

DELIVERABLE 3.1

Reports and survey data on identification of promising technologies and business practices of circularity for inclusion in decarbonization pathways

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For Annex C2:



- Wagner, B. A., van der Werff, E., & Steg, L. (2025, August 21). Values for Circular Work: Biospheric Beliefs, Self-Efficacy, and Social Norms in Circular Workplace Pro-Environmental Behaviours and Activism. DOI [10.17605/OSF.IO/B6AJV](https://doi.org/10.17605/OSF.IO/B6AJV) Retrieved from osf.io/b6ajv



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CircEULAR

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Executive Summary

This report evaluates circular technologies and business models for their potential contribution to decarbonization strategies. Circular practices encompass the 10R strategies, ranging from refuse and reduce to reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover, that aim to slow, close, and narrow resource loops.

The research undertaken for this deliverable addresses three objectives: (i) assessing the mitigation potential of circular technologies and business models, (ii) identifying policy interventions that align climate goals with circular economy achievements, and (iii) generating empirical insights on specific circular practices. The report tackles three critical knowledge gaps, including the uncertain translation of firm-level circular economy interventions into macro resource efficiency gains, limited understanding of synergies between circular economy practices and fossil fuel infrastructure transition, and misalignment between employee perceptions and consumers' willingness to engage in circular behaviours.

To respond to these objectives and fill the research gaps, this report explores three critical analyses, whose findings provide actionable insights for bridging the gap between the circular economy and climate mitigation outcomes.

First, the report presents a novel framework to determine the conditions under which firm-level circular strategies achieve macro-level resource reductions and climate benefits. The framework demonstrates that circular practices don't automatically reduce resource consumption due to offsetting mechanisms such as rebound effects, whereby economic gains are redirected to resource-intensive activities, incomplete substitution occurs, and circular production requires important resources. The findings highlight the need for strict, comprehensive policy packages that complement efforts to encourage circular practices.

Second, the report analyses infrastructure repurposing opportunities and identifies those promising for decarbonization pathways. In particular, infrastructure repurposing opportunities of steel and barite for cooling applications are identified as promising, while materials like copper and aluminum provide environmental benefits but cannot meet energy transition demand. Therefore, policymakers should prioritize selective material recovery strategies, focusing on high-impact opportunities like steel and barite while developing alternative approaches for materials that cannot meet transition demands.

Finally, the report presents data collected through two surveys across five European countries examining consumer and employee perceptions of values, circular beliefs and willingness to behave more circularly in the mobility and housing domain as well as examining workplace behaviours aimed at advancing organisations' circularity. This empirical research with employees and consumers across multiple countries reveals that employees slightly, but consistently, overestimate consumer circular beliefs and willingness for both mobility and housing. The findings



underscore the importance for companies to consider less circularity-inclined consumers when developing circular products and services as well.

Keywords

Circular goods and services; circular technologies; R-strategies; climate mitigation; perceptions of circular beliefs; willingness for circular consumption



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Abbreviations

CE	circular economy
EU	European Union
GHG	greenhouse gas
WP	work package

Circular Provision of Goods and Services

This deliverable contributes to Work Package 3 (WP3) of the CircEULAR project, which focuses on identifying the opportunities, strategies, and policy instruments needed to support the circular provision of goods and services in the EU. The aim is to advance CircEULAR’s broader objective of aligning circular economy pathways with net-zero greenhouse gas (GHG) emission targets.

Specifically, the deliverable addresses WP3’s three core objectives:

1. Assess the contribution of technological and business model solutions for circularity in the provision of goods and services to net-zero GHG emission targets.
2. Evaluate combinations of policy interventions and instruments that can align climate mitigation goals with the achievement of a circular economy in the EU.
3. Generate empirical insights on specific circular practices with the potential to reduce both material use and GHG emissions in digitalisation, mobility, and buildings and household services

The deliverable builds on activities in Task 3.1, including developing a framework linking micro circular practices to macro outcomes, such as climate mitigation, initial assessments of fossil infrastructure at risk of becoming stranded, and a survey-based analysis of employee–consumer perceptions.



1 Introduction

Circular economy (CE) practices — such as reducing, reusing, and recycling materials — are increasingly promoted as tools to improve resource efficiency and contribute to climate goals, particularly in the context of Europe's net-zero agenda.

While some studies highlight the potential of CE strategies in sectors like energy supply, transport, and industry, substantial uncertainty persists regarding whether firm-level circular interventions actually translate into macro-level resource efficiency gains and greenhouse gas emission reductions (Cantzler et al, 2020). Reaching climate goals necessitates the phase-out of fossil fuels which might generate significant stranded assets (Semieniuk et al. 2022) and makes material stored in fossil infrastructure available for circular use. Yet, limited research has examined the environmental and economic benefits of applying circular economy principles to potentially obsolete fossil infrastructure and its effect on infrastructure transition policies. Importantly, a critical knowledge gap exists regarding the misalignment between employees' perceptions and consumers' actual willingness to behave more circularly, potentially reducing the likelihood that companies adopt circular economy strategies. This is exemplified by distinct research streams focusing on either circular consumption behaviours and consumers' motivations or investigating producers' circular business models, in which consumers receive comparatively limited attention (see, for example, Camacho-Otero et al., 2018, and Kirchherr et al., 2013). Furthermore, existing literature predominantly treats firms as black boxes, overlooking the critical human dimensions — including employee perceptions of consumers, behavioural motivations, and organisational change processes — that fundamentally shape the adoption and effectiveness of circular strategies from within organisations.

This report aims to fill in three distinct research gaps. First, the report addresses what we call “**micro-to-macro translation gap**”. Little is known about the conditions under which firm-level circular strategies may (or may not) lead to macro-level reductions in resource extraction, use, and disposal—ultimately enabling climate mitigation. To fill in this gap, WP3 has focused on developing a conceptual framework which takes into account three central limitations of circular economy: (i) rebound effects, where efficiency gains may be offset by increased demand; (ii) the risk that circular practices increase total material availability, potentially stimulating further consumption; and (iii) thermodynamic limits, which imply that circular processes still consume resources and produce waste. Importantly, this work contributes to assessing the mitigation potential of technological and business model solutions for circularity (**objective 1**) by unifying fragmented insights across economic, sustainability, and engineering disciplines. By identifying supplementary market features and policies needed to guarantee a reduction in resource use, extraction and disposal, this work connects to identifying policy interventions and instruments that can align climate mitigation goals with the achievement of a circular economy (**objective 2**).

Second, this report assesses what we call “**the infrastructure transition policy gap**”, which is linked to the synergistic potential between circular economy practices in the domain of infrastructure and



energy transition (**objective 2**). Given that fossil infrastructure (e.g., oil and gas rigs, pipelines, coal mines, and power plants) will become obsolete through energy transitions over the coming decades—depending on the specific transition pathway—the research identifies promising examples for repurposing (e.g., recycling, reusing) fossil infrastructure that would allow improving decarbonization pathways, thus generating empirical insights on specific circular strategies (**objective 3**). The study specifically focuses on *repurposing*, defined as strategies that enable the production of green technologies using materials, components, or subsystems from existing fossil infrastructure parts or products. Examples have been classified as “promising” if they allow the acceleration of the energy transition and/or significantly reduce environmental impacts during the transition (Desing et al. 2024), therefore contributing to **objective 1**. One material identified as promising is steel, because it has been identified as capable of meeting additional demand for the energy transition (if recycled), and would avoid up to 1.85 Gt CO₂ emissions. Other materials used in low-carbon energy systems, such as silicon in photovoltaics or nickel in batteries, appear less promising due to the significantly lower stock available in existing fossil infrastructure than projected future demand.

Third, the report examines a potential “**employee-consumer misalignment perception gap**”. This misalignment may influence the likelihood that employees will implement circular strategies for providing circular goods and services with their company. To understand this potential misalignment, the current report explores employees’ perceptions of consumer beliefs and willingness to behave more circularly and compares them to consumers’ actual beliefs and willingness. Two large-scale online surveys were conducted across five European countries, thus generating extensive empirical insights on specific circular behaviours (**objective 3**). The first survey explored consumers’ beliefs regarding the current linear and circular economy, as well as their willingness to engage in circular behaviours (see Grealis & Rau, 2025). The second survey examined employees’ perceptions of consumers’ beliefs and willingness, allowing for a direct comparison of consumers’ self-reported beliefs and willingness with employees’ perceptions of these. Specifically, the research investigates consumers’ willingness to adopt circular behaviours in the domains of mobility (e.g., not owning a car and using car-sharing services instead of owning a car) and housing (e.g., downsizing to a smaller house or sharing living spaces with non-family members). The behaviours studied focus on *narrowing resource loops* and align with the R strategies thought to be most impactful for mitigation: *refuse*, *rethink*, and *reduce*. The research also examines underlying beliefs that may influence consumers’ willingness to behave circularly, such as awareness of environmental and social impacts of linear behaviours, perceived responsibility and capability to act, and belief in the effectiveness of circular behaviours in addressing environmental and social challenges.

Expanding the scope of the initially proposed research questions in the grant agreement, the employee survey also measured two types of workplace environmental behaviours aimed at advancing the organisation's circularity. The first focuses on individual, job-related actions that employees can take within their work roles to increase circular practices at work. These include carrying out work in a circular fashion, considering ways to include circularity into work-related



decisions, and contributing to projects or events at work that focus on circularity. These are known as workplace pro-environmental behaviours (WPEBs; Wagner et al., 2025). The second type captures more outward-focused efforts to influence others in the organisation to support circularity, such as discussing with colleagues how to implement circularity at work, encouraging co-workers and/or clients to behave more circularly, setting a good example to others in the organisation by engaging in circular behaviours; and putting forward ideas for the organisation on how to become more circular. These behaviours are referred to as workplace everyday environmental activism (WEEA), an emerging concept that captures actions by employees aimed at influencing others and, by extension, the broader organisation towards circularity (Van Valkengoed et al., 2025; see also Pacheco et al. (2025) for circular citizenship behaviours which are aimed at businesses becoming more circular).

The remainder of this deliverable provides an overarching summary of all the contributions in terms of methodology and main results. The detailed analyses can be found in Annexes A through C.

2 Micro-to-Macro translation gap (Annex A)

2.1 Methods

CMCC developed a comprehensive framework rooted in sequential reasoning to examine how micro-level circular practices may contribute to macro-level circularity. The framework focuses on three key transmission channels—termed counterparts—through which firm-level actions interact with broader economic and resource systems:

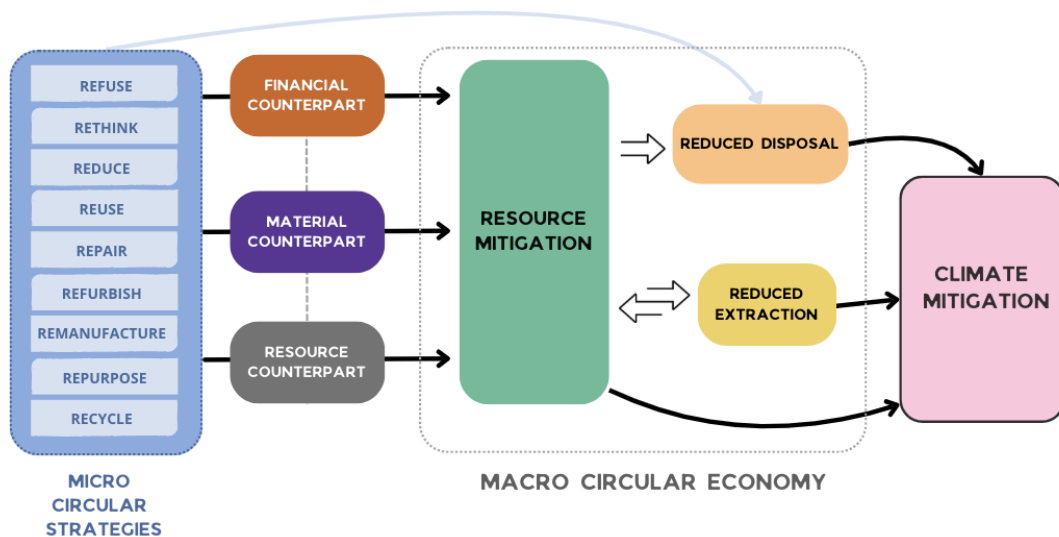
1. *Financial Counterpart*: This channel explores how circular strategies affect firms' production costs, pricing, profit margins and investment. In turn, prices and new features of circular products shape downstream demand. For example, if circular practices lower costs, savings may be passed on as lower prices, possibly triggering increased consumption, i.e., a potential rebound effect.
2. *Material Counterpart*: This channel captures how circular practices directly affect the supply and demand of materials, including substitution between virgin and recycled resources.
3. *Resource Counterpart*: This channel examines indirect effects, such as the infrastructure and energy demand that support circular systems. Implementing circular strategies consumes resources, partially reducing their potential resource savings.

To operationalise the framework, the authors adopt a set of simplifying assumptions. On the supply side, firms are assumed to be profit-maximising, operating within stable technological frontiers and competitive environments where circular goods can be profitably produced and sold. A sufficiently large share of firms is presumed to adopt these strategies, ensuring their macro relevance. On the demand side, consumers have fixed incomes and preferences are moderately evolving—some consumers are willing to pay more for circular goods, but they are not all committed to drastically lower consumption on environmental grounds.



The analysis focuses on the short- to medium-term macroeconomic effects of an exogenous shift toward firm circular practices (excluding energy recovery) on resource flows. The framework distinguishes resource flows between **resource mitigation** (less use), **reduced extraction**, and **reduced disposal**, treating them as related but analytically distinct outcomes. Finally, from these three outcomes (conceptualised as a macro CE), the framework emphasises the synergies with **climate mitigation**.

Figure 1: Outlook of the framework



2.2 Results

CMCC's analysis shows that circular practices do not inherently guarantee reductions in emissions or resource use. Achieving resource mitigation goals requires system-wide policies that constrain resource flows, enable substitution, and promote sufficiency-oriented behaviour. Figure 3 summarises the conditions for reaching a decreased use of resources at the macro-level.

Whether circular practices lead to resource mitigation depends on certain market features.

1. **Market power** can either reinforce or undermine mitigation efforts, but it is not identified as a condition for resource mitigation, as market power alone does not predict outcomes. The critical factor is how economic rents—profits or consumer savings generated from circularity—are allocated between resource-light and resource-intensive activities. This dynamic can be influenced through targeted policy instruments such as taxation.
2. **Demand saturation** is a condition ensuring resource mitigation. It means that demand cannot increase over a certain limit and becomes inelastic to price, preventing rebound effects. However, natural saturation is rare at the product level and inconceivable at the global level, especially given development needs in the Global South. Policymakers can



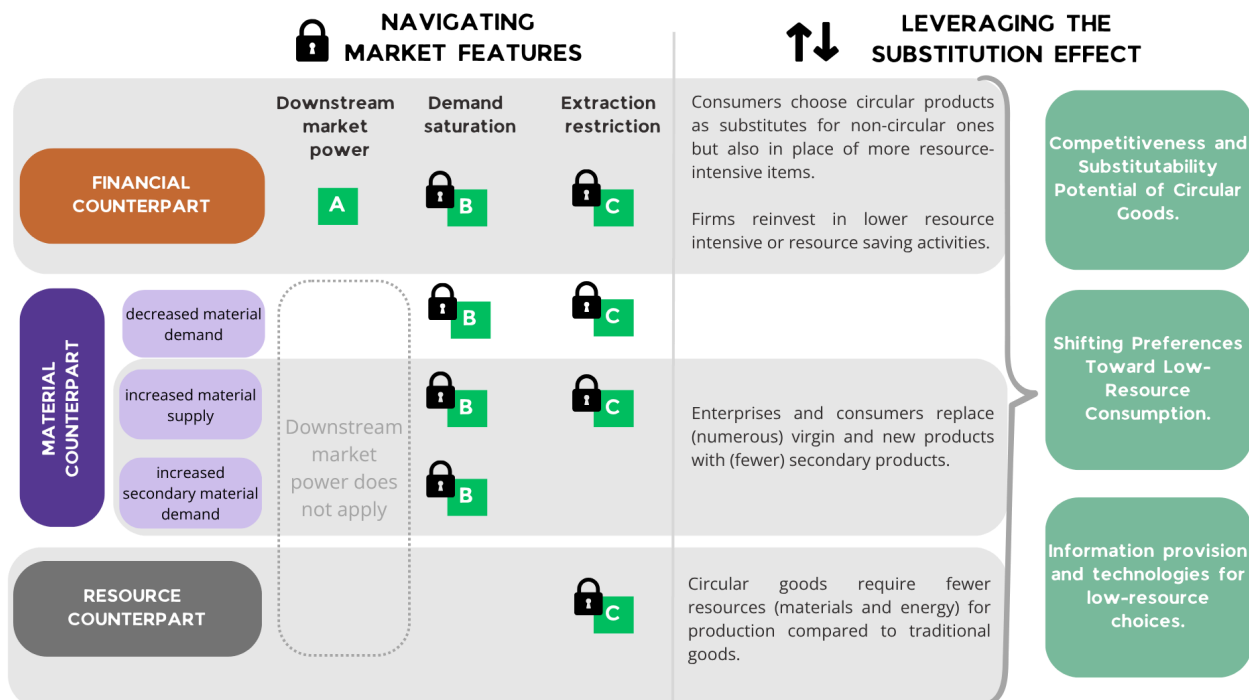
encourage and approach saturation via urban planning or sufficiency campaigns. They can enforce saturation levels through quotas for the highest-impact sectors.

3. **Limiting extraction** through quotas, regulation, or resource taxes can constrain resource increase at the source. While challenging in practice due to enforcement and political economy barriers, instruments like biodiversity conservation plans or extraction taxes (e.g., on aggregates) have shown promise.

Beyond demand saturation and extraction limits, we find several conditions to leverage the **substitution effect** towards resource mitigation. Circular goods must effectively replace non-circular alternatives without replacing more environmentally sound options. This requires three enabling conditions:

- **Price/quality competitiveness** of circular goods.
- **Strong preferences** for low-resource lifestyles and investment patterns.
- **Accessible information** about the actual resource intensity of goods and services, enabled through tools like life cycle assessment (LCA).

Figure 3: Conditions for circular strategies to lead to resource mitigation



Notes: The padlocks in the Figure indicate that activating the market conditions (demand saturation and extraction restriction) can block the rebound channels. The green boxes on the right indicate conditions to leverage substitution effects counteracting potential rebound effects on resource use.

The framework emphasises maintaining high recycling rates and maximising product lifespans as conditions to ensure that **resource mitigation** translates into **reduced disposal**. Policies such as



design for recyclability, extended producer responsibility, and emotional durability in product design can help achieve this. Care must be taken to limit trade-offs, such as excessive recycling incentives encouraging end-of-life to reclaim materials.

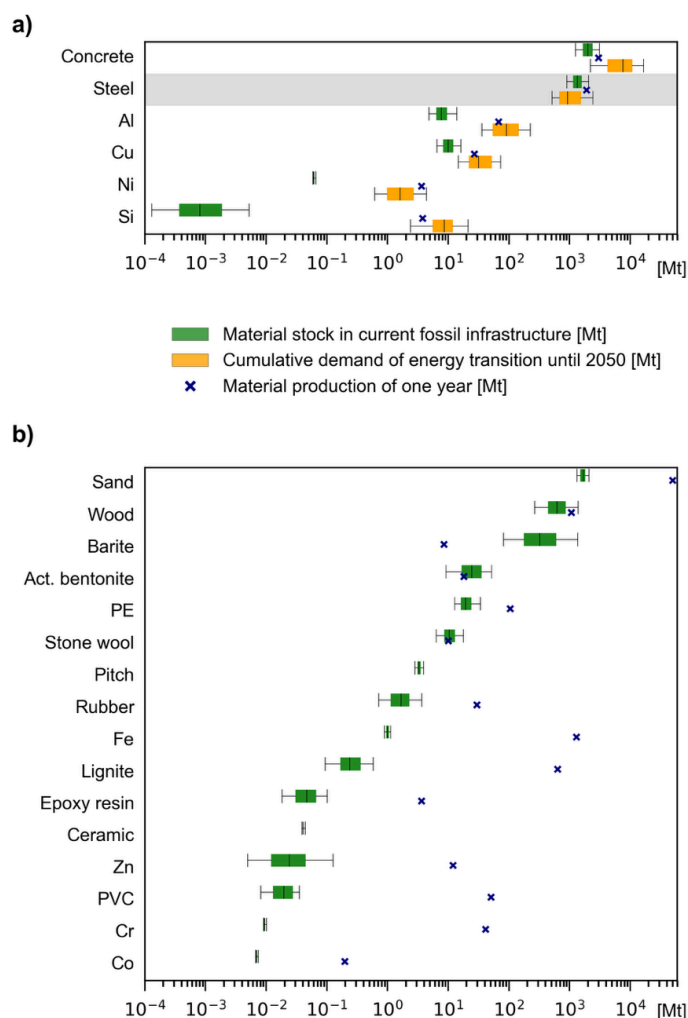
The framework establishes that circular economy practices can contribute to climate mitigation directly and indirectly. The direct channel involves prioritising the reduction of carbon-intensive resources within resource mitigation. Resources are not carbon-intensive by nature, but in the way they are used (e.g., combusted). The framework operates within a quasi-stable technological frontier, so we consider carbon intensity fixed. The indirect channel operates by protecting carbon sequestration services disrupted by resource extraction and waste disposal activities—including habitat destruction from mining and landfilling, altered water flows, forest loss— and methane emissions from anaerobic decomposition. Since ecosystems yield different types of services and their capacity for climate regulation varies spatially, the geographical aspects of resource provenance and disposal locations are critical factors in determining the overall climate impact of circular practices. While solid waste is estimated to contribute relatively little to climate change directly, landfills represent an opportunity cost by occupying land that could otherwise support biodiversity and climate services.

3 Infrastructure transition policy gap - Stranded Assets and Repurposing (Annex B)

3.1 Methods

After classifying fossil infrastructure components (oil and gas rigs, coal mines, pipelines, power plants; oil refineries omitted due to lack of data) that would become available for repurposing, Empa mapped the materials contained in those infrastructures for the EU and globally. This was done by combining geospatially explicit data on fossil assets from the GEM database (e.g. for coal power plants; Global Energy Monitor 2024) with material inventories from ecoinvent (Wernet 2016). The resulting material stocks were compared to estimates for material demand induced by the energy transition, revealing potentially interesting materials for recycling into renewable energy components. Using prospective LCA for repurposing such materials into renewable energy systems reveals the potential savings in environmental impacts and externality costs. Furthermore, engineering principles, LCA, and dynamic stock and flow modelling are used to evaluate repurposing strategies aiming at reusing parts of natural gas pipelines for district heating systems (described in more detail in D5.3 on buildings) and e-retrofitting diesel buses (more information in D5.2 on mobility).

Figure 2: Comparison of material availability in fossil infrastructure with projected energy transition requirements to 2050.



NOTES: **a)** Global stocks of 6 materials stored in currently operating, mothballed, or idle fossil infrastructure (green), compared to cumulative demand for global energy transitions until 2050 (data from Wang et al. 2023, yellow) and current annual production (blue cross, various sources, see SM Table S1). Uncertainties (box shows the inter-quartile range, whiskers show 2.5th and 97.5th percentile of distribution; calculated using a Monte Carlo simulation with $n = 500$) stem from the material intensity and linking infrastructure types. The distribution of demands shows the range within possible energy transition scenarios and models. **b)** 16 Material stocks in the current fossil infrastructure that are currently not in demand for energy transitions (or no demand reported in Wang et al. 2023, e.g., Cobalt). Yet they might become interesting when redesigning renewable infrastructure: PE=polyethylene, PVC=polyvinyl chloride.

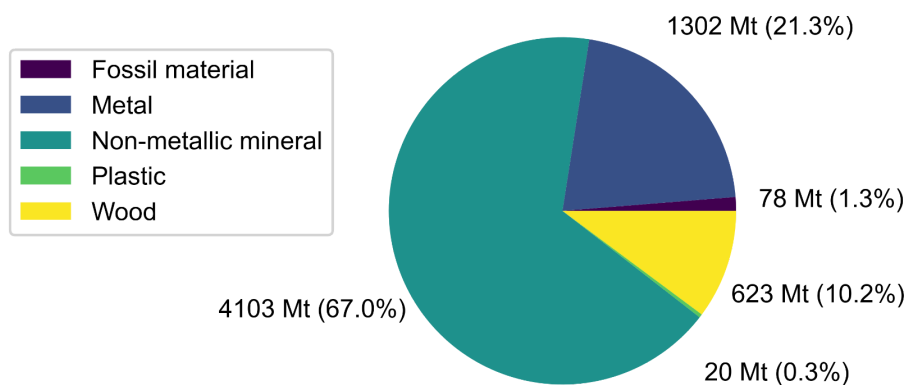
3.2 Results

Mapping soon-to-be-obsolete fossil infrastructure produced maps of locations and stock values for 22 materials (stocks in Fig. 3, share of material types in Fig. 4). Steel is the largest metal stock in fossil infrastructure (see Fig. 5 for stocks in Europe) and of similar magnitude as the demand induced by decarbonization pathways, making it the most promising material category for recycling



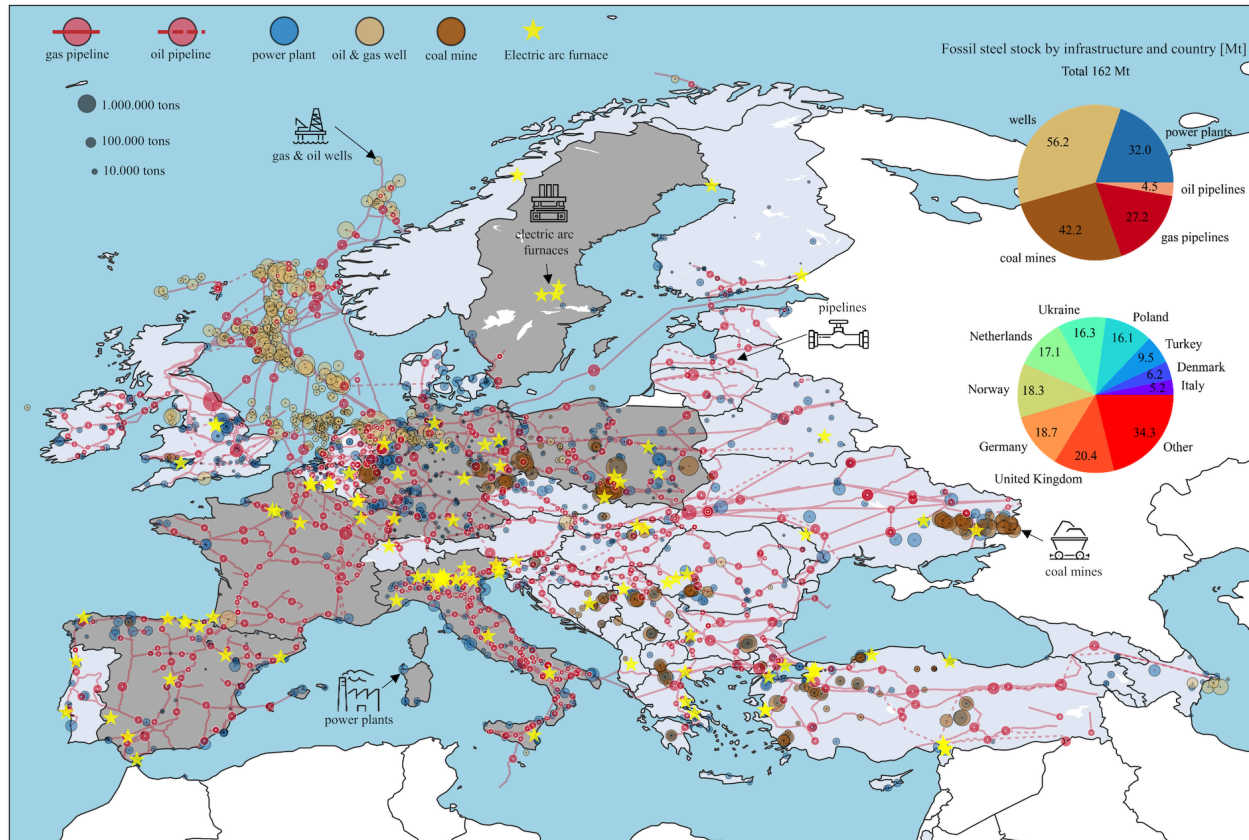
into renewable energy components. Therefore, recycling steel from fossil infrastructure was classified as promising due to its potential to decrease emissions of the energy transition. Copper and Aluminium also show significant potential to contribute to decarbonization; however, the fossil infrastructure alone would not be enough to satisfy material demand from the global energy transition.

Figure 4: Share of materials in global fossil infrastructure by type.



In addition to contributing to the energy transition, recycling steel from fossil infrastructure shows huge benefits both in terms of environmental impact savings and externality cost reductions (in magnitude of trillion US dollars; Schlesier et al. 2025) when comparing impacts of virgin and recycled production. Externalities are additional healthcare, adaptation or natural resource costs generated by pollution, environmental damage, and resource use. When recycled steel is used to construct wind turbine towers or replace aluminium used in mounting systems of solar photovoltaics, CO₂-eq emissions and externality costs of wind and solar electricity can be reduced by about 1/3.

Figure 5: Steel stocks in fossil infrastructure and steel recycling plants (yellow stars) in Europe.



Another promising candidate for repurposing is barite, a mineral used in drilling fluids in the oil and gas industry: it is present in fossil infrastructure at a sizable stock and used in novel radiative cooling paints to passively cool buildings. Yet, the environmental potential was negligible in this case, because the major contributor to environmental impacts from radiative cooling paints is the plastic binder, not the barite particles. Also, barite production is quite large today, resources are abundant, and the demand for radiative cooling paint is small compared to current use in the oil and gas industry.

Repurposing gas pipelines for district heating networks focuses on reusing parts (i.e., pipes) and can be technically feasible in certain contexts. When pipe diameters fit (-20% to +50%) and the remaining lifetime is at least half of new pipes, this strategy can deliver significant environmental benefits of up to 40% reduction in CO₂-eq emissions (Wiedmann 2024).

E-retrofitting existing diesel buses maintains the integrity of the buses, changing only the fossil drivetrain for a new electric one. Avoiding the production of new bus bodies already saves environmental impacts, but the larger environmental benefit comes from accelerating the phase out of diesel buses by about 15 years in Europe. Furthermore, this strategy allows expanding the electric bus fleet earlier than without retrofitting (Desing et al., in preparation).



4 Employee-consumer misalignment perception gap (Annex C1)

4.1 Methods

To examine potential (mis)alignments between employees' perceptions and consumers' actual values, beliefs, and willingness to engage in circular behaviours, the RUG and LMU teams conducted two large-scale surveys across five European countries: Germany, Italy, Lithuania, the Netherlands, and the United Kingdom. Data was collected from representative samples of consumers ($N = 5651$; see Grealis & Rau, 2025) and among employees from the same countries, whose consumer base is also located in (at least one of) these countries ($N = 3253$). From these employees, 525 work in the mobility sector, 1300 in the building sector, and 1428 in the manufacturing sector. For comparing employees' and consumers' answers, we focus on the mobility and building sector.

Consumers were asked about their willingness to engage in circular behaviours in two domains: mobility and housing. Mobility-related questions focused on participants' willingness to live without a car or to use car sharing as an alternative to car ownership. Housing-related questions focused on willingness to live in a smaller home (if one were readily available) or share certain living spaces (such as the kitchen, bathroom, or garden). Willingness in the mobility domain was measured on a 7-point scale from (1) *no, very unlikely* to (7) *yes, very likely*, and willingness in the housing domain on a 7-point scale from (1) *not at all willing* to (7) *very willing*.

To understand beliefs underlying the willingness, consumers were asked about four core value orientations: (1) *biospheric values* (concern for the environment and nature), (2) *altruistic values* (concern for the well-being of others), (3) *hedonic values* (focus on pleasure and comfort), and (4) *egoistic values* (focus on personal resources such as wealth and status).

Additionally, we assessed:

- *Problem awareness* – the extent to which consumers recognize that car use/living in a large home contributes to environmental and social problems;
- *Self-efficacy* – beliefs about their own ability to reduce their car use/live in a small home or share living spaces;
- *Outcome efficacy* – beliefs about whether these behaviours would help reduce environmental and social problems;
- *Personal norms* – feelings of moral obligation to engage in these behaviours.

All value- and belief-related questions were rated on a 7-point scale from (1) *fully disagree* to (7) *fully agree*.

Employees answered parallel questions using the same scales, but referring to their companies' consumers in a specific country, which they indicated at the beginning of the survey. For example,



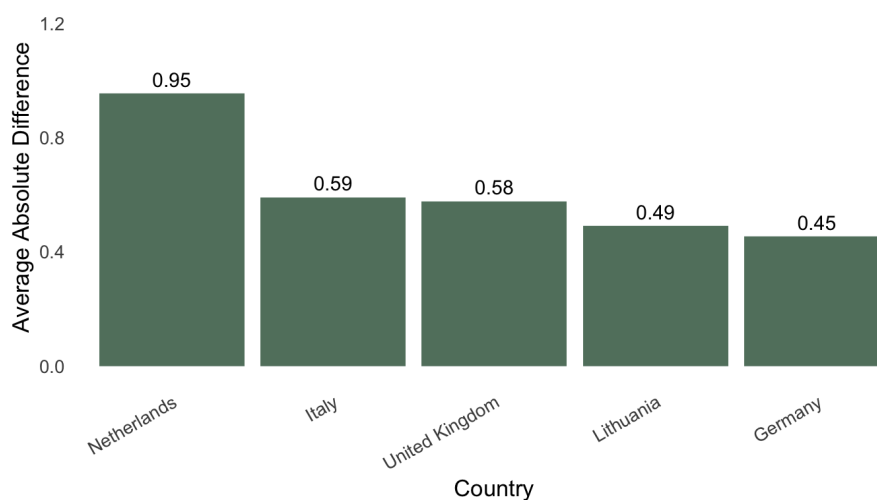
they were asked how strongly they perceive the self-efficacy of people in Lithuania to live without owning a car or living in a small home. For a more detailed description, see Annex C1.

4.2 Results

To understand possible misalignments between consumers' values, beliefs, and willingness and employees' perceptions of consumers, we compared the mean scores for each variable, i.e. for consumers' values, their problem awareness, self-efficacy, outcome efficacy, personal norms, and willingness to engage in the different circular behaviours (for more detail see Annex C). When employees' perceptions are higher than the measures among consumers, we speak of an overestimation. The consumer and employee surveys suggest that employees consistently overestimate consumers' values, beliefs, and willingness regarding circularity. They overestimate how much consumers care about the environment (*biospheric values*) and the well-being of others (*altruistic values*), but also how much consumers care about having influence, wealth and possessions (*egoistic values*), and having fun (*hedonic values*). Further, employees overestimate consumers' problem awareness, self- and outcome efficacy, personal norms, and willingness to engage in circular behaviours related to mobility and housing, respectively.

For mobility-related variables, overestimations exist for all countries and variables, with differences in strength. Employees most accurately perceive consumers in Germany and Lithuania, followed by Italy, and the UK. Perceptions of Dutch consumers are overestimated the most by employees (see Figure 6).

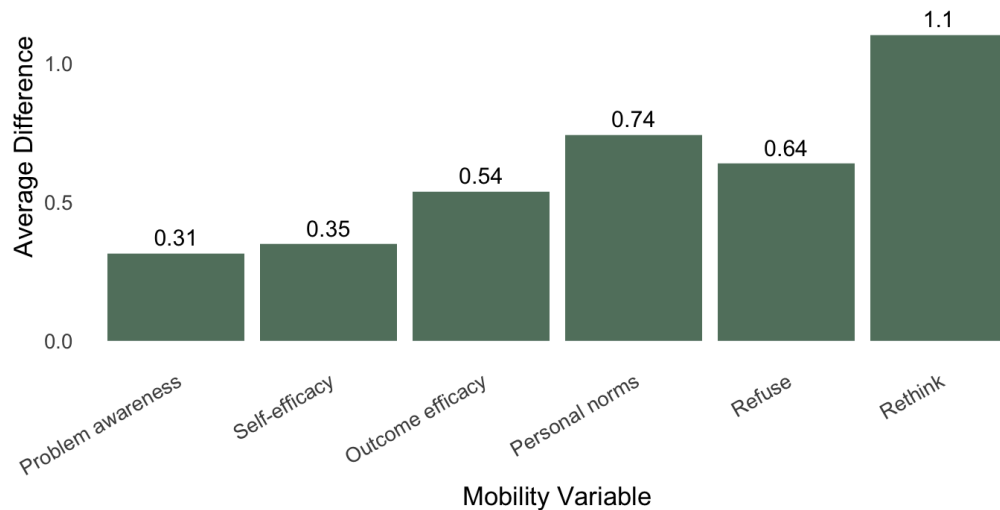
Figure 6. Employee overestimation of consumer ratings for mobility per country



Employees most accurately perceive consumers' mobility-related problem awareness and self-efficacy (see Figure 7). Employees most strongly overestimate consumers' willingness to use car sharing instead of owning a car, followed by consumers' personal norms to not own a car.



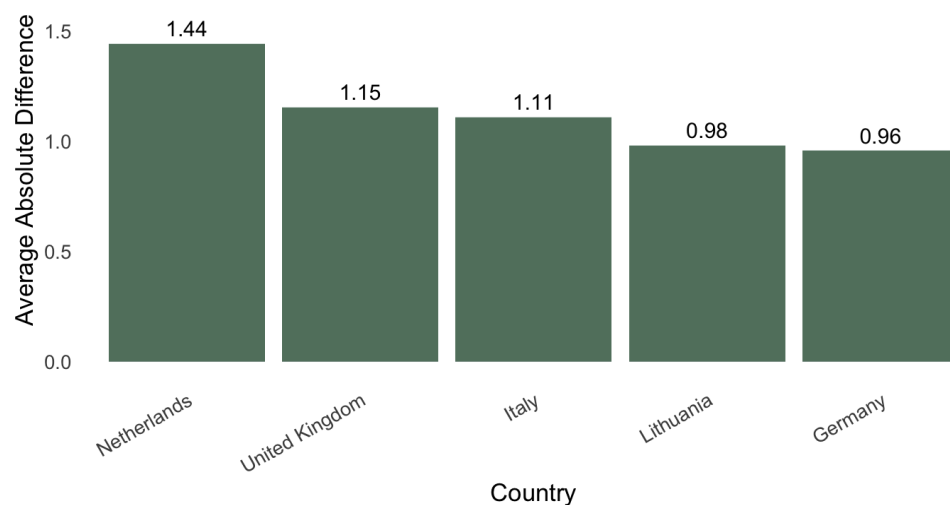
Figure 7. Employee overestimation of consumer ratings for mobility-related variables



Note. *Reduce* refers to the willingness to not own a car if adequate alternatives were available; *Rethink* to the willingness to use car sharing instead of owning a car.

For housing-related variables, similar patterns are found. Overestimations exist for all countries and variables, with differences in strength. Again, employee perceptions match those of German and Lithuanian consumers the closest, followed by perceptions of Italian and UK consumers. As for mobility, employees overestimate Dutch consumers the most (see Figure 8).

Figure 8. Employee overestimation of consumer ratings for housing per country

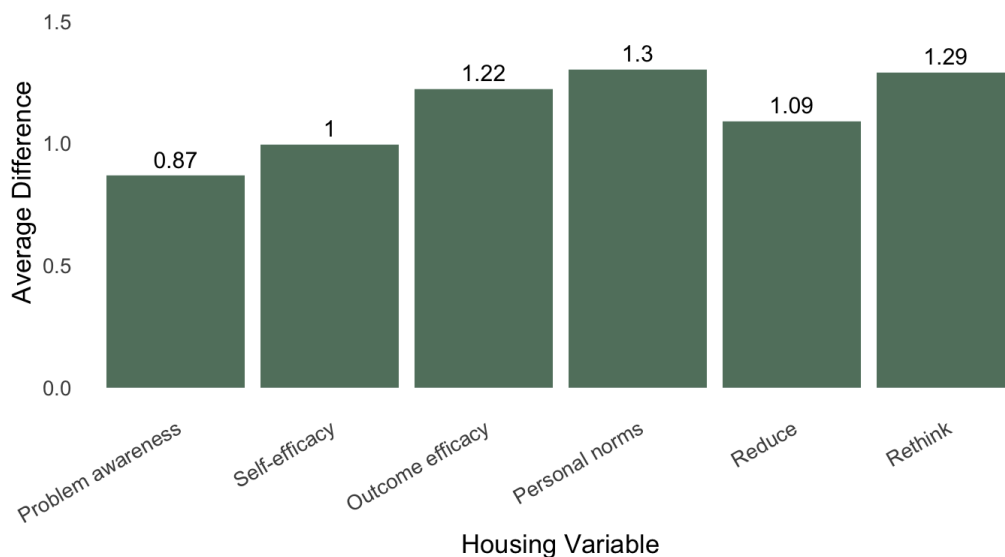


Employees overestimate consumers' housing-related problem awareness, followed by self-efficacy the least, which is in line with the findings for mobility. Employees most strongly overestimate



consumers' personal norms to live in a smaller home or share living spaces, closely followed by their willingness to share spaces and outcome efficacy (see Figure 9).

Figure 9. Employee overestimation of consumer ratings for housing-related variables



Note. *Reduce* refers to the willingness to downsize; *Rethink* refers to the willingness to share spaces

Taking mobility and housing together, employees most accurately perceive German and Lithuanian consumers and they overestimate Dutch consumers the most. This overestimation might be driven by Dutch consumers generally scoring lower than consumers of other countries. Employees most accurately perceive consumers' awareness of the environmental and social problems associated with car ownership and their ability to live without a car. Consumers' feeling responsible to live in a smaller home or share living spaces and their willingness to share their kitchen or entrance/hallway are overestimated the most by employees. Generally, consumers' beliefs and willingness regarding housing are slightly more overestimated by employees than regarding mobility.

5 Workplace Pro-environmental Behaviours and Workplace Everyday Environmental Activism (Annex C2)

5.1 Methods

Expanding the scope of the initially proposed research questions in the grant agreement, the employee survey also measured two types of workplace environmental behaviours aimed at advancing the organisation's circularity. To understand the extent to which employees in circularity-relevant industries, such as mobility, building, and manufacturing, engage in behaviours



to advance a CE the employee survey conducted by RUG and LMU included questions on workplace pro-environmental behaviours (WPEBs) and workplace everyday environmental activism (WEEA). WPEBs were measured using three items, and WEEA four items. Responses were rated on a 7-point scale ranging from (1) *never* to (7) *almost always* for both scales. For a more detailed description, see Annex C2.

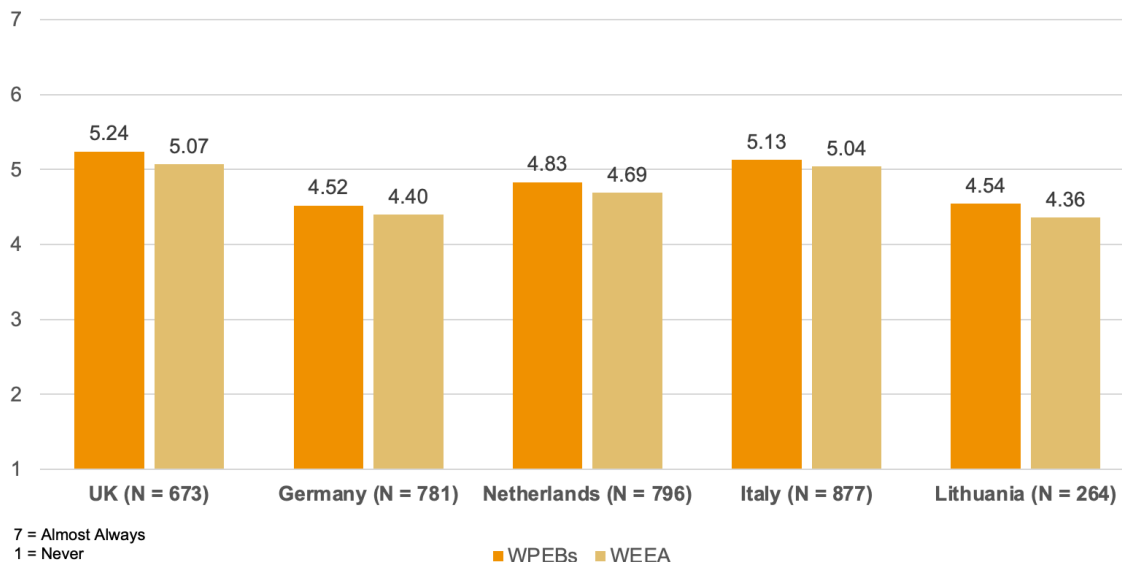
5.2 Results

Workplace Pro-environmental Behaviours (WPEBs) and Workplace Everyday Environmental Activisms (WEEA) are relatively understudied concepts but hold considerable potential for promoting circular behaviours among both consumers and employees, and for reducing environmental impact. Previous studies (e.g., Wagner et al., 2025) have found that these behaviours are typically reported at lower levels than found in the current dataset. One possible reason for this difference is the operationalisation of the behaviours: by embedding the principles of reduce, reuse, and recycle, the items may have felt more concrete and relevant to employees, making them easier to recognise and report.

We found that, WPEBs (e.g., carrying out your work by reducing, reusing, and recycling) and WEEA (e.g., encouraging co-workers and/or clients to reduce, reuse, and recycle) related to circularity are reported at moderate to fairly high frequencies (see Figure 10 for cross-country comparisons), with mean values consistently above the midpoint of the 7-point scale. For the total sample, mean scores of 4.89 for WPEBs and 4.77 for WEEA suggest that these behaviours are performed sometimes too often. The United Kingdom and Italy report the highest frequencies for both WPEBs and WEEA, while Germany, the Netherlands and Lithuania report lower engagement. Across all five countries, WPEBs are generally reported more frequently than WEEA, suggesting that employees may feel more comfortable engaging in circular behaviour within their own roles than in encouraging others to do so.



Figure 10: Bar chart showing the mean scores per country for Workplace Pro-environmental Behaviours (WPEBs) and Workplace Everyday Environmental Activism (WEEA)



6 Conclusion

This deliverable addresses the research gaps connected to WP3's three core objectives, revealing that the transition to circular provision of goods and services requires a nuanced understanding of multi-scale interactions and targeted policy interventions.

Regarding **objective 1**, on assessing the mitigation potential of technological and business model solutions, our analysis demonstrates that circular economy practices do not automatically translate into climate benefits. The CMCC framework reveals that achieving resource and emission reductions depends critically on specific market conditions, including demand saturation, extraction limits, and effective substitution mechanisms. Empa's infrastructure assessment shows significant variation in mitigation potential across materials, with steel emerging as the most promising candidate for recycling (potentially avoiding 1.85 Gt CO₂). In contrast, other metals and minerals needed for low-carbon energy systems like silicon and nickel show limited potential due to insufficient stocks. This underscores that mitigation potential varies substantially across different circular practices and material flows.

For **objective 2**, the report identifies specific policy levers needed to ensure circular practices deliver climate benefits. CMCC's framework particularly emphasises that, without constraining policies, rebound effects and increased material availability can undermine intended mitigation outcomes. Potential policies include targeted taxation to redirect economic rents toward resource-sober activities, quotas and regulations to limit resource extraction. Empa's work on infrastructure repurposing reveals additional policy opportunities, such as strategic planning for fossil asset transitions and coordinated policies that facilitate material flows from obsolete infrastructure to renewable energy systems.



Concerning **objective 3** on generating empirical insights on circular behaviour, the multi-country surveys reveal that consumers already have neutral to slightly positive beliefs towards circular behaviours and that employees slightly overestimate these. We expected that employees may underestimate consumers' values, beliefs, and willingness to engage in circular behaviours which may prevent them from implementing circular products and services. However, our findings suggest that this is not the case. The question arises what influence the overestimation of consumers' values, beliefs, and willingness to engage in circular behaviours has on advancing circularity. Currently, employees perceive consumers to be more aware, having higher agency, and being more willing to engage in circular behaviours than consumers actually are. We found that most consumers are neutral to positive regarding the CE, therefore businesses could pay special attention to support those consumers that might not be as ready to adopt circular behaviours yet. To promote a broader circular transition, businesses should ensure that their circular products and services are not only appealing to consumers who are already positive about the CE, but also feasible and accessible to all consumers, including those whose values, beliefs, and willingness are less in line with the CE. Additionally, WPEBs and WEEA, which focus on circular actions by employees, were found to be more prevalent than such behaviours aimed more broadly at reducing environmental impact (e.g., Wagner et al., 2025). This may suggest that employees are particularly ready for a more extensive shift towards the circular economy and, more specifically, circular business practices or models.

Empa's empirical analysis of specific repurposing strategies, including gas pipeline conversion to district heating (achieving up to 40% CO₂ reduction) and diesel bus e-retrofitting (accelerating fleet electrification by 15 years), demonstrates concrete circular practices with quantifiable impacts across the mobility and buildings sectors.

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ANNEXES



D3.1. ANNEX A

From (Micro-)Circularity To (Macro-)Mitigation

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Abstract

Within firms, circular economy practices aimed at reducing, reusing and recycling resources, have the potential to improve resource efficiency. Despite their clear objectives, these micro-level interventions may not necessarily result in economy wide reductions in resource consumption and greenhouse gas emissions. This paper presents a novel analytical framework to examine the pathways through which firm level circularity leads to a “macro level circular economy” characterized by lower resource use, extraction, and disposal and, ultimately, greenhouse gas emissions. Drawing from several strands of literature and employing sequential reasoning, we identify the necessary conditions under which circular practices at the firm level generate tangible benefits at the aggregate level. We show that these conditions correspond closely to principles of sufficiency. Subsequently, we examine policy instruments that can facilitate the achievement of a macro-circular economy.

Key Words: Circular Economy, Rebound Effect, Climate Mitigation

JEL Classification: Q53, Q54

1. Introduction

Circular economy practices - which aim to reduce, reuse and recycle resources at the firm level - have the potential to increase resource efficiency and are expected to play a significant role in achieving net zero emissions and avoiding major climate risks (IPCC, 2022). Europe is at the forefront of this debate, with a recent strong push towards circular economy practices to reduce resource consumption while addressing climate change (Communication 2020/18, 2021; CEAP, 2021). Yet, the implications of firm-level circular practices for aggregated resource use and greenhouse gas (GHG) emissions are unclear. Studies like Material Economics (2019, 2020); Ellen MacArthur Foundation (2021); Gallego-Schmid et al. (2020) and Mostert et al. (2021) indicate varying resource and emission saving potentials depending on the sector, with circular strategies in the industry, energy, and transport sectors being the most promising ones. However, according to Cantzler et al. (2020), most studies typically assume rather than provide decisive proof of the mitigation potentials connected to specific circular economy strategies.

There are at least three main reasons for which the implementation of circular practices and business models by firms might fall short of expectations and not translate into lower overall demand for resources - materials and energy - and associated greenhouse gas (GHG) emissions.

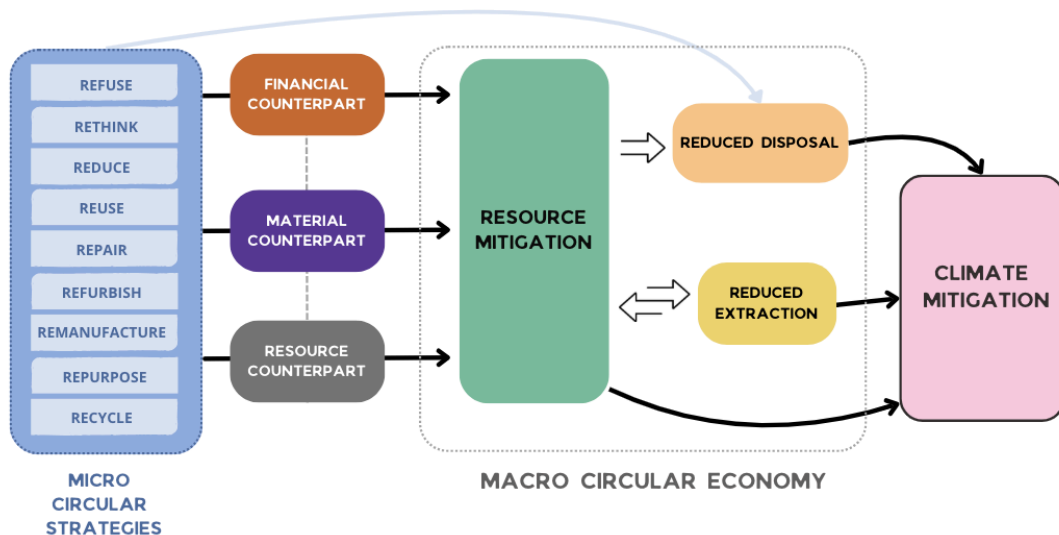


First, the "rebound effect" literature shows that efficiency gains may not fully translate into lower demand (Greening et al., 2000; Gillingham et al., 2013, 2016; Font Vivanco et al., 2016; Zink and Geyer, 2017; Skelton et al., 2020; Chenavaz et al., 2021; Castro et al., 2022), and can even increase consumption through a "backfire" effect (Saunders, 2000; Brookes, 2000; Druckman et al., 2011; Chenavaz et al., 2021). While studies on the rebound effects generally analyze the energy context, similar dynamics potentially characterize material efficiency. Second, circular practices can increase the quantity of material that is available in the market, for instance if recycled materials or goods that would otherwise be discarded are injected into the market (Zink and Geyer, 2017). Third, thermodynamic limits suggest that circular systems consume resources and produce waste, meaning strategies like recycling and reuse may still contribute to resource depletion (Korhonen et al., 2018).

While several strands of literature in economics and sustainability sciences offer key insights on the extent to which circular practices result in firm-level or economy-wide resource savings, they are currently disconnected and scattered, limiting the ability to inform policy decisions. To fill in this gap, we develop a novel framework that allows us to jointly identify and synthesize all conditions under which *firm-level circular practices* translate into a *macro level circular economy* - a situation characterized by lower resource use, extraction, and disposal - and ultimately, climate change mitigation.

Figure 1 illustrates the main components of our framework, which is built using sequential reasoning. First, we identify the channels that connect firm-level *circular strategies* to aggregate resource use and discuss the conditions that guarantee *resource mitigation* (Figure 1). The impact of firm-level circular practices on economy-wide resource savings are mediated by three channels: (i) the "financial counterpart", namely how circular practices affect firms' costs, pricing, and spending, all the way to downstream demand; (ii) the "material counterpart", that is how circular practices influence firms' demand and supply of materials directly (e.g., an increased supply of materials via recycling) and (iii) a "resource counterpart", that is how circular practices affect demand for materials and energy indirectly (e.g., infrastructure needs and digital support). For each of these counterparts, we identify the specific conditions that guarantee that firm-level circularity practices translate to macro-level resource savings. Second, we characterize the connections between resource mitigation and *reduced disposal* and *reduced extraction* and discuss their synergies with lower greenhouse gas emissions, i.e., *climate mitigation*.

Figure 1: Paper outlook



Our contribution to the literature is threefold. First, while qualitative in nature, our framework has the added value of allowing for the joint explorations of the several channels through which micro-level circularity translates to macro-level resource savings. It does so by building on three different streams of literature - the economic and sustainability literature on rebound effects (Greening et al., 2000; Gillingham et al., 2013; Figge et al., 2014; Gillingham et al., 2016; Font Vivanco et al., 2016; Zink and Geyer, 2017; Skelton et al., 2020; Chenavaz et al., 2021; Castro et al., 2022; Metić and Pigosso, 2022); the management literature describing the circular strategies and circular business models (Bocken et al., 2016; Nußholz, 2017; Geissdoerfer et al., 2020); and the industrial ecology literature on material flows, material footprints and life cycle assessment (Cantzer et al., 2020; Haas et al., 2020; Mostert et al., 2021; Desing et al., 2021).

Second, our framework informs and guides both researchers and policymakers. Researchers in engineering and material modeling of circularity can build on our results to improve the modeling of circularity and to clarify the main hypotheses under which model results are obtained. Many of the existing models generally abstract from market features or do not explore the sensitivity of their results to changes in economic assumptions (Pauliuk et al., 2017; McCarthy et al., 2018). We contribute to the policy debate by highlighting the need for a policy portfolio that can support the translation of micro circularity into macro-mitigation. Such a portfolio complements policies promoting circular practices of



firms with interventions to limit extraction through biodiversity programs, taxes, and standards; while supporting consumers towards sufficiency.

Third, the framework provides a key policy and research insight, namely that a macro circular economy —one that achieves reduced resource consumption in line with planetary boundaries — is closely tied to the concept of sufficiency. While circular economy and sufficiency concepts are often considered in isolation ([Figge and Thorpe, 2023](#)), we show that avoiding circular economy rebound effects is crucially conditional on strong environmental preferences, e.g., individual commitments to low-resource activities and environmental preservation.

The rest of the paper is organized as follows: Section 2 outlines the key assumptions of our framework. Section 3 examines the various pathways from micro circular practices to macro resource use, disposal, and extraction. Section 4 identifies the conditions and policy levers that help achieve a macro circular economy. Section 5 discusses how our insights help to identify the mechanisms through which a macro-level circular economy can contribute to climate mitigation and illustrates fruitful avenues of future research. Section 6 concludes.

2. Key Concepts and Assumptions

Our focus is on how circular practices affect the absolute variation in aggregate flows of resource used, extracted and disposed of.¹ Hence, our starting point is the circular behaviour of firms - i.e., their implementation of circular practices targeting material use. Circular practices are usually mapped into a hierarchical order through the R frameworks: the 3Rs-Reduction, Reuse, Recycle ([Ghisellini et al., 2016](#)) or the 10Rs: Refuse, Rethink Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover ([Potting et al., 2017](#); [Kirchherr et al., 2017](#)). We exclude the last R (recovery) from our analysis, as it only targets energy.² Firms' circular behaviour can simultaneously affect the type of input (e.g., use of recycled materials or used products), the production process (e.g., sharing business model), or the output proposed to consumers (e.g., thinner packaging). While we exclude practices targeting energy efficiency or recovery, we account for the impact that changes in material use can have on energy use. We consider practices that introduce circular goods with various potentials (from low to high) to replace non-circular alternatives. Lastly, we analyze the implications of companies implementing new circular strategies compared to a "no circular strategy" case. This is tantamount to conceptualizing an exogenous shock in



which circular strategies become profitable for a significant number of firms due to factors such as technological advancements or shifting consumer preferences. We analyze the short-to-medium-term consequences of this shock on the variation of resource use at the macro-level.³

Understanding under which conditions micro-level circular practices translate to macro-level circularity requires the use of simplifying assumptions regarding both the supply and the demand side of the economy. We summarize the key assumptions here, and refer the reader to Appendix A.1 for further details.

Our key assumption regarding the supply side is that firms are profit-maximizing. Firms choose to implement circular strategies when they result in the same or a higher profit than business as usual.⁴ This implies that firms operate in an environment which allows them to maintain or increase their profitability, e.g., through incremental innovation and knowledge supporting circular practices or the increased presence of supply and demand for circular products (Galarraga Gallastegui, 2002; Boyer et al., 2021). Firms operate in a setting in which the technological frontier is relatively stable and they are not confronted with radical or breakthrough circular innovation. Firms cannot influence the market price of the goods or services they buy in upstream markets, but have some control over the price in final goods markets, if (as detailed in the following sections) market conditions permit. In this case, companies set prices higher than the (marginal) cost of producing the products so they can earn a profit. We assume that a sufficient number of firms are implementing circular strategies, thus having a non-negligible impact at the macro level. Lastly, a key tenet of our framework is that the supply of goods and services is increasing in price.⁵

On the demand side, we assume that consumers earn money only through wages. This means their available budget is fixed —unless firms start paying them higher wages. Aggregate quantity demanded decreases as price increases.⁶ Societal preferences are slowly changing; that is to say, we do not analyze situations in which society-wide transformational effects are such that consumers suddenly fully embrace sufficiency and/or commit to drastically lower consumption on environmental and sustainability grounds. A significant proportion of consumers are willing to pay more for circular goods (e.g., Boyer, 2021), which would mean that these products can easily take the place of traditional ones in meeting their needs or preferences. This assumption should be viewed cautiously, as Boyer (2021) shows only a small segment actively prioritizes circular products over price considerations. However, our qualitative framework requires only that this consumer segments exist to enable the increased price channel mechanism, not that they constitute a majority.



3. From Micro Circularity to Macro Mitigation

In this Section, we identify the economic mechanisms arising from the implementation of circular strategies by firms. In this context, firm-level circular practices influence three key dynamics that have repercussions beyond company boundaries. First, implementing circular strategies affects production costs, prices and demand in downstream markets and firms' investment decisions. We label this channel "financial counterpart". Second, the implementation of circular strategies affects the aggregate demand and supply of materials and the materials embedded in intermediate and final goods. We call this channel "material counterpart". Third, implementing circular strategies ultimately affects the quantity of inputs and the mix of materials and energy required to produce circular goods and services. We label this channel "resource counterpart".

Table 1 summarizes the concepts related to the three counterparts and provides some illustrative examples. In the rest of this Section, we discuss each of these channels in detail.

Table 1: Micro-circular strategies and counterparts

counterpart	description	examples
FINANCIAL COUNTERPART	Impact on production costs, company revenues, prices and downstream markets.	• Lower production costs through material efficiency, reducing prices and stimulating downstream demand. • Higher selling prices from costlier repairable products, impacting competing products and other markets through effects on consumer budgets and preferences (substitution effect).
MATERIAL COUNTERPART	Aggregate material impact of the circular strategies on markets, until material markets.	• Reduced material demand through lightweight products, sharing systems, in-house reuse. • Additional supply of materials (in recycled form or embodied in products) through recycling, reuse, and remanufacturing, that would have otherwise been discarded as waste. • Additional demand for recycled materials and products substituting to demand for virgin materials.
RESOURCE COUNTERPART	Indirect impact of the circular strategies on the resource mix (materials and energy) to implement the circular strategy.	• Additional energy demand for recycling and digital sharing systems. • Additional material demand for creating stocks of spared parts, new machinery. • Substitution with traditional production methods.



3.1 Financial counterpart: pass-through on output prices, downstream market adjustments and allocation of gains

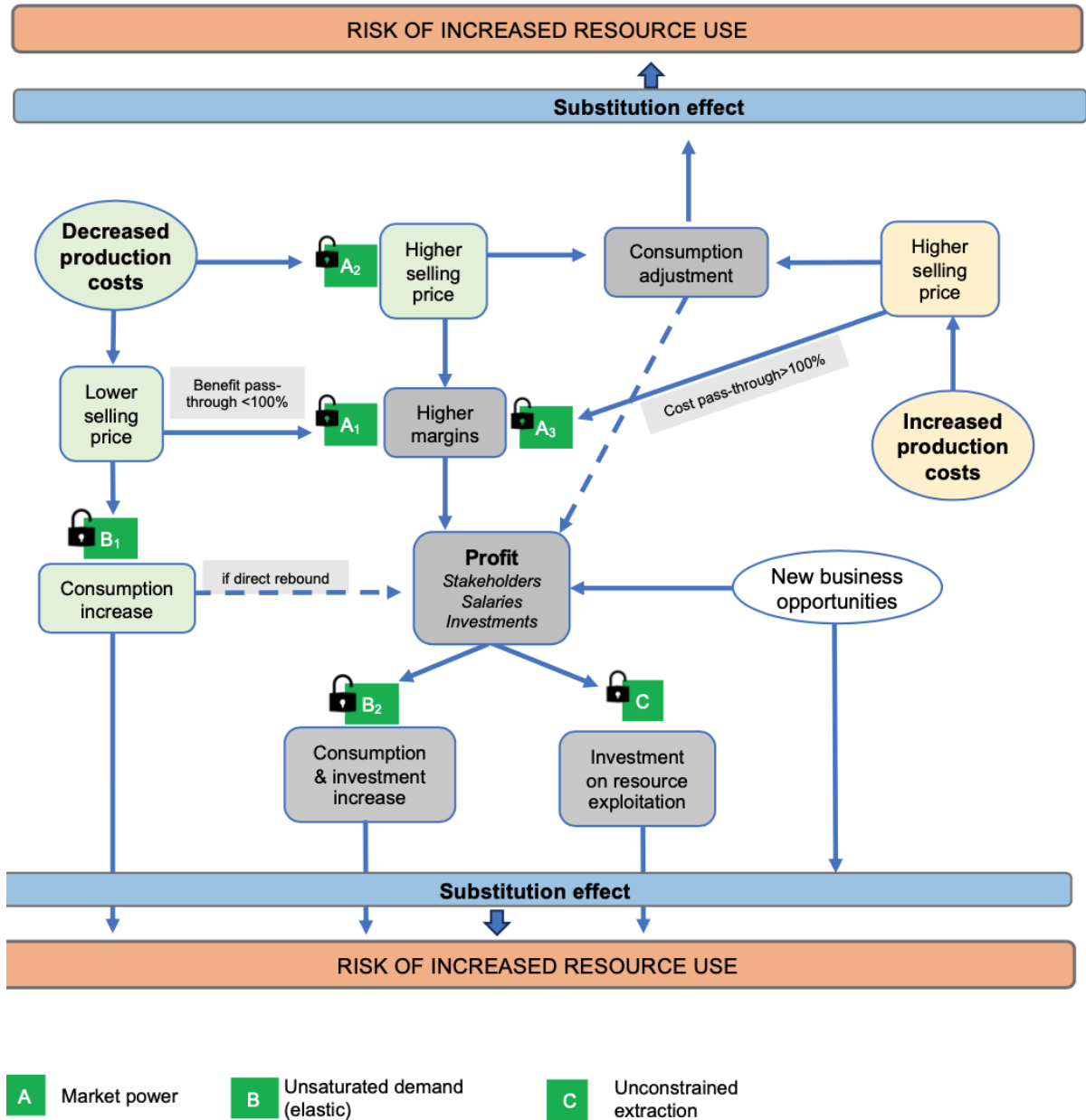
The financial counterpart encompasses all those effects which derive from the impact of circular practices on the firm's production costs and, consequently, the prices it charges and the profit it makes. Observing aggregate effects requires analyzing each firm's strategic pricing response within its respective market, then aggregating these individual market outcomes to determine the overall impact. Given that circular practices may both decrease and increase the firm's production costs, we analyze the two opposite cases separately. For each case, we discuss the firm's pricing behaviour and its decisions on the distribution of any additional profit. Lastly, since a product's circular characteristics can influence consumer preferences beyond its price, we analyze what we call *substitution effects*. We illustrate the implications on resource use for both higher and lower production costs and of the substitution effect in Figure 2.

3.1.1 Lower production costs

If circular strategies imply lower production costs, the revenue/cost ratio for the firm increases. Some firms may retain these cost savings fully as higher profit margins or to expand activities through higher wages or re-investment, while others may pass (part or all of) them onto consumers, resulting in lower output prices.

The extent to which a firm can translate cost savings into higher margins or lower prices depends on its market power, i.e., its ability to set a price higher than the unit cost of production. Economic theory predicts that the more competitive a market, the lower the firm's market power. In a perfectly competitive market, the output price will equal marginal cost. In such a market, any cost saving experienced by the firm will be fully passed onto consumers via reduced prices (e.g., [Loy et al. \(2016\)](#), [Genakos and Pagliero \(2022\)](#)). Conversely, the firm can keep a higher margin if it has market power, or gains it as a result of the perceived higher quality of the new circular product/service.

Figure 2: Possible pathways to increased use of resources in the financial counterpart



Note: Green indicates the pathway for decreased production costs, yellow shows the pathway for increased production costs, and grey represents the shared pathway common to both scenarios.



We first discuss the case of markets with a relatively high degree of competition, i.e., where cost savings almost fully translate into lower output price. According to standard economic theory, if the output price of the firm's good/service decreases, the quantity of the specific good demanded by consumers may increase (Sorrell and Dimitropoulos, 2008; Metić and Pigosso, 2022). As a consequence, the higher demand limits or completely offsets the potential material savings (if any) brought by adopting the circular strategy. This mechanism can be assimilated to a *direct rebound effect* as defined in relation to energy use by Greening et al. (2000).⁷ The magnitude of this "direct" rebound will depend on how elastic the demand for the circular good is, namely how strongly consumers react to price changes (Feature B_1 in Figure 2). If the demand is very elastic, consumers will markedly increase the quantity consumed as a result of the price decrease. In extreme cases, total resource consumption increases as a result of the circular strategy. The *direct* rebound effect will be nil only if consumers do not react to changes in price because their demand is inelastic or "fully saturated".⁸ Graphically, demand saturation implies that the demand of a given consumer group for given resources becomes price-inelastic, i.e., a vertical line, above a certain quantity.

Yet, a lower production cost for a given good does not only impact its price and demand, but also results in a higher available budget for consumers. As a result, they likely will choose to purchase other (non-circular) goods and services through *re-spending*, giving rise to a *indirect rebound* (Greening et al., 2000; Sorrell, 2009; Santarius, 2012; Metić and Pigosso, 2022).⁹ The overall resource mitigation of a given firm-level circular strategy will therefore depend on (i) the saturation of these other markets (Feature B_1), following a dynamics similar to the one described for the direct rebound effect, and (ii) the resource-intensity of the other goods (see Appendix A.2). On top of this, the presence of a circular product in the market can give rise to substitution effects. These effects, which are connected to consumers' preferences, will be discussed in detail in Section 3.1.3.

If firms operate in less competitive markets, output prices decrease only partially as a result of lower production costs and firms can retain part of the gains by increasing their margins (Feature A1 in Figure 2).¹⁰ The impact of higher margins on resource mitigation depends on the resource intensity of the firm's rent allocation. On the one hand, the firm can distribute additional rent to workers through wage increases. In this case, the wage earners (consumers) may spend their budget on additional consumption, thus generating a rebound. The size of this material rebound depends on the resource intensity of these additional goods (Feature B2 in Figure 2). On the other hand, the firm can decide to distribute the rent



to its shareholders or increase investment. A rebound effect will emerge if the newly-financed activities are resource-intensive (Santarius, 2012; Metić and Pigosso, 2022). Importantly, an “extraction” rebound can occur if investments are made in resource exploitation and extraction. This is likely when these activities are not constrained (Feature C in Figure 2). It is precisely for this reason that Thiesen et al. (2008) recommends that Life Cycle Assessments always account for how sales earnings are used.

Incidentally, when firms benefit from high market power, they can also increase the price of the circular good (Chenavaz et al., 2021), leading to even higher margins (Feature A₂ in Figure 2). Indeed products acquire new circular characteristics that modify consumer preferences and payment willingness, potentially allowing for higher pricing (e.g., Boyer et al., 2021; Chenavaz et al., 2021).¹¹ It can also occur if firms choose to limit production, as is the case with limited editions, leading to an increase in price via a scarcity effect. We discuss in more detail the dynamic of increased prices in the following Section 3.1.2.

3.1.2 Higher production costs

While many assume that circular practices lead to costless efficiency gains (Böhringer and Rivers, 2021), circular strategies can indeed result in higher production costs. This is the case if firms need to acquire knowledge, skills, or machinery, develop new processes, search for new partners in the value chain, or reorganize logistics. The right-hand side of Figure 2 illustrates the possible economic mechanisms following such an increase in production costs, starting from the output price of the firm and its profit margins.

If production costs increase, firms must then be able to raise prices to maintain (or to increase) their profit margin. As discussed above, if a sufficiently high share of consumers has a higher marginal willingness to pay for circular goods rather than traditional goods, sales remain sufficiently large despite the higher prices charged for the circular good.

In line with what is described in Section 3.1.1, in a market with a relatively high degree of competition, the output price would increase to the level equal to the marginal cost, as firms have no market power to increase it further and raise their margins. Conversely, if firms have market power (Feature A₃ in Figure 2), they can capitalize on consumers’ eco sensitivity by imposing a cost pass-through (CPR) superior to 100% and consequently increase their margin. In all these situations, the possibility of a *direct* or *indirect* rebound from the consumer’s side is limited (Chenavaz et al., 2021). Indeed, assuming an unchanged budget and abstracting from any decision to change the relative consumption of goods in their



basket (the so-called substitution effect, that will be described in Section 3.1.3), the consumers' purchasing power is now comparatively lower.¹² This will ultimately put downward pressure on the consumption of any good, whether more or less resource-intensive and whether circular or not.

However, higher resource use could still materialize if firms' increased profits are distributed via wages or to shareholders, likely resulting in higher consumption or investment. Note that this outcome is less likely if production cost increase rather than decrease (see Section 3.1.1). Indeed, higher resource use arising from the allocation of additional rents to resource-intensive activities can to a certain extent, in theory, be offset by the lower final demand resulting from higher prices of the final product.

In addition to the dynamics of higher or lower production costs, circular practices can also represent new business opportunities, leading to a situation where production costs cannot be compared at the firm level. This is the case, for instance, when a car-selling company develops a new branch or a subsidiary company providing a car-sharing service. In this case, firms introduce a new product that competes with existing goods, as we detail in the substitution effect below (Section 3.1.3). Yet, the profits generated from the new business follow the same pathways we just described: they can be allocated to salaries, stakeholder returns, and/or investments.

3.1.3 Substitution effect

The effects described in Sections 3.1.1 and 3.1.2 can be further compounded by “substitution effects” in the downstream market. When a circular version of a good or service is distinguishable from its non-circular counterpart, it can alter consumer preferences—that is, the relative weight given to the consumption of the different goods in consumer utility. In parallel, the introduction of the circular good reshapes the competitive landscape by influencing the relative prices of available alternatives. For example, when consumers are presented with new grocery shopping options, such as a ‘zero packaging’ store versus a traditional supermarket, they will reassess their previous consumption choices based on updated preferences regarding packaging waste generation and relative prices of grocery items.

The substitution effect differs from the re-spending effect discussed in Section 3.1.1. The substitution effect occurs when preferences change (while the budget remains fixed), whereas



the re-spending occurs when the budget changes (while preferences do not change).¹³

As pictured in Figure 2, the substitution effect triggered by the presence of a new circular good, can reduce, amplify, or even reverse any *direct* and *indirect* rebound effects. The final effect depends on whether the circular good replaces a less or a more resource-intensive good. For instance, if consumers redirect their consumption towards resource-sober goods, any direct rebound effect arising as a result of lower prices of circular goods can be dampened or canceled (Demonstration in Appendix A.3). However, the opposite situation is also possible. Circular goods can replace less resource-intensive goods, strengthening the rebound. For example, if engaging in car sharing substitutes walking or cycling, resource consumption increases as a result of a substitution effect (Metic and Pigosso, 2022).

Similar substitution dynamics also characterize firms' profit (re-)allocation since the development of circular strategies can attract firms' investments.

Summarizing what was discussed in the financial counterpart, we note that demand saturation (lock B) and constrained extraction (lock C) emerge as essential conditions to prevent resource increase. Additionally, substitution effects need to be such that they favor low-resource intensive consumption.

3.2 Material counterpart: Impact on supply and demand of materials

The material counterpart includes all effects stemming from the fact that circular strategies directly influence the aggregate demand and supply of materials —both as raw inputs and as goods embodied in products and components— all the way to upstream markets.¹⁴ Hence, the focus in this Section is on the aggregate effect on intermediate good prices and quantities deriving from the contemporaneous implementation of circular strategies by many small firms, which, alone, would not, by assumption, have any effect on upstream markets.¹⁵ This counterpart captures the rebound mechanism and other adjustments that emerge due to the direct and intentional outcome of circular strategies.

We detail three specific dynamics, which can compound at the aggregate level. Circular practices may result in: i) decreased material demand; ii) increased material supply; iii) increased secondary material demand. Finally, we describe the substitution effect, which refers to how effectively circular goods can replace non-circular ones.



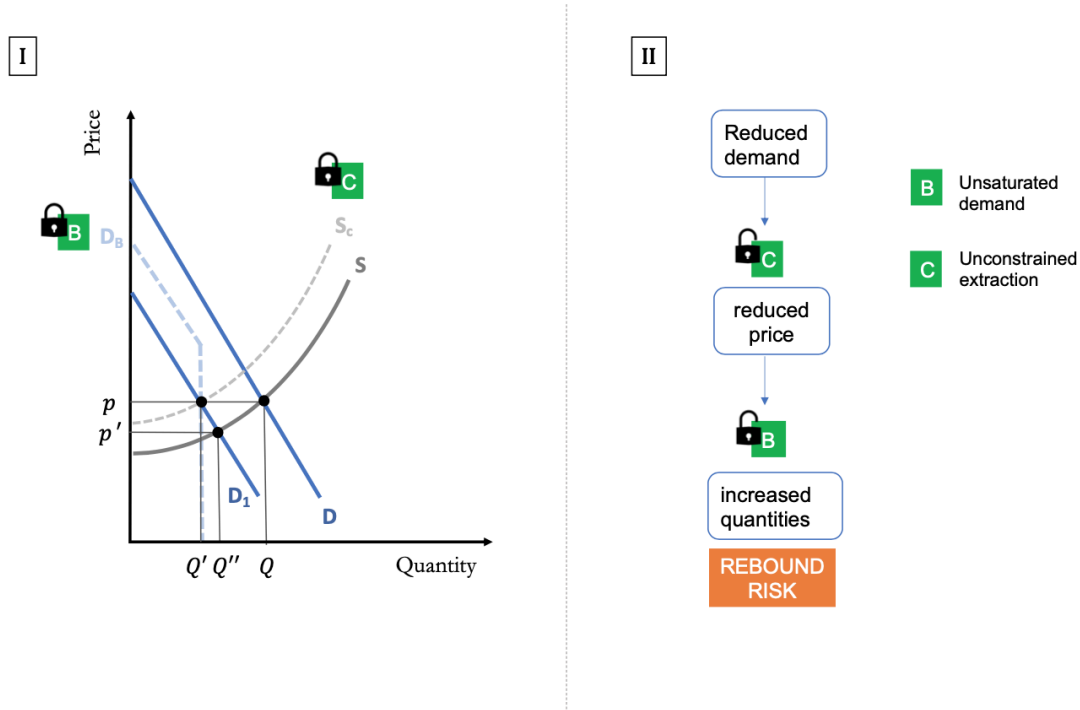
3.2.1 Decreased material demand

First, we discuss the dynamics triggered by companies that are positioned in the value chain as providers of a circular service or good, and as purchasers of materials or intermediate components. These companies can engage in circular strategies, such as implementing material-efficient design, in-house reuse, and sharing, which may reduce firms' material requirements. As illustrated in Figure 3, at the aggregated level, this results in a downward shift (from D to D_1) of the intermediate good demand curve across all price levels.¹⁶ According to standard economic theory, if supply is fixed (Feature C in Figure 3) this reduces the price of the good (from p to p'). This price adjustment induces a partial offset of the potential reduction in quantity demanded ($Q-Q'$), as lower prices encourage increased consumption.¹⁷ If demand is not saturated (Feature B in the Figure), in equilibrium the quantity of goods - and, hence, material - is higher (Q'') than it would have been if prices had remained constant (Q'). This standard economic adjustment characterizes the rebound effect pertaining to decreased material demand.

The extent of this rebound will depend on the magnitude of the price drop, which is influenced by the elasticity of both supply and demand (as demonstrated by [Borenstein, 2015](#) and [Böhringer and Rivers, 2021](#) for energy efficiency improvements). Note that even if the rebound is likely, material use decreases overall.

Rebound effects can be limited by preventing price adjustments that would otherwise stimulate additional demand. For instance, constraining the supply of materials (supply curve S_c), can maintain the original price level p , thereby avoiding the demand-side rebound that would result from lower prices. Alternatively, if demand saturates at the lower quantity level Q' (demand curve D_B), firms do not respond to price drops. These conditions, their feasibility, and the associated policy measures, are further discussed in Section 4.

Figure 3: Market adjustment following decreased material demand

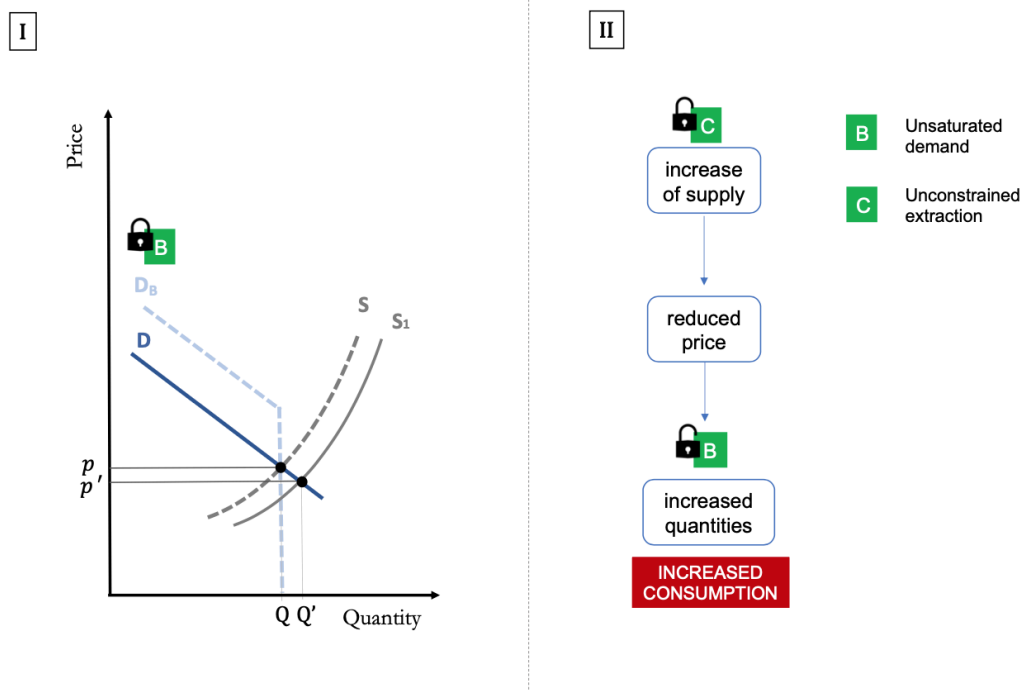


3.2.2 Increased material supply

Second, we discuss the dynamic triggered by companies that are positioned in the value chain as suppliers of secondary goods. In this case, companies engage in circular strategies by supplying recycled materials or reused intermediate and final goods. If recycled materials or goods that would otherwise be discarded are injected or reintroduced into the market, the total supply of materials increases relative to a scenario without circularity (Dace et al., 2014; Zink and Geyer, 2017). This adjustment is represented in Figure 4, through a downward shift in the supply curve (from S to S_1).¹⁸ According to standard economic theory, this downward shift in supply reduces the price of that good (from p to p'). As before, if demand is not saturated (Feature B) at the lower level Q , overall resource consumption increases (from Q to Q').

We acknowledge that this dynamic can be compounded by a possible substitution effect between circular and non-circular goods, detailed in Section 3.2.4. For the time being, we simply claim that the additional supply from circular inputs expands overall material availability (Zink and Geyer, 2017).

Figure 4: Increased resource use from increased supply (for a given material)



Demand saturation (lock B) and constrained extraction (lock C) are identified as essential mechanisms to avoid material increase. Indeed, restricting extraction possibilities (i.e., negatively impacting supply) could constrain price declines on the material market and, thus, the increase in resource use. Moreover, as we discuss in Section 3.2.4, the substitution effect can also be leveraged to prevent an increase in total material use (Zink and Geyer, 2017).

3.2.3 Increased secondary material demand

Third, we discuss dynamics arising when companies position themselves as buyers of secondary goods in the value chain, and decide to incorporate recycled materials into their products or use secondary intermediate goods. Examples include refurbished machinery as inputs in the firm's production processes. This type of circular practices results in a higher demand for circular goods.

This mechanism, which pertains specifically to secondary materials and goods, is the



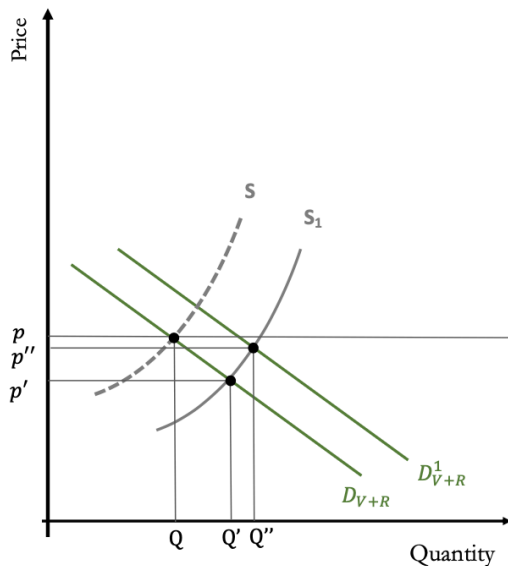
inverse of what was described in the “Decreased Material Demand” (Section 3.2.1). In Figure 3, it is represented as an upward shift in the demand curve for circular intermediate products (from D_1 to D). This increased demand raises prices of circular goods, further incentivizing the collection and processing of waste materials and limiting the overall increase in consumption of circular goods.

3.2.4 Substitution effect

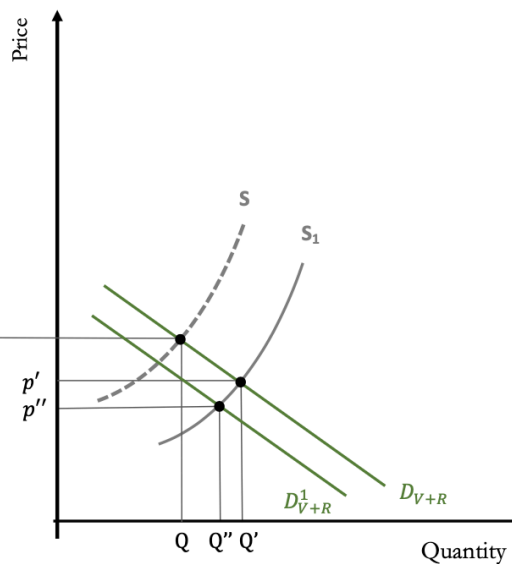
In this Section, we discuss how substitution dynamics between primary and secondary goods compound those discussed in Section 3.2.2 and 3.2.3. Indeed, a crucial assumption of our analysis is that circular products have a (high-to-low) potential to replace their non-circular counterparts (see Section 2), given their technical characteristics. The actual extent of substitution will depend on demand considerations, i.e., whether consumers and firms purchase the circular products in place of the non-circular alternatives.

Figure 5: Illustration of substitution scenarios: incomplete substitution (left) and over complete substitution (right)

a) incomplete substitution



b) over-substitution



In this context, two opposite scenarios need to be discussed: incomplete substitution and



over-complete substitution. The case of down-cycling is arguably a case of incomplete substitution (Afif et al., 2024); on the other hand, sharing systems can represent a case of over-substitution (e.g., when the sharing of a single item effectively replaces the purchase of multiple items).

As illustrated in Figure 4, if the supply of circular material increases, the supply curve shifts from S to S_1 and resource use increases from Q to Q' . If the demand for circular secondary material simultaneously increases, the demand for non-circular inputs may decrease, depending on the degree of substitutability.

In the case of incomplete substitution (Figure 5, Panel a), the increased demand for circular inputs does not fully offset the reduction in demand for non-circular inputs. Total demand rises from D_{V+R} to D^1_{V+R} . Combining both supply and demand shifts, resource use will increase up to Q'' . This is greater than Q' , namely the equilibrium that only results for a shift in supply. Hence, incomplete substitution gives rise to dynamics which compound the upward pressure on resource use.

In the case of “over-complete substitution” (Figure 5, Panel b), the use of one circular input makes it possible to replace more than one virgin/non-circular input. Total demand decreases (from D_{V+R} to D^1_{V+R}). Combining both supply and demand shifts, resource use will decrease to Q'' , which is smaller than Q' . The possibility of “over-complete substitution” between circular and non-circular inputs can therefore counteract the effect of a concomitant increase in supply.

Therefore, one potential strategy to favor resource mitigation is restricting the supply, i.e., constraining extraction and fostering a high substitutability potential. This is more likely if circular materials can be true substitutes for virgin and non-circular alternatives (Zink and Geyer, 2017).

3.3 Resource counterpart

The resource counterpart relates to the material and energy inputs needed to implement circular practices at the firm level. It also accounts for cascading effects on materials and energy across sectors, driven by value chain interdependencies and the adaptive responses of downstream actors.

At the firm-level, implementing a circular strategy likely requires additional energy and material, including those embedded in new capital inputs. These were so far not accounted



for in our analysis of the material counterpart. Producing thinner packaging may require new machinery; sharing systems often rely on digital infrastructure; and recycling or reusing materials typically involves energy use and capital investment, including those for transportation. Indeed, a rich literature points to the importance of accounting for the energy requirements of circular strategies, especially for energy-intensive processes like recycling (Gai et al., 2021; Di Domenico et al., 2023; Potting et al., 2017), or related to the lifetime extension of energy-intensive products (Hummen and Desing, 2021; Iraldo et al., 2017).

Spillovers in the value chain can occur if, for example, consumers spend more resources to access a circular good, e.g., drive to a more distant supermarket that offers zero waste choices (Metic and Pigosso, 2022).¹⁹

When discussing the implications connected to the resource counterpart, what matters is the degree of substitutability or complementarity between the materials and the energy used for the service provided by the circular good across the value chain, as well as how closely the circular good matches the quality of its conventional alternative (e.g., see Wei, 2010). For example, circular strategies like "refuse", which reduce plastic packaging for final consumers, might reduce the quantity of plastic in stores, but still result in larger overall resources used. This can happen if plastic and the other resources employed, such as energy and resources needed for logistics and transportation, are substitutes for one another across the value chain. This substitution effect is a technical one and does not relate to specific consumer preferences.

While fostering the use of circular goods over non-circular goods (Sections 3.1 and 3.2), it is important to account for the resource counterpart, thus verifying whether circular goods have a lower per unit resource impact compared to all the resources needed for non-circular goods (Zink and Geyer, 2017). To this end, a fundamental information gap regarding the degree of substitutability or complementarity between different types of materials and energy must be closed. Both the applied economics and engineering literatures show these relationships are not straightforward and vary across contexts (Long and Schipper, 1978).²⁰ Importantly, the literature suggests a certain degree of proportionality between materials and energy while also indicating that some materials can be substituted with energy. Such complex effects can be better understood through life cycle assessments at the product level (Iraldo et al., 2017) supplemented by market analyses to identify adjustments in value chains.²¹

These knowledge is fundamental to designing policy interventions that avoid



undermining the circular strategies. For instance, the overall effect of restricting the supply of a given resource (using Lock C) varies depending on its degree of sustainability with other materials and with energy. If the resource is complement with other materials/energy, restricting only its supply can ensure an overall reduction in resource use. If the resource is substitute with other materials/energy, this is not the case. Hence, achieving an overall reduction in resource use would require restrictions to all relevant resources. Yet, this may not be an optimal solution. For instance, if reducing plastic packaging for consumers requires higher material use in logistics (e.g., wooden pallets or larger containers) or more energy for transportation, overly strict extraction limits on all resources could prevent the implementation of the circular strategy.

Resource accounting and consistency between the counterparts

To assess the impact of circular strategies on resource use, we need to add up the effects of the three counterparts. Circular strategies might reduce resource use in one counterpart, but this could be counterbalanced by increased resource use in another. In addition, substitution effects, like replacing non-circular products with circular ones, must be carefully accounted for to avoid double-counting. Finally, it is crucial to ensure that the three key counterparts—financial, material, and resource—are consistent with one another. For example, assumptions made in one counterpart, like lower product quality or limited substitutability, should also be inform the other counterparts.

3.4 From resource mitigation to a macro circular economy

Beyond resource use, it is important to analyze extraction and disposal flows, which are connected to the overall level of resource use and have significant implications for climate change. In fact, resource extraction and processing, including biomass, fossil fuels, metals, and non-metallic minerals—contribute to over 90% of global biodiversity loss and water stress, and around 50% of global greenhouse gas emissions (not accounting for land use changes) (UNEP, 2019). Yet, global resource extraction has surged from 27 billion tons in 1970 to 92 billion tons in 2017. Along similar lines, waste disposal impacts land use, biodiversity, and climate change (UNEP, 2019).

Because lower total resource consumption (including virgin and recycled resources) can



occur alongside higher virgin material extraction or increased waste disposal, we examine the conditions that ensure resource mitigation leads to both reduced virgin extraction and lower disposal rates.

3.4.1 From resource mitigation to reduced extraction

Resource mitigation can be defined as $\Delta V + \Delta Z < 0$, where V denotes the use of virgin resources and Z represents the use of secondary materials. In this Section, we assume that $\Delta V + \Delta Z < 0$, namely that resource mitigation has been achieved, and we examine the conditions under which a reduction in extraction can also be achieved.

Quite obviously, resource mitigation leads to lower extraction if $\Delta V < 0$, meaning that the reduction in resource use is achieved through a decrease in virgin resource consumption and not solely through a reduction in the use of secondary materials. Recall that limiting extraction (feature C) has also been identified as a crucial condition for mitigating rebound effects in resource use. Reduced extraction is already a key favorable condition for achieving resource use mitigation. Hence, there is a two-way connection between resource mitigation and resource extraction, as illustrated by the double arrow in Figure 1. Indeed, a lower level of resource extraction is often used as a key indicator of the success in the implementation of the circular economy (Ottelin et al., 2020; Mostert et al., 2021).²²

3.4.2 From resource mitigation to reduced disposal

In this Section, we again assume that resource mitigation has been achieved, and explore the conditions under which it leads to reduced disposal. We do this at both the micro and macro levels. Unlike reduced extraction, reduced disposal also needs to be examined at the micro level, as circular strategies can both positively and negatively affect the lifespan of goods or intermediate inputs, and thus the flow of materials intended for disposal. For example, circular strategies could, in some instances, shorten product lifespan if they push firms and consumers to dispose of the goods before the end of their natural lifetime. This could occur, for example, if second-hand markets create resale opportunities, but buyers do not retain items for long (e.g., due to a lower perceived value of the goods) compared with the scenario of no reselling opportunities.

At the micro-level, a sufficient condition for circular strategies to reduce disposal is that circular strategies do not hasten the product's end-of-life. The direct effect from circular



strategies to reduced disposal is illustrated by the upper arrow in Figure 1.²³

To set the condition at the macro-level, let R represent total resource use in the economy, D disposal, S the quantity issued from the economy's material stock and Z the quantity materials that is recycled. Hence, $D = R + S - Z$, and its evolution is given by $\Delta D = \Delta R + \Delta S - \Delta Z$. Now, assuming resource mitigation ($\Delta R < 0$), we can observe a reduction in macro-level disposal ($\Delta D < 0$) if recycled quantities are stable or increase ($\Delta Z \geq 0$) or if they decrease less than resource use and destocking ($|\Delta R| + |\Delta S| > |\Delta Z|$).²⁴

On the contrary, if the recycling rate decreases, macro-level disposal could increase despite thinner material flows. Hence, at the macro-level, a sufficient condition for circular strategies to reduce disposal is that the recycling rate is maintained so that a reduction in the use of materials leads to a decrease in macro-level disposal – under constant destocking.

To summarize, there are two sufficient conditions to ensure that resource mitigation leads to reduced disposal. First, circular strategies must be put in place for products reaching end-of-life (destined for landfill otherwise). Second, at the macro level, a high level of recycling and/or a low level of de-stocking must be maintained with respect to the amount of resources used.

4. Conditions For A Macro Circular Economy And Possible Policy Levers

The systematic analysis of the possible channels through which the implementation of firm-level circular strategies impacts economy-wide resource use shows the need to jointly consider the financial, material and resource counterparts, while also ensuring that extraction and disposal are limited. It also emphasizes that whether resource use increases or decreases across the different counterparts depends on market characteristics and substitution dynamics.

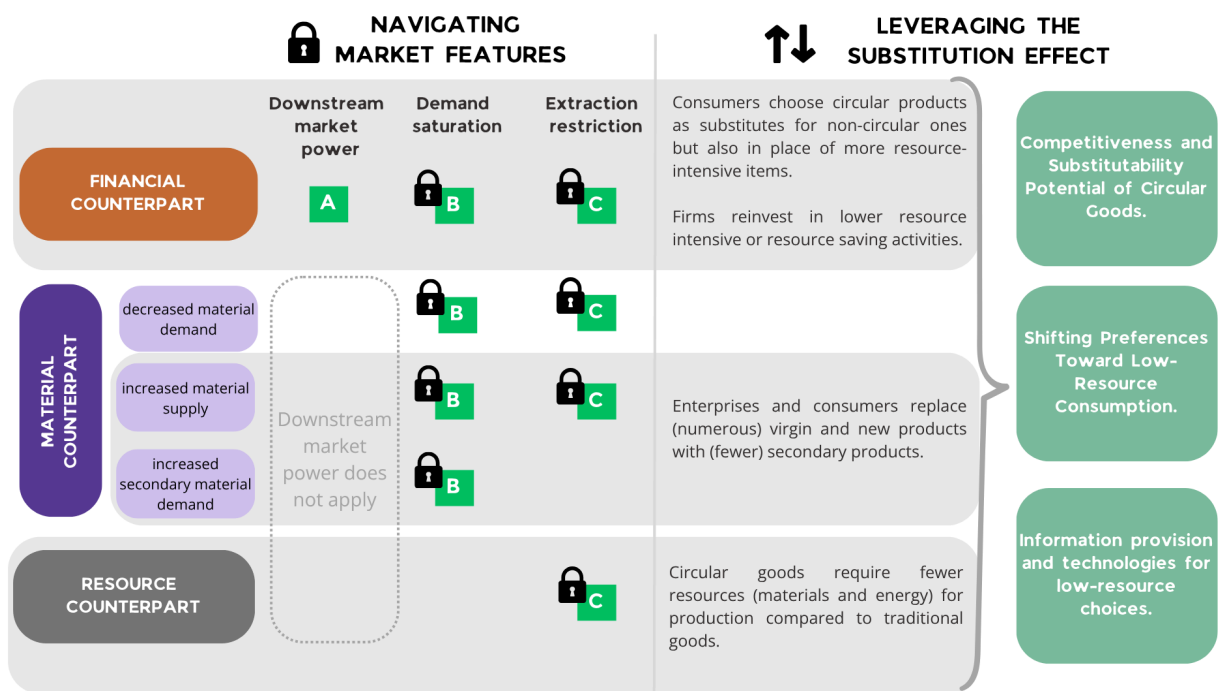
We now discuss the conditions that ensure that firm-level circular strategies translate to macro-level resource mitigation and we identify which policy levers can be exploited to this end. The first group of conditions discussed in Section 4.1, refers to the “locks” B, and C in Figure 6, namely saturated demand and constrained extraction - which emerge from our analysis as key market features. As we will detail later, no such condition can be identified with respect to feature A (market power). The second group of conditions, discussed in



Section 4.2- relates to the substitution effects, which were identified as counteracting mechanisms against the potential resource increase.

Lastly, in Section 4.3 we discuss policy measures related to high recycling rates and extended product lifespans which are necessary to ensure that resource mitigation efforts result in reduced disposal. This analysis is necessary for maintaining coherence across the three dimensions of a macro-level circular economy: resource mitigation, reduced resource extraction, and minimized disposal.

Figure 6: Conditions for circular strategies to lead to resource mitigation



4.1 Navigating market features

4.1.1 Feature A: Market Power

Market structure plays a key role in shaping the pathway through which circular strategies may or may not lead to resource mitigation. However, our analysis shows that a given degree of market competition - whether high or low - cannot give an indication of whether circular strategies will result in lower resource consumption. As detailed in Section 3.1, both



excessive firm margins (resulting from monopolistic markets) and low prices (resulting from competitive markets) can lead to increased resource use. This implies that a lower macro-level resource use cannot be achieved by simply regulating the degree of competition in a given market through, for example, antitrust regulation.²⁵ Indeed, our analysis highlights that what ultimately matters is whether the allocation of additional rents (by both consumers and firms) is directed towards resource-sober or resource-saving activities.

Yet, our analysis underscores that a precise understanding of whether the rents resulting from the circular practices are concentrated or distributed, and which actor they benefit, is a crucial piece of information to design appropriate policy interventions. Knowing the distribution of rents, politicians can target them with taxes and redirect them according to political objectives. Alternatively, they can influence the reallocation of rents, by encouraging their allocation towards resource-sober or resource-savings activities. We discuss policy incentives for resource/sober investments or demand-side interventions in 4.2.1.

4.1.2 Condition B: Demand Saturation

Saturation in either intermediate or final demand (the activation of the lock B) *de facto* results in a congestion effect. Importantly, saturation in final (i.e., consumer) demand emerges as most crucial from our framework, as it also implies a given level of saturation in intermediate demand - while the opposite is not true. Final (consumer) demand saturation can arise from either temporal or physical constraints (e.g., limited storage; Zink and Geyer, 2017), or from environmental convictions and preferences (Dace et al., 2014), resulting in a congestion effect.²⁶

Examples of (quasi-)saturation at the product and sectoral level can be observed: time series data on market penetration of representative products (e.g., cars) often follow a S-shaped curve (Aoki and Yoshikawa, 2002). Yet, natural saturation of aggregate final demand appears highly unlikely in reality, particularly in light of the pressing need from the Global South to achieve decent standards of living (IPCC, 2022; Kikstra et al., 2025).

Policy levers to promote saturation include nudging towards sufficiency lifestyles and encouraging the durability of bulky goods- creating a congestion effect. In the building sector, for example, strategies of urban planning such as compact city development, rationalization of living spaces, and innovative architectural design, can successfully restrict demand for floor space per capita and for long distance travel (Creutzig et al., 2022; Mas trucci et al., 2023).²⁷



Note that if supply is limited (e.g. in housing), competition drives prices up. Consumption will thus be saturated by a physical and budgetary constraint. Yet, this situation can create significant rent effects, the allocation of which impacts resource mitigation, as already discussed above.

However, the natural demand saturation of product or sector demand may still exceed current resource usage levels -failing to ensure resource mitigation- and planetary boundaries. In addition, saturation in one product or activity can be offset by increased consumption of other (more resource intensive) goods. Furthermore, sufficiency efforts by one group of consumers may trigger rebound effects through higher consumption by others (Figge et al., 2014).²⁸

In this case, a specific policy lever—quotas—can force the saturation *level* of certain demand for certain consumer groups. Xin et al. (2012) suggests quotas for energy consumption of four and five-star luxury hotel buildings in Hainan, China. However, quotas on one consumption item are not exempt from the risk of rebound, e.g., by encouraging energy efficiency development and shifting consumption expenditure to other resource-intensive items.

To effectively offset risks of increased resource use, policies to achieve demand saturation should ultimately be directed towards resource-intensive products and the largest resource holders and encompass as many products and consumers as possible, while reflecting on a *level* of saturation compatible with planetary boundaries. This is a complex exercise as saturation objectives require a trade off with other sustainable development goals and should not come at the expense of achieving decent standard of living for all (IPCC, 2022).²⁹

4.1.3 Condition C: Limiting the extraction of virgin resources through quantities or costs

Limiting resource extraction is a goal on its own for achieving a macro-circular economy (Section 3.4.1) and represents a potential lock to prevent increased resource use in the different counterparts (Sections 3.1, 3.2 and 3.3). There are at least two ways to reduce the quantity of resource extracted.

First, resource extraction can be directly limited through regulation, such as biodiversity conservation plans, limits and quotas on extraction activities, or more democratic decision systems (Bareille et al., 2023) and well-defined governance rules (Ostrom, 1990). For instance, the Natura 2000 network, established under EU Directives³⁰ to protect biodiversity,



spans 17.9% of the EU's terrestrial area (Tsiafouli et al., 2013). In Brazil, deforestation of Amazonian lands by land stewards is limited to 20% of the controlled land (Código Florestal; Börner et al., 2014). In the fishing industry, quotas are common (e.g., see Newell et al., 2005).

Second, a lower extraction rate can arise as a result of higher extraction costs (Faber and Proops, 1993). Indeed, environmental standards or taxation impose compliance costs onto the regulated firm (Pizer and Kopp, 2005), leading to higher costs of extraction, which translate to higher downstream resource prices and, consequently, lower demand. For example, the obligation to reclaim land after mining activities can add significant expenses to mining operations (Yu et al., 2020). In Europe, Directive 2006/21/EC requires the management of waste from extractive industries, mentioning soil rehabilitation following waste management activities. In parallel, note that if quantitative legal restrictions are implemented through penalties that are effectively collected, they end up increasing production costs, resembling taxes (Börner et al., 2014). Modeling by UNEP (2019) shows that rebound effects from increased resource efficiency can be managed through gradually increased extraction taxes; Söderholm (2011) shows that taxes on aggregates (gravel, rock, stone, etc.) in Europe have contributed to a reduction in virgin resource use.

However, in practice, restricting extraction through any policy intervention is far from easy. Virgin resources are traded in a fragmented legislative world and environmental policies intertwine with economic interests. In practice, biodiversity protection policies often permit certain extraction activities to maintain economic prosperity and oversight, and to prevent incentives of illegal operations. They sometimes fail to impose restrictions or raise extraction costs. According to Yu et al. (2020), for instance, when land reclamation is combined with economic development initiatives, the investment cost of reclamation can be recovered (Yu et al., 2020), thus offsetting increased costs. Tsiafouli et al. (2013) find that mining, extraction, and industrial activities were reported at 17.6 % of all sites in the national Natura 2000 networks. Although Europe's Habitats Directive foresees that biodiversity maintenance may require human activities (Directive 92/43/EEC), industrial and mining activities are likely to be connected with environmental degradation (Tsiafouli et al., 2013). In Brazil, most of the observed deforestation is carried out illegally (Börner et al., 2014).

Ultimately, effectively regulating extraction requires the implementation of either strong economic incentives or the development of strong environmental preferences in favor of preserving ecosystems and extractive limits.



4.2 Leveraging Substitution Effects

Three conditions ensure that substitutions effects support the achievement of resource mitigation. First, circular goods need to be competitive in terms of price or quality with their non-circular version. Second, preferences for low-resource consumption need to be strong. Third, effective information on product and service resource intensity and substitution and complementarity relationships between inputs needs to be widely available.

4.2.1 Competitiveness of Circular Goods Under Horizontal Competition

If circular goods and services are competitive in terms of price and/or quality, they easily substitute non-circular alternatives. Price competitiveness may arise naturally when circular production involves fewer materials, leading to lower production costs (as explained in Section 3.1). Alternatively, it can result from scaling up circular production, which reduces unit costs regardless of the amount of material used through economies of scale. However, policymakers should be careful of the rebound risks associated with lower prices.

Price competitiveness can also be fostered through policy levers, for instance economic instruments such a taxes imposed in non-circular goods combined with subsidies granted to circular goods (Palmer and Walls, 1997). Direct regulation favoring circular goods can also be implemented. An example is the use of recycled content norms, which how ever require ensuring that recycled content meets industry standards (i.e., that technical substitutability in production is high). In general, policymakers should prioritize subsidies and normative instruments for high-quality circular products with demonstrated high effectiveness at displacing conventional alternatives (high or "over-complete" substitution)

4.2.2 Shifting Preferences Toward Low-Resource Consumption

Shifting preferences toward goods and services that require fewer resources can reduce demand for resource-intensive items and avoid perverse outcomes resulting from circular products replacing low-resource intensive activities (e.g., car-sharing instead of walking).³¹ Consumer and investor preferences are shaped by factors such as moral satisfaction (Kahneman and Knetsch, 1992; Chowdhury, 2017), social norms (Lin and Niu, 2018; Bonan et al., 2025), habits, risk management strategies, and reputational concerns (Reinhardt et al., 2008).

Policymakers can leverage these factors to influence preferences toward less resource



intensive behaviours and investments through policy levers such as environmental awareness actions and education on citizens (Rosa et al., 2018; Ardoin and Bowers, 2020) and firms (Amore et al., 2019). For instance, Rosa et al. (2018) find that greater contact with nature during childhood is positively associated with self-reported pro-environmental behaviours as an adult.³² At the consumer-level, eco-labeling can alter perceived value, making low-resource goods more attractive (Bjørner et al., 2004). In parallel, Joel et al. (2025) show that green bonds are associated with firms' improved environmental performance. It is necessary to ensure that financial criteria actually embed lower levels of resource consumption.

Importantly, preferences for low-resource consumption require that consumers and investors are aware of the resource intensity of different activities, a topic explored in subsection 4.2.3.

4.2.3 Information provision and technologies for low-resource choices.

The availability of accessible and reliable data on product and service resource intensity is key to enable resource-efficient choices and prevent unintended rebounds. To this end, researchers need to leverage methods and tools that measure the resource use of certain processes,³³ such as life-cycle analysis (LCA), which is applied to each specific circular product and allows to check resource efficiency and any trade off between different resources of a given circular practice.³⁴ The analysis should be extended as far as possible to the effects of interdependence between sectors and, thus, to a more aggregated level than traditional life cycle analysis.

Furthermore, policy makers need to ensure that this data is regularly collected and widely shared. Policy levers to promote the monitoring of resource intensity in activities include the establishment of regulatory frameworks, such as mandatory reporting based on standardized LCAs or other methodologies, which are particularly useful for high-impact products. These requirements can be integrated into Extended Producer Responsibility (EPR) schemes to help track and mitigate rebound effects. Economic incentives, such as innovation grants, can also support the development, diffusion, and adoption of novel information technologies. Additionally, public procurement policies can be designed to favor suppliers that use verified LCA methodologies, further encouraging transparency and accountability across supply chains.



4.3 Maintaining a high recycling rate while maximizing products' lifetime, under resource mitigation

Section 3.4.2 presented two sufficient conditions that guarantee that resource mitigation effectively leads to reduced disposal. First, circular strategies must be implemented for end-of-life products that would otherwise be sent to disposal. Second, maintaining a high recycling rate and/or minimizing de-stocking is essential relative to the amount of resources consumed.

Various policy levers can help achieve these two conditions. For instance, cultural and design practices such as design for emotional durability (Chapman, 2009) can help avoid the shortening of products' lifetime. In addition, minimum recycling performance requirements, such as nationally mandated recycling targets, supported by financing mechanisms like Extended Producer Responsibility can be used to maintaining a high recycling rate. Volume-based targets can also help redirect waste away from incineration and landfills but may also incentivize low-quality recycling (Morseletto, 2020). Hence Morseletto (2020) recommends high-quality recycling policy levers such as design for recyclability. On the demand side, recycled content can ensure that the supply of recycled materials produced finds a demand.

Note that the implementation of recycling incentives might inadvertently generate economic motivations for premature end-of-life processing, particularly for products with high material value. A rigorous examination of potential trade-offs is needed to achieve the three dimensions of a macro-circular economy.

5. Implications for climate mitigation

The framework developed and discussed in this paper links circular economy practices at the micro level with resource mitigation efforts, extraction and disposal at the macro level. In this Section, we discuss how a *macro circular economy* can contribute to climate mitigation. The channels from circularity to climate mitigation can be direct and indirect. The direct channel relates to emissions arising from resource use through combustion and other chemical processes (e.g., calcification). When focusing on GHG mitigation heterogeneity in resource emission content needs to be factored in, which we have abstracted from so far. Indeed, resource mitigation can still lead to increased emissions if the use of carbon-intensive



resources increases relative to carbon-efficient ones. Yet, carbon intensity depends on the way in which resources are used (e.g., incineration) and thus varies depending on the given technology and production process. In our framework, we assume a stable technology and thus, implicitly, consider carbon intensity as constant for each resource. In this case, a key condition to ensure that circular practices contribute to climate mitigation is to prioritize the reduction in carbon-intensive resources.

The indirect channel relates to the fact that ecosystem carbon services are affected by resource extraction (ecosystem depletion) and waste disposal (disruption of ecosystem functions due to pollutants and waste discharge). Landfill and extraction destroy the potential habitat for flora and fauna, limiting biodiversity and climate services ([Boldy et al., 2021](#)). Mining activities impact climate change; harvesting subsurface resources can substantially transform the land typography and alter the flow of water ([Boldy et al., 2021](#); [Hoesen et al., 2023](#)). This can cause enduring adverse impacts on biodiversity and associated ecosystem services (*ibidem*). Mining forests leads to the release of greenhouse gases due to forest loss. Disposal activities generate greenhouse gas emissions: methane is produced when organic material decomposes anaerobically (45% to 60% CH₄, 40% to 60% CO₂, and 2% to 9% other gases, [Aljaradin and Persson, 2012](#)), for instance as a result of landfilling. According to [Gichamo and Gökçekuş \(2019\)](#), the contribution of solid waste to climate change is relatively low. However, landfills represent an opportunity cost in terms of land use and climate. This space could be allocated to maintaining an area of biodiversity that helps regulate the climate.

Since ecosystems yield different types of services and their capacity for climate stabilization varies spatially, the geographical aspects of resource provenance and disposal locations are critical factors in determining the overall climate impact of circular practices.

6. Conclusion

Our framework outlines three distinct channels—financial, material, and resource—that link firm-level circular practices to macro-level resource use. We identify the critical factors influencing the potential for lower or higher resource use, which need to be considered strategically. Importantly, this requires addressing demand saturation, constraining extractive possibilities and fostering preferences for resource-sober goods, services and activities.

Our analysis provides several useful insights to researchers in engineering and material



modeling of circularity. First, it points to potential shortcomings in currently available modelling tools, which generally lack the ability to precisely model the financial counterpart. Second, it clarifies the importance of being transparent in model assumptions - including with respect to the substitutability between circular and non-circular goods and the presence or absence of consumer preferences for circularity - and to explore the robustness of results to sensitivity analysis. Third, it calls for the development of circular narratives which can be used as a storyline to explicitly account for those aspects - such as market features - which cannot meaningfully be included to avoid over-complexity.

Our findings also put forward three additional policy implications. First, in line with the financial counterpart, taxation alone does not guarantee resource efficiency. A tax system is effective in achieving this objective only if it discourages resource-intensive expenditures and it ensures revenue recycling into resource-efficient or resource-saving activities. Without proper revenue recycling, taxation will fail to deliver meaningful decreases in resource consumption. For instance, investing in public transportation (i.e., sharing) could be an efficient tax recycling activity.

Second, environmental preferences are not only a key condition to leverage substitution effects, but also fundamental to the broader success of any policy measure. To be effective, policies aimed at limiting resource extraction or demand saturation must be widely accepted by the public, which largely depends on strong environmental preferences. This highlights the key role for political economy considerations, behavioural interventions and more broadly the importance of fostering awareness.

Third, our conditions closely align with the concept of sufficiency. Avoiding rebound effects requires robust environmental preferences, and demand saturation through consumption restrictions represents a sufficiency strategy in itself (Figge et al., 2014). While the concepts of circular economy and sufficiency are often examined separately (Figge and Thorpe, 2023), our research bridges them by demonstrating that sufficiency is a necessary condition for circularity to result in resource mitigation. However, Figge et al. (2014) show that sufficiency strategies themselves are not exempt from rebound effects (without backfiring), if the restriction of some lead to lower prices and increased consumption of others. Fostering a certain homogeneity of preferences could be an additional step into restricting rebound possibilities.

By providing insights into the conditions supporting climate mitigation through circular economy practices, our framework also highlights fruitful avenues for future research. For



instance, our framework is qualitative in nature because it needs to inform a large number of very different models. Future research should strive to improve the quantification of the effects we identified and of the associated resource savings and rebounds, which vary widely by sector and by country. In addition, future research should explore the robustness of our results by relaxing the key hypotheses our framework, such as the profitability of circular strategies or the absence of disruptive technical change. Furthermore, a key extension of this analysis is in the exploration of natural monopoly resource markets where supply quantity is inversely related to price.

End Notes Annex A

¹Flows are observed within a given period (e.g., a year).

²"Recover" is defined as energy recovery from incineration or by anaerobic digestion by [Potting et al. \(2017\)](#). The available R-lists ([Potting et al., 2017](#)) establish a *de facto* priority order based on the waste treatment hierarchy, whereby strategies higher in the hierarchy, such as "refuse", e.g., bulk selling, are considered more effective in managing waste than strategies lower in the hierarchy, such as "recycle". However, the basis of the waste hierarchy for such ranking is not strictly rigorous ([Rasmussen and Vigsoe, 2005](#)). This is illustrated by the fact that in the case of waste management, the EU Waste Directive recommends checking the environmental outcome of the hierarchy with life-cycle analyses.

³This means that we do not consider the implementation of circular strategies that replace existing ones. This would imply opportunity costs in terms of resource use in choosing one or another circular strategy ([Figge and Thorpe, 2019](#)), but this is relevant to the study of maximum resource use mitigation. In this framework, we simply study the variation of resource use at the macro level, i.e. whether resource use declines or not.

⁴According to [Reinhardt et al. \(2008\)](#), firms treat socially responsible actions like any other business activity, pursuing only those initiatives that align with their financial objectives rather than engaging in altruistic profit sacrifices.

⁵A supply increasing in price characterizes markets defined as natural monopolies. This scenario has yet to be thoroughly examined in the rebound effect literature.

⁶This implies that there is no "Veblen effect", i.e. luxury consumption where consumers are willing to pay more for an equivalent good to emphasize their status ([Bagwell and Bernheim, 1996](#)). Note that regarding intermediate demand, the assumption of decreasing demand in price is implied by the profit-maximizing assumption: Firms minimize costs and thus look for the cheapest inputs for a given quality.



⁷Our approach to the rebound concept differs from the existing literature in that we do not assume circular strategies automatically deliver environmental benefits. Instead, these benefits must be evaluated across all three counterparts. Nevertheless, the mechanisms are similar.

⁸Also note that increased sales mean more profit for the firm, thus potentially giving rise to dynamics similar to those which characterize less competitive markets, described below

⁹This is the case if the demand of other goods and services is not saturated, an assumption which is in line with the observed trends of increased consumptions worldwide.

¹⁰Indeed, the literature shows that in more concentrated markets, selling prices tend to be more rigid when it comes to lowering them following a reduction in production costs (Loy et al., 2016).

¹¹Note that a high marginal willingness to pay implies that consumers perceive the circular good as of the same or higher quality with respect to the non-circular good. A perception of too low quality is incompatible with setting a high margin.

¹²The profit-maximization hypothesis implies that the consumption adjustment does not negatively impact the firm's profit. Hence, decreased sales mostly affect other goods and services by assumption.

¹³This can be equivalent to a fixed basket composition, unless in the case of saturated demands, which can constrain the basket composition

¹⁴Contrary to the effect detailed in the *financial counterpart*, which is related to firms' downstream markets and individual firm pricing strategies.

¹⁵The material counterpart can thus refer to the *economy-wide rebound effect* in the terminology of Greening et al. (2000).

¹⁶We assume that circular strategies leading to reduced material needs do not change price elasticity, i.e., do not affect the demand curve slope.

¹⁷The effect differs from the financial counterpart in that it represents an aggregate adjustment in the upstream market, whereas the financial counterpart reflects a adjustment in the firms' downstream demand.

¹⁸If primary and secondary goods compete within the same market, the supply curve in Figure 4 (Panel II) can be interpreted as total material supply, comprising both primary and secondary sources. Conversely, if these goods compete in separate markets, the observed increase in supply reflects only the secondary goods component.

¹⁹In the example of the zero-waste supermarket, we can see the problem as a "quality" issue. The circular service is perceived as superior in terms of utility, as consumers are willing to spend additional



resources to access it. However, the service entails a "technical" drawback in terms of accessibility. Avoiding loss of quality services, which includes accessibility, could prevent this type of rebound. However, note that as consumers' budget is fixed, this type of increased consumption (e.g., driving) would substitute for other expenses and purchases impacting the financial counterpart.

²⁰e.g., see (Aditya et al., 2017) for an example of substitutability between insulation materials and energy consumption

²¹Note that these measures can be costly in terms of data collection and analyses, and modelers can account for them in the financial counterpart under production costs.

²²Alongside the material footprint concept, defined as the "total amount of raw materials extracted to meet final consumption demands" by the United Nations (2023).

²³Recall that the focus of our analysis is on circular strategies substituting "no circular strategy". Conversely, we do not consider cases in which firms shift from one circular strategy (e.g., recycling) to another (e.g. repair), in which case we would need different conditions for reduced disposal. ²⁴See resource flows in Haas et al. (2020)

²⁵Nevertheless, while our framework does not directly discuss the distribution of rents, we note that if this is such that inequality increases, the literature provides some evidence that overall environmental quality may be negatively affected (Boyce, 1994; Magnani, 2000; Berthe and Elie, 2015). We leave this topic for future research.

²⁶Demand saturation differs from simple preferences affecting the weight of utility and marginal will ingness to pay. In case of saturation, even for very low prices, a certain consumption threshold cannot be exceeded; while in "shifting preferences" (condition 4.2.2), the demand never becomes price-inelastic. As this is a very unlike situation, below we also explore quasi-saturation as an approximation.

²⁷Note that the effective potential of these solutions is still to be fully understood since their modeling is most often than not quite simplistic. In most of the modelling literature reviewed in our analysis, floorspace levels adjust exogenously to compact urban form and co-housing without explicitly accounting for the underlying socio-economic drivers (Mastrucci et al., 2023).

²⁸If only a minority of consumers shift toward sufficiency, prices may drop, encouraging higher consumption among others. In this case, only the demand curve for "sufficient" consumers becomes inelastic, while overall demand remains responsive (Figge et al., 2014).

²⁹To further explore the question of demand saturation, we refer readers to the work of Higgins (1972). Higgins (1972) theoretically demonstrates that, for a given income, there exist preferences that can allow for the saturation of demand for market commodities (e.g., energy or clothes) *relative* to non-market commodities (e.g., walks in nature or time spent with friends). Following our



framework, we would add to this theoretical consideration that to achieve resource mitigation, these non-market activities must be resource-saving, or at least resource-sober.

³⁰established under two EU Directives: the Birds (79/409/EEC; 2009/147/EU) and the Habitats (92/43/EEC) Directive ([Tsiafouli et al., 2013](#))

³¹Graphically, this is represented by a decreased willingness to pay for resource-intensive activities, causing an inward shift of their demand curve, while the demand for low-resource consumption items shifts outward. Changing preferences can also alter how sensitive consumers are to price changes (elasticity). If consumers become less attached to resource-intensive consumption, demand can become more elastic for these items, meaning price plays a larger role in their purchasing decisions. Conversely, demand for low-resource consumption activities may become less elastic. This suggests that price decreases should be contained for resource-intensive activities to prevent reinforcing their consumption. Note that "Shifting preferences" differs from our condition B, "Demand Saturation," as it pertains to the utility weight assigned to a consumption item, influencing both the intercept and slope of the demand curve. In contrast, demand saturation refers to a specific case of inelastic demand, where the demand curve becomes vertical beyond a certain threshold (maximum quantity). Unlike saturation, shifting preferences alone cannot fully lock the rebound effect because, if demand is highly elastic, any (high) quantity can still be reached at a given price ([Dace et al., 2014](#)). However, there exists a corresponding price level that can achieve the saturation quantity (i.e., "cap or tax" debates; [Karp and Traeger, 2024](#)).

³²The authors surveyed 224 young adults in Brazil.

³³Adhering to the R-hierarchy, where the Rs in the higher part of the hierarchy, such as refuse, are assumed to be more resource efficient than the Rs lower in the hierarchy, such as reuse, is only a rule of thumb, as there are many exceptions ([Potting et al., 2017](#)).

³⁴LCA is by no means an easy task since it requires very detailed data. Furthermore, LCAs are easier to run after a project is completed. This makes it difficult to use LCA to influence design decisions ([Desing et al., 2021](#)). There are ongoing developments in ex-ante analyses, but they require specialist knowledge to address uncertainty and face challenges related to data availability and comparability ([Desing et al., 2021](#)).



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A.1 Further Assumptions

We consider a global economy comprising a certain number of individuals who want to achieve a certain service/activity, which in turn provides them with a certain level of utility. We restrict our attention to market activities.

Resources are matter that was originally extracted from the ground, and that is used either as material support (recycled or not) or energy. *Materials* are defined as matter being used in the economy for service provision. Materials come from both virgin and recycled sources and include materials (re-)used within this period, and materials added to the stock, i.e., accumulated in buildings, infrastructure, and durable goods in use for more than one



year (as in the terminology of [Haas et al., 2020](#)).

In this paper, we take into account the stock of materials only in its relationship to the flow: demand for maintenance or replacement, or recycled materials from the stock. We focus on material flows rather than stocks because we aim to study the links with climate mitigation, focusing on GHG flows. However, the separability of material stocks and flows is not easy, given that the stock requires a certain amount of materials and energy to be maintained and/or replaced, likely to increase with time (durability). *Energy* is the force that enables a certain level of activity. It is through energy that materials can be extracted and circulated and stockpiles maintained. Hence, energy is an inherent part of the (final) service provided (substituting individuals' labor) and is using resources. Some resources are directly converted into energy, necessitating some material support. *Disposal* refers to materials that are returned to the environment in solid form or incinerated. Materials that are disposed of may come from material throughput or the destocking of stock materials. *Greenhouse gas emissions* refer to resources transformed into greenhouse gas emissions, interacting with climate. Greenhouse gas emissions originate from the year's flow of resources, and possibly also from the flow of previously stored materials.

An important assumption underlying our framework is that all time/energy/monetary resources are used.³⁵ For example, reuse can mean financial profits for the company, and these savings can be employed to purchase new items whose production will have a positive or negative ecological impact. The assumption that all resources are used implies that this new item would not be purchased otherwise. Similarly, changes in logistics or means of production imply a change in resource consumption, with impact reverberating down the value chain. All these transfers together can alter or enhance the outcomes at the macro level.³⁶

³⁵Note that we focus on resources and abstract in this paper from considerations related to labor.

³⁶Not making this assumption would mean omitting the secondary effects of circular practices and focusing solely on the direct effect (e.g, waste avoided by reuse), and therefore not being able to examine the macro-economic impact.

A.2 Indirect Rebound: *re-spending*

Let us assume that consumers consume the circular product c in quantity C_c , which remains unchanged. This product amounts to the consumption of resources R_c . We assume that the



circular strategy at the product level is consistent, meaning that it leads to $\Delta R_c < 0$. Note that this assumption is challenged in Section 3.3.

Consumers have a fixed budget. The price of c decreases, meaning they have a surplus of budget to allocate to other consumptions s : $\Delta C_s > 0$. this additional consumption is equivalent to consuming $\Delta R_s > 0$.

Therefore, overall resource use can still decrease if the reduction in resources from product c (ΔR_c) is greater than the increase from additional consumption (ΔR_s); that is, if the consumer's basket composition is sufficiently resource-efficient.

Note that since this effect does not include substitution, it presupposes that the resource savings from the circular strategy are very important and that the consumer's consumption basket was already low-resource intensive.

A.3 Substitution Effect *versus* Direct Rebound

In the case of the direct rebound, consumers having a fixed budget react to the decreased price of c by increasing the consumption of the product c : $\Delta C_c > 0$. If c competes with a resource-intensive good s , there can be a further substitution effect, hence an additional $\Delta C'_c > 0$ and $\Delta C_s < 0$. Hence the resource accounting gives:

$$\Delta R_c + \Delta R'_c + \Delta R_s \quad (1)$$

Resource mitigation requires that:

$$|\Delta R_c + \Delta R'_c| < |\Delta R_s| \quad (2)$$

Resource mitigation can still occur if the (partially) replaced good is specifically very resource-intensive.



D3.1. ANNEX B1

Digesting fossil infrastructure for cleaner energy transitions

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Abstract

The climate crisis mandates building renewable energy infrastructure faster, which increases demand for primary materials with large environmental footprints. Recycling can mitigate such impacts, but its potential depends on waste availability. Here, we use life cycle assessment and monetization of impacts to explore the environmental implications of recycling fossil infrastructure that may become obsolete during the transition. Among many materials in fossil infrastructure, recycling steel is particularly noteworthy, as its stock (1.35 Gt) aligns with projected demand for the energy transition. Recycling steel could save up to 1.85 Gt CO_{2,eq} emissions and \$5.20 trillion in externality costs while remaining competitive with current production methods. It would also reduce the carbon footprint of wind and photovoltaic power by one third. These findings provide strong evidence for the benefits of repurposing fossil infrastructure and underscore the need for policies to expedite the transition while considering socioeconomic and geopolitical issues.

1 Introduction

Meeting climate goals will require deploying 6.0 to 8.1 TW_p of wind and 8.5 to 14.0 TW_p of solar photovoltaic (PV) capacity in 2050 [1,2], for which metals involving mining and refining operations with large environmental [3–5] and social impacts will be needed [6,7]. Recycling bulk metals from waste streams—such as demolished buildings, end-of-life vehicles, industrial equipment, and consumer goods [8]—could reduce the demand for primary materials but the availability of waste is limited [9,10]. Besides avoiding impacts, building renewable infrastructure with recycled materials could accelerate the transition by circumventing the slow process of opening new mines (16.5 years on average [11]).

Previous studies showed that significant climate impact savings between 30 and 95 % could be attained by recycling bulk metals compared to primary production [12–15]. However, the limited availability of metal waste and its competing uses (e. g. , buildings, vehicles, packaging, machinery) makes it necessary to find additional metal waste sources to further enhance circularity and reduce impacts in the energy transition. Because this transition will make fossil energy obsolete, we here focus on materials contained in fossil infrastructures—such as coal mines, oil and gas rigs, pipelines, and power plants. Some of these infrastructures can be repurposed using other circular strategies than recycling, including repurposing boreholes of oil and gas wells for geothermal energy [16–19], converting oil-based refineries into bio-refineries

[20], reusing pipelines for hydrogen transport [21], constructing grid infrastructure (e. g. , large-scale battery storage) on former power plant sites [22], carbon storage in depleted oil and gas reservoirs [23], and producing synthetic fuels on offshore gas and oil platforms [20]. However, these options do not target the acceleration of building capacity in solar and wind, the dominant power sources in many transition plans [24–27]. Although previous work estimated the material stocks in fossil infrastructure in aggregated material categories [28,29], the feasibility and broad environmental implications of their recycling, especially for building renewable energy systems, are still unknown.

To fill this gap, we map global stocks in the current fossil infrastructure for 22 materials, quantifying the recycling potential and comparing it with estimated materials demand induced by transition pathways. We find that steel is the largest metal stock in fossil infrastructure (1.34 Gt) and is within the range of estimated demand in transition pathways aiming at 1.5 °C and 2 °C heating [30]. Using prospective life cycle assessment (LCA) and monetization factors (see Fig. 1 for method overview and Methods section for more details), we find that recycling steel could save externality costs of more than 5 trillion USD₂₀₂₃, and decrease environmental impacts of steel production in at least 17 out of 20 indicators—while remaining economically competitive.

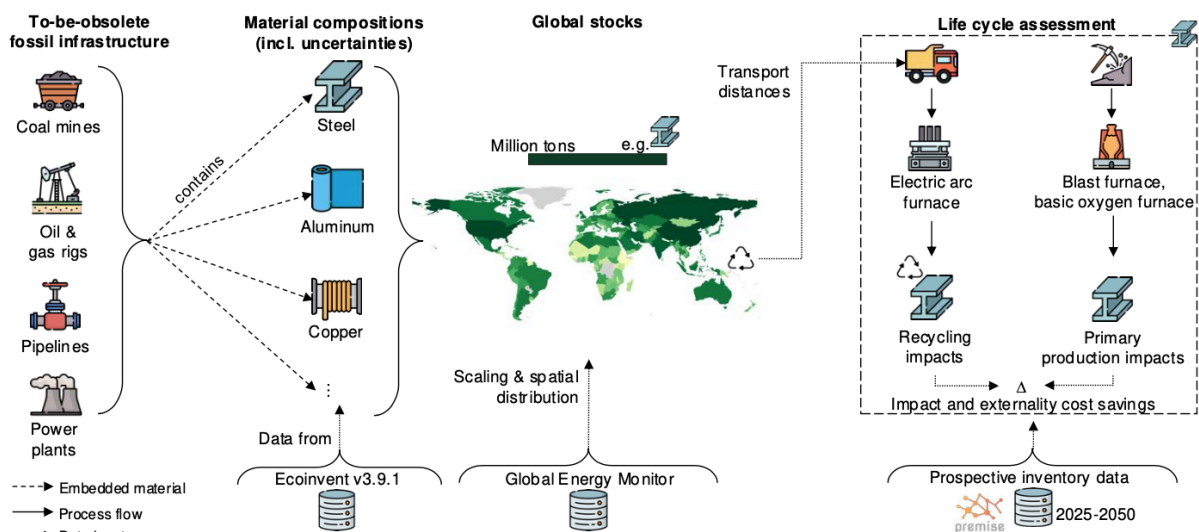


Figure 1: Calculating environmental impact and externality cost savings of recycling steel in current fossil infrastructure. Global material stocks in soon-to-be-obsolete fossil infrastructure are determined by scaling material intensities (ecoinvent v.3.9.1 database [31]) of coal mines, oil and gas rigs, oil and gas pipelines, and power plants with the size of global fossil infrastructure (according to Global Energy Monitor databases [32–37]). We then focus on steel, estimating the impacts of primary and secondary steel production (using scrap from fossil infrastructure) for 2025 to 2050 (using Premise [38]), and translating them into monetary units using externality factors to quantify the benefits of recycling it for the energy transition



Results

2.1 Fossil material stock estimate

We start by determining the amount of materials available in the current fossil infrastructure, finding that a total of 6.39 Gt ([4.71–9.06]Gt, 95 % confidence interval) of waste materials may become available through the transition. Concrete is the largest of these stocks, representing 2.01 Gt ([1.24–3.42]Gt) and is mostly used for pavements and structural components. Yet, this stock is well below the estimated median demand induced by the energy transition of 6.49 Gt [30]. Moreover, recycling of concrete is limited as only aggregates can be replaced by crushed concrete, still requiring new cement, the main driver of climate impacts for concrete [39].

Steel is the second largest stock, amounting to 1.35 Gt ([0.84–2.26]Gt, matching cumulative steel demand estimates for energy transitions until 2050 ([0.51–2.85]Gt depending on the scenario [30], see Fig. 2a). Steel is mostly used for structural purposes in oil and gas extraction equipment (47 %), power plants (26 %), pipelines (21 %), and coal mines (6 %). The five countries with the largest fossil steel stocks are China, Saudi Arabia, Russia, the United States, and Iran, with 162, 156, 153, 149, and 95 Mt steel respectively, accounting for more than half of global stocks (53 %).

Aluminum (Al) and copper (Cu) follow, used mainly in cables in fossil infrastructure (7.80 Mt ([4.36– 14.42] Mt) and 10.03 Mt ([5.94–18.33] Mt) respectively), and could contribute up to 9 % and 32 % of the Al and Cu required in median projections of energy transitions [30]. In contrast, stocks of Nickel (Ni) and Silicon (Si) in fossil infrastructure are insignificant in comparison to the induced demand (0.06 Mt and 0.83 kt, 4 % and 0.001 % of median demand for energy transitions until 2050 according to [30]; see Fig. 2a).

For some of the materials contained in current stocks, no demand for the energy transition was reported in [30] (e. g. for cobalt (Co); see Fig. 2b), or they are not typically contained in renewable energy infrastructure, such as barite; however, alternative uses could be explored. For example, 338.36 Mt ([58.64–1847.04] Mt) of barite—used in drilling fluids and representing at least seven years of annual production—could be repurposed as radiative cooling paints containing barite [40], while 10.42 Mt ([6.00– 18.32] Mt) of stone wool in power plants could be reused for insulating buildings or district heating pipes.

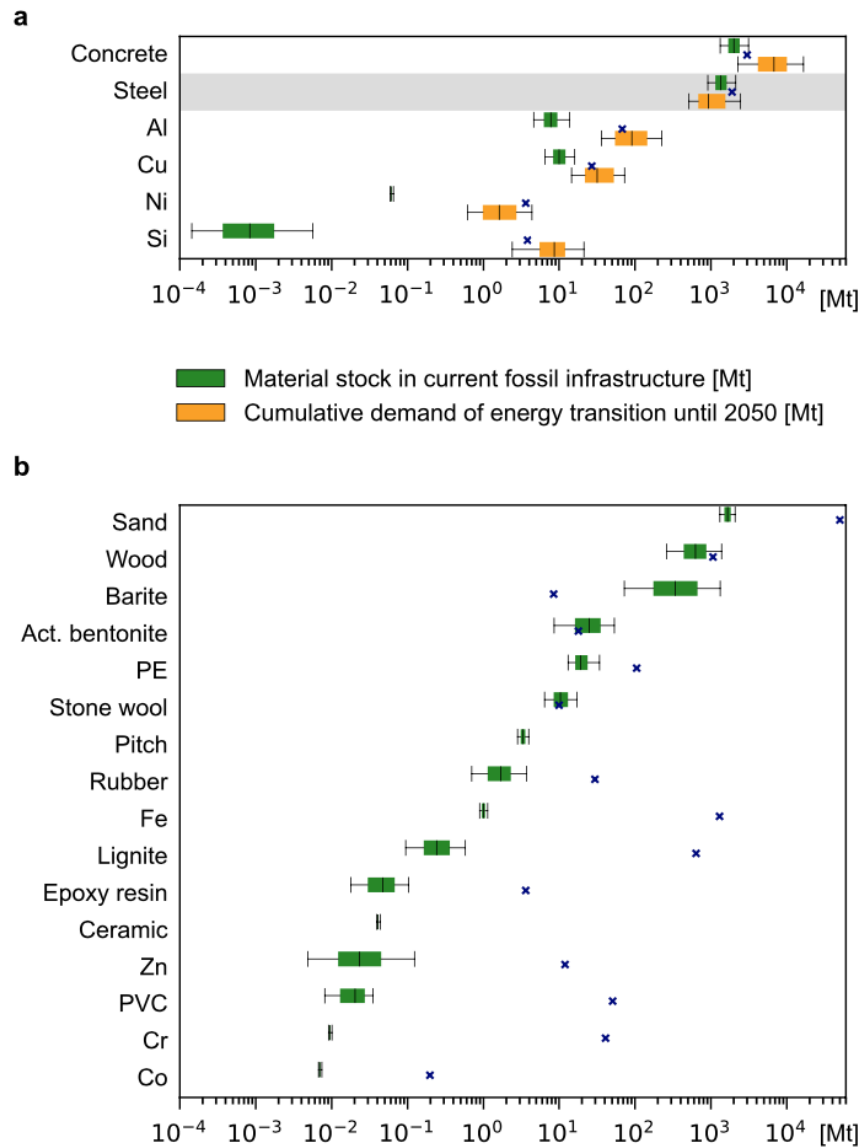


Figure 2: The size of steel stocks in current fossil infrastructure is of the same magnitude as required in energy transitions. **a**, Stocks of 22 materials stored in currently operating, mothballed, or idle fossil infrastructure (green), compared to cumulative demand for global energy transitions until 2050 (data from [30], yellow) and current annual production (blue cross, various sources, see SM Table S1). Uncertainties (box shows the inter-quartile range, whiskers show 2.5th and 97.5th percentile of distribution; calculated using a Monte Carlo simulation with $n = 500$) stem from the material intensity and linking infrastructure types. The distribution of demands shows the range within possible energy transition scenarios and models. **b**, Material stocks in current fossil infrastructure that are currently not in demand for energy transitions (or no demand reported in [30], e. g. Co). Yet they might become interesting when redesigning renewable infrastructure. PE=polyethylene, PVC=polyvinyl chloride.



2.2 Feasibility of recycling steel stocks and associated environmental benefits

We next focus on investigating the environmental savings of recycling steel stocks, given its relevance. We first compare steel stocks with the currently available recycling capacity to evaluate the feasibility of providing large amounts of secondary raw materials in the short term. The global capacity of electric arc furnaces (EAFs) and electric induction furnaces, with EAFs being today's dominant technology for steel recycling (97 %), can process a maximum of 743 ^{Mt}/a [41], yet EAF steel is produced at 541 ^{Mt}/a globally [42], allowing for an additional 202 Mt of steel to be processed annually. Would all this idle capacity be used for recycling steel from fossil infrastructure, this could be possible in just over seven years ([4–11] years).

However, neither steel stocks nor recycling infrastructure are distributed uniformly across the globe, implying that in some regions recycling could be achieved much quicker than in others. If scrap steel is traded on a continental scale, recycling of steel from fossil infrastructure would take five to 14 years with existing idle recycling capacity (see Fig. 3a), lying below typical multi-decade transition times investigated in Shared Socioeconomic Pathway (SSP) scenarios (see Supplementary Materials (SM), Fig. S1a). In Oceania, recycling of fossil infrastructure is not feasible within typical transition times due to limited EAF capacity, however, trading scrap with Asia could allow processing of fossil steel from both regions. Consequently, recycling steel from fossil infrastructure could be feasible well within the time frame of transition trajectories.

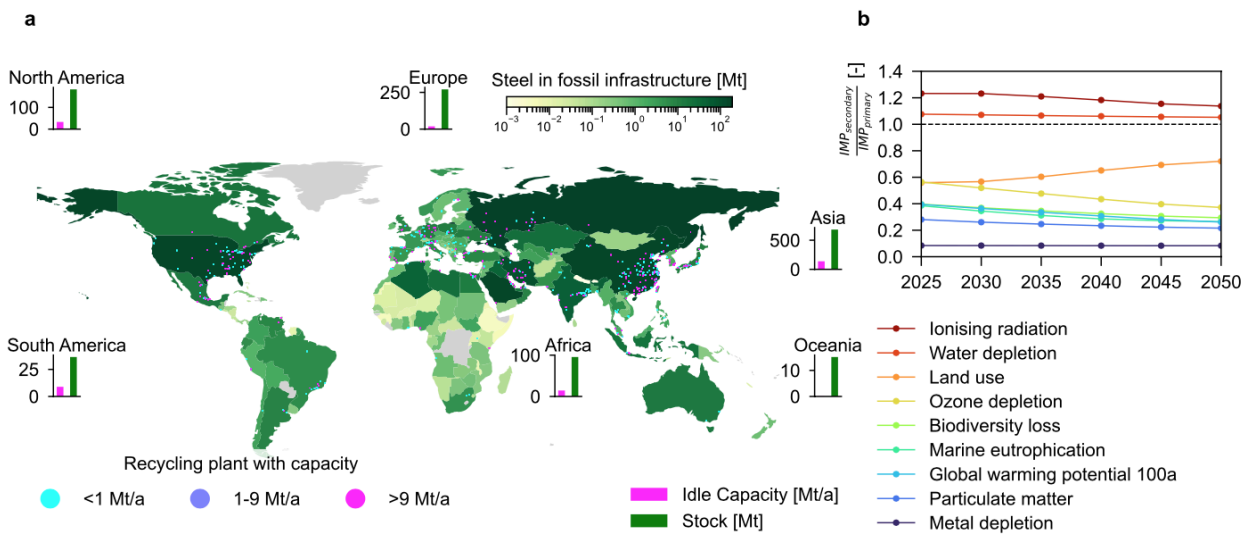


Figure 3: Recycling of steel from fossil infrastructure can be fast and shows significant environmental benefits across indicators. **a**, Global idle recycling capacity could process steel stocks in current fossil infrastructure within four to 11 years, and five to 14 years with continental trade. Green shades represent the magnitude of steel stored in fossil infrastructure in 200 countries. Gray color indicates countries or regions with missing data. Bar charts show total continental steel stocks in fossil infrastructure compared to the capacity to recycle steel within one year. Dots show the location and capacity of EAFs for steel recycling (data from [41]). **b**, Relative impact of recycling the fossil steel stock to primary production across nine environmental indicators in the SSP2-NPi scenario; other 11 impact categories in Extended results Figure E2 and E3.

Because environmental impacts from both secondary and primary production routes do change over time, e. g. through technological learning or changing energy mixes, we evaluate the environmental benefits of recycling with time (between 2025 and 2050) and consider six scenarios. These future trajectories are generated by the Integrated Assessment Model (IAM) Remind [43] following SSP1, SSP2, and SSP5 in both National Policies implemented (NPi) and Nationally Determined Contributions (NDC) variants. The LCA background database ecoinvent v3.9.1 is modified for each time step according to all IAM scenarios using Premise [38]. Projected global mean temperature increases until 2100 in the investigated scenarios range from 1.9 °C in SSP1-NDC to 3.9 °C in SSP5-NPi (see SM, Fig. S1b), with SSP2-NDC (2.3 °C) and SSP2-NPi (3.1 °C) being close to the currently projected increase of 2.5 to 2.9 °C until the end of the century [44].

We find that during the period 2025–2050, recycling steel from fossil infrastructure would improve at least 17 out of the 20 LCA indicators across scenarios relative to the dominant



primary production route (i.e., blast furnace and basic oxygen furnace; BF-BOF) (Fig. 3b for nine LCA indicators and Fig. E2 and E3 for other indicators). More precisely, in the SSP2-NPi scenario, the largest impact reductions are found in metal depletion (92 %), followed by particulate matter formation (72 to 78 %), freshwater eutrophication (71 to 82 %), and global warming potential (61 to 74 %), with similar results for other SSP scenarios. In contrast, impacts from water use and ionizing radiation would increase slightly (5 to 8 % and 14 to 23 % respectively). Environmental impact reductions of recycling are mainly driven by lower demand for coking coal, mining of coal and iron ore, as well as production of alloying metals, all of which cause significant climate impact and eutrophication, and particulate matter emissions. Blast oxygen furnace slag contributes to human and ecosystem toxicity in primary steel production, and can be avoided in secondary production.

Both higher water demand in the EAF route than in the BF-BOF route, and water consumption in hydroelectric power plants used for EAF electricity supply cause increased water use in secondary steel production. Substituting fossil energy in primary steel-making with electric energy in EAF generates a trade-off with ionizing radiation from nuclear power plant waste and Uranium production in the investigated scenarios. This trade-off can be completely avoided when no nuclear power is present in future electricity supply.

Scaling environmental benefits to the total steel contained in fossil infrastructure, between 1.62 and 1.85 Gt $\text{CO}_{2,\text{eq}}$ of emissions could be avoided depending on the scenario and year of intervention, which is comparable to Russia's greenhouse gas emissions in 2023 [45]. Between 25 and 45 billion m^2 a of land could remain unoccupied, representing roughly the land occupation of Hong Kong from 2025 to 2050. Around 3.35 Mt $\text{PM}_{2.5,\text{eq}}$ particulate matter emissions could be avoided, equivalent to two years of $\text{PM}_{2.5}$ emissions in the United States in 2023 [46]. In regard to biodiversity loss, around 7,500 species years could be saved. In general, the temporal evolution of the relative difference in impacts follows a monotonic decrease in ozone depletion, climate impact, biodiversity loss, and marine eutrophication, driven by efficiency gains and continuing defossilization of supply chains. Land use impact is increasing, due to increased use of biomass in lubricating oil production, however, this can be avoided by switching to green chemicals synthesized from the air and water.

Testing the robustness of our results with pessimistic assumptions regarding dilution of scrap with added primary metals to compensate for lower scrap quality and higher hexavalent chromium leaching from waste steel slag and dust, environmental impacts can still be saved, though at reduced levels. e. g. $\text{CO}_{2,\text{eq}}$ savings would be halving, and avoided particulate matter emissions decline from 3.35 Mt $\text{PM}_{2.5,\text{eq}}$ down to less than 1.85 Mt $\text{PM}_{2.5,\text{eq}}$. However, recycling



remains the ecologically preferable option for all indicators except for ionizing radiation and water use (see Fig.E2 and E3), where impacts can become slightly larger for recycling if consumed electricity is partly produced with nuclear and hydropower. Also, human toxicity of secondary steel production can become larger than of primary production due to increased levels of hexavalent chromium emissions, which can be reduced with better treatments of EAF slag and dust [47–50] (see Fig.E3).

2.3 Externality costs

Saving environmental impacts also avoids future externality costs for human health (HH) and ecosystem damage (ED) remediation, which are typically not accounted for in production costs (see Fig. 4a). Reducing impacts via recycling thus also leads to healthcare cost savings due to reduced pollution, less compensation for impaired ecosystem services, and lower demand for natural resources (see Sec. 4 for details). Recycling fossil steel stocks could avoid externality costs between 3.17 to 5.20 trillion USD₂₀₂₃ (Remind SSP2-NPi scenario; between 3.07 and 8.72 trillion USD₂₀₂₃ across investigated SSP scenarios), depending on the year of intervention. These cost savings are mainly realized by reducing damages to HH caused by human toxicity and particulate matter formation as well as climate change. Avoided externality costs correspond to 0.82 to 3.14 % of that year's GDP depending on the time of recycling and SSPs. Under pessimistic assumptions on EAF slag and dust treatment, externality cost savings can be realized in SSP1 and SSP2 scenarios, yet externality cost savings diminish to zero in 'fossil-fueled developments' scenarios (SSP5; see Fig.E1). The lowest externality costs of steel production are found in the secondary route in 2025, with costs increasing 0.7 to 4.1 % per year or nine to 270 USD₂₀₂₃ per ton steel per year on average depending on scenario (see Extended results section Fig. E1).

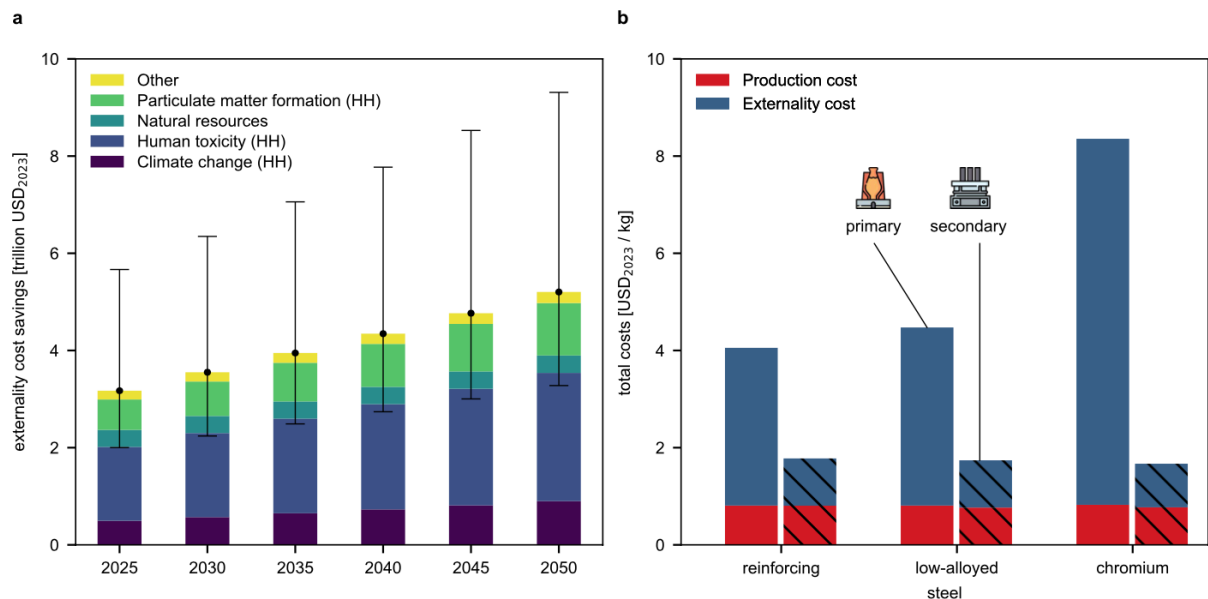


Figure 4: Avoiding primary steel production through recycling fossil steel stocks saves significant externality costs. **a**, Median externality cost savings are shown for different possible times of recycling between 2025 and 2050 following an SSP2-NPi scenario (see Extended results section for other scenarios). Error bars represent the uncertainty of steel scrap availability from fossil infrastructure (95 % confidence interval). **b**, Externality costs on HH and by ED dominate total costs of primary steel production (left bars) in 2025 in SSP2-NPi scenario. Total costs (sum of production and externality costs) are more than halved through recycling (right bars) without increasing production costs. Variability of externality costs among scenarios in extended results (Fig. E1).

The total costs of primary steel production are dominated by externality costs (see Fig. 4b). Depending on the steel type (reinforcing, low-alloyed, or chromium steel), externality costs can be as high as four to nine times the primary production costs (SSP2-NPi scenario). Recycling reduces externality costs, lowering the total costs per kilogram of steel compared to primary production by 56 to 80 %. Moreover, recycling steel could be economically competitive even when omitting externalities (-0.3 to -6.3 % plant average production cost depending on steel type compared to primary route; see SM Fig. S2) [51], suggesting a win-win strategy to reduce impacts while diminishing production costs.

2.4 Utilization in renewable energy systems

Recycling steel from fossil infrastructure for the energy transition could lead to cleaner renewable energy technologies. For example, using recycled steel for wind turbines allows reducing greenhouse gas emissions by 22.5 % and 31.3 % in on- and offshore systems respectively (in the year 2025, following an SSP2-NPi scenario, Fig. 5a), making externality costs

of wind turbine construction drop by 20.6 % and 36.6,% for onshore and offshore systems respectively (see Fig 5b). Using all steel from obsolete fossil infrastructure in wind turbines would allow covering steel needs required for building 8.8 TW_p or 14.2 TW_p of onshore or offshore wind capacity respectively, i.e., 1.7 to 2.8 times the global wind energy capacity projected in Remind SSP2-NPi scenario in 2050 (and 1.1 to 2.4 times the wind energy capacity in 2050 projected to reach climate goals [1,2], see SM Table S3).

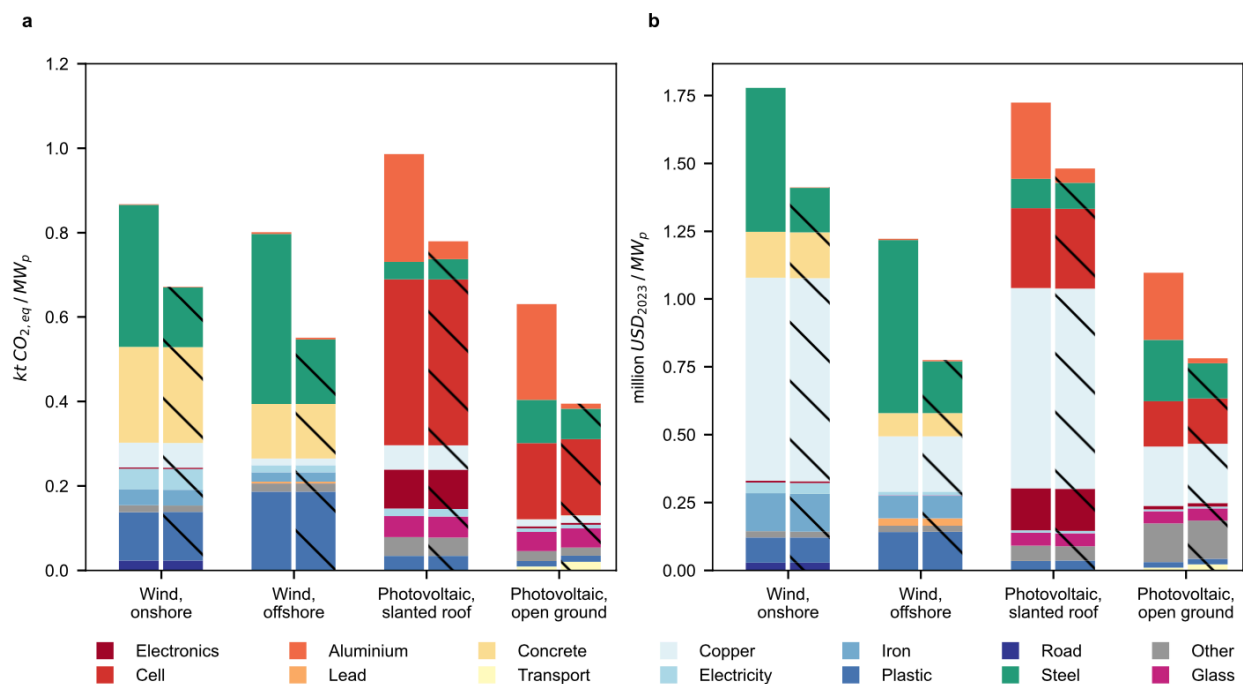


Figure 5: Constructing wind turbines and PV systems with recycled steel from fossil infrastructure reduces the climate impacts of renewable electricity. **a**, Greenhouse gas emissions from constructing low-carbon energy systems with primary steel (wind turbines) or a market mix of Al (PV mounting systems) are shown in the left bars, compared to construction with recycled steel from fossil infrastructure in the right bars (hatched areas). Wind turbine inventories represent global weighted average, open-ground PV systems represent the European weighted average, and slanted-roof PV systems represent the Rest of World weighted average in 2025 following an SSP2-NPi scenario. **b**, Externality costs for constructing energy systems with primary steel for wind turbines and market mix of Al for PV mounting systems (left bars) compared to recycled steel used in wind turbines and PV mounting systems (right bars).

Similarly, while steel is currently used in solar PV systems only for screws and hooks in rooftop installations and for support pylons in open-ground installations, it could replace commonly used Al for mounting systems [52] (for details see the SM Sec. S5). Replacing Al in mounting systems for solar PV with secondary steel would curb greenhouse gas emissions by 37.4 % and



20.9 % for open-ground and slanted roof PV system production respectively. Furthermore, externality costs from open-ground and slanted roof systems would be reduced by 28.8 % and 14.1 % respectively. Using the steel from fossil infrastructure for constructing PV systems would allow covering the steel needs (assuming the aforementioned replacement of Al) for building 24.4 TW_p and 45.1 TW_p of open-ground and rooftop PV respectively. This is 2.5 to 4.7 times the projected installed PV capacity globally in the Remind SSP2-NPi scenario in the year 2050 (and 1.7 to 5.6 times the PV capacity in 2050 projected to reach climate goals [1,2]; see SM Table S3). Therefore, recycling steel from fossil infrastructure could significantly lower the environmental impacts and externalities costs of transitioning to solar and wind energy.

3 Discussion

Many countries are phasing out fossil fuels [53,54]—one recent example being the coal power phase-out in the United Kingdom [55]—or planning to do so in the future [54,56]. Recycling steel from decommissioned fossil infrastructure could save significant externality costs for healthcare and adaptation to degrading ecosystems and worsening climate conditions. While adopting greener production routes is often hindered by higher costs [57–59], repurposing steel from fossil infrastructure could represent a win-win alternative. Moreover, using recycled steel for solar, wind, and other renewable infrastructure could improve the environmental performance of entire value chains, such as green chemicals (e. g. green hydrogen), glass, non-ferrous metals, or even secondary steel itself. For example, the carbon footprint of green hydrogen, an energy carrier and fundamental molecule to activate the inert CO₂ in carbon capture and utilization routes [60], could drop by as much as 30 %, making carbon capture and utilization routes much greener than originally thought (e. g. up to 6 % less carbon footprint for green methanol, see SM Fig. S3).

Furthermore, increasing metal waste availability by digesting fossil infrastructure may serve as a strategy to mitigate supply shortages for building renewable energy infrastructure [61], which might arise from geopolitical tensions and the concurrent need to accelerate climate action. For example, using recycled steel instead of Al—59 % of which is smelted in China [62]—in mounting systems could facilitate a fast and resilient transition process.

Opposition to this strategy may arise from owners of fossil infrastructure—which are both state-owned and private companies—, who would rather prefer to prolong the lifetimes of their assets, despite the current regulations and agreements aimed at phasing out fossil fuels [56,63–65]. Reduced externalized costs, which are savings for society at large, could help to



motivate the early retirement of state-owned fossil assets, potentially starting with the most polluting infrastructure [66]. In contrast, private owners have no direct benefits from reduced externality costs. In this case, regulation or incentives would be necessary to decommission infrastructure. The material value contained in the assets (around 472 billion USD₂₀₂₃ in the case of steel; see SM Sec. S7) could further motivate to scrap them instead of leaving infrastructure mothballed or idle, as is currently the status for 210 power plants in 52 countries [32,36].

Resistance to repurposing may vary depending on the type of infrastructure. For instance, coal power is becoming less economical compared to solar and wind energy [67–69], which might make power plant and coal mine owners more inclined to decommission their facilities. In contrast, oil and gas extraction continues to generate substantial financial profits [70], potentially making owners of oil and gas rigs less likely to decommission before the end of their lifespan. However, the average operating oil and gas rig is currently only six years away from the average retirement age [37]. Consequently, steel waste from oil and gas rigs might become available soon as they reach the end of their operational life.

Digesting fossil assets today would lead to lower externality costs and prevent them from being reactivated and causing further emissions. This has happened recently in Hungary, North Macedonia, and Italy [71], where coal-fired plants are converted into gas power plants. Early decommissioning would also prompt fossil firms to reorient their businesses, predominantly by investing more heavily in renewables. Early decommissioning would also have global implications on the supply and price of fossil electricity, fuels, and petrochemicals. Hence, a smooth transition should be sought by deploying alternative technologies on the right time (e.g. renewable power, electric cars, renewable carbon-based chemicals), so they would temporarily coexist with the fossil infrastructure [72].

Future research could further investigate implications of repurposing other materials in fossil infrastructure, for example, Cu to substitute silver—identified to potentially cause supply bottlenecks for PV production [73–75]—in silicon cell front metallization [76]. Moreover, future dynamic models could capture systemic saving effects of potentially faster and cleaner energy transitions [72,77]. IAMs could also use our results to integrate externality costs for steel production to enhance cost-benefit analysis [78, 79]. Our quantitative analysis is intended to guide policy-making in the sustainable transition towards cleaner energy systems, where socioeconomic and geopolitical dynamics should also be considered when delineating future plans. Our study is not exempt from limitations (SM Sec. S8), where the main ones are not including oil refineries and internal combustion engine vehicles in the potentially obsolete



infrastructure assessed and not including other strategies than recycling. However, we still believe the main conclusions are robust and would hold in the face of uncertainties.

4 Methods

4.1 Material compositions

We take material intensities of fossil infrastructure from ecoinvent v3.9.1 cutoff [31] accounting for geographical variability, different sub-technologies, power plant classes, and fuel types as represented in ecoinvent. Intensities are normalized to capacity for coal mines and power plants, to length for pipelines, and cumulative output for oil and gas rigs. Uncertainties of material intensities are considered from (i) life cycle inventory (LCI) uncertainties in ecoinvent and (ii) the necessity of linking and matching infrastructure classes in ecoinvent vs. the classes reported in Global Energy Monitor databases [32–37]. Borehead lengths in oil and gas extraction facilities are commonly not reported, though an important driver of material intensities. All these sources of uncertainties are propagated to the final stock estimates using a Monte Carlo approach with 500 runs. For more details, see the SM Section S9. We only consider on-site materials, thus neglecting grid connection and buildings, and excluding operational material flows, such as water and chemicals, as they likely do not accumulate in infrastructure stocks.

4.2 Scaling to global stocks

To calculate total stocks, we consider currently operating, idle, or mothballed fossil infrastructure. Capacities that are already decommissioned, currently under construction, or planned are excluded. Material stocks and their uncertainties are calculated individually for each infrastructure worldwide. Material intensities for each material are scaled with the size of each infrastructure taken from Global Energy Monitor databases [32–37] (for details, see SM Fig. S4). Data gaps occur for oil and gas wells and are filled by estimating cumulative production by multiplying the mean annual well production for a respective country with the well's years of operation. The capacity of coal mines—where missing—is calculated from annual production values assuming a capacity factor of 0.75 (based on the range of more than 0.5 to 0.9 depending on year and region [80]; total stocks are insensitive to the capacity factor). Pipeline stocks are allocated to countries proportionally with the segment's length in the respective country. Pipeline segments in international waters are assigned to the nearest country.



4.3 Life cycle assessment

We compare the environmental impacts and externality costs of primary and secondary steel production using life cycle analysis. The functional unit is 1.35 Gt ([0.84–2.26] Gt of steel produced and the geographical scopes are globally weighted averages in the years 2025, 2030, 2035, 2040, 2045, and 2050. LCIs are modeled for three types of steel—reinforcing steel, low-alloyed steel, and chromium steel—using adjusted data from Premise [38]. Premise is a Python package that translates the outputs of IAMs into changes in LCA background models, e. g. by adjusting for future energy mixes or efficiency changes of industrial technologies.

We model the primary and secondary production route with BF-BOFs and EAFs respectively as they are the by far dominant production technologies (61.3 % and 20.2 % of global steel-making capacity, with the alternative open hearth furnace only 0.6 % and the rest a combination of the three) [81]. Primary production consists of iron ore extraction, conversion to iron sinter and pig iron in blast furnaces, steel production via basic oxygen furnaces, and dust, slag, and sludge treatment. The secondary production model includes the collection, sorting, and pressing of steel scrap from fossil infrastructure, transport, melting in EAFs, and dust and slag treatment. For more details on system boundaries applied, transport distances, and process efficiencies, see the SM Section S10.

Low-quality steel scrap needs to be diluted with primary sponge iron and alloying metals to compensate for contamination. If steel scrap of the same type and quality is recycled in an unmixed waste stream—as could be possible for large stocks such as pipelines or other fossil infrastructure stocks—the need for dilution can be reduced. To reflect these two possibilities, we introduce pessimistic and optimistic recycling scenarios, assuming low and high scrap quality and slag composition respectively. Several adjustments are made to the LCI data from Premise: 1) Scrap supply is modeled reflecting country-weighted transport distances from fossil infrastructure to the closest EAF plant (assumed to be the most economic option). It is assumed that scrap is burden-free as it is collected at fossil infrastructure (same as in Premise databases). 2) Ecoinvent v3.9.1 likely overestimates hexavalent chromium (Cr^{6+}) contents in slag. We adjust Cr^{6+} emissions to values found in the literature (see SM Sec. S10.4), selecting the lower values for the optimistic scenario and upper values for the pessimistic scenario. We evaluate 17 environmental midpoint indicators included in the ReCiPe 2016 impact assessment framework [82] (hierarchical perspective, e. g. only impact mechanisms based on scientific consensus and impacts within 100 years) and three additional environmental indicators: Climate impact based on global warming potentials from the Intergovernmental Panel on Climate Change (IPCC) 2021 over 100 years [83], land use, and biodiversity loss. For details, see the SM Section S11. Environmental impacts are calculated by converting LCI flows—including raw materials, energy,



and water inputs as well as emissions to water, soil, and air—into impacts using characterization factors:

$$IMP_{m,f,j} = \sum_k LCI_{k,f,j} \cdot CF_{k,m} \quad \forall m \in M, \forall f \in FU, \forall j \in J \quad (1)$$

$IMP_{m,f,j}$ is the impact for indicator m (belonging to the set of all disaggregated indicators M) associated with the functional unit f (of all functional units FU , e. g. , different steels) in year j (belonging to the set of assessed years J). $LCI_{k,f,j}$ is the LCI input or output of the elementary flow k associated with supplying f in year j , and $CF_{k,m}$ is the characterization factor of k for indicator m .

To calculate externality costs, we multiply the endpoint indicator impacts—given in the unit DALY (Disability Adjusted Life Years) for HH and species years loss for ED—with monetization factors as follows:

$$EXT_{e,f,j} = MF_{e,j} \cdot \sum_{m \in M_e} IMP_{m,f,j} \quad \forall e \in E, \forall f \in FU, \forall j \in J \quad (2)$$

Here, $EXT_{e,f,j}$ is the externality cost in USD_{2023} generated in the endpoint externality class e (HH or ED; E) while supplying the functional unit f in year j . $MF_{e,j}$ is the monetization factor depending on the year j and externality class e (the cost of one unit of endpoint impact in HH or ED), and m denotes the disaggregated ReCiPe indicators, where M_e is the set of disaggregated endpoint indicators connected to the externality class e ($M_e \subseteq M$). Note that the ReCiPe endpoint indicator impacts on natural resources are already calculated in USD.

4.4 Monetization of impacts

To calculate the externality costs of environmental impacts, we follow the approach used in [84]. For the year 2018, the HH cost for one DALY is 176,624 USD_{2018} , with a lower and upper bound of 148,288 USD_{2018} and 200,236 USD_{2018} respectively [84]. The externality cost for one unit of species loss is 17,891,594 USD_{2018} , with a lower and upper bound of 4,472,899 USD_{2018} and 44,728,985 USD_{2018} respectively [84]. To estimate monetization factors in the future, we apply the benefit transfer concept [85] based on the approach followed in [86]:

$$MF_{e,j} = MF_{e,j'} \cdot \left(\frac{GDP_j}{GDP_{j'}} \right)^{\epsilon_e} \quad \forall e \in E, \forall j' = 2018, j \in J \quad (3)$$



Where GDP_j is the gross domestic product per capita in year j , and ϵ_e is the income elasticity for the willingness-to-pay for each externality class e , which is 1.10 and 0.38 for HH and ED respectively [87,88]. GDP per capita values are calculated based on GDP and population prospects for respective SSP scenarios from 2025 to 2050 (data from [89]).

4.5 Total cost estimation

The total cost of steel is comprised of production costs and externality costs. Whereas externality costs are outputs of our LCA, production costs are taken from the Global Steel Cost Tracker (GSCT) database [51], which contains steel production costs for individual steel plants in 12 countries covering around 90 % of global steel production. We link each steel plant to steel products they produce (e. g. , reinforcing steel, chromium steel) using data from the GSCT database [41] and then estimate the production costs for reinforcing, low-alloyed, and chromium steel individually taking plant averages.

5 Extended results

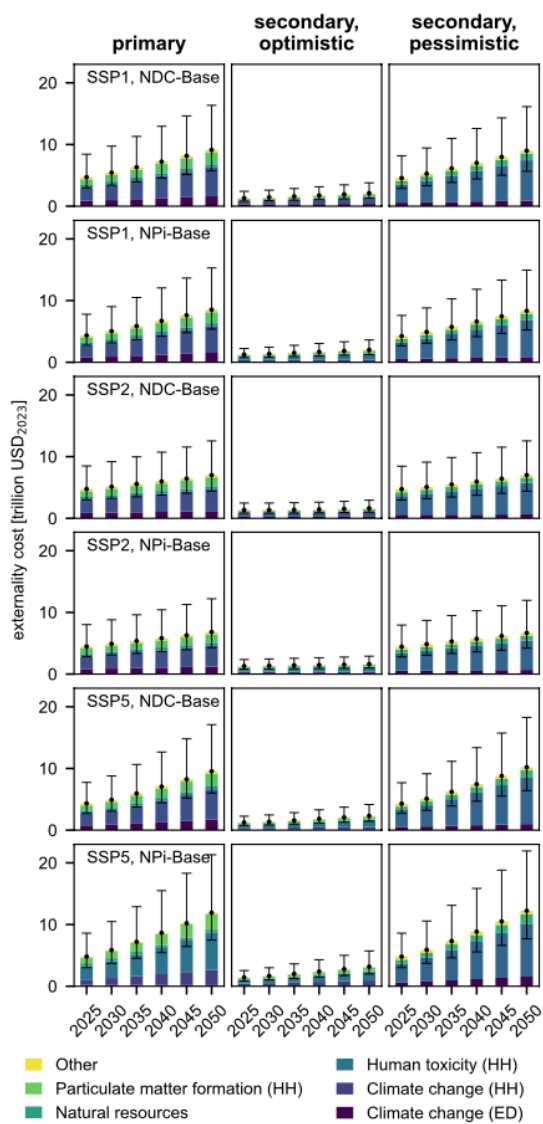


Figure E1: **Externality costs of producing primary or secondary steel in current fossil infrastructure.** Bars show median total externality costs of steel production for scenario (rows) and production routes (columns) and depending on year of recycling. Error bars show the uncertainty of steel stock.

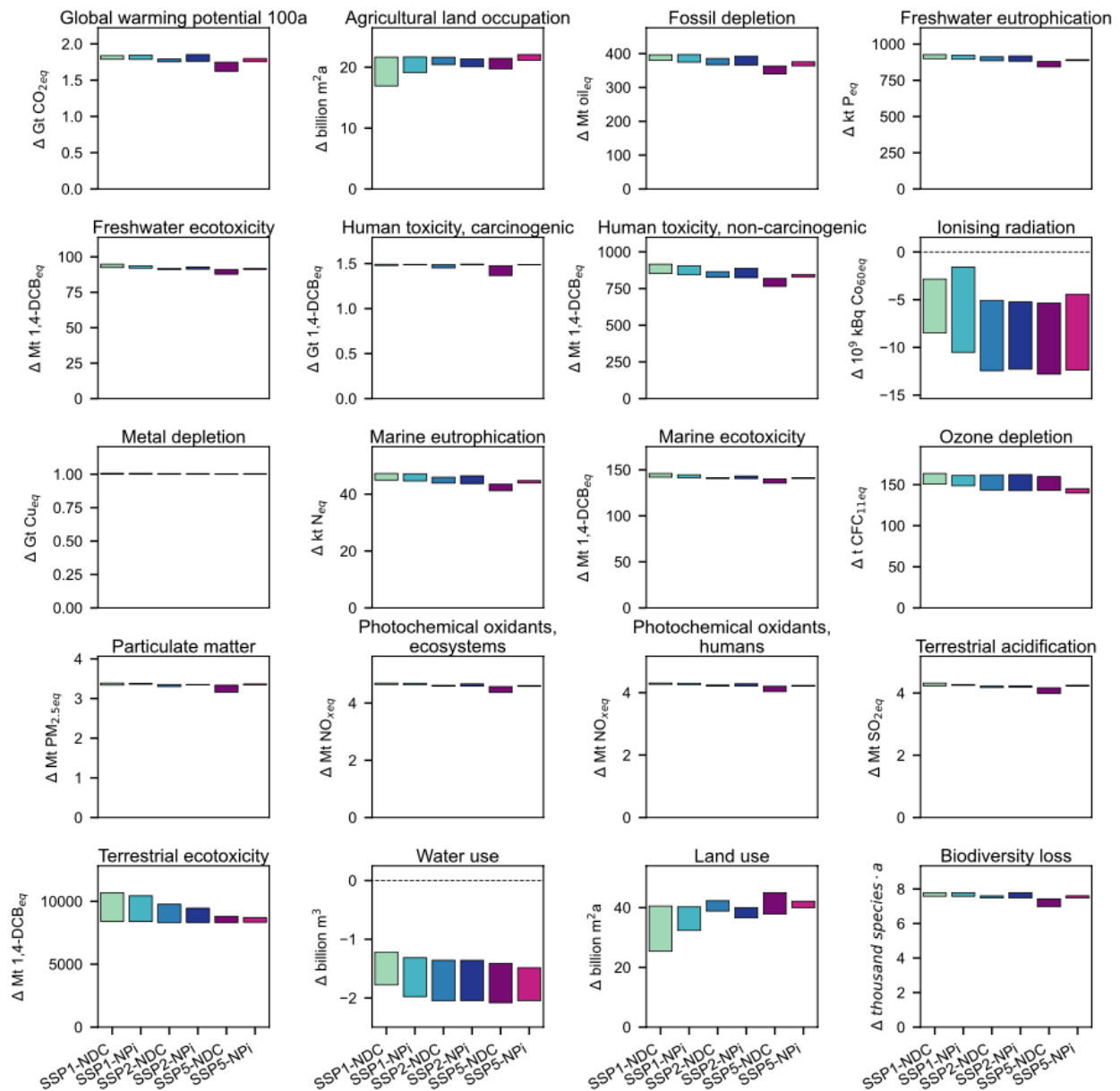


Figure E2: **Total avoided environmental impacts through recycling (optimistic)**. Bars show minimum to maximum range of impact savings (midpoint indicators) of recycling compared to primary production for scenarios depending on the year of recycling (2025 to 2050). DCB=dichlorobenzene, CFC=chlorofluorocarbons PM=particulate matter.

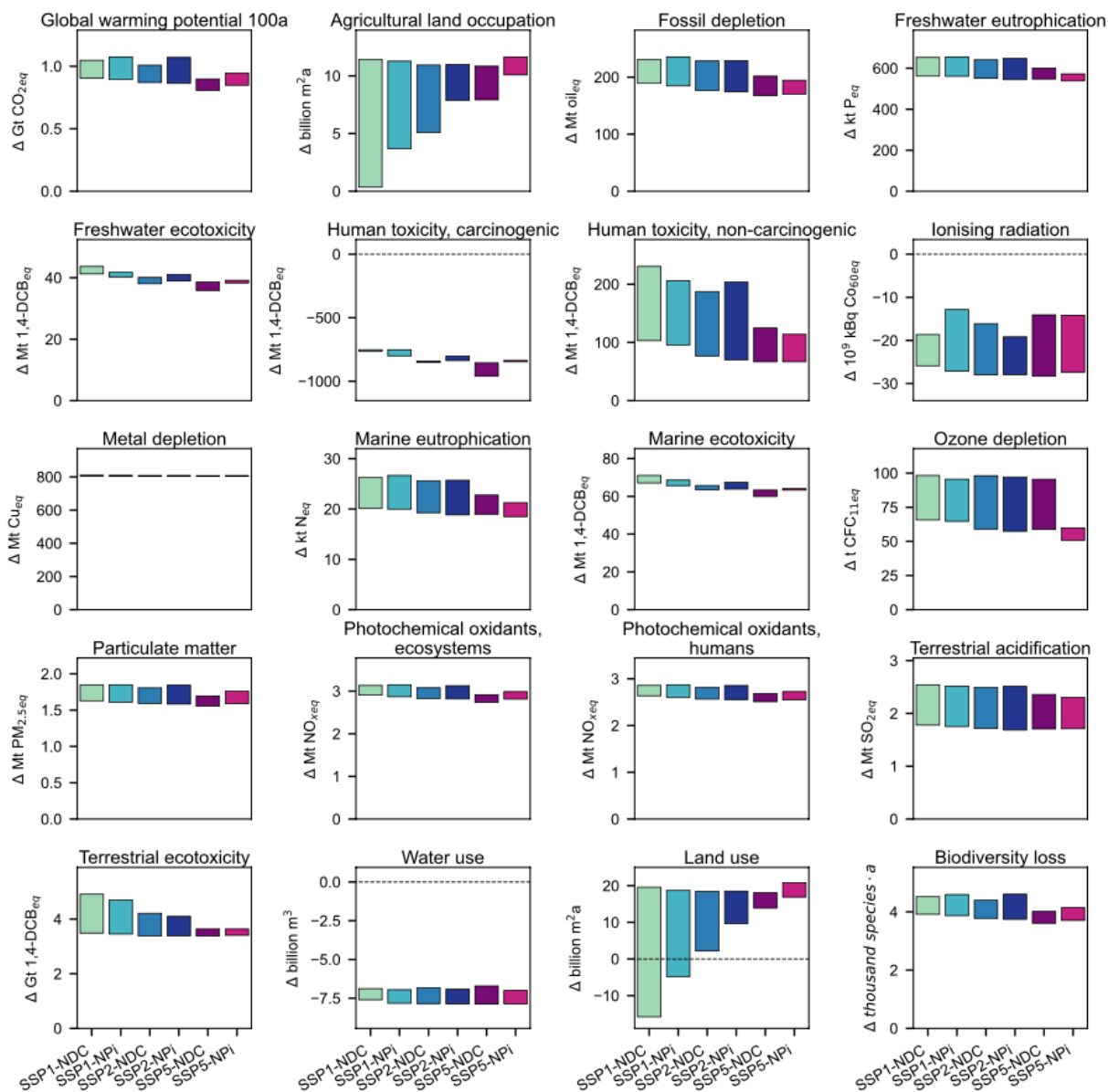


Figure E3: **Total avoided environmental impacts through recycling (pessimistic)**. Bars show minimum to maximum range of impact savings (midpoint indicators) of recycling compared to primary production for scenarios depending on the year of recycling (2025 to 2050). DCB=dichlorobenzene, CFC=chlorofluorocarbons PM=particulate matter.

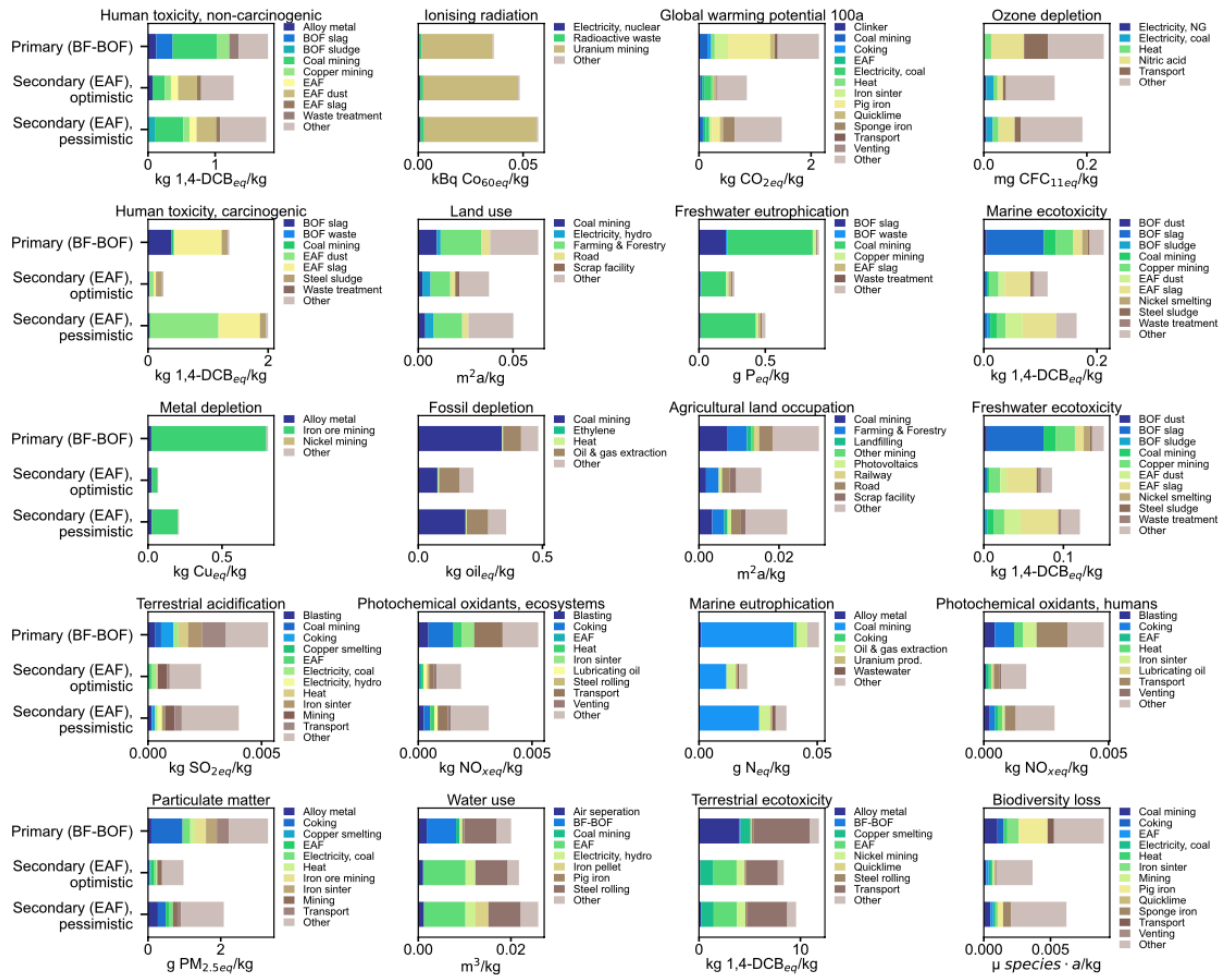


Figure E4: **Process contributions to environmental impacts of reinforcing steel.** Midpoint indicator impacts of 1 SSP2-NPi scenario in the year 2025. NG=natural gas, BF=blast furnace, BOF=basic oxygen furnace, EAF=melter, DCB=dichlorobenzene, CFC=chlorofluorocarbons.

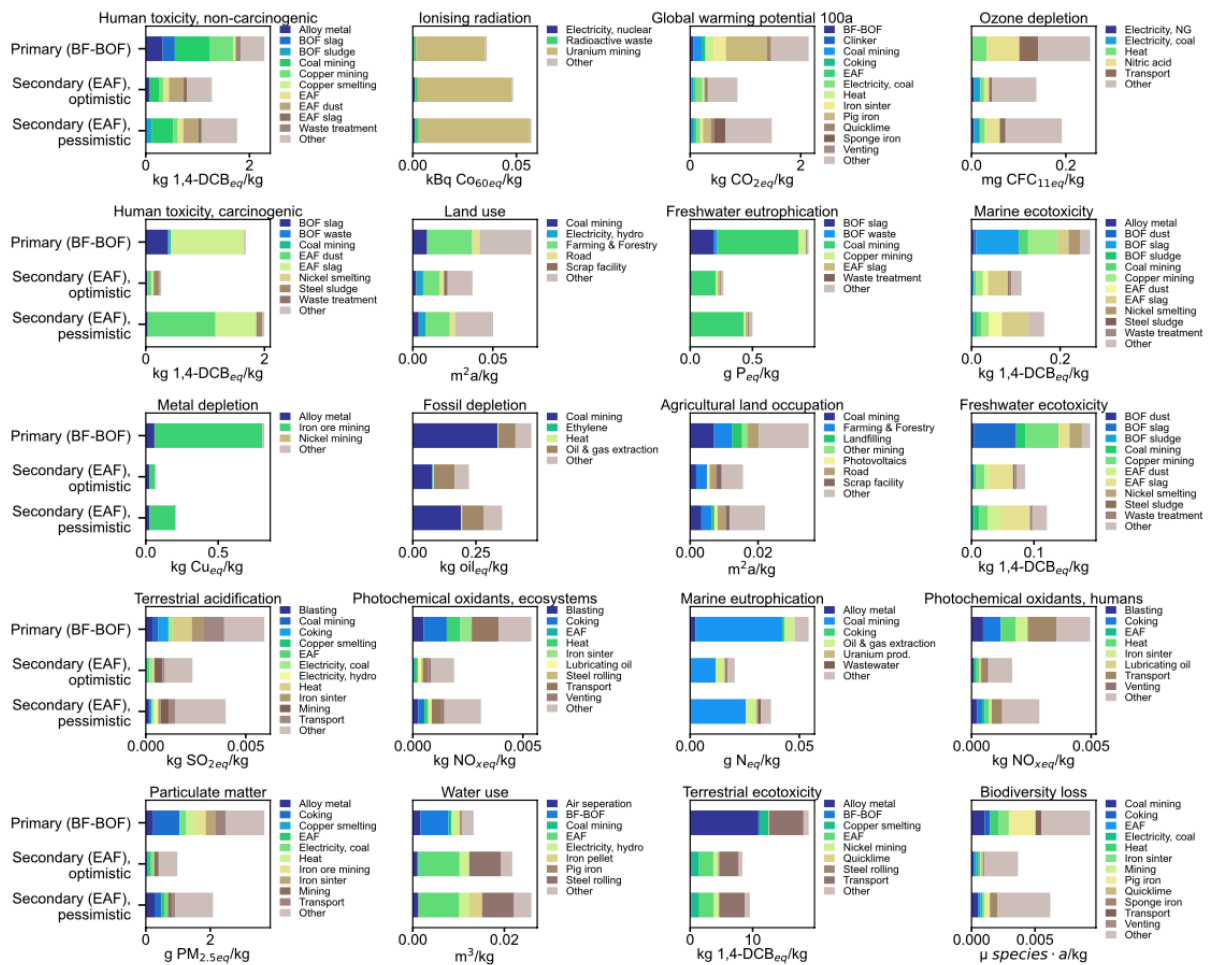


Figure E5: **Process contribution to environmental impacts of low-alloyed steel.** Midpoint indicator impacts of 1 kg low-alloyed steel are shown for the SSP2-NPi scenario in the year 2025. NG=natural gas, BF=blast furnace, BOF=basic oxygen furnace, EAF=electric arc furnace, PM= particulate matter, DCB=dichlorobenzene, CFC=chlorofluorocarbons.

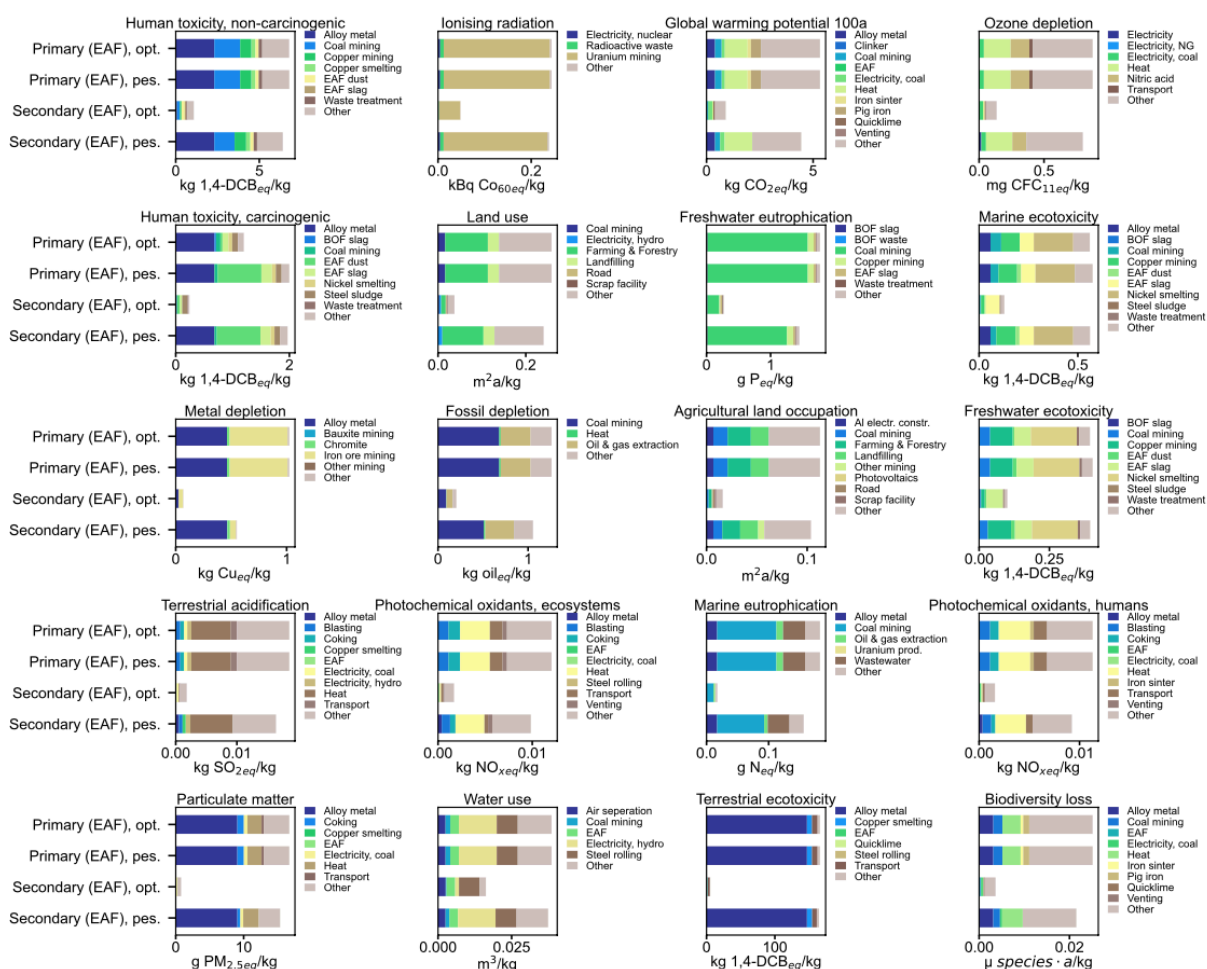


Figure E6: **Process contributions to environmental impacts of chromium steel.** Midpoint indicator impacts of 1 kg chromium steel are shown for the SSP2-NPi scenario in the year 2025. NG=natural gas, BF=blast furnace, BOF=basic oxygen furnace, EAF=electric arc furnace, PM=particulate matter, DCB=dichlorobenzene, CFC=chlorofluorocarbons.

Supplementary materials:

<https://assets-eu.researchsquare.com/files/rs-6346491/v1/48814455e351068ce8e4178f.pdf>



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D3.1. ANNEX B2

Mobilizing materials to enable a fast energy transition: A conceptual framework

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Abstract

Limiting climate heating while meeting basic needs for all necessitates large-scale deployment of renewable energy. Understanding the dynamics of mobilizing materials for the transition requires considering: 1) availability of resources in the environment and technosphere; 2) accessibility depending on resource quality and available technologies; 3) processability depending on energy availability, processing capacity, and impacts on planetary boundaries; and 4) operability depending on social acceptance and geopolitical agreements. Materials can be mobilized through four routes: 1) increasing primary production; 2) diverting existing primary production; 3) repurposing in-use stocks; and 4) re-mining wastes and emissions. The interplay of these enabling factors, material efficiency in design, and substitution with materials that are easier to mobilize determines the maximum possible rate of material mobilization and consequently the energy transition itself. This paper presents and discusses a framework to explore joint energy-material transformations, enabling to consider material aspects in transition modelling and guide technological developments.

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Full length article

Mobilizing materials to enable a fast energy transition: A conceptual framework

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ABSTRACT

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1. Introduction

Decades of delays in climate action reduced safe carbon budgets for the energy transitions. With every delay, increasingly fast energy transition pathways are required to stand a chance of limiting overshoot over 1.5°C or even staying below 2°C (IRENA, 2022; United Nations Environment Programme, 2022; IPCC, 2023), preventing a climate catastrophe while avoiding energy and food scarcities (IPCC, 2021, 2022; Mooney et al., 2022). Achieving such a transformation requires investing energy and materials for building renewable energy (RE) infrastructure, which will have to succeed the current fossil-based energy system at a much faster rate than is commonly projected (Desing and Widmer, 2021).

Traditionally, transition pathways are designed by using integrated assessment models (IAMs), which are based on economic transactions and the assumption of (partial) economic equilibrium in each time interval (typically 5a or 10a). As there are less than six years left before crossing 1.5°C with 50% probability¹, transition models that allow modelling a fast dynamic change (i.e., a system not in equilibrium) become necessary. Minimizing climate risks—necessary for both staying below or limiting overshoot above 1.5°C—requires to prioritize minimizing cumulative CO₂ emissions (Desing and Widmer, 2021). Furthermore, IAMs are usually “energy blind” because they disregard the energy investments needed to build the new RE infrastructure (Capellán-Pérez et al., 2020; Desing and Widmer, 2021; Hagens, 2020; Sgouridis et al., 2016; Hache et al., 2019; Andrieu et al., 2022). When modelling slow and gradual transitions over the time scale of decades,

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¹ <https://www.mcc-berlin.net/en/research/co2-budget.html>.

energy investments are insignificant. However, given the urgency of climate action, energy investments need to be much larger (Slamersak et al., 2022; Desing and Widmer, 2021) and this feedback loop needs to be taken into account. For example, a transition within a decade may be physically feasible, if fossil energy output is increased at the beginning of the decade to provide extra energy for kick-starting RE growth (and doing so minimizes cumulative GHG emissions) (Desing et al., 2022). After the initial fast transition is complete, the infrastructure has to be replaced repeatedly, necessitating additional capacity in the RE system (Desing et al., 2022). Besides that, the economic foundation of IAMs is increasingly challenged, as they tend to underestimate or even neglect future risks, damages and uncertainty (Stern et al., 2022; Anderson, 2019).

Moreover, transition models (including IAMs and others) usually disregard the physical requirements of materials (Pauliuk et al., 2017; Wang et al., 2022; Le Boulzec et al., 2023), the dynamics of mobilization, as well as social implications. Studies on raw material demand induced by the energy transition take pathways as exogenous inputs, and usually analyse the cumulative demand for selected time periods only, e.g., up to 2050 or 2100 (Kullmann et al., 2021; UBA, 2019; Visser, 2019; Zepf et al., 2014; IRENA, 2022; World Bank, 2020; de Koninck et al., 2018; Moreau et al., 2019; Zhang et al., 2023; Rinaldi et al., 2023; Xu et al., 2022; Kalt et al., 2022; Wang et al., 2023; IEA, 2023; Energy Transitions Commission, 2023). As with energy, material investments for building RE infrastructure can have a critical influence on the dynamics of the transition. If materials cannot be mobilized, the transition will slow down or even come to a halt. Reciprocally, the speed and extent of material mobilization has an influence on the energy demand for building RE infrastructure. Changing energy investments, measured in Energy Return on Energy Invested (EROI) or Energy Pay Back Time (EPBT) (Murphy et al., 2022), influence the dynamics of the transition. These interrelations are neither well understood nor explored in current models. This is also true for the United Nations Framework Classification for Resources (UNFC), a tool to communicate the availability of resources and the maturity level of resource development projects (UNECE, 2020, 2022). UNFC considers controlling factors for the viability of mining and recovery projects, but does not consider the complex dynamic relationships between energy and materials. The dynamics of primary mineral resource markets and their physical/geological limits are commonly neglected, while inflow of recycled resources based on previous product sales and global recycling rates are sometimes included (Vidal, 2018; IEA, 2021; Carrara et al., 2023). Additionally, fossil infrastructure will become obsolete during the transition, however, the extent to which this can contribute to the transition has been relatively little explored (Le Boulzec et al., 2022).

Consequently, there is a need for new modelling approaches that are rooted in the laws of physics, including essential feedback loops in the dynamic system, and integrating knowledge from geology, mineralogy, and materials processing. Building new RE infrastructure requires materials, and the mobilization of materials requires energy. This paper outlines a conceptual framework for exploring the physical dynamics of joint energy-material transformations. The purpose of the framework is to analyse from where, at which energetic costs, and when materials can be mobilized, ultimately enabling or limiting a rapid energy transition. Materials can originate from the lithosphere, biosphere, atmosphere, and hydrosphere. They can be either directly extracted as primary materials from the environment or retrieved as secondary materials from the technosphere. Here, the focus is on physical, chemical, biological, and geological factors determining quantities, timeliness and energy needed for material mobilization, which can be regarded as the “size of the valve” representing the mobilization potential: e.g., concentration, chemical bonds, mineralogy, or planetary boundaries (Richardson et al., 2023). Societal factors—such as economics, policies, acceptance—determine the fraction of this potential that may be realized, the “hand on the valve”. But they cannot increase the potential itself. Derived from the presented framework, this paper outlines research directions

to quantify and explore material mobilization dynamics and the interconnections between materials and energy.

2. Material mobilization framework

Building the required RE infrastructure implies building up a significant stock of materials during the transformation (Fig. 1), which necessitates to transform and expand the current socio-economic metabolism. Society currently extracts primary materials from the environment, accumulates them in societal stocks (e.g., buildings, IT equipment, or car fleets), and recycles some of its waste. Most of the outflow accumulates as losses in the technosphere (e.g., landfills, mining wastes) and the environment (e.g., emissions, pollution) (Circle Economy, 2021; Ciacci et al., 2015). For most materials, global stocks in society are still growing, as their inflows are larger than their outflows (Krausmann et al., 2018). Only a small fraction of outflows is currently circulated in a way that retains functions (e.g., through reuse, remanufacture, recycling (Desing et al., 2020b; Circle Economy, 2020)). Even when circular economy and recycling strategies are implemented, these often lead to losses in material quality (downcycling) (Cullen, 2017) and accumulation of impurities (Lovik et al., 2014). Besides, recycling tends to focus on increasing recycled content and recycling rates, especially of pre-consumer scrap (i.e., manufacturing losses). This type of material is generally easier to recycle but ultimately addresses an inefficiency of the system that should be minimized, not encouraged. Recycling of post-consumer scrap is important to maintain existing stocks without using more primary resources, but is only available with a delay and cannot contribute to the initial build-up of the stocks. Moreover, the complexity of materials used in technologies has increased significantly—requiring most of the elements of the periodic table (Zepf et al., 2014)—, which results in growing challenges not only to recycle all elements, but also to retain their functions (Graedel and Miatto, 2022; Desing and Blum, 2023).

The speed of the transition will depend on the flows of materials that can be mobilized, which in turn require energy from the current fossil and future RE systems (Fig. 2). Enabling factors for material mobilization can be categorized on multiple levels, which will be explained in the following subsections: availability of source stocks, technical accessibility of these stocks for extraction, processability of material flows during production, as well as operability for making materials flow. The latter refers to factors in distribution and operation, which includes aspects commonly referred to as criticality (Schrijvers et al., 2020; Frenzel et al., 2017)—i.e., supply chain vulnerability and geo-political risks—and additionally business models, markets, trade, as well as social acceptance. Here we focus on the bio-physically enabling factors of material mobilization, i.e., availability, (technical) accessibility and processability.

2.1. Availability and accessibility of source stocks

The first question is: are there enough materials available and accessible to build the needed RE stocks? Materials can be mobilized from anthropogenic and environmental source stocks. Availability describes the knowledge of location—Where are materials?—and quantity—How much is there?—of material stocks and is the prerequisite for making them accessible. Determining the accessibility requires to analyse the quality of these available stocks. A stock is only accessible, if suitable extraction technologies exist and when it is not vital to maintain Earth system functions. For example, technologies to extract scandium from wastes are still under development (Chernoburova and Chagnes, 2021; Shoppert et al., 2022), leaving it inaccessible for the moment. Or, current biomass stocks in natural ecosystems will have to be maintained or even increased for stabilizing vital ecosystem functions (IPBES, 2019; Steffen et al., 2015) and are thus accessible only to the extent of what can grow beyond ecosystem needs. Additionally, stocks are more or less accessible depending on factors determining the efforts for extraction.

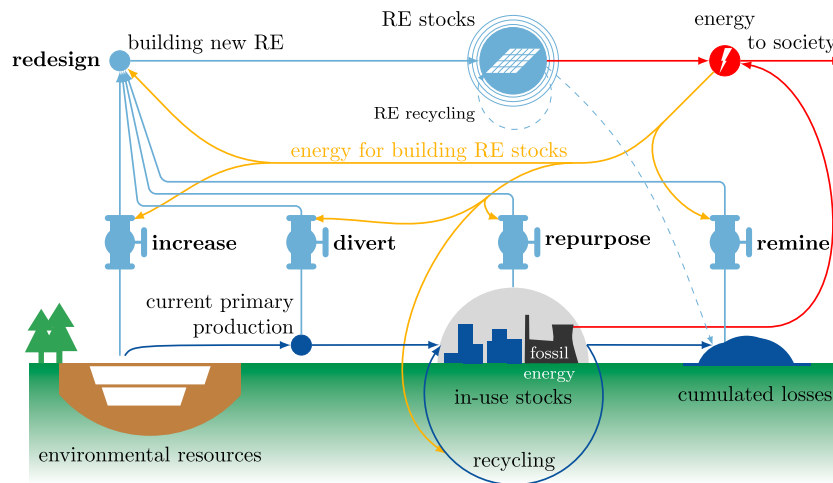


Fig. 1. Schematic representation of energy and material flows in the Material Mobilization Framework: dark blue flows in bottom part of figure depict current material flows from primary production out of environmental resources, through in-use stocks, which are to a small degree maintained by recycling, to cumulated losses. This metabolism is currently predominantly powered by fossil energy, itself consisting of in-use stocks (fossil infrastructure) and primary extraction (i. e., coal, oil and gas) leading to losses (i. e., emissions). To replace fossil energy with renewable energy (RE), new RE stocks have to be built. Four strategies can be applied for building RE (light blue): **increase** primary production, **divert** currently existing primary production by reducing material demand by society (e. g., by increased recycling), **repurpose** existing in-use stocks (e. g., obsolete fossil infrastructure), and **remine** cumulated losses (e. g., from landfills, tailings, emissions). Additionally, the **redesign** of RE components can help to reduce the demand for materials (material efficiency) and substitute with materials that are easier to mobilize. Recycling and losses of RE stocks will only come into effect once the first RE stocks reach their end-of-life (dashed blue arrows). Building RE stocks requires energy for mobilizing materials (yellow arrows), which has to be supplied by both fossil energy and RE, in addition to the demand from society (red arrows).

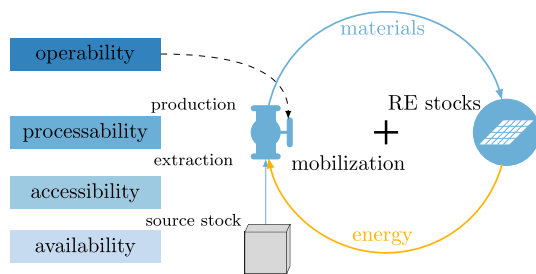


Fig. 2. Overview of enabling factors for mobilization (left) and their relation to the energy-material feedback loop (right): Building renewable energy (RE) infrastructure requires materials (blue), and mobilizing materials requires energy (yellow). The availability of source stocks in the environment and technosphere is limited, and the accessibility of these stocks depends on its quality and available technologies. Processability describes where from and how fast materials can be mobilized, which depends on the availability of energy, processing capacities, and environmental impacts on planetary boundaries. The operability, describing societal factors for actually making materials flow (geo-political relations, economics, organisational capacities, social acceptance), further limit material mobilization.

The energy costs for extraction depend mainly on the concentration (i. e., ore grade of minerals, atmospheric CO₂ concentration), but also on factors such as location (e. g., under water or land, depth below surface, remoteness), geometry (e. g., grain size and distribution in host rock), or binding energy of chemical compounds.

Anthropogenic stocks—such as currently in use, “hibernating”, or accumulating as wastes and emissions (Dewulf et al., 2021)—already contain large quantities of materials (Elhacham et al., 2020; UNEP and International Resource Panel, 2010; Wang et al., 2018; Wiedenhofer et al., 2021). Using secondary materials will need to take into account the quality of recycled materials obtained (Tonini et al., 2022), as well as the quantity and timing of released material flows (Streeck et al., 2021). Repurposing in-use stocks—such as materials contained in fossil infrastructure and related to luxury consumption—can, at most, provide as much material as is contained in society today. How much of it can be mobilized in practice depends on societal decisions discerning essential from superfluous consumption, which is a question of operability.

Even if the availability (location, quantity) and composition of these stocks are known with sufficient detail, they will only become accessible when released from previous use—for example, when fossil equipment becomes obsolete or consumption is reduced. Losses can be dissipative (i.e., unrecoverable, not accessible) or recoverable with current technologies. New technologies can make some of today's dissipated losses accessible (Beylot et al., 2020; Ciacci et al., 2015). For example in Europe, the location of mining wastes is more or less well known but knowledge on stored volumes and the characteristics of wastes—composition, mineralogy and total quantities—is partial and often does not cover the presence of critical metals (Šajin et al., 2022; Žibret et al., 2020). Furthermore, valuable elements in mining wastes have so far not been extracted due to inferior quality, lack of markets (e.g., Nd or Co were hardly in demand in the past) or suitable technologies. Making them accessible may thus require developing new technologies.

Additionally, materials are contained in environmental stocks in lithosphere, biosphere, hydrosphere, and atmosphere. Most of these stocks are dispersed at extremely low concentrations, a characteristic that makes extraction unfeasible, such as for Au or Li dissolved in seawater. The only minerals extracted from seawater today are the few highly concentrated ones (Na, Mg, K, Ca, and Cl). The extraction of uranium from seawater has been much discussed, but so far, there are no commercial applications able to produce it at reasonable prices (Bardi, 2010). Exploration can increase availability of known resources for minerals in the lithosphere, while changing economics and improved technologies determine how much of these known resources are mineable reserves, which is an aspect of operability. Exploration is not only an increasingly energy- and cost-intensive endeavour, it also involves high uncertainties. It is estimated that only one out of 1000 exploration sites will be able to be developed as an economically profitable mine (Gandhi and Sarkar, 2016). It is also a question of time, as it takes currently around 17 years from resource discovery to exploitation (Gar-side, 2022). For instance, it has been argued that Li is likely to remain a limiting factor in the transition, mainly because of the time delay for opening new mines (McNeil, 2022).

Even though there are likely enough materials for the energy transition in the anthroposphere and the environment as a whole (Kesler and Wilkinson, 2008; Henckens et al., 2014), knowledge regarding location, quantity and quality is limited or scattered. Availability and accessibil-

ity are dynamic and change with the state of knowledge, technological developments and state of depletion of source stocks. Gathering the necessary data and developing new technologies for making these stocks accessible represents a time delay for mobilizing materials.

Comparing yet-to-be-built stocks with potential source stocks may reveal needs to re-design RE infrastructure if materials are not available and accessible in sufficient quantities. To illustrate: if every person out of the expected ten billion people in 2100 (UN, 2022) should have access to 2000 W (2000 W Society, 2019)—roughly twice the annual average power demand per person today—it would require a RE capacity of 20 TW. Using a simplistic back-of-the-envelope calculation (see Supplementary Materials (SM)) and keeping current RE (about 1 TW) constant, it can be estimated that the additional RE capacity could theoretically be provided by solar PV on the already built environment alone, not needing any further land conversion and associated biodiversity impacts (Desing et al., 2019). Leaving the material requirements for energy storage, distribution, and other RE technologies aside, building additional 19 TW of PV output capacity (corresponding to roughly 155 TW peak capacity, which is in between the estimates for 80 TW by 2050 (Haegel et al., 2023) and up to 200 TW by 2100 (Keiner et al., 2023; Goldschmidt et al., 2021)) with currently available technologies (Frischknecht et al., 2020; Müller et al., 2021) without continuous improvements would require at least 8.8 Gt of materials (see SM). For some of these materials, the new stocks would be equal or higher than currently existing in-use stocks. One example is Ag used as current collector in Si solar PV cells (Zhang et al., 2021; Piano et al., 2019; Victoria et al., 2021). It has been widely recognised that, if current utilization rates remained unchanged, Ag availability would be critical for upscaling PV to multi-TW scale. In fact, efforts are under way to reduce the demand of Ag by design (Zhang et al., 2021; Victoria et al., 2021) or avoid it through substitution, e.g., with graphene (Zang et al., 2018), Al, or Cu (Grübel et al., 2021; Haegel et al., 2023). Promising are also perovskite and Si-perovskite tandem cells (Tockhorn et al., 2022; Tian et al., 2020), as they allow for higher efficiencies, but they still have to overcome significant development challenges (Fu and Jen, 2023; Shalan, 2020). Furthermore, they currently use significant amounts of In, Cs and Br, which are critical for upscaling perovskite PV technologies (Wagner et al., *under review*). Similarly, thin film PV technologies—such as CdTe—are advantageous in terms of embodied energy (Wikoff et al., 2022), however, they require specialty metals—e.g., Cd, Te—and scaling them to multi-TW scale could potentially exceed current availability by orders of magnitude. Consequently, these technologies may only play a minor role in the transition unless the demand for these elements can be cut substantially and/or availability and accessibility increased rapidly. A careful assessment of the required material stocks will be key in revealing the needs for reducing the material intensity of RE technologies; and, if such reduction were found to be not feasible, the assessment could possibly indicate that the maximum size of the overall RE system would be smaller. Furthermore, if material demand exceeds available source stocks, there is need for increasing availability for example through exploration. Ultimately, based on such assessments, the portfolio of RE technologies can be optimized according to the availability and accessibility of materials.

2.2. Processability: mobilizing flows

The second question regards the material flows needed to build RE infrastructure, which are to be extracted and processed from accessible source stocks. The processability describes where from and how fast materials can be mobilized. It is determined by available energy to build and operate processing facilities (Fig. 2) and constrained by environmental impacts caused on planetary boundaries (Desing et al., 2020a).

For filling RE stocks for the first time, materials can be mobilized through four distinct routes (Fig. 1), which are listed and briefly discussed below:

- **Increase** primary production: e.g., by upscaling output from existing extraction facilities as well as developing new extraction routes from the environment;
- **Divert** current primary production: by reducing demand from the rest of the economy during the transition, i.e., maintaining existing in-use stocks with less primary input by increasing residence time (Charpentier Poncelet et al., 2022) and reducing final losses through circular strategies (Desing et al., 2020b, 2021);
- **Repurpose** existing stocks: reducing in-use stocks and using its materials to build RE stocks, in particular from obsolete fossil infrastructure, reduced consumption, and “hibernating” stocks;
- **Remine**: extraction from losses, such as mine tailings (Adrianto and Pfister, 2022), landfills (Lucas et al., 2019), desalination brines (Lundaev et al., 2022), or past emissions (Desing, 2022).

There is no predefined hierarchy of these different routes, which necessitates optimizing material mobilization according to multiple criteria: each of these routes has implication on the energy demand for the transformation as well as the scale and dynamics of mobilized material flows. They also cause impacts on planetary boundaries and generate social benefits or adverse social impacts. Building new mining, processing, recycling and production capacities takes time and energy, which ultimately limits the rate of change (i.e., slow rate limits: restriction of how fast flows can change). Energy demand for material mobilization depends on the size and routes of mobilized flows, which in turn determine the maximum possible speed of the transition (Desing et al., 2022). In addition, energy intensity can be reduced with technological developments for extraction and processing. For example, non-biological extraction of CO₂ from the atmosphere requires direct air capture (DAC) technologies (Desing, 2022; Climeworks, 2022), which were only developed recently (outside niche applications in space crafts and submarines), and are still energy intensive. Technological improvements have the potential to reduce energy demand for DAC significantly, though. In more general terms, the availability of surplus net energy (i.e., energy not simply required to maintain the status quo) is critical to the achievable speed of mobilizing materials and building new RE infrastructure (Desing and Widmer, 2021).

Furthermore, environmental impacts on Earth system boundaries restrict the mobilization of materials (Desing et al., 2020a; Lebre et al., 2020). A fast increase in production may result in higher environmental impacts, as in the example of Ni (Young, 2021; Schenker et al., 2022a). Biodiversity conservation targets or boundaries for water consumption, for example, may limit the processable material flow (Desing et al., 2020a). Another example is biomass: the global potential of appropriable bio-based material flows (Haberl et al., 2007; Krausmann et al., 2013; Creutzig et al., 2015) for sustainable agriculture (Willett et al., 2019; Gerten et al., 2020) and forest management (O'Brien, 2015) is limited by land, nutrients, and water boundaries. Because feeding the still growing world population (UN, 2022) within planetary boundaries is a challenge (Gerten et al., 2020), bio-based material flows are limited, but may—whenever not in conflict with planetary boundaries—utilize unavoidable food waste, agricultural residues not needed for regenerating soils, and sustainable forest management. Such materials may, for example, be used for thermal insulation contributing to the transition by reducing heating and cooling demand (Wernery, 2023).

Increasing circularity in society can help to maintain current in-use stocks with less primary input, allowing to **divert** existing primary production for building RE stocks. While reducing final consumption and reuse can make more energy available for mobilizing materials, upscaling recycling may increase energy demand through the increased efforts for collection, sorting and purification (Schäfer, 2021; Schmidt, 2021; Baum, 2018). During the transition, parts of the current fossil infrastructure—primarily composed of steel, Al, Cu, and concrete (Le Boulzec et al., 2022)—gets replaced and becomes obsolete. Similarly, materials can become liberated when reducing consumption and mobilizing “hibernating” materials, such as unused pipings or mobile phones.

These materials can be **repurposed** for RE infrastructure when they become accessible. Energy demand for repurposing depends on the efforts for purification and processing.

Increasing the output of existing mines and processing facilities could be relatively quick, but it is limited by the capacity of existing infrastructure. Expanding extraction and processing infrastructure and thus further increasing primary production requires more time. The mean time between discovery and production of a new mine is found to be 17 years (International Energy Agency, 2021), and 20 years for minerals necessary for electrifying mobility (Petavratzi and Gunn, 2022). Moreover, it will also require more energy, affect local communities (Owen et al., 2022; Lebre et al., 2020), and cause additional environmental impacts—e.g., on biodiversity (IRP, 2019), or water resources (Schomberg et al., 2021). Increasing the primary activity is not only an onshore question, deep-sea mineral resources have been known for a long time but have been the subject of renewed interest in recent years. Presently, efforts are done to explore deep-sea resources such as polymetallic nodules with some related works assessing associated environmental risks (Amon et al., 2022; Levin et al., 2020; Alvarenga et al., 2022). Exploiting mineral reserves from the ocean floor carries with it a lot of unknown impacts, as the regions in discussion are vast and the ecosystems in place are poorly understood (Levin et al., 2020; Hein et al., 2020). Yet, increasing primary production will be inevitable for some materials, because of the different material composition of RE infrastructure in comparison to the current socio-economic metabolism (Petavratzi and Gunn, 2022). The energy demand for mobilizing materials will change non-linearly with material flows. Declining ore grades tend to increase energy demand in an inversely proportional way (Koppelaar and Koppelaar, 2016; Calvo et al., 2016; Magdalena et al., 2021; Northey et al., 2014), while learning effects from scaling production and improved technologies may reduce it (Schmidt, 2021). Given the need to accelerate the energy transition, it remains an open question how quickly learning can be realised (Desing and Widmer, 2022; Grafström and Poudineh, 2021). Additionally, energy demand of mining depends on accessibility factors, such as mineralogy, geometry of the ore body, depth of the deposit, or remoteness of the mine site (Frenzel et al., 2017). Differences in extraction technologies strongly influence energy and water demand, as shown for example for lithium mining (Schenker et al., 2022b). Many metals necessary for the RE infrastructure are currently mined and processed as co-products in bulk material production (e.g., Co with Cu, In with Zn or Pb) (Reuter et al., 2018). Increasing the output of the target mineral may, in these cases, require either upscaling the production of the host metal, or developing new extraction routes.

The energy demand for **remining** accumulated losses—e.g., mining wastes (Adrianto and Pfister, 2022; European Commission Joint Research Centre, 2019), landfills (Lucas et al., 2019; European Commission Joint Research Centre, 2019), or past CO₂ emissions (Desing, 2022)—will depend on historical evolution of waste composition and concentration. In the best case it may be lower than for current primary production, as some legacy tailings are expected to have higher concentrations than currently mined deposits, but generally it can be expected to be higher. Proper management of landfills and mining wastes is inevitable for reducing ecological risks (Nicholls et al., 2021), and regain land area (Winterstetter et al., 2018). Compared to “increase”, access, such as through roads or to permits, may be easier. Remining landfills and mining wastes can have environmental benefits (as opposed to impacts from new primary mining), such as reducing methane emissions, landfill volumes and risks of leaching hazardous substances (Yi, 2019; Lopez et al., 2018; Beylot et al., 2022), yet it may also cause significant environmental impacts and the quality of recovered metals may be lower (Lucas et al., 2019). Similarly, CO₂ concentration in the atmosphere must be reduced to stabilize the climate and avoid triggering tipping cascades (Steffen et al., 2015; Wunderling et al., 2022; Armstrong McKay et al., 2022). Spending extra energy for transforming CO₂ into useful materials substituting traditional materials may be

beneficial overall (Desing, 2022; Mertens et al., 2023; Galimova et al., 2022). Remining can also be performed on current waste streams, such as extracting materials—e.g., Mg or Li—from desalination brines (Lundaev et al., 2022).

Because of the efforts for and consequences of resource extraction and processing—i.e., energy demand and impacts on planetary boundaries—, it may be most sensible to prioritize the **redesign** of RE components with materials for which production is easier to scale up. For example, building 19 TW of PV panels with current technology, societal stocks of Al—used in PV for module frames—would need to more than double (just for module frames, mounting systems and grid integration not included; see SM). Even though Al resources would be available and accessible (USGS, 2021), mobilizing them would be a tremendous effort (Lennon et al., 2022). It would require as much energy humanity needed over eight months in 2019 just to mobilise enough Al (see SM) and cause environmental impacts correspondingly. This could be avoided by re-designing PV systems to avoid the use of Al: for example by designing frame-less modules (Müller et al., 2021), semi-flexible cells using existing structures for support (Holzhey et al., 2023), replacing Al with steel, or perhaps carbon-fibre reinforced plastics synthesised from atmospheric CO₂ (Lopez et al., 2023; Huo et al., 2023). Redesign can encompass the strategies of material efficiency (Allwood et al., 2010)—such as simply using less material (thinner wafers and sawing wires for PV cell production (Haegel et al., 2023; Goldschmidt et al., 2021)), or component reuse (applying solar layers on existing structures (Holzhey et al., 2023))—and substitution with materials that are easier to mobilize. For example, Lithium-Iron-Phosphate (LFP) batteries are gaining momentum and starting to replace current Nickel-Manganese-Cobalt (NMC) chemistries in less demanding applications (IEA, 2023), which substitute Co and Ni with the more abundant and easier to mine Fe and P. Yet such a substitution can lead to problem-shifting, as for example P is essential in food production (Lunde, 2022). Or even Na-ion batteries, which avoid the use of Li (Peters et al., 2021; Vaalma et al., 2018). New technological developments can help material mobilization by constantly improving material efficiency and providing substitution options. However, scaling such new technologies remains uncertain. Transition modelling may thus not rely entirely on yet-to-be-proven technologies.

Recycling of RE infrastructure can help maintain stocks but cannot contribute materials during the transformation. Yet once RE infrastructure is built, increasing lifetime and recyclability will be essential for preserving it throughout subsequent replacement cycles. Frequent substitutions, however, may reduce the recycling potential, as materials contained in older stocks may no longer be in demand in new generation technologies. Design considerations therefore have to focus on both minimizing the efforts for material mobilization during the transformation as well as losses during replacement cycles (e.g., for PV panels (IRENA and IEA, 2016), wind turbines (Mishnaevsky, 2021) or batteries (Neumann et al., 2022)).

3. Research directions

To plan fast energy transition pathways, it is important to better understand the effects of mobilizing materials on the overall dynamics of the transition. The scale and type of material mobilization can affect the dynamics in multiple ways that are poorly understood. Consequently, research will have to be conducted in the following directions.

Improving modelling of transition pathways based on biophysical principles

Due to the fundamental role of materials for the transition and the efforts associated to mobilize them, transition modelling will have to be based on the feedback loop between energy and materials. Time delays for building critical infrastructures—mines, processing facilities, production plants—, gathering knowledge, and building up skills, as well as the efforts for mobilizing materials will shape transition pathways. This will require to rethink current modelling approaches: energy demand

will not be an exogenous parameter, but a dynamic variable consisting of the energy required for material mobilization and the desired demand from the remaining societal metabolism (Desing et al., 2022). As energy supply is constrained by the installed capacity, which is dynamically constrained by mobilized materials and absolutely constrained by the maximum accessible materials as well as biophysical limits, it can then happen that supply does not meet demand. The energy available for mobilization changes over the course of the transition, making energy and materials inherently interlinked. And there are unavoidable time delays for gathering knowledge, and building extraction and processing facilities. It is important to investigate the dependence of energy demand on material flows and the feedback into energy-constrained transition pathways. It will be necessary to develop suitable modelling approaches out of a multitude of possibilities combining insights from technological models—such as process simulations—, supply chain models—such as (prospective) life cycle assessment or (dynamic) material flow analysis—, energy system models, and transition models—e. g., based on system dynamics or IAMs. Any such approach will need to ensure that materials and energy balances are fulfilled, requiring a new type of integrated models by dynamically integrating sub-models based on material and energy exchanges instead of monetary flows. Economic and agent-based models may inform on societal decisions related to operability and final material and energy demand. Future research will show which combination and concrete integration of models is best suitable to address the material-energy feedback loop in transition modelling. Scenarios on technological developments are crucial to understand what may become possible and where research efforts should concentrate on. However, transition planning should not rely entirely on prospective technologies, as they may come too late or fail. Therefore, baseline scenarios should use proven technologies with and without (most precautionary) continuous improvements. This is because technological learning (Goldschmidt et al., 2021), although observed in the past, may not materialize in the future, especially when ramping production extremely fast (Desing and Widmer, 2022; Grafström and Poudineh, 2021). Price developments will be a result of such modelling, as both supply and demand for raw materials and RE system components may change widely during the transition.

Understanding material mobilization dynamics and identifying bio-physically critical materials Materials represent potential bottlenecks to the transition not only due to their limited availability and accessibility, but also due to energy demand and environmental impacts during extraction and processing (processability). As knowledge about quantities and quality of source stocks is scattered and incomplete, efforts need to be taken to map the available and accessible material stocks. The energy needed for mobilizing one unit of material changes as a function of flow and the state of depletion and quality in the source stock, yet these relationships have to be still better understood. Models have to be developed that estimate time delays and correlate the efforts for extraction and processing to few key parameters, such as concentration, chemical state, and remoteness. Different mobilization routes may show synergistic effects or be in competition with each other and the rest of the economy. For example, early retirement and repurposing of fossil infrastructure may decrease the production of transition metals as by-products of fossil fuels. One example is synthetic graphite used e. g., in Li-ion batteries, which is today made from needle coke, a by-product of petroleum refining. Additionally, dynamic environmental impacts on planetary boundaries will constrain the maximum level of material mobilization. When designing rapid transition pathways, it will be important to investigate effects on biodiversity, nutrient cycles, water demand, etc. Knowledge regarding the bio-physical potential for mobilizing materials and their effect on the energy transition as well as planetary boundaries can inform about which parts of the future RE infrastructure should be redesigned, where technological developments and societal decisions need priority.

Material substitution and dematerialization Once bio-physically critical materials are identified, the question arises: how well can they be substituted by other materials and where are limits imposed by material physics? One example is substituting Ag in PV (Zhang et al., 2021; Pivano et al., 2019), another one is replacing Li in batteries (McNeil, 2022). It may be beneficial to research the possibilities to substitute with more abundant elements, such as H, C, N, O, Fe, Si, or Al (“elements of hope” (Diederer, 2010; Desing and Blum, 2023)), while improving the understanding of impacts on energy demand and planetary boundaries. Another research line could be to incorporate and immobilize (mandatory) abandoned elements—e. g., Hg (United Nations Environment Programme, 2019), Pb, Cd, atmospheric C—in long lasting infrastructure. E. g., Pb could be immobilized in perovskite PV (Lee et al., 2023), or excess atmospheric carbon (Desing, 2022) in plastics used in PV or graphite for battery electrodes. The effects of substituting, diverting and increasing material flows on the socio-economic metabolism are complex and need to be better understood (van der Voet et al., 2017), especially in the light of a rapid “emergency” transformation. Additionally, dematerialising RE technologies by design and in line with availability, accessibility and processability of materials can help speeding up the transition by minimizing energy and material demand, as well as easing subsequent replacement cycles.

New extraction and processing technologies Accessing, extracting and processing source stocks may require, or be eased by, new or improved technologies. For example, the majority of known mineral resources related to transition metals is located below the land of indigenous and pastoral peoples (Owen et al., 2022). Extracting them in the traditional way will cause environmental and social impacts, even if they have a societal licence to operate. Perhaps it might be possible to invent “minimally-invasive” mining technologies (in analogy to minimally invasive surgery) (Lopes et al., 2020); however, so far the only possibility to reduce the problem is to limit the amounts extracted, and focusing on areas where damage to the ecosystem is lower. Also, reining tailings, landfills and past emissions may benefit greatly by new extraction and processing technologies. As many transition metals are currently mined and processed as by-products, novel extraction routes may need to be developed. Additionally, mining and processing is today heavily reliant on fossil fuels, making it necessary to develop new de-fossilized extraction and production routes. All new extraction technologies will need to be assessed for their environmental and social impacts, e. g., by using life cycle assessments.

Enabling legislation, business models, governance and social acceptance All mobilization strategies will require changes in legislation, business models and social acceptance—be it for opening new mines, repurposing in-use stocks, or prolonging materials’ residence time in the economy. Acceptance can be influenced by the design of these strategies, which opens a new field of research: How can the design foster social acceptance and maximise social benefits, thus enabling implementation? Are there socially preferable strategies at different stages of the transformation? Mobilizing materials shall not come at the cost of local communities, which will require to envision national and transnational governance strategies for avoiding negative side effects and for learning from the disadvantages of the green revolution (Gloaguen et al., 2022). Furthermore, it is essential to devise political and economic strategies for implementation able to transcend social resistance and concerns of “societal security” aiming at maintaining the status quo (McLaren and Corry, 2023).

Monitoring and steering the socio-economic metabolism transformation The RE infrastructure lies at the interface between climate mitigation and resource criticality. The knowledge base of the energy-material nexus is still insufficient to adequately address this challenge. Existing models of the socio-economic metabolism are highly fragmented by countries, sectors, and materials and they lack the necessary spatial and

temporal granularity to capture the complex feedback loops between energy, materials, and environmental impacts. Improving our understanding of the energy-material nexus and the role of RE infrastructure is fundamental for informing, planning, governing, and monitoring energy transition strategies and ultimately for stabilizing the climate.

4. Conclusions

Trends and technologies can change faster (or more slowly) than expected. For instance: future batteries could be made out of abundant materials (such as Na and S), Ag in solar panels could be replaced by Cu, Al, or graphene, circularity could become “trendy” and effective recycling could boost companies’ reputation. Prospectively, materials and their applications can vary a lot, and simplistic views and conclusions should be avoided. Be that as it may, the general principles expressed in this paper reflect the natural laws of our physical environment and, as such, they are robust. The growth of RE stocks is physically limited by the available, accessible, and processable materials in natural (lithosphere, atmosphere, biosphere and hydrosphere) and anthropogenic resources (urban mines), as well as limited by the energy required and environmental impacts caused for their processing into RE devices. The speed of the transformation is then also limited by the willingness of society to invest in harvesting and processing infrastructure and operationalize the flows (i.e., the “hand on the valves”). The presented framework can help taking the dynamic interconnections between energy and materials into account in energy transition modelling and guide technological developments towards fast material mobilization.

CRedit authorship contribution statement

Conceptualization, H.D.; validation, all; visualization, H.D.; writing—original draft preparation, all; writing—review and editing, all.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.resconrec.2023.107314>.

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D3.1. ANNEX C1

Consumers' values, beliefs, and willingness to engage in circular behaviours.

Comparing perceptions of consumers and employees

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Executive Summary

This report presents results from two large-scale surveys on consumers' values, beliefs, and willingness to engage in circular behaviours, and how employees perceive these consumer beliefs and willingness. We focus on two sectors: the mobility sector and the housing sector. The consumer survey was conducted among over 5000 consumers from five European countries (the United Kingdom, Germany, the Netherlands, Italy, and Lithuania). The survey among employees in the mobility and housing sector was filled out by almost 2000 respondents in the same countries about consumers in these countries.

This report compares findings of the two studies regarding circular behaviours in the mobility and housing domain, and factors influencing consumers' willingness to engage in circular behaviours. Specifically, consumers' values, beliefs, and willingness to engage in certain circular behaviours are compared with employees' perceptions of consumers' values, beliefs, and willingness regarding the same behaviours.

For mobility, the willingness to not own a car (representing the *refuse* strategy of circular consumption; Kirchherr et al., 2017) and to use car sharing instead of owning a car (representing the *rethink* strategy of circular consumption) was investigated. For housing, the willingness to downsize one's living space (*reduce* strategy) and to share living spaces (*rethink* strategy) was examined.

We find that employees overestimate the strength of consumers' values, their problem awareness, perceptions of being able to engage in circular behaviours, and how impactful these behaviours would be, as well as consumers' feelings of moral obligations and willingness to engage in circular behaviours to some extent. The overall strength of overestimation lies between 0.31 and 1.33 scale points. Overestimation was observed for all countries, though to differing degrees. Consumers' beliefs and willingness to behave more circularly were overestimated the least for Germany and Lithuania (0.79 and 0.72 scale points on average) and overestimated the most for Dutch consumers (1.24 scale points difference).

Consumers' perceived ability to not own a car and awareness of environmental and social problems arising from car ownership were most accurately perceived by employees (one third of a scale point), while consumers' feelings of moral obligation to live in a smaller home or share living spaces and their willingness to share their kitchen or entrance/hallway were overestimated the most (around 1.31 scale points). Consumers' beliefs and willingness regarding housing were more overestimated than for mobility (1.13 scale points difference compared to 0.61). Overall, employees have a slightly more circularity-supporting perception of consumers.

The findings indicate that consumers have, on average, positive beliefs towards circular behaviours and that employees slightly overestimate these. Therefore, businesses may continue their efforts to advance circularity by ensuring that their circular products and services are attractive and feasible for consumers, with a special focus on consumers who might feel less



capable or are currently less willing to engage in circular behaviours. Businesses can focus on enabling these consumers to behave circularly as well.

These insights can support informed decision-making, helping businesses enhance their offerings and strengthen consumer engagement.

Keywords

Circularity, circular consumption behaviours, mobility, housing, representative survey, employee survey, values, beliefs, personal norms, misperceptions

Introduction

The CircEULAR (Developing Circular Pathways for an EU Low-Carbon Transition) project is a four-year-long Europe Horizon-funded research project that aims to develop circular pathways for an EU low-carbon transition in the mobility and housing sectors. The *circular economy (CE)* implies that we move away from the current economy's linear approach, where resources are extracted to make products that eventually end up as waste and are thrown away (Bocken et al., 2016). Instead, the CE implies using fewer virgin resources and materials when making products (*narrowing the loop*), using existing products for longer (*slowing the loop*), and reusing resources and materials that we already have, e.g., through recycling or restoring products to a like-new state (*closing the loop*). Circular consumption behaviours are categorised in 9R strategies (Kirchherr et al., 2017; see Table 1), with R0 *refuse* being thought to be most impactful in achieving circularity and R9 *recover* being the least impactful. By applying these strategies, the circular economy aims to reduce environmental problems like climate change, biodiversity loss, waste, and pollution.

Table 1. Circular consumption in the 9R framework by Kirchherr and colleagues (2017)

Strategy	Description	Pathway
R0 Refuse	Make a product redundant by abandoning its function or by offering the same function with a radically different product	Narrowing the loop
R1 Rethink	Make product use more intensive (e.g., by sharing a product)	
R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials	
R3 Reuse	Reuse by another consumer of a discarded product that is still in good condition and fulfils its original function	Slowing the loop
R4 Repair	Repair and maintenance of defective products so they can be used with their original function	
R5 Refurbish	Restore an old product and bring it up to date	



R6 Remanufacture	Use parts of a discarded product in a new product with the same function	
R7 Repurpose	Use discarded product or its parts in a new product with a different function	
R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality	Closing the loop
R9 Recover	Incineration of material with energy recovery	

This report aims to understand the extent to which consumers are willing to engage in circular behaviours in the areas of mobility (i.e., not owning a car and using car sharing instead of owning a car) and housing (i.e., moving to a smaller house or sharing living space with non-family members). All behaviours focus on narrowing the loop, and the R strategies refuse, rethink, and reduce. Furthermore, we examined to what extent consumers are aware of the problems caused by non-circular alternatives (i.e., owning a car and living in a large house), feel capable and responsible for engaging in the relevant circular consumption behaviours, and think that doing so would help reduce environmental problems. Besides, consumers indicated the extent to which they endorse different values that are relevant to understanding circular consumption behaviour. Next, we aimed to understand to what extent representatives of businesses working in the mobility and housing sector, respectively, think consumers are willing to engage in these circular behaviours, and to what extent they think consumers are aware of the problems caused by non-circular consumption (*problem awareness*), feel capable (*self-efficacy*) and morally obliged (*personal norms*) to engage in circular consumption behaviours, think that doing so would help reduce environmental problems (*outcome efficacy*), and to what extent they think consumers endorse different values. By comparing the responses from consumers and employees, we identify misperceptions that may prevent businesses from offering (more) circular products.

We collected data among representative samples of consumers in five European countries (the United Kingdom, Germany, the Netherlands, Italy, and Lithuania) and among employees with a consumer base in these countries.

Notably, we do not only ask employees about their perceptions of current consumers, but about all people in a country, as these also constitute potential consumers. As for planning future strategies for circularity, all people in a country are of potential interest, they may be taken into account as well. Thus, we ask employees about all people in a specific country.

Below, we will first briefly describe the characteristics of the consumer and employee samples. Next, we will report and compare the findings of the consumer survey and the survey among employees, and identify where perceptions are unanimous and where they differ.

Descriptives of the consumer survey participants

The consumer survey had a total of 5651 respondents from five countries: 1051 from the UK,



1100 from Germany, 1081 from the Netherlands, 1409 from Italy, and 1008 from Lithuania. Of all respondents, 2746 (48.6%) were men, and 2905 (51.4%) were women. The age ranged from 16 to 93 years, with a mean age of 50 years. The gender and age distribution are roughly similar across countries. More detailed information on the consumer survey and sample descriptives can be found in CircEULAR's D4.4 report (Grealis & Rau, 2025).

Descriptives of the employee survey participants

To grasp how businesses perceive (potential) consumers, we do not focus only on the heads of companies, but a diverse range of their employees, differing regarding the division they work in, to what extent sustainability is a part of their formal job description, or much much influence they have in the organisation. Through this approach, we hope to understand how diverse employees who can ultimately shape companies' strategies, processes, and products and services towards circularity, view consumers' beliefs and willingness regarding circularity. Importantly, only employees who consider consumers in their work at least somewhat could participate in the survey.

The employee survey was filled out by 1897 employees, of whom 630 worked in the mobility sector and 1262 in the building sector. Employees were based in Germany, Italy, Lithuania, the Netherlands, and the United Kingdom (see Figure 1). Most employees considered consumers in their work a lot (see Figure 2). At the beginning of the survey, each participant indicated the consumer base of their organization and was then allocated a country's consumer base to answer questions about (see Figure 3). For employees' age, gender, and education, see Figures 4-6.

Figure 1. Employees' country of residence

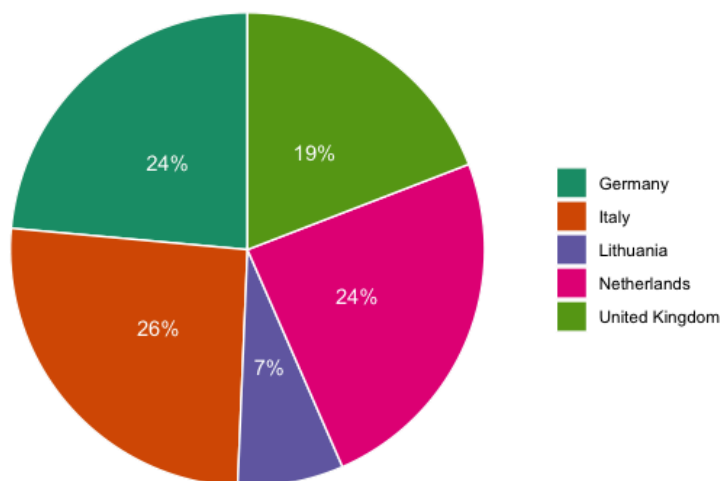


Figure 3. Country of the consumer base for employee ratings

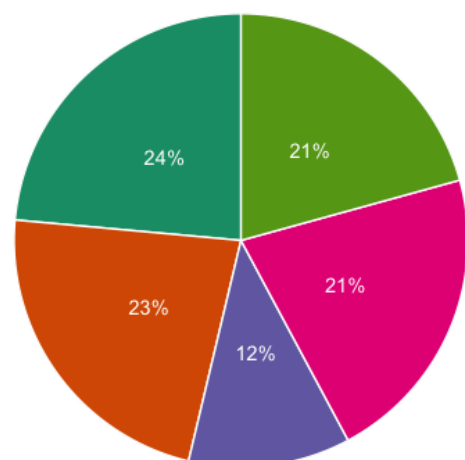




Figure 2. Consideration of the consumer in employees' work

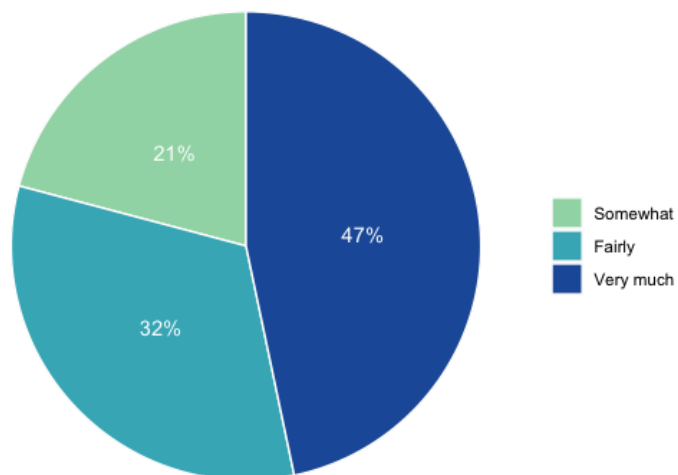


Figure 4. Employee age

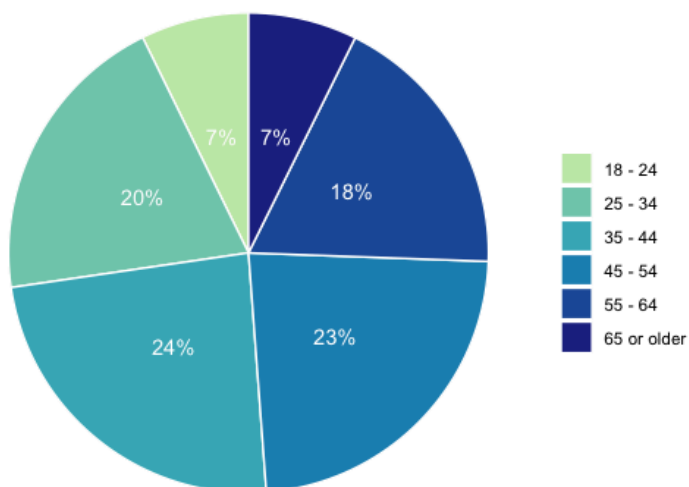




Figure 5. Employee gender

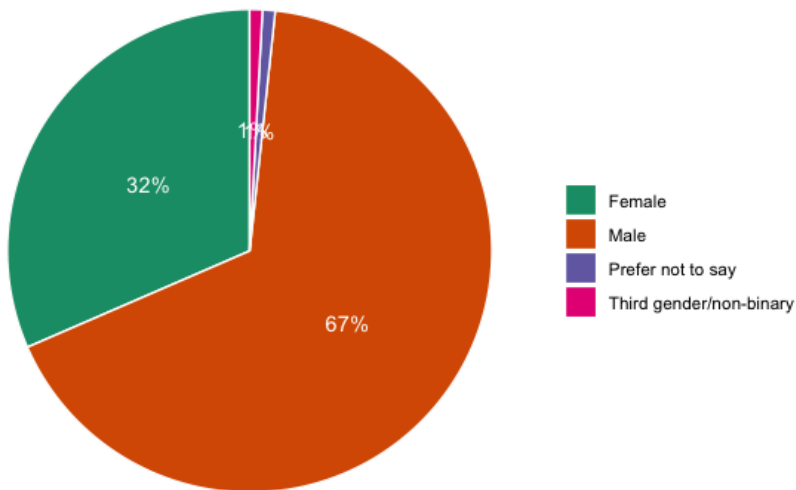
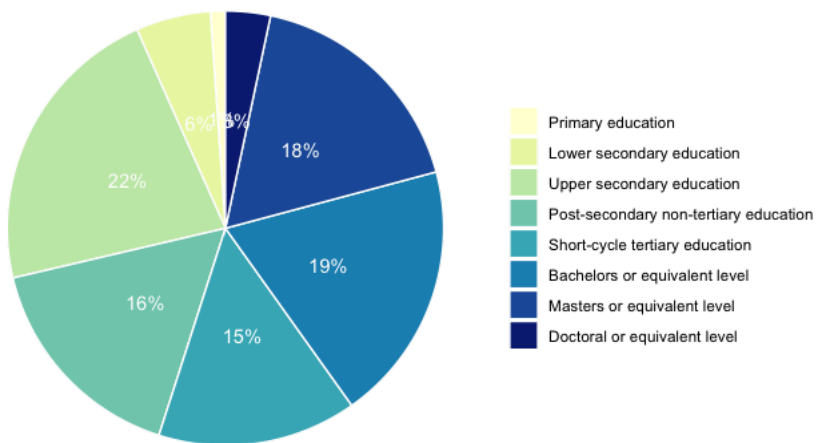


Figure 6. Employees' level of education



Employees were mostly team members, followed by being part of the middle management (see Figure 7). They work for various divisions within companies (see Figure 8) and have been in the organisation for less than 12 months up to more than 20 years (see Figure 9). The size of the companies varied from less than 10 to over 500 (see Figure 10). The degree to which sustainability was part of the employees' job description varied between not at all and very much (see Figure 11). The perceived level of influence of the employees within their organisation also ranged from not influential to extremely influential (see Figure 12).



Figure 7. Employee position

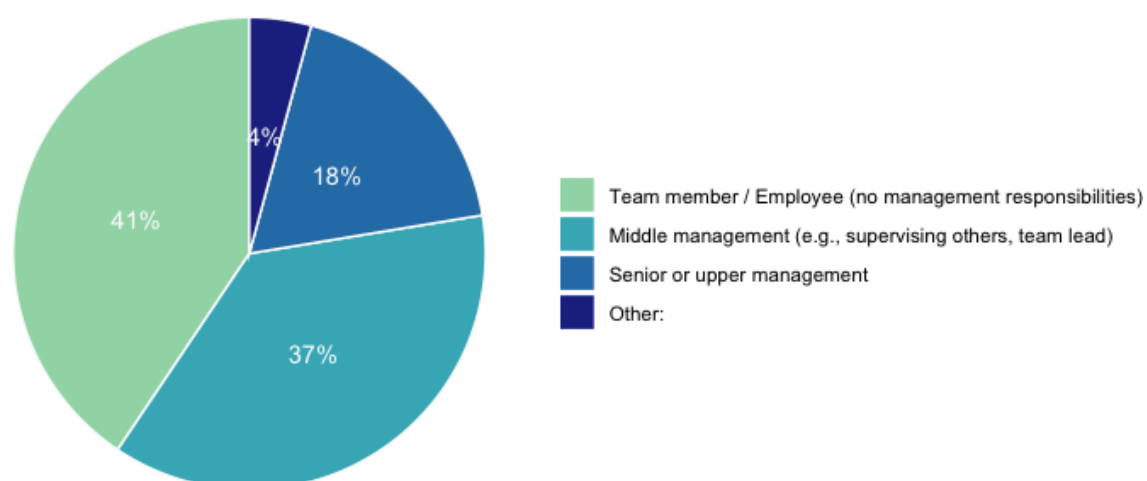


Figure 8. Organisational divisions for which employees work

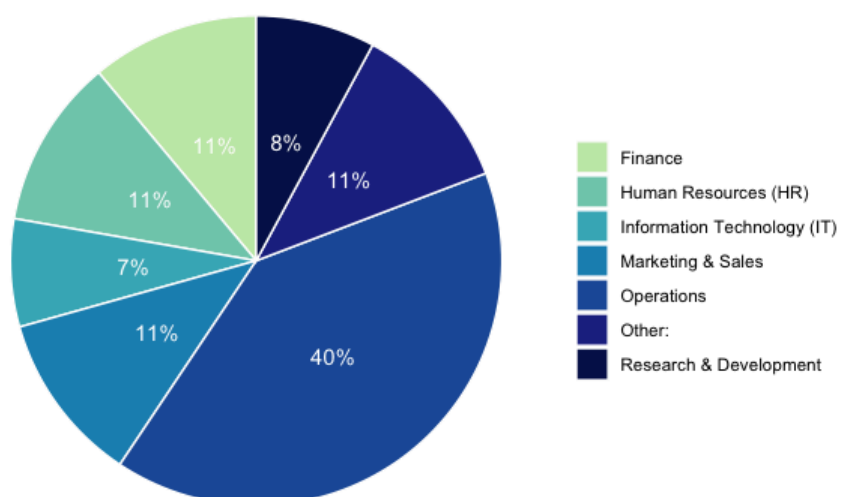




Figure 9. Employees' tenure in their company

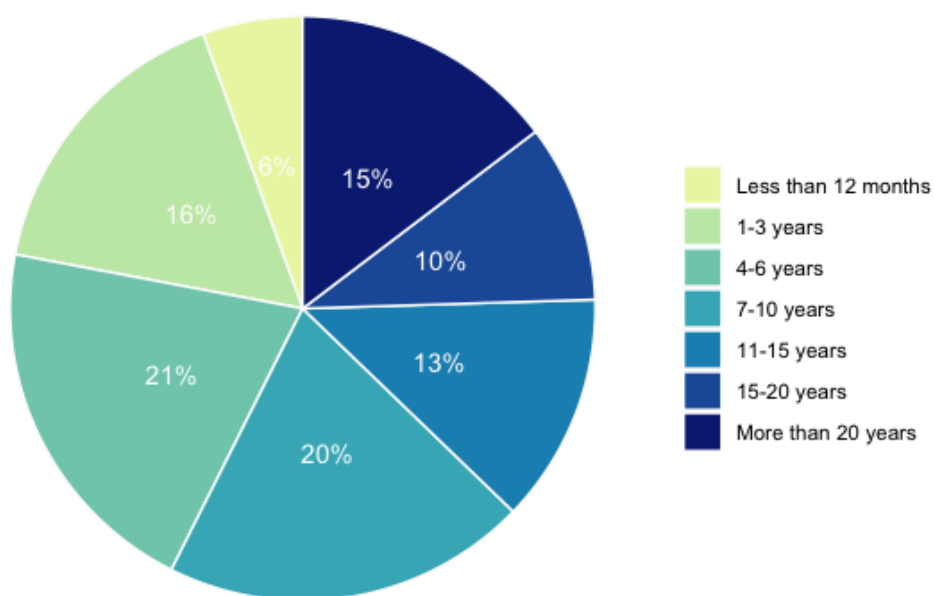


Figure 10. Company size

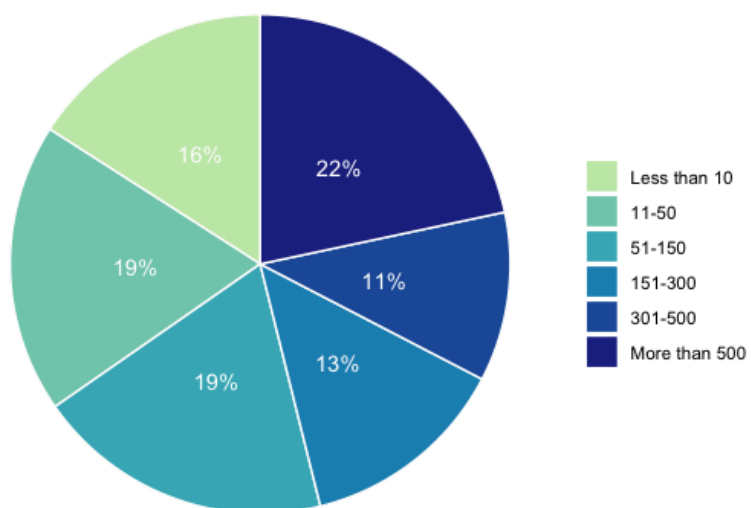




Figure 11. The level to which sustainability is part of employees' job description

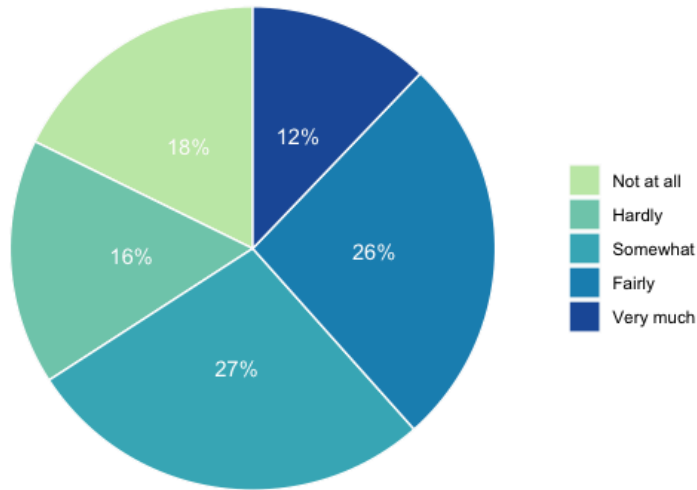
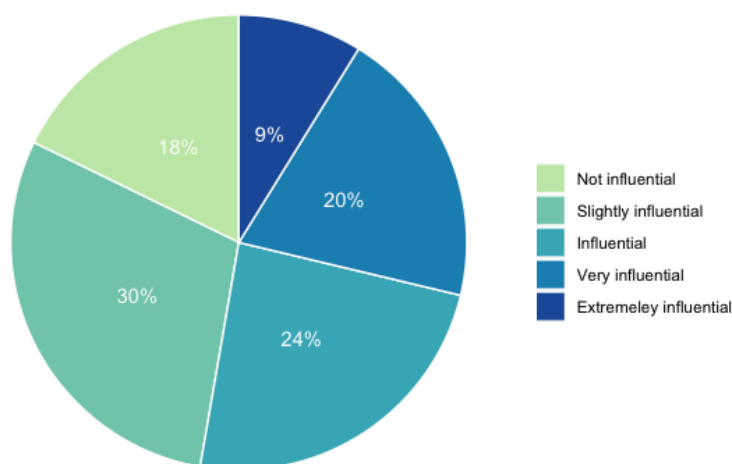


Figure 12: Perceived level of influence within an employee's organisation



Consumer values as perceived by employees and consumers

Values are guiding principles in people's lives that affect their preferences and the choices they make (Schwartz, 1977). We included four values that are most relevant for understanding pro-environmental behaviours, such as circular consumption (Van der Werff & Steg, 2016). On the one hand, there are values that make people focus on the collective interest, specifically: biospheric values that reflect a concern for the environment and nature, and altruistic values that reflect the extent to which people are concerned for the well-being of others. People with stronger biospheric and altruistic values are generally more likely to engage in pro-environmental behaviours, such as circular behaviour. On the other hand, some values make people focus on their own interests. Specifically, egoistic values focus on securing personal resources such as wealth and status, and hedonic values emphasize pleasure and comfort. People with stronger egoistic and hedonic values are generally less likely to engage in circular



consumption, as such behaviour is often associated with more inconvenience, effort, or higher costs (Van der Werff & Steg, 2016).

Consumers were asked to what extent biospheric, altruistic, egoistic, and hedonic values are guiding principles in their lives. Responses were given on a 7-point scale, ranging from (1) *fully disagree* to (7) *fully agree*¹. Employees were asked to indicate their perceptions of consumer values on the same scale.

Biospheric values

Biospheric values were assessed with the item “It is important to me to take care of, and live in harmony with, nature” for consumers and “It is important to people in [country base of employee’s company] to take care of, and live in harmony with, nature” for employees.

Consumers indicated that they endorse biospheric values ($M = 4.84$, see Figure 13). Biospheric values were strongest in Germany, followed by the UK, Italy, the Netherlands, and Lithuania. 60% of consumers overall agreed with the statement (answers above the midpoint of the scale), while 24% disagreed (answers below the midpoint of the scale), and 16% chose the midpoint (scale point 4; see Figure 14).

Employees rated consumers’ biospheric values slightly higher ($M = 5.24$), with 70% of the ratings above the midpoint and only 13% below. 17% were neutral. Thus, employees slightly overestimated consumers’ biospheric values. This was the case for all countries except Germany, where consumers' biospheric values were slightly underestimated (see Figure 13).

¹ Please note that in Grealis & Rau’s (2025) mid-term report on the circular consumption survey, the scale points for survey participants ranged from (1) fully agree to (7) fully disagree.



Figure 13. Average ratings of biospheric values by consumers and employees' perceptions

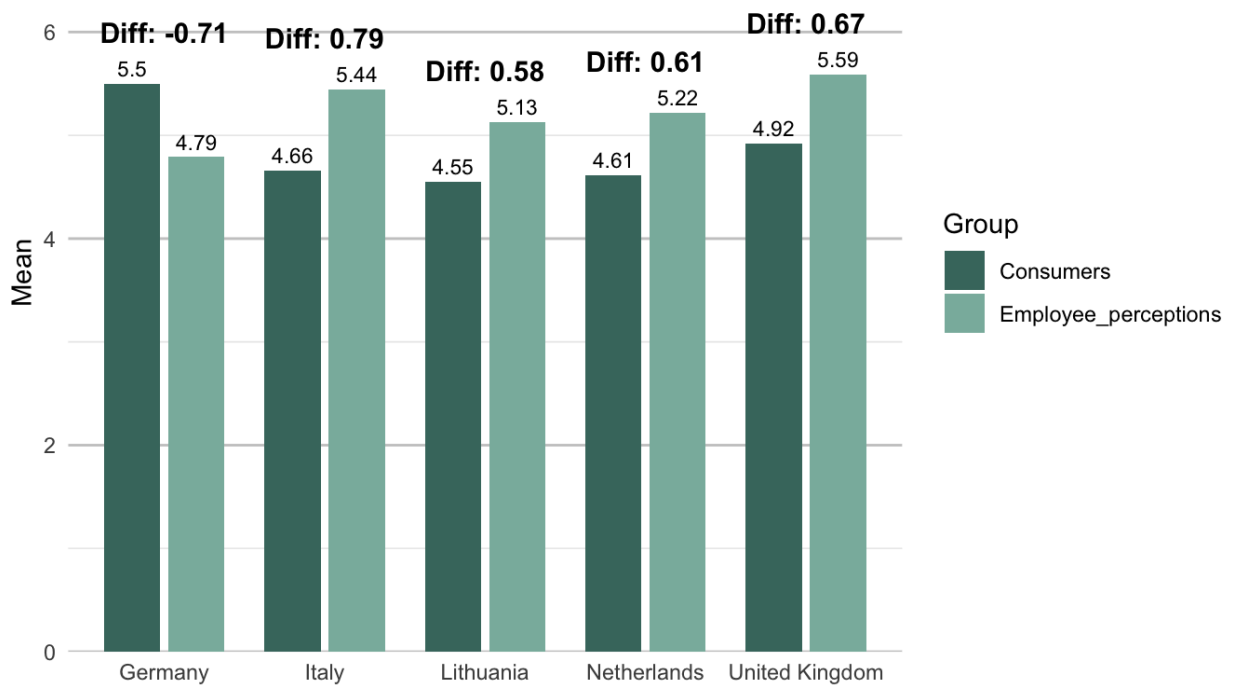
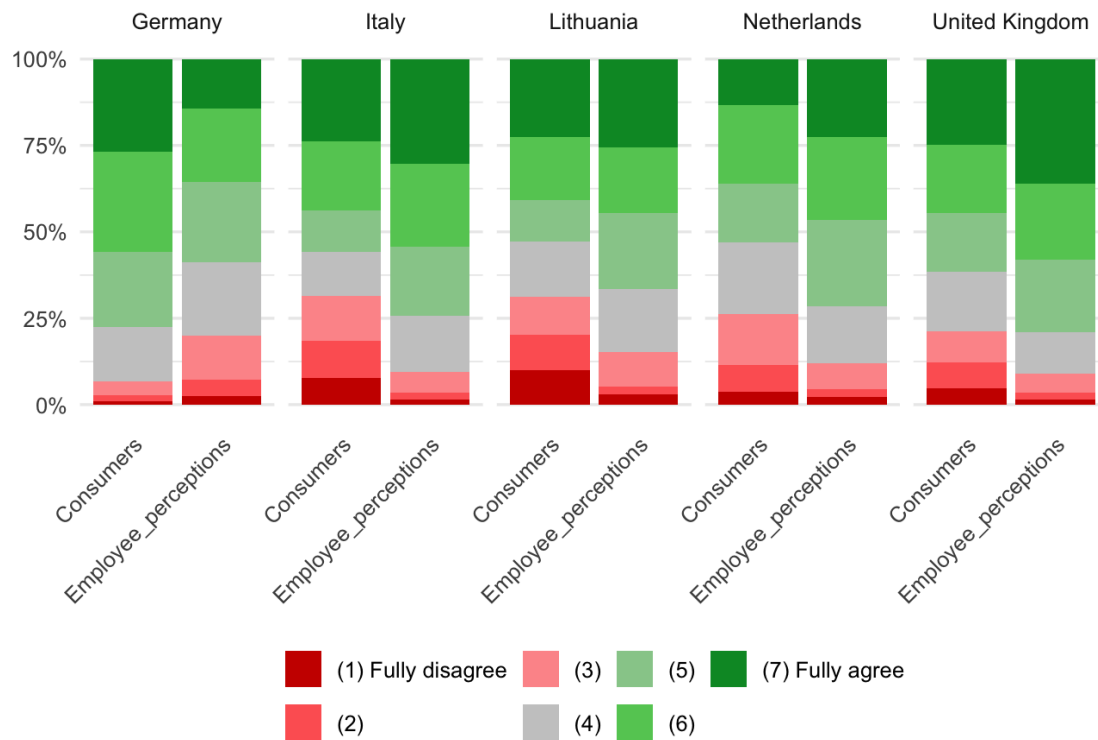


Figure 14. Distribution of biospheric values – ratings by consumers and employees' perceptions





Altruistic values

Altruistic values were assessed with the item “It is important to me to help others and that others are treated fairly.” for consumers, and “It is important to people in [country base of employee’s company] to help others and that others are treated fairly” for employees.

On average, consumers rather strongly endorse altruistic values ($M = 4.90$), with scores being highest in Germany, followed by the UK, the Netherlands, Italy, and Lithuania (see Figure 15). For 63% of consumers, it is important to help others and treat others fairly, 14% are neutral, and 23% disagree to some extent.

Employees rated consumers’ altruistic values slightly higher than consumers themselves ($M = 5.10$), with 67% agreeing that consumers care about helping others, 19% being neutral, and only 14% disagreeing. Thus, they slightly overestimated consumers’ altruistic values. This was the case for all countries, except Germany, where employees disagree with the statement more than consumers do (see Figure 15).

Figure 15. Average ratings of altruistic values by consumers and employees’ perceptions

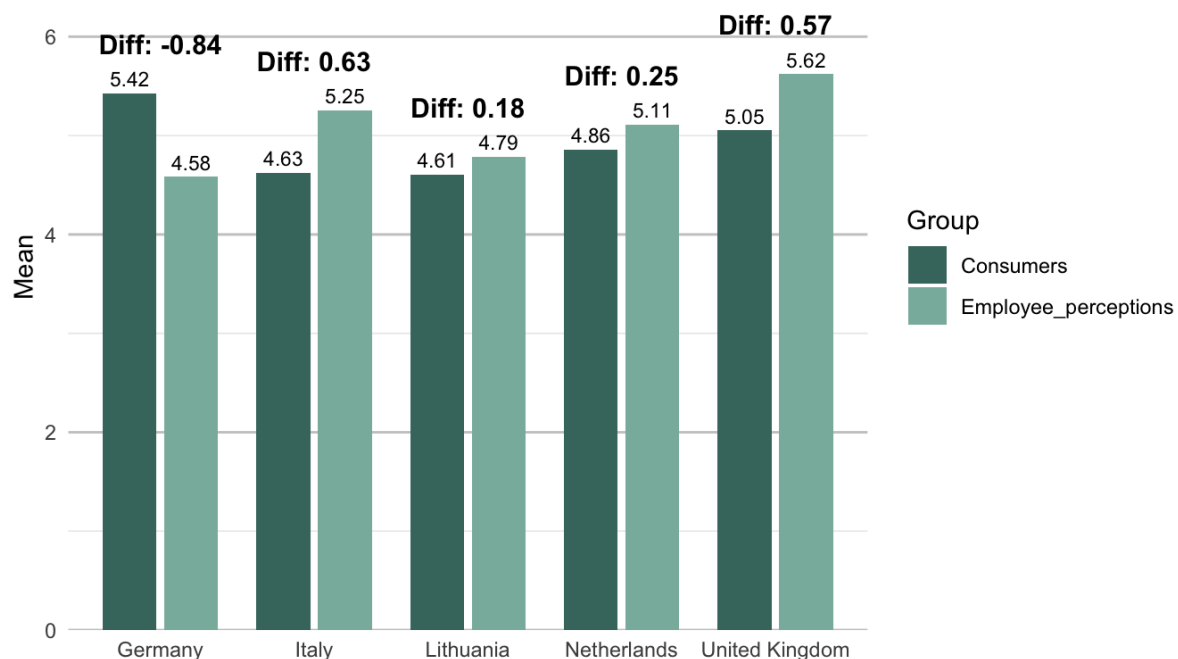
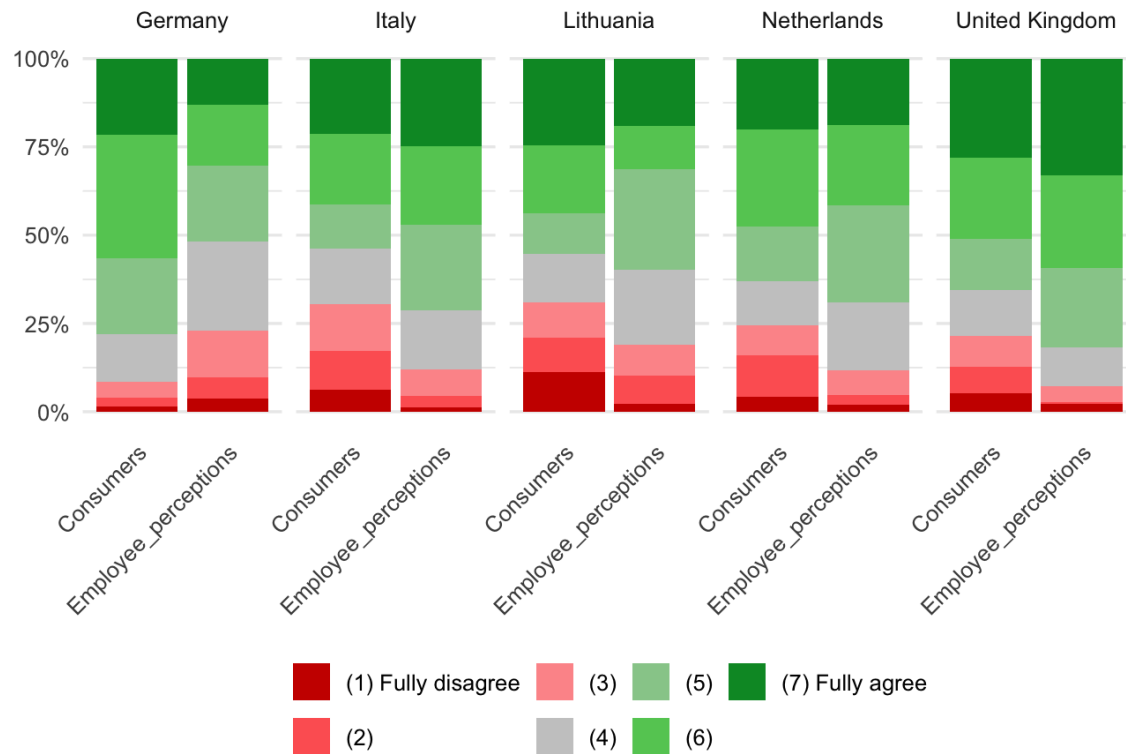


Figure 16. Distribution of altruistic values – ratings by consumers and employees’ perceptions



Egoistic values

Egoistic values were assessed with the item “It is important to me to have wealth, possessions, influence, and status” for consumers and “It is important to people in [country base of employee’s company] to have wealth, possessions, influence, and status” for employees.

Consumers did not strongly endorse egoistic values ($M = 3.84$), with the mean score being slightly below the midpoint of the scale. Egoistic values are lowest in the Netherlands, followed by Germany, Italy, the UK, and Lithuania (see Figure 17). Overall, 34% of consumers agreed with the statement, 25% were neutral, and 41% disagreed (see Figure 18).

Contrary to consumers, employees rated consumers’ egoistic values above the midpoint of the scale ($M = 5.00$). Thus, consumers’ egoistic values were strongly overestimated. This was the case for all countries, with the difference being most pronounced for Lithuanian consumers and least for Dutch consumers. One third (66%) of employees thought that consumers find wealth, possessions, influence, and status important, compared to 34% of consumers. 15% of employees disagreed (compared to 41% of consumers), and 19% were neutral.

Figure 17. Average ratings of egoistic values by consumers and employees' perceptions

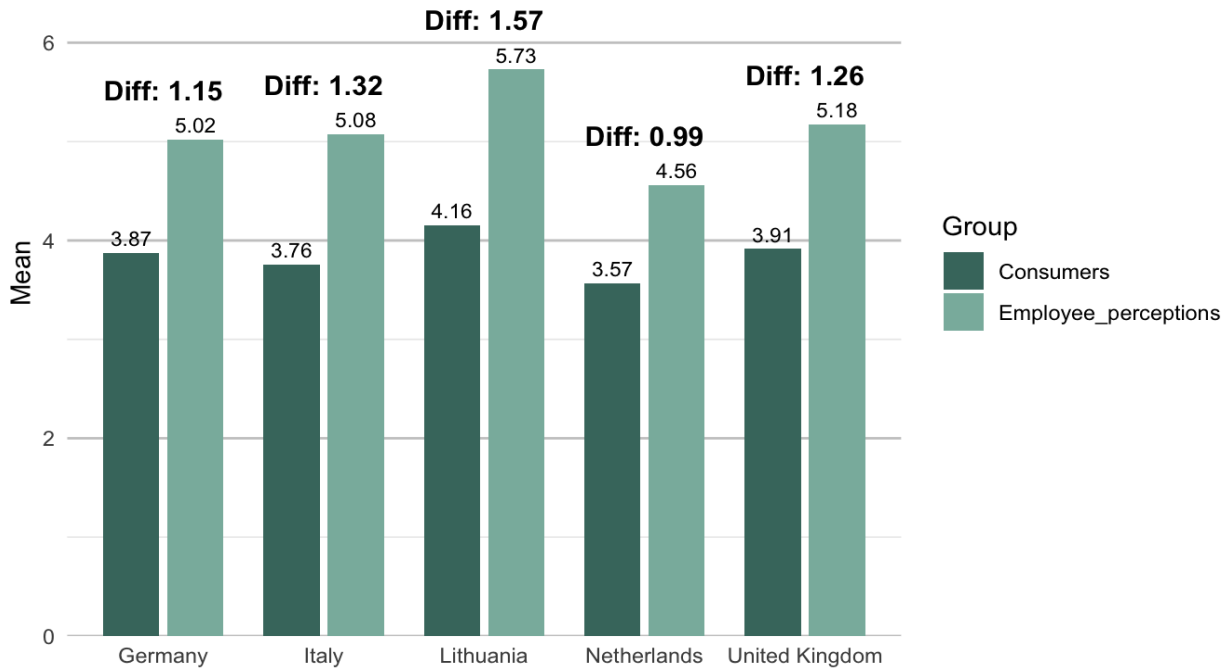
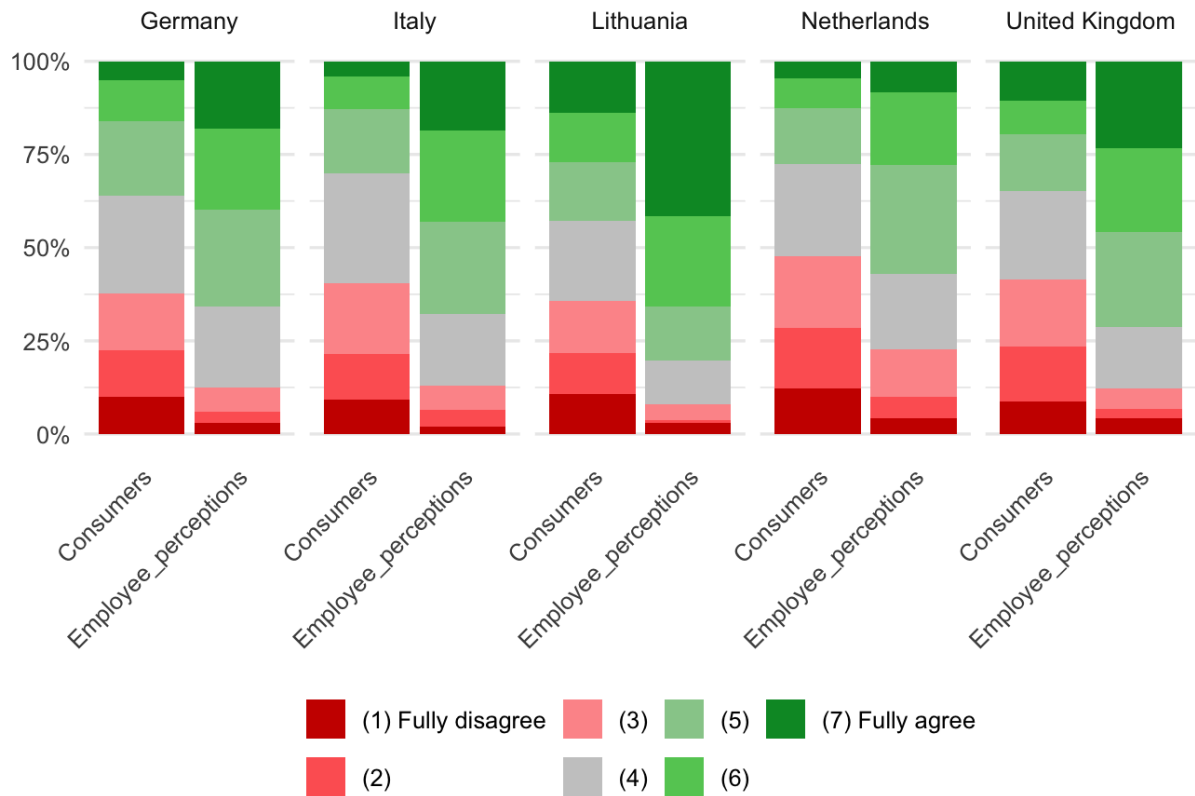


Figure 18. Distribution of egoistic values – ratings by consumers and employees' perceptions





Hedonic values

Hedonic values were assessed by the item “It is important to me to have fun and have a good time” for consumers and “It is important to people in [country base of employee’s company] to have fun and have a good time” for employees.

Consumers indicated rather strong hedonic values ($M = 4.75$), particularly in Germany, followed by the Netherlands, the United Kingdom, Italy, and Lithuania (see Figure 19). Overall, 58% of consumers found hedonic values important, while 16% were neutral, and 26% disagreed (see Figure 20).

Employees rated consumers’ hedonic values higher than did consumers themselves ($M = 5.51$), with 80% agreeing with the statement (compared to 58% of consumers), 12% being neutral, and only 7% disagreeing. Thus, employees somewhat overestimated consumers’ hedonic values. The strength of overestimation differed between countries, with perceptions about German consumers being most accurate and ratings of Lithuanian consumers being least accurate.

Figure 19. Average ratings of hedonic values by consumers and employees’ perceptions

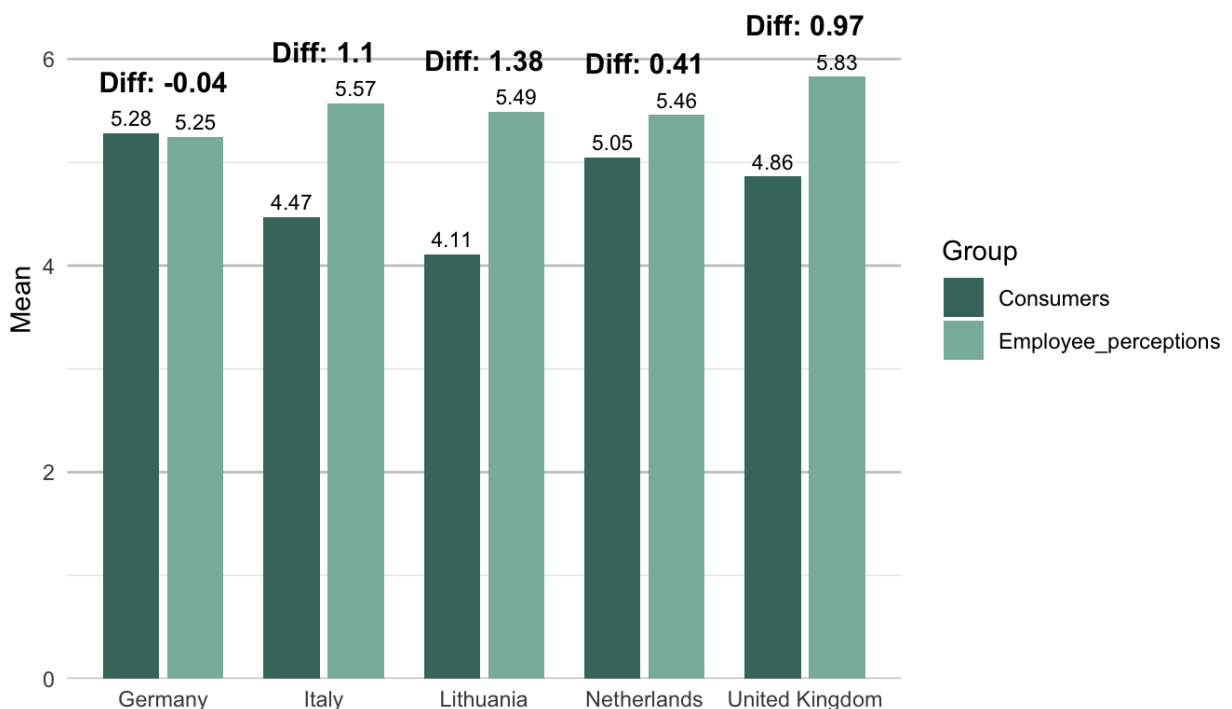
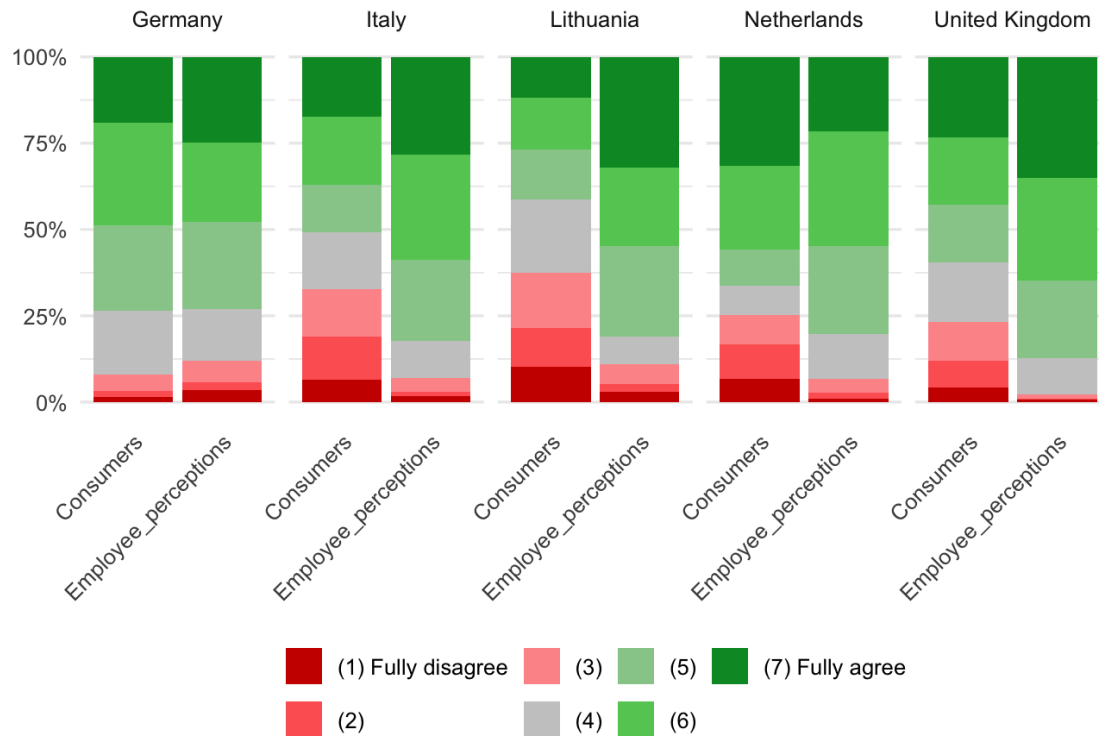


Figure 20. Distribution of hedonic values – ratings by consumers and employees’ perceptions



The consumers' pattern of value endorsement aligns with earlier findings from European countries, where biospheric and altruistic values were most strongly supported, followed by hedonic values, with egoistic values receiving the least endorsement (Bouman et al., 2021). Overall, employees seem to somewhat overestimate consumers' values.

Beliefs and actions related to mobility

As indicated earlier, we compared the beliefs and actions of consumers related to circular options to reduce car use: i) living without owning a car, and ii) using car sharing instead of owning a car. To provide some background information, we first report results on car ownership and car sharing. On average, 83% of respondents in the participating countries own a car (for more details on the number of cars, see Grealis & Rau, 2025; please note that the scale points are flipped around in this report with lower scores presenting higher agreement/willingness), with Italians being most likely (90%), followed by the Dutch (86%) and Germans (82%). People in the UK (79%) and Lithuanians are least likely to own a car (77%).

Overall, 28% of the respondents indicated that commercial car-sharing options (e.g., rental/share companies) are available in their local area. Community car sharing (e.g., car clubs) was less available (10% overall). About 21% of consumers indicated that they can use informal car sharing (e.g., through friends and family). Particularly few German consumers indicated



having access to informal car sharing (12%), compared to UK consumers (29%).

We assessed consumers' beliefs about car ownership and use: the extent to which they are aware that car use contributes to environmental and social problems (problem awareness), believe they could reduce their car use (self-efficacy), believe that reducing car use would help reduce environmental and social problems (outcome efficacy), feel a moral obligation to reduce their car use (personal norms), and are willing to give up owning a car or use car-sharing instead (willingness to engage in circular behaviour). Responses were given on a 7-point scale, ranging from (1) *fully disagree* to (7) *fully agree*. Employees were shown the same items, but this time were asked to indicate to what extent consumers would agree with the statements.

Problem Awareness: Consumers' awareness of the environmental and social impacts of car ownership and use

Consumers could indicate to what extent they agreed with the statement "Car ownership and use cause serious environmental and social problems". Employees received the statement "People in [country base of employee's company] think that car ownership and use cause serious environmental and social problems".

Overall, consumers are not particularly aware of environmental and social problems arising from car ownership and use ($M = 3.87$, see Figure 21). 39% of the consumers disagree to some extent with the statement, while 25% indicate a neutral view, and 36% agree (see Figure 22). Thus, almost the same number of people agree and disagree. Problem awareness was highest in the UK and lowest in the Netherlands.

Employees rated consumers' problem awareness slightly above the midpoint ($M = 4.17$), with 48% agreeing that consumers think that car ownership and use cause serious environmental and social problems, while 33% disagreed. 19% were neutral. The overestimation occurred for consumers in all countries except Germany.



Figure 21. Average ratings of problem awareness by consumers and employees' perceptions

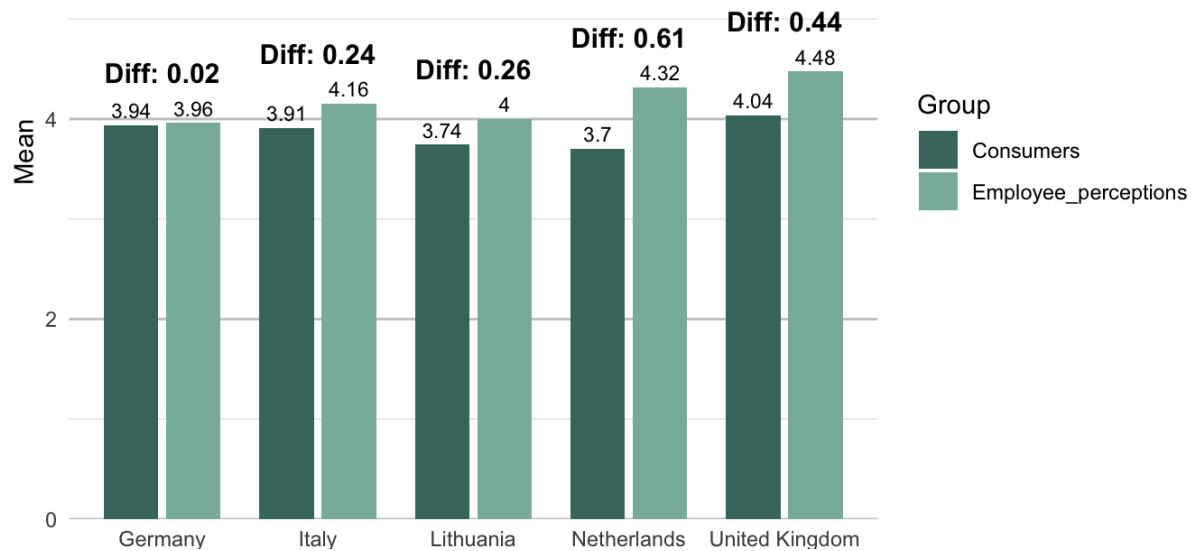
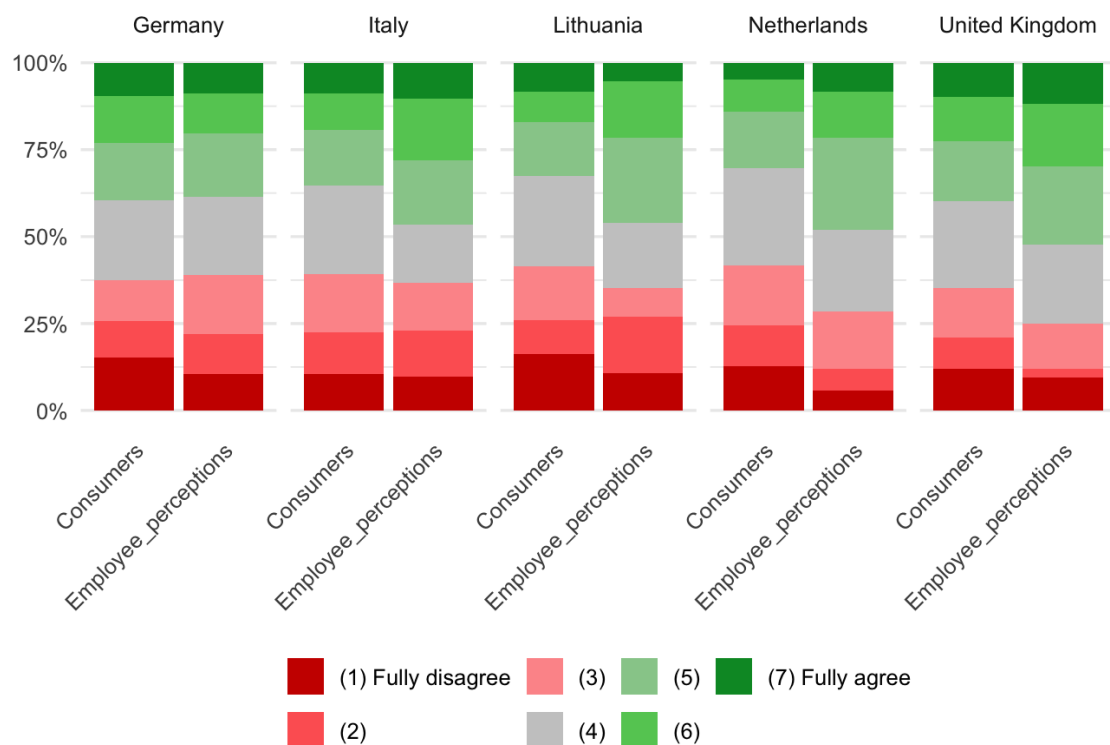


Figure 22: Distribution of problem awareness – ratings by consumers and employees' perceptions





Self-efficacy: Consumers' beliefs about their ability to live without owning a car

Consumers could indicate their level of agreement with the statement “I feel capable of living my life without owning a car” and employees on the item “People in [country base of employee’s company] feel capable of living their life without owning a car” (see Figure 10).

Overall, consumers did not feel particularly capable of living without owning a car ($M = 3.58$). Half of all consumers disagreed with feeling capable of living life without owning a car, whereas 17% were neutral, and 33% agreed with the statement (see Figure 24). Self-efficacy was highest in the UK and lowest in Italy (see Figure 23).

Employees rated consumers' self-efficacy similarly to consumers themselves ($M = 3.92$), though the percentage of (dis)agreement slightly differed. Almost the same number of employees believe that consumers do (and do not) feel capable of living without a car (43% disagreed and 41% agreed). 16% of employees were neutral. The ratings were most accurate in Germany and the United Kingdom, and least in Lithuania (see Figure 23).

Figure 23. Average ratings of self-efficacy by consumers and employees' perceptions

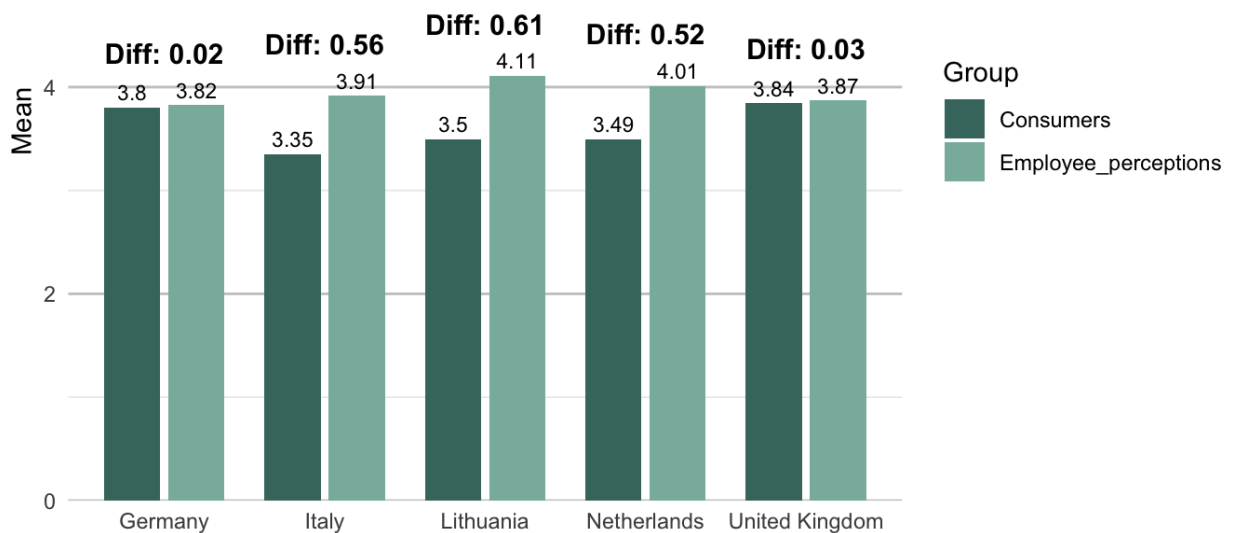
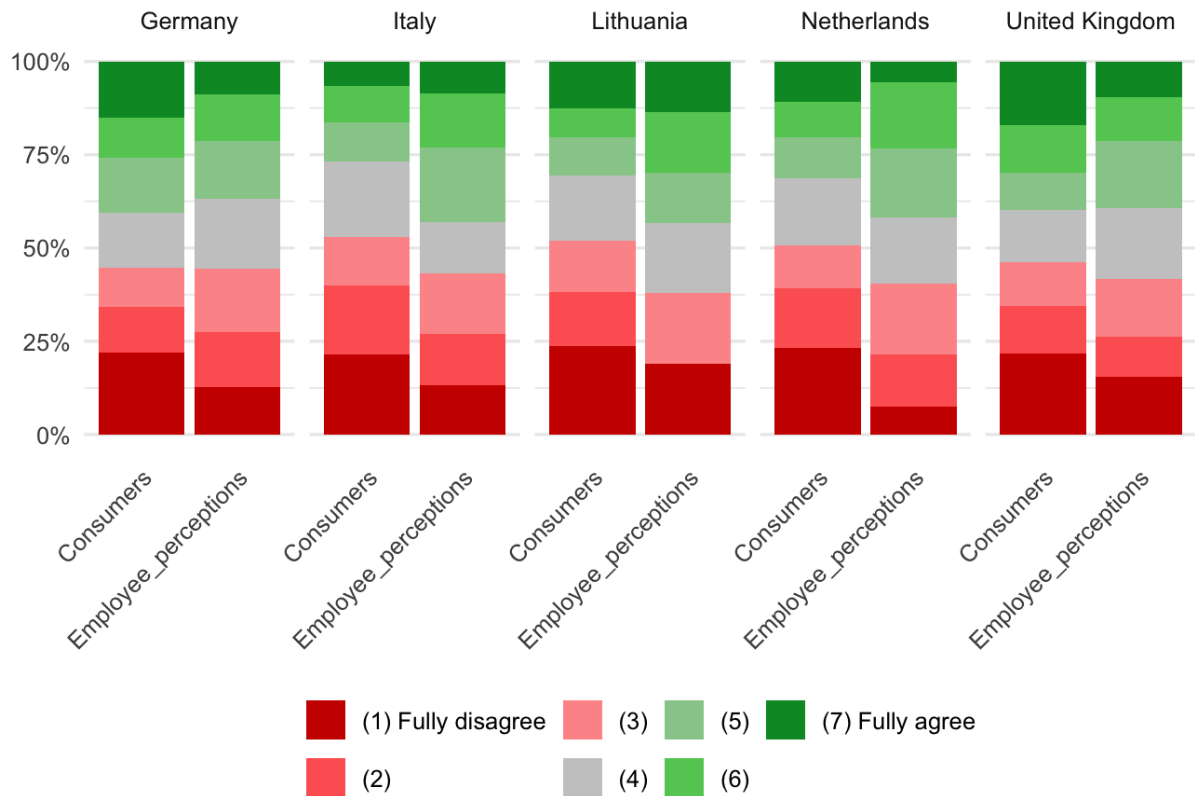




Figure 24: Distribution of self-efficacy – ratings by consumers and employees’ perceptions



Outcome Efficacy: Consumers’ beliefs about whether living without owning a car reduces environmental and social problems

Consumers could indicate their agreement to the statement “I think I can contribute to reducing environmental and social problems by not owning a car”. Employees could answer the item “People in [country base of employee’s company] think they can contribute to reducing environmental and social problems by not owning a car”.

Overall, consumers' average outcome efficacy was around the midpoint of the scale ($M = 3.66$, see Figure 25). 45% of consumers disagreed with the statement, 22% were neutral, and 33% agreed (see Figure 26). Outcome efficacy was highest in the UK and lowest in the Netherlands.

Employees rated consumers’ outcome efficacy slightly above the midpoint ($M = 4.15$) and therefore slightly higher than consumers themselves. Almost half of the employees agreed that consumers felt outcome efficacy (43%), while 35% disagreed, and 22% were neutral. The overestimation of consumers’ outcome efficacy was found in all countries, though with differing



strengths. Perceptions were most accurate in the United Kingdom and least accurate in the Netherlands and Italy (see Figure 25).

Figure 25. Average ratings of outcome efficacy by consumers and employees' perceptions

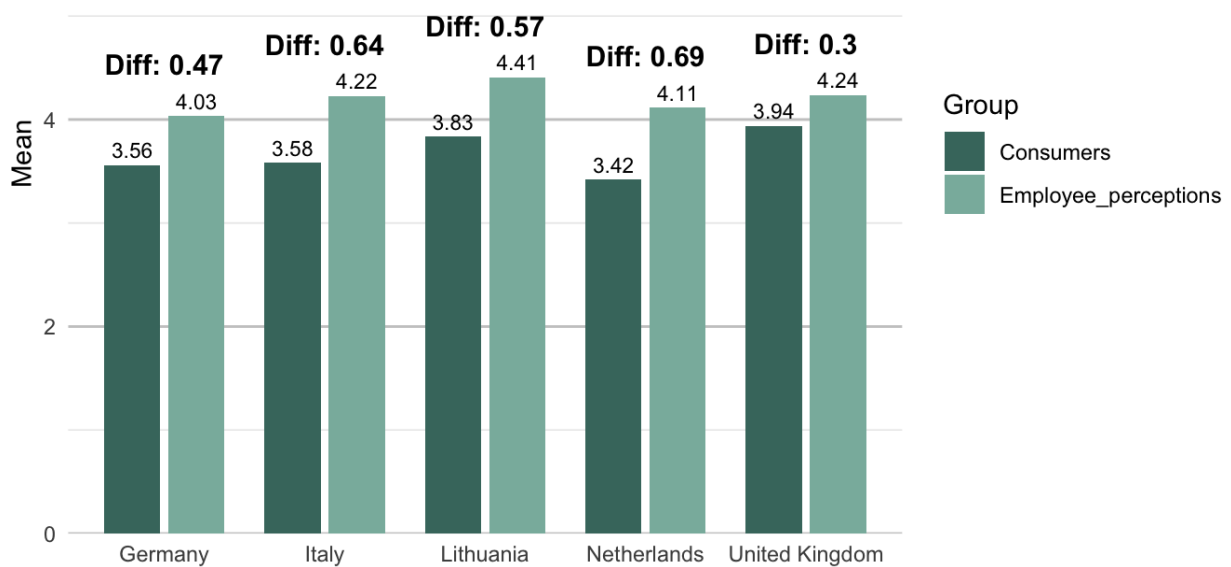
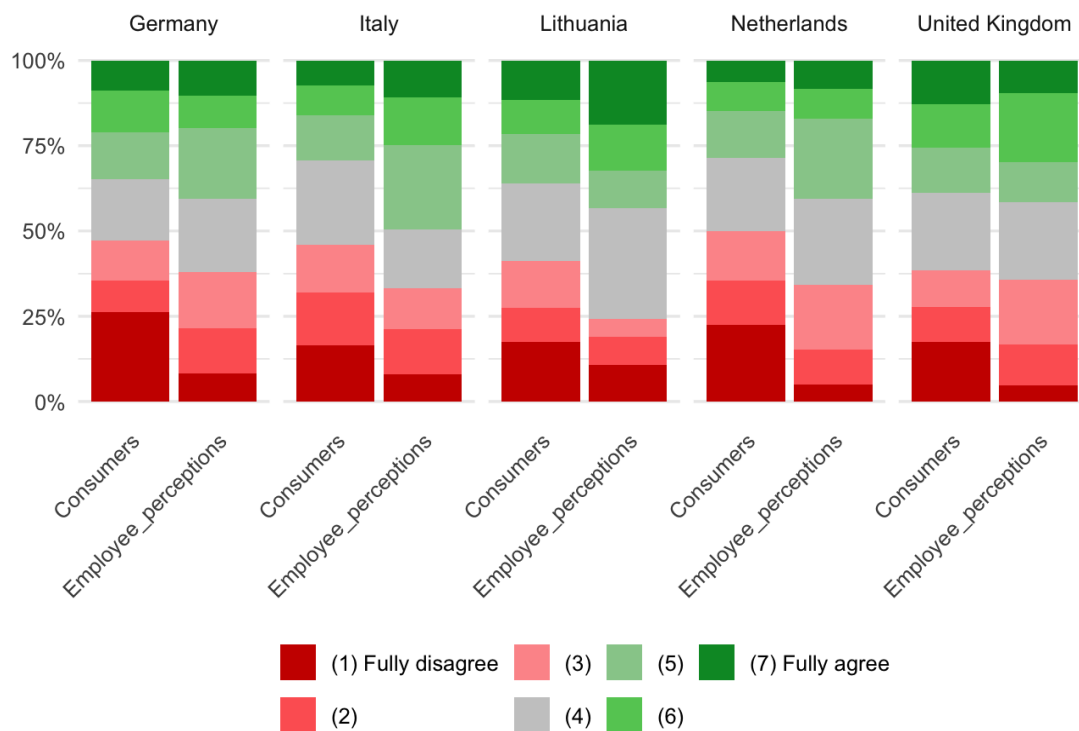


Figure 26. Distribution of outcome efficacy – ratings by consumers and employees' perceptions



Personal Norms: Consumers' feelings of responsibility not to own a car

Consumers could indicate their level of agreement with the statement: "I feel a personal responsibility to live my life without owning a car". Employees' perceptions of consumers' personal norms were assessed through the statement "People in [country base of employee's company] feel a personal responsibility to live their life without owning a car" (see Figure 12)

Overall, consumers did not feel a personal responsibility to live without a car ($M = 3.05$). Twice as many consumers disagreed to some extent with the statement (59%) compared to 21% who agreed, and 20% who were neutral (see Figure 28). Agreement was highest in Lithuania and lowest in the Netherlands, followed by Germany (see Figure 27).

Employees rated consumers' personal norms slightly higher than did consumers ($M = 3.79$), with similar numbers of employees agreeing (39%) and disagreeing (45%) with the statement. 16% were neutral. Dutch consumers' personal norms were overestimated the most, while ratings of consumers of the United Kingdom were closest to the self-ratings (see Figure 27).

Figure 27. Average ratings of personal norms by consumers and employees' perceptions

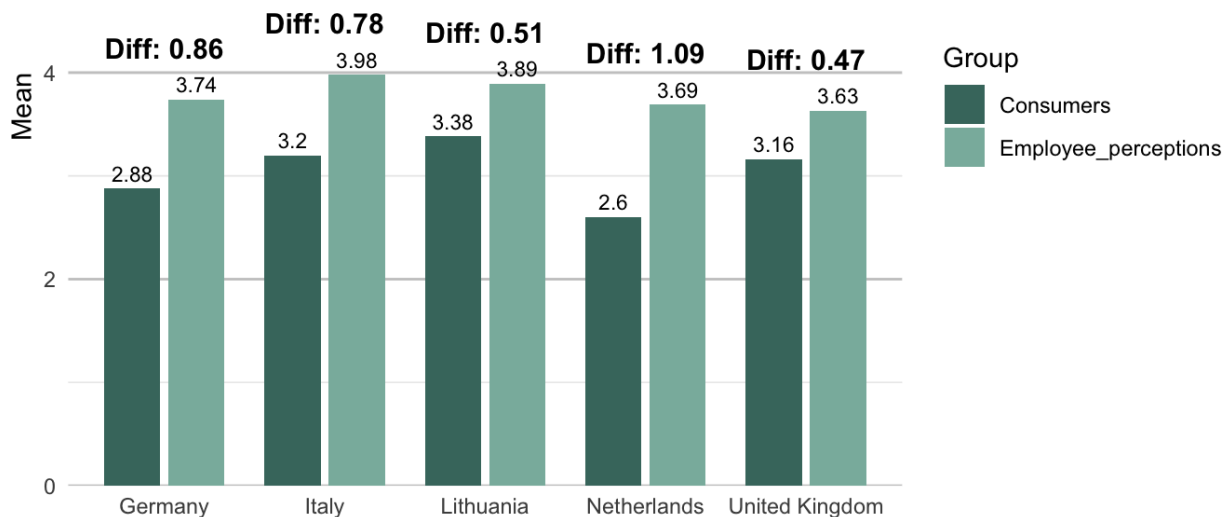
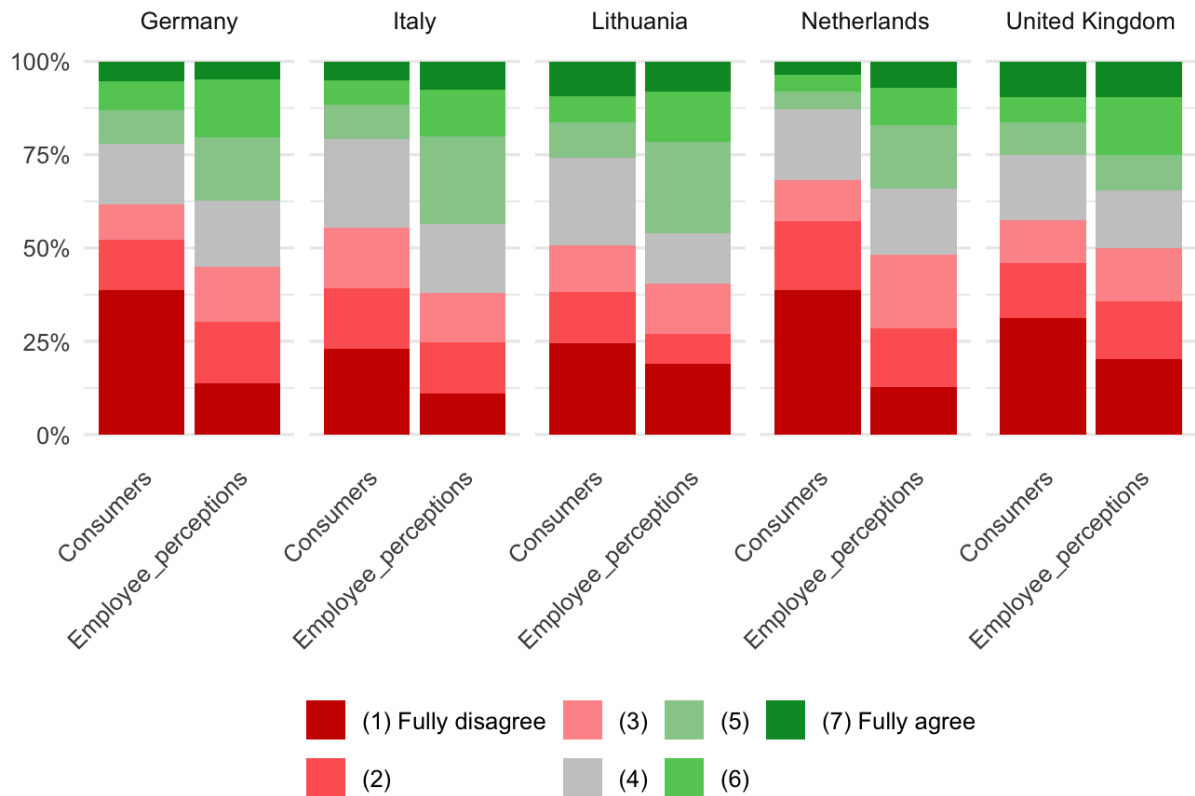


Figure 28. Distribution of personal norms – ratings by consumers and employees’ perceptions



R0 Refuse: Willingness to live without owning a car

Willingness to live without owning a car was chosen to represent consumers’ willingness to apply the R strategy *refuse* to their mobility behaviours.

Consumers, who currently own at least one car, were asked: “Would you get rid of your car if viable alternatives were available?”, which could be answered from (1) *no, very unlikely* to (7) *yes, very likely*. Employees were asked: “Would people in [country base of employee’s company] get rid of their car if viable alternatives were available?”, which was answered on the same scale.

Overall, consumers’ average willingness lay slightly above the midpoint of the scale ($M = 3.76$). Nearly half of the consumers currently owning a car (44%) were willing to get rid of their car if viable alternatives were available, while 37% found it unlikely, and 19% remained neutral (see Figure 30). Lithuanians were most willing to get rid of their car, while Dutch consumers were least willing (see Figure 29).



Employees rated consumers' willingness slightly above the midpoint, and therefore, also slightly higher than consumers themselves ($M = 4.32$). Employees overestimated consumers' willingness in all countries, with perceptions being most accurate for German consumers and least accurate for Dutch consumers (see Figure 29). Half of the employees (50%) found it unlikely that consumers were willing to get rid of their car. Almost one third found it likely to some extent (31%). 19% were neutral.

Figure 29. Average ratings of willingness to live car-less by consumers and employees' perceptions

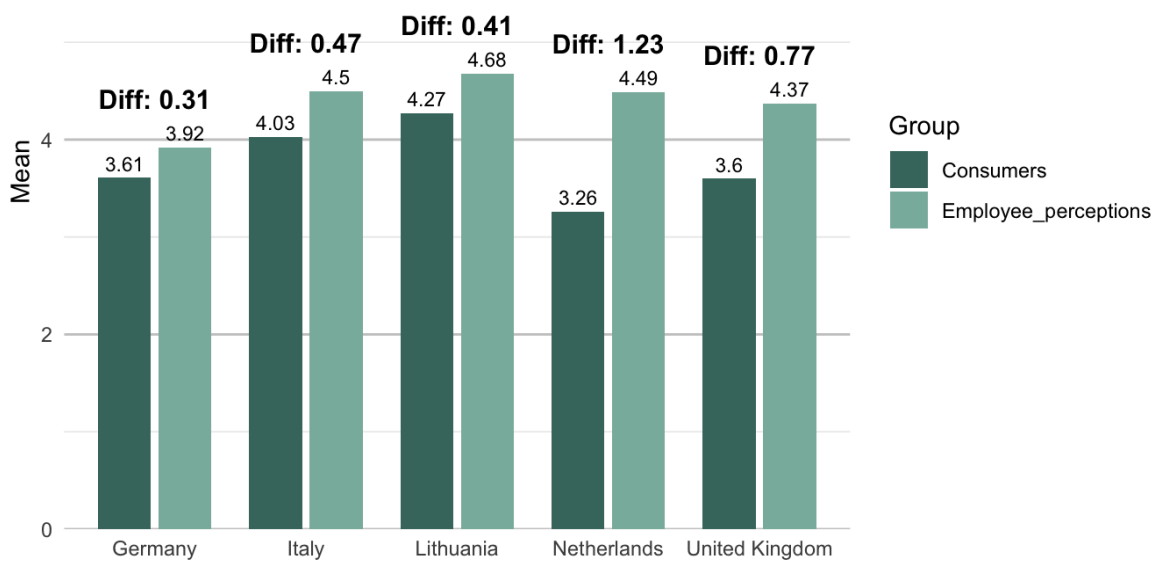
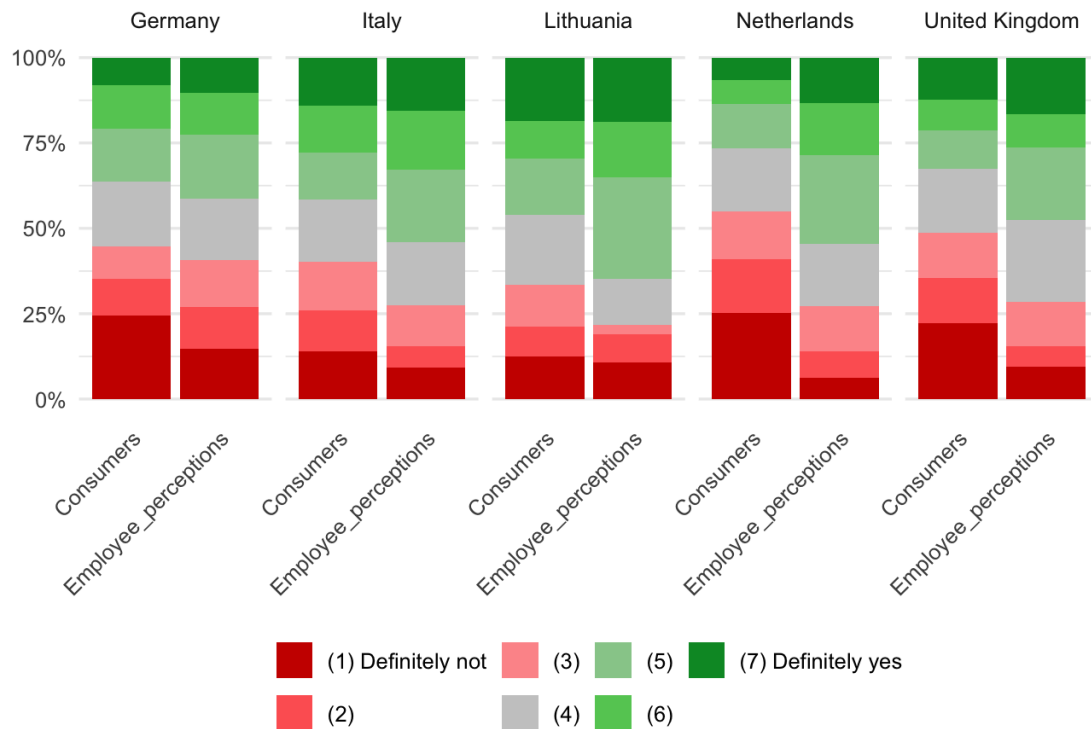


Figure 30. Distribution of willingness to live car-less – ratings by consumers and employees' perceptions



R1 Rethink: Willingness to use car sharing instead of owning a car

Willingness to use car sharing instead of owning a car represents the R strategy *rethink*.

Consumers, who currently own at least one car, were asked: “Would you get rid of your car if adequate car sharing were available?” (1) *no, very unlikely* to (7) *yes, very likely*. Employees were asked: “Would people in [country base of employee’s company] get rid of their car if adequate car sharing were available?” on the same scale.

Overall, consumers were somewhat unwilling to get rid of their car if adequate car sharing was available ($M = 2.78$). People in Lithuania were most willing, while people in the UK were the least willing (see Figure 31). The majority (66%) of consumers found it unlikely that they would get rid of their car if car-sharing were available, while 15% were neutral, and 19% indicated that they would likely get rid of their car (see Figure 32).

Employees strongly overestimated consumers' willingness to use car sharing instead of owning a car ($M = 4.08$), with almost half thinking consumers would be likely to get rid of their car if adequate car sharing were available (44%). 19% were neutral, and around one third did not think this would be likely (38%). Willingness was overestimated in all countries, with perceptions being most accurate in Lithuania and least in the Netherlands.

Figure 31. Average ratings of willingness to use car sharing by consumers and employees' perceptions

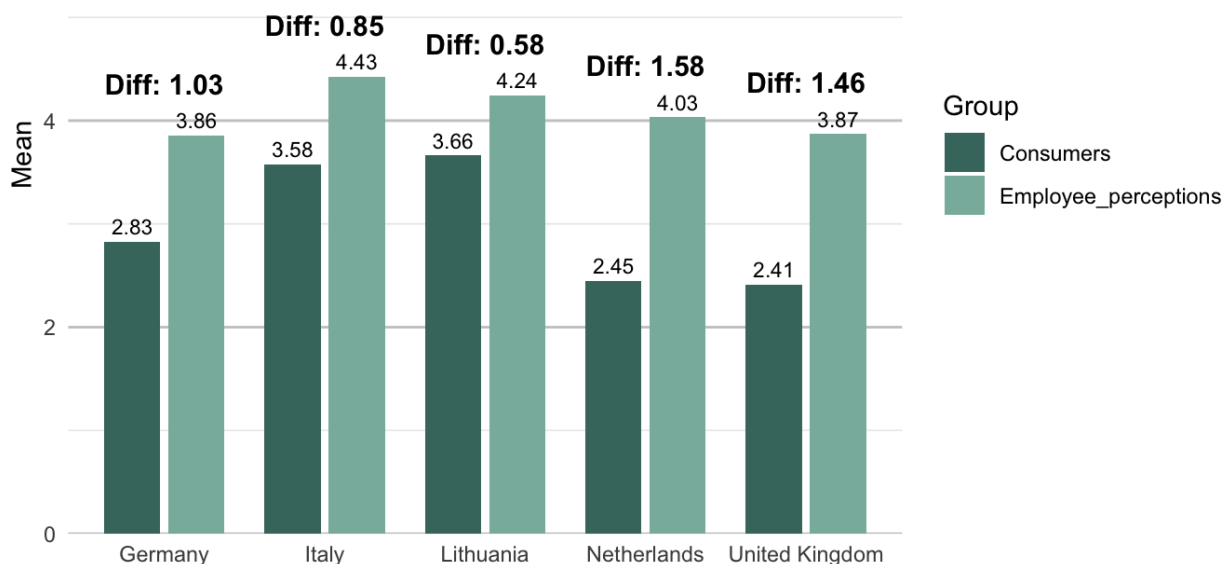
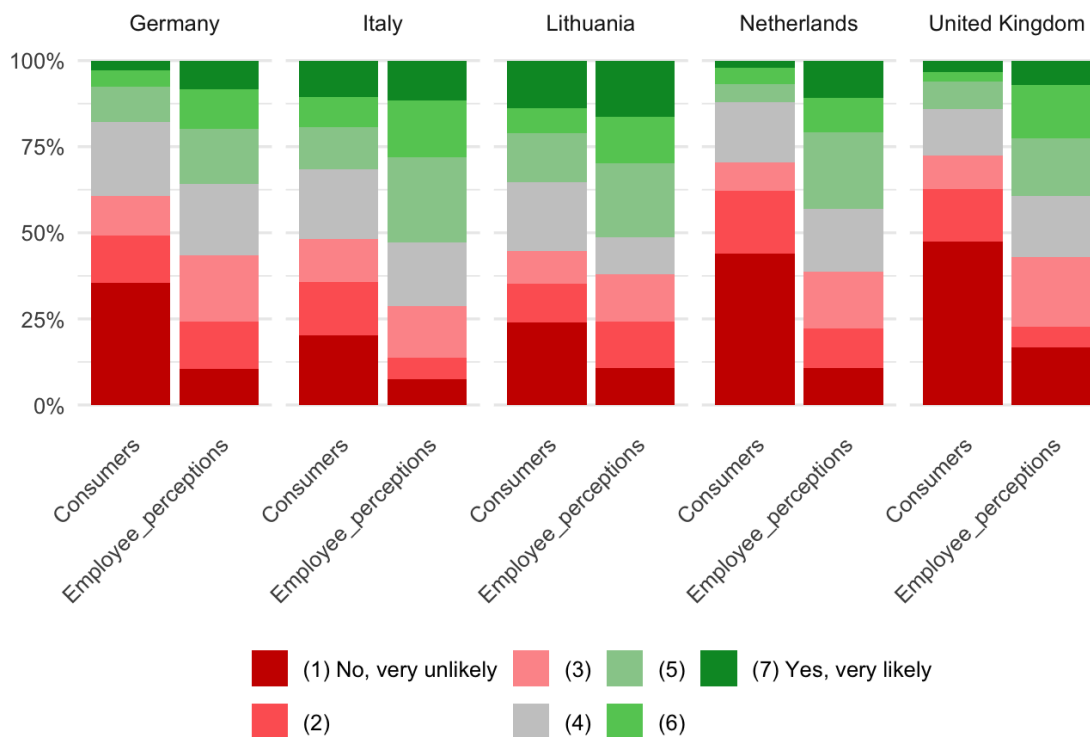


Figure 32. Distribution of willingness to use car sharing – ratings by consumers and employees' perceptions

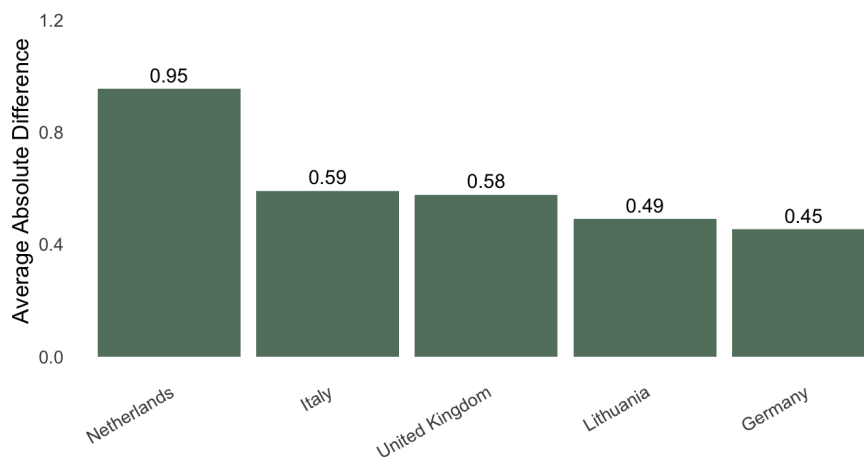




Conclusions for mobility-related perceptions of consumers' beliefs and willingness to engage in circular behaviours

Overall, comparing consumers' beliefs and willingness regarding car ownership and car sharing and the perceptions of employees revealed an overestimation for all examined variables. Overestimations were found for almost all countries and variables, with differences in strength. Perceptions of German consumers were most accurate, followed by Lithuania (see Figure 33). Perceptions of Dutch consumers were least accurate, followed by perceptions of Italian consumers and consumers in the United Kingdom.

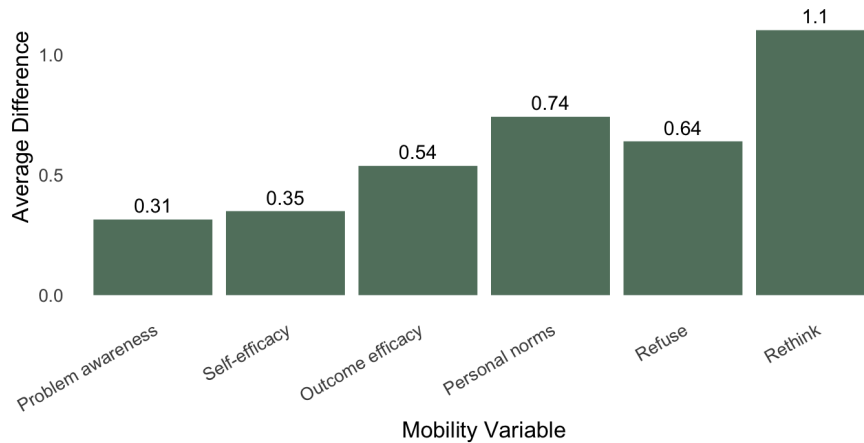
Figure 33. Differences in employee perceptions and consumers' actual beliefs and willingness per country



Employees most accurately perceived consumers' problem awareness and self-efficacy (see Figure 34). Consumers' willingness to use car sharing instead of owning a car was overestimated the most by employees, followed by consumers' personal norms.



Figure 34. Differences in employee perceptions and consumers' actual beliefs and willingness per mobility-related variable



Beliefs and actions related to housing

In this section, we examine consumers' beliefs and willingness to behave more circularly regarding their living situation. Specifically, we focus on downsizing and sharing living spaces, such as the kitchen, bathroom, hallway, basement, or garden. We asked a) consumers about their beliefs and willingness, and b) employees of companies within the building and/or housing sector about their perception of consumers' beliefs and willingness. We then compared employees' and consumers' responses to highlight (mis)alignments.

A total of six items were utilized to assess consumers' beliefs about their living situation: (1) the extent to which they are aware that living in a large home contributes to environmental and social problems (*problem awareness*), (2) feel capable to live in a small or shared home (*self-efficacy*), (3) believe that living in a small or shared home would have a meaningful impact (*outcome efficacy*), (4) feel personally responsible to live in a small or shared home (*personal norms*), and are willing to (5) downsize their living space or (6) share living spaces (willingness to engage in circular behaviour). Responses on all six items were given on a 7-point Likert scale, ranging from (1) *fully disagree/not at all willing* to (7) *fully agree/very willing*². Employees were shown the same items, but this time were asked to indicate to what extent consumers would agree with the statements.

Problem Awareness: Consumers' awareness of the environmental and social impacts of large homes

Consumers could indicate their level of agreement with the statement "Living in a large home causes important environmental and social problems." and employees with the statement "People in [country base of employee's company] think that living in a large home causes

² Please note that the scale points are flipped around in Grealis & Rau's (2025) report with lower scores presenting higher agreement/willingness.



important environmental and social problems.”.

Overall, consumers were not very aware of environmental and social problems arising from living in a large home ($M = 3.16$). Problem awareness was highest in the UK and Germany and lowest in the Netherlands (see Figure 35). More than half of the consumers disagreed with the statement (56%), only 22% agreed, and 22% were neutral (see Figure 36).

Employees overestimated consumers’ problem awareness by around one scale point ($M = 4.08$). Lithuanian consumers’ problem awareness was perceived most accurately, while Dutch consumers’ problem awareness was overestimated the most by employees. Almost half of the employees agreed that consumers were aware (44%), 20% were neutral, and 36% disagreed. Therefore, while around half of employees agreed, half of consumers disagreed to some extent. A similar number was neutral.

Figure 35. Average ratings of problem awareness by consumers and employees’ perceptions

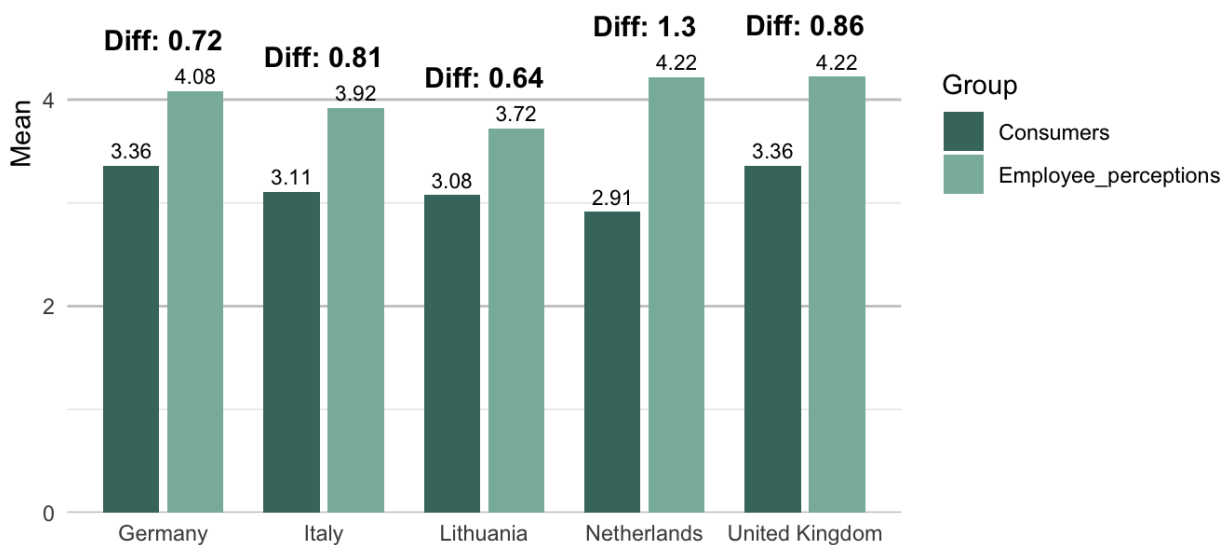
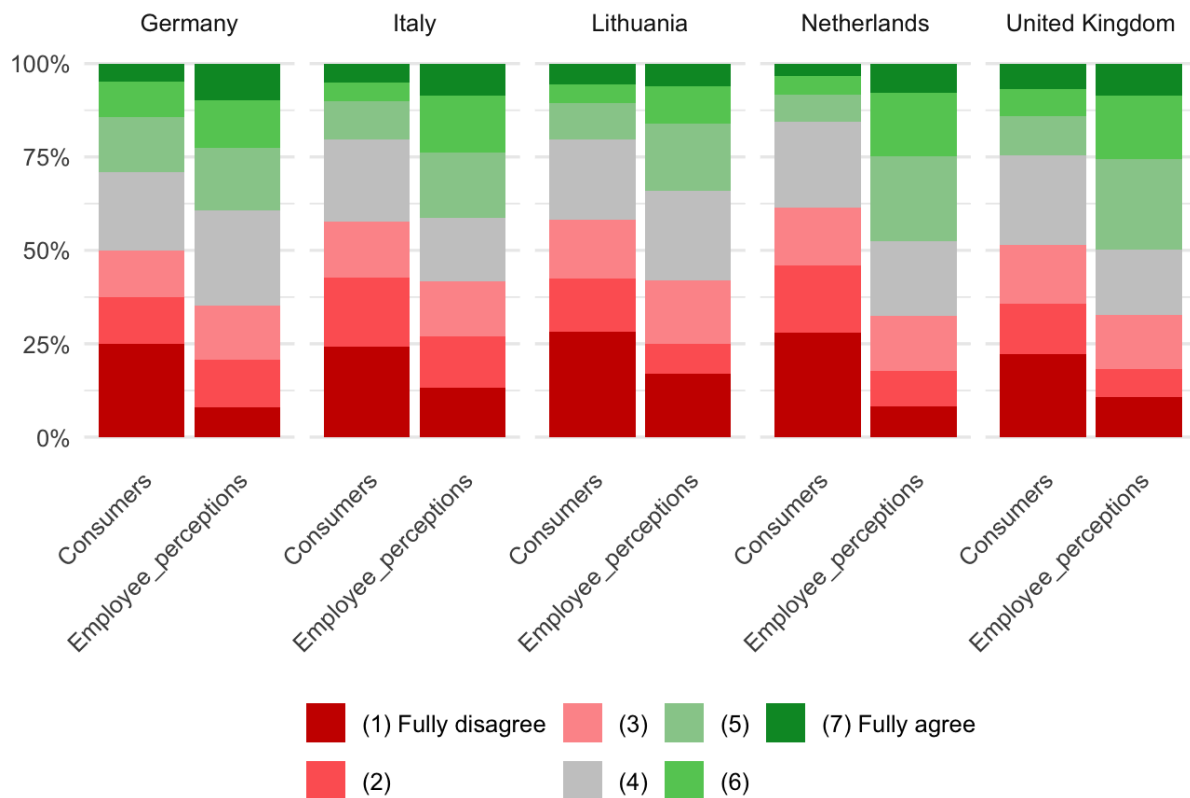


Figure 36. Distribution of problem awareness – ratings by consumers and employees' perceptions



Self-efficacy: Consumers' belief about the ability to live in a small home or share living spaces

Consumers indicated their level of agreement with the statement "I feel capable of living in a small home or sharing living spaces," and employees with the statement "People in [country of consumer base] feel capable of living in a small home or sharing living spaces."

Consumers, on average, felt somewhat unable to live in a smaller home or share living spaces ($M = 3.37$). Consumers in the UK felt most self-efficacious, while Lithuanians felt least self-efficacious (see Figure 37). When looking at the current square meters, this matches Lithuanians already having the least amount of living space. Overall, more than half of the consumers disagreed with the statement (52%), 20% were neutral, and around one-third agreed (28%, see Figure 38).

Employees overestimated consumers' self-efficacy by one scale point ($M = 4.39$), with half of the employees agreeing (51%; versus 28% of consumers), while 21% were neutral, and 27% disagreed (versus 52% of consumers). Therefore, while over half of consumers disagreed, the same proportion of employees agreed. Overestimation of self-efficacy was lowest in Germany and the United Kingdom and highest in Lithuania (see Figure 37).

Figure 37. Average ratings of self-efficacy by consumers and employees' perceptions

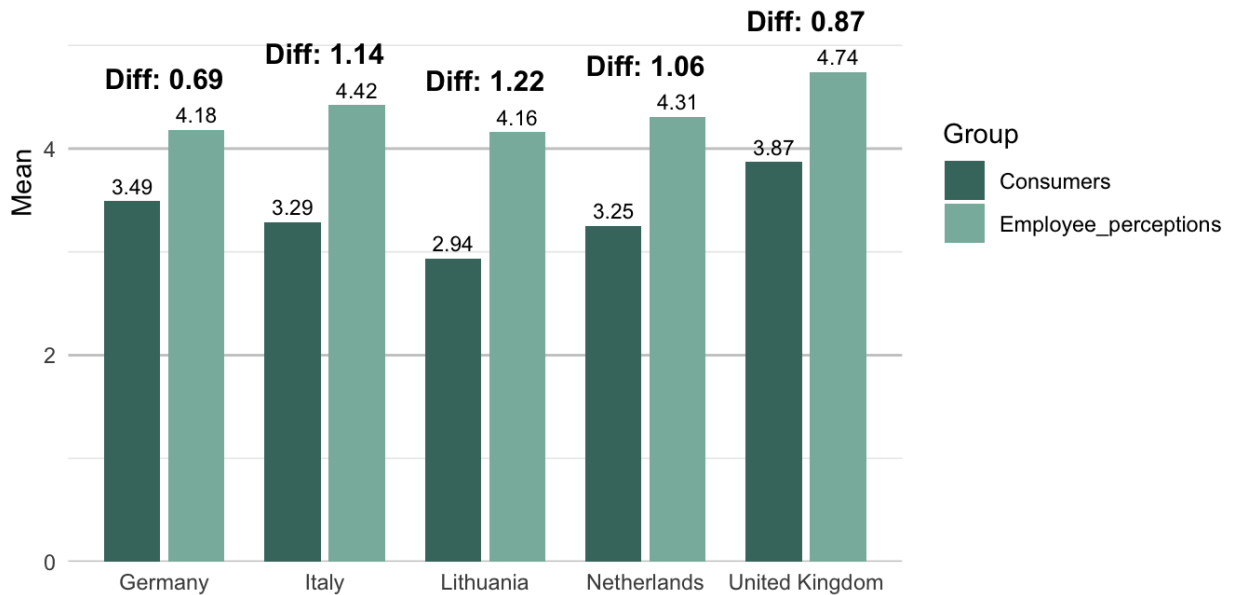
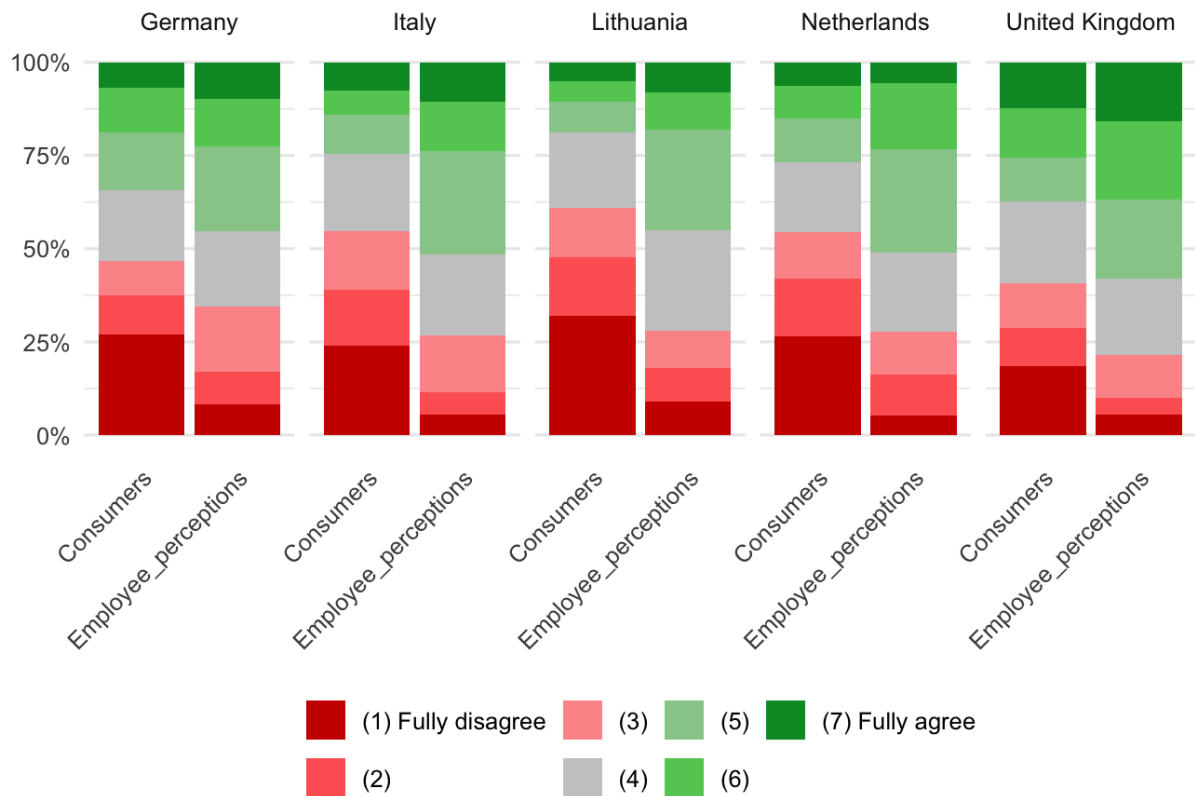


Figure 38. Distribution of self-efficacy – ratings by consumers and employees' perceptions





Outcome efficacy: Consumers' beliefs about a small home or shared living spaces reducing environmental and social problems

Consumers were asked to what extent they agree with the statement “I think I can contribute to reducing environmental and social problems by living in a small home or sharing living spaces.”. employees answered the item “People in [country of consumer base] think they can contribute to reducing environmental and social problems by living in a small home or sharing living spaces”.

Overall, consumers did not feel that they could contribute to reducing environmental and social problems by living in a smaller home or sharing living spaces ($M = 3.03$). Consumers in the UK felt the most outcome efficacy, Dutch consumers the least (see Figure 39). Only 21% of consumers agreed to some extent that they can contribute to reducing environmental and social problems by living in a small home or sharing living spaces, while 58% disagreed, leaving 21% of consumers with a neutral view (see Figure 40).

Employees strongly overestimated consumers' outcome efficacy ($M = 4.27$), with almost half agreeing (47%) that consumers think that their actions can contribute, 22% being neutral, and 31% disagreeing. Consumers' outcome efficacy was overestimated in all countries, with perceptions being most accurate for the United Kingdom's consumers and least for the Dutch and Italian consumers (see Figure 39).

Figure 39. Average ratings of outcome efficacy by consumers and employees' perceptions

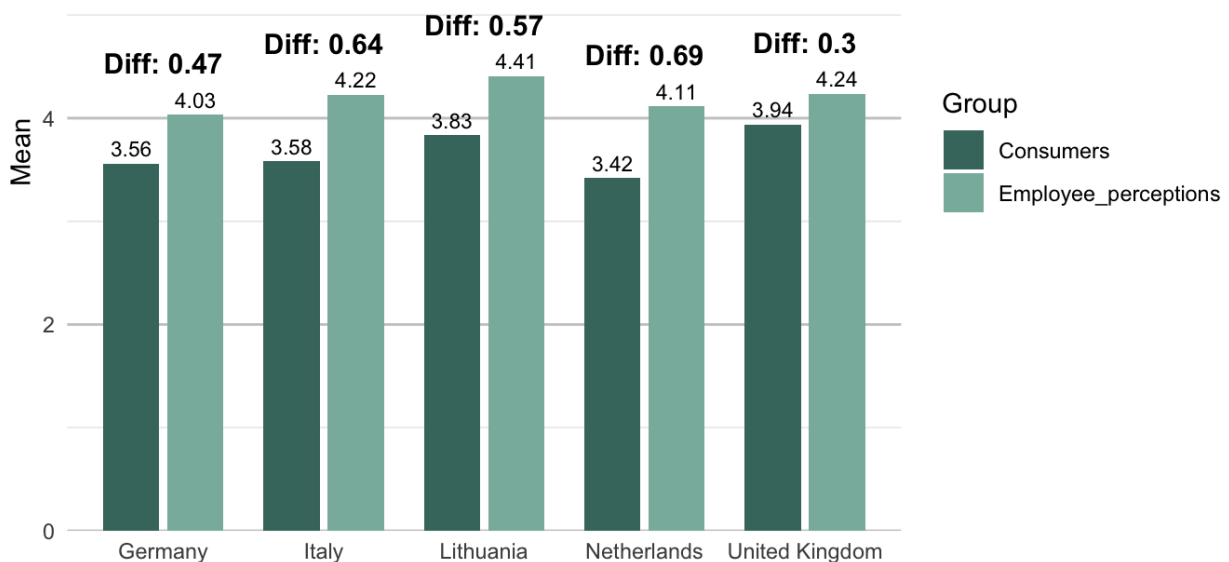
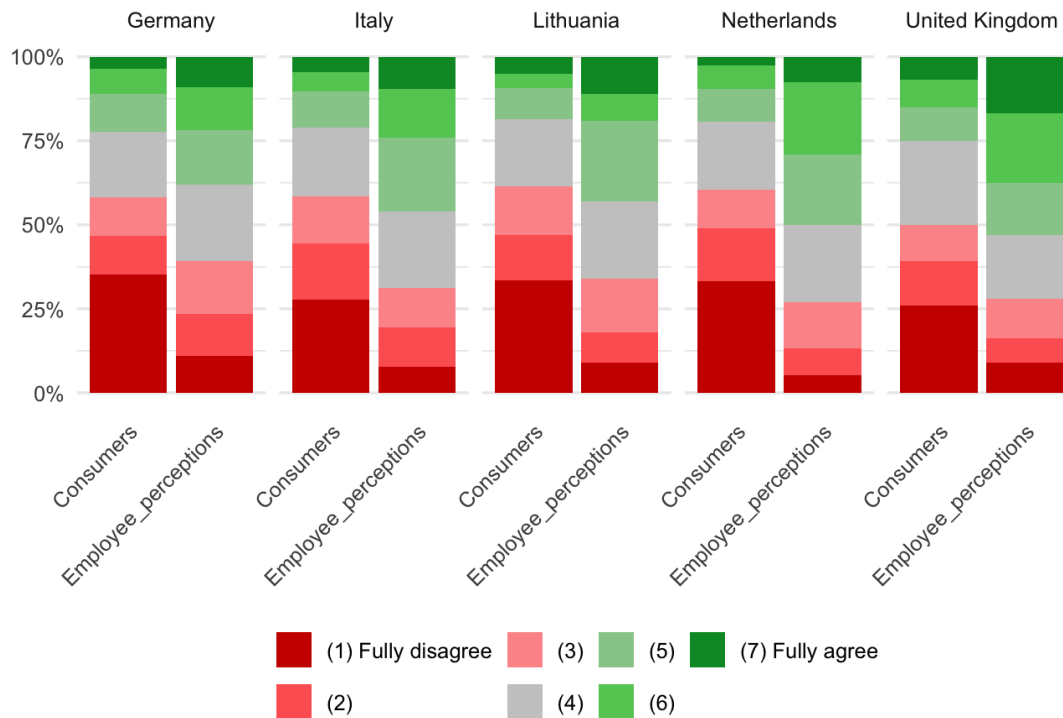


Figure 40. Distribution of outcome efficacy – ratings by consumers and employees' perceptions



Personal Norms: Consumers' feelings of responsibility about living in a small home or sharing living spaces

Consumers could indicate their level of agreement with the statement: "I feel a personal responsibility to live my life in a small home or share living spaces." Employees could indicate their agreement with the statement: "People in [country of consumer base] feel a personal responsibility to live in a small home or share living spaces."

Overall, consumers did not feel a personal responsibility to live in a small home or share living spaces ($M = 2.74$). Personal norms were strongest in the UK, though still below the midpoint, and lowest in the Netherlands (see Figure 41). The majority of consumers disagreed with the statement (65%), while an equal number of consumers agreed (17%), and were neutral (18%, see Figure 42).

Employees overestimated consumers' personal norms to a large extent ($M = 4.09$). Overestimation was found for all countries, though ratings of Lithuanian consumers were the most accurate, and perceptions of the Dutch consumers were the least accurate (see Figure 41). Almost half of the employees agreed with the statement (45% compared to 17% of consumers), while 19% were neutral, and a third disagreed (36% versus 65% of consumers).

Figure 41. Average ratings of personal norms by consumers and employees' perceptions

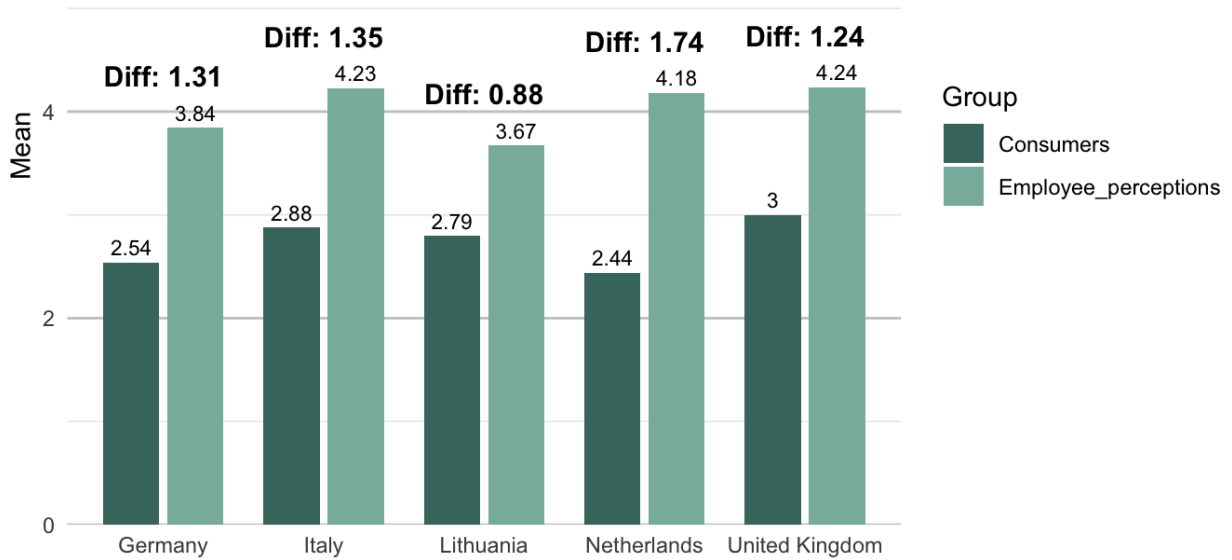
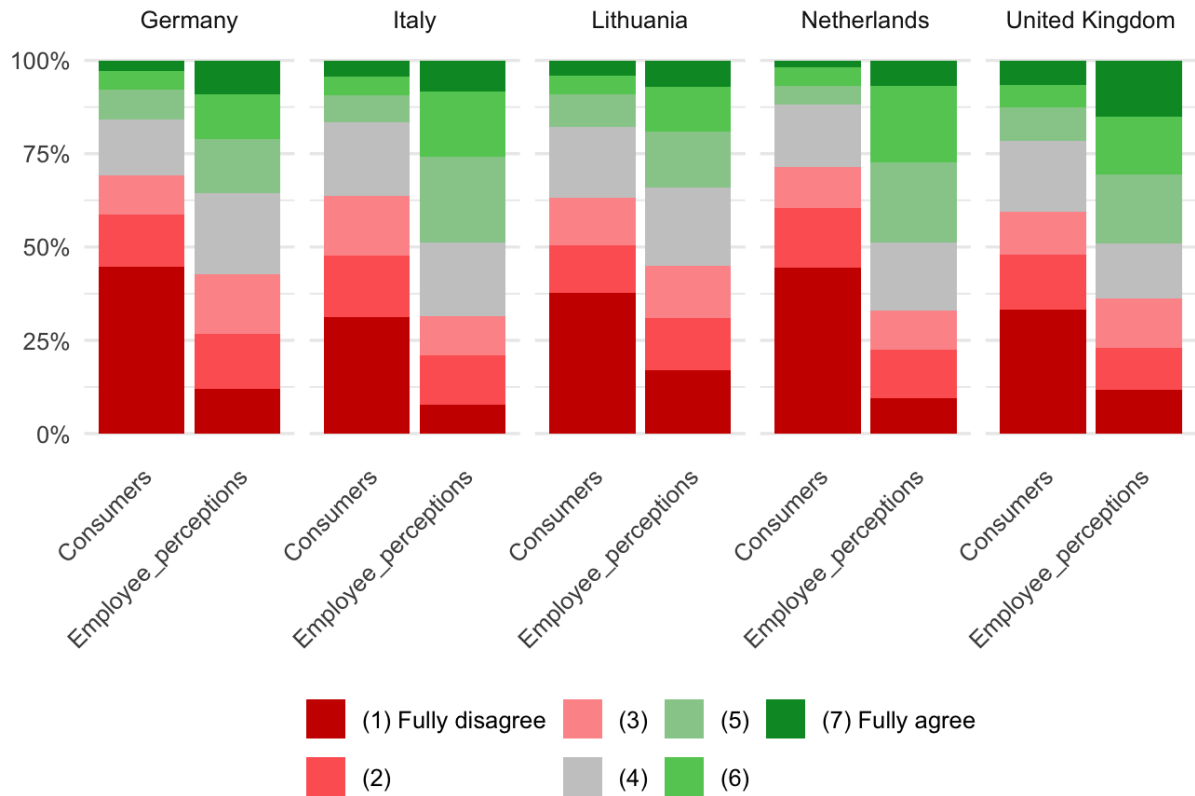


Figure 42. Distribution of personal norms – ratings by consumers and employees' perceptions





R2 Reduce: Willingness to downsize

Willingness to downsize reflects the extent to which people are willing to live in a smaller home than they are currently living in. This reflects the R strategy *Reduce*.

Consumers were asked: “To what extent would you be willing to live in a smaller home if one were readily available in your area?”, employees: “To what extent would people in [country of consumer base] be willing to live in a smaller home if one were readily available in their area?”. Answers could be given on a 7-point scale from (1) *not at all willing* to (7) *very willing*.

Consumers were not willing to live in a smaller home, even if it was readily available ($M = 3.24$). Notably, consumers from Lithuania had the lowest willingness to downsize, which aligns with the fact that they have the smallest living spaces, both in absolute numbers and in relation to household size, compared to the other countries. Among the remaining countries, the differences in willingness to downsize were minimal (see Figure 43). Overall, most consumers (56%) were not willing to downsize, while 28% indicated that they were willing, and 16% were neutral (see Figure 44).

Employees overestimated consumers’ willingness to downsize ($M = 4.34$) compared to consumers’ ratings. Half of the employees perceive consumers to be willing to some extent (51% versus 28% of consumers), while a third disagreed (32% versus 56% of consumers). 17% were neutral. Willingness to downsize was overestimated for all countries, though least strongly for Germany and Italy, and most strongly for Lithuania, followed by the Netherlands.

Figure 43. Average ratings of willingness to downsize by consumers and employees’ perceptions

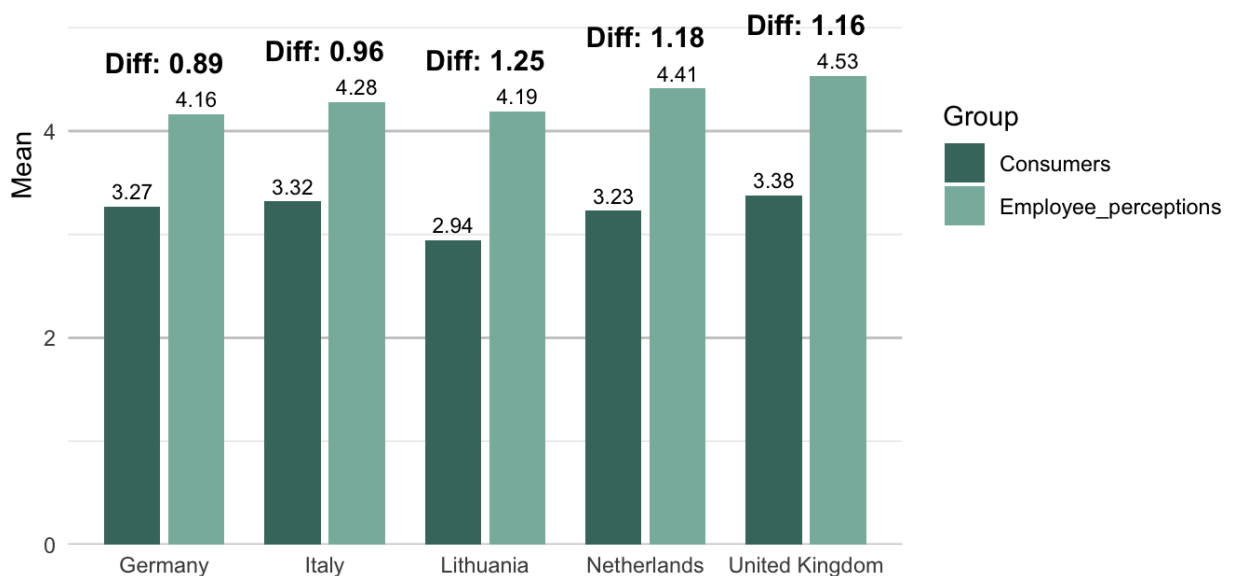
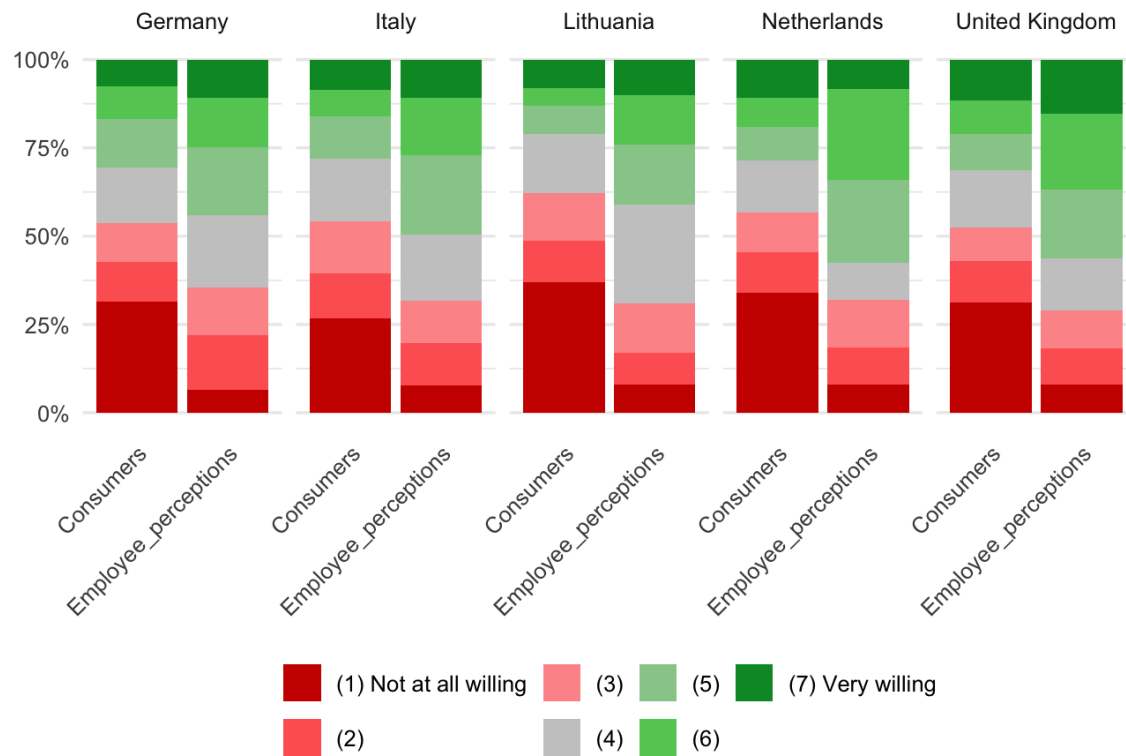




Figure 44. Distribution of willingness to downsize – ratings by consumers and employees' perceptions



R1 Rethink: Willingness to share living spaces

Willingness to share living spaces relates to different spaces of a home, such as the kitchen, bathroom, or garden, and people's willingness to share each of these rooms or spaces. In the studies presented here, this relates to how willing consumers are to permanently share these living spaces with a non-family member.

To assess how willing consumers are to share living spaces, they could answer the following question: "Where applicable, would you be willing to permanently share the following spaces with a non-family member (tenant, housemate, neighbour, or other)?" with answer options ranging from (1) *not at all willing* to (7) *very willing*. They were asked about the kitchen, bathroom, basement, garden, utility room, and entrance/hallway separately. Employees could answer the question: "Would people in [country of consumer base] be willing to permanently share the following spaces with a non-family member (tenant, housemate, neighbour, or other)?" on the same scale and for each space separately.

Overall, consumers are not willing to permanently share any living spaces with non-family members ($M = 2.49$). Living spaces that consumers are most willing to share are their garden ($M = 3.07$), followed by the basement ($M = 2.79$), utility room ($M = 2.68$), and entrance or hallway



($M = 2.77$). Consumers were least willing to share their bathroom ($M = 1.89$) and kitchen ($M = 2.01$). The overall willingness to share living spaces does not differ much between countries (see Figure 45). 84% of consumers are to some extent unwilling to share spaces, while only 9% are willing to some extent. 7% are neutral.

Employees overestimated consumers' willingness to share spaces overall ($M = 3.78$). Similar to consumers' ratings, employees perceived consumers to be most willing to share the entrance hall ($M = 4.16$) and garden ($M = 4.14$), and least willing to share the kitchen ($M = 3.44$) and bathroom ($M = 3.10$). Overestimation was found in all countries, though to different extents (see Figures 47, 49, 51 showing the willingness to share the kitchen, bathroom, and garden as examples). One third of employees think that consumers are willing to share spaces to some extent (34% versus 9% of consumers), 40% do not think so, and 26% are neutral.

Figure 45. Average ratings of willingness to share living spaces by consumers and employees' perceptions

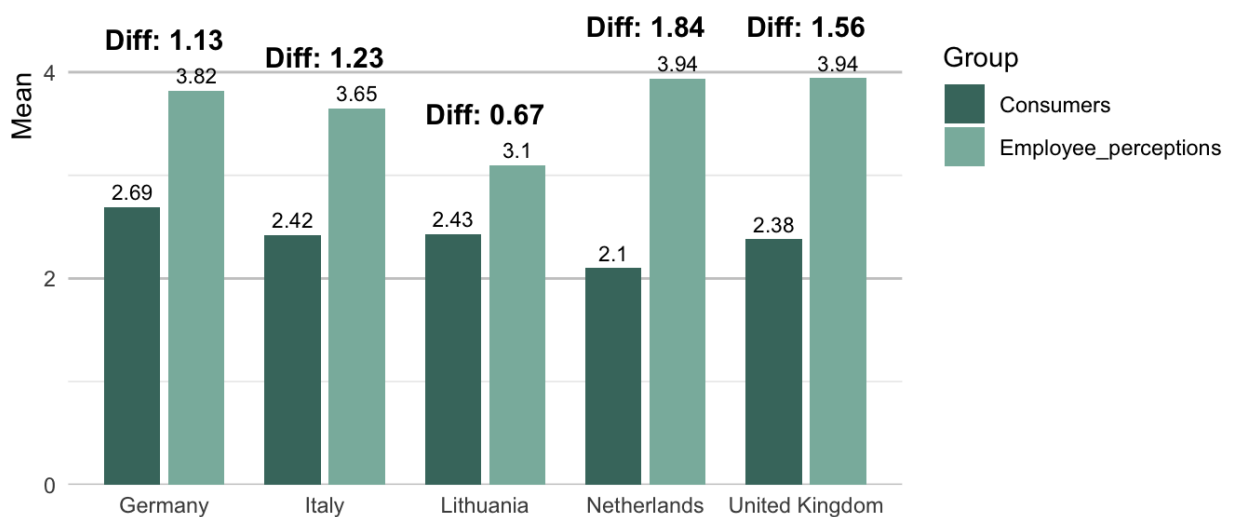




Figure 46. Distribution of overall willingness to share living spaces – ratings by consumers and employees' perceptions

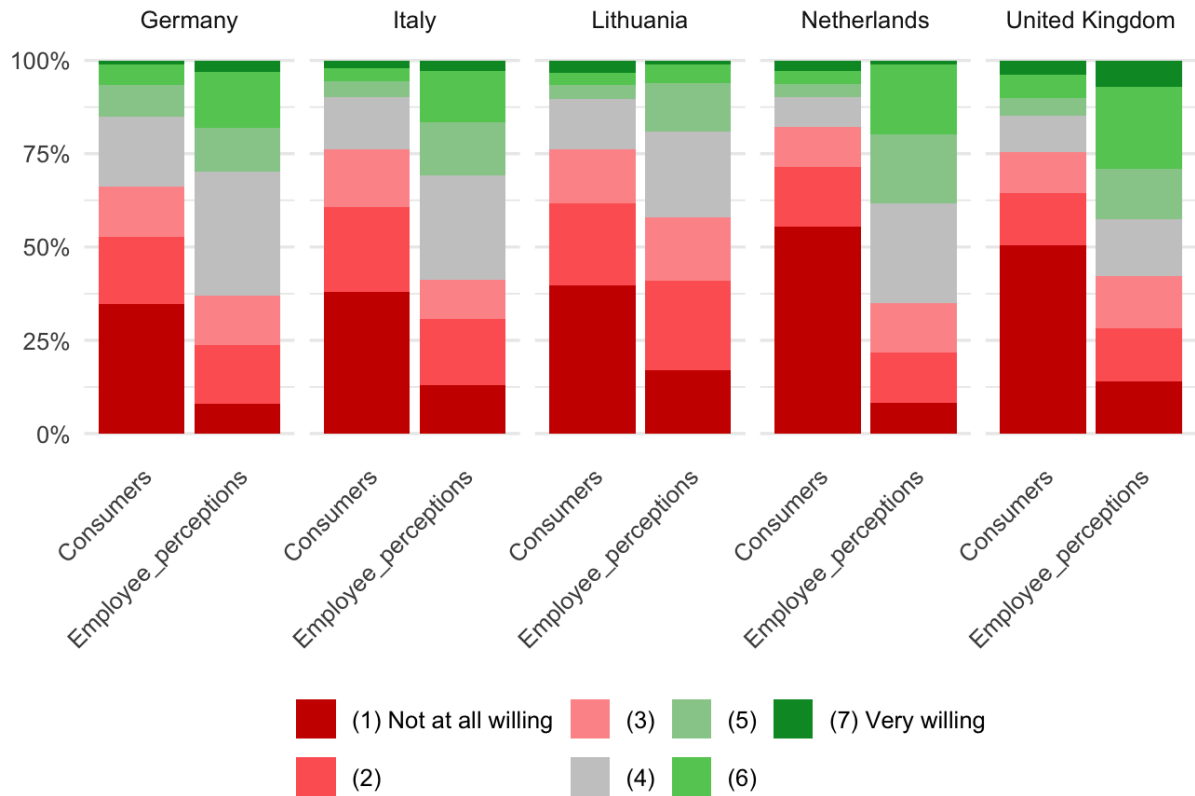


Figure 47. Average ratings of willingness to share the kitchen by consumers and employees' perceptions

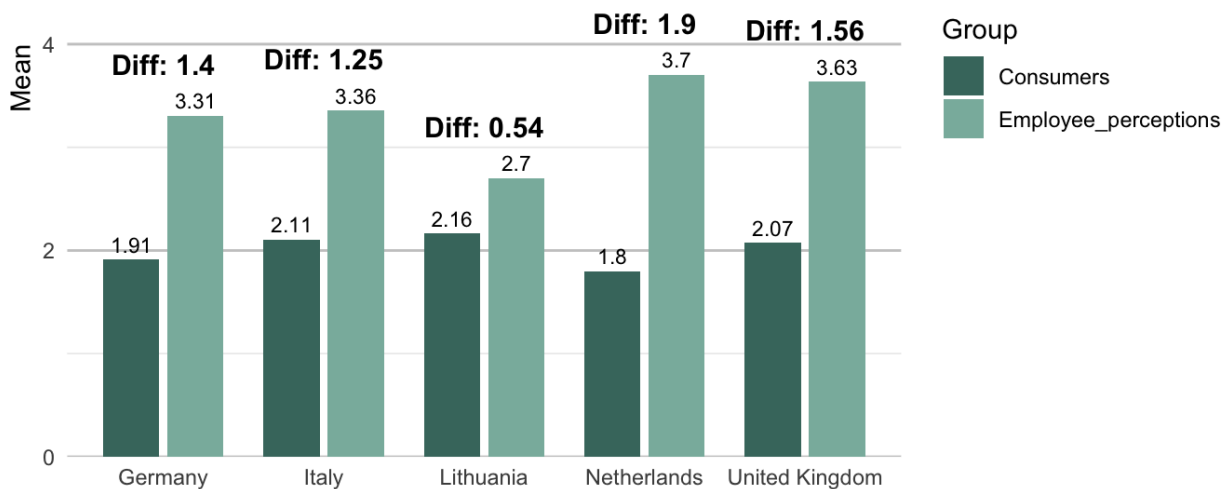


Figure 48. Distribution of willingness to share the kitchen – ratings by consumers and employees' perceptions

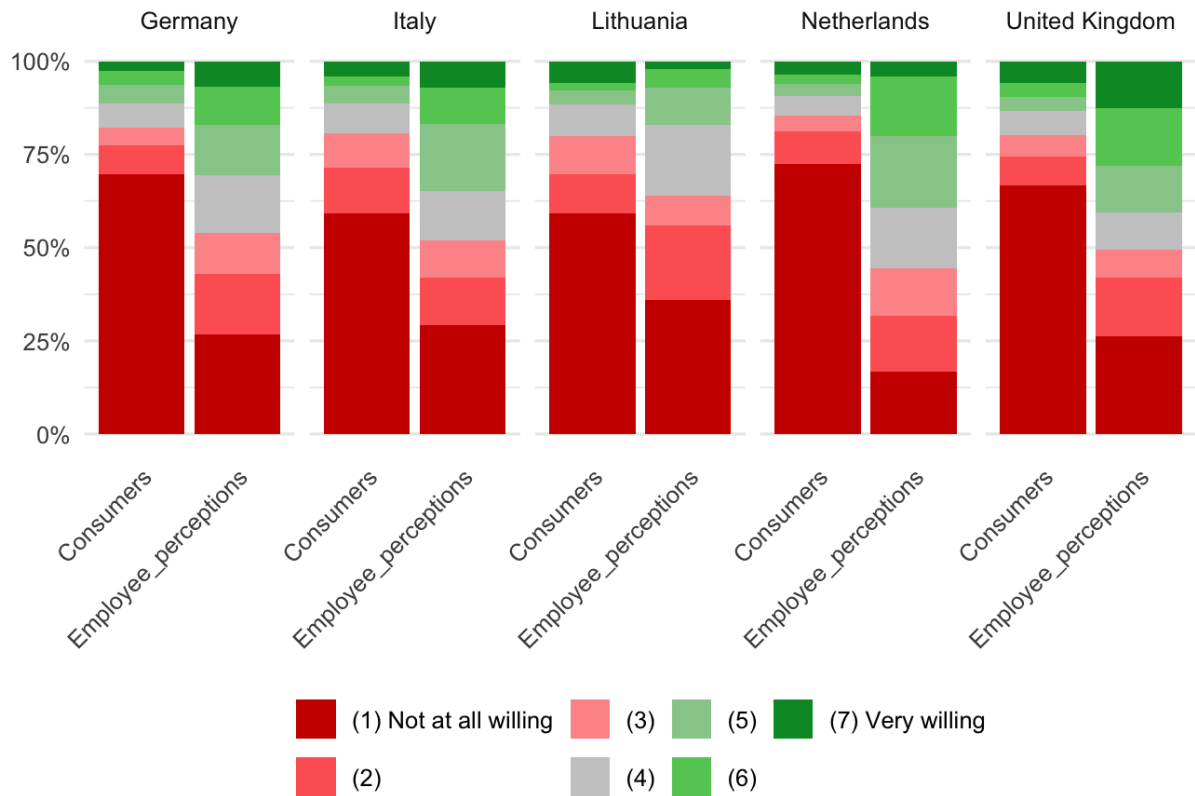


Figure 49. Average ratings of willingness to share the bathroom by consumers and employees' perceptions

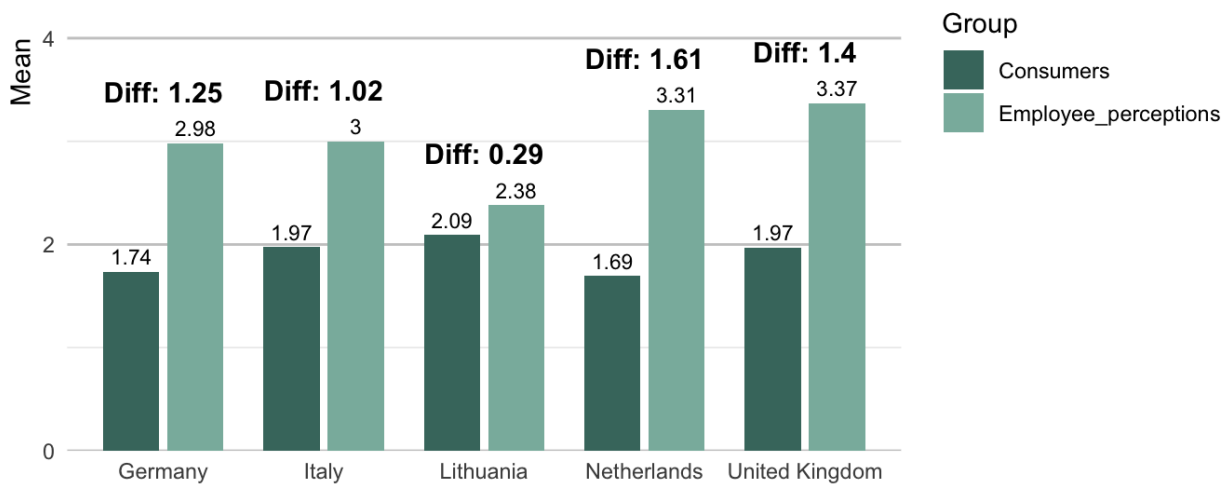


Figure 50. Distribution of willingness to share the bathroom – ratings by consumers and employees' perceptions

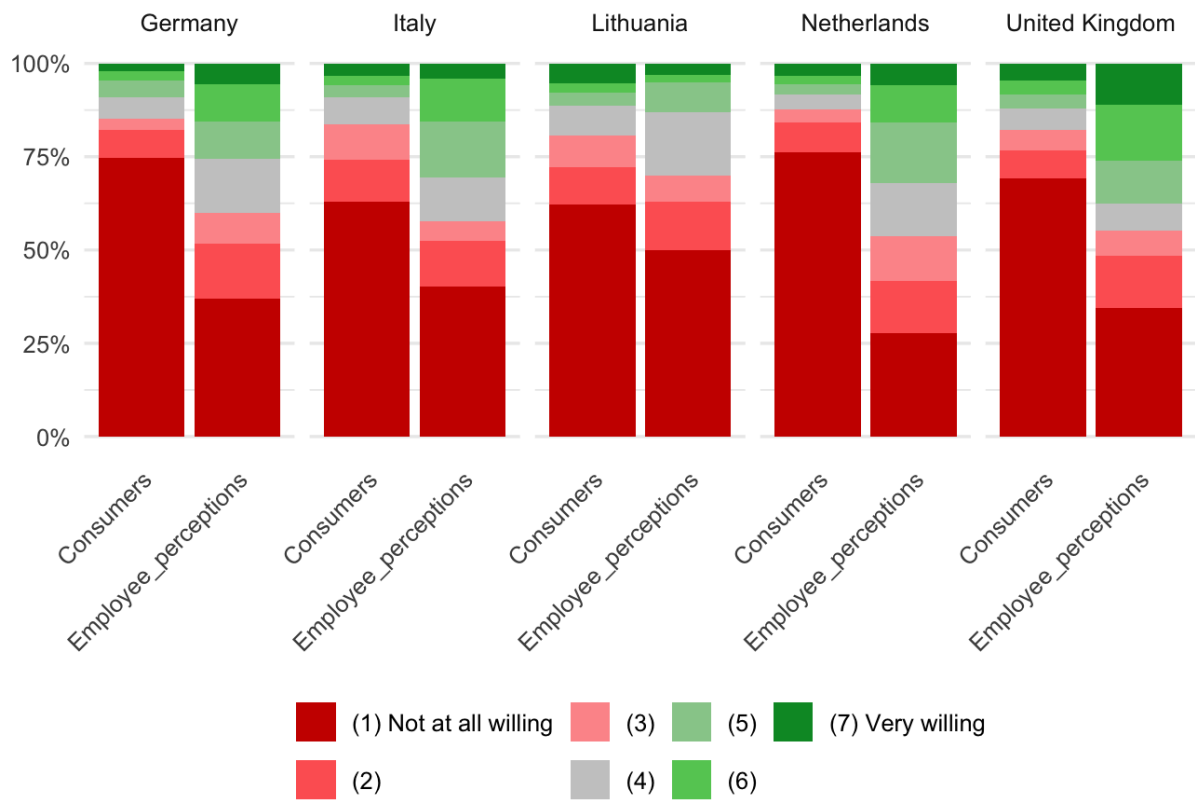




Figure 51. Average ratings of willingness to share the garden by consumers and employees' perceptions

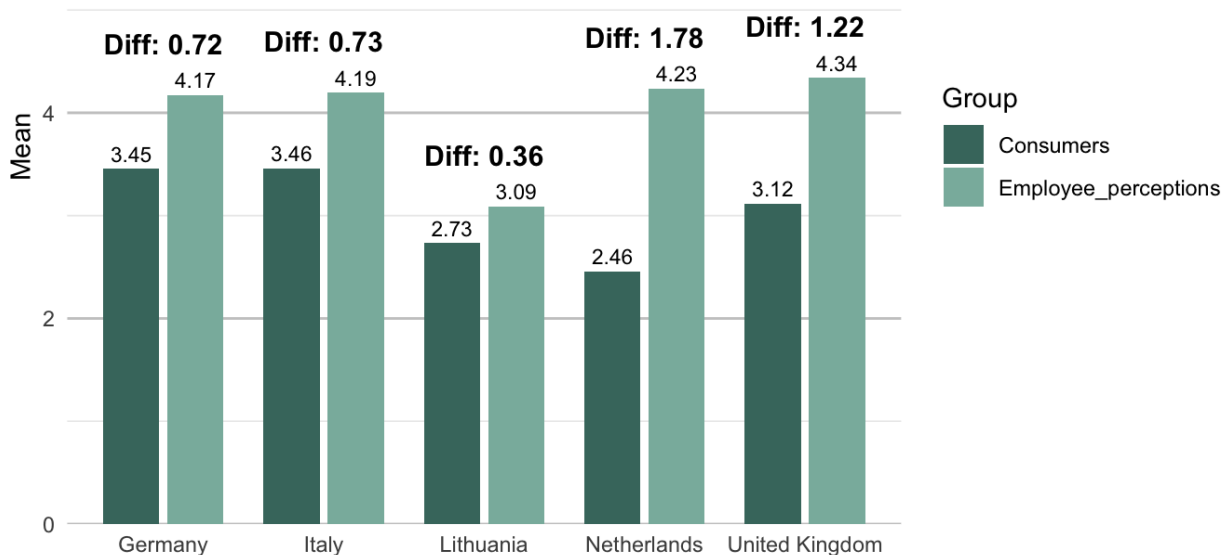
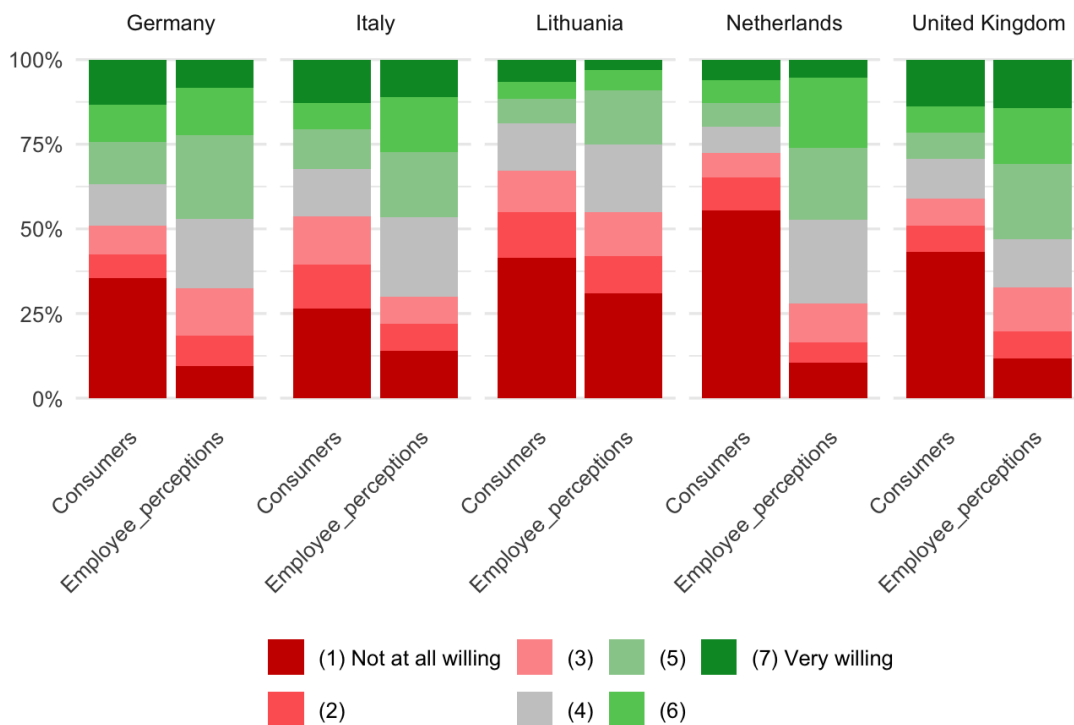


Figure 52. Distribution of willingness to share the garden – ratings by consumers and employees' perceptions

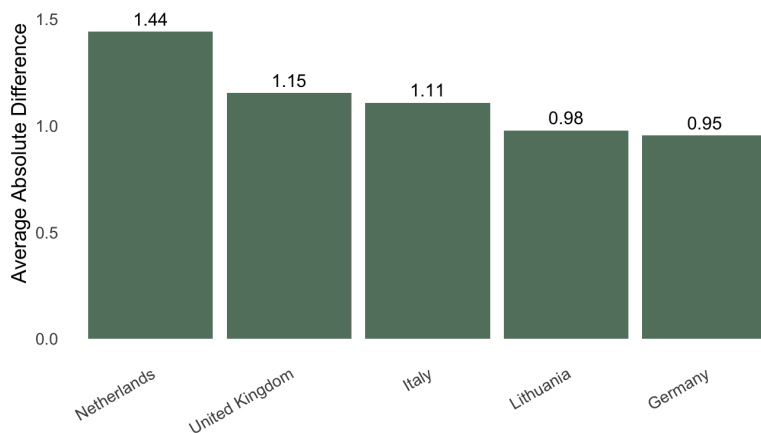




Conclusions for housing-related perceptions of consumers' beliefs and willingness to engage in circular behaviours

Overall, comparing consumers' beliefs and willingness regarding downsizing and sharing living spaces revealed an overestimation for all examined variables, similar to perceptions of consumers' values and mobility-related beliefs and willingness. Overestimations were found for all countries and variables, with differences in strength. Employee perceptions of German and Lithuanian consumers were most accurate (see Figure 53). Employees' perceptions of Dutch consumers were least accurate.

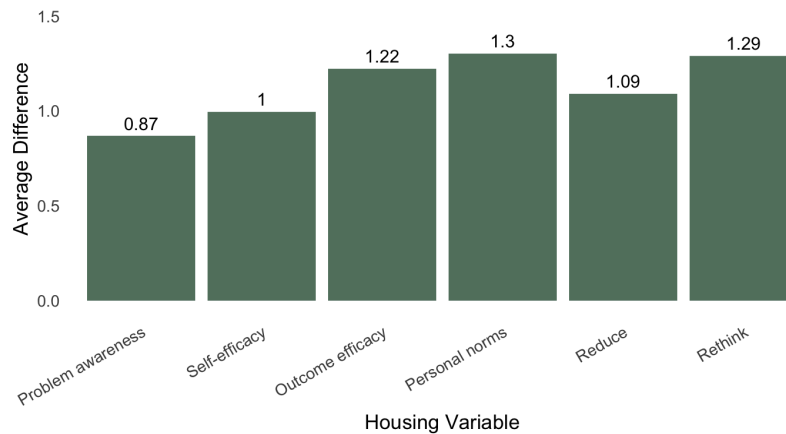
Figure 53. Differences in employee perceptions and consumers' actual beliefs and willingness per country



Employees most accurately perceived consumers' problem awareness and self-efficacy (see Figure 54). Consumers' personal norms to live in a smaller home or share living spaces, their willingness to share spaces, and their outcome efficacy were most strongly overestimated by employees.



Figure 54. Differences in employee perceptions and consumers' actual beliefs and willingness per housing variable



Conclusion

Overall, employees seem to overestimate consumers' value strength, their problem awareness, self- and outcome efficacy, personal norms, and willingness to engage in circular behaviours related to mobility and housing. Interestingly, generally, research suggests that people tend to under- rather than overestimate how much other people care about the environment, environmental problems, or how much they engage (Bouman & Steg, 2019; Andre et al., 2024), which results in less motivation and action. Our findings suggest that employees overestimate consumers' values, beliefs, and willingness to engage in circular behaviours. Therefore, employees' underestimation of consumers' values, beliefs, and willingness to engage in circular behaviours does not seem to be a barrier to advancing circularity.

More specifically, we find overestimations for all countries. Lithuanian and German consumers were most accurately perceived by employees, while the Dutch consumers were somewhat more misperceived, possibly due to generally lower consumer ratings compared to other countries' consumer ratings. Employees most accurately perceived consumers' awareness of environmental and social problems arising from car ownership, as well as consumers' perceived ability to not own a car. Consumers' willingness to share spaces and their feelings of moral obligation to live in a smaller home or share living spaces were overestimated the most. Generally, consumers' beliefs and willingness regarding housing were slightly more overestimated than mobility-related variables.

From these findings, the question arises to what extent overestimation of consumers' values, beliefs, and willingness to engage in circular behaviours poses a barrier to advancing the provision of circular alternatives and the uptake of circular behaviours. Currently, employees perceive consumers to be more aware, having higher agency, and being more willing to engage



in circular behaviours than consumers actually are. Thus, companies may continue their efforts to advance circularity and design circular goods and services in a way that keeps consumers in mind who are less inclined towards circularity. Future research is needed to test how employees' overestimation of consumers' values, beliefs, and willingness to engage in circular behaviours influences their decision regarding their businesses' circularity.

Additionally, employees also overestimated how much consumers care about wealth, possessions, influence, and status (i.e., consumers' egoistic values), as well as about having fun and a good time (i.e., consumers' hedonic values). Therefore, company efforts to create circular goods and services might need to focus somewhat less on simultaneously meeting these consumer values than currently thought. Thus, future research should focus on investigating a broad range of employee perceptions and testing how they together impact circularity strategies of businesses.



References Annex C1

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D3.1. ANNEX C2

Circular Workplace Pro-environmental Behaviours and Activism

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Workplace Pro-environmental Behaviours and Workplace Everyday Environmental Activism

In addition to Annex C1, the large-scale employee survey included measures on workplace pro-environmental behaviours (WPEBs; e.g., carrying out work by reducing, reusing, and recycling) and workplace everyday environmental activism (WEEA; e.g., encouraging co-workers and clients to reduce, reuse, and recycle). These behaviours are relatively understudied but hold considerable potential for promoting circular practices and reducing environmental impact.

A key novelty of this study was the focus of the behavioural measures on the principles of the circular economy (reduce, reuse, recycle), aligning with EU commitments to resource efficiency and climate mitigation. This approach allowed us to capture concrete workplace behaviours that employees are expected to perform regularly in support of broader circular economy objectives. Embedding circularity directly into the items appears to have enhanced their relevance and recognisability for respondents, which may help explain the higher levels of WPEBs and WEEA observed compared to earlier studies (e.g., Wagner et al., 2025). In addition, the survey assessed individual biospheric values, perceived Corporate Environmental Responsibility, self-efficacy, and social norms as determinants of WPEBs and WEEA. These relationships are explored in more detail in the paper listed on the title page of Annex C2. The current report focuses on WPEBs and WEEA as key behavioural measures, highlighting the extent to which employees adopt them and whether differences emerge across the five participating countries.

Methodology

WPEBs were assessed with three items: “I carry out my work by reducing, reusing, and recycling”; “I consider ways to reduce, reuse, and recycle when making work-related decisions”; “I contribute to projects and/or events at work that focus on reducing, reusing, and recycling.”

WEEA was assessed with four items: “I discuss with my colleagues how we can reduce, reuse, and recycle in our work”; “I encourage co-workers and/or clients to reduce, reuse, and recycle”; “I set a good example to others in my organisation by reducing, reusing, and recycling in my work”; “I put forward ideas for my organisation to reduce, reuse, and recycle.”

Responses for both scales were rated on a 7-point scale ranging from 1 (never) to 7 (almost always). Data were collected among representative samples of employees in five European countries: the United Kingdom, Germany, the Netherlands, Italy, and Lithuania.

Results

In this study, WPEBs and WEEA were reported at moderate to fairly high frequencies. Across the total EU sample, mean scores of 4.89 for WPEBs and 4.77 for WEEA indicate that these



behaviours were performed between “sometimes” and “often.” Country-level variation was evident, with the United Kingdom and Italy reporting the highest engagement, and Germany, the Netherlands, and Lithuania reporting lower levels. Across all countries, WPEBs were generally more frequent than WEEA, suggesting employees may feel more comfortable performing circular practices themselves than encouraging others to do so.

Figure 55 illustrates cross-country variation in workplace pro-environmental behaviours (WPEBs). Italy and the United Kingdom stand out with the highest levels of engagement, suggesting that circular practices such as reducing, reusing, and recycling are more strongly embedded in everyday work routines in these countries. The Netherlands shows moderate levels of engagement, while Germany and Lithuania report comparatively lower levels. Across all countries, employees most frequently describe integrating circular practices directly into their own work and decision-making, whereas participation in circular projects or events is less common.

Figure 55. Workplace Pro-environmental behaviours per behaviour and country.

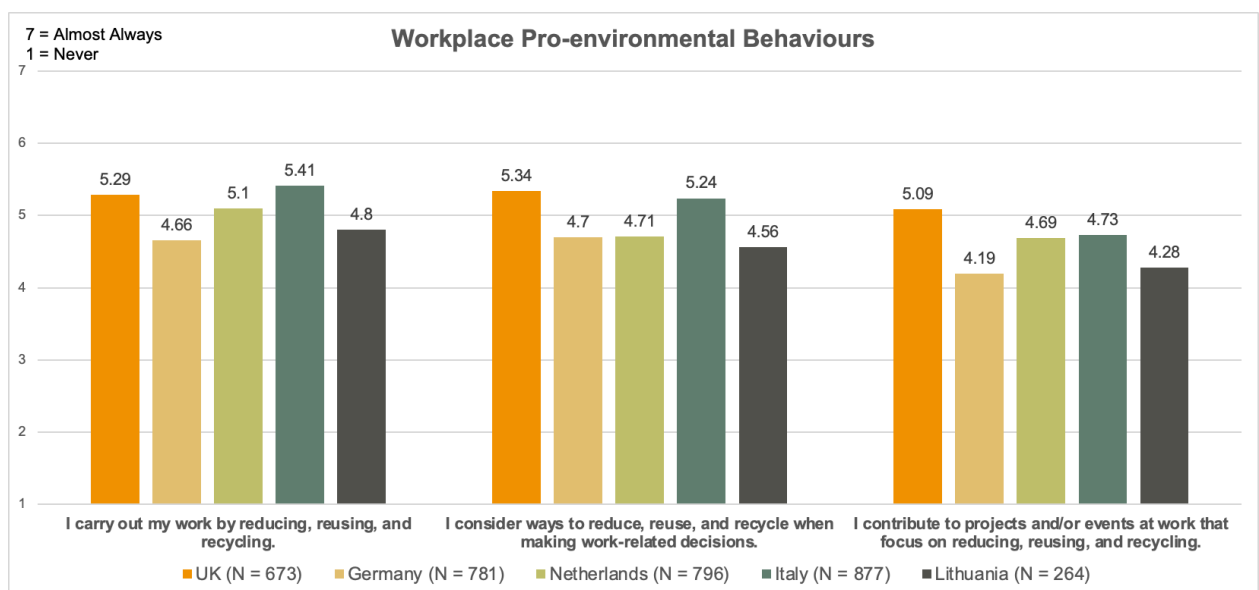


Figure 56 demonstrates differences across countries in workplace everyday environmental activism (WEEA). Italy and the United Kingdom display the strongest engagement, with employees more often encouraging others and setting examples for reducing, reusing, and recycling at work. The Netherlands follows with relatively high levels, while Germany and Lithuania show lower engagement overall. Across all countries, leading by example and motivating colleagues appear to be the most common forms of activism, whereas putting forward new organisational ideas is less frequent.



Figure 56. Workplace Everyday Environmental Activism per behaviour and country.



Conclusion

Employees across five European countries reported engaging in WPEBs and WEEA at moderate to fairly high levels, with overall frequencies somewhat higher than in earlier studies. Individual circular practices were more common than their activism counterparts, such as encouraging colleagues or proposing organisational changes. This suggests that personal action is more readily embedded in daily work routines. While Italy and the United Kingdom reported slightly higher levels than Germany, the Netherlands, and Lithuania, these differences were relatively small, suggesting that circular behaviours are broadly established across European contexts.



References Annex C2

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