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## How Circular Economy Innovation Can Backfire on The Environment: Quantifying the Rebound Effect of The Textiles and Clothing Sector

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## Abstract

Circular economy (CE) is championed as a sustainability solution, promoting reuse, recycling, and resource efficiency to reduce environmental harm. However, efficiency innovations can trigger a rebound effect (RE), where lower costs stimulate higher consumption and production, paradoxically negating sustainability gains. This study applies a multi-region, multi-sector Dynamic Computable General Equilibrium (DCGE) model to quantify the circular economy rebound effect in the textile and clothing (TC) sector, the second most polluting industry. Our findings reveal a 155% rebound backfire, showing that CE innovations in the TC sector may exacerbate rather than mitigate environmental pressures. This challenges the assumption that CE alone can drive sustainability and underscores the need for complementary policies. We explore one policy - a uniform Pigouvian tax on TC production, finding that a minimum rate of 1.25% is required to curb the RE. However, effective implementation requires targeted regulatory interventions that also account for socio-economic trade-offs, particularly in low-income countries. To achieve truly sustainable outcomes, we argue for exploring broader systemic shifts, including insights from Degrowth theory.

**Key Words:** Circular Economy, Rebound Effect, Computable General Equilibrium (CGE), Degrowth, Textile and Clothing Sector

**JEL:** O5, Q52, H21

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## Abstract

Circular economy (CE) is championed as a sustainability solution, promoting reuse, recycling, and resource efficiency to reduce environmental harm. However, efficiency innovations can trigger a rebound effect (RE), where lower costs stimulate higher consumption and production, paradoxically negating sustainability gains. This study applies a multi-region, multi-sector Dynamic Computable General Equilibrium (DCGE) model to quantify the circular economy rebound effect in the textile and clothing (TC) sector, the second most polluting industry. Our findings reveal a 155% rebound backfire, showing that CE innovations in the TC sector may exacerbate rather than mitigate environmental pressures. This challenges the assumption that CE alone can drive sustainability and underscores the need for complementary policies. We explore one policy - a uniform Pigouvian tax on TC production, finding that a minimum rate of 1.25% is required to curb the RE. However, effective implementation requires targeted regulatory interventions that also account for socio-economic trade-offs, particularly in low-income countries. To achieve truly sustainable outcomes, we argue for exploring broader systemic shifts, including insights from Degrowth theory.

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## 1 Introduction

The Circular Economy (CE) has emerged as a promising strategy to address pressing environmental challenges, offering an alternative to the linear "take, make, use, and dispose" model. By emphasizing reuse, recycling, and resource efficiency (Saha et al., 2021), CE aims to extend product lifespans, enhance recycling rates, and mitigate overconsumption, fostering a more sustainable economic system.

However, CE innovations also introduce the risk of a Rebound Effect (RE), where efficiency gains lower costs, inadvertently driving higher consumption and production—a phenomenon known as the Jevons Paradox (Jevons, 1865). Enhanced recycling and upcycling further reduce production costs, making it cheaper to create new products from old materials. As a result, consumers, perceiving these goods as more sustainable, may increase their purchases, intensifying resource use and waste generation.

This paradox is reinforced by market expansion, where CE innovations attract new consumers, further amplifying environmental pressures. Bianchi and Cordella (2023) empirically show that CE reduces primary resource extraction, but its mitigating effect is marginal compared to economic growth. However, their analysis does not explicitly frame this within the RE context, leaving a gap in understanding its broader implications—a concern briefly noted by Millar et al. (2019) in their literature review.

This paper critically examines the limitations of relying solely on CE innovations to achieve sustainability goals. Using a multi-region, multi-sector Dynamic Computable General Equilibrium (DCGE) model, we quantify the global rebound effect with a focus on the textiles and clothing (TC) sector – one of the most resource-intensive industries. While CE innovations may enhance economic welfare by lowering retail prices and increasing consumer spending, the resulting general equilibrium effects drive higher production, leading to significant environmental costs—externalities not internalized by conventional market mechanisms.

Our findings show that CE innovation in the TC sector can trigger an extreme RE, with a 155% *backfire*, driving production and consumption far beyond pre-CE levels. This underscores the need for complementary policies to ensure CE strategies deliver genuine sustainability benefits. As a potential solution, we propose a uniform Pigouvian tax on TC production, estimating that a minimum rate of 1.25% is required to mitigate the rebound effect. While our model can explore alternative policy strategies, we leave these for future research. We also discuss the need to explore broader systemic shifts, including insights from Degrowth theory to address the structural drivers of consumption growth.

We assess the TC sector because it ranks the second most polluting industry globally (after energy) and poses significant environmental and social challenges<sup>1</sup>. TC production is projected to reach 160 million metric tons by 2030,<sup>2</sup> the sector consumes 20% of global water resources, emits 1.7 billion tons of CO<sub>2</sub>

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<sup>1</sup> See the [2019 report by the United Nations](#) that highlights the environmental costs of staying fashionable – accessed 23/01/2025).

<sup>2</sup> See [Statista \(2024\)](#) Production of textile fibers worldwide from 1975 to 2020, with a forecast for 2025 and 2030 (accessed 20/01/2025).

annually—accounting for 10% of global emissions—and generates 92 million tons of waste, with less than 1% recycled into new clothing (Abbate et al., 2023).<sup>3</sup> These impacts threaten global sustainability efforts, potentially surpassing carbon budgets and contributing to oceanic plastic pollution and waste management crises (Ellen MacArthur Foundation, 2023).

While our intention is not to challenge the prevailing view that CE innovation offers a viable pathway to address the environmental impact of the TC industry, we aim to provide a more nuanced perspective by focusing on the RE associated with CE practices. The existing body of research on CE, and specifically within the TC industry, has significantly expanded over the past decade (Saha et al., 2024). We identified a notable rise in studies exploring the influence of the CE approach on business models, implementation challenges, benefits, and consumers' preference for sustainable products (e.g., Blomsma et al., 2023; Colucci and Vecchi, 2021; Rainville, 2021). Additionally, various reviews have been published, addressing different aspects of CE in the TC industry. For example, Bailey et al. (2022) reviewed the environmental impacts of fast fashion on water quality, while Jia et al. (2020) analysed the drivers, barriers, practices, and indicators of sustainable performance, and Khan et al. (2023) examined consumers' motivations for purchasing circular fashion.

Despite these advances, a critical gap remains in addressing the limitations of these themes, particularly in understanding how circular practices can sometimes exacerbate environmental impacts rather than mitigate them (Dzhengiz et al., 2023). Saha et al. (2024) undertook a comprehensive review of this evolving research and revealed the paradoxical outcome of the rebound effects and challenges the prevailing assumption that CE can simultaneously enhance environmental, economic, and social outcomes in the TC industry.

To the best of our knowledge, this study is the first to quantify the global circular economy rebound effect (CERE) in the TC industry. While previous research has primarily focused on demonstrating the effectiveness of CE practices in reducing the environmental impacts of the TC sector, these studies often assume that CE can simultaneously deliver environmental sustainability, economic growth, and social improvements. However, empirical evidence challenges this assumption. For example, Saha et al. (2021) found that among the various dimensions of CE, only the 'recovery' component consistently contributes positively to economic, environmental, and social outcomes.

Lin and Zhao (2016) analyse the TC sector in China, focusing on energy efficiency improvements as the primary driver of RE. They find that lower energy consumption reduces effective energy costs,

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<sup>3</sup> In Scotland, for example, fast fashion has resulted in textiles making up nearly a third of the country's household carbon impact despite accounting for only 4% of household waste (see [documentary here](#) – accessed 20/01/2025).

increasing TC demand and offsetting 21% of expected energy savings—an example of partial RE. Our findings indicate a much larger RE due to our use of a general equilibrium model that examines the economy-wide effect rather than just on its direct energy use. Building on these insights, our DCGE approach challenges prevailing assumptions about the CE and offers a more comprehensive perspective on the complexities of CE transitions.

By quantifying the RE, stakeholders can determine whether CE practices genuinely reduce the industry's environmental footprint or inadvertently increase consumption and waste. Such measurement allows for a comprehensive assessment of how different markets and consumer behaviours influence CE initiatives' overall impact. Additionally, this measurement is vital for creating effective regulatory frameworks and policies. Policymakers need robust data to design regulations that mitigate the rebound effect, such as limiting production volumes, promoting sustainable consumption, and incentivising longer product lifespans. Furthermore, understanding the CERE informs business strategies, helping brands and manufacturers recognise the potential unintended consequences of their sustainability efforts.

The next section reviews key literature on CERE, laying the groundwork for Section 3, which introduces our economy-wide model and methodology for quantifying RE. Section 4 presents the model results, followed by Section 5, where we discuss these findings, simulate the impact of a Pigouvian tax to mitigate RE backfire, and explore broader policy options. Finally, Section 6 concludes with a summary of the study's key findings and implications.

## 2 Literature on circular economy and rebound effect

For this section, we used a systematic literature review (SLR) - with full methodological details in the online supplementary appendix. First, we examine the core principles of the circular economy (CE) and the mechanisms driving the rebound effect (RE), showing how systemic responses can paradoxically offset CE's intended environmental benefits. Next, we review business models and analytical tools for quantifying RE. Finally, we highlight the advantages of DCGE modelling in capturing the broader economic and environmental implications of CE strategies at global and regional scales.

### 2.1 Core concepts of the Circular Economy and Rebound Effect

CE is built on three core principles: eliminating waste and pollution, keeping products and materials in use, and regenerating natural systems (Castro et al., 2022). It is a regenerative approach that minimizes resource input, waste, emissions, and energy leakage by slowing, closing, and narrowing material and energy loops (Geissdoerfer et al., 2017). The overarching goal is to maximize resource value, reduce

emissions, lower energy consumption, and minimize waste disposal while extending beyond traditional reverse logistics (Dey et al., 2022).

CE offers multiple benefits, including cost and risk reduction, competitive advantage, improved resource efficiency, lower environmental impact, and enhanced workplace conditions and skill development (Goyal et al., 2021). However, assessing CE's environmental benefits requires a holistic, global perspective (Korhonen et al., 2018). CE strategies often introduce unintended consequences, as they demand additional resources and infrastructure, such as spare parts availability and new logistics networks (Font Vivanco et al., 2022; Morsetto, 2020). Moreover, implementation challenges exist at multiple levels—policy, organizational, and consumer—adding complexity to CE adoption (Corvellec et al., 2022).

The circular economy rebound effect (CERE) occurs when increased production or consumption offsets eco-efficiency gains (Zink and Geyer, 2017). Originally discussed in the context of energy efficiency (Jevons, 1865), rebound effects (RE) manifest in three main forms: direct RE, indirect RE, and economy-wide RE (Greening et al., 2000; Sorrell and Dimitropoulos, 2008). A fourth type, the transformational effect, extends RE beyond efficiency to resource use in general (Castro et al., 2022; Giampietro, 2022).

RE arises when efficiency improvements lead to systemic responses that drive increased production and consumption (Lange and Berner, 2022). Even when more efficient machinery or processes reduce energy use per unit of output, the resulting cost savings can stimulate greater overall production and consumption, offsetting environmental benefits. Chen et al. (2021) emphasize that CE evaluation should extend beyond energy savings and job creation, as behavioural changes may undermine anticipated gains. CERE specifically occurs when secondary production does not replace primary production in equal measure, leading to greater overall environmental impact (Zink and Geyer, 2017). Thus, the net sustainability benefits of CE strategies may be lower than expected due to systemic shifts in productivity and consumption (Castro et al., 2022).

Overall, the literature confirms that RE emerges from shifts in production and consumption triggered by efficiency improvements that either free up or constrain scarce resources. These efficiency gains frequently lead to behavioural adaptations that increase consumption, reducing or even negating the intended environmental benefits.

*What are the main mechanisms of CERE?* Giampietro (2022) argued that the RE arises intrinsically within the CE itself. Similarly, Castro et al. (2022) identified key mechanisms that propagate the CERE, categorizing them into initiating, developer, and mitigating mechanisms.

The initiating mechanism acts as a trigger, altering the function or structure of a system and leading to RE. Castro et al. (2022) identified five key triggers: CE strategies, circular transition, innovation, new

business models, and environmental policies. These triggers set off developer mechanisms, which manifest through consumer behaviour, producer behaviour, and macroeconomic responses, further reinforcing RE.

However, the third category, the mitigating mechanism, serves to minimize or counteract CERE. Castro et al. (2022) highlights five key mitigating factors: early detection, environmental policy, sustainable research and development (R&D), price controls, and population motivation. These mechanisms highlight the complex interplay between CE initiatives and unintended economic and behavioural responses, underscoring the need for integrated policies, business models, and early warning tools to mitigate RE within circular systems – as discussed in the next section.

## 2.2 Circular business models and assessment tools

Well-designed circular business models (CBMs) have been shown to reduce environmental impacts significantly (Saha et al., 2024). A critical factor in achieving this is the design phase, where approximately 80-90% of a product's environmental footprint is determined (Das et al., 2023). However, many CBMs are vulnerable to RE, whereby initial gains in resource efficiency led to increased overall consumption. These effects can become embedded as early as the design stage, making it essential to anticipate and address them from the outset to preserve the intended environmental benefits. To mitigate these risks, business model experimentation offers a valuable approach (Bocken et al., 2017). This iterative process involves testing and refining innovations before large-scale implementation, allowing companies to gather data, reduce uncertainties, validate concepts, and make informed decisions (Bocken and Snihur, 2020; Konietzko et al., 2020). However, studies (e.g., Das et al., 2023) indicate that companies often use overly simplistic methods when assessing environmental impacts during the design phase, leading to inaccurate predictions. This oversight can make rebound effects more likely when scaled models are implemented. Thus, incorporating comprehensive environmental assessments during the initial design of CBMs is critical to prevent such unintended consequences.

Bailey et al. (2022) highlight ex-ante and ex-post tools that CBMs can use to evaluate the environmental effect. Ex-ante tools enable innovators to estimate the potential environmental impacts of their concepts before implementation, allowing for adjustments during the planning stages (Kravchenko et al., 2019). Conversely, ex-post tools assess the environmental outcomes after implementing a strategy. The systematic reviews by Lowe et al. (2024) and Zerbino (2022) provide a comprehensive review of various methods used across different economic levels—micro, meso, macro, and global—highlighting the prevalence various approaches in RE estimation. Their analyses emphasised the importance of understanding the intricate dynamics of REs, from direct and indirect effects to broader economy-wide

impacts. Table 1 delineates the existing estimation methods and their application across economic levels. (Please refer to Lowe et al. and Zerbino for specific references supporting this table.)

Building on this literature, our study is the first to shift the focus toward CE technology improvements in the textiles and clothing (TC) sector, addressing a critical gap in understanding how circular strategies influence broader economic and environmental dynamics.

**Table 1: CERE assessment tools**

<b>Tool/Method</b>	<b>Description</b>	<b>Micro Level</b>	<b>Meso Level</b>	<b>Macro Level</b>
<b>Life Cycle Analysis (LCA)/Materials Flow Analysis (MFA)</b>	Uses traditional environmental Assessment methods to estimate rebound effects (RE), focusing on the lifecycle stages of products and materials.	Evaluates product-specific environmental Impacts, such as the effect of reuse or recycling on resource consumption.	Assesses the collective impact of circular Practices within a regional or sectoral context.	Applies LCA/MFA to national or global Supply chains.
<b>Macroeconomic Models</b>	Includes CGE, Input-Output Analysis (I-O), and Stock-Flow Consistent (SFC) frameworks to simulate economy-wide impacts.	Rarely used at the micro level due to the complexity of macroeconomic modelling.	Analyses the ripple effects of CE practices across industries or regions.	Simulates the economy-wide impacts of circular strategies, including rebound effects.
<b>Elasticity Parameter Estimates</b>	Focuses on determining elasticity parameters that influence RE mechanisms through empirical methods.	Estimates consumer responsiveness to price changes and efficiency improvements.	Examines regional elasticity to understand how changes in circular practices influence demand and consumption patterns.	Models how national or global demand changes in response to efficiency improvements, influencing overall resource consumption.
<b>Econometric</b>	Utilises advanced statistical methods to analyse the determinants of RE, formulating and testing hypotheses on circular practices and consumption behaviours.	Analyses individual or household-level behaviour changes due to circular practices.	Investigates sector-specific consumption changes and their impact on regional markets.	Examines national-level consumption and production shifts due to CE practices.
<b>System Dynamics (SD) and Simulation</b>	Uses simulation models based on dynamic economic frameworks to estimate potential rebound effects over time.	Models the impact of circular innovations on product demand and use patterns over time.	Simulates sector-wide dynamics, such as the impact of new circular strategies on resource flows.	Analyses complex interactions between economic sectors and their response to circular policies.
<b>Hybrid Approaches</b>	Combines methods from different categories to provide a more comprehensive assessment of CER effects.	Integrates LCA with econometric or agent-based models.	Uses I-O analysis alongside econometric models to assess cross-industry impacts.	Blends CGE models with LCA data for a holistic view.
<b>Miscellaneous</b>	Includes methods that do not fit neatly into the other categories,	Field tests for product-specific rebound effects, such as real-world energy use	Unique case studies of sectoral rebounds that do not rely on	Case studies of national policies' unintended consequences, such as the impact of specific

Tool/Method	Description	Micro Level	Meso Level	Macro Level
	such as field tests or unique case studies.	comparisons for efficiency measures.	standardised models.	regulations on circular consumption patterns.

Source: authors' elaboration of Lowe et al. (2024) and Zerbino (2022) review of CERE assessment tools

However, these tools are often underutilised in practice, as many are developed within academic contexts without direct input from their intended users. Such tools also require detailed life cycle analysis data that are often unavailable to CBM developers (Das et al., 2023), making it challenging to predict how a product will perform in the use phase or how consumer behaviour might change with the introduction of the new CBM.

Our study identifies key areas for future research on CERE. First, developing models, methods, and standardized metrics is essential for quantifying RE within CE initiatives and guiding policy. Second, policy-oriented tools must enable measurement, detection, prevention, and mitigation of RE to ensure CE strategies deliver sustainability gains (Laurenti et al., 2016). Third, deeper analysis of technology's dual role is needed, as it can enhance efficiency while also triggering unintended rebounds. Finally, the social and behavioural dimensions of CE adoption require further study, as consumer behaviour influences whether CE strategies reduce environmental impact or drive additional consumption. These priorities inform our modelling approach, which applies a dynamic computable general equilibrium (DCGE) framework—a macroeconomic model summarized in Table 1—to assess the broader economic and environmental implications of CE policies.

DCGE modelling is a powerful tool for assessing CERE, as it captures economy-wide interactions within a systemic structural framework. It simulates how efficiency gains or shifts in material use propagate across sectors, shaping economic activity, resource use, and environmental outcomes. By modelling complex, interlinked interactions among multiple economic actors, it quantifies ripple effects across industries and regions, capturing systemic impacts on production, consumption, trade, and feedback loops that drive rebound effects. Additionally, DCGE modelling excels in “What if?” analyses, enabling the simulation of potential changes before they occur. In contrast, econometric analysis relies on historical data, limiting its ability to assess future scenarios and dynamic adjustments.

So far, existing CGE studies on REs have largely focused on energy efficiency as the primary driver of change. Huang et al. (2023) provide a review of CGE models that assessed REs from energy efficiency improvements. Specifically, Skelton et al. (2020) examines REs in the automotive sector, Wei and Liu (2017) estimate global energy-related REs, and Allan et al. (2007) assess REs within the UK economy. A related macroeconomic model

### 3 The rebound effect measured: an analytical framework

In this paper, we follow Saunders (2000), Wei (2010) and Wei and Liu (2017) in defining the Rebound Effect (RE) as the level of correspondence between technological efficiency gains and production growth. Focusing on the textiles and clothing (TC) sector, we define global welfare  $Y$  as the sum of all production sectors  $i$ , and across region  $r$

$$Y = \sum_{ir} Y_{ir} = \sum_{ir} f_i(L_i, K_i, Y_{ji}, \tau C_i) \quad (1)$$

where  $C \in Y$  represents the TC sector among all other sectors. In each sector  $i$ ,  $L_i, K_i$  denote labour and capital inputs, with  $Y_{ji}$  representing other intermediate inputs in the production excluding TC (with  $j$  alias to  $i$ ). Additionally,  $C_i$  captures intermediate inputs of textiles and clothing (TC) used as intermediate inputs in sector  $i$ , such as fabric for sails, tents, or clothing. Finally, to model circular economy technology improvements,  $\tau$  is a Harrod-neutral technology parameter, applied to clothing intermediate inputs across all sectors (Acemoglu, 2009).<sup>4</sup>

In the global economy, the market equilibrium of clothing production equals its use. We thus can define  $\eta$  as the elasticity between the change in clothing use  $C$  and TC technology improvements  $\tau$

$$\eta = \frac{dC}{C} / \frac{d\tau}{\tau} \quad (2)$$

and the rebound effect  $RE$  is

$$RE = 1 + \eta \quad (3)$$

For example, a *zero*-rebound effect ( $RE = 0$ ) happens when the change in use of  $C$  falls by the same rate as its gain in technology efficiency. As summarized in Table 2, by this definition, we have five different types of rebound effects: Backfire, Full, Partial, Zero, and Super Conservative.

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<sup>4</sup> In the applied (calibrated) model, we also incorporate a Hick-neutral total factor productivity parameter (Acemoglu, 2009). This parameter, however, plays no role in our analysis and is the same in both baseline and all counterfactuals scenarios. Its purpose is to calibrate the model to a baseline project – as discussed in Section 0.

**Table 2: Five types of rebound effects**

Description	Elasticity	Rebound Effect	Definition
Backfire	$\eta > 0$	and $RE > 1$	Clothing use rises even higher despite improvements in efficiency.
Full rebound	$\eta = 0$	and $RE = 1$	Clothing use remains unchanged despite technological advancements.
Partial rebound	$-1 < \eta < 0$	and $0 < RE < 1$	Clothing use decreases, but not at the same rate as the technological improvements.
Zero rebound	$\eta = -1$	and $RE = 0$	Clothing use decreases exactly at the same rate as technological improvements.
Super conservation	$\eta < -1$	and $RE < 0$	Clothing use declines faster than the gains in technology.

### 3.1 The economy-wide model

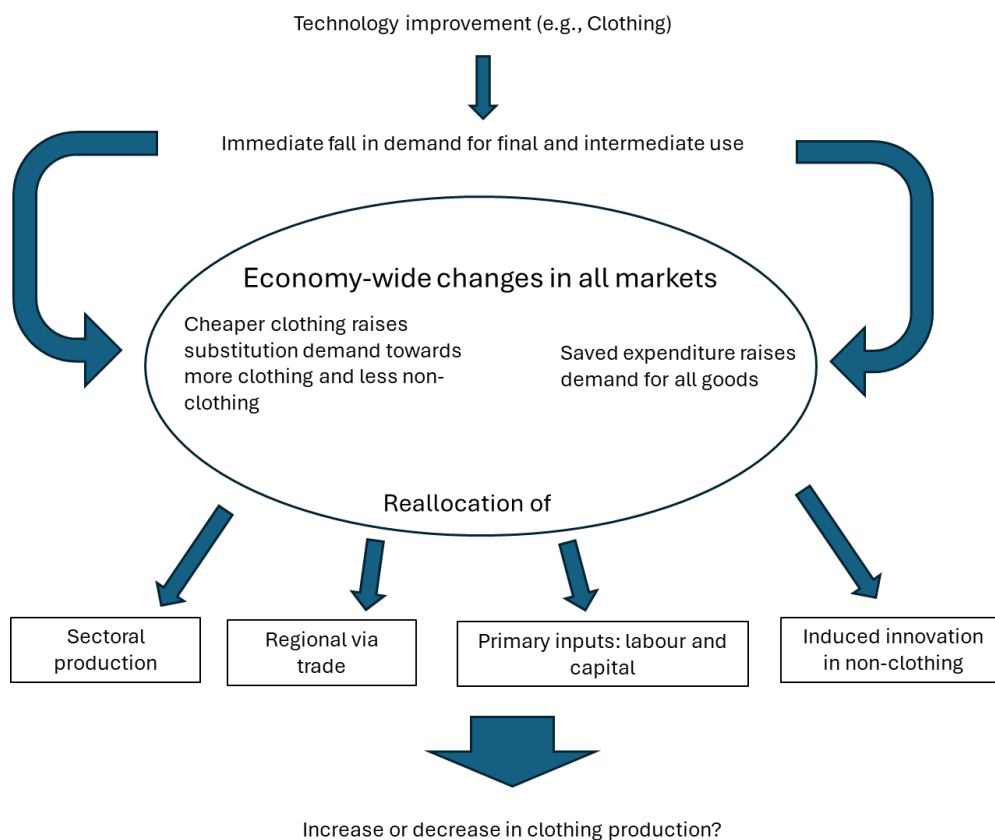
To quantify the RE, we employ a Dynamic Computable General Equilibrium (DCGE) model that simulates how CE innovations in the TC sector propagate through the economy, influencing key parameters such as prices, output, consumption, and trade via feedback loops. The model accounts for long-term effects, recognizing that RE evolves as markets and technologies adapt. It also aggregates micro-level dynamics to provide a global assessment of RE.

We simulate two counterfactual (“What if?”) scenarios that diverge from current economic conditions and are absent from existing datasets, making econometric and statistical methods unsuitable. Our primary simulation examines the adoption of CE innovations and quantifies its RE impact, while an extension explores a Pigouvian tax aimed at mitigating RE, offering insights into future policy design for achieving genuine environmental benefits.

Figure 1 illustrates the mechanisms driving RE. TC technology improvements reduce demand for final and intermediate goods, lowering their effective price across the supply chain. This triggers two key effects: (1) lower demand leads to cheaper TC, and (2) consumers and producers save costs while maintaining consumption levels. These shifts influence behaviour through: (i) the substitution effect, where cheaper clothing incentivizes higher consumption of more TC over other goods, and (ii) the income effect, where savings increase overall spending on all goods (i.e., TC and others).

These behavioural adjustments drive demand-supply shifts and price fluctuations across markets, prompting an economy-wide response: production activities adjust, resources reallocate across sectors and regions, innovation accelerates to adapt to improved TC efficiency, and the effective supply of labour and capital increases. Consequently, total TC consumption and associated carbon-equivalent emissions deviate from the original baseline.

**Figure 1: The mechanism of economy-wide circular economy rebound effect**



Two limitations warrant consideration. First, we introduce the technological improvements ( $\tau$ ) without a micro-founded framework to support its value. However, our sensitivity analysis shows that varying  $\tau$  has a stable effect on quantifying RE, suggesting this assumption does not significantly alter outcomes. Future research could refine  $\tau$  using a micro-founded resource flow model, as proposed by Figge and Thorpe (2019).

More critically, a rebound effect  $RE > 0$  indicates a rise in production, which, under the assumption of a fixed production-to-emissions ratio, implies a corresponding increase in carbon-equivalent emissions. While technological advancements could potentially decouple emissions from production, our model does not capture these dynamics. Specifically, we do not incorporate a micro-founded framework linking technological improvements to reductions in pollution intensity, leaving this for future research.

## 3.2 Model setup and calibration

We adapt a multi-region, multi-sector, recursive dynamic CGE model (Hafner et al., 2023, 2020) with Pigouvian Tax (Yerushalmi and Ziv, 2025). The model is programmed in GAMS<sup>5</sup> with MPSGE (Rutherford, 1999). Below we provide an overall description of the model.<sup>6</sup>

The simulated production follows a constant return to scale (CRS) function described in equation (1), utilising multi-level constant elasticity of substitution (CES) functions for production and consumption – standard to CGE models. The modelled economy is aggregated into seven geographic regions (summarized in Table 3), each functioning as an open economy interconnected through Armington trade links enabling the exchange of goods and services (Armington, 1969). Region-specific imports serve as intermediate inputs for production, or as final private or public consumption and investment. Within this framework, producers maximize profits, consumers maximize utility, and regional governments collect taxes to fund public services. The model employs a recursive-dynamic approach, capturing long-term economic adjustments.<sup>7</sup> Additional model details are provided in the online supplementary appendix.

**Table 3: Model regions**

	<b>Region name</b>	<b>Region acronym</b>
1	East Asia Pacific	EAP
2	South Asia	SA
3	North America	NorthA
4	Latin America and Caribbean	LAC
5	Europe and Central Asia	ECA
6	Middle East and North Africa	MENA
7	Sub-Saharan Africa	SSA

The model is calibrated to the latest 2017 base year using the Global Trade Analysis Project (GTAP) V11 database (Purdue University, 2023). Each region includes six main production sectors (outlined in Table 3), interlinked through an input-output matrix that captures their supply chain structure. Our analysis focuses specifically on sector 3: Textile and Clothing.

Baseline economic growth is driven by population dynamics, savings-investment, and technological change. Labour supply is updated exogenously, based on the medium fertility variant working-age

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<sup>5</sup> <https://www.gams.com/>

<sup>6</sup> See also Lanz and Rutherford (2016) that provide a technically rigorous documentation with GAMS code.

<sup>7</sup> Regional households make consumption-investment decisions to maximize their welfare based on past states of the economy only, implying that the role of expectation is limited. Lecca et al., (2013) discuss the different advantages and disadvantages of using a fully-forward looking versus a recursive approach.

population projections (ages 15-65 years) from the United Nations World Population Prospects (United Nations, 2024). This approach assumes no endogenous migration between regions, though labour is mobile across sectors within each region. Consequently, regional labour supply remains wage-inelastic in our model.

**Table 4: Sectorial aggregation**

	Sector	Description
1	Agriculture	Includes crops like grains, fruits, vegetables, oilseeds, spices, and forestry products, as well as livestock, dairy, aquaculture, fishing, and animal-based material processing.
2	Textile & Clothing	Wool, silk-worm cocoons and the manufacture of textiles and wearing apparel
3	Industry	All industrial sectors excluding clothing, food production and leather
4	Food production	Includes fresh, frozen, and processed meats, vegetable oils, dairy, rice, sugar, prepared foods, cereals, bakery products, beverages, tobacco, and animal or plant-based food derivatives.
5	Leather	Manufacture of leather and related products
6	Services	All services

Note: The table provides the model's sector aggregation based on the 65 sector GTAP11 database (Purdue University, 2023).

Capital accumulation follows standard endogenous adjustment assumption, where old capital depreciates while new investment replenishes the stock. Investment is allocated across geographic zones based on zone-specific internal rates of return, reflecting regional risk-return trade-offs in consumption and saving behaviour. Key parameters, including depreciation rates and total factor productivity (TFP) at the country level, are sourced from the PENN World Table 10.03 and aggregated by geographic zones. Finally, the baseline model is calibrated to align with regional GDP projections with “middle of the road” projections from the Shared Socioeconomic Pathways 2 (SSP2) (Cuaresma, 2017) and PWC (2017). These baseline parameters remain unchanged across all scenarios.

### 3.3 Scenarios

To study the impact of technology improvement, we consider alternative scenarios and assess the rebound effect (RE) in 2045. Defining  $sc = 0$  as a baseline, the change in level of CE technology is normalized to  $\tau = 0$ . In the counterfactual scenarios  $sc \neq 0$ , we assume that  $\tau$  rises by a % above the baseline. We test hypothetical technology improvements of 5%, 10%, 20% to assess the responsiveness of the model to these values.

To assess the role of labour and capital in the RE, we simulate two scenarios: Short-Run and Long-Run. In the Short-Run, clothing technology improvements are implemented instantly in 2045, with all other factors held constant. In the Long-Run, technological advancements occur gradually, reaching the final improvement level by 2045. For example, we assume a 0.4% annual growth rate over 25 years,

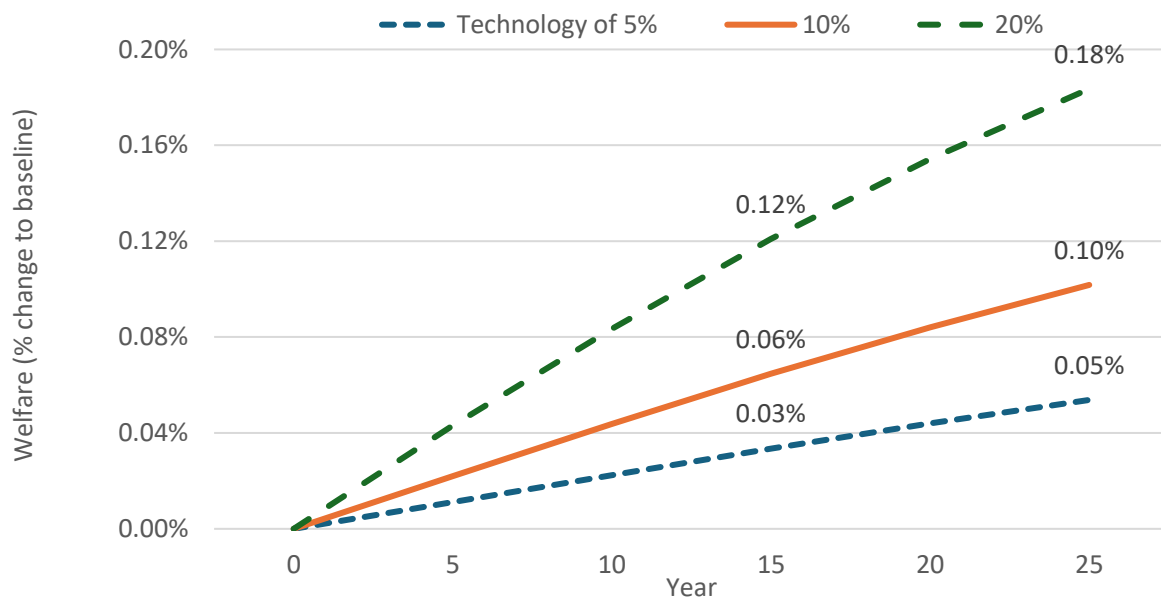
resulting in a 10% technology improvement above baseline, an approach consistent with Wei and Liu (2017) in their study on energy efficiency.

Additionally, in the policy extension (Section 5.1), we simulate a scenario incorporating a Pigouvian tax, designed to maintain RE at 1 or below, achieving either full or partial rebound mitigation.

## 4 Results

As expected, technological improvements enhance global and regional welfare, measured by economic consumption expenditure. Figure 2 presents the percentage increase in welfare relative to the baseline for long-run scenarios, where technology ( $\tau$ ) improves by 5%, 10%, and 20% over 25 years.<sup>8</sup>

**Figure 2: Change in global welfare relative to the baseline project (% , Long-Run Scenario)**

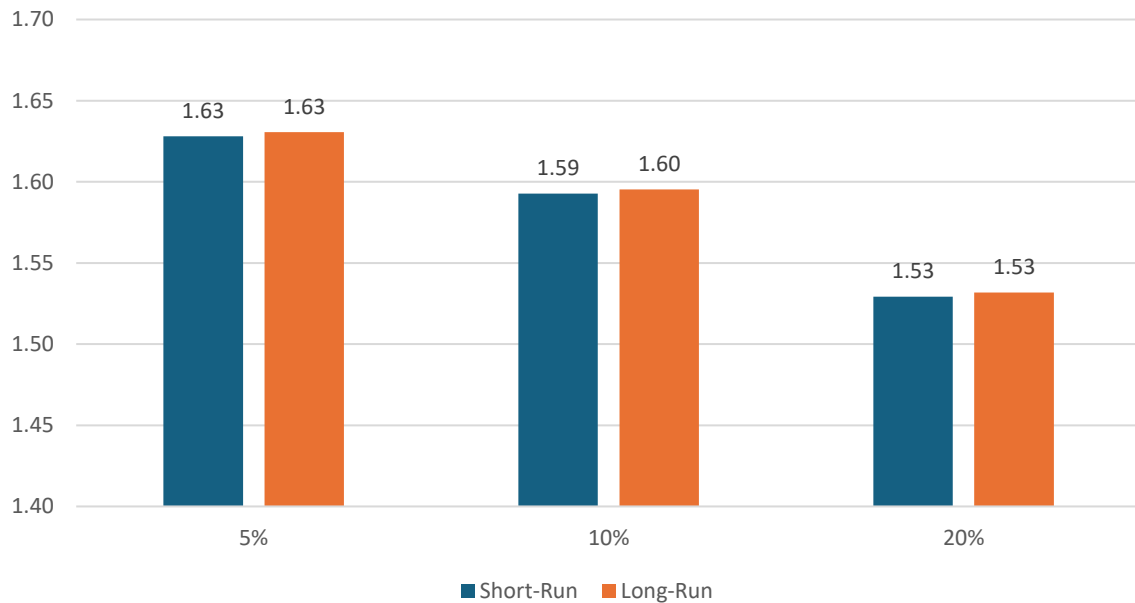


We next quantify the rebound effect (RE) driven by technological advancements in the textile and clothing (TC) industry. As shown in Figure 3, when  $\tau > 0$ , global RE is projected to significantly *backfire*, ranging between 1.5 and 1.6, depending on the scale of technological change. Notably, RE remains stable at approximately 1.55, regardless of the magnitude of technological improvement ( $\tau = 5\%$  to 20%) or whether changes occur in the Short-Run or Long-Run scenarios.

<sup>8</sup> The welfare projection in the Short-Run scenario is less insightful, as it reflects a single welfare improvement (jump) at the final projection year, with no variation from the baseline in preceding years.

This stability arises because RE is measured as an elasticity—the ratio of the percentage change in TC production to the percentage change in technological improvement. Despite the model’s nonlinearities, both variables increase proportionally across simulations, maintaining a consistent RE.

**Figure 3: Global rebound effect in the clothing sector across different levels of technological improvement**

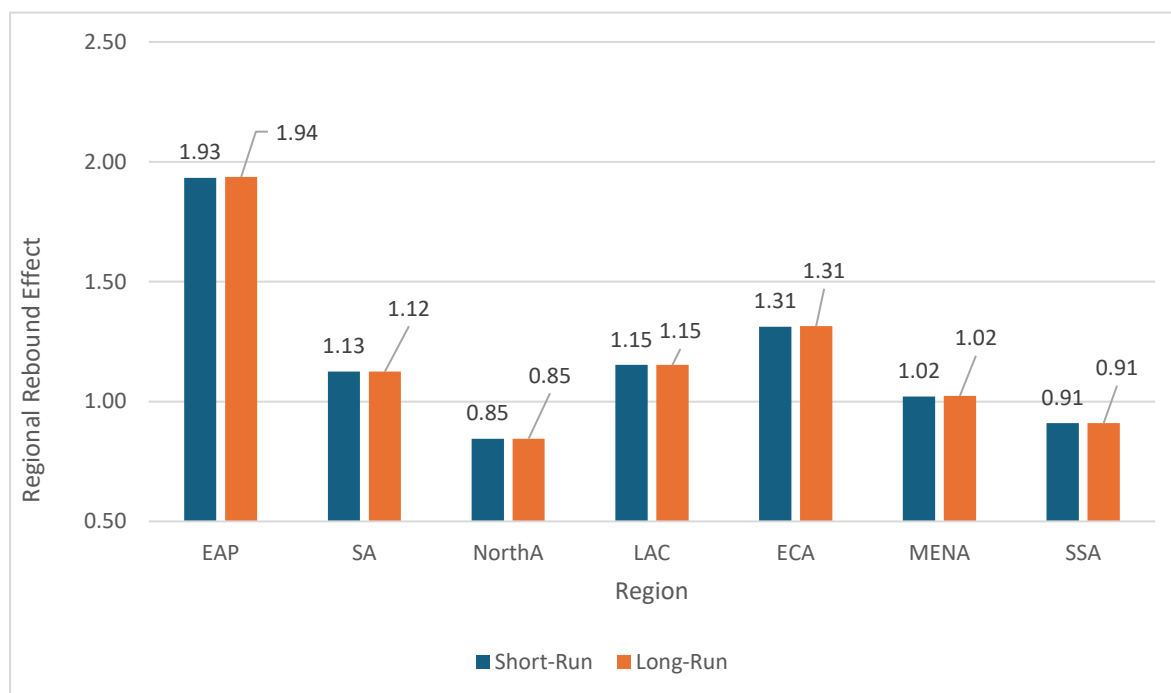


Furthermore, consistent with Wei and Liu (2017), we find that the Short-Run scenario is more conservative than the Long-Run scenario, though the difference is modest. In both cases, labour inputs are regionally fixed but can reallocate freely across sectors. In the Short-Run, only labour adjusts, while capital remains fixed, allowing for some shifts in marginal value without overall labour growth. This reallocation partially mitigates the rebound effect by shifting labour away from clothing-intensive sectors, limiting backfire. In the Long-Run scenario, capital accumulates over time, and efficiency improvements happen gradually, enabling greater economic adjustments. These dynamic responses enhance the utilization of efficiency gains, leading to a higher rebound effect than in the static Short-Run scenario.

Notable regional disparities exist in the Backfire RE, as illustrated in Figure 4. East Asia and Pacific (EAP), Latin America and the Caribbean (LAC), and Europe and Central Asia (ECA) are the largest contributors to global Backfire RE, exhibiting values well above 1. In contrast, North America (NorthA) and Sub-Saharan Africa (SSA) display a Partial RE, with values below 1, indicating more limited rebound effects. Meanwhile, South Asia (SA) and the Middle East and North Africa (MENA) experience a Full RE, where

RE approaches 1, suggesting that efficiency gains translate almost entirely into increased production and consumption.

**Figure 4: Regional Rebound Effect (10% technology improvement)**



Note: East Asia Pacific (EAP), South Asia (SA), North America (NorthA), Latin America and Caribbean (LAC), Europe and Central Asia (ECA), Middle East and North Africa (MENA) and Sub-Saharan Africa (SSA).

*What drives this regional variation in rebound effects?* The model simplifies real-world dynamics, applying identical functional forms across all regions, with differences arising from deep parameters calibrated using the global Social Accounting Matrix (SAM) (Section 3.2). Regions with clothing-intensive industries or large industrial sectors experience higher rebound effects, whereas those dominated by less clothing-intensive sectors see lower effects. Table 5 illustrates this disparity, showing a TC-adjusted direct impact factor of 1.6% for East Asia and Pacific (EAP) compared to just 0.2% in North America. The table is constructed by calculating clothing’s share as an intermediate input, weighted by its sectoral contribution to total production. Technological improvements amplify the economy both directly—through higher production—and indirectly, via spillover effects (e.g., income shifts, consumption changes, and trade flows), which the general equilibrium model captures.

Additional factors shape regional rebound effects, operating both directly and indirectly. Demand for domestic vs. traded clothing varies, with higher demand amplifying resource use and RE. Labor mobility influences production costs, as some regions reallocate labour between clothing and non-clothing sectors, affecting RE intensity. Lower clothing prices can drive stronger rebound effects, while differences in substitution elasticities across labour, capital, and intermediate inputs affect regional

adaptation to efficiency gains. Capital stock and investment levels also matter—regions with higher capital accumulation are better positioned to exploit efficiency improvements, potentially amplifying rebound effects. Finally, policy and regulatory frameworks, including environmental regulations, shape how efficiency gains translate into economic adjustments and the scale of RE. While these policy mechanisms are not explicitly modelled, they are explored through the Pigouvian tax scenario (next section).

**Table 5: Adjusted impact factor of clothing**

	East Asia Pacific (EAP)			North America (NorthA)		
	Textiles & Clothing as intermediate input in production, %	Weight of sector production from total, %	Adjusted impact factor	% clothing as intermediate input in production	% production of total production	Adjusted impact factor
Agriculture	0.1%	3.8%	0.0%	0.1%	1.5%	0.0%
Textiles and Clothing Apparel	44.4%	2.6%	1.1%	20.8%	0.3%	0.1%
Industry*	0.5%	50.6%	0.3%	0.3%	28.2%	0.1%
Services	0.5%	42.9%	0.2%	0.1%	70.1%	0.1%
Total adjusted impact factor			<b>1.6%</b>			<b>0.2%</b>

Source: Author’s calculations (rearrangement) based on the GTAP 11 SAM. \*Industry includes Food processing and Leather. The table presents TC's share as an intermediate input in total sector production, the sector’s contribution to overall economic output, and the adjusted impact of TC on the economy.

## 5 Discussion

Our systematic literature review (SLR) found limited research on the rebound effect (RE) in the textile and clothing (TC) sector for direct comparison. However, our findings align with studies in ecological and energy economics warning that CE innovations can drive increased consumption and waste without regulatory controls (Castro et al., 2022; Jia et al., 2020; Manolchev et al., 2024; Saha et al., 2024; Siderius and Poldner, 2021). We challenge the assumption that CE inherently promotes economic growth, sustainability, and equity, consistent with Saha et al. (2021), who find that most CE strategies in TC benefit only two of these three dimensions.

This study contributes to the debate by calling for critical research on the trade-offs, tensions, and paradoxes within CE strategies, particularly in balancing economic and environmental objectives. We emphasize the need for methodologies such as Life Cycle Assessment (LCA) and a deeper examination of the rebound effect's role in eco-efficiency initiatives.

This research broadens the scope of traditional RE studies by incorporating systemic and behavioural dimensions within CE transitions, going beyond the traditional focus on energy efficiency. It also introduces a novel framework for quantifying regional disparities in rebound effects, demonstrating how variations in production inputs and market structures shape different outcomes. We seek to

refine, rather than challenge, the assumption that technological efficiency improvements are inherently sustainable. By advancing RE theory, we highlight the importance of integrating socio-economic and behavioural factors into evaluations of CE innovations.

Our findings reveal two critical flaws. First, efficiency gains do not necessarily translate into reduced environmental impact. This view aligns with de Man (2022), who highlights that the CE's reliance on technological solutions often overlooks thermodynamic realities and systemic socio-economic behaviours. Challenges such as energy costs, material degradation, and rebound effects from sustainability marketing undermine the promise of 'closing the loop' through recycling and reuse. This is evident in H&M's Annual and Sustainability Report 2024<sup>9</sup> showing that despite extensive circularity initiatives—including investments in resale platforms, textile sorting ventures, and lab-grown cotton startups—less than 1% of its 2024 revenue stemmed from circular business models.

Second, circular strategies often drive market expansion, as recycled or sustainable products are marketed as guilt-free options (Spash, 2022), encouraging consumption growth rather than reduction. The European Environment Agency's current report on the textile value chain circularity<sup>10</sup> reveals a stark reality: despite major fashion retailers (like H&M) promoting circularity, average EU consumption of clothing, footwear, and household textiles increased from 17kg per person in 2019 to 19kg in 2022. This paradox of consumption is a clear case of rebound effect and is consistent with critiques, e.g., Lehmann et al. (2022).

Moreover, widely cited claims that the fashion industry loses over \$500 billion<sup>11</sup> annually due to underutilisation and lack of recycling have been challenged by critics such as Hussain (2025), stating that these figures are often based on speculative calculations that assume full recyclability and resale potential of all garments, ignoring the material, logistical, and behavioural barriers that inhibit circularity.

From these emerging insights, we conclude that the circular economy, when pursued within a fast-fashion business model, encounters a strong push towards rebound effect and requires regulatory intervention. Therefore, we discuss conventional solutions in section 5.1 and more transformative strategies in section 5.2.

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<sup>9</sup> <https://hmgroupp.com/investors/annual-and-sustainability-report/>

<sup>10</sup> <https://www.eea.europa.eu/en/analysis/publications/circularity-of-the-eu-textiles-value-chain-in-numbers>

<sup>11</sup> See pg.8 of the *UK House of Commons Environmental Audit Committee. (2019). Fixing Fashion: clothing consumption and sustainability. Available at: https://publications.parliament.uk/pa/cm201719/cmselect/cmenvaud/1952/1952.pdf*

## 5.1 ‘Conventional’ solutions to mitigate RE

*What policy measures can effectively mitigate the rebound effect?* Conventional approaches that align with environmental and ecological goals focus on curbing overproduction driven by market expansion and efficiency gains. These include policies such as production and consumption caps, resource extraction quotas, and restrictions on production volumes—policies that our economy-wide model is well-designed to simulate. Additionally, the introduction of tradable rights markets could achieve similar outcomes indirectly through market mechanisms (Sandmo, 2000), a scenario we can also model.

Another widely discussed approach is the implementation of Pigouvian taxes, which target activities that generate negative externalities, such as pollution. By aligning private costs with broader societal impacts, these taxes increase the cost of environmentally harmful behaviours. As a result, they incentivise individuals and firms to internalise these externalities, adopt more sustainable innovations, and ultimately reduce their environmental footprint.

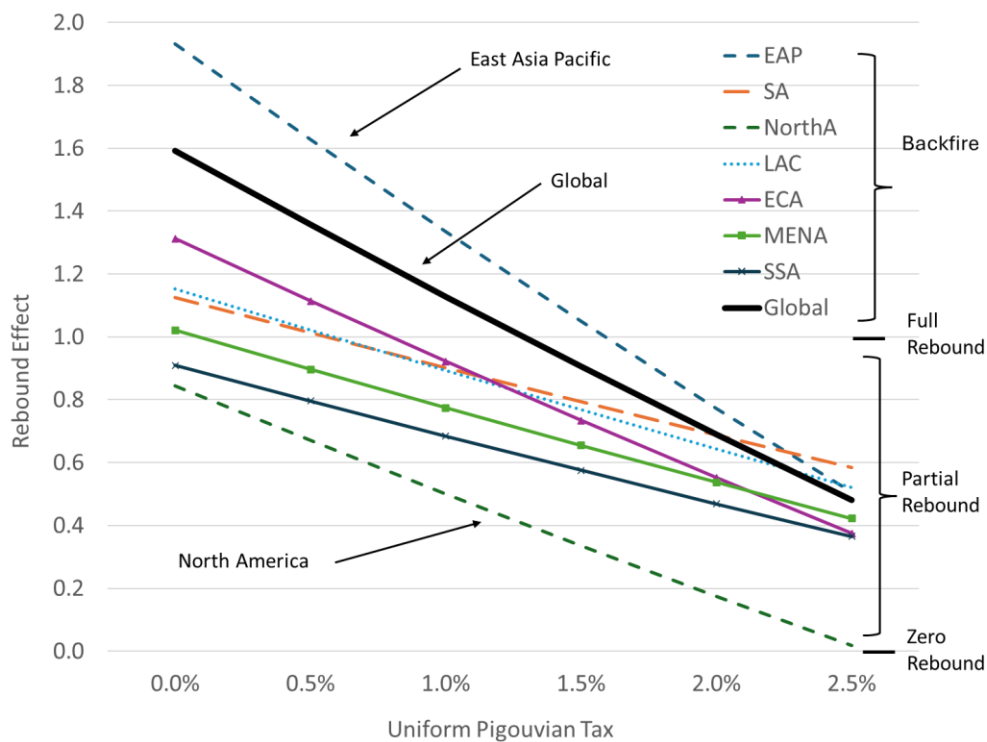
As an example, we experiment with a Uniform Pigouvian Tax on clothing sector production, with revenues redistributed to regional households. While a uniform tax represents a feasible second-best policy, a first-best approach would involve differentiated taxes and subsidies based on pollution intensity and regional RE levels. However, practical policymaking must balance environmental goals with considerations like employment, economic growth, and regional equity, which fall outside the scope of this study. The challenges of international coordination, as seen in the limited progress of the Conference of the Parties (COP) under the UNFCCC, underscore the difficulties of implementing such policies.

First, we vary uniform Pigouvian tax levels under a 10% technological improvement in TC within the short-run scenario.<sup>12</sup> Figure 5 shows the relationship between the tax rate and RE reduction. The model indicates that a 1.25% tax on TC production fully offsets the rebound effect globally (RE = 1) and a 2.5% tax promotes a partial reduction (RE < 1). Overall, the tax appears relatively modest.

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<sup>12</sup> We focus on the Short-Run scenario because it is more conservative - as discussed - and involve fewer assumptions. The Long-Run scenario would require additional assumptions regarding the timing and magnitude of tax implementation over the 25-year model projection period.

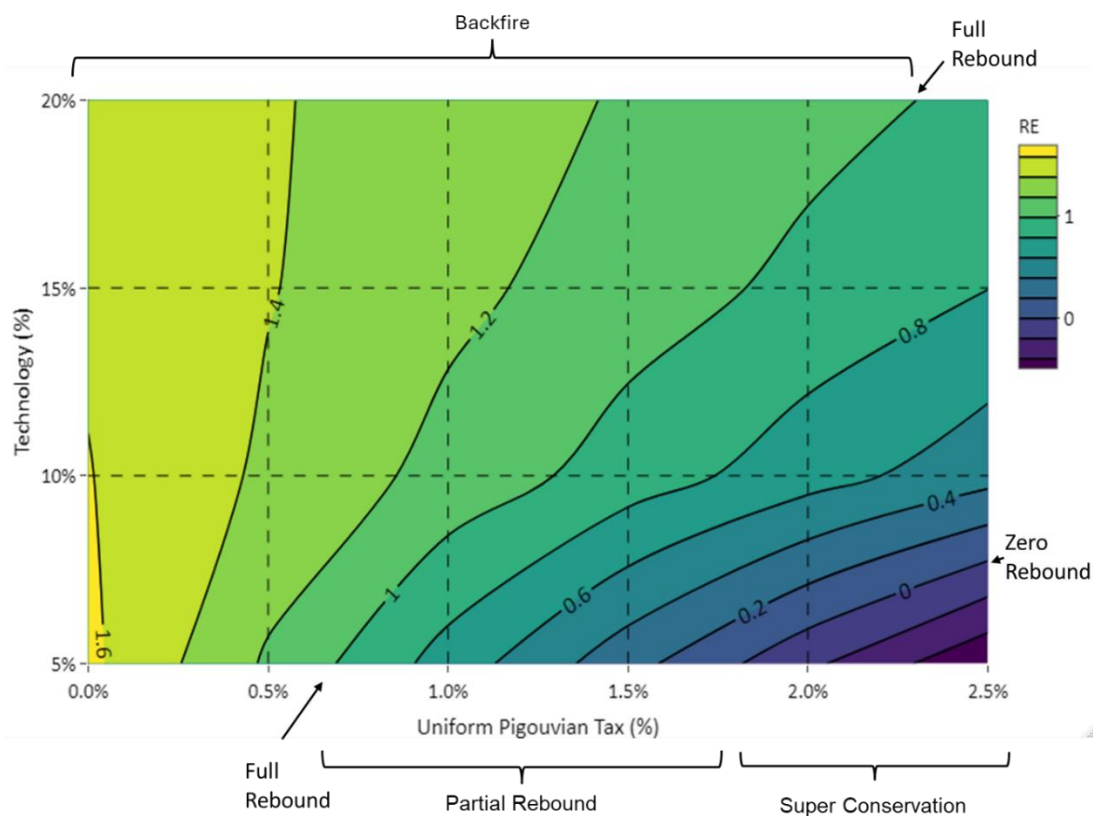
**Figure 5: Rebound Effect falls as a Pigouvian Tax rise (10% technology)**



The figure shows the gradual reduction in RE as the Uniform Pigouvian Tax rises. Here the model assumes technology innovation  $\tau = 10\%$  for a short-run scenario framework.

Second, our structural model enables the analysis of varying levels of a Uniform Pigouvian Tax and technological improvements, allowing us to generate a contour plot of the RE—a useful method for visualizing three dimensions in a two-dimensional chart. Figure 6 shows an upward-sloping contour plot of the RE, indicating that higher technological improvements require correspondingly higher Pigouvian tax rates to maintain the same RE level. Similarly, for a given level of technology, higher tax rates lead to a lower RE.

**Figure 6: Global Rebound Effect Contour plot**



The figure presents the contour plots of RE across technology innovation levels and a uniform Pigouvian tax. The upward-sloping contours indicate that higher innovation requires a higher tax to manage the RE.

## 5.2 Beyond the Limits of Circular Economy: The Case for Embracing Degrowth

*Can we go beyond 'conventional' policies?* CE was hailed as one solution. But given its limitations in addressing systemic challenges in resource-intensive industries like TC, insights from Degrowth literature (including the low-growth and steady-state economy) offer valuable guidance for reshaping sustainability efforts. Degrowth scholars, such as Lawn (2005), emphasise that the inherent conflict between economic growth and ecological sustainability necessitates a departure from growth-oriented economic models. For the TC sector, this would mean transitioning from focusing on recycling and efficiency gains to reducing production and consumption altogether—a core tenet of degrowth.

A transition from efficiency to sufficiency represents a critical pathway highlighted in degrowth literature (Daly, 1994; Farley, 2014; Jackson, 2019). While efficiency improvements often result in rebound effects—where cost savings drive increased consumption and production—sufficiency-oriented policies emphasize reducing resource use and waste generation. Such policies could include

limiting fast fashion cycles, promoting durable garments, and encouraging sustainable consumption patterns. Lawn (2005) and Kallis et al. (2018) argue that true sustainability requires addressing the root causes of overuse and waste, particularly growth-dependent economic structures.

We mentioned the main 'conventional' policies that could mitigate RE and simulate one experiment, among many, that our economy-wide model can test. However, these approaches operate within the framework of the current "economic order," relying on command-and-control approach. This raises a critical question: *can an entirely new system be envisioned to achieve sustainability beyond these paradigms?*

Behavioural change is crucial: Degrowth requires cultural shifts toward minimalism, reuse, and value-driven consumption, rather than constant acquisition (Jackson, 2019). For the TC sector, this could involve campaigns promoting reduced consumption and repairability, alongside policies that support systemic shifts in consumer behaviour. However, such policies may be unpopular, particularly in countries where the TC sector is vital for economic stability and employment. In developing economies like Bangladesh, the TC sector is a major source of export revenue and a key employer, especially for low-income and marginalized groups (Saha et al., 2021). Policies aimed at reducing production and consumption—such as production caps, resource quotas, or restrictions on fast fashion—could disrupt the economic balance in these countries, leading to unemployment, lower incomes, and social unrest. This would intensify the conflict between global environmental goals and the socio-economic realities of these nations. As a result, policymakers, industry leaders, and workers are likely to oppose such measures, fearing economic decline and social instability.

Additionally, degrowth policies conflict with the profit-driven motives of global fashion brands and manufacturers. The TC value chain relies heavily on economies of scale, meaning reductions in production could create inefficiencies, diminish global competitiveness, and undermine the profitability of international brands. Transitioning to degrowth may also require substantial investment in alternative production models, potentially disrupting supply chains and increasing operational costs—an unappealing prospect for stakeholders focused on short-term financial gains.

A combination of solutions is needed to address these challenges and align degrowth strategies with economic and social realities. First, degrowth policies must be paired with robust social safety nets, such as universal basic income or unemployment benefits, to shield vulnerable populations engaged in the TC value chain from economic shocks. Investments in skills development and workforce retraining can also help workers transition from resource-intensive sectors like TC to more sustainable industries.

International brands, governments and industry leaders should incentivise innovation and investment in sustainable production systems, such as circular supply chains, small-scale localised manufacturing, and garment repair and upcycling models. France’s pioneering €154 million repair fund certifies professionals and serves as a prime example of how such initiatives can be effectively implemented to encourage consumers to mend damaged clothing instead of discarding them.<sup>13</sup> Furthermore, collaboration between governments, brands, and NGOs can foster public-private partnerships to support these transitions, mitigating supply chain disruptions and cost increases. Organisations like the Waste and Resources Action Programme<sup>14</sup> play a pivotal role in such partnerships by providing data, resources, and actionable strategies to reduce clothing waste and promote sustainable consumption.

Lastly, international cooperation is essential to reduce the burden on producer nations. High-income countries, as major consumers of fast fashion, are responsible for driving behavioural shifts towards sustainable consumption and providing financial and technological support for green innovations in developing economies. For example, initiatives like the Better Cotton Initiative (BCI)<sup>15</sup>, Cascale<sup>16</sup> and Fashion Pact<sup>17</sup> demonstrate how international collaboration can foster sustainable practices in the fashion industry. Trade frameworks, such as the EU-Vietnam Free Trade Agreement<sup>18</sup>, and the African Growth and Opportunity Act (AGOA)<sup>19</sup>, offer opportunities to incentivise eco-friendly production while ensuring equitable market access for sustainably produced goods.

## 6 Conclusion

The circular economy offers a promising framework for industries like textiles and clothing to transition toward sustainability. However, its effectiveness is hindered by the rebound effect—a phenomenon where efficiency gains inadvertently drive higher levels of consumption and production, challenging the notion that technology alone can deliver sustainable outcomes. This paper quantifies the global rebound effect in textiles and clothing at approximately 155%, highlighting a significant

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<sup>13</sup> For example, [read how France launches cash aid for people to repair clothes](#). (Accessed: 3 February 2025.)

<sup>14</sup> <https://www.wrap.ngo/uk>

<sup>15</sup> <https://bettercotton.org/>

<sup>16</sup> <https://cascale.org/>

<sup>17</sup> <https://www.thefashionpact.org/>

<sup>18</sup> <https://trade.ec.europa.eu/doclib/press/index.cfm?id=2044>

<sup>19</sup> <https://agoa.info/>

backfire. In response, degrowth provides a necessary complement to CE, shifting focus from efficiency to reducing overall consumption and production. Yet, degrowth faces political and social resistance, especially in regions where industries like textiles are vital for economic stability and employment. Addressing this requires pairing degrowth strategies with robust social protections, such as income support and skills development, to ensure fairness during transitions. Moreover, promoting international collaboration, reshaping consumption patterns, and integrating degrowth principles into trade frameworks are crucial steps toward achieving sustainability. Recognising and tackling the systemic and behavioural factors driving resource use will be key to shaping a future that balances environmental goals with social equity, particularly within the textile and clothing industry.

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# How Circular Economy Technologies Can Backfire on The Environment: Quantifying the Rebound Effect of The Textiles and Clothing Sector

An online supplementary appendix

This version: April 2025

## 1 Appendix: Systematic Literature Review (SLR) Process

### A. Search Strategy and Sample Selection Criteria

This study adopted a systematic and rigorous search strategy to explore the Circular Economy Rebound Effect (CER) on sustainability, focusing on three central themes: circular economy, rebound effect, and sustainability.

### B. Application of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)

The PRISMA framework guided the study, ensuring precise, reproducible reporting. PRISMA's checklist and flow chart helped establish clear eligibility criteria to include only high-quality and relevant literature.

### C. Identification of Research Samples

The process involved a four-stage methodology: planning, execution, analysis, and reporting.

**Planning:** Defined research objectives and identified Scopus as the primary database.

**Execution:** The process involved selecting relevant keywords and eliminating duplicates using Endnote, followed by screening for relevance and extracting data aligned with the research objectives. Boolean operators were employed in the search query as follows: ("Circular Economy" OR "CE") AND ("Rebound Effect" OR "RE") AND ("Sustainability" OR "Environmental Impact"), ensuring the integration of synonyms and related terms for a comprehensive search.

### D. Inclusion and Exclusion Criteria

To maintain relevance and focus, this study applied the following criteria:

**Inclusion:** Journal articles, conference papers, and reviews published between 2015 and 2023 in English. The review's time frame was selected to ensure a contemporary and precise analysis of the Circular Economy Rebound Effect (CER) within the rapidly evolving TC industry. This period captures the most recent developments in technology, sustainability practices, and shifting consumer demands, which are critical to understanding rebound effects in CE transitions.

#### Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Document Type	Journal (articles), Conference Paper and Review	Book Chapter, Book, Report, Conference Review and Short Survey
Time	2015-2023	Before 2015
Language	English	Non-English

**Exclusion:** Non-English works, books, book chapters, reports, conference reviews, and short surveys.

#### E. Literature Selection and Quality Assessment

The final sample of 80 articles (see table below) was subjected to rigorous quality assessment involving title and abstract reviews followed by full-text analysis. Special attention was given to literature addressing the CER effect in sustainability and including these studies ensured both relevance to the research questions and a focused scope for analysis.

## Online supplementary appendix

Authors	Title	Year	Source title	DOI	Document Type	
1	Aguiar M.F.; Costa J.M.H.; Pigosso D.C.A.	HOW ARE EMOTIONAL ATTACHMENT STRATEGIES CURRENTLY EMPLOYED IN PRODUCT-SERVICE SYSTEM CASES? A SYSTEMATIC REVIEW UNDERSCORING DRIVERS AND HINDRANCES	2023	Proceedings of the Design Society	10.1017/pds.2023.210	Conference paper
2	André H.; Björklund A.	A framework to open the black box of the use phase in circular economy life cycle assessments: The case of shell jacket reuse	2023	Journal of Industrial Ecology	10.1111/jiec.13408	Article
3	André H.; Björklund A.	Towards a Conceptual Framework for Analyzing Circular Product-User Life Cycles: Learnings from the Sport and Outdoor Sector	2022	Procedia CIRP	10.1016/j.procir.2022.02.037	Conference paper
4	Bakker C.A.; Mugge R.; Boks C.; Oguchi M.	Understanding and managing product lifetimes in support of a circular economy	2021	Journal of Cleaner Production	10.1016/j.jclepro.2020.123764	Editorial
5	Bertassini A.C.; Calache L.D.D.R.; Carpinetti L.C.R.; Ometto A.R.; Gerolamo M.C.	CE-oriented culture readiness: An assessment approach based on maturity models and fuzzy set theories	2022	Sustainable Production and Consumption	10.1016/j.spc.2022.03.018	Article
6	Bertassini A.C.; Piller F.T.; Gerolamo M.C.	Opportunities and Challenges of Mass Customization for Circular Economy: A Literature-Based Analysis	2023	Lecture Notes in Mechanical Engineering	10.1007/978-3-031-34821-1_3	Conference paper
7	Beyeler L.; Jaeger-Erben M.	How to make more of less: Characteristics of sufficiency in business practices	2022	Frontiers in Sustainability	10.3389/frsus.2022.949710	Article
8	Birat J.-P.	Life-cycle assessment, resource efficiency and recycling	2015	Metallurgical Research and Technology	10.1051/metal/2015009	Article
9	Bocken N.M.P.; Niessen L.; Short S.W.	The Sufficiency-Based Circular Economy—An Analysis of 150 Companies	2022	Frontiers in Sustainability	10.3389/frsus.2022.899289	Article
10	Bressanelli G.; Adrodegari F.; Pigosso D.C.A.; Parida V.	Towards the Smart Circular Economy Paradigm: A Definition, Conceptualization, and Research Agenda	2022	Sustainability (Switzerland)	10.3390/su14094960	Article
11	Camana D.; Manzardo A.; Toniolo S.; Gallo F.; Scipioni A.	Assessing environmental sustainability of local waste management policies in Italy from a circular economy perspective. An overview of existing tools	2021	Sustainable Production and Consumption	10.1016/j.spc.2021.01.029	Review
12	Castro C.G.; Trevisan A.H.; Pigosso D.C.A.; Mascarenhas J.	The rebound effect of circular economy: Definitions, mechanisms and a research agenda	2022	Journal of Cleaner Production	10.1016/j.jclepro.2022.131136	Review
13	Chatzistamoulou N.; Tyllianakis E.	Green growth & sustainability transition through information. Are the greener better informed? Evidence from European SMEs	2022	Journal of Environmental Management	10.1016/j.jenvman.2022.114457	Article
14	Chen C.-W.	Clarifying rebound effects of the circular economy in the context of sustainable cities	2021	Sustainable Cities and Society	10.1016/j.scs.2020.102622	Article
15	Crocker R.	From 'Spaceship Earth' to the circular economy: The problem of consumption	2018	Unmaking Waste in Production and Consumption: Towards The Circular Economy	10.1108/978-1-78714-619-820181003	Book chapter
16	De Pádua Pieroni M.; Pigosso D.C.A.; McAloone T.C.	Sustainable Qualifying Criteria for Designing Circular Business Models	2018	Procedia CIRP	10.1016/j.procir.2017.11.014	Conference paper
17	Debref R.	Why should we fear energy and material savings? Deconstructing a sustainability myth	2021	Mineral Resources Economy 1: Context and Issues	10.1002/9781119850861.ch7	Book chapter
18	Figge F.; Thorpe A.S.	The symbiotic rebound effect in the circular economy	2019	Ecological Economics	10.1016/j.ecolecon.2019.04.028	Article
19	Flachenecker F.	The causal impact of material productivity on macroeconomic competitiveness in the European Union	2018	Environmental Economics and Policy Studies	10.1007/s10018-016-0180-3	Article
20	Flores J.; Cavique M.; Seixas J.	Energy Sustainability—Rebounds Revisited Using Axiomatic Design	2022	Sustainability (Switzerland)	10.3390/su14116737	Article

## Online supplementary appendix

21	Font Vivanco D.; Freire-González J.; Galvin R.; Santarius T.; Walnum H.J.; Makov T.; Sala S.	Rebound effect and sustainability science: A review	2022	Journal of Industrial Ecology	10.1111/jiec.13295	Article
22	Ghisellini P.; Santagata R.; Zucaro A.; Ulgiati S.	Circular patterns of waste prevention and recovery	2019	E3S Web of Conferences	10.1051/e3sconf/201911900003	Conference paper
23	Grădinaru G.I.; Maricuț A.-C.	FROM THE REBOUND EFFECT TO THE PERSPECTIVE OF CIRCULAR ECONOMY:A STRUCTURE CHANGES ANALYSIS AMONG EU COUNTRIES	2022	Economic Computation and Economic Cybernetics Studies and Research	10.24818/18423264/56.1.22.16	Article
24	Henry M.; Schraven D.; Bocken N.; Frenken K.; Hekkert M.; Kirchherr J.	The battle of the buzzwords: A comparative review of the circular economy and the sharing economy concepts	2021	Environmental Innovation and Societal Transitions	10.1016/j.eist.2020.10.008	Article
25	Holzinger H.	More efficiency is not enough. Capabilities and limits of the circular economy	2020	The Circular Economy in the European Union: An Interim Review	10.1007/978-3-030-50239-3_14	Book chapter
26	Horvath B.; Bahna M.; Fogarassy C.	The ecological criteria of circular growth and the rebound risk of closed loops	2019	Sustainability (Switzerland)	10.3390/su11102961	Article
27	Horvath B.; Magda R.	Possible bottlenecks in the strategic management of environmentally engaged companies - Transition to the world of circular businesses	2017	SMSIS 2017 - Proceedings of the 12th International Conference on Strategic Management and its Support by Information Systems 2017		Conference paper
28	Jia J.; Jian H.; Xie D.; Gu Z.; Chen C.	Multi-scale decomposition of energy-related industrial carbon emission by an extended logarithmic mean Divisia index: a case study of Jiangxi, China	2019	Energy Efficiency	10.1007/s12053-019-09814-x	Article
29	Jiang C.; Qiu Y.	Dynamic relationship between green finance, environmental taxes, and CO2 emissions in transition toward circular economy: what causes what?	2023	Environmental Science and Pollution Research	10.1007/s11356-023-28912-z	Article
30	Junge I.P.	Single Use Goes Circular—An ICT Proto-Practice for a Sustainable Circular Economy Future	2021	Journal of Sustainability Research	10.20900/jsr20210009	Article
31	Kjaer L.L.; Pigosso D.C.A.; McAloone T.C.; Birkved M.	Guidelines for evaluating the environmental performance of Product/Service-Systems through life cycle assessment	2018	Journal of Cleaner Production	10.1016/j.jclepro.2018.04.108	Article
32	Kjaer L.L.; Pigosso D.C.A.; Niero M.; Bech N.M.; McAloone T.C.	Product/Service-Systems for a Circular Economy: The Route to Decoupling Economic Growth from Resource Consumption?	2019	Journal of Industrial Ecology	10.1111/jiec.12747	Article
33	Koide R.; Murakami S.; Nansai K.	Prioritising low-risk and high-potential circular economy strategies for decarbonisation: A meta-analysis on consumer-oriented product-service systems	2022	Renewable and Sustainable Energy Reviews	10.1016/j.rser.2021.111858	Review
34	Koide R.; Yamamoto H.; Nansai K.; Murakami S.	Agent-based model for assessment of multiple circular economy strategies: Quantifying product-service diffusion, circularity, and sustainability	2023	Resources, Conservation and Recycling	10.1016/j.resconrec.2023.107216	Article
35	Laurenti R.; Singh J.; Sinha R.; Potting J.; Frostell B.	Unintended Environmental Consequences of Improvement Actions: A Qualitative Analysis of Systems' Structure and Behavior	2016	Systems Research and Behavioral Science	10.1002/sres.2330	Article
36	Laurenti R.; Sinha R.; Singh J.; Frostell B.	Some pervasive challenges to sustainability by design of electronic products - A conceptual discussion	2015	Journal of Cleaner Production	10.1016/j.jclepro.2015.08.041	Article
37	Lebossé M.; Besançon F.; Halin G.; Fuchs A.	VALUES OF RECLAIMED TIMBER	2023	13th World Conference on Timber Engineering, WCTE 2023	10.52202/069179-0470	Conference paper
38	Levanen J.; Uusitalo V.; Harri A.; Kareinen E.; Linnanen L.	Innovative recycling or extended use? Comparing the global warming potential of different ownership and end-of-life scenarios for textiles	2021	Environmental Research Letters	10.1088/1748-9326/abfac3	Article

## Online supplementary appendix

39	Liu X.; Wang S.; Li Y.; Ali S.; Khan Y.A.; Salem S.; Huang X.	Recycling in Textile Sector: A New Circular Economy Approach Towards Ecology and Environmental Sustainability	2022	Frontiers in Environmental Science	10.3389/fenvs.2022.929710	Article
40	Lombardi A.; Cembalo L.	Consumption Corridors as a new paradigm of sustainability	2022	Resources, Conservation and Recycling	10.1016/j.resconrec.2022.106423	Short survey
41	Makov T.; Vivanco D.F.	Does the circular economy grow the pie? The case of rebound effects from smartphone reuse	2018	Frontiers in Energy Research	10.3389/fenrg.2018.00039	Article
42	Mata É.; Kihila J.M.; Wanemark J.; Cheng S.H.; Harris S.; Sandkvist F.; Nyberg T.; Yaramenka K.	Non-technological and behavioral options for decarbonizing buildings – A review of global topics, trends, gaps, and potentials	2022	Sustainable Production and Consumption	10.1016/j.spc.2021.10.013	Review
43	Metic J.; Pigosso D.C.A.	Research avenues for uncovering the rebound effects of the circular economy: A systematic literature review	2022	Journal of Cleaner Production	10.1016/j.jclepro.2022.133133	Review
44	Michael Hall C.	Framing behavioural approaches to understanding and governing sustainable tourism consumption: Beyond neoliberalism, “nudging” and “green growth”?	2014	Understanding and Governing Sustainable Tourism Mobility: Psychological and Behavioural Approaches	10.4324/9780203771501-26	Book chapter
45	Mishra R.; Naik B.K.R.; Raut R.D.; Paul S.K.	Circular economy principles in community energy initiatives through stakeholder perspectives	2022	Sustainable Production and Consumption	10.1016/j.spc.2022.07.001	Article
46	Morimoto S.; Kuroki H.; Narita H.; Ishigaki A.	Scenario assessment of neodymium recycling in Japan based on substance flow analysis and future demand forecast	2021	Journal of Material Cycles and Waste Management	10.1007/s10163-021-01277-6	Article
47	Morseletto P.	Environmental principles for modern sustainable economic frameworks including the circular economy	2022	Sustainability Science	10.1007/s11625-022-01208-w	Article
48	Niero M.; Jensen C.L.; Fratini C.F.; Dorland J.; Jørgensen M.S.; Georg S.	Is life cycle assessment enough to address unintended side effects from Circular Economy initiatives?	2021	Journal of Industrial Ecology	10.1111/jiec.13134	Article
49	Oikonomou T.I.; Karytsas S.; Karytsas C.; Simoes S.G.; Seco Calvo O.; Sanchez Egidio M.N.; Soutullo Castro S.; Zerbino P.; Aloini D.; Genovese A.; Bimpizas-Pinis M.; Slabik S.; Lima A.T.	The CO2NSTRUCT European project: Modelling the role of Circular Economy in construction value chains for a carbon-neutral Europe	2023	IOP Conference Series: Earth and Environmental Science	10.1088/1755-1315/1196/1/012043	Conference paper
50	Onat N.C.; Kucukvar M.	A systematic review on sustainability assessment of electric vehicles: Knowledge gaps and future perspectives	2022	Environmental Impact Assessment Review	10.1016/j.eiar.2022.106867	Review
51	Ottelin J.; Cetinay H.; Behrens P.	Rebound effects may jeopardize the resource savings of circular consumption: evidence from household material footprints	2020	Environmental Research Letters	10.1088/1748-9326/abaa78	Article
52	Piscicelli L.	The sustainability impact of a digital circular economy	2023	Current Opinion in Environmental Sustainability	10.1016/j.cosust.2022.101251	Review
53	Rabiu M.K.; Jaeger-Erben M.	Appropriation and routinisation of circular consumer practices: A review of current knowledge in the circular economy literature	2022	Cleaner and Responsible Consumption	10.1016/j.clrc.2022.100081	Article
54	Rehfeldt M.; Porteron S.; Herbst A.	Modelling circular economy action impacts in the building sector on the EU cement industry	2020	Eceee Industrial Summer Study Proceedings		Conference paper

## Online supplementary appendix

55	Roy P.; Ashton L.; Wang T.; Corradini M.G.; Fraser E.D.G.; Thimmanagari M.; Tiessan M.; Bali A.; Saharan K.M.; Mohanty A.K.; Misra M.	Evolution of drinking straws and their environmental, economic and societal implications	2021	Journal of Cleaner Production	10.1016/j.jclepro.2021.128234	Review
56	Ruzzenenti F.; Font Vivanco D.; Galvin R.; Sorrell S.; Wagner A.; Walnum H.J.	Editorial: The Rebound Effect and the Jevons' Paradox: Beyond the Conventional Wisdom	2019	Frontiers in Energy Research	10.3389/fenrg.2019.00090	Editorial
57	Ryen E.G.; Babbitt C.W.; Kooduvalli K.	Circular Economy Research: From Theory to Practice	2022	CSR, Sustainability, Ethics and Governance	10.1007/978-3-030-94293-9_2	Book chapter
58	Safarzynska K.; Di Domenico L.; Raberto M.	The circular economy mitigates the material rebound due to investments in renewable energy	2023	Journal of Cleaner Production	10.1016/j.jclepro.2023.136753	Article
59	Salvador R.; Barros M.V.; Donner M.; Brito P.; Halog A.; De Francisco A.C.	How to advance regional circular bioeconomy systems? Identifying barriers, challenges, drivers, and opportunities	2022	Sustainable Production and Consumption	10.1016/j.spc.2022.04.025	Review
60	Salvador R.; Barros M.V.; Luz L.M.D.; Piekarski C.M.; de Francisco A.C.	Circular business models: Current aspects that influence implementation and unaddressed subjects	2020	Journal of Cleaner Production	10.1016/j.jclepro.2019.119555	Review
61	Salvador R.; Puglieri F.N.; Halog A.; Andrade F.G.D.; Piekarski C.M.; De Francisco A.C.	Key aspects for designing business models for a circular bioeconomy	2021	Journal of Cleaner Production	10.1016/j.jclepro.2020.124341	Review
62	Santarius T.; Bieser J.C.T.; Frick V.; Höjer M.; Gossen M.; Hilty L.M.; Kern E.; Pohl J.; Rohde F.; Lange S.	Digital sufficiency: conceptual considerations for ICTs on a finite planet	2023	Annales des Telecommunications/Annals of Telecommunications	10.1007/s12243-022-00914-x	Article
63	Sarancic D.; Metic J.; Pigosso D.C.A.; McAloone T.C.	Impacts, synergies, and rebound effects arising in combinations of Product-Service Systems (PSS) and circularity strategies	2023	Procedia CIRP	10.1016/j.procir.2023.02.092	Conference paper
64	Schröder P.; Bengtsson M.; Cohen M.; Dewick P.; Hoffstetter J.; Sarkis J.	Degrowth within – Aligning circular economy and strong sustainability narratives	2019	Resources, Conservation and Recycling	10.1016/j.resconrec.2019.03.038	Short survey
65	Siderius T.; Poldner K.	Reconsidering the Circular Economy Rebound effect: Propositions from a case study of the Dutch Circular Textile Valley	2021	Journal of Cleaner Production	10.1016/j.jclepro.2021.125996	Article
66	Siderius T.; Zink T.	Markets and the Future of the Circular Economy	2022	Circular Economy and Sustainability	10.1007/s43615-022-00196-4	Article
67	Skelton A.C.H.; Paroussos L.; Allwood J.M.	Comparing energy and material efficiency rebound effects: an exploration of scenarios in the GEM-E3 macroeconomic model	2020	Ecological Economics	10.1016/j.ecolecon.2019.106544	Article
68	Sourabh S.; Menon B.G.; Mahanty B.	Econometric analysis of circular economy co-flow process in metal industry	2023	Quality and Quantity	10.1007/s11135-023-01709-5	Article
69	Thomas J.-S.; Birat J.-P.	Methodologies to measure the sustainability of materials - Focus on recycling aspects	2013	Revue de Metallurgie. Cahiers D'Informations Techniques	10.1051/metal/2013054	Article
70	Van Der Linde L.; Pretorius L.; Oosthuizen R.	Behavioural System Dynamics: Conceptual Integration of Critical Bias Variables into Circular Economy Stakeholder Phases	2023	PICMET 2023 - Portland International Conference on Management of Engineering and Technology: Managing Technology, Engineering and Manufacturing for a Sustainable World, Proceedings	10.23919/PICMET59654.2023.10216826	Conference paper

## Online supplementary appendix

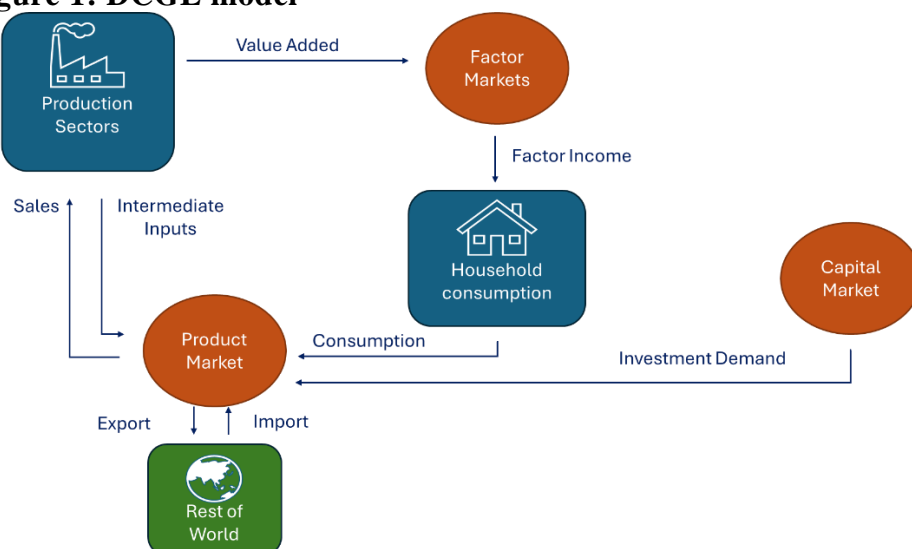
71	van Loon P.; Diener D.; Harris S.	Circular products and business models and environmental impact reductions: Current knowledge and knowledge gaps	2021	Journal of Cleaner Production	10.1016/j.jclepro.2020.125627	Article
72	Vegter D.; van Hillegersberg J.; Olthaar M.	Performance measurement system for circular supply chain management	2023	Sustainable Production and Consumption	10.1016/j.spc.2023.01.003	Article
73	Wang L.; Li H.-M.	Decomposition analysis on dematerialization for the further development of circular economy	2010	2010 4th International Conference on Bioinformatics and Biomedical Engineering, iCBBE 2010	10.1109/ICBBE.2010.5517248	Conference paper
74	Warmington-Lundström J.; Laurenti R.	Reviewing circular economy rebound effects: The case of online peer-to-peer boat sharing	2020	Resources, Conservation and Recycling: X	10.1016/j.rcrx.2019.100028	Article
75	Widmer T.; Tjahjono B.; Bourlakis M.	Defining value creation in the context of circular PSS	2018	Procedia CIRP	10.1016/j.procir.2018.03.329	Conference paper
76	Wiprächtiger M.; Rapp M.; Hellweg S.; Shinde R.; Haupt M.	Turning trash into treasure: An approach to the environmental assessment of waste prevention and its application to clothing and furniture in Switzerland	2022	Journal of Industrial Ecology	10.1111/jiec.13275	Article
77	Xie J.; Xia Z.; Tian X.; Liu Y.	Nexus and synergy between the low-carbon economy and circular economy: A systematic and critical review	2023	Environmental Impact Assessment Review	10.1016/j.eiar.2023.107077	Review
78	Zerbino P.	How to manage the Circular Economy Rebound effect: A proposal for contingency-based guidelines	2022	Journal of Cleaner Production	10.1016/j.jclepro.2022.134584	Article
79	Zhao X.; Han Z.; Li C.; Yue X.; Wang B.; Zhang W.	Research on Protection Performance of Via Hole Fender for Offshore Wind Turbine; [海上风力机设孔防护装置性能研究]	2021	Zhongguo Dianji Gongcheng Xuebao/Proceedings of the Chinese Society of Electrical Engineering	10.13334/j.0258-8013.pcsee.201426	Article
80	Zink T.; Geyer R.	Circular Economy Rebound	2017	Journal of Industrial Ecology	10.1111/jiec.12545	Article

## 2 Dynamic computable general equilibrium (DCGE) model

This DCGE model is an extension of Hafner et al. (2023, 2020) and resembles Lanz and Rutherford (2016) multi-region model. Below we provide an extended description of the model.<sup>1</sup> Each geographical zone  $z$  is modelled as an open economy. Zones are inter-connected with other zones through trade linkages of goods and services (e.g. intermediate and final goods).

Figure 1 is a simplified illustration of the model. It depicts the interaction of production sectors that require capital and labour inputs, which they access through the factor markets. Firms hire labour and rent capital from households, with which households obtain income. Goods are then sold in product markets, which households pay-for, given their available income. The economy also trades products with the rest of the world through bilateral international linkages. The model also includes government services and investment, which are not included in the figure for simplification purpose. The government collects taxes with which it buys (demands) final goods and thus provides public services. Furthermore, geographic zones save/borrow in the capital markets whereby an investment account demands final goods used to create new capital for the next period.

**Figure 1: DCGE model**



The model is programmed in GAMS using the sub-language MPSGE (GAMS, 2023; Rutherford, 1999). Further details about the static element of this model are provided in Hafner et al (Hafner et al., 2023).

### 2.1 Production structure

In each zone  $z$  and time-period  $t$ , sectors  $y_i$  produce goods and services with corresponding market prices of  $p_i$ . Each sector demands labour  $L_i$ , capital inputs  $K_i$ , and intermediate inputs

<sup>1</sup> For technically rigorous documentation of the functional forms, please see Lanz and Rutherford (2016).

$N_{ij}$  (with  $j$  other sectors). For simplification, we assume that technological progress follows a Hicks-neutral assumption (i.e., Total Factor Productivity - TFP) across all sectors.

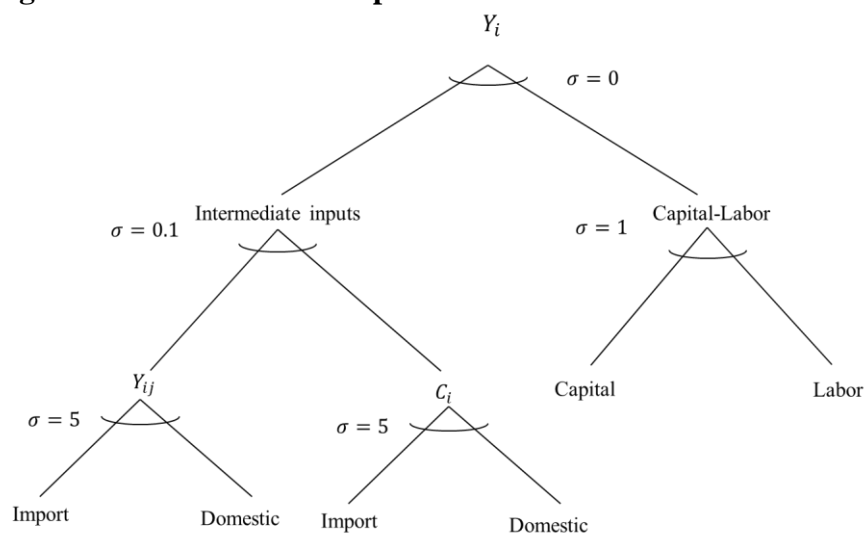
Next, we follow Saunders (2000), Wei (2010) and Wei and Liu (2017) that define the RE as the level of correspondence between technological efficiency gains and production. Suppressing indices for region  $r$  and time-period  $t$ , we use a multi-level constant returns to scale (CRS) production. We define the global welfare  $Y$  as the sum of all production sectors  $i$ , and across region  $r$

$$Y = \sum_{ir} Y_{ir} = \sum_{ir} f_i(L_i, K_i, Y_{ji}, \tau C_i) \quad (1)$$

with  $C \in Y$  defined as the TC sector – one among all other sectors. This is illustrated in Figure 2. At the top-level, for each sector  $i$ , the value added of  $L_i, K_i$  are labour and capital inputs are combined with intermediate inputs in fixed proportion. In the next level, capital-and labour, are combined using a Cobb-Douglas function which has a unitary substitution elasticity (i.e.,  $\sigma = 1$ ). Intermediate inputs are also combined using a using a Constant Elasticity of Substitution (CES) function that has a very lower substitution near zero (i.e.,  $\sigma = 0.1$ ) signifying very different intermediate inputs.  $Y_{ji}$  are other intermediate inputs in the production - excluding textiles and clothing apparel (with  $j$  alias to  $i$ ). Additionally,  $C_i$  represents intermediate inputs of textiles and clothing apparel used in the production of sector  $i$ , such as fabric required for sails for boats, tents, or clothing within the supply-chain of each sector.

To capture circular economy technology improvements,  $\tau$  is a Harrod-neutral technology parameter, applied to intermediate inputs of clothing for all sectors (Acemoglu, 2009).<sup>2</sup> Finally, at the lowest-nest, domestic and imported intermediate inputs are combined using a CES function with a high substitution elasticity  $\sigma = 5$ , signifying the high similarity between domestic and imported intermediate products.

**Figure 2: Multi-level CRS production structure**



<sup>2</sup> In the applied (calibrated) model, we also incorporate a Hick-neutral total factor productivity parameter (Acemoglu, 2009). This parameter, however, plays no role in our analysis and is the same in both baseline and all counterfactuals scenarios. Its purpose is to calibrate the model to a baseline project – as discussed in Section **Error! Reference source not found.**

## 2.2 Households, Government and Savings

Each regional household  $r$  represents a collection of countries that maximizes a welfare function  $W_r$  of private consumption, public consumption and investment in fixed proportions (i.e., Leontief function) with utility price index  $P^W$

$$\text{Max } W_r = f(C_r, G_r, I_r) \quad (2)$$

$$\text{s.t. } R_r K_r + w_r L_r + P_r^{CA} CA_r = P_r^W W_r$$

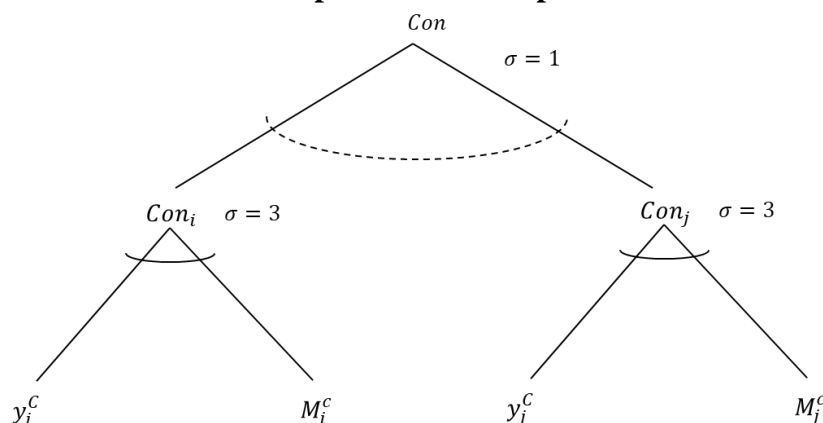
subject to their intra-temporal budget constraint with  $R$  the rental rate of capital,  $w$  wage rate,  $P^{CA}$  price index for the  $CA$  current account.<sup>3</sup>

In the next sub-levels, private consumption is structured as a two-level function,  $Con_{i,r} = f(y_i^C, M_i^C)$ , with consumer price index  $p^C$ . As illustrated in Figure 3, at the top level, goods and services  $i = [1 \dots N]$ , with  $i \neq j$ , are assembled as a Cobb-Douglas function. In the second level, domestic  $y_i^C$  and imported  $M_i^C$  final goods and services are combined using a CES function with a high substitution elasticity  $\sigma = 3$ , which captures the similarity and substitutability of the products within a sector.

Similarly, public consumption  $G = f(y_i^G, M_i^G)$  is also a two-level function, with price index  $p^{Gov}$ . At the top level, products are demanded in fixed proportion, while at the lower level, domestic and imported products are assembled within a CES function with a high substitution elasticity of  $\sigma = 3$ . Finally, investment  $I = f(y_i^{Inv}, M_i^{Inv})$  is similar to the government demand with price index  $p^{Inv}$ .

Not shown here, but all goods and imports have taxes and import duties, which are calibrated accordingly.

**Figure 3: The structure of private consumption**



The model uses an Armington formulation (Armington, 1969) to account for cross-hauling of goods and services. Regionally differentiated imports come from other regions and are used as intermediate inputs in production or as final goods for consumption and investment. As similar

<sup>3</sup> The current account is part of the balance of payments provided within the SAM. It includes trade balance, transaction on transport and marketing services, primary and secondary income flow transfers from/to other countries. To simplify this documentation, we provide a general overview, but further details can be found in Lanz and Rutherford (2016).

functional form is used for Government and Investment accounts in fixed proportions. Transportation services (trade margins) are applied proportionally to imports from different regions. For exports, production sectors  $Y_i$  allocate output among domestic supply, exports, and transportation services using a constant elasticity of transformation (CET) function.

Standard market clearance conditions ensure supply-demand equilibrium for all goods and factors.

## 2.3 Model dynamics

The model follows a recursive-dynamic approach, solving period by period while carrying variables forward. This myopic framework means regional households generate consumption-investment decisions solely on past economic conditions, with limited consideration of future expectations. Lecca et al. (2013) discuss the trade-offs between recursive and fully forward-looking approaches.

Two variables adjust recursively. First, physical supply of employed labour adjusts by  $L_t = L_0(1 + g_t)$  s introduced exogenously into the model. Demographics data for the working population aged 15-64 drives the rise in labour  $L_t$ . Since we do not have good estimates for changes in participation rates, we assume that  $L_t$  is driven by the change in the working population aged 15-64 provided by the World Bank. We furthermore use the total population for other metrics such as GDP per capita.

Capital adjusts based on a standard accumulation rule with depreciation rate  $\delta$ . Old capital remains after depreciation, while new capital is formed through investment:

$$K_{t+1} = (1 - \delta)K_t + I_t \quad (3)$$

To align with regional Social Accounting Matrices (SAMs), we convert capital stock to monetary returns by multiplying both sides by a region-specific five-year internal rate of return  $\rho$ , reflecting investors' risk-return trade-offs. This gives the regional change in capital returns:

$$VK_{t+1,r} = (1 - \delta_r)VK_{t,r} + \rho_r I_{t,r} \quad (3)$$

The parameters  $\rho$ ,  $\delta$  and TFP are provided from the PEN World Tables 10.03. We broadly group them by their geographic zones and adjust to align our baseline regional GDP projections with those estimated by Shared Socioeconomic Pathways 2 (SSP2), i.e., "middle of the road" scenario (Cuaresma, 2017) and PWC (2017).

As explained in the paper, counterfactual scenarios vary  $\tau$ , the textile and clothing technology parameter.

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