag{6}$$

In Eq. 6, $\mathbf{X}^b(k,l,v,t)$ is the material uses by business model, life cycle stage, vintage, and time.

4. Results and Discussion

In this article, we modelled and calculated simultaneously the production rates, installed bases, material flows, material stocks, and climate change impacts of the life cycle of washing machines in the Dutch market with different scenarios, including the adoption of two circular business models, halving detergent use, and the energy transition. We modelled fast and slow diffusion versions of the scenarios for the adoption of circular business models of washing machines because although the circular business models have gained acceptance in the Netherlands, their future adoption patterns are still uncertain.

To the best of our knowledge, this is the first environmental and material assessment to study product lease and pay-per-wash business models of washing machines performed at any technological and economy-wide scale. We implemented a dynamic and prospective approach to analyze the effects of probable technological changes and scaled them to a market-size system to zoom out from the traditionally technology-centered LCA perspective into an economy-wide picture, in which the effects of the adoption of technologies are easier to identify. In addition, we proved the usability of the modeling framework of Sigüenza et al. (2020) for circular business models and technological transitions, a modelling framework that combines LCA, material flow analysis, and diffusion of technologies. In the following sub-sections, we present and discuss the results of our case-study.

4.1. Installed Bases, Adoption and Production Rates

Figure 2 shows the results of adoption rate, installed bases and production rates of the circular transition scenarios. In contrast with the target-based adoption scenarios of the shared-access business models studied by Wasserbaur et al. (2020), where the penetration rates of such business model was targeted to 50% and 100%, we opted for a bottom-up adoption of our product lease and pay-per-wash business models with two adoption variants: fast diffusion variants, which represent the successful mass-market adoption of the circular business models, and the slow diffusion variants, which represent a successful, but rather niche-sized market share. In the fast diffusion variants, the circular business models reach market shares of 3% and 88% for the years 2030 and 2050 respectively, while the slow diffusion variants reach market shares of 1% and 19% in the same years. The installed bases of the circular business in all variants are relatively close until 2025. These results suggest that we could see a more defined pattern of adoption between the years 2030 and 2035, possibly signaling whether these circular business models will be adopted at larger scales. This could signify that the next 10 years of the market development of the circular business models are critical, since they would reflect an accelerated mass-market target or a slow-growing niche-market acceptance of the circular business models.

The increased longevity of the washing machines of the circular business models show to have an effect on the yearly production volumes of washing machines in the Dutch market. These effects, however, are also highly dependent on the penetration rate of the circular business models. In the BL scenario, the production rates range from 650k in 2020 to 700k washing machines per year in 2050. During the first 10 to 15 years of adoption of the circular business models, the production rates of washing machines seem unaffected, but from year 2035 onward, especially in the high diffusion variants of CT-PPWf and CT-PLEf, decreasing production rates become obvious, which shrink by 21 and 28% by 2050 in the CT-PPWf and CT-PLEf, respectively, compared with the 2020 production rates. The slow diffusion variants also had a decrease in the washing machine production rates, but much less significantly: only 3 and 4% for CT-PPWs and CT-PLEs in 2050. Such production rate reductions of the fast-diffusion scenarios could also be achieved by simply extending the life spans of the washing machines. The reduction of washing machine production volumes however, can be a point of concern for supporters of both the circular and the production-based economy. Although circular business models may compensate or exceed the economic benefits for the business owner (The Ellen MacArthur Foundation EMF, SUN, & SYSTEMIQ, 2015). It is possible that the supply chains of production become affected at different levels, for instance, by less labor required in manufacturing leading to reduced employment levels (Donati et al., 2020). In turn, more man work could shift from the manufacturing to the services sector, an effect for which we suggest further research. .

4.2. Material Uses and Stocks

The reduction of production rates of washing machines in the circular transitions CT-PPWf/s and CT-PLEf/s also has a positive impact in material uses as shown in Figure 3. In the slow diffusion variants, material use reductions become visible by year 2050 with material use reductions between 2 and 3% compared with the

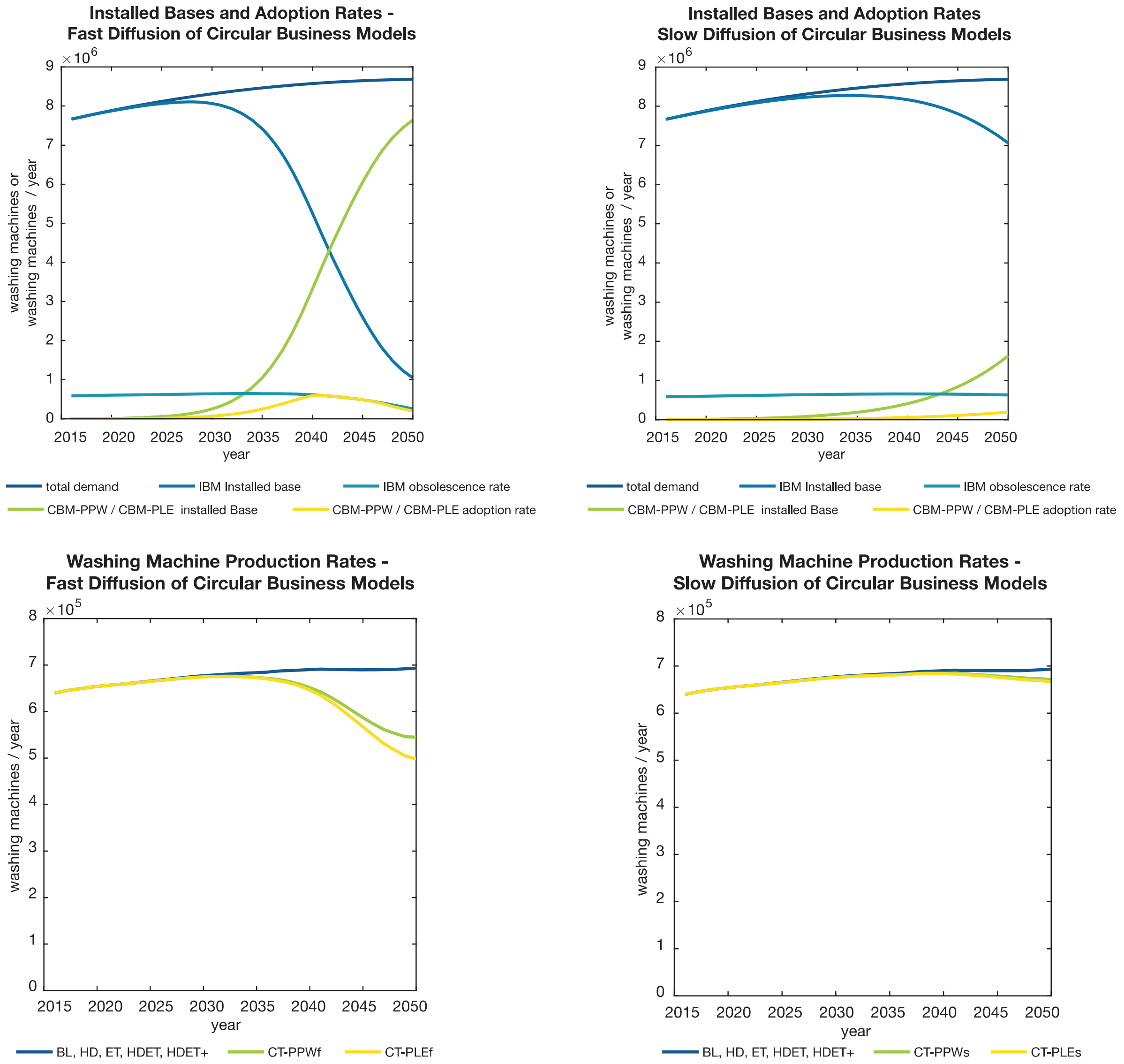

Figure 2. Diffusion and stock dynamics of the circular business models in the circular transition scenarios with fast and slow diffusion. BL: Baseline, HD: Halving Detergent use, ET: Energy Transition, ETHD: Energy transition and halving detergent use, ETHD+: ETHD with washing machine improvements, CT-PPWf/s: circular transition with pay-per wash model (fast or slow diffusion variant), CT-PLEF/s: circular transition product lease and lifetime extension model (fast or slow diffusion variant).

2050 BL. In the fast diffusion variant, CT-PPWf, the material use reductions reach 21% less than the 2050 BL. The CT-PLEf fast diffusion variant achieves the highest material savings: 24% by 2050, despite the temporary increase of less than 1% between 2030 and 2040, indicating that the longer lifetimes outrun the more robust construction of washing machines in material use benefits. The material use reductions of these fast diffusion variants are greater than those estimated by Amasawa et al. (2018) with an access-based business model, which in principle requires fewer washing machines per household. However, in their study, the population already had access to shared laundering services, while in the Netherlands, the social norm is to have one washing machine per household.

In contrast, with the circular business models, material uses decrease. Figure 3 shows the material uses of each scenario by material type. In this figure, ferrous metals observe the largest material uses followed by concrete, polymers and composites. Ferrous metals represent a large share of the materials in washing machines, and so does concrete, which is used in washing machines as counterweight blocks to control vibrations during the washing machines operation. Despite the significant weight of the concrete blocks (~20kg) they represent a very small fraction of the climate change impacts of the manufacture of washing machines, contributing to less than 1% to climate change impacts of the production phase (see Figure A.1 in Appendix A.2). Overall, material uses in the circular transitions by 2050 are reduced by as much as 23% in the fast diffusion variants, and as little as 3% in the slow diffusion variants.

The material circularity indices, which are the quotients of recovered materials vs the material uses year by year, indicate that the demand of materials to manufacture new washing machines is larger than the materials recovered at the end of life of the washing machines in all scenarios. The factors for such sub-optimal indices are several. First, the increasing demand of washing machines in the Dutch market and the amount of recovered materials from discarded washing machines is not sufficient to substitute entirely the materials needed for the production of new washing machines. And second, we assumed constant waste treatments for the different materials with below 100% recovery rates. Steel, for instance, has a 95% recovery rate, while polymers and composites have a constant recovery rate of 30% and 0% respectively. Therefore, what we see mostly in these circularity indices are the effects of the pro-

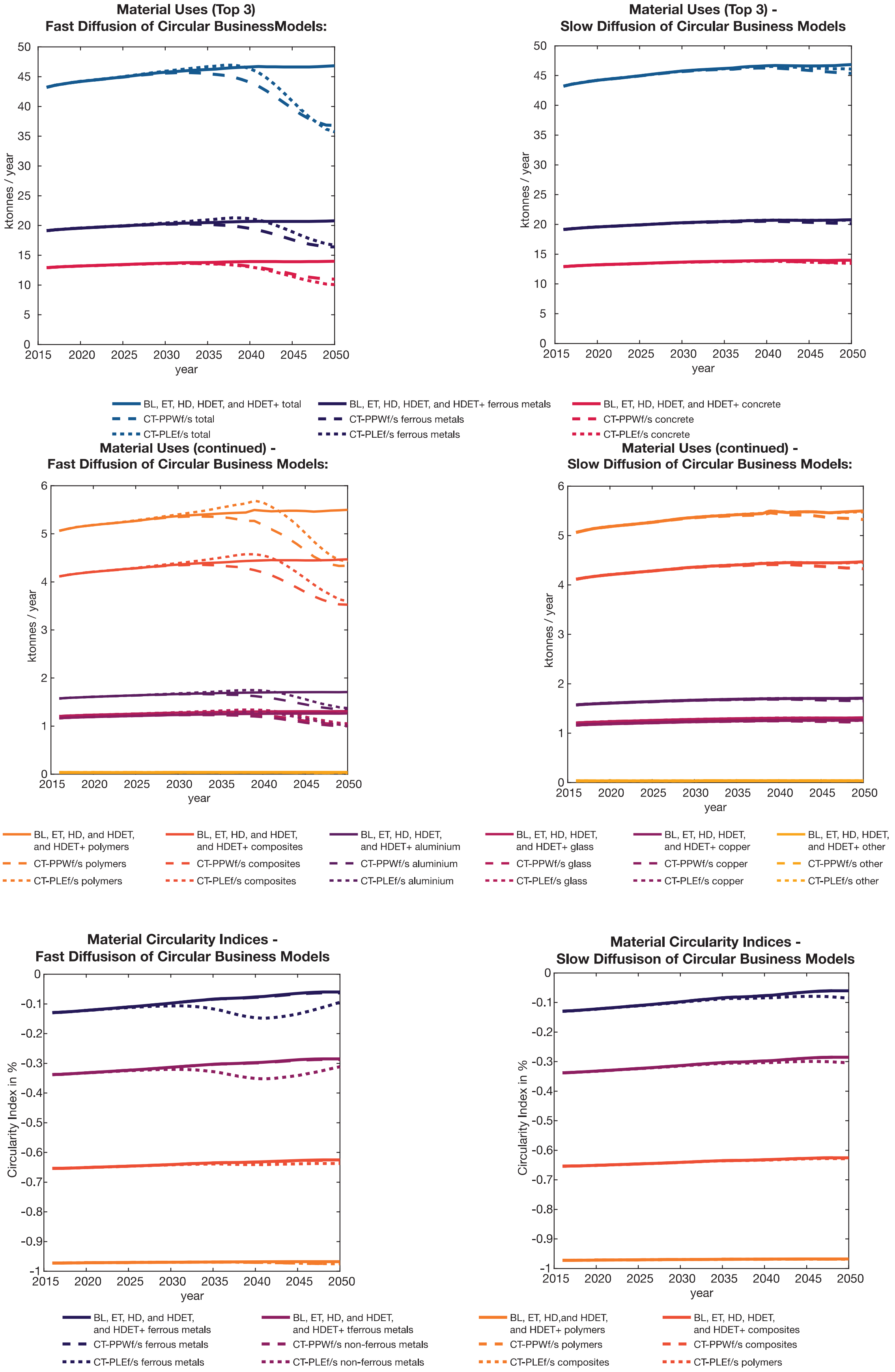

Figure 3. Material uses and circularity indices results. BL: Baseline, HD: Halving Detergent use, ET: Energy Transition, ETHD: Energy transition and halving detergent use, ETHD+: ETHD with washing machine improvements, CT-PPWf/s: circular transition with pay-per wash model (fast or slow diffusion variant), CT-PLEf/s: circular transition product lease and lifetime extension model (fast or slow diffusion variant).

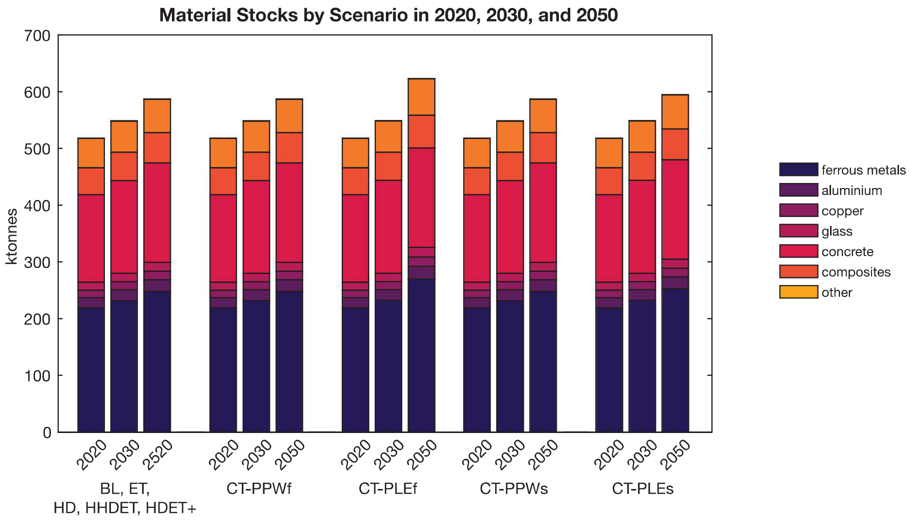

Figure 4. Material stocks results. BL: Baseline, HD: Halving Detergent use, ET: Energy Transition, ETHD: Energy transition and halving detergent use, ETHD+: ETHD with washing machine improvements, CT-PPWf/s: circular transition with pay-per wash model (fast or slow diffusion variant), CT-PLEf/s: circular transition product lease and lifetime extension model (fast or slow diffusion variant).

duction rates of washing machines, their lifetimes, and in the case of the CT-PLEf/s scenarios, the increased mass of some washing machines. Nevertheless, increasing the recovery rate of materials of currently low recovery materials such as plastics and composites could increase the overall circularity indices of the system.

Lastly, in this subsection, Figure 4 shows the results of the total material stocks embedded in the washing machines of the Dutch market in the years 2020, 2030, and 2050. In the scenarios HD, HDET, and HDET+, the total material stocks have the same growth pattern as the BL due to the growing number of households toward 2050. This is because we assumed a homogeneous material composition for the washing machines. In contrast, the CT-PLEf scenario accumulates 6% more material stocks by 2050 compared with the 2050BL and 20% more compared to the 2020 BL, contributing to the long term trend of material stocks accumulation (Krausmann et al., 2017) in spite of the reductions in yearly material uses as described in Figure 3. This material stock accumulation is likely to continue even when material uses are lower, such as in the fast adoption scenarios or circular business models.

4.3. Electricity and Detergent Use

For the year 2018, we calculated that the use of the washing machines in the Netherlands consumed 1.4TWh, equivalent to 1.2% of the total electricity consumption of the country reported in IEA data (IEA, 2020). Without technology or use changes, by 2050 the electricity use would rise to 1.6TWh. By the same year, the HDET+ scenario, which includes washing machine performance improvements achieves a reduction of 17% in electricity use compared with the 2050 baseline. In the fast diffusion transitions, the CT-PLEf scenario reduces the electricity use by an additional 2% due to the slightly better performing washing machines. The CT-PPWf scenario is the best performer in this category achieving a 38% energy use reduction by 2050 compared with the 2050 BL, or extra 23% than the CT-PLEf, due to the fewer washing cycles and lower water temperature as indicated in

TABLE 1. In contrast, the slow diffusion variants of the circular transitions show minimum improvements. The CT-PPWs shows an improvement of 5% by 2050 compared with the HDET+, while the CT-PLEs shows virtually no gains, even when the circular business models achieved a market share of 19% by that year, because the development in improvements of the washing machines in the HDET+ scenario and the CT-PLE are very similar.

When it comes to detergent use, all scenarios except the BL and ET show similar detergent use reductions (see Figure 5). The circular transitions with slow diffusion of circular business models have virtually the same detergent use results as the scenarios with halving detergent strategies: HD, HDET, and HDET+. This means that at low market shares, the circular business models have little influence in the detergent consumption in the market. On another hand, the fast diffusion variants of the circular transitions, CT-PPWf and CT-PLEf, show additional improvements in detergent use, suggesting that the diffusion of washing machines with auto-dosing systems has similar results as the population learning to use half of the detergent by 2050; naturally, if the auto-dosing systems are used consistently and correctly.

Regardless of the mechanisms of detergent use reduction, a 40% detergent use reduction by 2050, could mean 14% climate change impact savings compared to the 2050 baseline without any other interventions. We ventured to consider detergent use in the scenarios in light of the efforts and developments in detergent dispensing mechanisms and detergent formulations. In the last 20 years, the average recommended dose per washing cycle has downsized from 150 to 75g per cycle (AISE, 2019). However, it is also known that users can easily use excess detergent, hence the emergence of auto-dosing systems.

4.4. Climate Change Impacts

Figure 6 shows the results of climate change impacts of the different scenarios. The period of 2015 to 2018 shows a climate change impact reduction of 6% due to the recent improvements in the Dutch electricity mix. From 2020, the BL scenario shows that if technology improvements in the electricity mixes and washing machines stagnate, and user behaviors remain the same, the climate change impacts can increase 5% by 2030 and 10% by 2050 compared with the 2020 BL because of the increasing demand of washing machines of a growing number of households.

Of the scenarios without circular business models, the ET scenario shows the largest cuts in climate change impacts. If the energy transition in the Netherlands continues to improve as suggested in section 3.4, the life cycle climate change impacts could see a reduction of 17% by 2030 and 60% reduction by 2050 without further technological or behavioral interventions. These dramatic reductions in impacts are due to a steep reduction in the kg-CO_2-eq per kWh of the Dutch electricity mix, which reaches a 93% re-

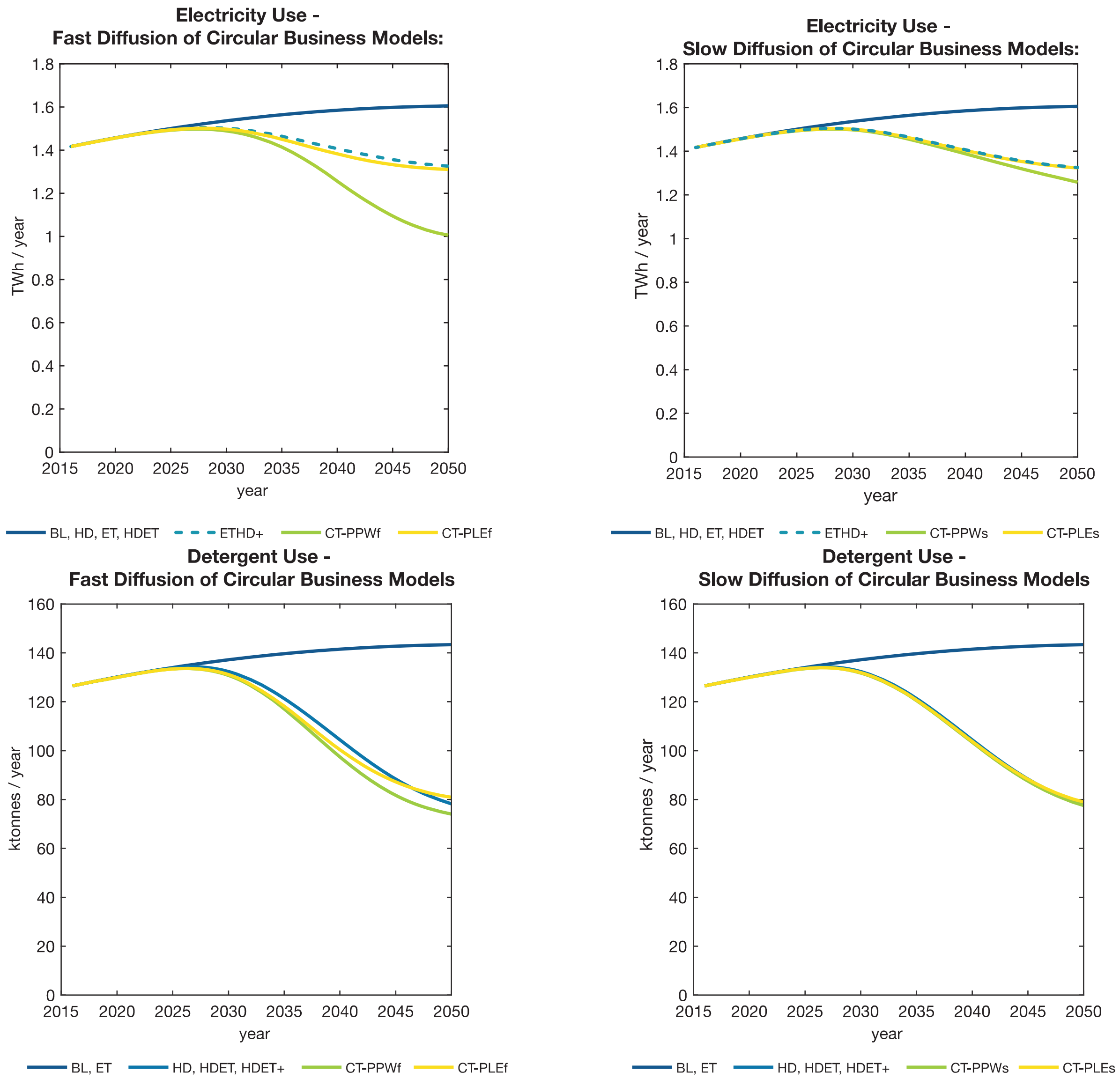

Figure 5. Electricity and detergent use by scenario. BL: Baseline, HD: Halving Detergent use, ET: Energy Transition, ETHD: Energy transition and halving detergent use, ETHD+: ETHD with washing machine improvements, CT-PPWf/s: circular transition with pay-per wash model (fast or slow diffusion variant), CT-PLEf/s: circular transition product lease and lifetime extension model (fast or slow diffusion variant).

Table 4
Climate change life cycle impacts results of the energy mixes of 2015, 2020, and 2050 for the Netherlands, European, and global regions.

	units	2015	2020	2050
NL (low voltage)	g CO_2-eq / kWh	618	570	42
Europe (medium voltage)	g CO_2-eq / kWh	452	417	384
Global (medium voltage)	g CO_2-eq / kWh	774	698	510

duction in 2050 compared with 2015, close to the 95% reduction modeled by TNO (TNO, 2020). Table 4. Climate change life cycle impacts results of the energy mixes of 2015, 2020, and 2050 shows the results of the climate change impacts per kWh of the Dutch electricity mix, the European mix, and the global mix per kWh. The less outstanding results of the average European and global regions have in turn, a small effect in the reduction of impacts of materials and manufacture of the washing machines, which for the European market, they come mostly from Europe and Asia (APPLIA, 2020).

The use phase of the washing machines remains as the largest contributor of climate change impacts in all scenarios (Figure 6). It contributes as much as 88% in the 2020 BL, and as little as 60% by 2050 in the ET scenario. The energy transition has a shallow effect in the impacts of the production phase of washing machines mainly because the global and European electricity mixes do not improve as much as the Dutch mix in our assumptions in section 3.4. In the ET scenario, although the impacts of the production per washing machine decrease by 10% by 2050, it represents only a 5% reduction in absolute terms due to the increased demand of washing machines in the same year. In all the other scenarios, as the contribution of impacts of the use phase decreases, the impacts of the production phase take a more important role. Using 2050 as example, in most scenarios the use phase contributes to about 60% of the impacts, meaning that 40% of the impacts will be regarded to material production and manufacturing, thus tilting the balance between the production and use phases for climate change mitigation strategies in the future.

Of the circular transitions, the fast diffusion variants perform best in total climate change impacts. By 2050, the CT-PPWf and the CT-PLEf have 14% and 5% less impacts, respectively, compared with the HDET+ scenario. At the same time, looking at the production

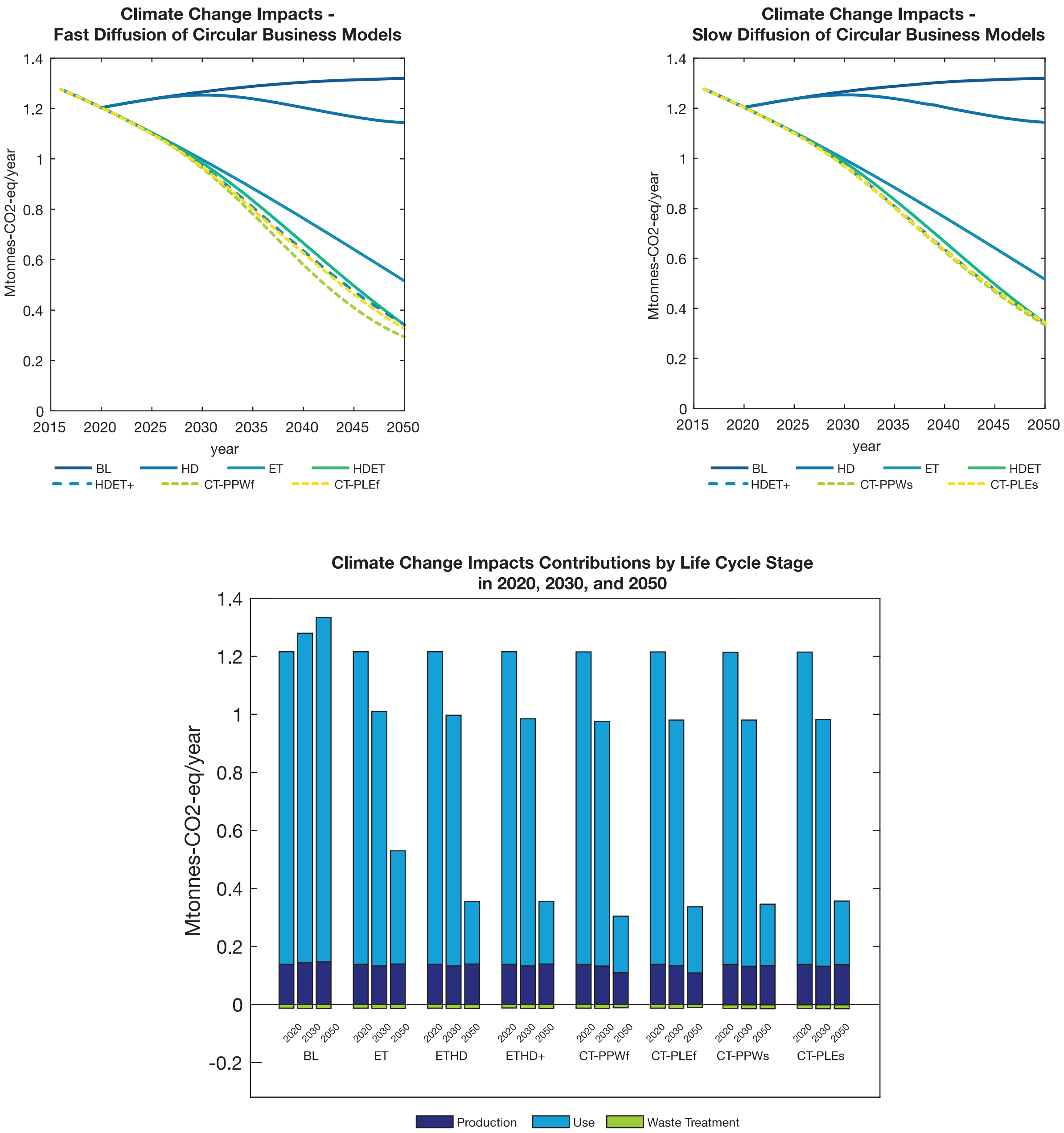

Figure 6. Climate change impacts by scenario. BL: Baseline, HD: Halving Detergent use, ET: Energy Transition, ETHD: Energy transition and halving detergent use, ETHD+: ETHD with washing machine improvements, CT-PPWf/s: circular transition with pay-per wash model (fast or slow diffusion variant), CT-PLEf/s: circular transition product lease and lifetime extension model (fast or slow diffusion variant).

phase alone, the impacts of the production of washing machines were reduced by 22% in both scenarios compared with the ET scenario in the same year. This means that the circular business models were effective in reducing the impacts of the manufacturing of washing machines by lower production volumes. In contrast to the fast diffusion scenarios, the results of the slow-diffusion variants CT-PPWs and CT-PLEs have virtually identical impacts to the HDET+ scenario, showing that at low market shares of 19% or less, the benefits of the circular business models are negligible.

5. Conclusions

In this paper, we developed different scenarios of adoption of circular business models of washing machines in the Dutch market to analyze their material and climate change impact implications toward 2050 including important technological advancements such as the energy transition, washing machine improvements, and changes detergent use.

From our study, decarbonizing the Dutch electricity mix has the largest climate change benefits regardless of the business models of washing machines. Even without changing laundering habits or business models, a successful energy transition would allow to achieve significant environmental benefits. In the Netherlands, at the current improvement pace, impacts could halve around 2040. In countries where home appliances have high penetration rates, focusing on the energy transition could provide the largest climate change impact benefits, while extending the life of appliances would be beneficial in both saturated and unsaturated markets in the long run. With a successful outlook of the energy transition, a shift from prioritizing the use phase only to prioritizing the use phase and the production phase equally, is foreseeable.

We also conclude that the circular business models can contribute to additional climate change impacts benefits, if deployed at a very large scale. However, such ambitious penetration rates of the circular business models could take decades to attain even with the most successful adoption pathways. At lower market shares of 20% or less, the benefits in climate change of the circular business models are negligible. In addition, the arguable benefits of the circular business models may also be threatened by the use patterns of the customer, especially in the case of the pay-per-wash model, whose benefits can be neutralized if the users do not respond to the incentives of the business model to change washing patterns.

In addition to the frequency of washing and the water temperature choice for washing cycles, detergent use is a relevant factor in the climate change impacts of laundering activities. Reducing the use of detergent is a simple, but potentially effective measure to mitigate climate change impacts even without washing machine technological improvements. Raising awareness among users about detergent use, can be added to the set of strategies for more sustainable washing activities. This is a measure that can be adopted by all kinds of users, who normally do not have control on the impacts of the electricity and the development of washing machine technologies.

In material use benefits, the circular business models perform significantly better than the regular ownership model. If adopted successfully, material uses could see substantial reductions, mainly due to the longer lifespans of the washing machines. Extending the life of the washing machines through leasing and pay-per-wash business models could achieve similar material use reductions as those by their shared-access-based siblings. Nevertheless, this enhanced material use performance of the system is also subject to the successful deployment of the circular business models, whose benefits could materialize toward 2050 with a fast diffusion profile. For material use reduction, an alternative strategy could consist in extending the lifetime of the washing machines of all users, while keeping an eye on energy efficiency. In this line, extending the life of the washing machines did not result in concerning higher environmental impacts due to their energy efficiency, as long as there are continuous improvements in new washing machine models.

We finalize this article with some recommendations for policy makers, washing machine manufacturers, circular business stakeholders, and washing machine users, as well as some suggestions of further research. For policy makers and washing machine manufacturers, we recommend to consider minimum standard lifetime for domestic washing machines of at least 25% more than the present average of 12.5 years, while maintaining the current material intensities of the appliances and include dematerialization strategies as much as possible. Further research could focus on developing combined design for dematerializaiton and longevity strategies for washing machines, as well as for other home appliances and durable products. For manufacturers, the potentially lower profits from reduced production rates and consequent sales can be offset by access and subscription-based business models. For circular business models creators, our recommendations are to research and develop mechanisms aimed towards consumer behavior to ensure the capture of environmental and material benefits of the circular business models. These strategies could include use-feedback-systems both for the user and the business owner. Other strategies could target brand loyalty to ensure the lifetime extension of the washing machines. For consumers, our recommendations are to use detergent moderately and in case of the need of replacing their current washing machine, choose carefully a high efficiency model keeping in mind that it is a long-term investment, which should not be replaced before 12.5 years to effectively contribute to material use mitigation. Lastly, for environmental studies of circular business models that involve durable products, we recommend adopting a dynamic approach and a regional scope, and possibly, consider multiple product systems to better assess the potential extension of the impacts and benefits of the circular business models in wider economic contexts. We believe that the environmental studies of scalable circular business models with regional contexts and perspectives represent cases that need more scientific attention.

Declaration of Competing Interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.spc.2021.01.011.

Appendix A1. On the Diffusion and Stock Dynamics Model Combination

The obsolescence rate of washing machines of each business model was modeled as defunction function, with a normal probability distribution. This normal distribution is dependent on the lifetime of the washing machines (τ), their vintage (ν), the year (t), and a lifetime standard deviation (σ) as shown in the following equation:

$$O(t) = \sum_{t=0}^{t=\nu} I(\nu)\frac{1}{\sqrt{2\pi}}e^{\frac{-(t-\nu-\tau)^2}{2\sigma^2}} \tag{A.1}$$

Complementing Eq. 2 in the main text, for the circular business models, the replacement rate of washing machines is equal to their obsolescence rate, because it is assumed that customers will be subscribed to the circular business model indefinitely, so that $RR^*_{CBM}(t) = O_{CBM}(t)$. Thus, the installed base of the circular business model, $U_{CBM}(t)$, at each year is:

$$U_{CBM}(t) = \sum_{t=0}^{t} (I_{CBM}(t) - O_{CBM}(t)) \tag{A.2}$$

In this equation, the total demand of new washing machines for the CBM, $I_{CBM}(t)$, is the sum of the constrained adoption rate $AR^*_{CBM}(t)$ in Eq.2 in the main text plus the replacement rate $O_{CBM}(t)$.

For the IBM, the installed base and washing machine production rates are calculated by balance:

$$U_{IBM}(t) = m(t) - U_{CBM}(t) \tag{A.3}$$

$$I_{IBM}(t) = \Delta U_{IBM}(t) + O_{IBM}(t) - AR^*_{CBM}(t) \tag{A.4}$$

In Eq. A.3, $U_{IBM}(t)$ is the installed base of the IBM by time. In Eq.A.4, $I_{IBM}(t)$ is the total production of washing machines of the IBM necessary to fulfill the installed base $U_{IBM}(t)$. Both $U_{IBM}(t)$ and $I_{IBM}(t)$ are always equal or larger than zero.

Appendix A2. Climate Change Impact Contributions of the Production of Washing Machines

Figure A1

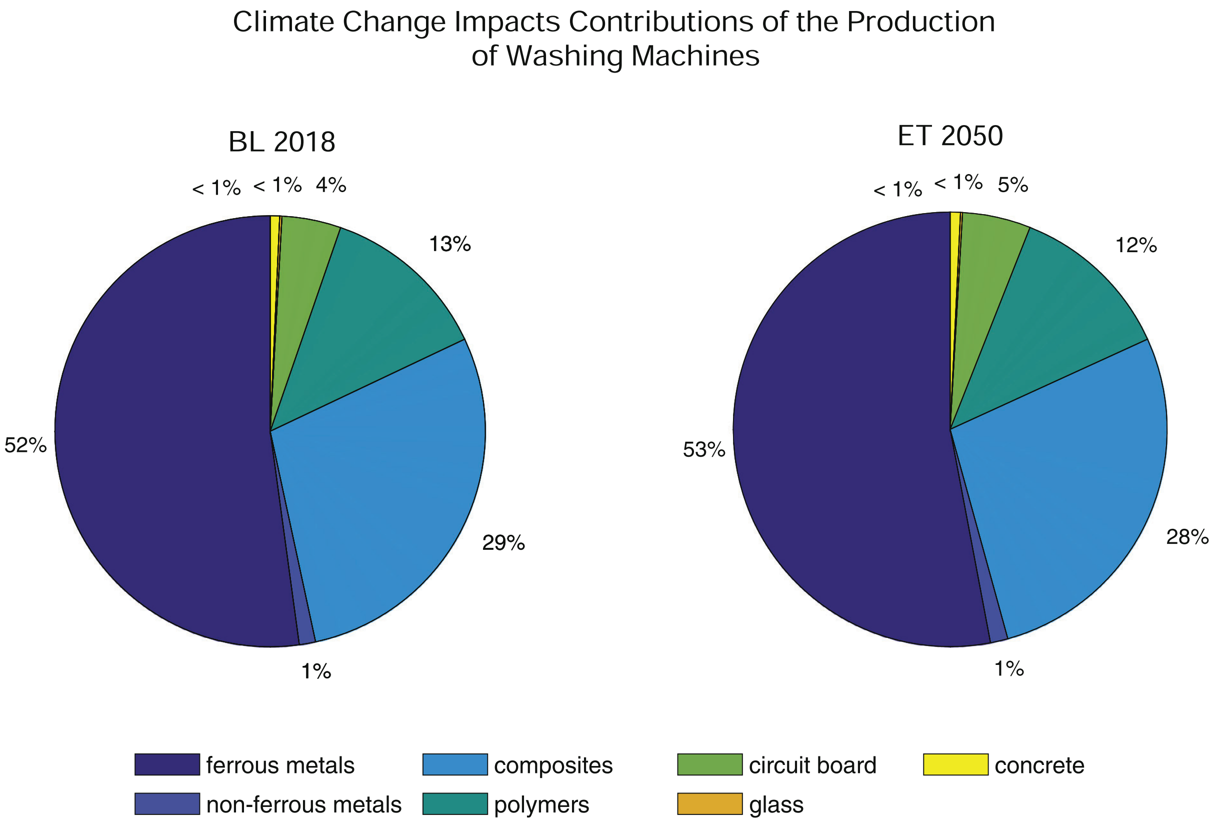

Figure A.1. Climate change impact contributions of the production phase by materials of washing machines in different years. BL: baseline, ET: energy transition

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