

An Economic Classification of Circular Economy Strategies

Reyer Gerlagh¹, Julie Metta^{1,2}, Claudia Ranocchia¹

¹Tilburg University, ²USMB & ZHAW

CEEMinars, Zurich, 17 September 2026

Overview

- 1 Motivation
- 2 Contribution
- 3 A simple macro CE model
- 4 Market failures and policies
- 5 Conclusion
- 6 Appendix CGEs

To name something is to begin to understand it

Existing CE literature

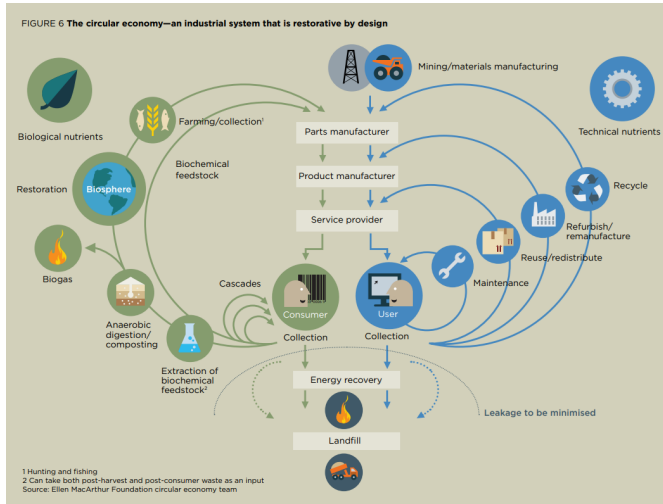
- Increasing # of Circular **Economy** papers, most of them considering a particular CE strategy
- R-strategies (CE words that start with R): popular with Industrial Ecologists and Policy Makers

Q: How do these studies & strategies connect and integrate in an economic context?

Our contribution:

- we map CE strategies to economic **margins**: adjustment (action) of behavior and technology
- identify **agents** operating in **markets** where they trade **goods**.
- this helps clarify boundaries between strategies
- and supports describing strategies by **model parameter** changes
- clarifies connections to degrowth and limits-to-growth & gives more weight to product(ion) innovation (CE2) and 'resourcing' (CE5)

CE strategies: the Butterfly (EMAF, 2012)



- Consumption focused
- smaller loops are better

R-strategies (Potting et al., 2017)

Smarter product use and manufacture	R0	Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1	Rethink	Make product use more intensive (e.g. through sharing products or by putting multi-functional products on market).
	R2	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources
Extend lifespan of product and its parts	R3	Reuse	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function
	R4	Repair	Repair and maintenance of defective product so it can be used with its original function
	R5	Refurbish	Restore an old product and bring it up to date
	R6	Remanufacture	Use parts of discarded product in a new product with the same function
	R7	Repurpose	Use discarded products or its part in a new product with a different function
Useful application of materials	R8	Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9	Recovery	Incineration of material with energy recovery

(Morseletto, 2020) group strategies R0–R9 from high circularity (R0) to low circularity (R9) in 3 classes

- Demand decrease ('narrow'):
Refuse (R0) / Rethink (R1) / Reduce (R2)
- Extend life spans ('slowing'):
Reuse (R3) / Repair (R4) / Refurbish (R5) / Remanufacture (R6) / Repurpose (R7)
- Close the loop:
Recycle (R8) / Recover (R9)

Most consider higher strategies (lower numbers) as **preferable**...

Other CE classifications

Existing CE taxonomies: mainly designed for policy, business practices, & monitoring.

Framework	Key unit	Logic	Distinctive feature
EMAF (2012)	Biological & technical cycles	Value retention by design	Broadest scope; regeneration is constitutive, not a separate strategy; no priority order among interventions
Potting et al. (2017)	Product/material strategy	R-ladder R0–R9, ordered by value preserved	Most granular R-hierarchy; widely used in policy but not linked to formal economic models
Morseletto (2020)	Policy target	Typology of measurable targets (resource, waste, emissions)	Only framework centred on verifiable goals; closest to welfare-economic optimisation
Topi et al. (2016)	Stakeholder × sector	Eight building blocks mapped to actor types	Institutional orientation; emphasises enabling conditions over product-level strategies
Blomsma and Tennant (2020)	Resource physical state	Particle state vs. product state	Ontologically prior to R-strategies; maps material entropy and life-cycle transformations before naming interventions
Eisenreich et al. (2022)	Firm value-chain stage	Porter's VC adapted for CE	Firm-level; connects CE to competitive advantage rather than to material flows or policy targets
Kirchherr et al. (2017, 2023)	CE definitions	Content analysis (114 in 2017; 221 in 2023)	Meta-framework; maps definitional content; reveals that consumption and sufficiency remain under-represented

Our contribution: for economic modelling, we instead want to classify CE strategies by their **economic context**.

Our Reclassification

- Existing CE taxonomies are highly useful for communication of policy classification, business models and monitoring circularity.
- But economic models require **margins** of adjustment for **agents** operating on **markets** where they trade **goods**.
- Our preliminary list of CE margins + parameters:
 - responsible consumption, χ (behavior)
 - product and production efficiency, θ (technology)
 - usage intensity and extension, λ (dedicated CE markets for users)
 - material loop closure, σ (recycling)
 - regenerative sourcing, R (resource substitution)

Why the distinction matters

Suppose we want to reduce material use by 20%.

For policy design and instrument choice, we need to understand

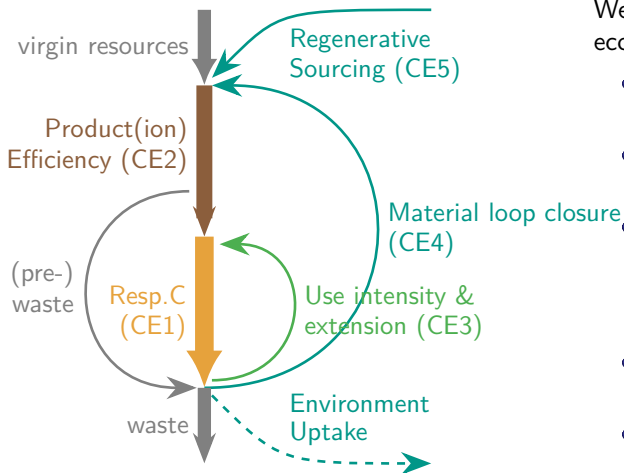
- which **margins** (activity / entry-exit; intensive / extensive) do we want to change?
- which **agents** need to be activated?
- can we improve relevant **markets**?
- what are economic consequences for **income**, **distribution**, and **employment** varying between strategies?

Circular Economy Strategies: An Economic-Modelling Classification

	CE margin	detail	R-strat	Agents	Markets	Model
1.	Responsible consumption	Lower demand for footprint-intensive goods	Refuse, Rethink, Reduce , Reuse	Consumers	products, services, waste	$X = \chi C$
2.	Product(ion) efficiency	Reduce material waste+embodied per product	Reduce (Ecodesign)	Manufacturing	materials, products	$m_i = \theta_i y_i$ $w_i = \omega_i y_i$
3.	Usage intensity & extension	Increase services per product	Reuse , Repair, Refurbish, Repurpose	CE platforms	products, services, PaaS	$c_i = \lambda_i y_i$
4.	Material loop closure	Replace virgin with secondary materials	Recycling, Re-manufacturing	Material supply	waste, materials	$X + R = (1 - \sigma)(M + W)$
5.	Regenerative sourcing	Replace exhaustible by renewable sources	Bioplastics	Agriculture	land, mines, materials	$R + X = (1 - \sigma)(M + W)$

Note: 'sharing' can be in Responsible consumption when informal (= no market) or Lifetime extension when formal (through market)

Mapping CE margins graphically



We structure CE-strategies according to five economic margins:

- CE1: Responsible consumption:
Refuse (R0) / Rethink (R1) / Share
- CE2: Product and Production efficiency:
Reduce (R2)
- CE3: Usage intensity and extension (shorten the loop):
Reuse (R3) / Repair (R4) / Refurbish (R5) / Remanufacture (R6) / Repurpose (R7)
- CE4: Material loop closure:
Recycle (R8) / Recover(R9)
- CE5: Regenerative material sourcing
e.g. biomaterial

Reclassification notes

Compared to [Potting et al. \(2017\)](#), we

- split smarter product use and manufacture (narrow: R0–R2) into CE1 Responsible consumption and CE2 Product(ion) efficiency;
- add CE5 regenerative sourcing (from butterfly) ([EMAF, 2012](#));
- apply strategies to [both](#) investments and consumption goods.
- Not obvious where to put R9: incineration with energy recovery.

The mapping from R-strategies to CE margins is by [margins, agents and markets](#). A concrete policy can activate several CE margins at once.

Throughput Reduction versus Circularity

Flavor of R-strategies

- low R-number (refuse) = more 'circular' = better than high R-number (recycle)
- narrowing the loop: $R0 \succ R1 \succ \dots \succ R9$

Economics is not so clear-cut in ordering. We maximize welfare given reduced environmental impact. We propose considering two margins (without prior ranking):

- **Throughput reduction** ($\approx$ low R-number): reduce physical flows per service (compare energy savings)
- **Circularity**: reduce environmental impact per economic-physical flow (compare renewable energy; keeping material flows **inside** economy)

Conjecture: sustainability develops from focus on throughput reduction $\rightarrow$ focus on circularity

- 1 degrowth/limits-to-growth literature ([Solow, 1974](#); [Dasgupta and Heal, 1974](#)) focuses on throughput reduction
- 2 green growth will require almost complete recycling...
- 3 classification is **not** about **assumptions** re feasibility of substitution; it is about where and by whom.

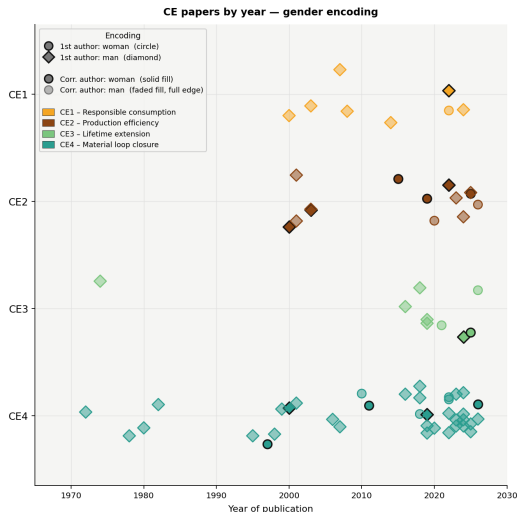
Throughput Reduction versus Circularity, ctd

R-strategies have flavor that lower R is more 'circular' is better (narrowing the loop:
 $R_0 \succ R_1 \succ \dots \succ R_9$)

CE Margin	Throughput reduction	Circularity	Main mechanism
1. Responsible consumption	✓✓✓	✓	Fewer material-intensive goods demanded
2. Product(ion) efficiency	✓✓✓	✓	Less material used for and embodied per unit produced
3. Usage intensity and extension	✓✓	✓✓	More services extracted from existing product stocks
4. Material loop closure	✓	✓✓✓	Virgin materials replaced by secondary materials
5. Regenerative sourcing		✓✓✓	Exhaustible sources replaced by renewable sources

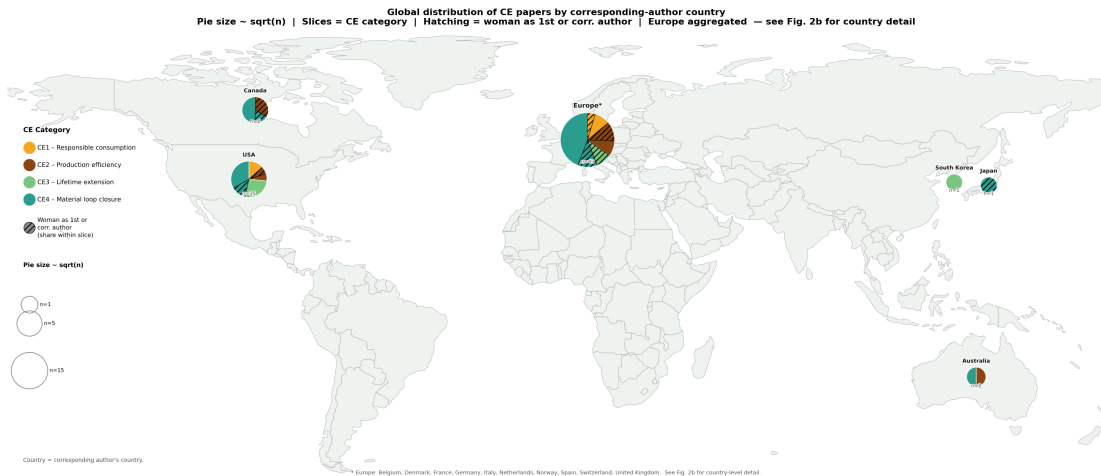
Note: think, does it fit the Dasgupta-Heal-Solow 1972 model as well?

CE literature by decade, gender and category



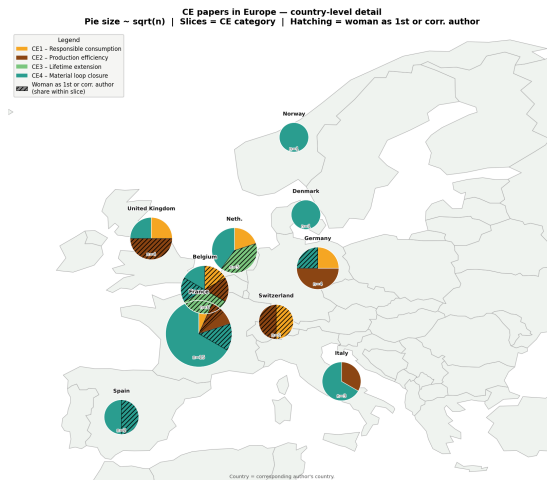
- Steep rise of CE-economic papers, but remaining small field (n=68)
- Classical interest in CE4 from 1970s
- CE1+CE2 starting 2000
- CE3 starting 2015
- No economic papers on CE5 yet
- Share of women first/corresponding authors rising from 0 to about 50%

Geographical distribution of CE papers (world)



Country = corresponding author. Pie radius $\propto \sqrt{n}$; slices = CE category; hatching = woman as 1st or corr. author. Europe aggregated on main map; detail in inset. $n = 68$.

Geographical distribution of CE papers (Europe n=43/68)



Country = corresponding author. Pie radius $\propto \sqrt{n}$; slices = CE category; hatching = woman as 1st or corr. author. $n = 68$.

Modeling: welfare (the ultimate objective)

- Households demand services C (e.g. mobility) and supply labor L .
- Investors demand capital K ; (often high material intensity per value)
- We treat both as substitutes, providing immediate or long-term utility
- Individual leisure provides utility (labour L disutility)
- Aggregate exhaustible resource use X generate disutility

$$\max U(C, L, X) \quad (1)$$

(no (separate) disutility from waste / assumes regenerative sources do not become pollutants)

- where for convenience, we drop K from notation, with $U_C > 0, U_L, U_X < 0$.

CE margins in a simple macro model with heterogeneous goods

$$\max U(C, L, X)$$

maximize welfare

$$C = \left(\int_i c_i^\alpha \right)^{1/\alpha}$$

aggregate consumption over varieties i ; composition resource intensity λ

$$m_i = \theta_i y_i$$

material embodied in products, θ_i

$$w_i = \omega_i y_i$$

material wasted at production, ω_i

$$c_i = \lambda_i y_i$$

usage intensity & extension λ_i for effective consumption services

$$R + X = \int_i (1 - \sigma_i)(m_i + w_i)$$

virgin material extraction plus renewable resources equal demand
(implicitly assumed: R becomes non-polluting waste)

$$AL = L_y + L_c + L_m + L_r$$

effective labour supply meets demand

$$L_y = \int_i (1 + c_2(\theta_i, \omega_i)) y_i$$

labor in production, costs of increased efficiency

$$L_c = \int_i c_3(\lambda_i) y_i$$

costs of reuse/repair activities

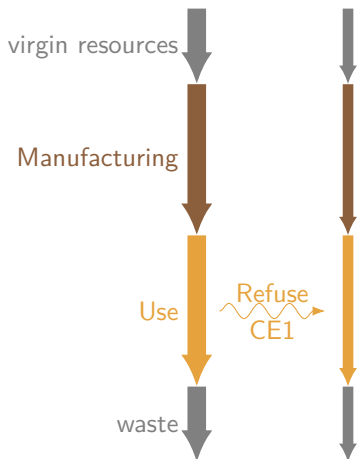
$$L_m = \int_i c_4(\sigma_i)(m_i + w_i)$$

costs of collection and recycling depend on recycling rate σ and scale w

$$L_r = c_5(R)$$

renewable resource costs depend on resource supply R

CE1 Responsible consumption (R0,R1: refuse/rethink)



- **Refuse & Rethink (R0, R1):** Consumers can refuse material/waste-intensive goods and **substitute** demand to other goods. (**extensive** margin)
- requires **behavioural and lifestyle change**: lower demand, shared use, modal shift, sufficiency-oriented consumption.
- illustration: public transport and bike versus private car
- Modeling: heterogeneous consumer goods and footprint intensity χ .
- Responsible consumption affects resource use through

$$X = \chi C. \quad (2)$$

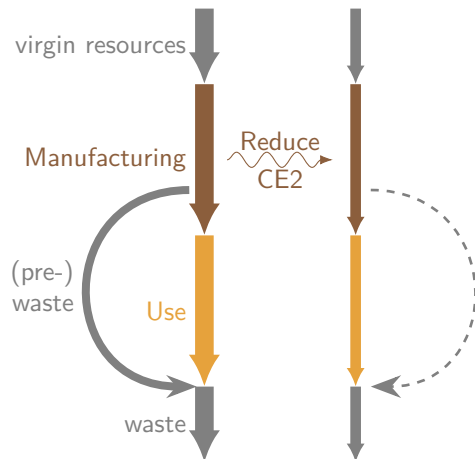
CE1 Responsible consumption (cost of behavior change)

somewhat more complicated compared to other CE margins

- heterogeneous goods: binary $\mathcal{I} = \{c, d\}$ or continuous varieties $\mathcal{I} = [0, 1]$.
- aggregate consumption (and capital) consist of varieties $C = (\int_i c_i^\alpha)^{1/\alpha}$ for $\alpha \leq 1$.
- let $\chi_i = (1 - \sigma_i)(\theta_i + \omega_i)/\lambda_i$ be the consumption (exhaustible resource) footprint: $X = \int_i \chi_i c_i$.
- footprint intensity is $\chi = X/C$ (weighted average χ_i).
- given prices p_i , we have aggregate price $\bar{P} = \left(\int_i p_i^{\frac{\alpha-1}{\alpha}} \right)^{\frac{\alpha}{\alpha-1}}$ per unit aggregate consumption and cost-minimizing footprint intensity $\bar{\chi} = \int_i \chi_i \bar{c}_i / \bar{C}$.
- responsible consumption can reduce footprint intensity χ by shifting to low- χ_i goods
- costs of reducing footprint is convex with $c(\chi) = P(\chi) - \bar{P}$:

$$P(\chi) = \min_c \int_i p_i c_i \text{ s.t. } \int_i \chi_i c_i = \chi \text{ and } \int_i c_i^\alpha = 1. \quad (3)$$

CE2 Product and production efficiency (R2 reduce)

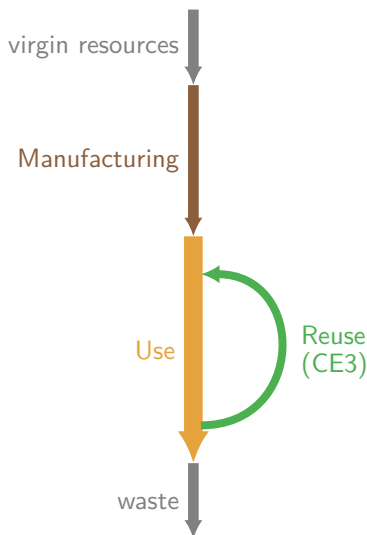


- **Reduce (R2)**: Firms can reduce material intensity of goods, **Redesign** products or **Reinvent** manufacturing with less resources (**intensive** margin).
- Material product + process waste intensity:
 $\theta_i = m_i/y_i; \omega_i = w_i/y_i$.
- Better designs for both products and processes with lower material intensity cost more effort:

$$L_y = (1 + c_2(\theta; \omega))y, \quad c'_2 < 0.$$

- Note: innovative and often cost-reducing (cheaper cars)

CE3 Usage intensity and extension (R3 reuse)



Reuse (R3) can consist of

- more **intensive** use (sharing)
- **extended life-time** (after first use)

Illustration: car-sharing

Model

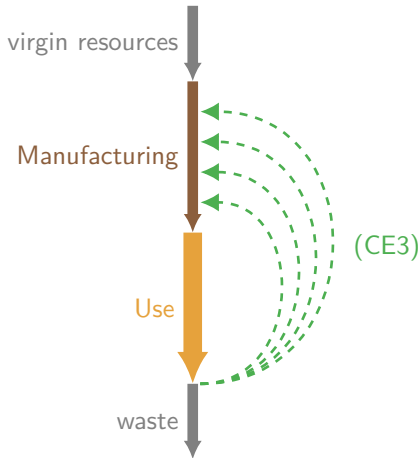
- Service sector transforms products y_i into services c_i :

$$c_i = \lambda_i y_i, \quad \lambda = c/y.$$

- Costs of reuse/repair activities: $L_c = \int_i c_3(\lambda_i) y_i$.

Note: durability by manufacturing design is listed in CE2.

CE3 Lifetime extension (R4–R7 repair/refurbish/remanufact./repurpose)



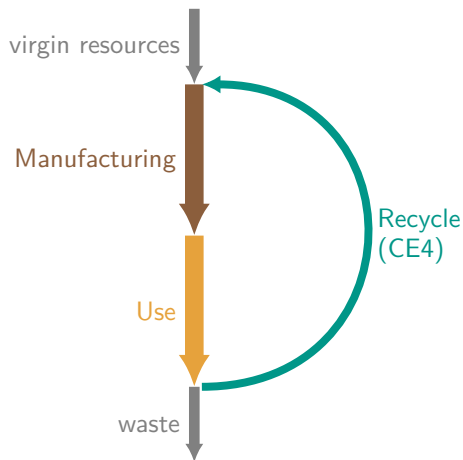
R3–R7 are grouped as CE3 because they all increase services per unit produced, but they differ in the mechanism.

Life-time extension can consist of:

- utilisation intensity, e.g. sharing/reuse;
- durability or lifetime, e.g. repair;
- quality retention, e.g. refurbish/remanufacture/repurpose.

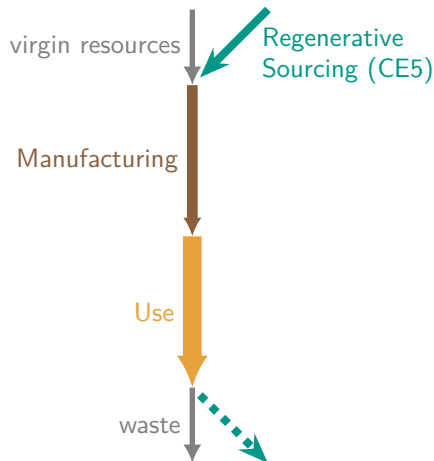
In many cases **new markets** are developed

CE4 Loop closure (R8, R9 recycle/recover)



- Turn waste into valuable resources.
- Increase rate of **recycling (R8)**.
- Improve **recovery** = quality of recycled resources ($\neq R9$).
- Illustration: more secondary steel and plastics in cars
- Recycling increases material available for products $M + W = \int_i (\theta_i + \omega_i) y_i$:
- $R + X = (1 - \sigma)(M + W)$,
- $L_m = c_4(\sigma)(M + W)$.
- Note: recyclability by manufacturing design is listed in CE2.

CE5 Regenerative sourcing



Replace exhaustible resources by regenerative resources

- biobased
- abundant minerals

natural rubber versus synthetic Model

- $L_r = c_5(R)$
- $R + X = \int_i (1 - \sigma_i)(m_i + w_i)$

A simple macro CE model (recap)

$$\max U(C, L, X)$$

$$C = \left(\int_i c_i^\alpha \right)^{1/\alpha}$$

$$m_i = \theta_i y_i$$

$$w_i = \omega_i y_i$$

$$c_i = \lambda_i y_i$$

$$R + X = \int_i (1 - \sigma_i)(m_i + w_i)$$

$$AL = L_y + L_c + L_m + L_r$$

$$L_y = \int_i (1 + c_2(\theta_i, \omega_i)) y_i$$

$$L_c = \int_i c_3(\lambda_i) y_i$$

$$L_m = \int_i c_4(\sigma_i)(m_i + w_i)$$

$$L_r = c_5(R)$$

maximize welfare

aggregate consumption over varieties i ; composition resource intensity λ_i

material embodied in products, θ_i

material wasted at production, ω_i

usage intensity and extension λ_i for effective consumption services

virgin material extraction plus renewable resources equal demand

effective labour supply meets demand

labor in production, costs of increased efficiency

costs of reuse/repair activities

costs of collection and recycling

renewable resource costs

Market failures and policies

- what margin is targeted? ($\chi, \theta, \omega, \lambda, \sigma, R$)?
- what market failure is corrected (what are the symptoms)?
(consider product markets: is the products' recyclability and (damaging) waste content salient to buyers? (Fullerton and Wu, 1998; Calcott and Walls, 2000; Büttner and Kesselring, 2024; Pommeret et al., 2026))
- what are the bottlenecks we resolve: information, missing markets?
- what direct problems have been identified for policies?
- rebounds (next slide)
- what indirect problems to expect: capital, labor, partial and equilibrium feedbacks, income distribution)?

Rebounds

CE margins result in direct reduced resource and material use, but

- reduced material use → reduced price per service → increased demand ([direct rebound](#))
- reduced material use → reduced costs → increased income → increased demand for other (high-footprint) services ([indirect rebound](#) → [macro CE model](#))

Example: Two goods, clean/dirty, which are inferior and luxury, respectively. Then dirty halves its costs and resource use. If demand is very elastic, dirty demand may go up by $\gg 2$.

dependent on the size of rebound

- weak rebound ($< 100\%$)
- strong rebound ($> 100\%$)

rebounds seem unavoidable when focusing on efficiency improvement for CE activities ([Sorrell, 2009](#); [Zink and Geyer, 2017](#); [Berg et al., 2025](#)). But driver of rebound matters:

- when margins adjust through regulating standards, substantial rebounds possible through inelasticity resource supply
- when margins adjust through innovation, strong rebounds possible when demand is elastic

Solution: to directly price resource extraction and waste?

Market failures and policies: CE1 Responsible consumption

Economic mechanism	Demand substitution; sufficiency
Market failure	Consumers may not observe product footprints or waste consequences; social norms and visibility matter (Büttner and Kesselring, 2024)
Target	Consumption choices and lifestyle decisions
Policy instrument	information provision, nudges, footprint pricing, standards (Büttner and Kesselring, 2024)
Social & institutional issues	Acceptance, habits, convenience, equity
Rebound	Medium; savings and leisure can be redirected to high-footprint services; behavioural response is central → combine footprint pricing with information and equity-sensitive design
Other caveats	Behavioural responses are clustered through life styles (Baumgartner et al., 2022); risk of consumption reallocation (Grimaud and Rouge, 2008)

Market failures and policies: CE2 Product(ion) efficiency

Economic mechanism	Material efficiency, green design, process innovation
Market failure	Firms do not fully internalize environmental damages embodied in materials (Fullerton and Wu, 1998 ; Calcott and Walls, 2000 ; Eichner and Pethig, 2001 ; Bernard, 2015)
Target	Material intensity of production processes and products
Policy instrument	Material taxes, standards, R&D support, eco-design regulation (Choe and Fraser, 2001 ; Fullerton and He, 2024)
Social & institutional issues	Sectoral adjustment; possible employment shifts
Rebound	High when demand is elastic; lower material intensity often lowers product costs (Jevons-type rebound) → efficiency policy needs resource pricing or caps to protect absolute reductions (Smulders and de Nooij, 2003 ; Sorrell, 2009 ; Skelton et al., 2020 ; Di Domenico et al., 2023)
Other caveats	Material balances required in multi-sector IO models (Krysiak and Krysiak, 2003 ; Lorang and Gerlagh, 2024)

Market failures and policies: CE3 Usage intensity & extension

Economic mechanism	Repair, reuse, PaaS, CE platforms, secondary markets
Market failure	High matching costs for second-hand/repair/... supply & demand (Einav et al., 2016 ; Oh, 2019 ; Zhou and Smulders, 2021 ; Brusselaers et al., 2022)
Target	Extended product lifetime, utilization rates, repair and reuse activities
Policy instrument	Right-to-repair, repair subsidies, durability standards, platform regulation (Metta et al., 2025)
Social & institutional issues	Trust, quality uncertainty, repair skills, spare parts, rent-capture by platforms
Rebound	Medium to high; sharing, repair and secondary markets can lower price per service and expand markets (Benjaafar et al., 2019 ; André et al., 2024) (notice model-similarity to CE2)
Other caveats	May have unexpected income distribution effects through factor markets

Market failures and policies: CE4 Material loop closure

Economic mechanism	Secondary materials replacing virgin materials
Market failure	Environmental costs of extraction and disposal are not fully reflected in prices (Smith, 1972 ; Hoel, 1978 ; Palmer et al., 1997 ; Lafforgue and Lorang, 2022)
Target	Recycling, collection, sorting and secondary material markets
Policy instrument	Resource taxes, waste taxes, deposit-refund systems, recycling standards (Fullerton and Kinnaman, 1995 ; Fullerton and Wolverton, 2000 ; Lorang and Gerlagh, 2024)
Social & institutional issues	Quality degradation, sorting jobs, exposure to waste risks, regional burden sharing
Rebound	Medium; lower input costs can expand production, but quality and scrap constraints may limit scale → quality standards and resource pricing matter (Sørensen, 2018 ; Lafforgue and Rouge, 2019 ; Dai et al., 2024)
Other caveats	Secondary materials may remain imperfect substitutes for primary materials; market power may dampen recycling incentives (Chazel et al., 2023 ; Arbex and Mahone, 2024 ; Dai et al., 2026)

Market failures and policies: CE5 Regenerative sourcing

Economic mechanism	Substitution from exhaustible to regenerative inputs
Market failure	Resource scarcity, ecosystem services and biodiversity impacts are imperfectly priced
Target	Material sourcing and resource composition
Policy instrument	Certification, procurement standards, innovation support, environmental pricing
Social & institutional issues	Land-use conflict, biodiversity, food/material competition
Rebound	Uncertain, potentially high; regenerative inputs relax resource scarcity but may shift pressure to land/ecosystems → account for land, biodiversity and ecosystem constraints
Other caveats	Environmental pressures may shift rather than disappear

Model limitations & extending the scope 1

- **capital formation** specifics: CE margins → different type of capital needed → material needed for that capital ([Krysiak and Krysiak, 2003](#))
- **dynamics** (stocks and flows): storage of materials in capital; transition towards CE ([Lorang, 2025](#))
- **endogenous innovation**: long-term effects differ from short-term effects / innovation or activities in one domain may undercut incentives to innovate in other domains ([Zhou and Smulders, 2021](#); [Dugoua and Noailly, 2025](#))
- **factor distribution** (capital, high-skilled and low-skilled labor, wages, unemployment): PaaS substitutes platform-capital for labor → income distribution (value flows change) ([André et al., 2024](#)).
- **flexible goods and IO structure**: for simulating policies it is often useful to use CGE-type models with multiple sectors and intermediate use. ([Lorang and Gerlagh, 2024](#))
- **resource-based / no pollution**: current model neglects (polluting) waste ([Bernard, 2015](#); [Lorang, 2025](#))
- **goods characteristics**: the model is (still) silent on whether upstream design and process choices can be observed by buyers

Model limitations & extending the scope 2

- **multiple jurisdictions**: second-best policies and 'CE-leakage' ([Bernard, 2015](#); [Metta et al., 2026](#))
- **climate complementarity**: Using less material also saves on GHG emissions? ([Metta et al., 2026](#); [Pommeret et al., 2022](#))

Conclusion

- Existing CE taxonomies are highly useful for communicating policies, business models and monitoring circularity.
- But not designed for (macro)economic modelling. We need better understanding of boundaries and connections.
- We propose five economic CE **margins** of adjustment for **agents** operating on specific **markets** where they trade **goods**:
 1. responsible consumption, χ (behavior)
 2. product and production efficiency, θ (technology)
 3. usage intensity and extension, λ (dedicated CE markets for users)
 4. material loop closure, σ (recycling)
 5. regenerative sourcing, R (resource substitution)
- economic models can help analyse welfare, employment, distribution, policy design and rebound.
- We hope this classification helps build connections between an expanding CE economics literature, to contribute to a more circular economy

Thank you!

Questions & Discussion

Reyer Gerlagh, Julie Metta, Claudia Ranocchia

`r.Gerlagh@tilburguniversity.edu`

`j.metta@tilburguniversity.edu`

`c.ranocchia@tilburguniversity.edu`

Appendix CE1 and CE2 in CGE models

- CE1: to represent endogenous responsible consumption, one may specify household preferences to prevent waste / reduce footprints:

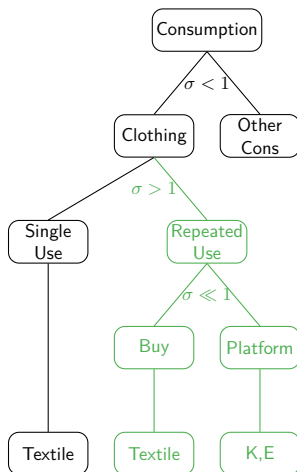
$$U(C, \theta) = \sum_i \alpha_i \ln(C_i) - \chi \sum_i \chi_i C_i \quad (4)$$

- χ represents a preference; can be modeled similar to (embodied material) tax (if CGE represents χ)
 - relative preference for immaterial consumption increases with income
- CE2: standard property of CGEs: a **resource tax** (upstream, not downstream!) causes firms to substitute labor and capital for material inputs.

Appendix: consistent materials in CGE models (θ)

- Gerlagh & Lorang (2024): how to **endogenously represent θ in CGE**, for multi-sector, when intermediate flows have individual intensities.
- Gerlagh, Lorang, Pommeret & Pottier (2026): Regulation can use end-of-chain (consumption) taxes on material intensity (CE1). **This induces CE2** if these good features are salient in markets.
- Gerlagh & Ranocchia (2026 WIP): how to include θ -salience in CGEs.

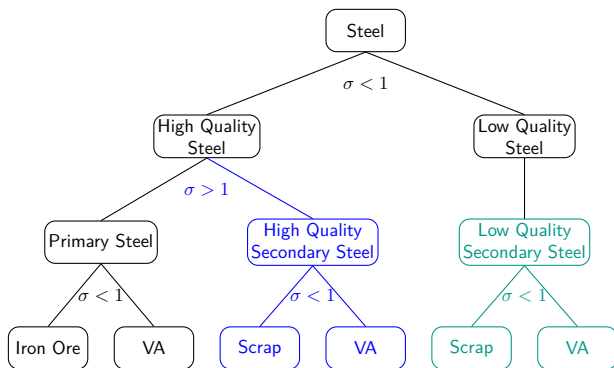
Appendix: CE3 usage intensity and extension in CGE model



Model needs to represent

- platform (sector) that supports Reuse (using transport, capital, electricity, **almost no labor**)
- need to think about drivers for reuse: lower platform costs / preference change / ...?
- if platform becomes 'cheap', it will induce buys for reuse ($\sigma < 1$)
- which substitute for single use, thus reducing 'textile' demand (at market prices: share parameter for repeated use > share single use)
- for repair, similar structure, but 'platform' being labor intensive
- for refurbish, remanufacture, repurpose: original sector contributes to platform

Appendix: CE4 closing the loop in CGE model



Model needs to represent

- At current prices: **secondary steel** has a substantial share of steel, but its share cannot grow as it is **low quality** (compared to primary steel)
- If primary steel becomes more expensive, **secondary steel** can upgrade to become **high quality** and substitute for primary steel

- Francisco J. André, Carmen Arguedas, and Sandra Rousseau. Strategic pricing, lifespan choices and environmental implications of peer-to-peer sharing. Journal of Environmental Economics and Management, 125:102953, 2024. doi: 10.1016/j.jeem.2024.102953.
- Marcelo Arbex and Zachary Mahone. Materials, technology and growth: Quantifying the costs of circularity. Working Paper (University of Windsor), 2024. URL <https://web2.uwindsor.ca/economics/RePEc/wis/pdf/2402.pdf>.
- Anne Baumgartner, Frank C. Krysiak, and Florian Kuhlmeier. Sufficiency without regret. Ecological Economics, 200:107545, 2022. doi: 10.1016/j.ecolecon.2022.107545.
- Saif Benjaafar, Guangwen Kong, Xiang Li, and Costas Courcoubetis. Peer-to-peer product sharing: Implications for ownership, usage, and social welfare in the sharing economy. Management Science, 65(2):477–493, 2019. doi: 10.1287/mnsc.2017.2970.
- Rasmus Berg, Peter K Kruse-Andersen, and Thor Donsby Noe. Is recycling wasted? circular economy and the material rebound effect. SSRN Working Paper, 2025. doi: 10.2139/ssrn.5467608.
- Sophie Bernard. North–south trade in reusable goods: Green design meets illegal shipments of waste. Journal of Environmental Economics and Management, 70:1–13, 2015. doi: 10.1016/j.jeem.2014.10.004.
- Fenna Blomsma and Mike Tennant. Circular economy: Preserving materials or products? introducing the resource states framework. Resources, Conservation and Recycling, 156:104698, 2020. doi: 10.1016/j.resconrec.2020.104698. Introduces the Resource States framework and the Circularity Compass tool.

- Jan Brussaers, K. Breemers, T. Geerken, M. Christis, B. Lahcen, and Y. Dams. Macroeconomic and environmental consequences of circular economy measures in a small open economy. The Annals of Regional Science, 68:479–508, 2022. doi: 10.1007/s00168-021-01079-6.
- Thiess Büttner and Anne Kesselring. Banning products with low energy efficiency: Market response and adjustment cost. Journal of the Association of Environmental and Resource Economists, 2024. doi: 10.1086/730148.
- Paul Calcott and Margaret Walls. Can downstream waste disposal policies encourage upstream design for environment? American Economic Review, 90(2):233–237, 2000. doi: 10.1257/aer.90.2.233.
- Simon Chazel, Sophie Bernard, and Hassan Bencheekroun. Energy transition under mineral constraints and recycling: A low-carbon supply peak. Resource and Energy Economics, 72:101361, 2023. doi: 10.1016/j.reseneeco.2022.101361.
- Chongwoo Choe and Iain Fraser. On the flexibility of optimal policies for green design. Environmental and Resource Economics, 18(4):367–371, 2001. doi: 10.1023/A:1011170816440.
- Miao Dai, Mouez Fodha, and Francesco Ricci. Efficient recycling policies under tight markets for scrap. Working Paper, 2024.
- Miao Dai, Hassan Bencheekroun, Gerard van der Meijden, and Cees Withagen. Recycling and oligopolistic competition in markets for critical minerals. Working Paper, 2026.
- Partha Dasgupta and Geoffrey Heal. The optimal depletion of exhaustible resources. The Review of Economic Studies, 41(5):3–28, 1974. doi: 10.2307/2296369. Symposium on the Economics of Exhaustible Resources.

- Lorenzo Di Domenico, Marco Raberto, and Karolina Safarzynska. Resource scarcity, circular economy and the energy rebound: A macro-evolutionary input-output model. Energy Economics, 128:107155, 2023. doi: 10.1016/j.eneco.2023.107155.
- Eugénie Dugoua and Joëlle Noailly. Critical minerals and the clean energy transition: The role of innovation across the supply chain. Working Paper, 2025.
- Thomas Eichner and Rüdiger Pethig. Product design and efficient management of recycling and waste treatment. Journal of Environmental Economics and Management, 41(1):109–134, 2001. doi: 10.1006/jeem.2000.1126.
- Liran Einav, Chiara Farronato, and Jonathan Levin. Peer-to-peer markets. Annual Review of Economics, 8:615–635, 2016. doi: 10.1146/annurev-economics-080315-015334.
- Alessa Eisenreich, Julia Bleicher, Lukas Falke, Heike Geissler, Luisa Herrmann, Fabian Hille, Carl von der Osten, Sven Rusch, Jan Stroh, and Lorenz Wiener. Toward a circular value chain: Impact of the circular economy on a company’s value chain processes. Journal of Cleaner Production, 378: 134375, 2022. doi: 10.1016/j.jclepro.2022.134375.
- EMAF. Towards the circular economy: Economic and business rationale for an accelerated transition. Technical report, Ellen MacArthur Foundation, 2012. URL <https://content.ellenmacarthurfoundation.org/m/27265af68f11ef30/original/Towards-the-circular-economy-Vol-1.pdf>.
- Don Fullerton and Shan He. Do market failures create a “durability gap” in the circular economy? Journal of the Association of Environmental and Resource Economists, 11(6):1387–1417, 2024. doi: 10.1086/729541.

- Don Fullerton and Thomas C. Kinnaman. Garbage, recycling, and illicit burning or dumping. Journal of Environmental Economics and Management, 29(1):78–91, 1995. doi: 10.1006/jeem.1995.1032.
- Don Fullerton and Ann Wolverton. Two generalizations of a deposit-refund system. American Economic Review, 90(2):238–242, 2000. doi: 10.1257/aer.90.2.238.
- Don Fullerton and Wenbo Wu. Policies for green design. Journal of Environmental Economics and Management, 36(2):131–148, 1998. doi: 10.1006/jeem.1998.1044.
- André Grimaud and Luc Rouge. Environment, directed technical change and economic policy. Environmental and Resource Economics, 41(4):439–463, 2008. doi: 10.1007/s10640-008-9201-4.
- Michael Hoel. Resource extraction and recycling with environmental costs. Journal of Environmental Economics and Management, 5(3):220–235, 1978. doi: 10.1016/0095-0696(78)90010-4.
- Julian Kirchherr, Denise Reike, and Marko Hekkert. Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling, 127:221–232, 2017. doi: 10.1016/j.resconrec.2017.09.005.
- Julian Kirchherr, Denise Reike, and Marko Hekkert. Conceptualizing the circular economy: An analysis of 221 definitions. Resources, Conservation and Recycling, 194:107001, 2023. doi: 10.1016/j.resconrec.2023.107001.
- Frank C. Krysiak and Daniela Krysiak. Production, consumption, and general equilibrium with physical constraints. Journal of Environmental Economics and Management, 46(3):513–538, 2003. doi: 10.1016/S0095-0696(03)00034-7.
- Gilles Lafforgue and Etienne Lorang. Recycling under environmental, climate and resource constraints. Resource and Energy Economics, 70:101327, 2022. doi: 10.1016/j.reseneeco.2021.101327.

Gilles Lafforgue and Luc Rouge. A dynamic model of recycling with endogenous technological breakthrough. Resource and Energy Economics, 57:101–118, 2019. doi: 10.1016/j.reseneeco.2018.09.003.

Etienne Lorang. The social costs of waste. Working Paper, 2025. URL <https://www.etiennelorang.fr/research>.

Etienne Lorang and Reyer Gerlagh. Resource extraction taxes versus waste taxes in general equilibrium. CESifo Working Paper Series, (11091), 2024.

J. Metta, X. Li, C. Brink, R. Gerlagh, and E. Lorang. Beyond protectionism: Circular economy policies as a geopolitical strategy for sufficiency and equity. Technical report, Working Paper, 2026. Available upon request.

Julie Metta, Kris Bachus, and Sandra Rousseau. Socio-economic and volume effects of a circular value chain for clothing. Ecological Economics, 224:108287, 2025. doi: 10.1016/j.ecolecon.2025.108287.

Piero Morseletto. Targets for a circular economy. Resources, Conservation and Recycling, 153:104553, 2020. doi: 10.1016/j.resconrec.2019.104553.

Hyunseung Oh. The role of durables replacement and second-hand markets in a business-cycle model. Journal of Money, Credit and Banking, 51(6):1735–1758, 2019. doi: 10.1111/jmcb.12610.

Karen Palmer, Hilary Sigman, and Margaret Walls. The cost of reducing municipal solid waste. Journal of Environmental Economics and Management, 33(2):128–150, 1997. doi: 10.1006/jeem.1997.0986.

Aude Pommeret, Francesco Ricci, and Katheline Schubert. Critical raw materials for the energy transition. European Economic Review, 141:103991, 2022. doi: 10.1016/j.euroecorev.2021.103991.

- Aude Pommeret, Reyer Gerlagh, Etienne Lorang, and Antonin Pottier. Source taxes versus end-of-chain taxes in general equilibrium. Presentation (TSE), 2026. URL <https://www.tse-fr.eu/sites/default/files/TSE/documents/conf/2026/energy/pommeret.pdf>.
- José Potting, Marko Hekkert, Ernst Worrell, and Aldert Hanemaaijer. Circular economy: Measuring innovation in the product chain. Technical Report 2544, PBL Netherlands Environmental Assessment Agency, The Hague, 2017. URL <https://www.pbl.nl/sites/default/files/downloads/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pdf>.
- Alexandra Skelton, Leonidas Paroussos, and Julian Allwood. Comparing energy and material efficiency rebound effects: An exploration of scenarios in the GEM-E3 macroeconomic model. Ecological Economics, 169:106536, 2020. doi: 10.1016/j.ecolecon.2019.106536.
- Vernon L. Smith. Dynamics of waste accumulation: Disposal versus recycling. Quarterly Journal of Economics, 86(4):600–616, 1972. doi: 10.2307/1882010.
- Sjak Smulders and Michiel de Nooij. The impact of energy conservation on technology and economic growth. Resource and Energy Economics, 25(1):59–79, 2003. doi: 10.1016/S0928-7655(02)00017-9.
- Robert M. Solow. Intergenerational equity and exhaustible resources. The Review of Economic Studies, 41(5):29–45, 1974. doi: 10.2307/2296370. Symposium on the Economics of Exhaustible Resources.
- Peter Birch Sørensen. The basic environmental economics of the circular economy. Working Paper (SSRN), 2018. doi: 10.2139/ssrn.3064684. URL <https://ssrn.com/abstract=3064684>. EPRU Working Paper Series No. 2017-04.
- Steve Sorrell. Jevons’ paradox revisited: The evidence for backfire from improved energy efficiency. Energy Policy, 37(4):1456–1469, 2009.

- Corrado Topi, Igor Taranic, and Arno Behrens. Understanding the circular economy in europe, from resource efficiency to sharing platforms: The CEPS framework. Special Report 143, Centre for European Policy Studies (CEPS), Brussels, 2016. URL https://cdn.ceps.eu/wp-content/uploads/2016/07/SR%20No143_Circular_Economy_0.pdf.
- Sophie Lian Zhou and Sjak Smulders. Closing the loop in a circular economy: Saving resources or suffocating innovations? European Economic Review, 139:103857, 2021. doi: 10.1016/j.euroecorev.2021.103857.
- Trevor Zink and Roland Geyer. Circular economy rebound. Journal of Industrial Ecology, 21(3): 593–602, 2017.