



DELIVERABLE 5.1

Synthesis Report on the Potential Contribution of Digitalisation to the Circular Economy

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CircEULAR

Developing circular pathways for a EU low-carbon transition

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Executive Summary

This synthesis report examines the potential contribution of digitalisation to the circular economy from two perspectives. First, it evaluates the significance of indirect impacts through specific applications and consumer perceptions of digitalisation as an enabler. Second, it assesses whether the direct impacts of digitalisation threaten or outweigh its potential benefits. The analysis of indirect impacts focuses on five key use cases: Building Information Modelling, digital provenance and sorting, additive manufacturing, smart bins, and AI techniques for urban planning. These technologies demonstrate significant potential to support the circular economy through various mechanisms. However, realising this potential depends on key preconditions for adoption and addressing the associated challenges. These are discussed throughout this report. Regarding direct impacts, the global energy and material consumption of the ICT sector are relatively moderate compared to other sectors and can be mitigated through appropriate strategies. Nevertheless, localised effects and challenges persist, including high concentrated power demand in area where facilities are densely located and a strong dependence on critical raw materials that are scarce and unevenly distributed across a few countries, yet indispensable for digital economy. The report discusses the conditions required to realise the enabling effects of digitalisation on the circular economy while mitigating its negative impacts. Parts of this deliverable are confidential as underlying work summarised is being prepared for publication in scientific journals.

Keywords

digital technologies, materials, enabling effects, policies



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Abbreviations

AI	Artificial Intelligence
AM	Additive Manufacturing
BIM	Building Information Modelling
CE	Circular Economy
CRM	critical raw materials (or Critical Raw Materials Act)
DC	Data Centres
DPP	Digital Product Passport
EPBD	Energy Performance of Buildings Directive
EPR	Extended Producer Responsibility
EU	European Union
GHGs	Greenhouse Gases
IAM	Integrated Assessment Model
ICT	Information and Communication Technology
LCA	Life Cycle Assessment
LIBS	Laser-Induced Breakdown Spectroscopy
PSS	Product-Service Systems
WEEE	Waste Electrical and Electronic Equipment Directive
WLC	Whole Life Carbon legislation
WP	Work Package



Synthesis Report on the Potential Contribution of Digitalisation to the Circular Economy

1. Introduction

Digitalisation is a potential enabler of the circular economy (CE) by optimising resource use through various mechanisms. These enabling mechanisms include data-driven resource management, product lifecycle tracking, enhanced recycling and recovery processes, as well as sharing and service-based business models (see Table 1). However, benefits for the CE are not automatic. Digitalisation also poses risks for the CE through exacerbating mechanisms that include rebound or induced demand for goods and services, and the intensification of new forms of energy- or material-intensive consumption. These enabling and exacerbating mechanisms of digitalisation affect production and consumption activity in all sectors of the economy including buildings, retail, transport, industry, and the energy supply. In this report, we also refer to this as the *indirect effects of digitalisation on the CE*.

In addition, digitalisation poses direct risks to the CE through its own material footprint. This includes the critical raw material requirements for information and communication technology (ICT) infrastructure and equipment, as well as the energy demand of data centres, networks, and digital devices. In this report, we call refer to this as the *direct effects of digitalisation on the CE*.

To ensure a net positive effect on the CE, digitalisation must be implemented within a circular framework that amplifies enabling mechanisms, mitigates exacerbating mechanisms, and manages direct material needs throughout the lifecycle of ICTs.

In this report we synthesise new research, data, analysis, and stakeholder insights from the CircEULAR project in response to these aims.

We begin with a short literature synthesis of existing studies that assess the potential contribution of digitalisation to the CE. We also use the literature to map digitalisation enablers against common CE taxonomies including the 9Rs (Bocken et al., 2016) and Narrow-Slow-Close (Potting et al., 2017).

Using this mapping we then focus on several potentially high-impact use cases that assess digitalisation opportunities as enablers of the CE (indirect impacts):

- Building Information Modelling (BIM) for material efficiencies in building design and construction [CE 'narrow' strategy]
- Laser-Induced Breakdown Spectroscopy (LIBS) for improving scrap aluminium sorting [CE 'close' strategy]
- 3D printing for circular design & material efficiencies in manufacturing [CE 'narrow' & 'slow' strategies]
- Smart bins for enhancing recovery or recyclable waste from households [CE 'close' strategy]
- AI techniques for urban planning for improving design of resource-efficient new building developments and transport infrastructures [CE 'narrow' strategy]
- Consumer uptake of digital CE solutions

Following these case studies of digitalisation as potential CE enabler, we then address the direct energy and material needs of digital infrastructure at a systems scale (direct impacts). For this we also zoom out to an EU and global perspective:



- digital transformation as a broad economy-wide enabler of CE and underlying explanatory factor for the growth of ICT infrastructure
- historical and future energy demands of data centres (DCs) and ICT devices
- historical and future material demands of DCs and ICT devices, together with CE strategies

These case studies of digitalisation use cases for potentially enabling the CE, and the ICT sector studies, provide the main content of this report in Sections 2-11. Each section covers a specific topic in the form of a one page summary of a paper, report, or other output from the CircEULAR project. Each section is standardised for comparability with an abstract, considerations of both opportunity and risk for the CE, and then enabling conditions necessary for digitalisation to align with CE outcomes.

1.1 Digitalisation as a Potential Enabler of the Circular Economy

The relationship between digitalisation and circularity can be examined along two key dimensions: direct versus indirect effects, and upstream versus downstream interventions within the value chain. As noted above, direct and indirect effects distinguish digitalisation's impact on material flows within the ICT sector (direct effects) from those in other sectors (indirect effects). While the direct effects are detrimental to the CE, the indirect effects can be both beneficial (through enabling mechanisms) or detrimental (through exacerbating mechanisms).

Table 1. Examples of digital applications as potential enablers of the circular economy in buildings, transport, and industry.

Narrow	Slow	Close
• Real-time monitoring for production efficiency & energy savings. • Robotics & automation to reduce errors, scrap, and equipment wear. • Digital twins for lifecycle data-“product biography” to support circular design. • AI for design optimisation & material substitution (renewable/recycled inputs). • 3D printing to minimise waste (additive process). • Support product-service systems (PSS). • Digital Product Passport (DPP) guides sustainable procurement.	• Data platforms to match supply & demand for reuse. • IoT for data sharing across users, technicians, service providers, and resale markets. • Support for remanufacturing (identify, disassemble, repair, resell) (e.g., DPP). • Predictive maintenance (AI) for failure detection, condition-based servicing, and scheduling. • 3D printing of spare parts for repair & upgrades. • Remote assistance for maintenance.	• IoT/barcodes to track reverse logistics (location & condition of used products) → higher collection & recovery (e.g., DPP). • Robotics for material separation & recycling.

Note: Various sources including Chauhan et al., (2022) and (Hariyani et al., 2024).

From a value chain perspective, digitalisation can be differentiated into upstream (production-oriented) and downstream (consumption-oriented) applications. In the upstream stages, digital tools can enhance design, manufacturing, and logistics processes. For instance, technologies such as digital twins and additive manufacturing (3D printing) enable product simulation, design optimisation, and waste reduction. In contrast, downstream applications influence how products are distributed, used, and recovered. Examples include the use of blockchain technologies and digital product passports to ensure transparency, traceability, and efficient material recovery at the end of a product's life cycle. Table 1 gives examples of both upstream and downstream digital applications.



Digitalisation does not only create opportunities for the CE, but also risks. Strategic integration of potential digital solutions across design, production, consumption, and recovery systems can help accelerate the transition. However, this potential can only be fully realised by aligning technological innovations with supportive business models, policy frameworks, and behavioural change (Chauhan et al., 2022).

1.2 Evidence Synthesis on Aggregate Digitalisation – Circular Economy Relationships

Table 2 synthesizes evidence from empirical studies that use econometric methods to test associations between digitalisation as the independent variable and specific indicators of CE performance as the dependent variable. These studies use country and time panels, focusing on the EU over the past 20-25 years. Overall, these studies show a beneficial impact of digitalisation through its indirect effects on the CE across economic sectors, but a detrimental impact on the CE within the ICT sector itself due to the direct effect on increased material waste.

Table 2. Evidence synthesis from statistical models assessing digitalisation as a potential enabler of the circular economy in the EU.

Findings	Scope	Countries & Time	Reference
1% increase in household internet access is associated with a 1.4% increase in the circular materials use rate 1% increase in high-speed internet coverage is associated with a 0.08% increase in circular materials use	Whole economy	EU, 2011-2022	(Georgescu et al., 2025)
- At low levels of digitalisation, a 1% increase in e-commerce activity is associated with a 4% decline in CE performance measured by municipal waste per capita. This negative relationship gradually reverses as digitalisation increases - Digital public services consistently improve CE indicators (+2.21 %)	Whole economy	EU, 2012-2019	(Hong Nham & Ha, 2022)
A 1% increase in digitalisation improves a CE index by 0.43-0.63%	Whole economy	EU, 2010-2021	(Afolabi, 2025)
- Internet orders increase municipal waste volumes (+2.68) - More ICT personnel in total employment improves material efficiency and circular materials use rate (+1.65%) - More ICT output raises waste generation (+24.7)	Whole economy	EU, 2009-2021	(Hysa et al., 2024)
- Digital practices are positively associated with CE performance (measured by Likert-scale statements tied to CE business model) - Digital business innovations have a significant positive effect on CE performance - Together, digital practices & business innovations explain 67.3 % of the variance in CE performance	Financial sector	Greece, 2021	(Kalogiannidis et al., 2022)

As noted in the introduction, the potential enabling effect of digitalisation for the CE cannot be assumed. It depends on certain conditions being in place.



In the upstream (production-oriented) value chain, these conditions include:

- economic & market incentives aligned with CE;
- targeted deployment of digitalisation for clear CE use cases;
- mechanisms to manage or constrain activity-rebound induced by energy or material-efficiency gains (discussed further in concluding section to this report);
- effective governance institutions to enable CE outcomes.

In the downstream (consumption-oriented) value chain, these conditions include:

- skills & training to ensure widespread access to digital solutions;
- trust & confidence in data acquisition, transparency & security;
- sufficiency norms that reduce consumption rebound risks.

We address these enabling conditions further in each section of the report and in the conclusions.

Table 3 provides a high-level summary of insights from aggregate or systems-level empirical studies of digitalisation as a potential enabler of CE. These provide broad conditions under which beneficial outcomes have been identified from the indirect effects of digitalisation on CE outcomes outside the ICT sector. These can be summarized as:

- *Innovation*: More investment in R&D and innovation drives better CE outcomes.
- *Human capital and digital technology integration*: Digital public services and digital readiness accelerate CE transitions.
- *Socio-economic development*: Wealthier regions and countries show stronger CE performance.
- *More youthful demographics*: Old-age dependency ratio linked to lower circular material use.

The studies in Table 3 also point to important variation in CE outcomes across the EU.

- *EU disparities*: Significant variation in CE adoption and performance across EU countries and regions.
- *Regional clusters*: Clustering and governance structures shape regional CE outcomes.

Table 3. Evidence synthesis from econometric models on the system conditions that enable digitalisation to contribute positively to the circular economy.

Dependent Variable (Indicator)	(CE Independent Variable)	Key Findings	Countries & Time	Reference
Government effectiveness	Government use of ICT	Government use of ICT is a strong predictor of government effectiveness	Developing & developed countries	(Wandaogo, 2022)
CO ₂ emissions	Individuals using the Internet (%)	Digitalization increases carbon emissions	OECD countries	(Ullah et al., 2024)
Ratio of circular material use (% of total material use)	Old-age dependency ratio	Negative relationship: aging populations decrease circularity	19 EU countries, 2010-2019	(Neves & Marques, 2022)
Waste generation per GDP, recycling rates, circular material use	R&D investment	Positive impact of R&D investment on circularity indicators	28 EU countries, 2011-2017	(Lehmann et al., 2022)



Dependent Variable Indicator)	(CE Independent Variable	Key Findings	Countries & Time	Reference
Composite weighted indicators of circular economy	R&D expenditure	R&D positively contributes to circularity, though effect size varies across contexts	26 EU countries, 2010-2019	(Galdeano-Gómez & García-Fernández, 2024)
Circular Economy Static & Dynamic Index (CESI, CEDI)	Regional cluster analysis	Identified disparities in CE performance across EU regions	169 EU regions	(Silvestri et al., 2020)
EU circularity clusters	Human capital, digital tech integration, digital public services	Positive drivers of CE: human capital and digitalization	27 EU countries, 2014-2021	(Gil-Lamata et al., 2024)
Composite index of CE development	Socio-economic development	Higher socio-economic development is linked to improved CE performance	EU countries	(Stanković et al., 2021)
Circular Economy Composite Indicator (CECI)	-	Comprehensive overview of CE levels in EU, highlighting regional disparities	EU countries, 2014-2020	(Martínez Moreno et al., 2023)
Circularity readiness	-	Developed a readiness index for circular economy transitions	EU countries	(Momete, 2020)
Dynamic CE goals	-	Provided dynamic goals assessment of circularity progress across EU countries	EU countries, 2010-2016	(Škrinjarić, 2020)



1.3 Mapping the landscape of digitalisation use cases for enabling the CE

Table 4 and

Table 5 provide a set of general CE strategies organized using the 9Rs framework which itself can be categorized using the Narrow-Slow-Close taxonomy (fewer materials – longer use of materials – recovery of materials) (Potting et al., 2017). Note that the 9Rs framework commonly includes a tenth R (Reduce) (Bocken et al., 2016).

Table 4 illustrates how these CE strategies can be implemented in four bulk material sectors (upstream in the value chain).

Table 5 illustrates how the CE strategies can be implemented in three material end-use sectors (intermediate manufacturing and downstream use in the value chain).

In both these tables, CE strategies that can potentially be enabled by digitalisation are **shown in red font**. These are numerous.

In the CircEular project, we selected several of these CE strategies for further analysis in our case studies. These are shown in **yellow highlight with bold outline**, and are covered in detail in subsequent sections of this report.

Other CE strategies were investigated from consumers' perspectives in the Circular Consumption Survey. These are shown in **blue highlight**, and relevant insights are summarised in Section 24 of this report.



Table 4. Mapping of 9R strategies onto four bulk materials: steel, plastics, aluminium, cement.

Note: Red text = strategy for which digitalisation is a potential enabler. Yellow highlight with bold outline = selected as CircEULAR case study.

9Rs	General CE strategies	CE strategies applied to bulk materials			
		Steel	Plastics	Aluminium	Cement
Narrow: R0 Refuse		Make product redundant by abandoning its function or offering the same function with a radically different product			
R0.1	Dematerialise service provision (e.g. telework)				
R0.2	Reduce overall activity (e.g. 'avoid', sufficiency)				
R0.3	Substitute resource-intensive activity (e.g., active modes)				
R0.4	Design provisioning systems to reduce activity (e.g. urban planning)				
Narrow: R1 Rethink		Make product use more intensive (e.g., through sharing products, or by putting multi-functional products on the market)			
R1.1	Increase utilisation rates (e.g. sharing, leasing, product-service systems)				
R1.2	Design systems for resource efficient operation (e.g. logistics optimisation)				
R1.3	Increase multi-functionality of products (e.g. smartphones, AVs)				
R1.4	Design & use materials for recovery or reuse (e.g. fewer variants)	Design to facilitate recycling; Avoid contamination of steel by copper	Design to facilitate recycling (fewer additives)	Design to facilitate recycling (fewer alloys)	
R1.5	Design products for end-of-life (e.g. modularity, disassembly)		Design for disassembly; Marking of high-value materials or products		
Narrow: R2 Reduce		Increase efficiency in product manufacture or use by consuming fewer natural resources and materials			
R2.1	Improve efficiency of manufacturing or construction (inc. reduce process waste)	Reduce fabrication scrap		Reduce scrap forming during production	
R2.2	Rightsize for service provision				
R2.3	Substitute for cleaner materials (e.g. lower GHG alternatives)				Substitute clinker in cement production
R2.4	Redesign products for material efficiency (e.g. lightweighting, durability, long lifetimes)				
Slow: R3 Reuse		Reuse by another consumer of discarded product which is still in good condition and fulfils its original function			
R3.1	Increase reuse rates			Use deposit schemes	Increased use of recovered concrete in construction



R3.2	Develop reuse markets	Enable high-quality secondary production through more advanced scrap markets		Develop markets for scrap with additional category specifications; Real-time information on scrap flows	Development of local markets for reuse of structural segments
Slow: R4 Repair		Repair and maintenance of defective product so it can be used with its original function			
R4.1	Maintain products in use				
Slow: R5 Refurbish		Restore an old product and bring it up to date			
R5.1	Refurbish products in use				
Slow: R6 Remanufacture		Use parts of discarded product in a new product with the same function			
R6.1	Create new life for products by remanufacturing				
Slow R7 Repurpose		Use discarded product or its parts in a new product with a different function			
R7.1	Create new life for products by repurposing				
Close: R8 Recycle		Process materials to obtain the same quality (high grade) or lower quality			
R8.1	Increase recovery rates	Increase collection of post-consumer scrap	Increase collection of high-value secondary materials; Real-time tracking	Reduce collection losses	
R8.2	Increase recycling capacity		Increase scale and specialisation of recycling operations; Regional integration of recycling markets		
R8.3	Improve sorting & recycling technologies & processes		Improve technology for sorting (e.g. sensors) and automating recycling	Improve automated disassembly and sorting systems (e.g. sensors, LIBS)	Increased development of smart crushers
R8.4	Reduce downgrading, downcycling & loss of materials	Improve alloy-to-alloy sorting	Improve processes for removing impurities	Improve processes for removing impurities	
Close: R9 Recover		Incineration of materials with energy recovery			
R9.1	Increase waste-to-energy capacity				
R9.2	Divert landfill to waste-to-energy plants				



Table 5. Mapping of 9R strategies onto three material-use sectors: vehicles, buildings, and ICTs.

Note: Red text = strategy for which digitalisation is a potential enabler. Yellow highlight with bold outline = selected as CircEULAR case study. Blue highlight = included in Circular Consumption Survey.

9Rs	General CE strategies	CE strategies applied to end-use sectors		
		Vehicles	Buildings	ICTs
Narrow: R0 Refuse		Make product redundant by abandoning its function or offering the same function with a radically different product		
R0.1	Dematerialise service provision (e.g. telework)	Reduce travel activity (e.g. telework)	Reduce floorspace	Increase use of cloud-based services
R0.2	Reduce overall activity (e.g. 'avoid', sufficiency)	Reduce use of private vehicles (e.g. carlessness, mobility-as-a-service apps)		Reduce numbers of, and use, of devices (sufficiency, digital detox)
R0.3	Substitute resource-intensive activity (e.g., active modes)	Reduce use of private vehicles (mode switch to active, public, micro)		
R0.4	Design provisioning systems to reduce activity (e.g. urban planning)			
Narrow: R1 Rethink		Make product use more intensive (e.g., through sharing products, multi-functional products, redesign products for end-of-life management)		
R1.1	Increase utilisation rates (e.g. sharing, leasing, product-service systems)	Increase sharing of cars and rides (inc. platforms); Increase occupancy per vehicle	Increase sharing or usage of floor space; Real estate as a service	
R1.2	Design systems for resource efficient operation (e.g. logistics optimisation)	Data-driven optimisation of traffic flow		Design efficient data exchange & streaming protocols
R1.3	Increase multi-functionality of products (e.g. smartphones, AVs)	Autonomous vehicles for mobility-as-a-service (MaaS)		Substitute for single purpose devices (multi-functional device convergence)
R1.4	Design & use materials for recovery or reuse (e.g. fewer variants)			Design devices for user-maintenance and repair
R1.5	Design products for end-of-life (e.g. modularity, disassembly)	Increase modularity of vehicle components	Design for disassembly and high-value recycling	Increase modularity & substitutability of device components; Design devices for disassembly
Narrow: R2 Reduce		Increase efficiency in product manufacture or use by consuming fewer natural resources and materials, or redesigning products to extend use		
R2.1	Improve efficiency of manufacturing or construction (inc. reduce process waste)	Reduce waste during production	Reduce construction waste (inc. prefab, 3D printing & self-assembly), drones & 3D scanners for monitoring	
R2.2	Rightsize for service provision	Rightsize vehicle for trip purpose & occupancy	Design for flexible use	Miniaturise components
R2.3	Substitute for cleaner materials (e.g. lower GHG alternatives)		Substitute cement for wood	



R2.4	Redesign products for material efficiency (e.g. lightweighting, durability, long lifetimes)	Increase vehicle lifetime; Reduce vehicle size & weight; Accelerate transition to EVs with less low-grade aluminium	Reduce material use per m2; Engineer for light-weighting; Avoid over-specification, BIM	Design devices for durability; Avoid obsolescence
Slow: R3 Reuse		Reuse by another consumer of discarded product which is still in good condition and fulfils its original function		
R3.1	Increase reuse rates		Reuse buildings and structural components; Develop reuse markets for consumer goods	Reuse devices via second-hand stores & exchanges
R3.2	Develop reuse markets		Develop local markets for reuse of building components and building renovation	Link reuse markets across geographies (relocations)
Slow: R4 Repair		Repair and maintenance of defective product so it can be used with its original function		
R4.1	Maintain products in use	Replace modular components; Maintain shared vehicle fleets for longevity	Improve maintenance to extend key component lifespan; Extend building lifetimes	Increase accessibility of repair cafes, shops; Increase repair skills & information resources (how-to guides)
Slow: R5 Refurbish		Restore an old product and bring it up to date		
R5.1	Refurbish products in use			Refurbish high-value subassemblies to avoid obsolescence
Slow: R6 Remanufacture		Use parts of discarded product in a new product with the same function		
R6.1	Create new life for products by remanufacturing	Improve automated disassembly systems	Repurpose building use to adapt to demands (avoiding demolition)	
Slow: R7 Repurpose		Use discarded product or its parts in a new product with a different function		
R7.1	Create new life for products by repurposing	Repurpose components for second lives (e.g., EV batteries on grids)		Develop 'adaptive reuse' business models (e.g. LCDs as TVs)
Close: R8 Recycle		Process materials to obtain the same quality (high grade) or lower quality		
R8.1	Increase recovery rates		Recycle materials from end-of-life buildings; Monitor household waste sorting	Incentivise recycling of 'hibernating' stocks of devices (stored, unused)
R8.2	Increase recycling capacity			Develop infrastructure for waste electronics collection & recovery
R8.3	Improve sorting & recycling technologies & processes	Improve automated disassembly systems	Dismantle buildings to enable high-value recycling; Improve separation of materials	
R8.4	Reduce downgrading, downcycling & loss of materials		Reduce concrete downcycling by recovering unused cement and aggregates	
Close: R9 Recover		Incineration of materials with energy recovery		
R9.1	Increase waste-to-energy capacity			
R9.2	Divert landfill to waste-to-energy plants			



2. Building Information Modelling

2.1 Summary

Building Information Modelling (BIM) contains data facilitating energy and material-efficient design and construction. We assessed the current state-of-the-art in BIM adoption and use, identifying both barriers and opportunities across six dimensions defined by the PESTLE framework (political, economic, social, technical, legal, environmental). We combined market survey, literature review, and new insights from 41 expert interviews with architects, consultants and constructors across 11 European countries. We find BIM is used only by larger firms and principally as a design and data-processing tool to enable collaboration between project partners. BIM's value to industry actors is primarily to speed construction not improve material efficiency or reduce embodied emissions. Overall the current use of BIM is limited by interoperability, value chain fragmentation, and weak economic incentives. This limits its contribution to the circular economy to date. However, in the medium-term we find two important drivers of BIM adoption and value. First, institutional investors in the commercial buildings sector are increasingly pushing green certification standards for which compliance is demonstrated by BIM. Second, lifecycle emission regulations for buildings mandated by the EU from 2030 will require design digitalisation and modelling of completed construction. Again, both are provided by BIM. Four pioneer Northern European countries already have such regulations in place, setting upper limits on embodied and operational CO₂-equivalent emissions per m² floor area of new buildings. Here BIM use is already widespread, but further diffusion will require training of constructors in digital systems. We estimate that under realistic assumptions, material and energy-efficiency savings enabled by BIM could deliver 21%-31% of embodied emissions after 10 years.

2.2 Challenge & Opportunities for the CE

Building Information Modelling (BIM) presents significant opportunities to advance the circular economy (CE) by improving material efficiency, supporting lifecycle assessment (LCA), and enabling data-driven design for disassembly, reuse, and refurbishment. BIM's capacity to generate precise Bills of Materials, coordinate multi-disciplinary design inputs, and simulate material flows across a building's lifecycle can reduce waste, embodied carbon, and construction inefficiencies. These advantages align BIM closely with CE principles of narrowing, slowing, and closing resource loops. However, there are numerous challenges to realising this potential, including low BIM adoption rates among small and medium-sized firms, fragmented data interoperability, insufficient training, and entrenched industry cultures that resist information sharing. Economic disincentives also persist—many of BIM's material and cost-saving benefits accrue to clients or contractors rather than architects, who face the upfront costs of BIM adoption. Furthermore, while BIM can theoretically optimise material use and embodied energy, its effectiveness depends on user intent and the integration of complementary tools such as LCA software and Environmental Product Declarations (EPDs).

2.3 Conditions for Enabling the CE

BIM's capacity to make a positive contribution to the circular economy is contingent on enabling conditions that integrate technological, regulatory, and educational factors. The introduction of whole life carbon (WLC) legislation under the 2024 Energy Performance of Buildings Directive (EPBD) is expected to drive BIM uptake by making digital models essential for embodied emission calculations and compliance reporting. Effective implementation will require harmonised LCA methodologies, robust verification mechanisms, and governmental capacity to interpret BIM-based submissions. Equally, sustained investment in digital literacy, both within firms and in public authorities, is necessary to overcome the current skills deficit and ensure accurate data handling. Regulatory



flexibility will also be essential to accommodate new low-carbon and reused materials, while clear standards for data interoperability and model sharing are needed to support collaboration across the construction supply chain. When these political, technical, and social enablers align, BIM can serve as a critical digital infrastructure underpinning material circularity and decarbonisation across Europe's built environment.

Summary based on CircEular project article currently under review in Energy & Buildings:

Burgess, M., C. Wilson, C. and Y.V. Fan (under review). Adoption Drivers and Barriers of Building Information Modelling (BIM) in Europe.

3. Digital provenance and sorting for materials recirculation

3.1 Summary

Reducing GHG emissions without reducing living standards implies recirculating materials rather than discarding or downcycling them: in particular, the emissions associated with the four major bulk materials (steel, cement, plastics and aluminium) are around two-thirds of the entire industrial emissions. This study examines, through a series of expert interviews, how digitalisation, both through provenance systems and analysis tools for sorting discarded materials, could improve circularity in Europe. It finds that whilst there is a large and sudden interest from construction companies and the automotive sector in using recycled materials due to self-imposed low-carbon targets, almost nothing digital is being developed for recirculating either steel or cement. The exception is Business Information Modelling which could assist building or material reuse in second lives (see Section 2). For plastics, on-pack provenance systems could be implemented in the short-term, but this depends on cross-supply chain cooperation which is generally lacking. Only for aluminium is there the prospect of substantial near-term improvement, where the introduction of Laser Induced Breakdown Spectroscopy could greatly reduce the downcycling of wrought aluminium into cast grades, potentially eliminating a forecast surplus of cast aluminium by 2030.

3.2 Challenge & Opportunities for the CE

Digital provenance and sorting technologies present both significant opportunities and substantial challenges for enhancing circularity in bulk materials. On the opportunity side, advanced tools such as high-speed compositional analysis (e.g., Laser Induced Breakdown Spectroscopy or LIBS), AI-enabled optical recognition, and digital watermarking enable more precise identification and separation of material grades, thereby reducing downcycling and retaining high-value properties in steel, aluminium, and plastics. Provenance systems can also support traceability of material flows across the value chain, enabling verification of recycled content for Extended Producer Responsibility (EPR) schemes and Deposit Return Systems.

However, major challenges persist, including limited market demand for high-purity secondary materials, technological immaturity of some solutions, insufficient investment in automated sorting infrastructure, and the complexity of aligning fragmented supply chains that are often incentivised to prioritise low-cost downcycling over quality recycling. These barriers mean that, while the technological potential is evident, scaling adoption remains uncertain without systemic change.



3.3 Conditions for Enabling the CE

For digital provenance and sorting technologies to make a positive contribution to the circular economy, a set of enabling conditions must be in place. Regulatory frameworks are critical, particularly where mandates for minimum recycled content or tax incentives tied to proof of recycling create demand pull for digital tracking and sorting systems. Equally important are collaborative supply chain arrangements, since the benefits of digital marking or provenance systems typically accrue downstream while costs are borne upstream, requiring cooperative business models to share value fairly. Technological integration with existing recycling operations must be accompanied by investment in high-capacity, multi-machine sorting lines, alongside advances in AI-driven process optimisation. Finally, transparency and trust in provenance data will be essential to build markets for high-quality secondary materials, supported by consumer and producer confidence in verified recycled content. Under these conditions, digitalisation can act as a catalyst for narrowing, slowing, and closing material loops in line with circular economy principles

Summary based on published CircEULAR project report:

Burgess, M., Wilson, C., (2023). Bulk material manufacture: the potential impact of digitalisation and provenance systems on materials recirculation. <https://doi.org/10.5281/zenodo.8054783>

4. Additive manufacturing for circular design

4.1 Summary

Additive manufacturing (AM), or 3D printing, is a production method in which objects are created layer by layer from digital 3D model data. Unlike traditional subtractive manufacturing that removes material from a larger block, AM adds only the necessary material to build a part, minimizing waste and enabling the fabrication of complex geometries in a single process. By shortening design-to-production time and reducing material use, AM aligns well with sustainable and low-energy manufacturing goals. Originally developed in the 1980s for rapid prototyping, AM has evolved into a versatile technology for direct manufacturing applications due to its precision, flexibility, and ability to produce customized products. There are several AM technologies, for use with different materials such as plastics, polymers, ceramics or composites. AM technologies are particularly attractive for sectors requiring high performance and design freedom, such as biomedical devices, aerospace, and automotive industries. Using a taxonomy of 3D printing technologies for use in different industrial sectors, our analysis shows that currently all 3D printing technologies are applied mainly in three domains of manufacturing: concept modeling, prototyping, and tooling. In concept modeling and prototyping, AM accelerates product development, reduces material waste, and facilitates early design improvements. In tooling, it enables rapid production of specialized tools and molds, offering manufacturers high flexibility and responsiveness to market needs. Most of the 3D printing technologies are being explored for large-scale production (e.g., in the construction sector). AM's penetration is also growing steadily in sectors such as aviation, where lightweight parts reduce downstream energy use; in automotive manufacturing for small-batch customized components; and in healthcare for personalized implants and prosthetics. Yet, the deployment of AM for large scale production in line with CE principles in industry depends on overcoming several technical, economic, and institutional barriers.

4.2 Challenges & Opportunities for the CE

Additive manufacturing (AM) presents significant opportunities to advance the circular economy by enabling resource-efficient, localized, and on-demand production systems. Its additive nature



minimizes material waste by using only the quantity required to form each part, contrasting with the high scrap rates of subtractive manufacturing. Furthermore, AM facilitates lightweight component design, modular construction, and product life extension through repair and remanufacturing, thereby reducing both embodied energy and material intensity across supply chains. The capacity to produce complex geometries and customized parts without extensive tooling allows for distributed production and the reshoring of manufacturing activities, shortening logistics chains and lowering transport-related emissions.

However, several challenges constrain AM's full potential contribution to circularity. These include the high energy intensity of certain printing processes (especially those involving metal powders or high-temperature sintering), dependence on polymer-based and non-renewable feedstocks, and the lack of standardized post-processing and recycling systems for AM materials. Moreover, the absence of universally recognized certification and metrology standards, limited economies of scale, and unresolved intellectual property and cybersecurity concerns continue to hinder its sustainable industrial adoption. Thus, while AM holds clear potential to close material loops and reduce energy use, realizing these benefits requires overcoming substantial technical and systemic barriers.

4.3 Conditions for Enabling the CE

For additive manufacturing (AM) to deliver measurable gains in circularity and energy efficiency, several enabling conditions must converge across technological, institutional, and social dimensions. Technologically, continued R&D is required to improve printer energy efficiency, expand the range of recyclable and bio-based feedstock materials, and enhance process automation to reduce post-processing demands. At the systems level, the integration of AM within circular production networks depends on effective knowledge diffusion, resource mobilization, and market formation—functions that require coordinated public–private investment, policy alignment, and infrastructure for distributed manufacturing. Policy frameworks that incorporate AM into industrial decarbonization and circular economy strategies, alongside the development of international standards for quality assurance, metrology, and recycling, are critical to scaling adoption. Social and behavioral enablers, such as workforce training, open-source innovation, and inclusive governance, further enhance AM's sustainability outcomes by promoting collaboration, transparency, and equitable access to technology. When these conditions are met, AM can transition from a niche prototyping tool to a cornerstone of a low-energy, low-waste industrial paradigm—one in which production is flexible, materials circulate in closed loops, and environmental burdens are substantially reduced.

Summary based on CircEular project article in preparation prior to journal submission:

Verdolini, E. et al. (in preparation). Additive manufacturing, circularity and energy demand.

5. Smart bins for household waste recovery

5.1 Summary

Smart bins are technologically advanced containers equipped with sensors, connectivity, and data analytics that allow utilities to precisely monitor waste disposal at the household level. This digitalization of waste management makes it possible to provide tailored feedback to families and to benchmark their behavior against that of similar households. Building on this functionality, we conducted a field experiment in collaboration with an Italian utility to test whether digital feedback and social norms could reduce unsorted waste. In our setting, households face a two-part tariff: they pay a fixed fee for unsorted waste up to a predefined cap, and an additional fee per disposal once the cap is exceeded. We randomized households to receive a report containing a social comparison



of their waste disposal relative to similar households, while another group received the same information coupled with a reminder of their distance from the tariff cap. We found that the social norm and feedback intervention reduced the volume of unsorted waste up to 5%. We also observe an increase in sorted waste, suggesting that households responded to the intervention not only by reducing overall disposal but also by improving their separation and recycling behaviors.

5.2 Challenge & Opportunities for the CE

These results highlight how digitalization can act as an enabler of circularity. By harnessing data collected through smart bins, utilities can design low-cost, scalable, and behaviorally-informed interventions that promote waste sorting and reduce reliance on landfill or incineration. Beyond household behavior, smart bins generate data that can improve collection routes, predict capacity needs, and reduce emissions from logistics. Once the digital infrastructure is in place, interventions can be rolled out at low marginal cost, allowing widespread adoption of circularity-oriented practices. Digital technologies thus provide the infrastructure needed to align household behavior with broader sustainability goals, illustrating how data-driven feedback can strengthen the transition toward a circular economy and a low-resource future.

However, the reliance on digital technologies also brings important risks and challenges. For example, monitoring waste disposal or resource consumption at the household level may raise concerns about data protection and surveillance. If households perceive feedback as intrusive or punitive, they may disengage or find ways to game the system. Overemphasis on monitoring can also undermine the effectiveness of social norms.

5.3 Conditions for Enabling the CE

Digitalization provides the data and infrastructure necessary for innovative policy design, but its effectiveness depends on careful consideration of governance, policy integration and social acceptance. For smart bins to make a positive contribution to the circular economy, several enabling conditions need to be in place. Some conditions have to do with robust data governance, through transparent rules on data collection, use, and sharing, in order to maintain trust. Data should be anonymized where possible, and utilities must clearly communicate how information is used to benefit both households and the community. Second, smart bins alone are not sufficient. They need to be integrated with policies and regulations. Tariff structures, recycling infrastructure, and education campaigns must complement digital interventions to sustain behavioral change. Another important issue is related to social acceptance. Households must perceive digital monitoring as legitimate, fair, and non-intrusive. Feedback should be designed to be understandable, motivating, and respectful of privacy. Interventions need to be tailored to different demographic and socio-economic groups to avoid exclusion.

Summary based on published CircEULAR project article:

Bonan J., C. Cattaneo, G. d'Adda, A. Galliera and M. Tavoni (2025) "Social norms and tariff salience: An experimental study on household waste management". Journal of Environmental Economics and Management. <https://doi.org/10.1016/j.jeem.2025.103124>



6. AI techniques for urban planning

6.1 Summary

Artificial intelligence can directly contribute to decarbonization by providing new causal evidence on the relationship between urban form and transport emissions. We developed and applied a double machine learning framework to quantify the impact of the built environment on travel-related CO₂ emissions while correcting for the problem of residential self-selection. Using travel diary data from more than 32,000 Berlin residents, we showed that conventional linear models overstate the climate benefits of compact urban form by 13-18%, whereas our AI-based approach isolates the true causal effects by flexibly capturing nonlinear confounding and moderating influences of socio-demographics and travel preferences. The architecture, based on causal forests and cross-fitting, reveals heterogeneities, showing that built-environment impacts are strongest for high-income, car-owning households, and that destination accessibility explains the bulk of observed CO₂ variation between neighborhoods. Applied to Berlin's current development pipeline, the system estimates that spatially differentiated, compact siting of 64,000 new housing units could cut induced mobility emissions by up to 43% compared to business-as-usual dispersal. More broadly, we argue that double machine learning provides a scalable digital tool for cities worldwide: it can integrate diverse big data sources, generalize across contexts, and rapidly generate evidence for low-carbon urban planning at relatively low cost, thereby offering a replicable digital pathway to decarbonization of urban transport.

6.2 Challenge & Opportunities for the CE

The use of double machine learning illustrates how digital approaches can underpin “narrow” CE strategies by helping cities prevent the lock-in of future transport emissions through smarter planning decisions. Disentangling the true causal effect of the built environment on mobility-related CO₂ emissions can show where new housing developments should be located to minimize induced travel and thereby avoid unnecessary emissions before they occur. Translated to circular economy contexts, digital provenance and sorting technologies serve a comparable function: by making product histories transparent and enabling precise classification of materials, they allow systems to avoid waste generation and downcycling in the first place. Both cases show that digital intelligence is not only about optimizing existing flows but about creating foresight that narrows resource and energy use through design and planning choices.

The challenge, however, is ensuring that these AI-driven ‘narrow’ strategies are applied consistently across scales and sectors, that they are supported by governance frameworks to prevent rebound effects, and that data infrastructures are interoperable enough to make such anticipatory decisions reliable.

6.3 Conditions for Enabling the CE

To make a positive contribution to the circular economy, similar enabling conditions are needed as for the uptake of AI-based methods in urban planning. Nachtigall et al. demonstrate that double machine learning becomes valuable when it is embedded in accessible, low-transaction-cost tools that municipalities can use to test alternative development scenarios without needing specialist knowledge. AI systems must be designed so that practitioners—urban planners, waste managers, procurement officers—can easily “play around” with them, experimenting with scenarios and instantly visualizing material or emissions consequences. This requires standardized data interfaces, intuitive visualization dashboards, and integration into existing municipal workflows, so that AI enhances rather than complicates decision-making. Equally important are governance processes that reduce institutional risk and provide trusted validation of results, ensuring that decisions based on digital tools are defensible in public and political debates. When AI-enabled technologies are



transparent, interoperable, and easy to handle, they can lower the cost of experimenting with circular options and thus create the conditions for their systematic uptake in city-level planning and infrastructure management.

Summary based on published CircEULAR project article:

Wagner, F., Nachtigall, F., Franken, L., Milojevic-Dupont, N., Pereira, R. H., Koch, N., ... and Creutzig, F. (2023). Using machine learning to understand causal relationships between urban form and travel CO2 emissions across continents. arXiv preprint arXiv:2308.16599.

7. Consumer perspectives on digitalisation as a potential enabler of the CE

7.1 Summary

Digitalisation offers significant potential for reducing the material resource impacts of certain economic sectors, allowing people to engage in circular economy actions that were previously not feasible. However, like many previous historical transformations rooted in efficiency gains, digitalisation's potential as an enabler of the circular economy is conditional. We explored this tension between CE opportunity and risk from consumers or users' perspectives through household interviews and the *Circular Consumption Survey* conducted in 4 EU countries plus the UK (Grealis et al. 2025). We found that, on average, people perceive digitalisation to have increased their levels of consumption in certain consumption categories, including household goods, energy and media. This is consistent with a recent report of the German Environmental Protection Agency that found personalized advertising and recommendation algorithms deliberately channel consumption impulses toward buying new, while sustainable or circular alternatives are less visible in online environments (Umweltbundesamt, 2025). Digitalisation as a potential enabler of the CE (or other environmental goals) is undermined by these ratcheting effects on overall consumption levels.

7.2 Challenges & Opportunities for the CE

Digitalisation offers many opportunities for reducing the material impacts of work and non-work-related practices. Examples include videoconferencing reducing the need for people to physically travel, smarter production processes reducing the material intensity of products through, or more efficient handling of the organizational and administrative burden of transformation from purchase to service markets. Digitalisation also help transform secondary markets in which buyers and sellers are able to locate each other more easily, facilitating trade and increasing the useful life and value of second-hand products.

However, increased digitalisation also entails risks for the CE, primarily due to rebound effects through which overall consumption increases due to the convenience of digital applications. While on average, Circular Consumption Survey respondents reported a neutral impact of digitalisation on their travel practices, they reported increases in their energy use, media consumption, and their consumption of household goods due to digitalisation (Grealis & Rau 2025). Additionally, second-hand purchases do not always substitute for new product purchases. Rather, buying second hand can serve as an 'excuse' for additional consumption. Second-hand sales can also create additional rebound effects, with additional funds spent elsewhere.



7.3 Conditions for Enabling the CE

For digitalisation to make a positive contribution to circularity, significant structural conditions must be met. Digital infrastructures and platforms need to be deliberately directed to promote sufficiency-oriented circular practices such as repair, reuse, and other product life extending practices such as borrowing and lending rather than primarily prioritizing demand for first-hand products. Structural conditions limiting the lifespan and attractiveness of refurbished products need to be challenged. The effective lifetime of many products is nowadays dictated not by the material durability of its hardware but by decisions of software service providers, thereby reducing consumer confidence in refurbished options and reinforcing the market for new devices. Policy interventions are needed to align business incentives with CE outcomes, for example by requiring that digital service providers prioritise repair information, product longevity, and secondary markets in their recommendations. Fostering digital literacy and awareness among consumers can additionally help ensure that the benefits of digitalisation, such as improved access to repair services or second-hand goods, actually enhance circularity.

Summary based on published CircEular project reports:

Grealis, E., & Rau, H. (2025). *Preliminary results from the Circular Consumption Survey (CircEular Deliverable 4.4)*. Zenodo. <https://doi.org/10.5281/zenodo.16636919>

Grealis, E., Rau, H., Pacheco, I., van der Werff, E., & Steg, L. (2025). *Circular Consumption Survey [Data set]*. Zenodo. <https://doi.org/10.5281/zenodo.15267507>

8. Digital transformation as an enabler of the CE

8.1 Summary

For the enabling functions of digitalisation for the CE to materialise, countries must first undergo a substantial level of digital transformation: building infrastructure, ensuring access, developing digital skills, and embedding digital governance capacity. Without this foundation, the promise of digitalisation for the CE risks being confined to high-income regions, while large parts of the world are left behind. We examine projected levels of digital transformation across countries (to 2050), using the framework of Shared Socioeconomic Pathways (SSPs) to map how socioeconomic, demographic, and innovation factors drive digitalisation. Using empirical data from 62 countries, we show that digital transformation (measured via the UN E-Government Development Index, combining ICT infrastructure, access/use, digital skills, online services) will increase globally but unevenly. Key drivers include GDP per capita, R&D expenditure, and population size. Under less favourable SSPs (regional rivalry, weak growth), persistent digital divides are likely: up to 45% of populations may still live in countries with low or very low digital transformation by mid-century. These divergence trajectories have implications for the CE. Digitalisation can enable CE (via monitoring, traceability, enabling low-carbon/low-resource processes), but unequal transformation limits where and how those enabling benefits grow. Moreover, the growing dependence on digital technologies also amplifies direct and indirect environmental footprints (energy, materials, e-waste) and risks of rebound or unintended consequences.

8.2 Challenge & Opportunities for the CE

Digital transformation creates new opportunities for advancing CE strategies by embedding intelligence, traceability, and optimisation across value chains. Higher levels of digitalisation expand the toolkit available to support circularity, positioning digitally advanced economies at the forefront



of innovation and competitive advantage. These functions create opportunities for circular practices such as improved product lifetime management, resource optimisation, and greater supply chain transparency.

However, several challenges limit these contributions globally. Persistent digital divides mean that many regions may lack the infrastructure, skills, or governance capacity to adopt CE-enabling digital solutions, creating uneven global progress. Structural barriers such as low GDP per capita, weak R&D ecosystems, and small market size constrain the rollout of transformative technologies. Even where infrastructure exists, gaps in digital literacy, regulatory oversight, data privacy concern and institutional capacity may prevent digital transformation from translating into CE outcomes. The benefits of digital transformation for the CE are dependent on the socioeconomic and governance contexts in which it unfolds.

8.3 Conditions for Enabling the CE

For digital transformation to support the CE, several conditions are essential. Economic capacity, R&D, and population scale lay the groundwork for investment in technology. Equitable access to digital infrastructure, affordable connectivity, and inclusive services are needed so rural and low-income regions are not left behind. Human capital is equally critical: widespread digital skills and literacy enable individuals, firms, and governments to leverage digital tools for circular practices. Strong governance, regulatory frameworks, and supportive policies are needed to align digital growth with sustainability outcomes while reducing inequality by ensuring that disadvantaged groups can participate fully in digital and circular opportunities. The EU's Digital Compass 2030, for example, sets concrete targets for universal skills, secure infrastructure, and equal access to services, while global digital inclusion programs led by UNESCO and the ITU expand affordable connectivity and training in low-income countries. In addition, the ICT sector itself must also internalise circular principles by designing durable and modular devices, enabling reuse and repair, improving recycling of critical materials, and minimising rebound effects through efficiency gains. When infrastructure, access, skills, governance, and policy align, digital transformation can accelerate circular economy strategies. Without them, it risks reinforcing inequalities or adding to environmental pressures.

Summary based on published CircEULAR project article:

Fan, Y.V., C. Wilson, M. Andrijevic, H. Carlsen and S. Joshi (2025). *Digital transformation in the Shared Socioeconomic Pathways*. *npj Climate Action*, 4(1), 79.
<https://www.nature.com/articles/s44168-025-00283-w>

9. ICT sector challenges for the CE: data centre energy footprints

9.1 Summary

Data centres provide the computational services to enable digital CE solutions, but the sector poses environmental risks due to its high energy footprint. Many studies have projected near-term data centre energy demand, but few extend beyond the next five years due to uncertainty and concerns about innovation trajectories. However, climate mitigation and CE strategies require longer time horizons to anticipate impacts on energy systems, material cycles, and end-of-life infrastructure. In this study, we extend data centre energy demand projections to 2050 within the Shared Socioeconomic Pathways (SSP) framework, aligning with common approaches in climate scenario analysis. Our method draws on historical trends observed during periods dominated by either service



demand growth or efficiency gains, as well as anticipated future trends in digital transformation levels. Across the SSP1–5 scenarios, our central global projection of data centre electricity consumption reaches between 1,811 and 4,996 TWh by 2050, with SSP2 (the middle-of-the-road scenario) at 2,451 TWh. To remain compatible with 1.5°C climate targets, the weighted average carbon intensity of electricity for data centres must fall to 72 (67th percentile)–103 (50th percentile) gCO₂/kWh or lower from 2030. These scenario-based long-term data centre energy projections inform strategies to align digital infrastructure growth with climate goals and to explore how circular economy principles such as resource efficiency, waste heat recovery, and e-waste mitigation can be integrated.

9.2 Challenges & Opportunities for the CE

The rapid expansion of data centres globally is creating significant challenges for sustainable energy systems. Despite ongoing improvements in efficiency, the projected electricity consumption (especially in North America and Asia Pacific regions) continues to rise, particularly due to AI-driven workloads. Balancing sustainability with performance and reliability remains a central challenge. Currently, rapid infrastructure development often prioritises operational reliability and cost efficiency, with less emphasis on environmental performance. This has led to a persistent reliance on non-renewable energy as a firm energy source. Furthermore, site selection criteria for data centres frequently prioritise access to affordable and reliable electricity rather than access to renewable generators. Facilities tend to cluster in regions with robust network connectivity, favourable policies, and cooling conditions rather than where low-carbon energy potential is highest. The paradox is that while digital technologies enable resource efficiency in other sectors, data centres themselves are becoming one of the fastest-growing contributors to global electricity use and associated GHG emissions. The misalignment between the rapid growth in energy demand and the slower pace of clean energy deployment within the sector risks reinforcing dependence on fossil fuels and undermining progress toward global climate goals.

On the other hand, data centres also present opportunities to support and accelerate the energy transition. Many major operators are leveraging their scale, financial capacity, and long-term commitments to emissions reduction to drive investment in low-carbon energy infrastructure. From an energy system perspective, data centres can enhance grid flexibility by participating in demand response programs, providing balancing services, and enabling better integration of intermittent renewable sources. Moreover, advances in efficiency measures such as AI-driven energy management, server virtualisation, and waste heat recovery further contribute to reducing their operational footprint and improving overall energy circularity. In the long term, the sector holds the potential to decouple digital growth from carbon intensity through technological innovation and strategic alignment. Data centres can evolve from being intensive energy consumers to becoming integral enablers of a resilient, low-carbon energy ecosystem by embedding circular energy principles into their design, operation, and location strategies. For this to happen, the right conditions and policy frameworks are needed to be in place.

9.3 Conditions for Enabling the CE

Careful infrastructure planning and investment in clean energy are central to reducing the sector's growing carbon footprint. We demonstrated that using renewable energy sources such as solar and wind can enable data centres to operate within their carbon budget limits, underscoring the importance of aligning data centre energy use with decarbonisation goals. Governance and policy play a decisive role in ensuring these opportunities are realised. Standards and regulations can promote energy efficiency, renewable integration, and transparent reporting of resource use. Incentives for waste heat utilisation and refurbishment can embed data centres more fully into circular systems. Incentives for waste heat recovery, grid flexibility, and equipment circularity can further embed data centres within the CE. The EU's Code of Conduct for Data Centres and the



Energy Efficiency Directive already provide frameworks for continuous improvement in efficiency, while the Climate Neutral Data Centre Pact (over 100 data centre operators and companies that own or operate data centre within EU) commits operators to achieving 100% carbon-free energy and effective heat reuse by 2030. In other regions, green data centre certification schemes, such as Singapore's BCA-IMDA Green Mark, are other means of driving best practices. However, implementation and monitoring remain inconsistent worldwide. Globally, the policy landscape still lacks binding targets, harmonised metrics, and consistent reporting mechanisms for energy and carbon performance in data centres. While several initiatives exist and reporting obligations are emerging, they vary in scope and enforcement, leaving aspects that could be further strengthened, including: (1) integrating data centres into national energy and climate strategies to ensure that capacity expansion aligns with renewable energy availability and grid-decarbonisation pathways; and (2) advancing internationally recognised standards for energy efficiency, performance reporting, and operational transparency.

Summary based on CircEular project article in final editing prior to journal submission:

Fan, Y.V., Wilson, C., Kamiya, G., Mastrucci, A. (in preparation). Future projections of data centre energy use in the Shared Socioeconomic Pathways.

10. ICT sector challenges for CE: data centre material footprints

10.1 Summary

As digitalisation accelerates globally, the demand for physical infrastructure, including servers and other IT equipment, power infrastructure, cooling equipment, rack and containment is driving a rapid increase in material use. In this study we quantify material demand across data centre types and projects future trends to 2050. We also compare data centre material demands to limits set by the EU's Critical Raw Materials (CRM) Act. We find that total material demand (Ag, Al, Au, Cu, Fe, Ni, Pb, Pd, Plastics, Pt, Ru, Sn, Zn) is projected to increase by roughly 25-fold by 2050 compared with 2020 levels, with critical raw materials accounting for 7.5%. Hyperscale facilities exhibit higher total demand but lower intensity per unit of energy use compared to traditional (enterprise) and cloud data centres. (See Appendix for method and further results).

These are baseline projections that assume a constant material composition over time. Anticipated shifts in material technologies or the introduction of emerging materials will be addressed in subsequent scenario analyses. We also explore CE pathways for data centres through narrow, slow, and close (NSC) strategies that aim to reduce material demand by improving efficiency (narrow), extending product lifetimes (slow), and closing material loops through recycling and recovery (close). Among the NSC strategies, the 'slow' approach currently has the weakest drivers for implementation, as energy and cost efficiency remains a higher priority, particularly for ICT equipment like servers for which performance and reliability requirements limit lifetime extension. This observation is also supported by expert opinions gathered during a stakeholder workshop with EU data centre experts.

10.2 Challenge & Opportunities for the CE

Data centres provide the computational service that supports digital tools and data-driven systems for potentially enabling resource efficiency across sectors. However, data centres consume not just energy but also materials, including several designated as critical under the CRM (see Appendix). The sector's fast growth, short hardware lifespans, and limited recycling infrastructure intensify its



environmental and supply-chain impacts. Several opportunities exist to embed circularity in data centre material systems. These include designing modular and repairable equipment, implementing component reuse and remanufacturing programs, adopting procurement standards that prioritise recycled or responsibly sourced materials, and improving material traceability across supply chains. Circular business models, such as product-as-a-service for servers or leasing schemes for hardware, can further reduce waste and extend lifetimes. In combination, these actions can align the sector more closely with CE principles and CRM act.

Key challenges include limited design-for-reuse standards, the rapid obsolescence of ICT equipment/hardware, and difficulties in recovering valuable or rare materials from complex assemblies. Moreover, end-of-life management practices often prioritise secure data destruction, which discourages reuse (e.g., cascading uses as a ‘slow’ strategy) or recycling (as a ‘close’ strategy) due to perceived data security risks exacerbated by weak economic incentives. From a CE perspective, particularly within the EU context, further challenges lie in ensuring that recovered materials can be effectively reintroduced into manufacturing processes and in establishing economically viable business models to support such closed-loop systems. Even when materials are successfully recovered, limited domestic refining and manufacturing capacity restricts the extent to which these materials can be reused within the EU. As a result, secondary raw materials are often exported for further processing or component production abroad, where economic feasibility depends on whether recycled materials can compete with virgin alternatives. Consequently, much of the value of circularity is realised outside Europe, while dependency on imported finished products persists.

10.3 Conditions for Enabling the CE

Governance in the ICT sector has not kept pace with its rising material footprint: most existing regulations still prioritise energy efficiency over material sustainability. A more integrated approach is needed to manage the full material lifecycle of data centre infrastructure. Existing initiatives provide a foundation. The EU Critical Raw Materials (CRM) Act sets targets for extraction, processing, and recycling that can guide operators in diversifying supply and supporting material recovery networks. The Eco-Design for Sustainable Products Regulation (ESPR) and the Waste Electrical and Electronic Equipment (WEEE) Directive also promote sustainable design and responsible end-of-life management, although they are not yet tailored to the specific characteristics and material intensity of data centres. To strengthen these frameworks, policy should integrate material use and circularity targets into ICT and data centre strategies aligned with the objectives of the CRM Act. This should be supported by mandatory lifecycle reporting to enhance transparency and accountability across the value chain. In addition, incentives and design standards that promote modularity, repairability, and recyclability are needed to encourage circular design and more efficient material use throughout data centre infrastructure.

The introduction of Digital Product Passports (DPPs) under the ESPR framework could significantly strengthen traceability of materials across servers, racks, cooling systems, and other data centre components, thereby facilitating reuse, refurbishment, and better end-of-life recycling. Although technically feasible through existing product data systems, uptake remains limited due to a lack of regulatory mandate, standardisation, and data-sharing across supply chains. Under ESPR, delegated acts will determine which product groups must carry DPPs, and when those obligations will take effect, including potentially for certain ICT and electronics products. These forthcoming requirements could help bridge current gaps in traceability and better align data-centre operations with objectives under the CRM Act and WEEE legislation. When combined with new circular business models and stronger governance, DPP-enabled traceability could be a critical enabler for enhancing data centre circularity and reducing material dependencies over time.



Summary based on CircEular project article in preparation prior to journal submission:

Fan, Y.V. and C. Wilson (in preparation). Future data centre material demands and circular economy strategies.

Note: As yet unpublished material accounting and projections for data centres are provided in the Appendix. The Narrow, Slow, and Close strategies mapping for data centres are also included in the Appendix. The quantitative CE pathway modelling based on these strategies will be presented in a separate CircEular deliverable for WP6.

11. ICT end-use device challenges for CE: smartphone energy and material footprints

11.1 Summary

The ICT sector accounted for approximately 4% of global electricity consumption and 1.4% of total GHG emissions in 2020 (Malmudin et al., 2024). More than half (57%) of these emissions were associated with user devices, with the remaining share from data centres and networks. Digital devices with rapid turnover, such as smartphones, have become indispensable tools in modern life, driving connectivity, innovation, and social inclusion. In this study we estimate the material composition and embodied energy associated with smartphones, providing insights into resource footprints and dependencies, including for critical raw material (CRMs). We also establish a basis for subsequent projections and modelling of CE strategies. We find that the annual smartphone inflow increased sharply from 2010 to 2023, rising from approximately 296 million to 1.33 billion units. We assessed 14 materials of which aluminium, cobalt, lithium, magnesium, palladium, tungsten, and tantalum are classified as CRMs, collectively accounting for 27.2% of the total cumulative material inflow up to 2023. The findings highlight the significant share of CRMs in smartphones and underline the importance of extending device lifespans and lengthening replacement cycles. Various narrow, slow, and close strategies are being developed to explore potential CE pathways under both baseline and policy-driven scenarios, although their quantitative impacts are yet to be fully assessed. Slow strategies including the use of secondary or refurbished phones have the potential to capture up to 60% resource savings under policy interventions, taking into account end-users' intentions towards reuse identified in survey responses. In the next stages of this work, we will use comprehensive stock-flow modelling with refined CE strategies to identify future potentials to manage material footprints of ICT devices.

11.2 Challenge & Opportunities for the CE

Rapid product innovation, combined with short consumer replacement cycles and design obsolescence of ICT end-use devices including smartphones all continue to hinder circularity. Devices are often engineered for high performance and aesthetic appeal rather than for longevity, repairability, or recyclability. Consequently there are significant opportunities to reimagine how devices are designed, used, and recovered over their life cycles. Circular Consumption Survey conducted by the CircEular project in five European countries, and separately by the ICT industry association, GSMA (GSMA Intelligence, n.d.), highlight the mixed readiness of consumers to embrace circular practices. When asked to rate statements such as "I prefer to buy second-hand rather than new", respondents cluster into three broad groups: early adopters who are likely to engage in reuse or refurbishment under existing conditions; mainstream adopters who are open to shifting their consumption habits if provided with supportive measures, such as financial incentives, product guarantees, or easy access to repair services; laggards who are resistant to change,



suggesting that targeted awareness campaigns, regulatory nudges, or changes in product design will be insufficient to move them toward more circular choices. These differing propensities of consumers towards CE practices is useful input for scenario modelling of behaviourally-realistic CE potentials with respect to ICT end-use devices.

Beyond consumer attitudes, supporting systems and technologies for ICT device circularity are evolving rapidly but remain uneven. Limited collection infrastructure, fragmented repair ecosystems, and the scarcity of certified refurbishment facilities constrain the closing of material loops. However, secondary markets and new service models are rapidly growing. The refurbished smartphone market, for example, was valued at USD 71.7 billion in 2023 and is projected to reach USD 187.9 billion by 2032 (SNS Insider, 2024). This expansion reflects both consumer interest and market opportunities. Leasing and “Device-as-a-Service” (DaaS) models are emerging in which manufacturers retain ownership and responsibility for end-of-life management, effectively transforming hardware sales into long-term service relationships. Globally, 5 billion mobile phones are currently sitting unused, representing a massive stock of recoverable materials and components (USD 8 billion worth of gold, palladium, silver, copper, rare earth elements, and other critical minerals, and enough cobalt for 10 million electric car batteries) (GSMA, 2023). If even a fraction of these were collected and processed, materials could be recirculated into new production with knock-on reductions from mining and refining. Smartphones now integrate multiple functionality including cameras, GPS, and payment cards, reducing the need for single-purpose hardware, a phenomenon called ‘device convergence’ (Bento, 2023). If multifunctional devices substitute for other devices and can be kept in use for longer, the cumulative material and energy footprint per function decreases substantially. Yet this opportunity is often offset by the very pace of innovation that defines the sector. Emerging ICT applications including AI and edge computing demand increasingly powerful processors and specialised chips. Each major performance leap can render previous generations incompatible with new software or services, driving premature replacement and limiting the potential for second-hand use. Design practices also create both challenge and opportunity. Sealed ICT devices optimised for thinness and water resistance has traditionally come at the expense of easy disassembly and repair. Eco-design approaches improving modularity would allow consumers to replace or upgrade specific components. Policy and industry initiatives are beginning to support this shift. Several governments and regional bodies have introduced or strengthened right-to-repair regulations, obliging manufacturers to provide spare parts and repair information. Voluntary or mandatory take-back programs are increasingly common among major smartphone brands, creating pathways for both refurbishment and responsible recycling. The business case for material recovery is also becoming clearer as demand for critical minerals rises and geopolitical supply risks increase.

11.3 Conditions for Enabling CE

CE principles need to be structurally embedded in how ICT devices are designed, regulated, and managed throughout their lifecycle. At the design stage, mandatory eco-design and right-to-repair requirements are critical. Regulations such as the EU Eco-Design Directive and Right-to-Repair rules are already pushing manufacturers to improve the availability of spare parts, repair manuals, and modular components. It could encourage designs that prioritise durability and easy disassembly without compromising performance. Integrating Digital Product Passports (DPPs) can further enhance traceability, allowing users and recyclers to identify material composition, repair history and facilitating efficient reuse and recycling. Equally important are market and business model conditions that support longer product lifetimes and efficient recovery of materials. Leasing and Device-as-a-Service schemes that move beyond one-off hardware sales create a direct economic incentive for manufacturers to retain ownership, extend device lifespan, and take responsibility for refurbishment and recovery of components at end-of-life. Trade-in and buy-back programs run by telecom operators or retailers can help unlock the potentials of “dormant phones”, converting unused stocks into a feedstock for refurbishment and material recovery industries. For these systems to scale, they



must be supported by trusted data-wiping standards, efficient logistics networks, and accessible collection points. In terms of policies, Extended Producer Responsibility (EPR) remains the cornerstone of circular ICT governance. Strengthening EPR schemes to include binding collection and recycling targets, together with fiscal incentives such as reduced sales tax on repair services or eco-labelling for circular devices, would create a motivation for circular business models. In parallel, international harmonisation of e-waste regulation is necessary to prevent the leakage of obsolete devices to informal recycling markets in developing countries. Collaboration between manufacturers, recyclers, policymakers and user is essential.

Summary based on CircEular project article in preparation prior to journal submission:

Fan, Y.V. et al. (in preparation). Quantifying smartphone energy and material footprints with circular economy strategies.

Note: As yet unpublished material accounting and projections for ICT devices are provided in the Appendix. Quantitative CE pathway modelling based on these projections will be presented in a separate CircEular deliverable for WP6.

12. Policy Insights

Each of the preceding sections on specific digitalisation & CE case studies (Sections 2-6) and on systemic digitalisation-CE challenges (Sections 7-11) has identified enabling conditions for ensuring beneficial outcomes for the CE while mitigating risks of adverse or worsening outcomes for the CE. In this final concluding section, we provide two additional perspectives on these enabling conditions: the EU policy environment; and rebound management.

12.1 Policies & Enablers of Digitalisation's Direct Impact on the CE

In the CircEular project, we ran a series of workshops and interviews with policy experts and other stakeholders at the intersection between digitalisation and CE.¹ Overall, experts claim the policy landscape for digital circularity is taking shape but remains fragmented.

Key elements of the EU policy environment

The [EU Taxonomy for Sustainable Activities](#) provides a foundational classification system that improves literacy around circularity, though stakeholders note it does not yet go far enough. A critical gap is the lack of shared terminology and principles across sustainability, ESG (environmental, social, and governance), climate, net-zero, industrial policy, and biodiversity domains, resulting in divided rather than coherent strategies.

[Digital Product Passports](#) (DPPs), part of the [Eco-design for Sustainable Products Regulation](#), emerged as central to stakeholders' circularity vision. DPPs enable product comparison, improve material transparency (including high-risk materials), and enhance reparability for high-value items

¹ T6 Ecosystem researchers conducted 16 interviews with experts in mobility, buildings, digitalisation or circularity more broadly. Interviewees represented industry (including identified best practice business models), research/policy and civic society. The interviews were conducted from January to March 2024. Interviews lasted between 45 to 60 minutes and were online and recorded. The interviews were semi-structured and used a thematic topic guide to encourage a more free-flowing discussion. Topics covered included: links to circular approaches within their business models, challenges to circular strategies, enablers of circularity and future visions for their sector or business in a more circular society. The first stakeholder workshop, entitled "Towards Net Zero through a Circular Economy", was organised on 14th March 2024 in Brussels, in coordination with Bruegel, partner in fellow EU Horizon Project PRISMA. 29 stakeholders attended from across policy, industry, research and civil society covering the three focus areas of digitalisation, mobility and housing. T6 Ecosystems conducted these interviews and organised the first workshop as part of their stakeholder analysis work in Task 1.1 and 1.2 as part of Work Package 1 – Stakeholder Engagement and Outreach.



like computers through better access to spare parts. By improving information availability and visibility, DPPs could also help make circularity more accessible to the public. The [EU Green Deal](#) established a centralised data portal for DPP information, but implementation faces substantial challenges. Each country is developing different systems, creating interoperability problems which were said to be particularly costly for start-ups. While APIs should eventually enable cross-system functionality, this remains aspirational. More fundamentally, DPPs need global coordination since products cross continents. Multiple international initiatives exist but parallel efforts also risk fragmentation. As one example, the UN is involved in a [SDG Digital Acceleration Agenda](#) running in parallel with UNIDO initiatives on textiles and World Business Council protocols. DPPs also face regulatory and legal hurdles around liability when repairs modify products. Since liability rests with whoever put the product on market, self-repair and repair cafés create ambiguity requiring resolution as the system matures.

The [Right to Repair Act](#) operates across the EU with varying fiscal models. For example, France finances support through producer taxes while Austria uses consumer taxes. However, coverage excludes many small appliances that consumers want to repair, and manufacturers' repair manuals remain copyright-protected, limiting detail and third-party modifications.

Reverse logistics—returning products through supply chains—shows potential for circularity, particularly when manufacturers handle returns. Home repair often proves uneconomical due to logistics costs for both repairers and customers, while manufacturers have established systems. However, distributing repair across local installers faces spare parts availability challenges. Sector-specific barriers also exist. In construction, material reuse requires separation into multiple bins, demanding significant urban space and transport energy. These practical constraints underscore the need for context-specific rather than universal circular solutions.

Broader enablers of digital circularity, and the distinct challenges of AI

Beyond specific policy conditions, expert stakeholders noted important enablers for digitalisation to contribute positively to the CE. These included data ownership and accessibility.

Data ownership is important to avoid the control of citizen data by a small number of actors, typically large private-sector firms. This has become particularly salient with AI. The [EU Data Act](#) grants data sovereignty to generators of data (e.g., ICT device or appliance users) enabling them to share data with third parties for fault detection and repair. This breaks manufacturer monopolies over product data and could significantly boost repair practices. Despite difficulties in its negotiation, the [Common Charging Solution](#) demonstrates standardisation's waste reduction potential. Meanwhile, the new [Waste Shipment Regulation](#) will limit EU waste exports, supporting an internal market for waste management.

Digital accessibility concerns permeate circular propositions. Solutions requiring credit cards, online banking, or payment apps risk excluding populations without digital access, creating two-tier participation. Service-based circular business models (e.g. bike-sharing schemes) similarly need an inclusive design.

According to the stakeholders, AI presents contradictions: it's both a potential gamechanger for circularity yet a significant energy and material consumer. Countries must assess whether renewable energy can meet AI-driven demand. Technology serves both linear and circular practices, requiring careful policy framing rather than assumptions about inherent benefits. The [AI Act](#) is welcomed as a step in the right direction.



The [European Green Digital Coalition](#) has developed ICT sector measurement standards, but uptake remains limited due to difficulties assessing rebound effects, defining activity boundaries, and data scarcity. This reflects broader measurement challenges in capturing digitalisation's systemic circularity effects.

Stakeholders also emphasised the importance of developing narratives that support quality of life with fewer resources, addressing the tension between narrow and slow CE approaches. Ultimately, ICT can function as a circularity enabler only with appropriate policy framing. Technology is neither inherently beneficial nor neutral, and organisational management culture often presents barriers to ICT adoption for sustainable practices. Success requires coordinated regulatory harmonisation, global coordination beyond EU borders, upstream circular design thinking, and recognition that digitalisation and AI use cases must be tailored rather than standardised across sectors and populations.

12.2 Policies & Enablers of Digitalisation's Indirect Impacts on the CE

The enabling conditions and elements of the CE policy environment in the previous section are focused on reducing and managing the direct impacts of ICT infrastructure and devices on material flows. In this final section, we turn to enabling conditions for ensuring the indirect impacts of digital applications on material flows in non-ICT sectors can make a positive contribution to the CE. One of the major problems here is rebound and induced demand. If digitalisation reduces the cost, time, inconvenience or friction of an economic activity, industrial process, or system function, then – *ceteris paribus* - demand for that activity, process, or system function will increase. This applies also to activities that are seemingly CE-aligned such as trading second-hand goods online. If rebound drives aggregate growth then CE-outcomes may be undermined.

Heuristic framework for linking indirect impacts of digitalisation for the CE

Taking a firm-level perspective, we have developed a framework examining the channels and conditions that enable circularity strategies to translate into resource reductions (both virgin and recycled materials), while connecting to reduced extraction, disposal flows, and climate mitigation.

The framework identifies three main channels through firms' actions affect the broader economy and resource systems: finance, material markets, resource requirements.

The 'financial aspects' channel examines how circular strategies influence production costs, pricing, profit margins, and investment decisions. These changes, in turn, affect consumer demand for circular products. For instance, if circular practices reduce costs and firms pass those savings to consumers through lower prices, consumption may increase, potentially creating a rebound effect. Firms may also retain higher profit margins and reinvest them in resource-intensive activities. When digitalisation is involved, it is essential to assess whether it raises or lowers production costs, alters the firm's market power, or changes consumer preferences regarding product attributes. This will help determine where costs or benefits are likely allocated and the potential substitution effects within consumers' consumption baskets.

The 'material markets' channel captures how circular practices directly affect the supply and demand of materials, including substitution between virgin and recycled resources. Three potential impacts are: decreased demand for materials (e.g., material efficiency), increased demand for secondary materials (e.g., integration of recycled materials), and increased supply of secondary materials (e.g., development of recycling activities). Whether the increased supply of secondary materials replaces the supply of virgin materials also determines overall supply variation (including virgin and recycled). As noted, digitalisation is a potential enabler of the circular economy (indirect effects) rather than a circular strategy itself. Its role in the material channel is also indirect. Digitalisation can amplify or



attenuate these three impacts. For instance, digitalisation might help circular strategies reduce material use more effectively, thereby strengthening the overall decrease in material demand.

The ‘resource requirements’ channel examines the infrastructure and energy requirements needed to support the implementation and functioning of circular systems. Implementing circular strategies consumes resources, which partially offsets their potential savings. In addition, the value chain ripple effect describes how customers and other downstream actors will require resources to access or consume circular products or services. For instance, customers could spend additional time and resources accessing circular options (like driving further to repair cafes or zero-waste shops). Digitalisation is particularly relevant here, and it is essential to account for the resources it requires and weigh them against its contribution to enhancing the impacts of circular strategies in the material channel.

Table 6 summarises this heuristic framework for characterising the indirect impact of digitalisation on the CE and the likely presence of rebound effects that need mitigating.

Table 6. Assessing potential impacts of digitalisation on the framework’s channels

Financial channel	What is the effect of digitalisation on production costs? How does digitalization impact firms’ market power and consumer preferences?	This determines whether production costs increase or decrease and how these changes pass through to final consumer prices (linked to willingness to pay). Depending on the effect on final prices and product substitution, overall consumption may rise or fall, potentially triggering a rebound effect. If firms capture additional rents, their allocation toward resource-intensive versus resource-sober activities will directly impact resource use.
Material channel	How much can digitalisation increase the efficiency of circular strategies?	This will determine whether the direct effect of circular strategies on material markets is amplified or not.
Resource channel	What is the resource consumption of digitalisation? Will digitalisation imply ripple effects in the value chain?	This will determine whether digitalisation consumes more resources than it helps to save.

Conditions for mitigating digital rebound that undermines CE outcomes

Figure 1 set out conditions needed to mitigate rebound effects from digital applications. These conditions include limiting virgin resource extraction through enhanced governance systems, quotas, environmental standards, and taxation mechanisms. These constraints should be directed primarily at resources whose use is expected to increase, particularly if such resources tend to complement the use of other resources. Constraints should also target virgin materials whose recycling supply is expanding. Steering demand toward saturation through policy instruments like quotas and storage constraints that prevent unlimited accumulation of goods are more challenging to implement.

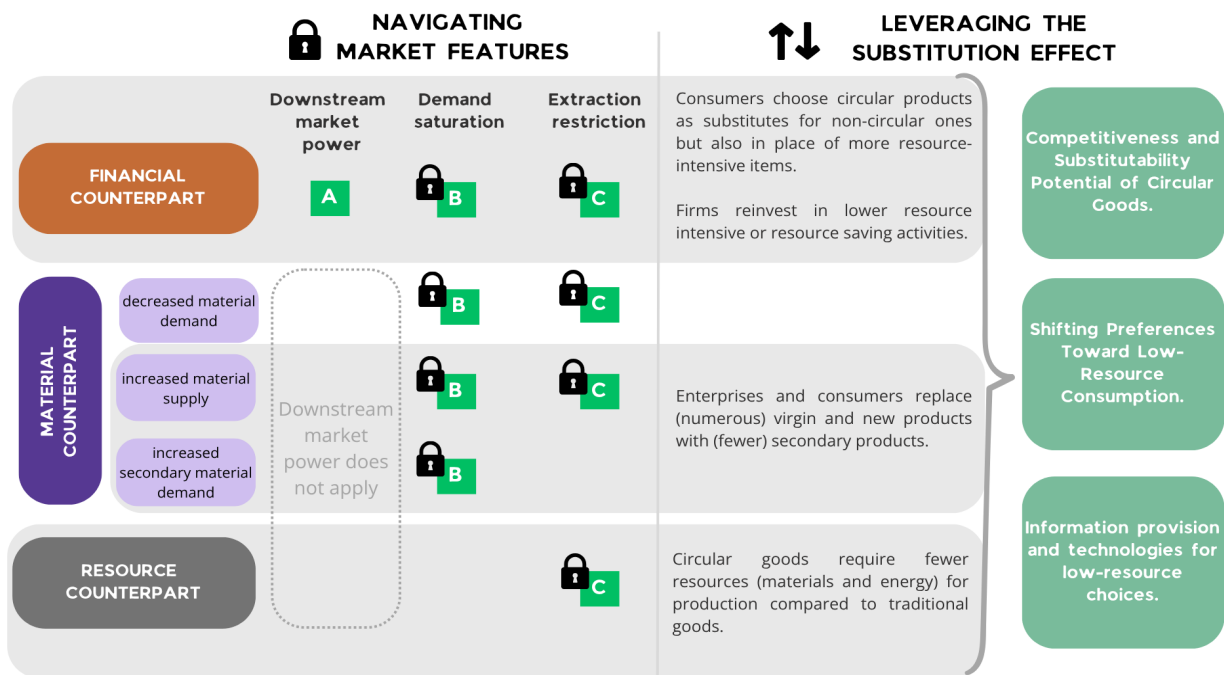
Making circular goods economically competitive with virgin alternatives through tax subsidy schemes or extended producer responsibility systems helps incentivise substitution effects. Consumer preferences must systematically favour low-resource activities to ensure that circular goods (e.g., lightweight shared vehicles) replace high-intensity products (e.g. single occupancy SUVs) rather than displacing goods that were already less resource-intensive (e.g., public transportation).



Consumer preferences can be addressed by environmental education and institutional design that make consumption of resource-intensive goods more difficult (e.g., reduced parking space). Comprehensive information systems are needed to enable producers and consumers to track, assess, and choose genuinely low-resource-intensive goods and activities, ensuring transparency and accountability throughout the supply chain.

While market power plays a crucial role in determining the effectiveness of circular strategies, no single degree of market competition guarantees lower resource consumption. Both monopolistic margins and competitive low prices can drive increased resource use, meaning antitrust regulation alone cannot ensure resource reductions; what matters is that any rents generated by circular strategies should be allocated toward resource-saving activities. Policymakers can either tax concentrated rents and redirect them toward environmental objectives or create incentives that guide allocation toward lower-resource investments and sustainable consumption patterns.

Figure 1. Conditions for circular strategies to lead to reduced demand for materials.



Overall, this framework shows that digitalisation must be assessed across financial, material, and resource channels to determine whether its indirect impacts on material resource consumption is beneficial, or whether it inadvertently increases material needs through rebound effects, infrastructure demands, or value chain ripple effects.

Ultimately, digitalisation's resource footprint (direct impacts) must be weighed against its contributions to enhancing CE outcomes (indirect impacts). The conditions enabling firm-level and consumer-level circularity to translate into macro-level resource reductions include: limiting extraction, steering demand toward saturation, ensuring competitive circular alternatives, and support consumers in adopting low-resource-intensive lifestyles.

Summary based on published CircEULAR project article:

Joltreau, E., Verdolini, E and Cattaneo, C. (2025) From (Micro-)Circularity To (Macro-)Mitigation, <https://doi.org/10.5281/zenodo.16982589>



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Note on Use of Generative AI

The authors of this report used generative AI (ChatGPT5 educational license) for assisting with synthesis of CircEULAR researchers' own work (e.g. digesting longer papers and reports into short summaries). All text generated was reviewed, validated, and edited by the authors.

[Oxford University guidelines](#) for responsible use of generative AI in research were followed. These guidelines are informed, inter alia, by research funders' guidelines including Horizon Europe. In short form, the guidelines state that:

All users should:

- 1 Remain ultimately responsible for GenAI content used in research
- 2 Understand the implications of uploading material subject to Intellectual Property Rights
- 3 Follow information security advice on using generative AI safely
- 4 Declare use of GenAI in research and communicate openly
- 5 Aim for reproducibility/transparency and robustness in results and conclusions
- 6 Learn how to use GenAI tools responsibly to maximise their benefits, including by undertaking training
- 7 Be mindful of the environmental impact of using GenAI tools

Appendices

Appendix: ICT sector challenges for CE: data centres material footprint

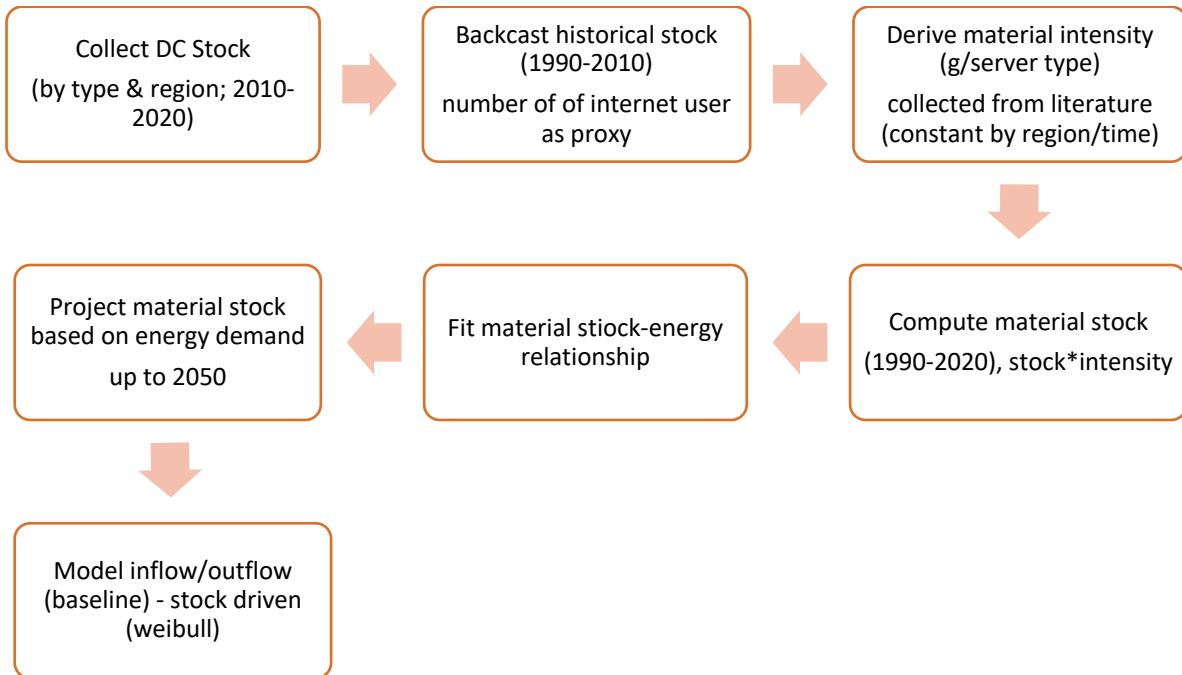


Figure A 1. Steps Involved in modelling the material demand and flows of data centres.

Note: Parameterise Lifetime Distributions: Weibull shape parameter (k) = 2; Baseline scale (λ): IT Equipment = 5 years, Power = 15 years, Racks/Containment = 20 years, Cooling = 15 years

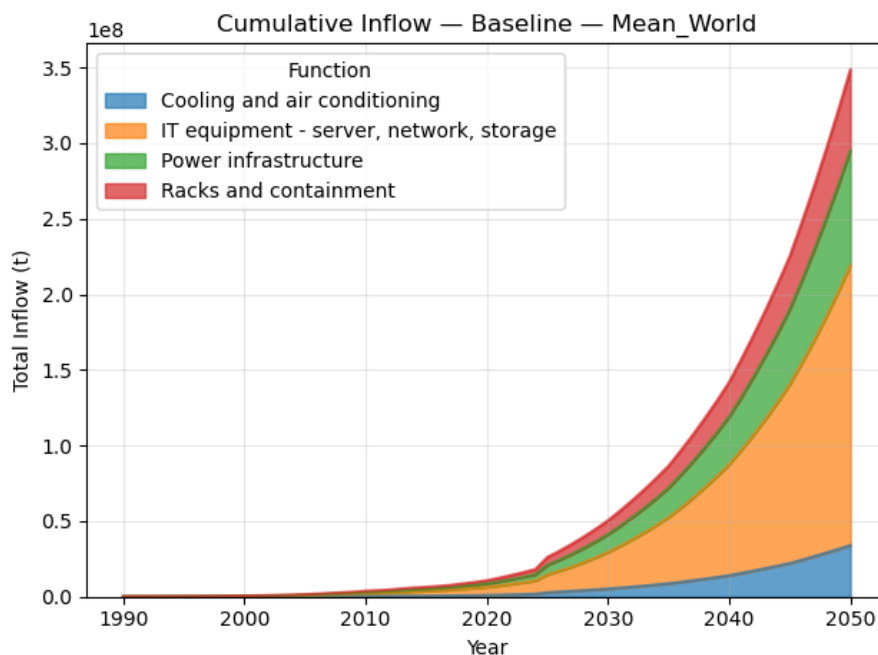


Figure A 2. Cumulative material inflow of data centre by component.

Note: The larger share of IT equipment is driven by shorter replacement rates

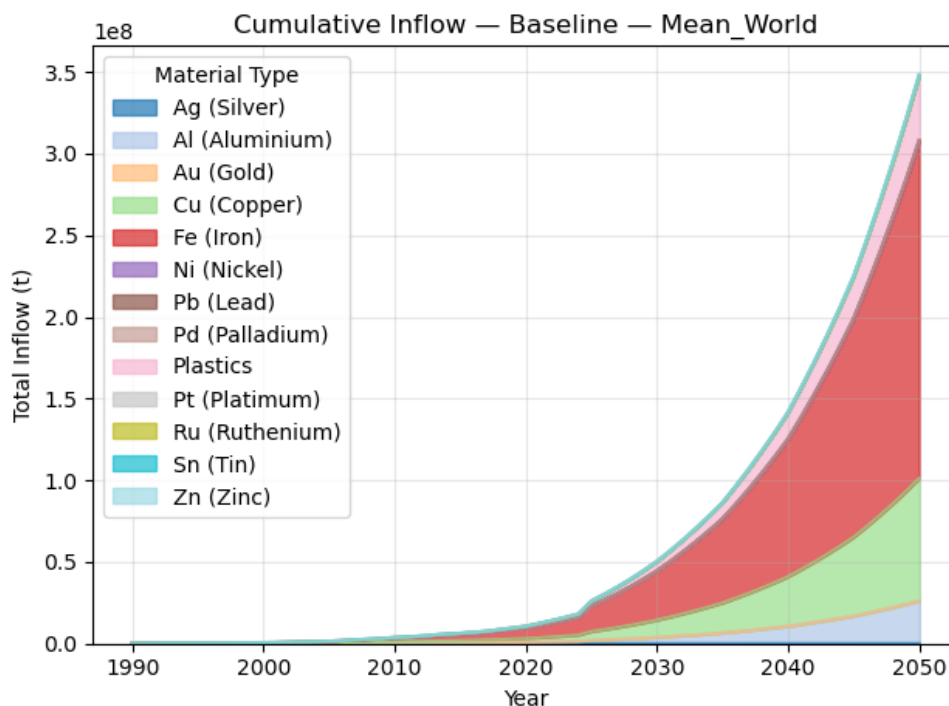


Figure A 3. Cumulative material inflow of data centre by material type.

Note: The material selection follows the materials included in an LCA study of data centres by type. Among the assessed materials, Al, Pd, Pt, and Ru are classified as critical raw materials, accounting for 7.5% of the total cumulative material inflow up to 2050. Emerging materials such as gallium will be addressed next in scenario modelling rather than in the baseline projection.

Table A 1. Cumulative material inflows range (low, mean, high).

Region	Cumulative Materials Inflows Range (Total) up to 2050 (t)		
	Low	Mean	High
Latin America	1.433575e+06	1.790449e+06	2.147323e+06
Middle East and Africa	1.850128e+06	2.139710e+06	2.429291e+06
Europe	1.642011e+07	2.646896e+07	3.651781e+07
North America	6.874067e+07	1.517909e+08	2.348410e+08
Asia Pacific	7.603676e+07	1.663416e+08	2.566465e+08
Total	1.644812e+08	3.485316e+08	5.325819e+08

Note: The mean values are plotted in Figure A1 and A2



Table A 2. Global annual material inflows in 2020, 2030, 2040, 2050.

Material Type	Annual flow (t/y)			
	2020	2030	2040	2050
Ag (Silver)	91.04	483.96	1071.45	2381.24
Al (Aluminium)	79945.56	415480.75	907737.38	2014229.04
Au (Gold)	21.85	116.15	257.15	571.50
Cu (Copper)	225101.93	1196662.10	2649328.27	5888012.37
Fe (Iron)	632649.47	3287908.30	7183382.71	15939608.07
Ni (Nickel)	1444.44	7678.77	17000.27	37782.34
Pb (Lead)	1687.20	8969.32	19857.46	44132.31
Pd (Palladium)	9.71	51.62	114.29	254.00
Plastics	120308.53	625248.96	1366036.46	3031174.40
Pt (Platinum)	0.21	1.10	2.43	5.40
Ru (Ruthenium)	0.22	1.16	2.57	5.71
Sn (Tin)	2694.67	14325.10	31714.80	70484.70
Zn (Zinc)	655.46	3484.48	7714.41	17144.93
Total	1064610.29	5560411.77	12184219.65	27045786.01

Note: Orange = critical (exceeding thresholds), blue = below CRM thresholds but are included as strategic raw material, others = below CRM thresholds, based on CRM list 2023

Table A 3. Critical Raw Materials (CRMs) with projected data centre (DC) material inflows in Europe for 2050, measured in t.

CRM	Global Production ^a	Import Reliance	EU consumption ^a	DC Demand (Europe) in 2050
Bauxite (E)	336,197,330	89 %	16,146,077	
Aluminium (P)	62,734,647	58%	4,980,933	106,065.85
Palladium	213	High	20	13.60
Platinum	185		72	0.29
Ruthenium	35.1 (Ir, Ru, Os)		17.25	0.31

Note: ^aValues represent the 2016–2020 average from SCRREEN (2023): <https://screen.eu/crms-2023>. By 2050, the projected Palladium demand from European data centres (not just EU member states) represents approximately 68% of the EU's average annual consumption and 6.4% of global production. Palladium already exhibits a high import reliance, exceeding the indicative resilience threshold (60%) inconsistent with the CRM's aim to ensure that at least 40% of annual consumption is processed within the EU. Continued data-centre growth could therefore intensify pressure on supply chains and hinder progress toward other CRM objectives, including sourcing at least 10% of annual consumption from EU extraction, 25% of annual consumption of strategic material come from recycled materials produced within the EU, and limiting dependence on any single third country to no more than 65% of annual consumption. Strengthening circular strategies and improving recovery rates are important to alleviate these pressures.



Table A 4. Circular economy strategies of data centres

Strategy	C E	Description	Technical Potential	Behaviour Potential	Policy Potential
Zombie server removal	N	Removal or decommissioning of idle servers that consume power and occupy capacity without performing useful tasks.	High: Readily achievable using monitoring tools to detect idle or underutilised servers. Automation and virtualisation make implementation technically simple. Mainly issue with enterprise servers	Moderate: Operators may resist due to perceived operational risks, data redundancy requirements, or lack of visibility into server use.	Moderate/High: Could be addressed under the EU Ecodesign for Sustainable Products Regulation or data centre energy efficiency standards - indirectly supportive through energy efficiency standards; lacks direct material relevance.
Consolidation	N	Reducing total equipment needs by consolidating workloads through virtualisation	High: Proven and widely available	Moderate/High: Operators often motivated by cost and performance optimisation, but end-users may resist shared infrastructure for control or latency reasons.	Moderate/High: Can be promoted via EU Energy Efficiency Directive, no explicit material efficiency measures
Reduce material: design efficiency	N	Reducing the material content through lightweight, modular, or minimal material design.	Moderate/high: Through product redesign, and additive manufacturing	Low/Moderate: Uptake (especially IT equipment) depends on manufacturer innovation, trade off with energy efficiency and demand for eco-designed equipment.	Moderate: ESPR provides potential framework, but implementation for data centre hardware is still emerging
Lifetime extension	S	Extending product lifespans through repair, refurbishment, modular upgrades, & long-term maintenance.	Moderate: software and modular hardware can extend server lifetimes by several years.	Low/Moderate: Operators often replace equipment early for performance or reliability	Moderate: Emerging policy support through proposed Right to Repair Directive and existing WEEE and Circular Electronics Initiative
Redeployment/cascade	S	Reusing decommissioned servers in secondary markets or less performance-demanding area	High: Feasible with proper data erasure, testing, and compatibility assurance.	Low/Moderate: Operators cautious due to data security and brand perception	Moderate: Current policy partially supportive; reuse encouraged but not mandated for professional ICT equipment
Collection-recycling	C	Collecting and processing end-of-life data centre equipment for recovery	Moderate/low: Technically feasible, economically limited, disassembly & separation remain challenges.	low: cost and security risk	High/Moderate: regulated under WEEE Directive; strengthened by CRMA recycling targets; and eco-design

Note: The quantification of high, moderate, and low levels, as well as the corresponding references, will be provided in the dedicated deliverable report on circular economy pathway modelling. This table presents only the qualitative narrative at this stage.

Appendix: ICT sector challenges for CE: Device's energy and material footprint

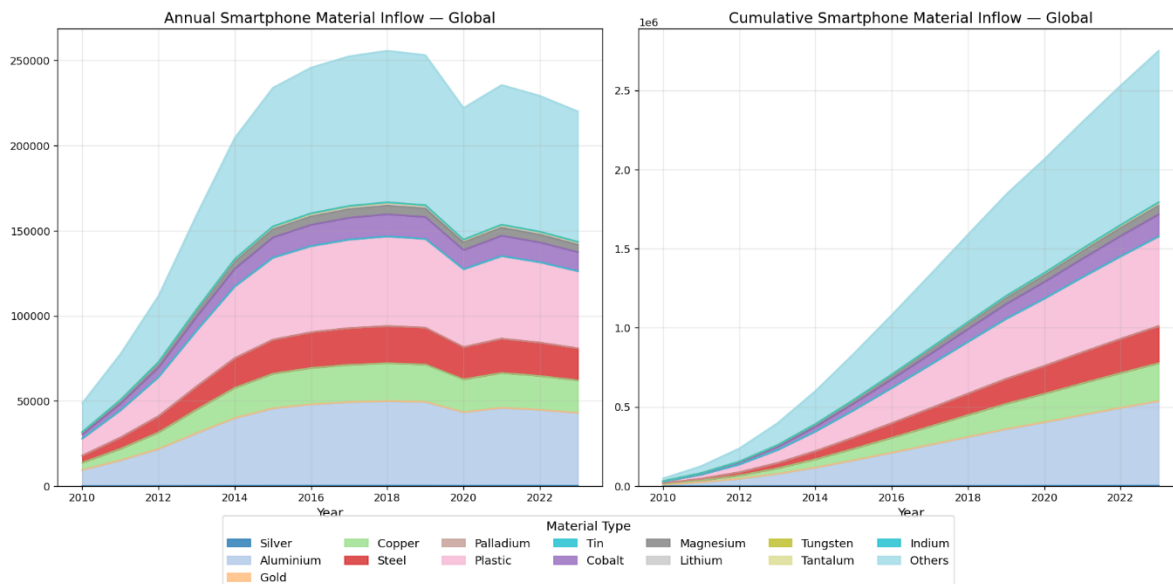


Figure A 4. The annual and cumulative material inflow (t) of smartphone from 2010-2023.

Note: Estimates are modelled based on the number of smartphones sold to end users worldwide, as reported by Statista, and the material intensity values reported by (CEPS et al., 2019). A broader range of materials has been identified in (Gómez et al., 2023) and (Bookhagen et al., 2020). Among the assessed materials, aluminium, cobalt, lithium, magnesium, palladium, tungsten, and tantalum are classified as critical raw materials, collectively accounting for 27.23% of the total cumulative material inflow up to 2023.

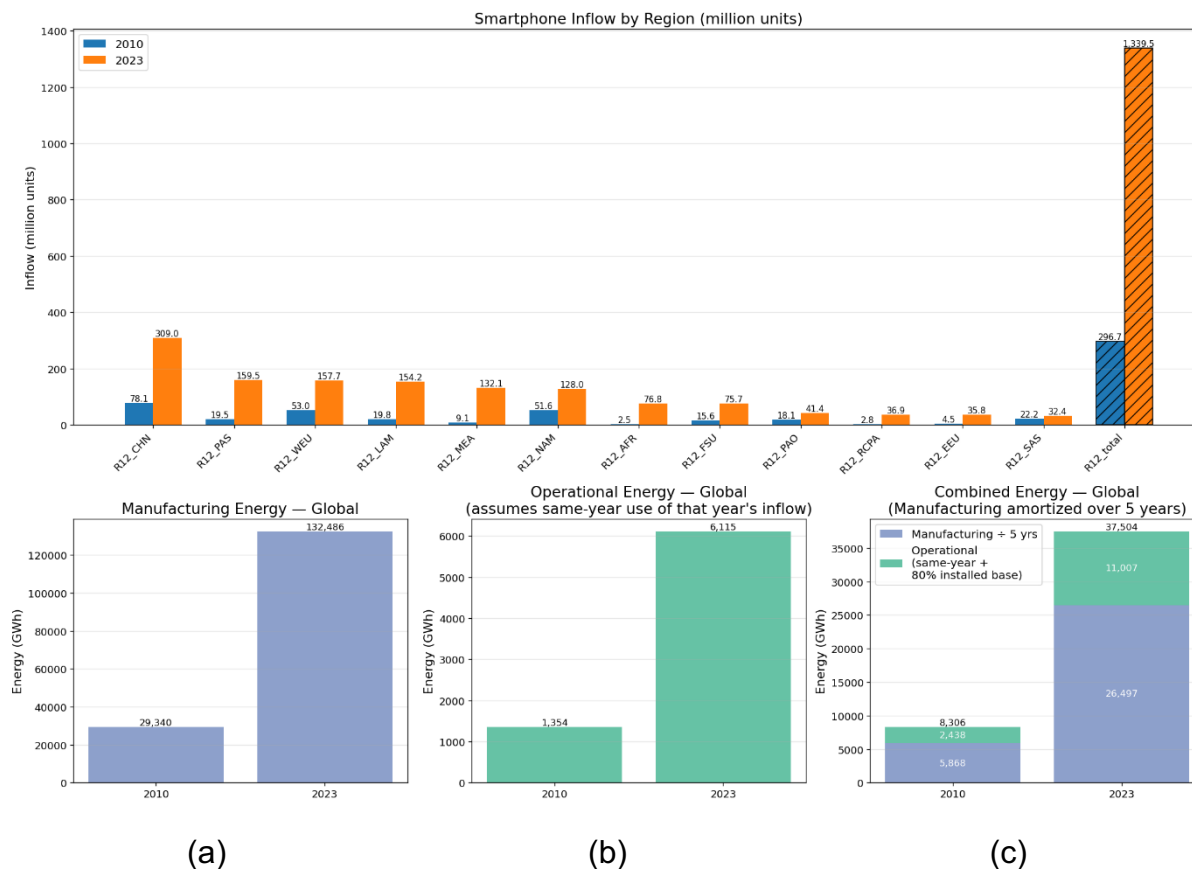


Figure A 5. Smartphone inflow by region and estimated energy consumption associated with smartphones in 2010 and 2023.

Note: (a) energy consumed by manufacturing (embodied) the smartphone inflow in 2010 and 2023, (b) operational energy of smartphone inflow in 2010 and 2023. (c) Sum of embodied energy (divided by 5) of smartphone inflow in 2010 and 2023 and the operational energy of inflow smartphone and additional 80 % of operational energy from existing stock. Manufacturing energy intensity is assumed to be 98.91 kWh per unit, based on the average of ten reported data sources. Annual operational energy is estimated assuming one hour of charging per day with a charger power rating between 5 W and 20 W. These values represent the baseline estimates and assumptions: manufacturing energy is distributed over a five-year average device lifetime, while operational energy includes an additional 80 % adjustment assumption to account for the existing installed stock beyond new devices. Further modelling stages, including the stock estimation, will include sensitivity analyses and scenario pathway modelling. The complete dataset will be made openly available in the final publication and accompanying documentation.

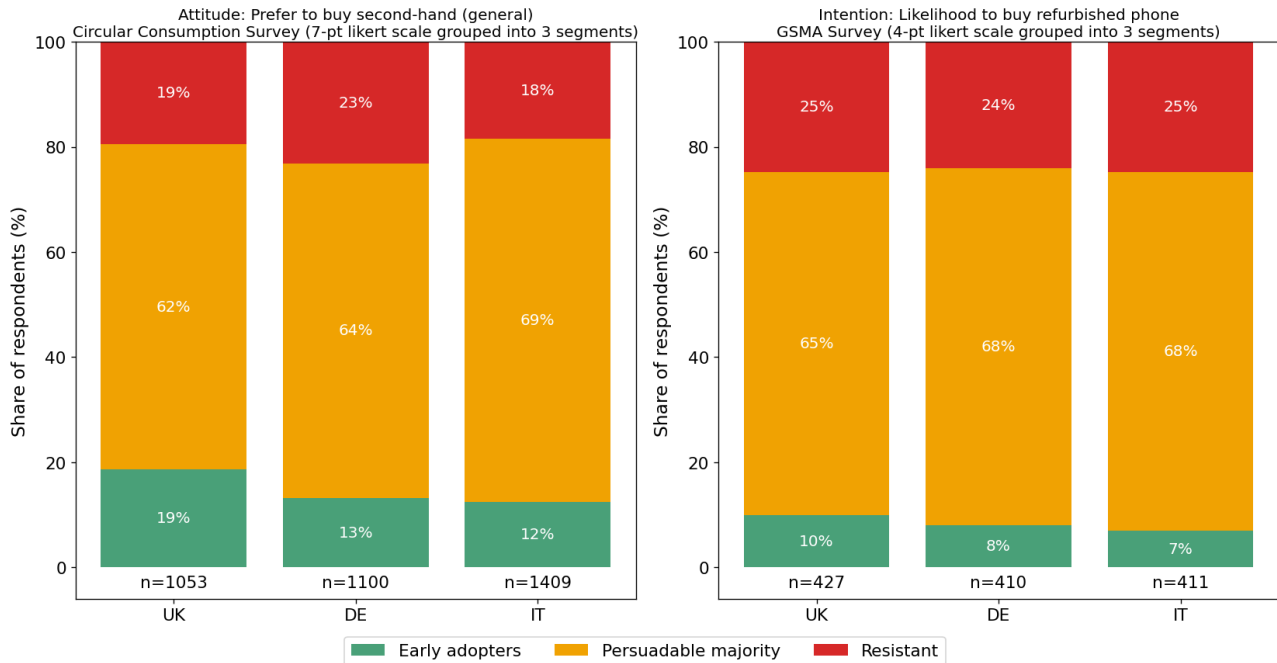


Figure A 6. Consumer readiness toward circular smartphone practices based on survey responses in the United Kingdom (UK), Germany (DE), and Italy (IT).

Note: Responses to two questions (in different survey): “I prefer to buy second-hand rather than new” (7-point Likert scale) and “How likely are you to consider buying a pre-owned refurbished phone?” (4-point scale) were grouped into three potential categories: early adopters, persuadable majority, and resistant. Early adopters represent respondents already inclined to circular practices (Likert 1–2 / “Very likely”), the persuadable consumer includes those who may shift with appropriate incentives or policy measures (Likert 3–6 / “Somewhat likely–Somewhat unlikely”), and resistant consumers (Likert 7 / “Very unlikely”) indicate strong preferences for linear consumption.

In the 7-point Likert scale, we grouped respondents who selected values 1 and 2 as early adopters, 3–6 as the persuadable majority, and 7 (strongly disagree) as resistant. We acknowledge that this grouping involves a degree of subjectivity—particularly the inclusion of respondents with a value of 2 as early adopters and the exclusion of those with a value of 6 from the resistant category. This choice reflects the specific framing of the question, which asked whether respondents would buy second-hand rather than new. Those selecting 1 (“very likely”) or 2 (“likely”) can be reasonably interpreted as individuals already inclined to choose second-hand even in the absence of additional incentives or policy interventions. In contrast, responses from 3 to 6 suggest varying degrees of openness or hesitation, which we interpret as persuadable, rather than firmly committed or resistant positions. We acknowledge that alternative cut-offs (e.g., defining only 1 as early adopter and including 6 as resistant) could yield different visual or interpretive outcomes.



Table A 5. Summary of “narrow,” “slow,” and “close” strategies to enhance the circularity of ICT devices.

CE Strategies	Narrow	Slow	Close
Strategies	Optimise device use (e.g., multipurpose, dual profiles, BYOD)	Extend component lifetime (behavioural, technical, software support)	Formal collection and recycling
	Material substitution & lightweight design with standardised components, reduce raw material demand	Resale to secondary markets	
Drivers or Interventions	Eco-design sustainable product regulation/green design	Right to repair/ repairability index/modular design	Digital product passport initiatives
	Technologies development (material intensity)	Online second-hand platform	Circular supply chains
	Low carbon lifestyle movements	Product as a service	WEEE directives
			UN e-waste coalition
			Product as service & buy-back or take-back programs
			Basel convention/global e-waste monitor
			Advanced recycling of CRM/Robotics-assisted disassembly

Note: BYOD refers to “Bring Your Own Device.” The strategies summarised in this table form the basis for the scenario modelling conducted in this study.



DELIVERABLE 5.1

Synthesis Report on the Potential Contribution of Digitalisation to the Circular Economy (Supplementary Materials)

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Building Information Modelling

Title

Adoption Drivers and Barriers of Building Information Modelling (BIM) in Europe

Abstract

Building Information Modelling (BIM) enables time, cost, and materials savings in building design and construction. However, the promise of BIM is yet to be realised. We assessed the current state-of-the-art in BIM adoption and use, identifying both barriers and opportunities across six dimensions defined by the PESTLE framework (political, economic, social, technical, legal, environmental). We combined market survey, literature review, and new insights from 41 expert interviews with architects, consultants and constructors across 11 European countries. We find BIM is used principally by larger firms as a design and data-processing tool to enable collaboration between project partners. BIM's value proposition is primarily to streamline construction processes not improve resource efficiencies. Barriers to BIM adoption include interoperability issues, split incentives and value chain fragmentation, and weak economic incentives particularly for small firms. In the medium-term we find two important drivers of more widespread BIM adoption. First, institutional investors in the commercial buildings sector are increasingly pushing green certification standards for which compliance is demonstrated by BIM. Second, whole building lifecycle emission regulations for buildings mandated by the EU from 2030 will require BIM calculations. Four pioneer Northern European countries already have similar emission limits in place. Under realistic assumptions, we estimate material savings enabled by BIM in new building construction could deliver 21-31% embodied emission reductions after 10 years.

1. Introduction

Buildings and construction account for about 41% of European greenhouse gas emissions (Ramboll, 2023). Building information modelling (BIM) can help identify material and operational efficiencies in buildings particularly at the construction stage (Waqar et al., 2023). BIM is a generic name for software models used in the design, build, operation, maintenance, refurbishment, reuse and demolition of buildings as well as other infrastructure such as roads and tunnels.

BIM has support in European policy as a tool for providing data on buildings (EU, 2023), for reducing design and build costs through process and material efficiencies (ECTP, 2022), and potentially for reducing buildings' embodied carbon emissions (EPBD, 2024). The European Construction Technology Platform (ECTP) have estimated BIM can achieve cost savings up to 13-21% from design and construction and 10-17% from operations (BCG, 2016; ECTP, 2022).

1.1 BIM: What it is & what it does.

BIM is defined as “a set of processes, tools, and technologies capable of producing, using, and updating a virtual model of information throughout the life cycle of the building” (Schamne et al., 2022). There are numerous BIM platforms such as ArchiCad, Autodesk Revit, Infurnia, Navisworks, Tekla and Trimble. Multiple applications or tools can run using model data. Many incorporate third party data that are self-created or purchased, such as tools to calculate points for green certification schemes (Wong & Zhou, 2015). Data standards have been established to enable interoperability between BIM and tools, although data losses remain an issue (Chong et al., 2017; Han et al., 2021; Schamne et al., 2022). The main BIM dimensions and applications are shown in Table 1. A full description of BIM and related tools is provided in Appendix A1.

Table 1. BIM dimensions & applications.

BIM Dimension	Potential Applications
level 3	3D design co-ordination & input from different skills & trades. Clash detection. Calculation of material quantities. Bills of Materials (BoM) production.
level 4	includes all level 3, plus time element, e.g.: Phased ordering and planning.
level 5	includes all level 4, plus costings, e.g.: Costing of Bills of Materials.
level 6	includes all level 5, plus end-of-life, e.g.: Recycling and reuse planning.

Kreider and Messner (2013) distinguish 18 use cases for BIM grouped into 5 categories describing the handling and use of building information: gather, generate, analyse, communicate, realise. For example, the ‘realise’ category includes use cases for building information to fabricate, assemble, control, and operate the building. Charef and Emmitt (2021) extend this to 38 BIM use cases, of which 11 inter-relate to similar aspects of building design and management, 19 are potential enablers of circular economy approaches during the building’s active lifecycle (prior to decommissioning), and 8 relate to buildings’ end-of-life and waste management.

Designing a building in BIM creates a coherent set of drawings that can be updated automatically when a design change is made in one area. Coherent drawings lead directly to early detection of design inconsistencies and accurate Bills of Materials. This can help reduce materials waste. BIM allows multiple professionals to collaborate on individual copies of the model simultaneously before combining the results and checking for inconsistencies. In addition to collaboration, BIM facilitates document management, time saving in a multi-user environment, virtual reality to assist design, and the ability to use mobile devices on site (Autodesk Revit, Undated). When combined with job scheduling, BIM offers an advanced, integrated control mechanism to ensure timely delivery of projects. These time and cost efficiency use cases for BIM apply more to multi-actor, multi-firm jobs than single architect-contractor relationships.

1.2 BIM at different stages of the building lifecycle.

BIM has applications throughout the building lifecycle from design through construction, refurbishment, and end-of-life. Giorgi et al. (2022) describe BIM as “an enabling tool for monitoring the use of resources during the building lifecycle, sharing information between operators, and stimulating reuse potential”.

However, architects and owners prioritise immediate transactional value from using BIM rather than material or energy efficiencies over the full building lifecycle (Nikmehr et al., 2021). Consequently, most scientific studies on BIM relate to the design, planning and construction phases of buildings (Çetin et al., 2022; Hollberg et al., 2020; Nuttens et al., 2018).

Refurbishment costs can amount to over half the building’s total lifetime cost. Despite the potential for BIM to facilitate material-efficient refurbishment, its use at this stage of the building lifecycle is limited (Chong et al., 2017). BIM’s relative newness means most buildings needing refurbishment do not have a BIM, and tendering processes mitigate against costly BIM creation (Okakpu et al., 2022).

BIM can also be applied to construction, demolition and waste management (Akinade et al., 2018; Han et al., 2021; Schamne et al., 2022). This includes BIM functionality for designing for disassembly particularly for temporary buildings or internal fit-outs (Katebi et al., 2024), and aiding the incorporation of existing structures into renovation designs. BIM can further assist reuse of existing end-of-life building sections, particularly carbon-heavy structural load-bearing elements (e.g. Bertin et al., 2020; Mohammed et al., 2024).

1.3 Aim of this study

BIM can enable process efficiencies in building design, build and management, with resulting benefits along not just economic dimensions but also environmentally by reducing buildings' material footprints. However, these benefits are preconditioned on BIM being in widespread use throughout the building value chain and lifecycle.

In this study we characterise the current state of BIM use among architects and construction firms in different European countries and market segments. Our aim is to identify the drivers and barriers of BIM adoption as a basis for projecting its future potential contribution to material savings and embodied emission reductions in building construction.

Box 1. Definitions & Terms.

AEC	architecture, engineering and construction
BIM	building information modelling
CAD	computer assisted design
EBPD	European building performance directive
LCA	lifecycle analysis or lifecycle assessment (for estimating emissions over a building lifetime)
WLC	whole life carbon

2. Literature Review

We review scientific and grey literature in three main areas: current barriers to BIM adoption; BIM use in lifecycle materials, energy, and emissions analysis; the BIM regulatory landscape. Details of our literature search terms and methodology is provided in Appendix A2. From this literature review we identify knowledge gaps that our research design aims to fill.

2.1 BIM current adoption, and barriers to adoption

Rates of BIM adoption vary significantly across Europe (Charef et al., 2019). Some European countries including UK, Denmark and Italy have made BIM mandatory for government-procured public building contracts and have developed standards governing its use (Giorgi et al., 2022). As a result the Nordic countries and the UK are market leaders in the use of BIM (Charef et al., 2019); see also Figure 1.

Around two thirds of European architects' firms use 3D computer assisted design (CAD), but the overall BIM adoption rate is estimated at 31%, with significant variation among firms of different size (ACE, 2020). 80% of European architects work in 1 or 2-person firms; 54% of all architectural work is residential and over 50% of all work is refurbishments. Larger firms write their own BIM tools in response to perceptions of need or customer demand, potentially to gain a competitive edge (Foster & Partners, 2023). But creating a BIM is costly: any savings accruing to the clients during design and construction are unlikely to benefit the architects directly (Walasek & Barszcz, 2017). Architects may

adopt BIM if they foresee cost savings in their own practices, but BIM is not perceived to save office time or money (Okakpu et al., 2022).

Several other barriers to BIM adoption by architecture, engineering and construction (AEC) firms have been identified (Andersson & Eidenskog, 2023; International Bar Association, 2022; Pidgeon & Dawood, 2021a). This include difficulties implementing BIM (Lindblad & Vass, 2015; McLoughlin & Hayes, 2019) and devising protocols for its use (Akinade et al., 2015; Basta et al., 2020; Nikmehr et al., 2021).

Adoption and implementation issues principally relate to the systematic precision needed to make use of BIM tools (Table 1), requiring working practices within the firm to be reorganised during implementation (Cesnik et al., 2019). This changes job roles and perceptions of seniority (Andersson & Eidenskog, 2023), typically favouring those with digital skills and away from those competent in established pre-BIM practices. This changes power relations and invisible knowledge infrastructures within firms (Andersson & Eidenskog, 2023; UK BIM Alliance, 2021).

Efficient use of BIM also requires sharing model data with contractors: the short-term project-by-project culture in the AEC industry and an unwillingness to share information for perceived competitive reasons (Andersson & Eidenskog, 2023) mitigates against collaborative practices and reduces incentives for BIM adoption (EMF, 2013; Jacobsson et al., 2017).

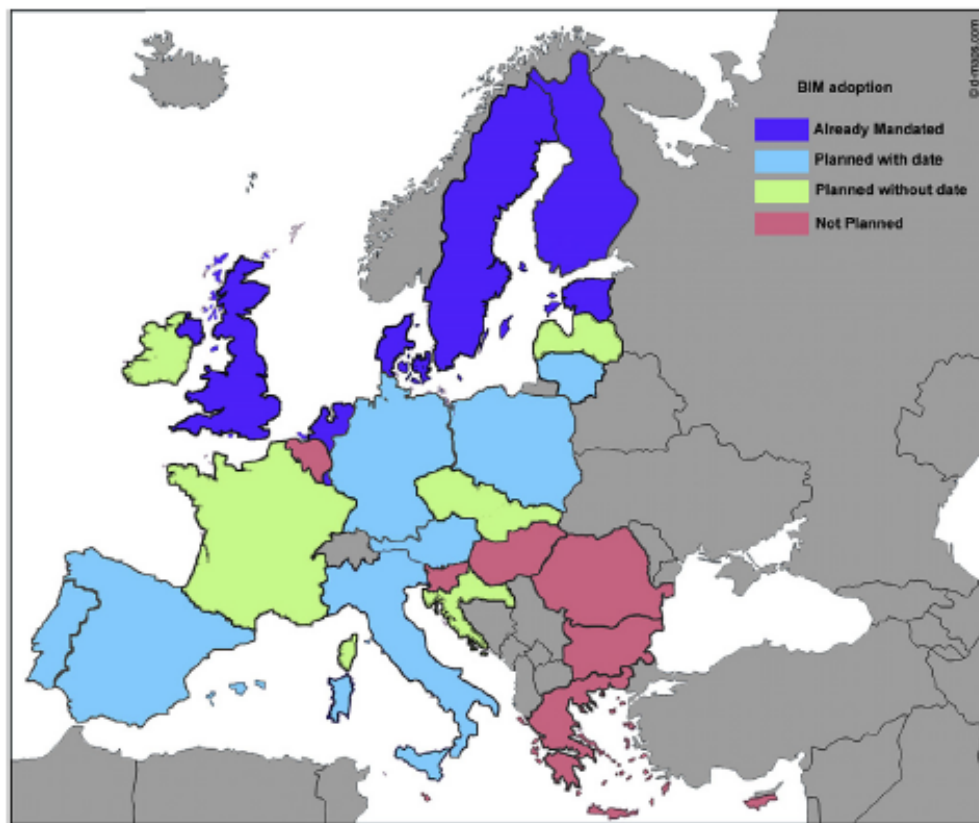


Figure 1. Extent of BIM Adoption across Europe as of May 2017. Source: Charef et al. (2019).

2.2 BIM, materials savings, and embodied emission calculations

BIM lifecycle analysis (LCA) tools create inventories of the energy and materials needed across the supply chain and value chain for a building in order to calculate resulting greenhouse gas emissions.

Various studies apply BIM-LCA to buildings at either design stage (e.g. Basbagill et al., 2013) or construction stage (e.g. Hollberg et al., 2020).

BIM offers a data foundation that can be used for narrowing, slowing and closing material loops in line with circular economy frameworks (Giorgi et al., 2022; Çetin et al., 2022), though few studies involve real-world cases (Gharaibeh et al., 2024). Materials savings are primarily determined at the design stage (Han et al., 2021; Nikmehr et al., 2021; Schamne et al., 2022). Studies of BIM use for clash detections that avoid rectification work emphasise labour savings rather than materials savings (e.g. Azhar, 2011; Giel & Issa, 2013).

Few studies quantify purchased materials which are wasted during the build. Available statistics commonly aggregate construction and demolition waste into a single category. One study in the Netherlands found that the amount of building material wasted was 1-10% of the amount purchased, with a further 9% by weight ending up as construction waste (Bossink & Brouwers, 1996). These provide a reference point for the magnitude of potential material savings from BIM use. A firm survey found tender prices that reflect both labour and materials costs can be reduced by 6-10% using BIM (Gharaibeh et al., 2024).

A South Korean study assessed two buildings where the design was revalidated by BIM, achieving savings of 4.3% and 15.2% of materials (Won et al., 2016). As building types vary across international geographies, these results are not directly transferable to Europe.

BIM-LCA also facilitates iteration of building design towards minimising both embodied energy and projected operational energy over the building lifespan (Deng & Lu, 2023; Soust-Verdaguer et al., 2017). ‘Embodied energy’ refers to energy used in the extraction and fabrication of components and to energy used in the construction process. Emissions embodied in new buildings are many times the annual operational emissions (Ness & Xing, 2017); most also occur immediately rather than over a building’s life. Material selection, component reuse and prefabrication are key for reducing embodied energy (ECTP, 2022; Ness & Xing, 2017; Waqar et al., 2023). These are largely independent of BIM use.

Embodied carbon (or greenhouse gas) emissions are derived from the materials and their embodied energy. Embodied emissions data for each building element is held in individual Environmental Product Declarations (EPDs). Using BIM for LCAs requires automated data exchanges with an EPD database, although data interchange is recognised as a BIM weakness (Deng & Lu, 2023; Kim, 2019).

Relatively few studies focus on BIM’s use for helping meet emission reduction or circular economy goals. Those that do tend to assume BIM is an enabler of cost savings and material efficiencies as a basis for energy and emission savings (ECTP, 2022; Olanrewaju et al., 2022; Waqar et al., 2023).

2.3 BIM and the regulatory landscape

The focus of legislation in EU member states has been on optimising building performance to improve operational energy efficiency (EU, 2023). This has led to a 32% reduction in operational carbon emissions since 1990 but only 6% fewer embodied emissions (Green Alliance, 2018). Regulations on operational energy usage stipulate maximum levels of heat loss per square metre through walls, floors and ceilings. Architects and constructors can achieve these levels by selecting materials with specific properties; BIM is not necessary.

However, in 2024 the revised Energy Performance of Buildings Directive (EPBD) gives member states until 1 January 2027 to set regulations for limiting and reporting on “whole life carbon” (WLC) for all new buildings by 1 January 2030, and those over 1000m² by 1 January 2028 (EPBD, 2024). Whole life

carbon (WLC), also referred to as “lifecycle global warming potential” is an indicator that quantifies the carbon emissions attributable to a building throughout its full life cycle, including both embodied and operational emissions. These encompass the manufacturing, transportation, construction, use, and end-of-life phases of buildings.

LCA will be necessary to report on a building’s whole life carbon. This will likely boost BIM adoption. Although LCAs are possible using 3D CAD, they are easier from BIM as it holds more data on each building element. The EPBD does not specify whether calculations should be carried out at planning or completion, or both.

Prior to the EPBD for all EU member states, legislation limiting embodied emissions or whole life carbon emissions in buildings has already been passed in four countries in the past five years: Denmark (BR18), France (RE2020), Sweden (Swedish Climate Declarations) and Netherlands (MPG); see Table 2 for details. All differ in methodology, coverage and exemptions. However, well before 2030 these limits will have legal force: buildings exceeding the limit can be denied occupation permits (see also Nair et al., 2021 for the Swedish case). Norway, Finland, Belgium and Iceland are developing similar regulations (One Click LCA, 2022). Certain cities like London also require whole life carbon calculations in larger developments, but as yet there is no legal limit (London Assembly, 2024).

2.4 BIM knowledge gap: firms’ perspective

Overall, scientific literature on BIM has been concerned with its development, applications, use cases, and potentials. There are fewer studies on BIM adoption drivers and barriers from firms’ perspective, as noted by Çetin et al. (2022) and Walasek & Barszcz (2017).

An exception is Charef and Emmitt (2021) who interview 20 BIM practitioners and related experts to understand BIM use cases that could contribute to circular economy. They identify a range of relevant new BIM uses including: digital mock-ups for end-of-life; materials passports; project databases; data checking and updates; circularity assessments; materials recovery processes; and materials banks (Charef & Emmitt, 2021). However, in their case they were interested in how BIM could overcome barriers to circular economy practices, rather than the barriers to BIM adoption which is a necessary precondition to its beneficial use cases.

Giorgi et al. (2022) used semi-structured interviews on the drivers and barriers of circular economy with 38 stakeholders from 5 countries in the value chain for buildings including policymakers, investors, designers, manufacturers, construction companies, and waste managers. Others have similarly used expert interviews to understand architects, constructors, and other stakeholders’ perspectives on circular economy practices and challenges (Kanters 2020, Cruz Rios et al. 2021, Kirchherr et al. 2018). However, none of these firm-oriented studies has focused specifically on BIM.

In terms of technical potential, BIM can save time, money, and materials. In the absence of firms’ perspectives, firms which don’t adopt BIM are assumed to lack information, education and process understanding (Huang et al., 2021; Mirarchi et al., 2020; Muller et al., 2019). This is particularly the case in smaller firms among which BIM adoption is lower (Nast & Koch, 2021).

However, reliable adoption data is sparse and generally based on market surveys for which respondents are self-selecting. For example, a 2023 industry survey suggests that BIM’s penetration rate is 70% amongst construction professionals, but two thirds of responders were consultants and so not representative of the AEC sector (NBS, 2023). Other data showed only 5% of small business

adopters have implemented level 3 BIM (e.g. cost and material saving functionality such as clash detection and Bills of Materials) (Hosseini et al, 2016).

We address the use to which BIM is actually put and the value the users see in it, ranging from being an essential business tool in large firms to a costly irrelevance for many smaller firms (Soust-Verdaguer et al., 2017; Hollberg et al., 2020).

Table 2. Current regulations limiting buildings' embodied emissions from materials and construction in four EU member states.

Country	Timeline	LCA calculation notes	Exemptions	Key Sources
France Reg = RE2020	From 1 Jan 2022 for residential & office buildings, 2023 for all buildings. Limits tightened in 2025, 2028 and 2031.	Life cycle emissions (embodied and operational). Result expressed in kgCO ₂ e/m ² . Over 50 year life. 'Dynamic LCA': future emissions are discounted, so embodied emissions in the build has greater impact. Assessed at permitting and completion.	Industrial buildings.	Ministere de la Transition Ecologique, (2024), storaenso.com (2023)
Denmark Reg = BR18	LCA submissions necessary from 2023 for all buildings unless < 1000m ² (due 2025).	Limit: 12 kgCO ₂ e/m ² /year for all buildings > 1000m ² , lowering to 8.6 kgCO ₂ e/m ² /yr in 2025. Over 50 year life. Modules A1-A5*. Single assessment at completion. The limit ratchets down further every 2 years.	Buildings <1000m ² until 2025. Renovations. Plumbing and electrical works.	Burohappold, (2023)
Sweden Reg = Swedish Climate Declaration	Submissions necessary against building permits issued from 1 Jan 2022. Legal limits enforced from 1 July 2025.	Life cycle emissions (embodied and operational). Limit as kgCO ₂ e/m ² /year set in 2025 at 75% percentile of reported values in 2022. Over 50 year life. Modules A1-A5*. Plans to lower limit in 2030 (25% reduction), then 2035 and 2043. Single assessment at completion.	Operational emissions until 2027.	Boverket, (2023), One Click LCA (2022), Storenso.com, (2022)
Netherlands Reg = MilieuPrestatie Gebouwen (MPG)	From 1 Jan 2018. Residential buildings from 1 July 2021.	Limit: expressed as € environmental damage**: €1.0/m ² /year, reduced to €0.8/m ² /year from 2021. Covers fabric of new building plus any component replacements. Over 50 year life. Single assessment at planning.	All exempt except new offices and residential. Excludes operational emissions.	Dutch Environmental Database, (2020), Knowledge Hub (2023)

* Modules of whole life carbon assessments: A1 Raw Material Supply; A2 Materials Transport; A3 Manufacturing; A4 Materials Transport; A5 Construction & Installation processes. (B1-B5 cover materials during building use; B6 is operational energy for heating, cooling and powering the building; C1-4 covers end-of-life).

** Environmental damage valued at the social cost of carbon and the result expressed in €/m²/year. Includes measures other than CO₂e, such as material toxicity and ozone layer depletion.

3. Research Design

We use a series of semi-structured expert interviews with architects and construction firms to test and extend findings from the literature review on real-world adoption and use of BIM, and BIM's potential contributions to material, energy, and carbon emission reductions.

We answer the following research questions:

RQ1. What are the drivers and barriers of BIM adoption among firms for building design and construction?

RQ2. What contribution can BIM make to reducing whole life carbon emissions from buildings if it becomes widely adopted?

3.1 Method: Expert interviews

We conducted interviews on our research questions in two tranches: (i) architects and construction firms in EU countries; (ii) architects in the four countries in which whole life carbon legislation has already been introduced (Denmark, France, Sweden, and Netherlands). Interviews in the first tranche covered BIM adoption drivers and barriers from the practitioners' perspectives and experiences. Interviews in the second tranche focused specifically on BIM use in whole life carbon (WLC) assessments in pioneer countries to help understand the wider potential for BIM once the revised EPBD enters into force.

3.2 Sample & sampling strategy

Expert interviews aim to cover the main sources of variation in understanding and experience of BIM. As noted in the literature review, this varies as a function of firm size and country context. These provided the two dimensions of our sampling frame. We use a simple stratification to split a practical number of interviews across different firm types and sizes, and country groups (Table 3; full details in Appendix A2). Small architect firms account for 80% of architects and 41% of turnover, medium architect firms 17% and 41%, and large architect firms 3% and 18%, respectively (ACE 2020). The sample covered each market segment.

In total, we contacted and followed up with 114 firms, leading to 41 interviews (Table 3).

We contacted European architects through internet-accessible registers of professional body memberships. This sampling frame omitted certain countries (e.g. Lithuania) where the publicly available register does not include contact details, and Finland where there is no public register in English.

Construction firms and contractors are not members of registered bodies in the same way as architects: there is no central list in each country to select from. We contacted construction firms at trade shows, through snowball sampling (recommendations from architect interviews), and through institutional contacts (see Appendix A2 for details). Few interviewees specialised in a single sector (residential, commercial, infrastructure).

Both literature and our initial interviews found that relatively few BIM models were used in construction, fewer were passed to new owners, and of these only a small proportion would be used in facilities management (Durdyev et al., 2022). Accordingly, we did not seek to recruit facilities managers for interviews.

Our 41 interviewees included multiple users of BIM and related tools: architects, engineering consultancies, project managers, constructors and building facility managers.

In the first tranche of interviews, architects in the sample are labelled A1-A18 and constructors C1-C11. In the second tranche, architects, valuers and other firms are labelled L1-12 (as this second tranche was focused on lifecycle emissions).

Table 3 also summarises the interviewees' current use of BIM levels 2-4 with more functionality (and complexity) at higher level (see Table 1 for explanation). Architects using BIM level 2 used BIM to draw but did not make use of the data associated with the drawings. The constructors not using BIM included a household name UK housebuilder. The constructors using BIM level 4 scheduling were all multinationals, with the clients prepared to pay for additional third-party software licences.

3.3 Data & Analysis

We use a topic guide to semi-structure our interviews, covering the key themes identified from the literature review related to our research questions. The full interview guide is provided in Appendix A3.

All interviews were in English which was generally the interviewee's second language, resulting in variation in how words were used. Accordingly, we avoid analysis of specific words and word counts.

We transcribed the interviews before summarising and coding the interview data in Nvivo. For our coding analysis we use the PESTLE framework which is widely used to understand how Political, Economic, Social, Technological, Legal, and Environmental factors affect an organisation's strategy or practices – in our case, BIM adoption. The PESTLE framework is useful for systematically identifying pressures, weaknesses and opportunities for organisations in both current and potential contexts (Housni et al., 2024; Kansongue et al., 2023). In their study of BIM use cases for the circular economy, Charef & Emmitt (2021) similarly use a PESTLE-type framework (with Organisational instead of Legal) to organise their analysis of barriers – but of circular economy applications of BIM rather than BIM adoption and use *per se*.

We use a thematic coding template derived from applying the PESTLE framework to the literature. A summary of the thematic categories and codes is provided in Table 4, rank ordered by the number of interviews in which codes were mentioned.

Within PESTLE, the line between 'Political' and 'Legal' can be blurred. We included political and legislative support within 'Political' and compliance with regulations in 'Legal'.

Table 3. Expert interview sample characteristics and identifier labels (upper rows) and summary statistics on use of BIM (lower rows).

	Tranche 1 interviews on BIM adoption drivers and barriers				Tranche 2 interviews on BIM use in whole life carbon assessments
Country group	Small architect (1-2 people)	Medium architect (3-9 people)	Large architect (>10 people)	Constructors	Architects, Valuers & Others
BIM use already mandated	A1 (UK) A2 (Netherlands) A3 (Norway) A4 (Sweden)* A5 (UK)* A6 (UK)*	A8 (Netherlands) A9 (Netherlands) A10 (Norway)* A11 (Netherlands) A12 (Netherlands)	A14 (Netherlands)	C1 (UK) medium builder C2 (UK) international consultancy C3 (UK) large builder C4 (UK) building data automation firm C5 (Netherlands) large developer C6 (Netherlands) family builder	L1 (Denmark) large architect L2 (Denmark) architects association L3 (Denmark) large architect L4 (Denmark) large architect L5 (Denmark) large architect L6 (Sweden) small architect L7 (Sweden) small architect L8 (Sweden) medium architect L9 (Sweden) financier & developer L10 (international) climate bonds L11 (UK) property valuer L12 (UK) property valuer
BIM mandate planned but not yet implemented	A7 (Croatia)	A13 (Ireland)	A15 (Latvia) A16 (Latvia)	C7 (France) medium sized BIM consultancy C8 (Spain) tier 1 contractor C10 (France) multinational contractor	
No BIM mandate planned **		A18 (Slovenia)	A17 (Belgium)	C9 (Belgium) BIM software start-up C11 (Greece) multinational contractor	
Total n	7	7	4	11	12
of which ..					
do not use BIM	4	3	0	2	-
use BIM level 2	2	1	1	0	-
use BIM level 3	1	3	3	4	-
use BIM level 4	0	0	0	3	-
n/a (consultants)	-	-	-	2	-

Notes: * short interviews; ** prior to EPBD entering into force

Table 4. PESTLE framework themes used to code interview data, rank ordered by frequency of occurrence (number of interviews, and number of references within interviews). Codes in bold in each PESTLE dimension box were the original codes in the interview guide.

# interviews # references			# interviews # references		
POLITICAL			TECHNICAL		
regulations, government support			prefabrication, calculations, tools, design, data		
regulations	6	11	design	10	14
ECONOMIC			designing issues	8	11
value, costs, savings, strategy			comms (technical)	6	8
demand	9	11	consultants	6	9
cooperation	6	9	digital divide (roles)	6	7
better control	5	7	digitalisation	6	7
efficiency	5	7	no calculations	5	8
strategic	4	5	BIM use or not	4	7
tangible cost	4	5	building maintenance	4	4
better design	3	6	discipline	4	5
business models	2	2	methods	4	11
marketplaces	2	3	standards	4	7
intangible values	2	5	tool writing	4	4
other	2	3	comms (people)	3	4
size	2	3	data transfer	3	3
skills shortage	2	2	workflow	3	4
digital divide (economic)	1	1	approach	2	3
embodied C savings	1	1	age	1	1
LCA economic	1	1	LEGAL		
speed	1	1	clients, model ownership, reuse		
use of 2D	1	2	building regs	13	19
SOCIAL			government work	6	8
BIM skills, BIM use issues, digital divide, practices			BIM ownership	4	4
BIM training	6	10	use of consultants	2	2
no interest	6	8	ENVIRONMENTAL		
education	5	5	reuse, design for disassembly		
decisions	4	6	clients (sustainability)	3	3
interest	4	6	design for disassembly	3	3
varying use	4	6	awareness	1	1
BIM other	3	6	operational C calcs	1	1
culture	3	4			
other	3	4			
3D CAD other	2	2			
levels 4&5	2	2			
3D training	1	3			
client choices	1	1			
digital divide (social)	1	1			
country differences	1	2			
qualifications	1	1			

3. Results

We first present and discuss our main findings from the expert interviews on the drivers and barriers of BIM adoption, using the individual dimensions of the PESTLE framework as way of structuring the data, before providing an integrated perspective.

3.1 Political

In the 'Political' dimension of PESTLE, we cover EU regulations, BIM mandates and rules, and whole life carbon regulations (see Table 4 for thematic codes).

BIM adoption rates have stalled over the last 5 years (NBS, 2023). Interviews support this: either firms were BIM-reliant or they rarely, if ever, used it. Only interviewee A11 planned to implement BIM in the future (to enable tendering for municipal work). Two others (A7 & A13) had BIM capability but constructor indifference meant little opportunity to use it. Most firms work in market niches that may not require BIMs for publicly funded buildings (C4, C8). No interviewee mentioned the revised EPBD with its mandate for whole life carbon (WLC) assessments for all new buildings by 2030 (EPBD, 2024).

Interviewees in Belgium, Latvia and Slovenia (A16, A17, A18) expected their governments to follow France, Denmark, Sweden and the Netherlands in passing building lifecycle emission regulations. They regarded BIM as necessary to enable detailed embodied emission calculations, although 3D CAD can be used (C3). Almost all buildings are designed digitally and lifecycle emission regulations incentivise use of the model for environmental purposes, otherwise embodied emission calculations are infrequent and only advisory. Constructors are resistant to change (A2, A7, A12) unless required by regulations. In countries where current regulations need an as-built model on building completion this places significant new demands on constructors (e.g., investment, training, work practices), many of whom currently work from architects' 2D plans and do not use or update models at all.

While there are many imperfections in BIM calculations and process (see 'Technical' section below), building lifecycle emission legislation has 'changed the landscape' of the industry (L4) and concentrated minds in ways which would not have happened otherwise (L5). For example, suppliers are now producing more Environmental Product Declarations (EPDs) on embodied emissions in building components and materials (L4, L9). This is viewed positively (L4, L5, L9; see also Boverket, 2023). However, concern was expressed that municipalities have no expertise to check the resulting LCA-derived estimates (C4, C5, L4). For example, in Spain, legislation requiring submission of a BIM was passed without industry support: many councils do not have software licences to open the model (C8). Moreover, there is suspected manipulation of EPDs by manufacturers (L2). This lack of verification is potentially serious: if there is no difference between buildings with apparently low and high lifecycle emissions then credibility will be undermined (L2). Borderline illegitimate practices in tendering have already been experienced (C5).

Both Denmark and Sweden have introduced embodied emission regulations with relatively weak initial limits that did not force immediate changes in material use or construction methods. In Denmark the initial limit of 12 kgCO₂e/m²/yr was higher than the prevailing norm (10 kgCO₂e/m²/yr) (L3). In Sweden, the limit in 2025 is to be set at the 75th percentile of reported lifecycle emissions from 2022 (Table 2). Both cases allowed time for firms to prepare for compliance, including BIM adoption. Mandatory lifecycle emission limits in France will force material changes from 2028 (C10). This will in turn affect roles and responsibilities within the sector. In practice one LCA value is needed at design/planning stage, and one from an as-built BIM on handover and building occupation. In most countries, these two LCA calculations will be carried out by two different organisations:

architects and constructors, and even the architects may not have been responsible for selecting all the materials (C9, L2). Constructors, often untrained and inexperienced in using or amending BIMs, may need to complete the as-built model. This faces skills barriers (see ‘Social’ section) (L2).

3.2 Economic

In the ‘Economic’ dimension of PESTLE, we cover the value of BIM to firm processes and business models, including through realisable cost and time savings (see Table 4 for thematic codes). Interviewees’ perceptions and experiences varied across different firm types and market segments.

Adoption drivers of BIM cited by architects include coordination and communication between designers and specialists, better design, better control of the design, more accurate tendering, and more efficient working practices. Adoption barriers raised included system costs, time investment in both training and building design, and lack of demand from clients - even large clients needed educating about the benefits of BIM (C11; see also Andersson & Eidenskog, 2023). Both architects and constructors see the potential for BIM uptake to help with more accurate Bills of Materials, less rework, and so material savings, as well as higher speed (A3, A11, A13, C6, C8, C11).

Adoption barriers were emphasised in particular by interviewees from small firms. Notably, the economic benefits of BIM are intangible and difficult to convert to monetary value, but the costs are more directly experienced. In an economic environment in which each project must make a standalone profit, this mitigates against both experimentation with BIM and collaboration with project partners with whom the relationship will end once the project completes (C8).

Larger architect firms were generally unequivocal in their support of BIM’s communication and coordination benefits (A2, A3, A15, A16). One interviewee gave an example of BIM supporting projects with over 100 cooperating designers across 70 disciplines and trades (A17). Another interviewee remarked that “the business is run on BIM, and that time saving, money saving or client demands for BIM are irrelevant, the business will use it anyway” (A8). Others commented on the efficiencies and better control gained through BIM: in error reduction (A15); in reduction of information losses on data exchange (A11, A15); in more accurate material specification (A2, A3, A13); and in improved (though unspecific) efficiency (A7, A16, A18).

In contrast, smaller architect firms saw less economic value in BIM. All but one (A6) small-firm architect interviewee used 3D CAD or BIM, but most identified significant barriers to BIM use. Reasons included lack of demand from clients (A3, A13, A15), no constructor demand for data beyond the 2D drawings and 3D visuals from a CAD system (A1, A7, A13), and time spent learning new software (A1, A5, A10, A11): “it’s a time thief” (A10), “too fiddly” (A1), “cumbersome” (A6). 80% of EU architects work in 1-2 partner firms and their staple is the 54% of the market that is single homes (new builds, extensions, renovations) (ACE, 2020). Creation of a project from new takes more time in BIM (A7). Creating it by adapting a pre-existing design is quicker if BIM is set up to do this (A9, C6). More than compensating savings are expected in time and material during the build (NBS, 2023), but these savings generally do not accrue to the architects, although this depends on architects’ roles which vary by country and by firm. Vertically integrated firms (design and build) do not have this split incentive problem.

The picture on economic incentives for BIM use from contractor interviewees was different from architects. Not all contractors working for large firms use BIM, some simply take 2D printouts (A14) and the benefits of BIM to constructors are not always apparent. One interviewee said: “to my mind, there’s no point in having a BIM that isn’t also connected to construction program and cost” (C2). The benefit of BIM was undermined if it could not be continuously compared with actual progress

during the build. Newer tools for constructors include systems utilising a mobile camera to automatically compare build accuracy to the schedule and plan in BIM. This offers more reason for contractors to use a BIM, but is unlikely to result in material efficiencies through waste reduction (C9, C10). BIM enables offsite modular construction (A8): this saves materials as well as time, but for a constructor, quantifying the material savings remains difficult (C8).

3.3 Social

In the 'Social' dimension of PESTLE, we cover the skills and training implications of BIM for personnel, the effect of BIM on roles and responsibilities both within firms and across industry networks (see Table 4 for thematic codes).

Earlier papers observe that disciplined use of BIM is essential (Eastman et al., 2011; Nast & Koch, 2023): this is reinforced by interview findings. Decisions such as allocation of responsibilities, setting key immutable design coordinates and the level of detail in the planned model are initial requirements (A3, A15, A17, A18). Internal company procedural manuals are key to control of the process (A15). Furthermore, in some EU states the division of responsibilities for the BIM between different entities in the supply chain is documented and codified (A8, A18).

In some areas, there is clearly a BIM skills shortage (A7, C11). For small-medium sized firms in countries where BIM adoption is low, using BIM as a communication and cooperation tool is difficult (A7, A18) due to network effects: the benefits of BIM increase with user numbers. Adoption by smaller builders is slow (A1, A2, A7, A12, A18). Constructors have enough work and cannot see reasons to change their materials or methods (A2, A7). Resistance to change current practices is high (Aksenova et al., 2019; Lindblad & Vass, 2015).

There are two 'digital divides' detectable in architects' interview data: within firms and between firms. Younger architects develop into more skilled software users (A18) once they have been trained to firm standards (A14, A15). Some firms also spend money on external training (A9, A15, A16). In Latvia, technical school trainees are trained on BIM principles (A16), but this seems to be exceptional (A3, A7, C8). The digital divide between firms is evidenced in literature (NBS, 2023), and interviews showed larger firms use more software and have more training, though much of it in the sample of interviewees was done on-the-job and in-house (A1-A10, A14-A17).

Within larger architects firms, there is a tangible split between 'designers' and 'technical architects', the latter using BIM in more detail than the designers (A15, A16). In medium and large firms the technical architects outnumber the designers (A8, A15), and "you need a very skilled architect overseeing the process, though the younger ones may be more fluent in the computer skills" (A16). "There is a danger that the company leaders get left behind with the technology and the detailed knowledge of the processes in their own firms" (A16), as "the technical skills are held by [technical architects]" (A8). This impacts the power structures within the business: "it's always discussion like, OK, the technical drawers [make] a big part of the income of the company" and "Still, we are with 30 people and we are with eight or nine architects and the rest of the company is the case managers and technical drawers? So they have a bigger vote" (A12).

The construction sector demonstrates a large digital divide between the majority who did not use 3D CAD or BIM beyond the printed output from an architect's model (C1, C3, C9, C10), to large firms integrating the latest video-to-BIM comparison systems for progress chasing (C8) and self-developing IKEA-like building kits-and-diagrams to turn construction sites towards assembly operations only (C10). The higher-tech operations were focusing on speed to save money: secondarily, there are material savings from better cutting plans and less rework (the former rated at 7%-10% of materials

cut in factories) (C10). The high-tech initiatives tend to de-skill the build process: recognising that workers tend to have a “low level of education and in some cases they are not very fluent with the language either” (C8, also C2). Only one constructor was trying to move from paper to digital-only on-site: a Dutch family firm with a very stable workforce (C6). This requires giving workers the right level of detail in small models which update continuously and can be interrogated simply on small devices (C5): they do not access the main model. At the higher tech end, interviewees in France and Belgium reported difficulties getting the BIM as they required it from architects, to the extent that they rebuilt their own (C9, C10) or became heavily involved in its making (C7). Two interviewees from different southern European states flagged serious cultural issues with BIM adoption as construction practice is to make money from cost overruns and problem rectification. The constructors in these states will not welcome the control and transparency that BIM brings and are unlikely to implement it swiftly or thoroughly.

When smaller buildings are covered by lifecycle emissions legislation, smaller architects and constructors will be impacted. Interviewees were divided on probable outcomes: views ranged from the need for small architect firms to specialise in order to survive (L1) to thoughts that in the near-term there will be better software and more consultants, and with the primary responsibility for LCA compliance resting with the contractor (at completion stage) the impact on architects will not be too significant (L3). This ignores the large culture change for small contractors and a significant investment and training need across the AEC sector (NBS, 2021).

There is awareness that building design, structural calculations and embodied emissions calculations should be done simultaneously, and some firms are creating software to do this (L8). Only one firm interviewed did so (A14). On finalisation it used a consultancy to recalculate the structural analysis for liability reasons. The more technically minded firms often had intellectual property concerns about sharing the models beyond collaborating firms or consultants (A9, C9). Use of a structural consultant to calculate a building’s structural integrity transfers legal responsibility out of an architect’s firm (A2, A8, A9). It also places a barrier in the way of iterating designs towards optimisation of embodied and operational emissions at any realistic speed, as the consultant is used only after the design is finished and additionally may not use BIM (A14).

The handover of a building to the new owner is a time when the use of the BIM may cease. This varies greatly within and between states, with clients of large firms in certain states (Latvia, Netherlands) apparently far more likely to use the digital twin to ‘manage the building’ than others (A2, A16, A17, L8). ‘Managing the building’ generally means using the data for maintenance (to look up building or parts details) rather than operational energy, as BIM does not lend itself to automatic input from sensors (C6). Maintenance engineers would require experience of BIM to use it (A18), which would not be normal. More user-friendly software is being written to update the BIM or to extract data from it and import it into facilities management software (e.g. Glidertech.com, Kabandy.com), but data operability and interoperability issues generally curtail BIM use after construction completion. Most small firms do not supply clients with anything more than pdfs electronically (A1, A12) and some did not even do this (A2, A6), though it is possible to export data from 3D CAD (in IFC format) if it is needed occasionally (A10, A11).

As staff need BIM training to access BIM data, the BIM is not generally used in facilities management unless the constructor is also managing the completed building (C5, C6). Skilled constructors can tailor output from BIM for various facilities management systems, if the manager is chosen in advance and their system known (C8). Unskilled constructors may pass on a BIM of limited completeness and usefulness (C9) and not all facilities managers can work with BIM anyway (C6). Essentially, the BIM holds vast amounts of detailed relationship data between building elements, but

the facility managers only need spatial data plus a look up facility to check parts details for maintenance or replacement purposes. It appears that normally much or all data is lost on handover of the completed building.

BIM data can be used in lifetime building management. However, the inflexibility of data handling in BIM, together with the training and access controls required to use it, make it unsuitable as a basis for facilities management software. This commonly leads to a break point in the data trail with apparent loss of much of the building information which could otherwise have greatly assisted planned maintenance programs and reduction of replacement parts. While this break point is starting to be addressed by third party software companies, it implies that many buildings coming to the end of their first lives will continue to be BIM-less.

3.4 Technical

In the 'Technical' dimension of PESTLE, we cover BIM vintages, data handling, functionality, tools and applications (including LCA), and accuracy (see Table 4 for thematic codes).

The heart of BIM software is old, as highlighted in this open letter from the Nordic architects associations to Autodesk, owners of the market leading Revit software:

Every day digital design leaders around the world wrestle with software, which at its core is twenty years old and incapable of the potential of multi-core computing and graphics power designed to process within today's real and virtual workstations. Project productivity in architectural and engineering practices is hit daily because of the lack of scalability and product performance, which then requires sophisticated and practice specific 'work arounds'. (Nordic Architects Letter, 2022).

Interviewee A1 (UK small firm; non-BIM user) made the same point: the software is too old and needs a complete rewrite to modern software standards.

Although the level of design functionality has improved markedly in the last 10 years (C10), BIM software does not lend itself to rapid input/output of data necessary to iterate a design to minimise lifecycle emissions (L2), collect real-time building management data (C6) or interface with a non-BIM trained user (C9).

There is no single way to use BIM: setting up the model differently is widespread (C10) and when combined with firms' different data inputs, normally precludes the model from being used for the full range of functions such as design parameterisation (C6), Bills of Materials (A7, C5, L2) or scheduling (C7). Most architects using BIM thought it made them better architects and designers (A7, A15, A16) although few initially design directly into BIM. A common practice is to first design using pen and pencil, or applications such as Sketchup, Rhino or Allplan, and transfer these rapidly into BIM (A2, A11-A14, A16, A17). Linked virtual reality tools allows designers to 'walk around' inside the building and improve its design (A15, C5), though it's also a sales aid (A16, C6).

BIM functionality is highly dependent on tools that analyse exported data. The amount of exportable data held on each building component distinguishes BIM from 3D CAD (A8, A16), and enables a variety of consultants to perform calculations/operations in which they are specialist (structural, heat loss, thermal comfort and many others) (A2, A7, A8, A12, A15, A16). Using consultants is partly about sharing responsibility (A15), but also demand is insufficient to employ specialists even in larger firms (A8).

In contrast to earlier papers (e.g. Kim, 2019), none of our interviewees emphasised data handling as a major issue. Uploads and downloads, though imperfect, work well within products from the same software house [“You can do it like five times per day and you can ... control this project really easily” (A16)]. In contrast, for firms not using advanced data functions, the limited digitalisation of 3D CAD still enables apartment block construction (C3).

Tools written in-house are significant in larger businesses for process control and time saving (A1, A14, A16, C11), for example, different tools for calculating and reporting regulatory requirements for the 3 areas of Belgium: Flanders, Wallonia and Brussels (A17). Digitalisation of data also allows more options to be considered, and weight and stresses to be calculated more accurately. It does not override professional judgement, which ultimately determines the use of materials (A16). The technical difficulty of running BIM accurately leads to a lack of trust in the data and a reluctance to take decisions based on it (C4). Inability to produce Bills of Materials precludes gaining one of the most obvious benefits of BIM, as these are known to be highly accurate (A3). So BIM models are generally “not as sophisticated as you would think or hope” (C2).

Embodied and lifecycle emission calculations using LCA tools require a strict methodology to make results comparable: these rules are still developing. For example, the Danish method is set out in LCA Byg (lcabyg.dk), and many software firms are writing LCA interfaces to BIM (L3, L5). Nevertheless, there is still a ‘big debate’ on methods (L2, L4), including what it should cover (e.g., groundworks, foundations, kitchens, mechanical, electrical and plumbing are likely to be 11-15% of a building’s total embodied emissions (Rodriguez et al., 2020)) and what level of detail it should cover (e.g., pipework under 25mm diameter) (L2, L3). There are discussions around credits for design for deconstruction and for use of recycled materials, the latter currently included at zero value (L2, L4, L5). These will all need defining before limits can be enforced and its potential fulfilled. The recent EPBD permits methodologies to vary by country to adapt to local conditions (EPBD, 2024).

3.5 Legal

In the ‘Legal’ dimension of PESTLE, we cover compliance with codes and regulations, risk and liability issues with new materials, and insurance (see Table 4 for thematic codes).

Whilst acknowledging the importance of governments promoting BIM, the usefulness of BIM as a control measure is currently limited (A16). Interviewees assert that building codes are all satisfied by submission of 2D pdfs supported by relevant calculations. In many countries hand drawings suffice. However, for certain government agencies in some countries a BIM model is required for certain building types (examples from interviews include Latvia, Norway, Slovenia and the UK). Respondents were unclear (or dismissive) about authorities ability to read a BIM, though Latvian interviewees were positive about their municipalities determination to get a BIM education (A15 & A16).

Although BIM enables new lower emission materials and reused building elements, but these pose legal or regulatory issues.

First, standards and current regulations governing (for example) concrete and laminated wood products are quite specific. Concrete excludes new alkali activated cements (expensive, but on average 50% lower embodied emissions (Segura et al., 2023)), and laminated wood must exclude recycled wood. Regulations generally act as a brake on the use of new materials (L2) and regulatory flexibility to enable experimentation with new materials varies across Europe (C10). Significant material changes require the approval of products, including bio-based ones, which cannot currently be shown to last 50 years or so.

This creates a second issue: accepting new or reused products for insurance purposes (L5, HoC, 2022). If steel beams from a building are removed, individually subjected to testing, and resold, an insurance company will need to cover them. This is currently only a nascent market. It is difficult to find trios of owners, architects, and constructors willing to incorporate such products (L1, L2, L3).

Third, careful removal of products from buildings for reuse, such as steel beams, takes significantly longer than demolition and lengthens overall construction time, which is an economic problem (Iacovidou & Purnell, 2016).

3.6 Environmental

In the 'Environmental' dimension of PESTLE, we cover material substitution (e.g. to wood), offsite construction, modularity and other BIM applications that provide environmental benefits such as green certification (see Table 4 for thematic codes).

Structural elements hold 45-55% of total embodied emissions in a building (Eberhardt et al., 2019; Fisher, 2023; Huang et al., 2018). BIM enables building designs and constructions with novel materials, rightsized elements, and materially-efficient onsite practices. All these can help deliver lower environmental footprints (A2, A14). However, sustainable materials (including bio-materials) are seen as more expensive (C1, L2) (Came, 2018). Their relative pricing may change if they become higher volume and the EU's carbon taxes are applied to imported cement, due from 2027 (L8).

Interviewees were specifically asked about using wood or more specifically cross-laminated timber (CLT) as a structural material. Several use it (A2, A3, A8, A10, A18) but it can be specified from a 3D CAD system; BIM is not required for straightforward shapes (A3, A10, A12, A18). Using Denmark as an exemplar, CLT is not seen as a standard material, and there is a large concrete lobby (L3). The closest CLT factories are in Sweden and Austria (L4), signalling supply issues if CLT use becomes widespread as a means of limiting a building's lifecycle emissions (L5). No alternatives to concrete other than using structural wood, steel or low emission concrete were suggested in interviews (C5, C10, L5) despite specific questioning. 'Low emission concrete'¹ is not approved under EU building codes (C10).

Time, money and knowledge mitigate against the use of new environmentally-friendly materials (A2, A9, A12). Education is lacking: "I think most architects have no clue...what is the [emissions] impact of the decisions that they make" (A14). Architects may specify materials in detail, or they may specify the qualities of the different materials and contractors are left to make the final selection, or they may simply design the 'look and feel' of a building – norms vary between countries (C1, C5, C9). Clients have the ultimate choice and focus more on cost than environmental impact (A16, C1). Architects have to persuade clients to use new materials, then constructors, lacking familiarity with the new material, will try to dissuade the client from doing so. Only two firms interviewed, both Dutch, used BIM to actively design using alternative materials to lower the whole life carbon of their buildings. One was a vertically integrated constructor currently building to a level 30%-60% lower than the Dutch lifecycle emission standard, MPG (C6); see Table 2 .

Offsite construction, enabled by BIM, is an alternative strategy to material substitution for reducing embodied emissions - up to 66% savings against benchmarks (VBC, 2023; WRAP, Undated). Lighter, less carbon-intensive offsite fabricated office or apartment modules in turn need lighter concrete structures and foundations to support the modules on site (A14). In combination these techniques

¹ Low emission cement is an umbrella term for cements not using the same chemical reaction as Ordinary Portland Cement in their binders: they need approval on a case-by-case basis for specific applications.

should yield substantial material savings but durability is unproven (House of Commons, 2019). Modularisation can amplify the environmental benefits of prefabrication but its use currently for sections of rooms (rather than whole units) is driven by constructors' desire for speed, not by achievable material or emissions savings (C10).

One clear driver of BIM adoption linked to environmental performance is green certification. Commercial buildings are increasingly built with green certifications, which include compliance with standards including BREEAM (UK), LEED (US) or DGNB (Germany). All these are widely used in Europe. Green certification incurs higher costs, and BIM is necessary to complete the data requirements for many of these standards. For example, DGNB requires an LCA calculation, for BREEAM an LCA is useful, while LEED does not require one (Veselka et al., 2020). Certifications add value through two mechanisms. Firstly, lower operational energy requirements reduce occupant outgoings so space can be rented for more money (L1, L9). Secondly, in oversupplied markets they provide comfort against obsolescence for property investors and for banks (L11), so loan finance may be cheaper (L9, L10). It is unclear (to developers or banks) whether lower embodied emissions leads to a higher building value, as operational energy is independent of this (L9, L11). Potentially, new low emission materials would assist qualification for green certifications, but until these become recognised by the certifying bodies they will not be used (C2). Hence the need for regulation, without which there is no incentive to reduce embodied emissions levels (L9, L11).

3.7 PESTLE synthesis

Overall, applying the PESTLE framework to our interview data, we visualise our findings under each of the six dimensions in Figure 2, distinguishing BIM adoption drivers (green) and barriers (red). These are further summarised as follows:

Political. Regulatory and legislative drivers of BIM adoption have been weak outside pioneer countries with existing mandated limits to building lifecycle emissions. However, the policy landscape is changing, with more widespread regulatory incentives set to diffuse across EU countries.

Economic. Economic costs with BIM use are more direct and salient to firms compared with the efficiency and time-saving benefits, particularly among smaller architect and constructor firms for whom skills' shortages compound barriers to BIM adoption. The economic value of BIM is clearer in larger, complex, multi-actor projects or in vertically integrated firms.

Social. An important barrier to the use of complex BIM tools are technical skills upgrades and training needs for personnel. BIM upskilling in turn changes roles and relationships within firms as part of wider cultural change necessary for embedding BIM in firms' practices. The exchange of BIM between different actors along buildings' value chains, particularly between constructors and facility managers, is further complicated by varying technical capabilities and interoperability issues.

Technical. Enablers of BIM adoption include easy data handling and in-house tool development. Barriers include outdated software and the non-substitutability of professional expertise and judgement for key decisions. BIM's usefulness to firms is derived from the tools and applications built off its data resources, and these are many and varied such that there is no standardised technical use case for BIM among practitioners.

Legal. Liability and insurance issues with BIM applications constrain its use for designing with novel building materials or reusing building components. This affects the potential for BIM to integrate lighter weight, bio-based, or otherwise more materially-efficient elements into buildings. Even

though monitoring compliance with building codes and standards could be another use case for BIM, this is currently not needed as 2D drawings still largely suffice.

Environmental. BIM is useful for demonstrating compliance with performance standards and green certifications that can command a price premium in commercial building markets. The wider potential for BIM to stimulate the use of lighter, lower carbon, or otherwise more sustainable building materials (including wood) and building components is still largely unrealised due to a lack of strong incentives and inertia to change among firms.

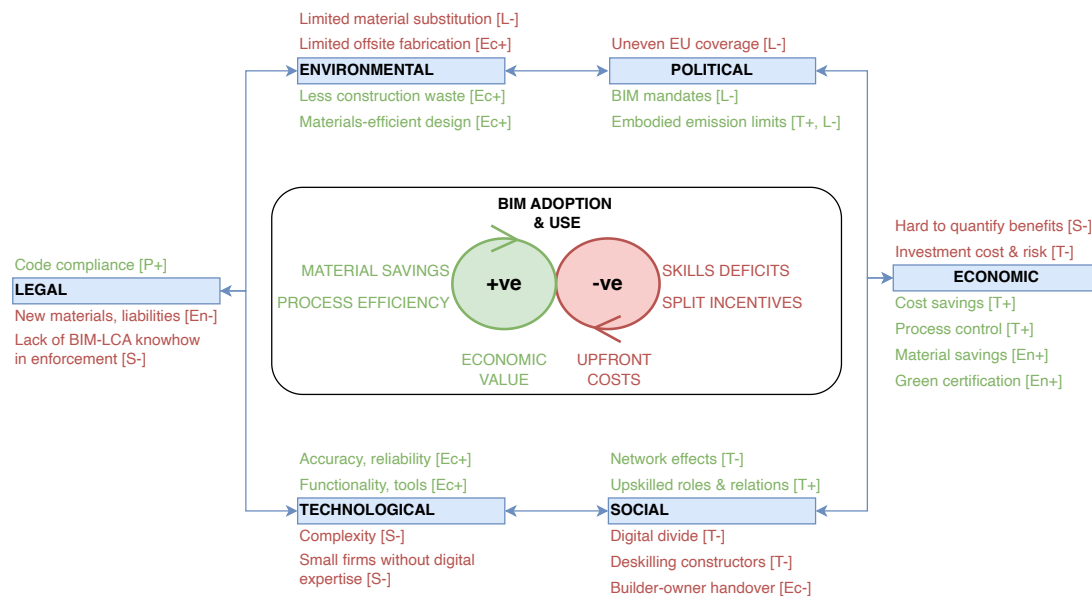


Figure 2. Main drivers and barriers of BIM adoption and use along the six dimensions of the PESTLE framework. Key: +ve = positive feedback loop; -ve = negative feedback loop. *green* = BIM adoption drivers; *red* = BIM adoption barriers. [] = link to other PESTLE dimension, e.g. [S-] link to adoption barrier under Social, e.g. [En+] link to adoption driver under Environmental.

4. Discussion

Our expert interviews build on the literature reviewed by providing a rich practitioner perspective on the current state of BIM adoption and use, and how the drivers and barriers vary across both firm type and size, and by country. In this discussion, we return to our research questions and set out the new insights from our integrated PESTLE analysis..

RQ1. What are the drivers and barriers of BIM adoption among firms for building design and construction?

BIM still has a relatively low adoption rate. BIM suffers from low penetration amongst smaller architects and in small and medium sized contractors, and more so for any moderately advanced functions such as clash detection and Bills of Materials, with a 5% usage level even amongst BIM adopters (Hosseini et al., 2016). Penetration rises to about 32% of users in larger firms (Abdelaal & Guo, 2022).

BIM's economic value proposition remains unclear. There remains considerable confusion within industry over what BIM actually is (Pidgeon & Dawood, 2021b). This makes it difficult to identify and

quantify time, process, and material savings (Walasek & Barszcz, 2017). BIM should lead to a more accurate and overall lower price tender than CAD (Gharaibeh et al., 2024). This helps clients and constructors, but the savings to architects investing time in the initial BIM are more intangible (Walasek & Barszcz, 2017). Only one interviewee – a constructor – was able to estimate savings figures in any area. All interviewees from vertically integrated firms (design and construction) who did not face this split incentive issue between design and construction were committed to BIM. Increased BIM penetration is unlikely without more tangible, visible business needs or benefits. BIM produces better accuracy and control - continued into construction, it delivers shorter build times, which is the primary financial incentive for constructors for BIM use. However, one interviewee who supplied automation software to the construction industry remarked that she had rarely seen a BIM model that was updated throughout construction. Without any checks on the final model, quality implementations of BIM that contribute to control and savings are less likely. Better tools now being marketed, such as automated integration of BIM with site video recordings to enable precise progress chasing, suggest that incentives for larger constructors to install BIM are growing.

BIM use requires upskilling to overcome digital divides within and between firms. With few exceptions, university and colleges do not teach students the principles or use of BIM. This is a major opportunity for improvement which would aid adoption, reduce business training costs, and reduce the digital divides found across architects and construction firms. Firms need a BIM education to see its value (Andersson & Eidenskog, 2023). Much of the current training is carried out in-house, hindering the growth of BIM into smaller firms. External training carries a cost: smaller firms, struggling to see payback from BIM, are well aware that the costs of implementation greatly exceed the software licence cost (Charef et al., 2019). Additionally, the more obvious payback items such as clash detection, Bills of Materials production and modification of existing designs to fulfil new commissions need significant competency in the set-up and structured use of the BIM.

Continuing digital innovation is opening up new use cases for BIM. AI can generate designs for sections of buildings, subject to a set of energy constraints (Ma & Wang, 2025) or simplify structural design (He et al., 2025). Digital twins in conjunction with the Internet of Things offer potential for real-time monitoring and control (Arsiwala et al., 2023), though these would be constructed from a BIM extract, as BIM is not capable of real-time multiple sensor input-output or use with digital twin tools (Pereira et al., 2021). These novel BIM applications are still in their infancy but could contribute significantly in future. Alongside this, the rapid creation of EPDs by manufacturers and software are enabling easier calculation of buildings' whole life carbon emissions (Giorgi et al., 2022). Coupling BIM with buildings' material passports and LCA can inform material use and reuse decisions from design to end-of-life (Giorgi et al., 2022). Technical issues with the use of BIM-LCA tools are being rapidly overcome, and LCA provides a means of ensuring that expected 'design efficiencies' incorporated in third parties' modelled projections are realised.

RQ2. What contribution can BIM make to reducing whole life carbon emissions from buildings if it becomes widely adopted?

BIM can enable material savings but this is more technical potential than reality at present. BIM enables material savings in design (avoidance of over-specification), in early clash detection (UK BIM Alliance, 2021), in build accuracy (less rework as mistakes spotted earlier), in reduced on-site waste through more accurate Bills of Materials, in modular construction (Nikmehr et al., 2021), and in maintenance of the completed building (Walasek & Barszcz, 2017). Although BIM users and clients can speak to these benefits of BIM in general terms, they are rarely quantified (Pidgeon & Dawood, 2021b). Of these potential material savings, clash detection and build modularisation are BIM-specific and are unlikely to be achieved through CAD. Few interviewees clearly saw the usefulness of

BIM in terms of materials or energy savings; rather, BIM was understood through its fit to internal business practices. Apart from in specialist consultancies and for green certified construction of commercial buildings, BIM is not being used to design for material and energy savings beyond current legal requirements.

Regulated limits to buildings' lifecycle emission will drive BIM adoption. As BIM or CAD is essential to calculate embodied and projected operational emissions under whole life carbon legislation (EPBD 2024), this should provide the impetus to: (i) use BIM for material and energy efficiencies among firms already using a high degree of BIM's functionality; (ii) incentivise the 95% of smaller firms not using more advanced BIM capabilities to do so; (iii) induce firms which have not yet adopted BIM to try it. As legal emission limits on buildings will be tightened over time, BIM and CAD are the only available tools to recalculate the impacts of changing design and materials. However, progress to full implementation relies on several factors. First, governments across Europe must set legal limits and then reduce them till an impact is felt, at which point resistance is likely from industry. This dictates a widespread increase in the use of 3D CAD or BIM across construction, implying major cultural change and upskilling amongst smaller constructors even in countries regarded as more digitally advanced, and yet more culturally difficult in countries with little practice in data sharing between architects and constructors. Second, municipalities have to skill up to understand the LCA calculations and be competent to query them, otherwise unaudited 'self-declarations' may cause the regulations to lose credibility. Third, building codes must adapt to allow new materials to be used, which will be resisted by vested interests based on perceived risks and costs of change. A balance will need to be drawn between safety, pragmatism and risk, especially if new materials do not have proven lifespans or are reused and for which there are warranty or insurance issues.

BIM design functionality enables greater use of low-emission materials including wood. BIM tools can facilitate replacement of (for example) concrete beams with cross-laminated timber, or concrete partitions with bio-based alternatives. However the attitude of the BIM software user is more fundamental to the environmental outcome than the BIM itself. There is still very limited evidence that BIM is affecting the selection of materials, outside the four countries with embodied emissions legislation and specialist architects firms building to green certification standards.

Lifecycle emission reductions of 21-31% are realistically achievable 10 years since policy inception. We quantify projected savings from whole life carbon legislation based on the published targets in the four pioneer Northern European countries with existing regulatory limits (Table 2). We estimate that after 10 years from a policy decision, including a 3-year familiarisation period before limit imposition, embodied emissions in new buildings could be reduced by 21-31% with further gains possible if targets are tightened (Figure 3). This assumes no building types are exempted from the limits. (We provide full details of our projection method and assumptions in Appendix A4).

Other European countries may not be as ambitious with their target emission reductions as the four pioneer countries. However, positive signs are evidenced by a Dutch interviewee already delivering to the Dutch standard less 30%-60% depending on building type (C6) and a Danish interviewee arguing 6kgCO₂/m²/yr is achievable against an initial target of 12kgCO₂/m²/yr (L2). Published national aims are also ambitious, for example Sweden is aiming for an 80% saving by 2043 (Boverket, 2020).

There is overlap between embodied emission reductions driven by legislation and reductions from projected design efficiencies (particularly in cement and steel), such as those estimated at 20% to 2050 by the UK Green Building Council (UKGBC, 2021). However the EU's whole life carbon legislation (EBPD, 2024) is a key for unlocking these savings in practice.

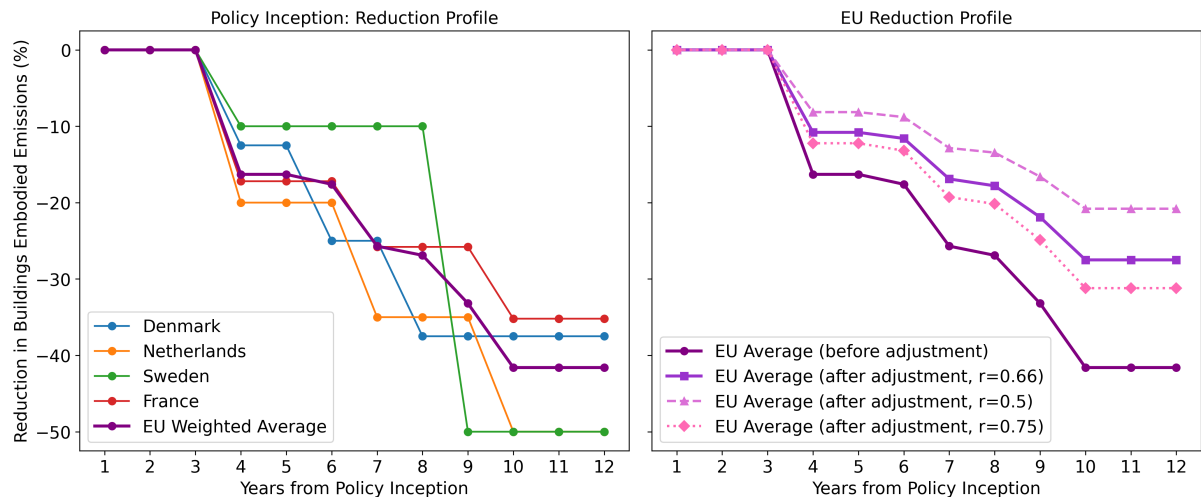


Figure 3. Potential Impact of Embodied Emissions Legislation in 4 Pioneer Countries (left panel) extrapolated to EU average (left panel central estimate, and right panel for range). Note EU averages based on adjustment factor, r , as estimate of legislated limit achievable in practice. (See Appendix 4 for details).

5. Conclusions

Our study of expert practitioners' experiences with, and perceptions of, BIM found a settled pattern of limited adoption, with a marked digital divide between high-tech (BIM and tools) and lower tech (3D CAD) architects. Constructors predominantly worked from 2D plans without BIM, though some larger firms had higher level of BIM adoption. We found significant barriers to more widespread adoption across the dimensions of the PESTLE framework. These barriers include current practices, work cultures, regulations, and skills needs for digital systems, particularly in construction.

We also investigated whether further use of BIM across the architecture, engineering and construction (AEC) sector is changing materials use and efficiencies, with a beneficial impact on embodied emissions through material selection, using less material and extending the life of building components. We found the use of BIM for material savings depends largely on the motives of the users to incorporate new lower-emission materials, and on the sophistication of the model and its ability to act as a tool for delivering control, implying better specification of bills of materials, improved clash detection and less rework. To-date, this drive towards lower emission materials has been limited to a medium-sized environmentally-oriented firms. However, governments across the EU now have to formulate and implement whole life carbon limits for buildings from 2028-2030 in line with the EPBD 2024, following the precedent of pioneer Nordic countries and France. This will force design and practice changes by architects and constructors, together with rapid approval of new and reused materials to enable embodied energy reductions. BIM will be a critical enabler but not a panacea. We found that public authorities have limited capacity to understand BIM-LCA calculations, monitor and enforce embodied emission limits. At best this risks reducing the effectiveness of the legislation and at worst will bring it into disrepute as a control mechanism. Whole life carbon regulations in countries with limited digitalisation in construction is a long-term process involving education and changes in practice. The digital skills base in constructors across Europe is very low and needs rapid improvement to meet the goals of the new regulations.

The major challenge for BIM use depends on how compliance to the EPBD can be achieved across the EU by 2030 as planned, while minimising disruption and cultural resistance from constructors and obtaining understanding and control of construction data by local authorities, against a background of low preparedness levels. This is a key question for further research.

Finally, we note specific limitations to our study. First, the number of interviewees, spread across the whole of Europe, necessarily limits generalisability of results. Second, despite attempts to contact architects and constructors uniformly across Europe, northern states are over-represented as are firms which did not use BIM: these interviews were harder to obtain. However, our two main conclusions – that firms are not designing or building for material and embodied energy savings, and that EPDB 2024 could significantly impact BIM uptake as an enabler of lifecycle emission reductions are robust to these sample characteristics, given that states with lower penetration of BIM (under-represented in the sample) have fewer advanced users.

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Digital provenance and sorting for materials recirculation



Bulk material manufacture: the potential impact of digitalisation and provenance systems on materi- als recirculation

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Disclaimer

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Executive Summary

Reducing GHG emissions without reducing living standards implies recirculating materials rather than discarding or downcycling them: in particular, the emissions associated with the four major bulk materials (steel, cement, plastics and aluminium) are around two-thirds of the entire industrial emissions. This study examines, through a series of expert interviews, how digitalisation, both through provenance systems and analysis tools for sorting discarded materials, could improve circularity in Europe. It finds that whilst there is a large and sudden interest from construction companies and the automotive sector in using recycled materials due to self-imposed low-carbon targets, almost nothing digital is being developed for recirculating either steel or cement. The exception is Business Information Modelling which could assist building or material reuse in second lives, some 15-40 years into the future. For plastics, on-pack provenance systems could be implemented in the short-term, but this depends on cross-supply chain cooperation which is generally lacking. Only for aluminium is there the prospect of substantial near-term improvement, where the introduction of Laser Induced Breakdown Spectroscopy could greatly reduce the downcycling of wrought aluminium into cast grades, potentially eliminating a forecast surplus of cast aluminium by 2030.

Keywords

Digital sorting, Steel recycling, Aluminium Recycling, Plastics Recycling, Laser Induced Breakdown Spectroscopy



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Bulk material manufacture: the potential impact of digitalisation and provenance systems on materials recirculation

1. Introduction

The contribution of industrial emissions to global warming is significant, so reducing it is a significant opportunity. Direct industrial emissions are generally calculated to be around 24% of world totals, with a further 10% of the total emitted to generate electricity and heat for industrial purposes, illustrated in Figure 1. (IPCC, 2022).

Direct and Indirect Emissions by Sector (59GtCO₂e)

Direct	Indirect	Direct	Direct	Direct	Indirect	Direct
Buildings		Transport		Agriculture, Forestry & other land use	Industry	Other Energy
16%		15%		22%	34%	12%

Figure 1: Global emissions broken down by end-use sector (Redrawn from (IPCC, 2022)).

Global industrial emissions are 20Gt CO₂e (34% of 59Gt CO₂e). In the EU four bulk materials (steel, cement, plastics and aluminium) account for around 66% of GHG emissions (including embodied carbon in imports). About half of emissions from the four materials are used in the mobility and buildings sectors (Material Economics, 2018).

The research starts from an assumption that the high-emitting industrial bulk material industries will be subject to the same data transformations affecting society more generally, and may have the potential to radically change the possibilities for narrowing, closing and slowing the usage of these materials. It looks at the potential for digitalisation (for example, using provenance systems) to increase European circularity of the materials in accordance with the principles of the Circular Economy (CE). This paper focuses on areas where the potential for an almost immediate impact of digitalisation appears greatest: recirculation post waste collection, through sorting and recycling or reuse. Longer term, the need for better, probably computer-assisted, design to lightweight material parts through stronger or better designed materials which can be readily recycled is vital, but this area is outside the scope of this study.

It is approached through the standard logic of Narrow, Slow and Close, where narrowing material usage loops implies using less material to achieve the same ends (increased material efficiency or dematerialisation). Slowing the circulation loop is brought about through longer lives (reuse, repair, repurpose, redesign) and Closing loops implies recycling or recovering the material at its end of life without downcycling (making an inferior product from the material because it has reduced properties) (Bocken et al., 2017).

1.1 Salient background on Steel, Cement, Plastics and Aluminium

1.1.1 Steel

European steel is produced in about 26 blast and basic oxygen furnaces and around 100 Electric Arc Furnaces, though the capacity of the blast furnaces is larger and they account for 56.4% of



production in 2021 (Eurofer, 2022). Steel production accounts for 5% of total European GHG emissions (Material Economics, 2020), equal to about 25% of industrial emissions. European steel stocks have largely reached saturation levels: scrap arisings (115mtpa (Dworak & Fellner, 2021)) are increasing towards the level of new steel supplied (152mtpa in 2021 (Eurofer, 2022)). So scrap arisings are c.75% of production. However, the quality of the end-of-life scrap element (“old scrap”) is poor: much is downcycled into reinforcing bar and mesh (“rebar”) which is highly tolerant of contaminants and the remainder exported, also for rebar. While post-fabrication scrap of known composition (“new scrap”) is all recycled, much of the new steel supplied in Europe is made from virgin iron ore and its derivatives, not old scrap. This mismatch of scrap quality with new demand means that the CE in steel is currently a mirage. Further ahead, a world surplus of highly contaminated and unusable scrap is forecast beyond 2040 (Dworak et al., 2022)..

1.1.2 Cement

CEMBUREAU, the European Cement Manufacturers Association, reports that 172Mtpa of cement is produced (CEMBUREAU, 2016), as are 7.9% of EU industrial emissions (EEA, 2017). Whilst CEMBUREAU claims that cement is 100% recyclable, it gives the two main reuses as aggregates in new concrete and aggregate in new roads and construction. This is not recycling: it is either downcycling or repurposing. CEMBUREAU does not suggest that recycling of reacted cement into more cement is possible: there is a real issue of non-circularity.

1.1.3 Plastics

The EU uses 49Mt of plastics each year: production of each ton causes about 2.5t of CO₂ and there is another 2.7t of embedded carbon in each ton, which is released if the plastic is burnt in energy-from-waste plant at its end-of-life. Mechanical recycling at end-of-life produces less than 20% of the emissions coming from new plastics, although some degradation of the plastic occurs, leading to downcycling (Material Economics, 2018). Chemical recycling is under development for a wide variety of plastics, though many are at early stages, with potentially larger emissions savings than for mechanical recycling as the resulting monomers can be made into new virgin plastic without any degradation from the original properties: true circularity.

More than 40% of plastics are made into packaging and other single use products: these come through the supply chain as waste almost as soon as they are placed on the market. Accordingly, some 42Mtpa of plastics waste needs processing each year, much of which can be mechanically recycled in principle. However, only 10% of value is retained (Material Economics, 2020). There are many reasons for this: difficulties in separation of post-consumer plastics – value is only retained if the separation is into single polymer types; low collection rates, burning plastics in Energy-from-Waste plants, and degradation/conversion losses, as mentioned above.

1.1.4 Aluminium

Worldwide, about 100 Mt (million metric tons) of aluminium are currently produced per year, about 35% of which comes from post-consumer scrap and 40% from processing or fabrication scrap (Raabe et al., 2022). In Europe, about 10 Mt (million metric tons) of aluminium are currently produced per year, about 60% of which comes from scrap (both post-consumer scrap and processing or fabrication scrap) (Alucycle, 2022). Due to the very high electricity consumption when alumina is smelted in the production of aluminium, recycling takes only about 5% of the energy that it takes to create virgin aluminium (Material Economics, 2018). There are multiple grades of aluminium within each of two classes: wrought and cast. Wrought aluminium contains small specific percentages of alloying elements such as magnesium, zinc and manganese. Cast aluminium contains higher levels of silicon, and can tolerate higher levels of impurities than wrought. When wrought is recycled in Europe, fabrication scrap lots from a single factory are normally of known grade and kept separate for recycling directly back into a similar wrought grade. Mixed post-consumer scrap is shredded



(wrought and cast together). This is either shipped to low-wage countries for hand sorting (wrought and cast shreds can be separated by skilled eye) or both are remelted together, downcycling the wrought into cast, because of its tolerance of impurities. Currently, there is considerable demand for cast aluminium internal combustion engine blocks, though this will decline over the next decade, potentially leaving an excess of cast aluminium between 2030 and 2050 (Løvik et al., 2014; Modaresi & Müller, 2012). Thus there is a demand for an automated method of separating wrought and cast shred to preserve the wrought and avoid downcycling.

1.1.5 Sectoral use

The building and mobility sectors are high consumers of steel, plastics and aluminium, with building using 33% of steel, 20% of plastics and 25% of aluminium, and vehicles using 20%, 10% and 20% respectively (all EU figures) (Material Economics, 2018). So end-of-life releases of these materials back into the economy is a very significant resource for reuse and recycling, for the Circular Economy and for GHG reduction compared to replacement with virgin materials.

Cement is used wholly in the construction sector (65% in buildings (ibid)), but the other three materials are used throughout the manufacturing economy, with hundreds of grades of each used across construction, automotive, household appliances and almost any other fabricated item. The variety of grades (or for plastics, completely different materials) causes complexity in material recovery, and without easy separation of grades ultimately causes inefficiency and losses in recycling.

1.2 Recycling and Downcycling

Current usage of all four of the materials is far from circular. Although recycling rates for steel (85%) and aluminium (78%) are respectable, most end-of-life steel is downcycled in Europe as is 80% of the recycled aluminium. Relatively little plastic is recycled (21%) and almost no cement (Allwood & Cullen, 2011; Material Economics, 2020). Many industrial initiatives focus on decarbonisation rather than circularity, for example fuelling cement production with alternative energy sources, which reduces the operational energy but ignores end-of-life recycling.

When manufacturing plastics, steel and aluminium from virgin materials specific grades are created from specific ingredients to give the finished material specific properties and create a high value product. For steel and aluminium, this involves alloying with more-or-less precise percentages of other metallic elements such as nickel, chrome and manganese. Current reprocessing of plastics, steel and aluminium suffer greatly from different high-value grades with specific compositions and properties being recycled together, creating a mixed product with unspecific and variable properties – dependent on the varying source material – of limited value (Burgess et al., 2021; Ohno et al., 2017; Stotz et al., 2017). This is referred to as ‘downcycling’ and indirectly causes the extraction of more resources to create additional high value materials with specific properties from virgin feed-stocks. Additionally, when downcycling occurs in metals the valuable metal elements added to create the high-value properties are mostly lost into the downcycled product, causing more metal additives to be manufactured, mined or refined (Ohno et al., 2015). Downcycled mixed plastic has limited uses, for example in making fence posts, and so waste household plastics are usually burnt to recover the energy value (Malinauskaite et al., 2017; McKinsey & Co, 2018), regarded as a great waste of the embedded carbon compounds and causing more virgin material to be created and used.

The key to retaining the functional value of the material is separating materials by formulation before reprocessing to allow items with similar formulations to be recycled together, thus allowing the recycled material to have known properties and preserving it in its highest value state. Established separation and sorting processes based on density, colour, shape and manual separation are gradually improving but do not normally produce outputs of a high enough quality to recycle directly into high quality materials: the material is generally downcycled. This occurs as non-digital systems physically sorting proportionately more of one material than another into a certain channel are never 100%



accurate: depending on the parameters the machine is set to, either there are small proportions of the unwanted element in the sort, or there is a proportion of the wanted element left unsorted in the residue. Improved digital systems which could recognise items with certainty have the potential to improve this situation.

Figure 2 summaries the current position. Note that in all three cases the value losses far exceed the volume losses: the recycling is downcycling into lower quality materials.

	Original value of End-of-Life materials	Combined Price and Volume Losses	Recycling Rate by volume	Volume loss	Value loss
Steel	€63bn	€32bn	85%	15%	51%
Aluminium	€12bn	€ 5bn	78%	22%	42%
Plastics	€62bn	€55bn	21%	79%	89%
Reworking costs		(€14bn)			
	€137bn	€78bn	43%		

Source: Material Economics, 2020, Preserving Value of Materials in the EU, p6-8

Figure 2: A statement of the value destruction through recycling in Europe

1.3 Provenance Systems

Loosely defined, these are systems which enable a user to access data giving information about an item's origin, history, material content or any other matter which the originator may think is beneficial to the user. Users may be human or machine and may have passed security checks or may be members of the general public. Examples are company employees entering data on shipping movements, and a consumer scanning a QR code on a cosmetic product to check its history because the manufacturers have created the data for marketing purposes.

There are three principal types of provenance system. The first uses some sort of on-product code to access the data from a remote database. This could be as simple as the cosmetic example above, or more complex, such as an embedded molecule in handbag leather which can be read by a scanner and cross-checked against a secure database to prove authenticity (Security Matters Ltd, smx.tech). These databases may run on proprietary systems or on distributed ledger technology (DLT: also known as blockchain). The second type are 'chain-of-custody' databases which track the movement of products as they are created and moved through distribution channels: these are normally in place to discharge ESG responsibilities, for example the avoidance of so-called blood diamonds (tracr.com) or origin of bulk minerals such as cobalt (re-source.tech). Finally, the last type simply holds information securely, in a manner that enables updating, so that it is available to be interrogated by unknown users in the future. The exemplar of this is Building Information Modelling, where theoretically all information about the construction of a building is held for its subsequent users, to determine how best to refurbish it, or reuse components, typically when it reaches a second life (Zhao & Taib, 2022).

1.4 Digitalisation as an enabler of materials recirculation

In the context of this paper, digitalisation means the use of advanced information collection, storage and processing to further the aims of the CE. Provenance systems are just one instance of digitalisation in materials recirculation: others are data collection and analysis tools applied during waste sorting, and design tools used before the product is made. Digitalisation may or may not be applied to vast amounts of data, and occurs in multiple forms, such as (but not limited to):



- Provenance systems: remote access to data. Examples are given above, though in the context of recycling this could be envisaged as the ability to look up the precise alloy that a specific part, such as a car bonnet from a known model and year, was made from;
- Provenance systems: high-speed look-up systems in a Material Recycling Facility to read a code on an item as it moves along a conveyor belt and access a (probably local) database to better sort materials into purer streams which have higher value as they produce better quality recycled material (Burgess et al., 2021);
- Data collection and analysis: high-speed compositional analysis tools used in a Material Recycling Facility, to directly assess what an item is made from and sort it accordingly. These typically use X-rays or lasers (David & Kopac, 2015; Díaz-Romero et al., 2022);
- Data collection and analysis: process control through artificial intelligence (AI) with product identification (eg it's a can or a carton) but without sorting. Essentially this uses optical recognition and (in early incarnations) analyses the inputs and outputs of a Material Recycling Facility to optimise recoveries over a longer term by prompting management actions (Greyparrot.ai);
- Provenance systems and Data collection and analysis together: potential cross-matching of data to enable financial recoveries in the operation of Deposit Return Systems for bottles and in Extended Producer Responsibility. In some scenarios the bottle depositor could have an ID card which enabled the system to credit their bank account directly. Also, if each bottle had a unique serial number then other analysis linking time and place of purchase with time and place of return for marketing and fraud prevention purposes is also possible. In some theoretical Extended Producer Responsibility (EPR) scenarios, it is envisaged that producer taxes will be reduced by the proportion recycled. If proof of recycling is required on either an item-by-item or sampling basis then data collection and matching to the quantities placed on the market by each supplier will be necessary;
- Design tools: complex modelling of stresses in the design of parts with the twin aims of reducing material usage and eliminating bonding, welding or lamination of parts which prevent recycling (Suschem, 2020).

2. Research Design

2.1 Aims

The aim of the research is to understand the potential for new and emerging digital innovations and systems related to provenance and recirculation to significantly increase recycling rates or decrease downcycling rates in the period to 2050 for steel, cement, plastics and aluminium.

2.2 Research Questions

- How can chain-of-custody provenance data on material content increase recirculation rates of bulk materials?
- How can on-product provenance data on material content increase recirculation rates of bulk materials?
- How can improved data collection and analysis tools for examining materials during waste processing improve recirculation of bulk materials?

2.3 Approach, Scope and Boundaries

The study has originated as part of a pan-European project looking at future European emissions from a materials flow viewpoint, particularly focused on the application of materials projections to the



areas of mobility and buildings. The research focuses on the impacts that digitalisation technologies may bring. Consequently, this study is also grounded in innovations in these areas, although most successful digital innovations can have applications across multiple domains.

GHG reduction strategies which do not utilise digitalisation as a prime enabler were noted but were not investigated in detail. Furthermore, the work was bounded by innovations already in commercial use, including those being piloted within a commercial environment. Hence, innovations still in laboratories with likely unknown commerciality or scalability, (for example (Ness et al., 2015; Stotz et al., 2017)) were not considered further.

3. Method

3.1 Analytical Framework

The transformative potential of digitally-enabled CE strategies being deployed by firms in relevant bulk material value chains was analysed along technical, market, firm, and regulatory dimensions. Furthermore, it suggested the prerequisite conditions necessary to enable widespread adoption of any new CE initiatives.

3.2 Data Collection and Analysis

This is detailed in Appendix 1. A Rapid Evidence Review was conducted to establish the key recycling themes for each of the four materials, using both academic and grey literature. These topics were used as a basis for expert interviews, interviewees being suggested from the literature and contacted by email or through LinkedIn. All interviews were recorded if possible.

.3 Details of the Interviewees

Sector	Steel	Aluminium	Plastics
Scrap handlers, traders and sorters	Scrap Buyer, pan-European Electric Arc Furnace steel producer (Interviewee 2)	Managing Director of an innovative pan-European aluminium waste sorting company (Interviewee 9)	Manager, Materials Recycling Facility and integrated plastics recycling company (Interviewee 15)
	Scrap Controller, worldwide integrated steel manufacturer (Interviewee 4)	Senior manager, recycling innovation, pan-European aluminium company (Interviewee 7)	
		Senior manager, aluminium scrap trading company (Interviewee 8)	
	Innovation Director, pan-European metal and plastic scrap processing and management company (Interviewee 12)		
	Innovation Manager, metal and plastic waste sorting and processing company, northern UK (Interviewee 14)		
Finished Metal Producers	Innovation Manager, pan-European Electric Arc Furnace steel producer (Interviewee 1)	Senior Manager, technical aluminium producer (Interviewee 13)	



	Two Technical Managers, worldwide integrated steel manufacturer (Interviewee 3)		
Academics and Consultants	Two steel consultants from a materials institute (Interviewee 5)	Highly experienced academic professor, specialising in aluminium industry (Interviewee 6)	Academic, researching business models in the plastics industry (Interviewee 16)
Sorting Machinery Manufacturer	Metal Manager, Northeast Europe, sorting machinery manufacturer (Interviewee 11)		
Artificial Intelligence	General Manager, AI information company focusing on waste sorting (Interviewee 10)		
Business Information Modelling	Building Consultant (Interviewee 17)		

4. Results

The sections below note all the main points made by the interviewees and attempts to place them in the context of themes mentioned by several interviewees. As such, they do cover points unrelated to provenance systems and digital technologies. Specific points are summarised at the end of each section. Each Interviewee is referred to by a number: on some occasions the number is replaced by the industry of the interviewee where not to do so might endanger their anonymity when read together with their other comments.

Results are based on interviews, and as such represent innovations close to commercialisation. Innovations discovered in literature which may have been discussed in interviews but which do not form interviewees views of the future are not included in results.

General Themes

This section covers themes which applied to most sectors: they can be grouped into two topics: the increase in demand for lower embodied-carbon products, and the importance of regulations in driving change.

The sudden interest in, and pressure from, the construction, automotive and packaging industries to reduce embodied carbon in their production over the last few years was remarked on by several interviewees (3,7,9,11,14): this is not being driven by legislation but apparently by these industries customers. *“What we’re seeing is an absolutely dramatic change in the last couple of years in the number of people that are wanting to engage with us and the sort of people that want to engage with us and especially on steel and aluminium”* (Scrap recycling interviewee). *“OEMs trying to reduce the carbon footprint through the value chain”* is driving the business (Sorting machinery manufacturer). It’s a *“really, really important driver”* (Interview 3) adding that the *“Institute of Structural Engineers...are kind of setting out an embodied carbon limit per metre squared of your building”* which sets a standard for the construction industry. As a result, many companies, both in production of materials and recycling of them, are starting to use the methodology and structure of Environmental Product Declarations as a standard measure of embodied carbon (Interviews 1,3,12,17). In particular, this highlights the benefits of reuse of existing construction materials compared to new (Interviewee 12).

In the context of refurbishing or replacing buildings, the pressure to reduce carbon footprints has led to a wider use of Building Information Modelling systems, where embodied and operational carbon can be compared for different options. Caution was advised against governments specifying targets



here: refurbishment is highly contextualised dependent on the existing building and the clients' requirements, so placing mandatory targets on outcomes for refurbs is extremely difficult. Targets would have to be stratified dependent on the level of work envisaged. The more a building is refurbished, the more embodied carbon is added but the greater operational savings: demolishing and rebuilding adds greater carbon but will be better in some cases after a short payback period (Interview 17). The more knowledge an architect has of the detailed contents of a building structure, the more likelihood there is of being able to give those contents a second life.

There was a strong feeling across the interviews in all materials that regulations were crucial in driving change. Perhaps because of the context in which the interviews were requested and agreed to, the senior management interviewees were strongly pro-recycling, with one voicing the clear view that anything which creates demand for recycled materials is good (Interviewee 12) and another wanting *"mandatory recycled content in durable plastic items. Or in fact any, any item, any plastic, any metal, aluminium, mandatory recycled content"* (Interviewee 14).

The potential influence of government procurement policies was raised in two interviews, one in the context of specifying materials which would help the CE agenda, such as lower embodied carbon steel, and one because his experience was that where specific items were specified, such as UK steel content, these were not enforced years later when the materials were purchased by sub-contractors (Interviews 1 and 12).

A theme which emerged for both plastics and aluminium is the degree to which end users are historically anchored to precise specifications, readily obtainable by producing from virgin feedstock. If the end users are now wanting, or obliged to, use a proportion of recycled material then the specifications have to be widened, as the recyclate is made of mixed materials with different chemical compositions and is specified to be within a range of values and properties. Commonly, this will necessitate a whole new test programme for each component which adds inertia to the process. However, there was a common feeling that many, if not most, components were unnecessarily tightly specified through custom and practice (Interviewees 6, 9, 11, 12, 14).

With particular regard to steel, there was a view strongly expressed by two interviewees that regulations favoured downcycling steel in end-of-life vehicles, because they led to shredding of the vehicles and highly contaminated steel and aluminium (Interviewees 1 and 7). This theme of regulations favouring downcycling will be repeated for plastics also.

Other than the last point (end-of-life vehicles) all the above themes apply to Buildings, and apart from Building Information Modelling, they all apply to Mobility. So there is a large overlap of themes: perhaps a reflection that steel, aluminium and plastic are all incorporated in buildings and vehicles, and the recycling processes are somewhat independent of the source of the waste.

4.1 Steel

4.1.1 Economic - steel

A single clear theme emerged repeatedly: that a ready international market exists in steel scrap, irrespective of its quality or chemical content. *"Where's the drive for them to sort it [scrap] properly, if they can just ship it overseas and get it off their hands and get a decent price for it. Why put value into it by sorting it?"* (Interviewee 5). It was explained that EU scrap is ideal for making long products (reinforcing bar and mesh - 'rebar') for construction, which is principally taking place in the developing world, *"So there's this kind of overwhelming logic of export in scrap from the developed world to developing worlds"...* *"So you don't really need to spend a lot of money sorting that scrap"*. (Interviewee 3). This led to agreement that the steel industry was primarily focused on decarbonization rather than circularity (Interview 3).



Whilst this does not remove the price premium from higher quality, better sorted end-of-life scrap, it eliminates the motivation to do so in most participants minds. The study found no evidence whatsoever of any automated sorting of end-of-life steel scraps into different qualities.

On the other hand, post-fabrication scrap (also known as new scrap or factory scrap) was much in demand for recovery (“All the new production scrap is being chopped up already”: Interviewee 12), which raises a concern about the expected decarbonisation of the European steel industry by moving from blast furnaces to EAFs. EAFs are currently charged with 100% scrap, much of it poor quality producing only rebar. To produce high quality steel from scrap requires high quality scrap. “It’s clear in the UK that there’s nowhere near the availability of very clean scrap that there is in America” (Interviewee 3). He referred to America’s high manufacturing base and the UK’s “hollowed out” one. These interviewees feel the situation is better in Europe, though they cite EAFs pulling scrap in from a wide area to get enough supply. This issue is covered in more detail in the technical section 4.1.3 below.

More positively, one of the participants had started a business in reused construction steels and other building materials. *“We’re operating commercially. Yeah, we got several 1000 tonne projects happening”* and much demand as they can cope with (Interviewee 12). A better known online pan-European network was cited by another interviewee: *“There is a really great thing called Globe Chain, which I’m just starting to get more au fait with, it’s really good because you can re-sell material and they can sell them on. Almost like a secondary materials market and in places like the Netherlands, as a Swedish we have business arms in Sweden and the Nordics, in places like Sweden and The Netherlands they’ve got a big market for materials that we really don’t see in the UK”*. (Interviewee 17).

One company had tried to work with provenance data on cars to determine which body panels could be profitably removed before shredding. While databases of some sort do exist, they are not in a consistent format and ‘for the sort of people who work in scrappies that’s a big barrier’. They did not think it would work at scale (Interviewee 14).

4.1.2 Steel Firm Characteristics

From comments made across interviews on all the materials it is clear that most supply chains are non-collaborative, when mutually cooperative supply chains is one of the known characteristics for a successful CE (Ellen MacArthur Foundation, 2013). There’s a “*huge void*” between scrap collectors and steelmakers (Interviewee 11) and *“I was trying to close the gap between the carmaker and the scrap industry also bring some thought into what ultimately happened at end of life”* (Interviewee 13). This is clearly a hindrance to progress on circularity. In the case of steel, the overwhelming excess of poor-quality end-of-life steel scrap and consequent drive towards its export appears to overshadow any need for partnerships along the supply chain.

The need for new business models were mentioned by two interviewees. The first, in respect of the new reuse business mentioned by Interviewee 12 (above), noted that each part needed separate electronically stored data describing it– a video, test results, dimensions etc – which is in complete contrast to the normal bulk scrap business, and that this was a significant diversion. The second noted that there was no business model for steel as a service, or for design for disassembly, both of which he felt would be good developments (Interviewee 1). By ‘steel as a service’ he meant a process of take back of end-of-life steel from demolition and replacement with an equal weight of new steel rebar.

Decarbonisation of the steel industry (as opposed to making steel circular) tends to focus on the replacement of blast furnaces with Electric Arc Furnaces (EAFs). The sunk costs in coke ovens, sinter plant, blast furnaces and the like make this very difficult for European companies to contemplate (Interview 3).



4.1.3 Technical - steel

Steel quality is lowered by the copper content, with the best steel plate being around 0.1%, construction steels up to 0.2% and anything over 0.3% being usable only for rebar. Most end-of-life scrap in Europe is 0.25% copper or higher. Despite the prevailing economics of selling unsorted scrap overseas, two of the interviewees (approached separately by different routes) were collaborating on a project to produce high-quality shredded scrap. The logic runs along the following lines: (i) cars are shredded at end-of-life as this is by far the cheapest way of reducing them to usable material (ii) car body panels are some of the best steel there is, at about 0.1% -0.15% copper, but (ii) once they are shredded with the rest of the car, including copper electrical wiring and motors, the resulting shred is conventionally 0.3% to 0.6% copper, which is some of the most contaminated scrap available, and (iv) logically the copper is extrinsic to the steel – it's on the outside of the shred, not incorporated into the metal, so (v) it must be possible to find ways of removing it. The aim is to produce a high quality shred at 0.15% copper which would command a premium price (Interviewees 3 and 12). This is being attempted by undisclosed means, which could involve digitalisation in the form of laser sorting, but is as likely to be in clever automated separation techniques involving more traditional shaking and movement over grilles and suchlike.

Removing copper from scrap steel is a fundamental long term issue for the industry: once the copper has been melted into the steel it is economically impossible to get out again (Lu et al., 2022). While there is still huge growth in world stocks of steel, high copper scrap can be utilised in rebar. However, by 2040 to 2050 the demand for rebar will lower and on present projections there will be a growing excess of unusable high-copper steel (Dworak et al., 2022). Similarly, while industry, governmental and academic talk is of moving to lower-emitting EAFs which smelt scrap, there is not enough high-quality scrap to dilute the copper in the poor-quality scrap in order to make high quality steel. There is no home for high-copper steel: the EAFs will have to be filled with iron ore derivatives ('ore based metallics') to make steel usable for non-rebar applications. To find only limited discussion of this issue, forecast to become an overwhelming problem, is noteworthy of itself. It appears to be too far away and too insoluble to be of current interest.

Currently the two routes for using high copper steel scrap are dilution with fresh iron ore (blast furnaces) and producing rebar (EAFs). Both processes appear to manage the blend for melt characteristics, buying scrap on size, density and thickness, and not chemical composition (Interviewees 2 and 4). Spot checks can be made (*"they will either use the X-ray gun to check the actual chemical composition"* - Interview 2), but purchases are priced by eye: the buyers are very experienced and know the likely chemical composition of different scrap types, but ultimately pricing is by eye. Similarly, a 30,000t vessel sent full to Turkey is priced by eye (Interviewee 12). There is a need to develop a digitised test, which is being worked on, but the number of samples statistically required to achieve reasonable accuracy is large and creating a test is not easy (Interviewee 12).

4.1.4 Regulatory - steel

The points made above about regulations being key to drive change were relevant to steel (Interviewees 12 & 14).

The steel industry purchase scrap based on a set of grades set down by the industry body (Interviewee 2), based on size and the level of processing of the scrap – mixed sizes give an even melt and are predictive of energy usage (Interviewee 1): ultimately these are based on melt characteristics not chemical content. The trade standards are important in creating and maintaining a market: it is notably absent from the relatively newer waste plastics industry (Interviewee 14).

Interviewees were generally unclear about the impacts of a Carbon Border Adjustment Mechanism in Europe or the UK. A general lack of detail about how it would work is evident. One interviewee felt that it would come in to avoid the government having to give energy subsidies to UK steelmakers, which he thought was inevitable if the steel industry is to survive in the UK (Interviewee 3). However,



it is clear that it is likely to make reusing and recycling steel in the EU relatively more attractive than today.

4.1.5 Steel summary

- In the context of the research, there were no digital innovations found (commercialised or not) to greatly impact GHG emissions or to increase recycling. No use of provenance systems, either databases or on-product marking, were discovered, and no sorting of scrap material by automated technology appears to exist;
- Some reuse of construction materials is happening in a niche manner. It is unclear how widespread this could become, but it can be postulated that regulation such as a Carbon Border Adjustment Mechanism can only make reuse more economically attractive;
- The existence of a simple route for selling poor-quality scrap all but eliminates the need and motivation to sort it into different qualities;
- Without sorting poor quality scrap most of it cannot be included into a CE strategy for steel in Europe;
- There is a project to sort shred by chemical composition, but it does not appear to be wholly digitally based;
- Regulations are regarded as crucial in driving change;
- Current regulations on end-of-life vehicles were felt to be perversely incentivising downcycling.

4.2 Cement

“There is no recycling route for cement” (Allwood & Cullen, 2011). Since 2011, there have been some trials with ground up and reused concrete from buildings (McKinsey & Co, 2023), though McKinsey paint a bleak picture of the cement industry reducing emissions significantly in the short term. An alternative binder in concrete is *“not anticipated in the near to mid-term”* (IPCC, 2022). Any initiatives are small and disparate and are not yet being scaled, if this is even possible (McKinsey & Co, 2020). Implicitly this eliminates the current possibilities of provenance systems or digitalisation being part of recircularization. Consequently, no interviews were arranged to pursue the digitalisation focus of the project.

There are a number of methods for substituting part of the clinker element (accounting for 90% of concrete emissions (McKinsey & Co, 2023)) with pozzolans, named after the Italian town of Pozzuoli after a compound discovered there by the Romans. Pozzolans react chemically with calcium hydroxide, an unwanted by-product created as the clinker sets the concrete, to enhance binding and some also help dried concrete resist the ingress of chlorinated compounds which cause reinforcing steel to corrode, thus lengthening the life of reinforced concrete. The best known pozzolans are some types of ground blast furnace slag and pulverised fly ash from coal fired power stations, though both these sources are forecast to decrease in future years.

A third type of pozzolan is in use in the US but does not appear to have any traction in Europe: ground up bottle glass (sioneer.com; pozzotive.com, KLAW Industries; Vitro Minerals), which now have an ASTM Standard (ASTM C 1866/C1866M-20). This is in principle available in large quantities and can substitute 20%-40% of the clinker, is claimed to use about 5% of the energy compared to the clinker it replaces and would appear to be a possible abatement route.

The initiatives that there are centre on decarbonisation of the current processes and materials, not reuse or recycling in a circular economy.



4.3 Plastics

4.3.1 Economic - plastics

Economics vary with the particular plastics. Virtually all collected PET and HDPE bottles are recycled, and in the UK new capacity is being added steadily to increase the proportion recycled domestically (letsrecyle.com, 2023). However, as with steel, there is a ready international market in some types of unsorted plastics which (for some) reduces or eliminates incentives to sort more in the UK. For example, Interviewee 14 explained that plastic pots, tubs and trays (a common waste category referred to as PTT) can be separated at present, but it is not done because if the valuable PP (polypropylene) is extracted and sold, there is no market for the remainder which has to be disposed of at a cost, whereas the mix can be sold unsorted for export. This is a view not shared by all: at least one industry player is building plant to sort PTT (Biffa, 2020).

Export orientation is reinforced by the Packaging Recovery Note regime which favours exporting unsorted plastics and is widely regarded as manipulated (Interviewees 7 and 9, (Burgess et al., 2021)).

There are no standards that recycled plastics are produced to (Interviewee 14) though his company and others produced to consistent grades for their customers (Interviewees 12 and 14).

The usage of polymers will always be much higher than that recycled, partly because of the range of polymers used for different purposes. This causes many valuable materials to be used in relatively small quantities, making them difficult and uneconomic to extract in processes which can never separate used polymers with 100% precision. In addition, there are issues of legacy additives now banned, and yield losses, which further complicate sorting and reduce recycled volumes (Interviewee 12).

The UK Plastics Pact (and more recently, the EU Plastics Pact) pledges to eliminate PVC and PS (polystyrene) from packaging by 2025, which the supermarket chains can largely control by working with their suppliers to eliminate stocking of products which do not comply. However, in the wider sphere this is more difficult for economic reasons, for example on PS *“there are still customers holding on to it because it's millions to try and replace it”* (Interviewee 15), reflecting sunk costs in plant and the costs of new plant to process alternative materials.

4.3.2 Firm Characteristics - plastics

The comments made under the Steel section (4.1.2) about a non-collaborative supply chain apply here also. *“What stakeholders want doesn't fit in to one business model”* (Interviewee 16).

There is a definite focus on extracting more and better recyclate. *“I think people are really focusing now on this residue fraction to close, to try to close the loop. Purity is becoming even more important in the waste, where before it was mainly driven by production [volume]”* (Interview 11). Certainly, investments are being made in new plant, such as Biffa's £27.5m PET bottle recycling plant in Seaham, UK (Biffa, 2020).

4.3.3 Technical - plastics

There are technical developments underway in several areas. Separation of films from rigid plastics has long been a problem – it was clearly stated by one interviewee that there is no commercial solution yet (Interview 15) although another stated that there was a machine available to do it (Interviewee 11). Black plastic – which absorbs the Near Infra-Red spectrum used to sort most post-consumer plastics – continues to be an issue, though Mid Infra-Red is being targeted to address it: *“So it's very difficult technology and a very difficult material”* (Interviewee 11, also Interviewee 14).



Unimplemented provenance technologies exist for marking packaging plastics during manufacture or filling to enable cleaner separation in household waste Materials Processing Facilities (MRFs), although the supply chain would have to cooperate to enable this to happen, as in principle the financial benefits accrue to the entity able to separate the waste into purer streams whilst the costs of marking are borne by other upstream entities (Burgess et al., 2021). One solution, using machine-readable codes printed on the packaging and backed by some leading brands, is in semi-commercial trials (Holy Grail, 2023). Any solution would involve digital reading and analysis of the printed codes.

Artificial Intelligence (AI) is making an impact by analyzing the composition of materials on a recycling facility's conveyor belt in real time. By using a few of these camera-based devices, analysis of input/outputs and mass balances can be obtained, improving process control and profitability. One interviewee, whose company had already installed AI monitoring, expected it to become more important over time, for composition data only or for both data and sorting (Interviewee 15). Though another disagreed: *"In terms of game changing, kind of separation, I don't really see it having an impact"* (Interviewee 14). Optical sorting has already been used for bottle identification and sorting for a number of years, though AI analysis of data has not yet been connected to sorting in any major sense. AI's use with a robotic arm to sort has been trialed, but this is too slow for Materials Recycling Facility use which would require investment in sorting from a conveyor running at 2-3m/s.

The Deposit Return System for drinks containers mandated in Scotland from 2024, depending on how it is formulated, may lead to advanced optical recognition with complex back-end functionality to recognize bottles and return deposits correctly, which could be an almost immediate application for AI (see 1.4 above). Further ahead, the advent of Extended Producer Responsibility (EPR), when taxes are paid by producers when product is placed on the market and (perhaps) refunded if and when the product is recycled, may not be possible without advanced optical recognition and AI to match data read from returned products to data held on product placed on the market with a high degree of accuracy. Interviewee 10 saw a direct line from EPR to enforcement through big data and AI.

Additionally, there are considerable existing investments in glycolysis, pyrolysis and other plants for chemically recycling polymers into smaller molecules which can then be fully recycled (revalyu.com; quantafuel.com; impact-recycling.com), the first two of which are building commercial scale facilities and the latter is a pilot plant. Historically, one of the main issues with developing chemical recycling plant has been the need for purity of inputs: and pure inputs have a cost of creation and can be mechanically recycled (Interviewee 14), so the cost-benefit window for chemical recycling was small. Logically, this problem must have been overcome to a necessary extent.

4.3.4 Regulatory - plastics

The importance of regulation was probably stressed in the plastics sector most strongly: it is notable that they have already experienced the introduction of the UK-only Plastics Packaging Tax (PPT) which levied a tax on plastics not having at least 30% recycled content.

Perhaps bizarrely the tax was implemented without there being a test for the level of recycled content in the marketed plastic: one is now being developed, Recon² (reconsquared.com), a University of Manchester spinout. This attaches a short chemical chain to the recycled polymer which fluoresces when radiated: the strength of the fluorescence can be digitally read and the concentration determined. At European level two provenance systems, RecyClass and PolyRec, are being used to provide a chain of custody and assurance that the offered product does indeed contain the recycled material which it claims (recyclclass.eu; polyrec.eu). No interviewee referred to this topic, potentially implying that proof of the 30% level of recycled content was not an issue for the plastics industry at this point. This appears to be a likely interpretation, as regulators can hardly clamp down on proof if there are only two fledgling systems in Europe able to do so. It was reported in January 2023 that RecyClass had certificated 50 manufacturers in 2022, so its use is currently low (Recycling Magazine, 2023). The EU plans to implement a minimum recycled content in plastics by 2030.



Currently EPR covers WEEE, batteries and vehicles (EU & UK). The principles of EPR (originally an EU policy and taken on by the UK government before Brexit) are to be extended to plastic packaging in 2024 in the UK. There is no implementation date for EPR on plastics in the EU. In principle, EPR requires producers to pay for the destruction of their products at the end of their lives, and in theory the payments can be reduced if the materials in the product are recyclable (or in some versions, actually recycled).

It is not perfectly clear how EPR for plastics will work. UK Government post-consultation proposals (Defra, 2022) are that from 2024 fees will be paid by producers to a scheme administrator and then distributed to local authorities to compensate them for costs of collection. After a year modulated fees will be payable dependent on recyclability of the product. All products will have to be marked with a 'Recycle' logo or a 'Do not recycle' logo, though no intention to mark product any more specifically, such as with a QR code indicating the polymer content. Further, there is no recognition of a difference between 'recyclability' and 'recycled' either in total or on a producer-by-producer basis: maybe this is too advanced at this stage. Subsequently, retailers' organisations have lobbied the government, claiming that the proposals as drafted will not meet their aim of increasing investment in recycling (Financial Times, 2023). Also, without linking recycled items back to manufacturers there is no pressure to design for recycling.

Auditing of figures provided by recyclers is possible by sampling: the *"government in the UK ... has been quite vocal as to how do we potentially use digital techniques to start really auditing and digitizing sampling and then understanding that better"* (Interviewee 10). AI/optical recognition suppliers will be well favoured. At present, *"legislation is crucial to all decisions that are made"* (Interviewee 15) and industry participants are waiting to see the detail of the final EPR legislation before making investments. For example, it is unclear whether there will be funding for investments in equipment (Interviewees 14 and 16): the proposals contain no additional incentives for recyclers to invest in the necessary capacity expansion over and above anything that they feel is viable at present. The uncertainty helps no-one: the point was made that if manufacturers had an idea of their potential liabilities then it would kickstart designing for recyclability (Interviewee 10).

4.3.5 Plastics Summary

- Two EU wide chain-of-custody provenance systems, RecyClass and PolyRec, to provide proof of the level of recycled content claims, are being developed. Once in the new plastic, the identity of the recycled material is lost: it will not, of itself, act as a provenance system to improve the volume of recycling.
- On-pack marking systems exist which could, subject to trialling and industry-wide agreement, be used to identify product at a MRF to enable better sorting and higher value recycle. There is limited sign of industry-wide agreement.
- Sorting systems have not yet been impacted by the advanced data analytics and machine learning that AI offers when attached to optical recognitions systems. However, a combination of Deposit Recycling Schemes and Extended Producer Responsibility may further the impact of combined AI/optical recognition systems to improve process control, design for recyclability and recycling rates, though the specifics will only become clearer when the detail of the regulation is known.
- As bulk post-consumer plastics are of little intrinsic value, enhanced and detailed regulation is key to further recycling: it is expected by the industry but it is powerless to move before the detail is known. Digital technology will be fundamental to improved plastic sorting.
- A digital test for 30% recycled content is under development.
- There are no digitalisation initiative being imminently commercialised that will radically increase volumes of recycled plastics in the short term.



4.4 Aluminium

4.4.1 Economic - aluminium

Whilst most interviewees were aware of the profit to be made by meeting the demand for better separated waste fractions, this was not a universal view, viz: *“we’re seeing now people want more and more cleaner fractions, so they have to add less and less primary to the secondary melt”* (Interviewee 11), and *“We’ve also looked at sorting the aluminium into different grades, so cast versus rolled aluminium. And it’s all possible, but the market is not there for it. The market just wants all zorba”* (Interviewee 14). (Zorba is mixed shredded non-ferrous metals). However, one company is marketing ‘green billet’ which is 75% recycled, and so has a lower carbon footprint (Interview 8): the company must think that there is demand for it.

As with steel, a ready international market in zorba exists. Historically, UK zorba has probably gone abroad (Interviewee 11). It’s also the case in Europe: for example, most zorba in Spain is sold to China (Interviewee 9). There is also a liquid market for post-fabrication (new) scrap: one interviewee explained how his company tried to match trades, buying and selling to avoid price fluctuations (Interviewee 8). So the market is thriving, which aids development and competition (it is more difficult for investors to make financial commitments which are predicated on pricing or supply from a few actors for reasons of monopoly and precarity).

4.4.2 Firm Characteristics - aluminium

Looking at Europe as an entirety, there is a capacity problem: Interviewee 9 suggested that the EU will state that it wants to keep scrap aluminium in Europe, but he did not believe that the capacity existed to make this possible.

The UK is limited by the lack of primary smelting capacity, limited to about 0.05Mtpa compared to a c.1.25Mtpa recycling market (Defra, 2021). Without the primary production *“the UK really... has no significant extrusion plants.... And it has no significant rolling mills”* (Interviewee 6). Sales of high-quality recovered material are *“98%”* abroad because smelters in the UK are not set up to take a product which can be mixed directly with virgin in primary smelting (Interviewee 9).

Investment in multi-machine sorting lines in Europe is very limited: one highly experienced professional named the only two companies he believed had them (Interviewee 6). *“One of the biggest challenges I see is getting local recyclers to invest in proper technology”* (Interviewee 11) and another pan-European recycler claimed that UK aluminium remelters do not understand how to make automated sorting work *“They buy one machine”* and put material through it multiple times: *“you can’t sort in volume with one machine”* (Interviewee 9). This is not true throughout Europe: in regions where aluminium smelting has been preserved - Italy, Spain, Germany, parts of central Europe – it has been worthwhile for the local industry to invest in sorting machinery (Interviewee 11). The previously expressed UK view was also contradicted by one aluminium technology business, which knew of smaller companies investing in advanced laser machinery (Interviewee 13). So the picture is mixed, but it is clear that there is relatively little automated sorting currently, even if some smaller companies have the financial ability to purchase the equipment.

One forward-thinking company had already created a provenance system for their recycled material, showing which sources the original waste came from, because they thought customers would be requesting the data before long. But this appeared to be a one-off (Interview 9), although the inference that the purchase and sales invoicing systems can readily provide data to establish a provenance system is evidenced.



4.4.3 Technical - aluminium

Research was conducted knowing that high speed Laser Induced Breakdown Spectroscopy (LIBS) was a technology about to be marketed by two of the largest sorting machinery manufacturers, Tomra and Steinert. (Tomra were first to the market in June 2023 following the end of the research). A laser pulse fired at the material vaporises a tiny amount and this plasma is digitally analysed to identify it. Potentially this could transform aluminium recycling, allowing the wrought fraction to be separated from the cast fraction, and for the wrought fraction to be further separated into the individual series. This would not only create value to the sorters, but potentially would reduce, or even largely eliminate, downcycling of wrought aluminium. One interviewee company is already planning to build a European plant incorporating LIBS: another is building a post-consumer aluminium sorting line with a spot earmarked for a LIBS machine when it becomes available. Here is real evidenced belief that LIBS is the answer to aluminium sorting, and that the problem will be solved *“within five years”* (Interviewee 6), but not all are convinced that separation beyond broad wrought and cast grades is possible (Interviewee 13) or even that LIBS is any use at all *“So we also looked at LIBS. It's very early days for LIBS”* ... *“For scrap, for true scrap, I think it's a long, long, long way off”*. He did not think companies would be rushing to buy it (Interview 14).

Interviewee 6 also felt that LIBS would be combined with optical sorting and AI to replicate and improve on the visual sorting carried out in low wage economies who currently buy zorba (*“It's been known for a long time that, you know, if you look at a pile of shred. You can look at it and you can pick out the bits that are casted. So the thing is to teach an intelligent system,to do what the human eye can do”*).

4.4.4 Regulatory - aluminium

EPR is expected to *“drive up the need for more recycled content, for sure”* (Interview 11), but he cautioned that *“A lot of companies here also I think are using post production scrap and promoting it as recycled content..... legislation has to also recognize this”*. This is the distinction between new scrap, straight from factory offcuts (all currently recycled), and the much larger volume of post-consumer scrap which is dirtier and more difficult to clean, process and sort (most currently downcycled).

The comments on regulations from the aluminium interviewees differed qualitatively from most others, probably because aluminium is a profitable business using a valuable metal and there is an incentive to recycle it without underpinning regulation to force the issue. One of the few positive comments about regulations was made: that their business had been given a tailwind by the EU stance on supporting the CE (Interviewee 9).

Aluminium used for consumer packaging (most obviously drinks cans) qualifies for Packaging Recovery Note incentives and their comments about its failings are aligned with the plastic PRN problems noted in 4.3.1 above.

Permitting for new waste processing facilities were particularly mentioned by one of the aluminium processors, who regarded regulations as the most difficult challenge preventing expansion (Interview 9). This was echoed by another interviewee in a different field: *“reduce the burden of too much legislation in the wrong place for recyclers. Start helping them. Particularly in location to relocate to more state-of-the-art premises and locations”*. He noted that changing environmental legislation is making things more difficult and pleaded for future regulations to be written with an understanding of the sector (Interview 11).



5. Impact: Analysis of the potential impact of LIBS on the forecast surplus of cast aluminium

Across all four bulk materials, this is the one digital initiative discussed with potential to make an almost immediate impact. It is analysed in four stages. Firstly, published forecasts for the global surplus are used to derive a forecast surplus in Europe. Secondly, a calculation is performed from literature sources to estimate how much wrought aluminium is currently downcycled into cast grades, and thirdly this wrought figure is adjusted downwards by losses in reprocessing before comparing the result to the forecast surplus. Finally, preconditions for a rollout of LIBS across Europe are summarised.

There are a number of modelling papers which forecast a global surplus of cast aluminium. Only one paper was discovered which estimates the global surplus using detailed series-by-series¹ level model of the different wrought grades, which suggests a global surplus of 5.4Mtpa by 2030 and 8.7Mt by 2040 (Van den Eynde et al., 2022). Earlier models suggest global surpluses 4.2Mtpa to 6.1Mtpa by 2030 (Hatayama et al., 2012; Modaresi et al., 2014; Modaresi & Müller, 2012). Based on total consumption, the European share of this would be about 14% (13.5Mtpa/95Mtpa (Material Economics, 2020) / (International Aluminium Institute, 2021), or 0.8Mtpa in 2030. A second paper provides a series-by-series analysis suggesting a surplus in Austria by 2030 without suggesting a specific figure (Buchner et al., 2017). Both Buchner and van den Eynde suggest proportions of wrought and cast in scrap arisings by use category, key numbers used in this analysis.

This potential surplus of cast aluminium could theoretically be alleviated to an extent by avoiding the downcycling of post-consumer wrought scrap into cast. Calculation of how much wrought aluminium scrap is currently downcycled, and how much of this could potentially be prevented by an implementation of LIBS, is given in Appendix 2, together with details of method and assumptions.

Two calculations based on the two different series modelling papers (Buchner and van den Eynde) suggest that between 1.5Mtpa and 1.9Mtpa of wrought is currently downcycled into cast, both significantly greater than the forecast surplus (0.8Mtpa). The difference in the two authors figures is due to differing assumptions about the wrought content of scrap arisings in the different use categories (buildings, automotive, etc). Neither gives any clear indication on the source of their figures, though the International Aluminium Association is heavily mentioned in both papers.

It is necessary to adjust any figure for wrought scrap downcycled by losses in reprocessing in order to compare it to the figure for the forecast surplus. Applying the following factors to adjust the potential recovery of 1.5Mt (using the lower figure of downcycled wrought calculated): 10% shredder losses (so 90% recovery) (Løvik et al., 2014), 90% sorting accuracy (ibid) and 8% remelting losses (Material Economics, 2020), a recovery factor of 74.5% is derived. This appears highly optimistic, especially for the early years of LIBS implementation. Accepting that 10% shredder losses is reasonable, a lower 80% sorting accuracy (ie 20% of wrought remains in the cast) and 15% remelting losses - [(Løvik et al., 2014) suggests that his modelled 90% recoveries may be beyond 'physical and thermodynamic limits'] would give a recovery factor of 61%. Applying 61% to 1.5Mtpa gives a recovery of about 0.9Mtpa, close to the derived European surplus of 0.8Mtpa. Clearly, using the higher figure for wrought arisings of 1.9Mtpa would give comfort that most wrought could be recycled.

It is therefore possible to conclude that the successful introduction of LIBS offers a realistic possibility of averting much or all of the forecast surplus of cast aluminium in 2030. However, there are a number of prerequisites for rolling out LIBS across Europe. Starting with the technical points, the equipment has to become widely available and to do what its proponents believe it will – to identify and sort wrought and cast aluminium series on a metre-wide conveyor belt running at 2-3 metres per

¹ There are hundreds of types of aluminium, split into the two major grades of aluminium, wrought and cast. Wrought is then broken into 7 series of sub-grades and cast into four series of sub-grades. Limited transferability between series during recycling means that a series level model is appropriate for forecasting surpluses and deficits.



second. At this point this remains an act of faith: LIBS has been in development for many years and proving it has been difficult (Interviewee 12) (Løvik et al., 2014). Secondly, it needs to sort to a high level of accuracy, say 90% (Løvik et al., 2014). Thirdly, there is skill required to set up and tune sorting equipment (Interviewee 12): if there is to be widespread rollout, this skill premium needs to be small, particularly since the input material will vary and the machine settings may need adjusting as the material changes. Fourthly, while there is much talk in the industry at present about the need to widen content specifications for materials input into industrial fabrication if recycled materials are to be incorporated (Interviewees 6, 9, 11, 12, 14), this needs to become a reality. The demand for low carbon content (recycled) material across industry (Interviewees (3,7,9,11,14), suggests that this may well occur. Fifthly, to an extent the volumes of scrap arising in the different series of wrought needs to approximately match the demand in those series, although some conversion of scrap between series is possible: this is beyond the scope of this report and analysis may be beyond the data currently available (Løvik et al., 2014). However, losses in reprocessing are caused by complexity: one must be careful in making simplifying assumptions.

Economically, a continuous and sufficient price premium for recycled wrought has to exist over unsorted grades destined for cast. In a world market where demand for engine blocks will probably not fall as fast as in Europe, this is not guaranteed. However, as a surplus of cast in the world comes closer, a real and permanent price premium for sorted recycled wrought is likely. The existence of a price premium for recycled high-quality aluminium (low carbon aluminium) (Interviewee 9) suggests that this is happening, and should a carbon border adjustment mechanism be introduced this can only help. Lastly, unless larger companies take over the market, results suggest that firm characteristics may slow adoption, as the perceived reluctance of smaller businesses to invest in advanced sorting machinery needs to be overcome, partly by the profits from doing so becoming clear. Regulation, through bans on the export of unsorted aluminium scrap would help, as Interviewee 9 thought the EU wished to do, while being aware that the capacity to sort the resulting volumes did not yet exist in the EU. It is this lack of sorting capacity that needs to be overcome in a LIBS implementation.

5.1 Aluminium Summary

- Of all the four bulk materials, aluminium is the only one where there is a realistic and near-term chance of digitalised technology transforming the reprocessing of post-consumer materials and potentially dramatically reducing downcycling.
- This is through the introduction of Laser Induced Breakdown Spectroscopy-based sorting equipment.
- There are plenty of doubters alongside some who will be early adopters.
- Longer-term, a combination of LIBS, optical sorting and AI – all digitally based – could make shipping unsorted non-ferrous metals to low wage countries for hand-sorting obsolete.
- The UK aluminium industry is missing primary smelter and large extruders, so it is highly likely that scrap will continue to be sold into the EU and further abroad, even if well sorted.

6. Discussion and Conclusions

Table 1 summarises the empirical research, covering potential impacts of provenance and digitalisation developments.

The table has a column for 'Other CE initiatives' which do not involve significant digitalisation or use of provenance systems. Additionally, there are a host of other decarbonisation initiatives in each material, such as use of previously reduced iron ore in blast furnaces and better energy efficiency in the cement making process, which are not part of the CE or of this research. Use of ground glass



bottles as a pozzolan in cement manufacture is strictly a decarbonisation measure: it is included it only because it does not appear to be much known in Europe and it needs to be acknowledged.

Chain-of-custody provenance databases, as currently constituted, offer marketing information but will not offer any short-term improvement in emissions. Further ahead, continued investment into Building Information Modelling (BIM) (see 1.3 above) systems offers hope of increased circularity of not only key parts of the structure but also internal fittings such as office partitions. In that all buildings are designed in computer, BIM appears highly scalable across all building sectors relatively quickly. However, the benefits only impact at the time of second life, in 15-40 years time for commercial buildings and longer for domestic. Plastics in buildings (20% of new plastics usage (Plastics Europe, 2021)) are similarly impacted by BIM over similar timespans.

RecyClass and PolyRec, the pan-European chain-of-custody systems for certifying the proportion of recycled plastics with a final resin, may, by ensuring that false claims over recycled content levels are not made, make some impact in years to come, but is unlikely to contribute short-term.

For packaging plastics (40% of the total), use of marking systems (essentially on-pack provenance systems) – not necessarily of one single type across all plastics – is possible within a very few years should the supply chain be able to agree on one or more solutions. The economic imperatives of Deposit Return Systems (DRS) and EPR may provide the stimulus to bring this about, once the detail of the legislation is set.

For aluminium, digital technologies, in the form of Laser Induced Breakdown Spectroscopy (LIBS), could have huge impact on the ability to separate wrought and cast grades and so prevent downcycling of the wrought grades almost completely, depending on speed of adoption.

For plastics in the longer term, the integration of AI and optical recognition systems with current Near Infra Red and X-Ray Fluorescence detectors could bring significant increases in the identification and sorting of products, again possibly stimulated by the economic forces introduced with EPR. Such sorting systems are currently embryonic at best. Plastics recirculation is hindered by the range of materials used, notably for automotive plastics (9% of use), but recovery through shredding and separation will continue.

For steel, there are no short-term solutions enabled by either provenance systems or digitalisation, only longer-term impacts from BIM (facilitation of reuse, as noted above) together with an unproven expectation of some gains in material efficiency through better design.

Recirculation of cement in any meaningful way seems far off: there are some experiments in different countries, including in Europe, testing cement recycling but no large-scale plans for commercial exploitation.

Table 1: A summary of the research, showing potential for impacts of Provenance Systems and Digitalisation

	Provenance Systems	Digitalisation	Other known CE initiatives for materials recirculation
Steel	<u>Short term</u> None <u>Long term BIM leads to reuse + refurb</u> (Provenance databases)	<u>Short term</u> None <u>Long term</u> BIM leads to reuse + refurb (Provenance databases) Material efficiency thru better design (Data analysis)	Recovery & reuse of construction beams. Cleaning extrinsic residuals from shredded output to avoid downcycling.
	<u>Short term</u>	<u>Short term</u>	Partial cement substitution by pozzolans incl. ground blast



Cement	None <u>Long term</u> None	None <u>Long term</u> None	furnace slag, fly ash, ground bottle glass ²
Plastics	<u>Short term</u> Possible for packaging: economic and collaborative barriers. Economic barriers may fall with EPR. (Provenance on-product marking) RecyClass certification scheme for % content (Provenance databases) <u>Long term</u> Possible for construction plastics with legislation. Will be helped by BIM. (Provenance databases)	<u>Short term</u> Digital recognition systems possible for packaging: economic and collaborative barriers. Economic barriers may fall with EPR3. (Provenance on-product marking) <u>Long term</u> BIM leads to reuse + recycling (Provenance databases) AI aligned with optical recognition to improve waste sorting and reduce non-recycling taxes under EPR (Provenance on-product marking + data analysis)	DRS, EPR, PPT extension. Potential ban on UK/EU plastic waste exports. Elimination of PVC & PS in packaging. Reduction of laminates in packaging. Investment in mechanical & chemical recycling plant. Commercial glycolysis of PET. Pyrolysis of thermosetting polymers.
Aluminium	<u>Short term</u> None <u>Long term</u> None	<u>Short term</u> Laser Induced Breakdown Spectroscopy (LIBS) to sort wrought waste from cast waste based on chemical signature. Potential to avoid large-scale downcycling of wrought into cast grades. Unproven at scale. (<i>Data analysis</i>) <u>Long term</u> AI aligned with optical recognition and LIBS to improve separation further. (<i>Data analysis</i>)	Companies developing separation of wrought alloys into different grades by other means than LIBS. Industry discussion about whether and how tight alloy specifications can be loosened to accommodate recycled material.

² Blast furnace slag and fly ash are diminishing in supply in Europe. No evidence found of recycled glass pozzolan substitution in Europe, though prevalent in USA. Increased use of pozzolans is strictly speaking a decarbonisation activity, not part of a move to the CE.

³ Depends how the legislation is worded: if specific proof of item recycling is needed to reduce taxes then provenance marking/digital reading will be highly incentivised.



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Appendix 1 – Data Collection and Analysis

This was done in two stages: a literature search followed by expert interviews.

A1.1 Literature search – overall method

- This did not seek to extract all available evidence to inform a further technical piece of work: rather, it sought to understand the key recycling concepts so that their practical adoption can be investigated. This was a Rapid Evidence Review (also called a Scoping Review or Targeted Review) rather than a Systematic Literature Review. It sought key recycling themes for each of the four materials (provenance, data collection and analysis) to assist the direction of unstructured interviews with academics and industrial partners: such partners are likely to be more aware of up-to-date industrial practice than published literature. (Munn et al., 2018)
- Additionally, the desire to select 'best practice' and 'state-of-the-art' literature requires selection of papers and articles, which is permissible in Scoping Reviews but not under a Systematic Review (Munn et al., 2018). 'State-of-the-art' is defined here as technologies under investigation in multiple universities or in commercial trials/implementation.

A1.1.2 Literature search - scope

- Grey literature – trade journals, trade press, industry bodies websites in addition to academic literature;
- Used all of Google Scholar, Google and Web of Science;
- Started with terms “Aluminium Recycling”, “Steel Recycling”, “Plastic Recycling” and “Cement Recycling” and snowball from references obtained from initial papers. Search using the names of specific processes as these become known;
- Focused on EU, but included worldwide;
- Focused on recent: within the last five years;
- Considered reuse as well as recycling, though *prima facie* this appears to be a minor area.

The literature search is necessary not only to establish the industrial background but also allow the interviewer to learn about the subject material in some detail: it is well established that interviewees respond more positively and effectively to well briefed interviewers (Trinczek, 1995).

A1.2 Expert interviews

The aim of these was to test and build on understandings gained from the literature and to build on these to find answers to the Research Questions. Experts are likely to be more aware of the most recent developments than the academic literature and more understanding of implementation realities of new technologies than grey literature. Results from the Rapid Evidence Review were used to construct a set of topics to guide the interviews. The interviews themselves were unstructured, using the guide to let the conversation flow whilst keeping it relevant (Meuser & Nagel, 2009).

The variation or consistency between experts is more important than the number of experts interviewed: a few cases, if triangulated with other sources, can be more informative than a larger number less deeply studied (Flick, 2014). Through the literature search potentially useful academics and industry figures were identified and then approached by email or via LinkedIn if possible. Those approached were a mixture of academics and industrial figures appearing – from their writings and/or publicity material - to have the appropriate insights to answer the issues arising from the literature. Pan-European businesses were deliberately selected if possible (8 of the 17 interviews). In addition, two interviewees were contacted having been participants in a previous project three years ago, one



of whom was interviewed and the second suggested another member of their team would be more appropriate. One relevant transcript was included from another study using a different interviewer. There are known difficulties in recruiting the 'right' interviewees with the correct level of detailed knowledge (of both process and strategy, in this case) and they may be circumscribed by both time and confidentiality (Flick, 2014). Many will simply not respond to emailed requests: these will be followed up a second time, but if there is still no response then an alternative will be sought.. Interviewing was continued until no new themes emerge across the four materials, 2 categories and 3 research areas (provenance, marking and sorting), with at least three people spoken to in each section. The literature review of the cement industry turned up nothing whatsoever in the way of digitally-influenced innovation for materials recirculation which was remotely close to commercial implementation: the planned recruitment was cancelled.

Record the interviews, if possible.

A1.3 Themes for interviews with metal partners

This is the original set of themes and sub-questions for metal interviewees derived from the literature review. It was amended in the light of each interview and paying attention to the company's activities. Points in the right-hand column were largely included as aide-memoires if the theme was relevant to the interview.

It is angled towards recycling and digital systems rather than the CE more generally.

Theme	Potential list of points to cover
Background on steel and aluminium recycling acknowledged: it would be expected that they are fully up with this.	
Overarching open question: What do you think are the major current challenges associated with recycling steel/aluminium? How could your technology and expertise be brought to bear on the problem?	When sidelined into detail, possibly in the sections below, this may need to be returned to several times. Need to cover thoughts on sorting and its complexities with different alloys.
Amidst all the talk of the Circular Economy by governments, is recycling talked about in your business? If so, in what sense?	
Is recycling a significant theme in the 5 year plans of your business?	Try to determine if it's a major theme or merely a nice-to-have talking point. New technology?
Are there databases (for example, from car manufacturers) which detail the precise material content of materials? Are these available?	Try to understand what potential there is for a provenance system based on product look-ups of existing databases.
If the business is making products with recycled content, ask about their perceptions of its quality and applications. Ask about their customers and their potential customers perceptions of its quality and applications, and any limitations they perceive because of the expectations of	Establishing if they perceive there are business reasons for not increasing sales of products with recycled content.



their customers. Are their customers much concerned with EoL?	
Are there issues are with standardisation of materials in packaging, motor, building or other use classes?	Trying to understand whether manufacturers use different alloys indiscriminately, which adds to the recycling problem.
Do your company have specific suppliers of recycled material, or is it bought freely as an easily tradeable standardised commodity?	Discover whether markets in the raw recyclate or recycled materials exist.
Are there standards for recycled material or skips(?) of recyclate?	Establish if they buy based on weight or on chemical content.
How big an issue is changing raw material supply prices for recyclers? (eg used cars)	Draw out how many value points there are and how many loss-making operations involved in creating the value (eg removal of contaminants)
How big an issue is changing output prices for recyclers? (eg PET prices)	
Do waste regulations cause any issues?	
If there are one or two actions you would like to see the government take to facilitate [plastics, steel, aluminium] re-use and recycling, what would they be?	
Specific Issues: Aide Memoire if subjects are not covered by open questions above.	
Issues with recyclate quality	Sort quality Tramp elements Organic contamination Bonded materials Additives Toxic substances
How recyclate is sorted/identified. Use of better technology to sort	Barriers to this (eg cost, lack of time, lack of knowledge)
Issues with Recyclate markets	Who buys? UK, EU, China, other Far East? How many intermediaries? What is it used for? Blending, prime feedstock? How is value created currently? How should value be created? Ideas to improve?
If appropriate: What is removed from cars before shredding? Does this change as market prices for metals change? How much [plastics, steel, aluminium] is not recovered from the shreds?	Issues and opportunities with car dismantling/shredding



What is the likely impact of Extended Producer Responsibility? (EPR)	Is it being discussed already? Is the impact of the proposals being seen already? How should the tax be assessed? Who should get some money or all the money? Experience of design for reuse? More investment in sorting technology? Are there likely risks because more money will be in the 'waste ecosystem'?
Local Authorities	Facilitator or inhibitor? Waste handling or transportation regulations an issue? Would regulatory changes help?

A1.3 Data Analysis

Each interview was recorded (if possible) and transcribed using the functionality of MS Teams. The interviews were replayed and the automatic transcripts corrected as necessary. The data was reviewed as collected to enhance the topic guide for later interviews.

17 people were interviewed in total, including a transcript of an interview performed by a colleague working on another study on building refurbishment. Given the relatively small numbers of people being interviewed in each area, mechanical analysis approaches (eg repeated word counts) are unlikely to produce valuable results. This similarly prevents the usefulness of grounded theory, and thematic analysis was used for analysis, although this is regarded as underdeveloped by some (Bryman, 2016) and in need of methodological support by others (Braun & Clarke, 2006). Under this approach, in past years it was usual to limit transcription to relevant passages (Meuser & Nagel, 2009). Modern transcription software reduces the overhead of transcription and the whole interviews were transcribed. The transcripts were the basis of analysis, in which relevant passages were summarised and compressed into themes, while keeping close to the terminology of the interviewee if possible. The first interview was analysed in detail to establish the likely themes (Flick, 2014). Themes or patterns relevant to the investigation were coded onto the summaries as discovered. They were compared for similarities to assess the adoption potential within industry, aiming to do this holistically with scientific, legal and financial viewpoints.

It was necessary to regularly check back to the transcripts to ensure that the meaning of the interviewee was maintained through the summarising and cross-tabulating procedure (Meuser & Nagel, 2009).

If themes do not involve digital systems, then the potential impacts were noted but the research of that theme was ended. Answers were qualified with likely problems, such as the possible need for new business models or the limitations on market penetration. If the aluminium industry, where digital technology is part of the solution, then potential impacts were quantified by assessing the EU market sizes relevant to the development. Several prerequisites were noted for the spread of the technology across the corporate sector.



Appendix 2 – Potential impact of LIBS on downcycling of post-consumer wrought aluminium scrap into cast grades.

As discussed in 4.4.5 above, the estimated size of the European surplus by 2030 is around 0.8Mtpa.

Method

The calculation is in two halves: firstly, to compute the probable weight of wrought aluminium currently downcycled, and secondly, to work out a realistic percentage of this that could be recovered based on the losses incurred at different stages of the recycling processes.

To produce a sensible estimate of the impact of sorting wrought and cast grades before they are recycled together and the wrought thus downcycled, it is necessary to look at the scrap arising from different uses and the likely proportions of wrought and cast in each of these uses. This starts with the global distribution of scrap arisings by category (building and construction, for example) from (Van den Eynde et al., 2022). Each use category is then downscaled proportionately by category to sum to the European total from the International Aluminium Institute (Alucycle, 2022). These scrap arising figures need to be further downscaled to the amounts collected in each use category. Where the percentage collections in Europe in a use category are known to be different from the global percentages, the European figures are used: these convert the scrap arisings to the scrap collections.

There are significantly differing estimates of the wrought and cast content in each category of post-consumer scrap in previous studies (Buchner et al., 2017; Van den Eynde et al., 2022), so two separate versions of the same calculation are then carried out to provide upper and lower boundaries for the amount of wrought collected in each category.

The working assumption then applied is that unless the wrought aluminium is identified and separated at this stage then it will be mixed with the cast and downcycled. So, for building materials, where aluminium is used in window profiles (window frames), some gutterings, fascias, pipework and grilles, it is likely that the majority of window profiles, which are known to be normally made of one of a few distinct aluminium alloys, will be kept separate and sent to a specialist recycler, whereas the rest will be merged into general aluminium scrap. In categories such as consumer durables the aluminium is unlikely to be identified or removed before shredding: no preservation of wrought is assumed.

So, applying this separation percentage to the categories allows derivation of a weight of wrought aluminium downcycled in Europe each year: depending on whether the Buchner or van den Eynde percentage of wrought by category is used, the total comes to 1.5 or 1.9Mtpa respectively.

Table A1 shows the derivation of the low-side figure of 1.5Mtpa: the high-side derivation is identical except that Column D is replaced by figures from van den Eynde which suggest a higher volume of wrought material across the Use Categories.



Distribution by category: van den Eynde et al (2022) *Figures from supplementary data 2 & 5* Proportion of cast alloy in Use Category: Buchner et al (2017)

Global				Europe										Column A takes the Global distribution from van den Eynde, keeps the same distribution, and reduces the total to the European arisings. Column B adjusts the proportion collected by known European literature, in the major Use Categories, to achieve the total in Column C which also corresponds to IAI figures for 2021. Column D applies the known % of cast aluminium to this distribution. Columns E derives the weight of wrought aluminium collected Column F uses known recycling methods to suggest a proportion of wrought aluminium that is preserved in its wrought state: the remainder being recycled with the cast and currently downcycled. Column G applies the percentage in F to the weight of wrought collected to derive the weight of wrought currently downcycled.
				European end-of-Life old scrap arising is 5565 ktpa (c1) 5,810kt arising total less 245kt cans										
Old Scrap	Collected	Not Collected	%	End-of-Life	Collected %	Collected	Cast alloy in	Wrought	Proportion	Wrought				
				Distribution	Input	Derived	Use category	Alloy	of wrought	that is				
				as global	Ref		from literature	Collected	preserved	downcycled				
				Column A	Column B	Column C	Ref d	Column D	Column F	Col G=E x (1-F)				
				'000tpa	%	'000tpa	%	'000tpa		'000tpa				
Building & Construction use	3,457	593	85%	689	92%	a	634	10%	571	50% i)	285			
Automotive use	11,045	726	94%	2202	95%	a	2092	75%	523	20% ii)	418			
Aerospace use	182	46	80%	36	72%	b	26	0%	26	100%	0			
Other transport use	2,296	461	83%	458	83%		380	75%	95	20% ii)	76			
Foil use	1,946	4,132	32%	388	42%	a	163	0%	163	100% iii)	0			
Machinery use	1,330	750	64%	265	56%	b	147	10%	133	0 iv)	133			
Cable use	1,465	608	71%	292	63%	b	183	0%	183	100% iv)	0			
Other electrical use	1,643	579	74%	328	66%	b	215	10%	193	0 iv)	193			
Consumer durables use	3,457	1,269	73%	689	65%	b	445	10%	401	0 v)	401			
Other use	1,091	1,015	52%	217	44%	b	96	50%	48	0 iv)	48			
Destructive use	0	4,067	0%	0			0		0					
	27,912	14,246	66%	5565	79%		4381 (c2)		2335		1554			
							= 4,618kt-245kt cans							
							= 4,373kt							
							Small discrepancy							
Cans use	(4,073	1,692												

Figure 3: Derivation of the low side figure of 1.5Mt for the amount of wrought scrap downcycled in Europe in 2021.

References

- a) UK Aluminium Federation, UK Aluminium Industry Fact Sheet No.5
- b) World averages, less 8%, to reach a balance with the totals from the IAI for amounts collected - small inconsistency in their figures.
- c1) <https://alucycle.international-aluminium.org/public-access/public-global-cycle/>
- c2) <https://alucycle.international-aluminium.org/public-access/public-global-cycle/>
- d) Buchner et al (2017)
- i) Windows, guttering, fascia, pipes, grilles. Assume 50% preserved as wrought
- ii) 20% from Buchner et al (2017); remainder assumed shredded
- iii) If foil is collected, it will be recycled at MRFs. I have no evidence that it is downcycled: I'm assuming not
- iv) No evidence of dismantling prior to shredding.
- v) Other than fridges, these are generally shredded

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Smart bins for household waste recovery



Social norms and tariff salience: An experimental study on household waste management

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ABSTRACT

We study the introduction of a social information program on waste disposal in a setting characterized by a two-part tariff. Households pay for unsorted waste a fixed amount if their yearly disposal is below a pre-defined cap, and pay per disposal after exceeding the cap. We randomize the receipt of a social information intervention, where customers' disposal is compared to that of similar ones. An additional treatment couples the social comparison with information on the customer's distance from the cap. We find that the report containing the social norm alone leads to a 5% reduction in the volume of unsorted waste. Making the cap salient significantly reduces the effectiveness of the social norm. The two treatments have a similar negative effect on the likelihood of exceeding the disposal cap. The reduction in unsorted waste is partly achieved through an increase in waste sorting, and is not accompanied by higher illegal disposals or lower quality of sorted waste. Our results confirm the effectiveness of descriptive norms in coordinating behavior but indicate that providing information on economic incentives can permanently crowd out their effect.

1. Introduction

The growing popularity of behavioral interventions implies that they are often implemented in settings where traditional policies, such as those relying on economic incentives or sanctions, are in place. In such cases, nudges often add social or other intrinsic motivations to the extrinsic ones provided by economic incentives or sanctions. Other times, these interventions are used to increase the salience and individuals' understanding of the existing taxes and pricing schemes. In spite of the large literature evaluating behavioral policies, our knowledge of their impacts is still limited in several respects. In this study, we focus on three main research gaps. First, the existing evidence on the effectiveness of behavioral interventions, leveraging intrinsic motives in the presence of extrinsic incentives, is mixed. Second, there exists limited evidence on whether information provision on taxes or pricing schemes works by increasing their salience or improving individuals' knowledge. Third, most studies give limited consideration to the negative externalities connected to an intervention. A comprehensive assessment of the impact and cost-effectiveness of policies requires going beyond the behavioral outcome directly targeted by the policy.

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In this paper, we study the impact of leveraging social information on top of existing economic incentives, both in isolation and when the latter are made more transparent and salient. We do so in the context of a social information program on the disposal of unsorted waste. The program's roll-out follows the introduction of a new tariff and collection system by the Italian utility with which we partner.¹ The tariff is based on a hybrid pay-as-you-throw scheme. Users pay a fixed amount if the volume of their yearly disposals of unsorted waste is below a threshold, determined by the utility depending on household size and other characteristics. If they pass the yearly threshold or cap, they pay a fixed amount per disposal above the cap. The collection system allows the utility to track each bag of unsorted waste disposed of by the users. Disposal of sorted waste is instead free and not monitored at the user level.

The social information program consists of a report delivered by mail (or email when available). Users randomly assigned to the Standard experimental treatment receive a report featuring, among other content, social information on how their level of disposal of unsorted waste compares with that of similar neighbors. Users in the Cap treatment see, in addition, information on how their cumulative volume of unsorted waste since the beginning of the year compares with their yearly cap.² Users in the control group receive no report.

We evaluate the interventions' impacts on the targeted behavior, as well as on other related outcomes. Using administrative data at the household level, we evaluate the impact of the two treatments on the volume of unsorted waste and the likelihood of exceeding the yearly cap. We exploit post-experimental data to explore the mechanisms behind the treatments' effects, particularly that of providing information on the tariff structure. We monitor outcomes for a year after the experimental period, when all households receive the standard report, to evaluate the persistence of the information on the cap. We hypothesize that any effect of the tariff information based on salience would disappear together with the treatment. Through data available at the unsorted and sorted waste truck route level, we also assess whether the program's introduction affected the quantity of unsorted waste and the quantity and quality of sorted waste.

We show that the standard treatment decreases unsorted waste volume by 6%, while the cap treatment reduces it by 4%. The difference between treatments is statistically significant. The report reduces the risk of exceeding the cap by 13.4%, with no difference by treatment. Using truck-route level data, we provide suggestive evidence that the reduction in the volume of unsorted waste is accompanied by a reduction in its weight. The program, therefore, appears to have led households to lower the frequency of disposals by actually reducing the quantity of waste produced, rather than by filling each bag more (Fullerton and Kinnaman, 1996). Heterogeneous treatment effects by baseline level of waste disposal reveal that the Cap treatment performs worse than the Standard one for the majority of customers. The two treatments perform similarly only among users close to the cap at baseline, who are likely to reap economic benefits from waste reduction.

The decrease in unsorted waste is achieved partly through an increase in sorted waste. Exploiting quasi-random variations in the share of treated households along the routes of trucks collecting sorted waste, exploratory analysis indicates that the amount of sorted waste increases by 7.6% if the intensity of treatment increases by ten percentage points. Finally, we show that these effects are not accompanied by negative consequences of the intervention in terms of lower quality of sorting or more littering.

We provide suggestive evidence that the information on the cap works by improving users' knowledge about the tariff scheme, rather than through a salience channel. In the latter scenario, the cap treatment would affect behavior by providing an arbitrary, salient, reference point for users, which, once removed, would cease to exert influence on disposals (Bordalo et al., 2022; Donk and van Zoest, 2008; Ariely et al., 2003; Kahneman, 1992). We observe persistent differences in disposal volumes between treatment groups in the post-experimental period, when all households receive the standard report. This result differs from Chetty et al. (2009)'s seminal paper on tax salience.

One reason behind the negative effect of adding information on the cap to the social one may lie in the interaction between the intrinsic incentives provided by the social information and the extrinsic ones given by the information on the tariff. In our setting, increasing users' understanding of economic incentives on top of social information does not improve the latter's effectiveness. The growing literature testing the effect of behavioral nudges and economic incentives on pro-social behavior yields mixed results (Drews et al., 2020). Crowding-out effects prevail when economic incentives are weak (Gneezy and Rustichini, 2000b), as they are in our setting where the cost per bag above the cap is low (1.5 Euro). In the electricity conservation domain, there is evidence that combining norm nudges with economic rewards leads to a higher reduction in usage (List et al., 2017); that it has the opposite effect of crowding out the intrinsic motivation to conform to the descriptive norm (Pellerano et al., 2017; Sudarshan, 2017); or that it makes no difference with respect to providing social information alone (Jessoe et al., 2021). Our results are in line with those of Pellerano et al. (2017), who also examine the effect of making a pricing scheme salient on top of a social information program on electricity usage in Ecuador. As in their setting, providing economic information backfires by reducing pro-environmental behavior.

The welfare implications of these results are nuanced. Providing information to consumers can, in principle, enhance welfare by increasing awareness and informing decision-making. However, if economic information undermines consumers' intrinsic motivation to preserve the environment, it may conflict with both policymakers' environmental objectives and consumers' preferences.

We focus on a relatively understudied behavior in the environmental domain: unsorted waste disposal. This domain is policy-relevant, given the severe environmental costs and externalities resulting from the generation, collection, and disposal of unsorted waste. Fostering waste prevention and sorting is important for sustainable waste management. Existing research demonstrates the

¹ Under the previous system, the tariff paid by each user was fixed depending on household size, and individual disposals were not monitored.

² The report's contents, detailed in Section 3 below, include standard features of similar types of social information programs, such as tips, environmental appeals, and comparisons of the users' disposals over time. These contents are common to the two versions of the report.

effectiveness of traditional policy tools, such as taxes and regulations, on the reduction of unsorted waste (Poortinga et al., 2013; Bueno and Valente, 2019; Messina and Tomasi, 2020; Colussi et al., 2022; Bucciol et al., 2023). The effectiveness of pricing policies is confirmed by a meta-analysis on unit-based pricing elasticities (Bel and Gradus, 2016). However, concerns about the public acceptability of a high-price policy on waste generation, with consequent risks of leakage to unregulated areas (White et al., 2019; Fullerton and Kinnaman, 1995, 1996; Erhardt, 2019; Bucciol et al., 2023), motivate the use of non-price interventions to reduce unsorted waste.

The literature that analyses the effectiveness of non-price interventions primarily focuses on waste sorting. Generally, these studies offer evidence of the effectiveness of behavioral interventions, and social information programs in particular, on waste sorting, with positive spillover effects in terms of reductions in the quantity of unsorted waste (Bucciol et al., 2015; Varotto and Spagnoli, 2017; Ek and Miliute-Plepiene, 2018; Alacevich et al., 2021).³ However, economic incentives are found to be more effective than social information in promoting waste separation (Xu et al., 2018).

The few studies that specifically test the effect of social information programs on unsorted waste find them to be effective (Ek and Söderberg, 2024; van der Werff and Lee, 2021), consistent with non-experimental evidence on the importance of behavioral factors in general, and social norms in particular, on household waste management (Hage et al., 2009; Halvorsen, 2012; Raghu and Rodrigues, 2020). In the closest study to ours, Ek and Söderberg (2024) implement a field experiment embedded in a pay-as-you-throw system in two Swedish municipalities. The intervention delivers different versions of a social information message and generates a reduction of 7%–12% in unsorted waste. The presence of a pure pay-as-you-throw system differentiates their setting from ours. In our paper, we exploit the discontinuity in the marginal price of disposals generated by the hybrid pay-as-you-throw scheme. Our paper also looks at the potential impacts on sorted waste and littering, providing a more complete evaluation of the impact of the social information program on the entire set of strategies that households can use to manage their waste.

The remainder of the paper is organized as follows. We describe the context where the field experiment was implemented in Section 2. We present the experimental design in Section 3. Section 4 describes the data we use in the empirical analyses. We show the results in Section 5 and discuss them in Section 6. Section 7 concludes.

2. Context

Collection and disposal management of solid waste in Italy is decentralized at the municipal level. Municipalities contract or are shareholders in disposal management firms under different waste collection and payment systems. The most common methods are flat fees, which are determined according to household characteristics such as house type and size or the number of household members. Over the last decade, an increasing number of municipalities adopted pay-as-you-throw (PAYT), also called Unit Pricing, systems, whereby unsorted waste is charged per unit, and sorted waste can be disposed of for free.⁴

In this paper, we study the effect of a social information program implemented by an Italian multi-utility in a city located in the Northern part of Italy. The hybrid PAYT collection system employed by the utility was first introduced in 2018. Households pay a fixed fee for the disposal of unsorted waste⁵ as long as the volume of their yearly disposal is within a certain threshold or cap. As the volume exceeds the cap, households pay an extra fee for each unit exceeding the cap. Each disposal unit corresponds to a volume of 30 liters; payment above the cap is 1.5 € per unit.

The cap is set for each household based on the number of members. The utility defined six basic cap levels for household sizes of 1, 2, 3, 4, 5, and 6 or more members, and the corresponding yearly volumes are 1,080, 1,380, 1,560, 1,740, 1,920, and 2,100 liters.⁶ These caps are raised in the presence of babies, elders, or members with health problems. These special categories are connected to the production of sanitary waste. Specifically, when children are born or the customer notifies of specific health problems, the utility increases the cap by about 1,900 liters per year for each child or person with health problems in the household.

Unsorted waste is disposed of in specific locations – collection points – throughout the city. There are about 1,500 unsorted waste collection points for residential disposal in the city area (around 400 Km^2). Users can access the unsorted waste bins at the collection points through a card. This allows the utility to track disposals for each household for correct billing.⁷ Collection points also host bins for sorted waste. Users do not need a card to open these bins and can dispose of sorted waste free of charge. Waste is collected by trucks along routes formed by a sequence of collection points for each type of waste (unsorted, paper, cardboard, glass, and plastic). At the end of the truck's route, an operator weights and rates the quality of sorted waste of the truck's content. Collection points of sorted and unsorted waste are routinely cleaned by utility operators. Before cleaning the area, operators rate the tidiness of the collection points using a tablet.

Users can also access waste collection centers (WCC) to dispose of special waste, such as batteries, electronic appliances, and bulky waste. Disposal of special waste at the WCC is rewarded through refunds on the waste bill proportional to its weight and type.⁸ Accesses to WCC are recorded at the user level.

Users pay the waste management bills quarterly and can access all the information on their disposals and dues using the utility's web portal and app. The latter two also offer notifications about utility services and tips on correct waste disposal.

³ Social information programs, like the one that we evaluate, have been applied and tested in various settings, from resource conservation (Allcott, 2011; Allcott and Rogers, 2014; Andor et al., 2020; Ferraro et al., 2011; Bonan et al., 2021b, 2024), contributions to charitable causes (Frey and Meier, 2004; Shang and Croson, 2009; Linek and Traxler, 2021), technology adoption (Bonan et al., 2021a), voting (Gerber and Rogers, 2009), and financial decisions (Beshears et al., 2015; Dur et al., 2021; Andrieș and Walker, 2023).

⁴ Over the period 2010–19 the share of municipalities adopting PAYT systems moved from 4 to 8.3% (Colussi et al., 2022).

⁵ By unsorted waste we refer to the residual waste that is not recycled.

⁶ The average payments are 74€, 117€, 142€, 161€, 192€ and 248€ for households with 1, 2, 3, 4, 5 and above 6 members, respectively.

⁷ A door-to-door collection system is also available for a restricted number of citizens living in the city center.

⁸ Users weigh their waste by major categories at the collection center and obtain a refund, ranging from 0.01 to 0.3 € per kilogram, in the next bill.

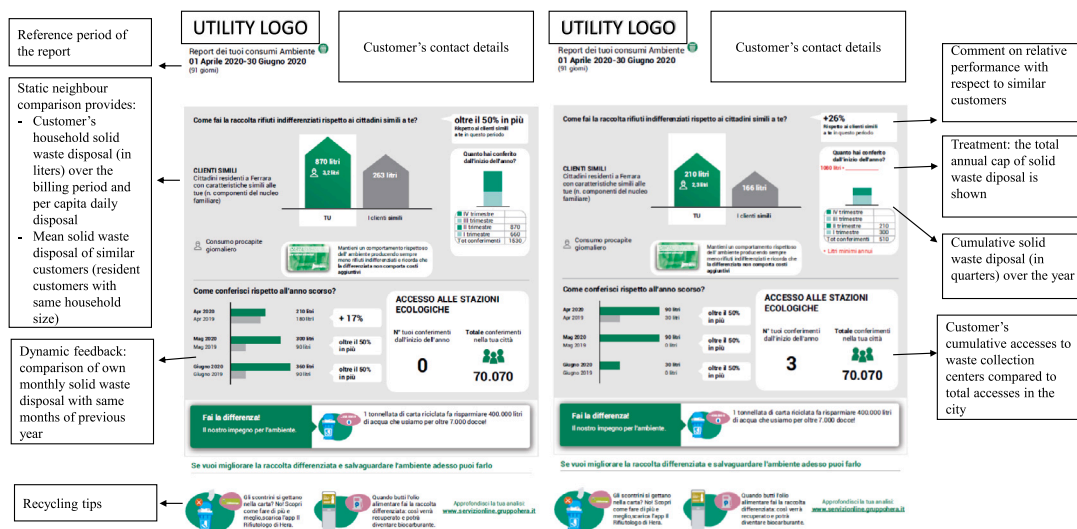


Fig. 1. Waste report.

3. Design

In collaboration with the utility, we designed and evaluated a large-scale social information program targeting unsorted waste, the "home waste report". The program was launched in July 2020, and the reports were delivered by post or email to customers. Only residential utility clients in the municipality were eligible to participate in the program.

Each report, which referred to unsorted waste disposals in specific quarters of the year, was expected to be sent quarterly after the delivery of the waste bill. In practice, implementation issues on the utility's side meant that reports were not sent at regular intervals nor at the end of the quarter they referred to.⁹

The experiment randomly assigns two-thirds of eligible customers to a treatment group receiving one of two versions of the home waste report and one-third to a control group receiving no report. Half of the treated households, or one-third of the overall sample, receive the standard social report (Standard treatment). The other half receives the standard report augmented with information about the disposal cap (Cap treatment).

The standard report is reproduced in Fig. 1 (left panel) and includes the following elements:

- **Static neighbor comparison.** Unsorted waste volume disposed of over the reference quarter, expressed as total liters and liters per capita per day. The user's level of unsorted waste is compared with that of similar customers living in the city over the same period. Similar customers have similar characteristics. In particular, they have the same solid waste disposal cap.
- **Cumulative unsorted waste disposal.** Cumulative unsorted waste disposal since the beginning of the year.
- **Dynamic feedback.** Unsorted waste disposal over the reference period, compared with one's disposal over the same month of the previous year.
- **Access to waste collection centers.** Cumulative number of accesses to WCC since the beginning of the year, alongside the total number of accesses by other citizens over the same period.
- **Make the difference.** This section delivers an environmental message, underlining the importance of recycling in reducing CO2 emissions. This part of the report is not customized.
- **Recycling tips.** Tips on how to improve recycling and its importance. Each report features different tips, but they are not personalized across customers.

Clearly, the report does not include only social information. Some of the additional features, such as tips, are common elements of this type of report (Allcott and Mullainathan, 2010; Bonan et al., 2020); while others, such as dynamic feedback or environmental appeals, are not. While we refer to the treatments in terms of their most prominent features, we evaluate the impact of the report in all its components.

Customers assigned to the cap treatment receive a slightly modified version of the report, where the figure reporting the cumulative solid waste disposal since the start of the year shows how it compares with the user's yearly cap (Fig. 1, right panel). If the volume of waste disposed of by the customer in the quarter exceeds one-fourth of the yearly cap, the figure makes this salient

⁹ Appendix Table A.1 reports the date of delivery of each wave of the report and the reports' reference period. In terms of our analysis, this implies that we cannot rigorously test the heterogeneous effect of the report depending on its quarter of reference, which is one of our pre-specified dimensions of heterogeneity.

Table 1
Descriptive statistics and balance.

	(1) Control	(2)	(3) Standard	(4)	(5) Cap	(6)	(7)
	Mean	SD	Mean	SD	Mean	SD	P-value
Disposal cap 2020	1723.751	1699.115	1714.44	1658.309	1727.759	1715.914	0.772
Allowances in 2020	0.046	0.21	0.046	0.209	0.046	0.21	0.935
Monthly disposal in 2019	73.79	75.15	73.15	74.50	73.64	75.23	0.733
Exceeded the cap in 2019	0.097	0.295	0.096	0.294	0.097	0.296	0.937
Above median house size	0.501	0.5	0.502	0.5	0.503	0.5	0.974
Has e-mail	0.384	0.486	0.383	0.486	0.382	0.486	0.966
Access to WCC in 2019	0.439	0.496	0.437	0.496	0.437	0.496	0.93
N. of Accesses to WCC in 2019	1.56	4.22	1.58	4.35	1.58	4.68	0.98
N. of households	15,585		15,663		15,685		

Note: This table reports means and standard deviations of baseline variables by treatment group. The last column reports the *p*-value of a joint significance test of treatment coefficients in a regression with the baseline variables as dependent, with robust standard errors. WCC: waste collection center.

through a message.¹⁰ These pieces of information allow treated customers to keep track of their performance against the yearly cap.

Besides the neighbor comparison, the standard and cap treatments do not disclose new information. The waste bill, delivered quarterly, already informs all customers of their disposals during the period, of the yearly cap, and alerts them if their quarterly disposal exceeds one-fourth of the yearly cap. This information is, however, buried within the several pages of the bill and provided in written form. Through its simplified graphical representation, the home waste report makes these pieces of information more accessible and salient.

The cap treatment responds to a specific need of our partner utility, originating from the limited effectiveness of information delivered through the bill. As mentioned above, the share of households disposing above the cap at baseline is low, specifically below 10%. Nevertheless, these users impose large costs on the utility, not just in terms of waste management. The high bills received by users with disposals above the threshold are associated with complaints and difficulties in repayment. By warning users who are on course for a high bill in a salient and simple way, the cap treatment aims to both reduce the likelihood of users exceeding the threshold and minimize complaints in case they do.

4. Data and samples

The study period for unsorted waste disposal ranges from January 2019 to October 2021, for a total of 34 months. Of these, 18 months are in the pre-experimental and 16 months in the experimental period. We select the study sample from the population of residential customers the program targets. Specifically, from the initial sample of 54,150 resident households eligible for the program, residing in the municipality since (at least) January 2019, which we identified in the PAP, we restrict the study sample to 46,933 households. That is, we exclude from the study customers for whom the information on unsorted waste disposal is completely missing over the period or available only after or before the program's launch.¹¹ In addition, we deal with outliers in terms of monthly unsorted waste disposal by winsorizing the top 0.1% of disposals. Our final study sample comprises around 75% of all households residing in the city.

All data used in the analysis are provided by our partner utility after being anonymized. At the household level, these data consist primarily of our main outcome variable, which is unsorted waste disposal. We have information on the date and location, in terms of collection point, of each disposal of unsorted waste made by the customer. With this information, we compute the primary outcomes: the volume of solid waste disposed of in the month, expressed in liters, and the probability of exceeding the cap in the year. The administrative data also include contract information: house and household size, the household's yearly cap, and whether the household is entitled to a cap increase due to the presence of infants or members with health problems.

We follow a stratified individual-level randomization procedure to maximize ex-ante balance across the three experimental arms along a battery of observable characteristics. Strata are obtained from the combination of the following variables: the household's disposal cap for unsorted waste in 2020; whether the household is entitled to an increase of the cap due to the presence of infants or members with health problems (at the time of data extraction, i.e. April 2020); house size above the median; whether the household accessed any WCC in 2019; having valid e-mail access, hence possibly receiving the report by email rather than by post. We end up with 96 strata. Within each stratum, we sort customers by baseline unsorted waste disposal volume in the baseline period (April 2019–March 2020) and assign adjacent customers to treatment and control groups.

We conduct balance tests across treatment groups for the variables used to construct the randomization strata, the pre-registered dimensions of heterogeneity, and the outcomes at baseline. Table 1 reports the mean and standard deviation in each treatment arm and a test of the joint significance of the treatments.¹² The results confirm that households' characteristics and outcomes measured

¹⁰ Customers visualize the following message “Be careful. If you keep disposing at this rate, you are likely to exceed your yearly cap”.

¹¹ The resulting sample is an unbalanced panel as we do not observe all households for the same number of months. In a robustness check, we restrict the analysis to a balanced sample of households.

¹² Balance is assessed by looking at the F-statistic of the test for joint significance of the treatment dummies in the following equation: $y_{it0} = \beta_0 + \beta_2 Std_Report_{it} + \beta_3 Cap_Report_{it} + \varepsilon_{it0}$, where y_{it0} are the variables reported in the table.

at baseline are balanced across treatment groups.

On average, households in our sample had a disposal cap of 1,723 liters in 2020, at the report launch, or about 143 liters per month. This threshold is quite generous, given that the yearly cumulative disposal was 885 liters and the average monthly disposal was 74 liters in 2019. As mentioned already, 9.7% of customers exceeded the cap; and a larger share, about 15% of households, produced yearly cumulative disposal volumes within 30% from the cap in 2019 (Appendix Figure A.1). Among those who exceeded the cap in 2019, the mean volume of disposals above the cap was 800 liters. Almost half of the households accessed a WCC in 2019, with an average frequency of 1.6 accesses over the year.

Besides the household-level information, we have additional information on unsorted and sorted waste at the truck-route level from January 2020 to October 2021. Truck routes are unordered sequences of collection points and are material-specific (unsorted, paper, cardboard, plastic, glass, and cans). For each truck route, we know the collection points covered, the collection date, the type of material, the total weight of material collected, expressed in tonnes, and for sorted material, its quality. The quality assessment of sorted waste follows the company guidelines and classifies recycling waste from low to high quality, using a 3-point scale. We use these data to analyze the effect of the social information program on the quantity and quality of sorted waste at the level of the truck route. We also use this data to analyze if the program affects not only the volume but also the weight of unsorted waste.

Routes change over time: some routes are common and are observed multiple times over the study period; others are observed only once. In our study of the program's effect on weight of sorted and unsorted waste, we restrict the attention to routes observed more than once over the study period, which is 411 for sorted materials and 105 for unsorted ones. The routes differ in the number of collection points that they cover. In the case of sorted waste, it ranges between 1 and 132, with an average of 13 collection points.¹³ We make this restriction as it allows us to use a panel model and control for time-invariant route characteristics through route-fixed effects. However, routes could change endogenously in response to changes in the quantity of waste disposed of in the collection points they cover, and such changes could possibly be due to the treatments. We discuss below the implications of this choice for our estimates.

The average monthly weight of the unsorted and sorted waste collected at the end of the route is 4.8 and 1.4 tonnes, respectively. The average recycling quality in our data is good, corresponding to an average rating of 2.2 (on a scale from 1 to 3). Glass and cans are materials displaying the highest score. These figures are consistent with the fact that the city that we study is among the first in Italy in terms of the share of recycling over the total volume of waste (Legambiente, 2020).

Finally, for each collection point ($N = 1,572$), we have a rating of the cleanliness of the area around it from January 2020 to October 2021. The rating of the collection points is performed by utility workers in charge of cleaning the area around collection points and uses a 4-point scale.¹⁴ The average rating over the study period is 3.2. Checks are performed on average 4 times per week. These ratings are a proxy of littering, specifically of customers abandoning their bags of unsorted waste outside the bins. Such anti-social behavior could be motivated by the desire to avoid swiping their cards and having the bag accounted for in the bill, and thus represents a possible undesired effect of providing information on the tariff.

5. Results

5.1. Impact on unsorted waste

5.1.1. Impact on the volume of disposal

We first analyze if the home waste report affects the volume of unsorted waste, which we denote as the intensive margin of disposal. We estimate the intention to treat effect (ITT) of receiving the report as follows:

$$y_{it} = \beta Treat_i * Post_t + h_i + g_i + \varepsilon_{it} \quad (1)$$

where y_{it} is customer i 's volume (liters) of unsorted waste disposed of in month t .¹⁵ $Treat_i$ is a treatment dummy that takes the value of one for customers receiving the report, irrespective of the type of treatment, and zero otherwise; $Post$ is a dummy variable that becomes one after the delivery of the first report, i.e., July 2020. The regression also includes month-by-year fixed effects, h_i , and household fixed effects, g_i . Standard errors in all specifications are clustered at the household level to allow for within-customer correlation over time in the error term (Bertrand et al., 2004). We control for multiple hypothesis testing for all the hypotheses presented in the PAP.¹⁶ In particular, we calculate and report the false discovery rate (FDR) adjusted p-values (q-values) (Benjamini et al., 2006).

We also assess if providing information on the yearly unsorted waste disposal cap on top of the social information is more or less effective than the standard social comparison alone. To do so, we estimate the following model:

$$y_{it} = \beta_1 Standard_i * Post_t + \beta_2 Cap_i * Post_t + h_i + g_i + \varepsilon_{it} \quad (2)$$

¹³ For unsorted waste, we observe an average of 19 collection points. We exclude 9381 and 34 routes from the analysis of sorted and unsorted waste, respectively, as they are observed only once.

¹⁴ Unfortunately, we cannot identify workers doing this job.

¹⁵ Given that, on average, households dispose of waste less than once per week, we organize the data as a monthly panel. In a robustness check, we run the same analysis at the weekly level.

¹⁶ The pre-registered results are the analysis on the individual level unsorted waste volume; on the probability of exceeding the cap; the heterogeneous effects by pre-treatment levels of disposal, passing the cap and the reference quarter of the report.

Table 2
Treatment effects on disposal and the probability of exceeding the cap.

	(1)	(2)	(3)	(4)
	Monthly Disposal		Pr. Exceeding cap	
Treat*Post	−3.724*** [0.496] (0.001)		−0.012*** [0.003] (0.001)	
Standard*Post		−4.442*** [0.574] (0.001)		−0.013*** [0.003] (0.001)
Cap*Post		−3.008*** [0.567] (0.001)		−0.012*** [0.003] (0.001)
Observations	1,499,733	1,499,733	140,799	140,799
N. of hh	46,933	46,933	46,933	46,933
Mean Dep	73.72	73.72	0.0893	0.0893
P-val(Std=Cap)		0.0111		0.825
q-val (Std=Cap)		0.003		0.101

Note: This table reports panel estimates of the effect of the report on monthly volume of disposal and on the probability of exceeding the gap in the year. The study period is from January 2019 to October 2021. The model includes individual and period fixed effects. Periods are months in columns 1–2 and years in columns 3–4. Post takes the value of one from July 2020, and zero before in columns 1–2; it takes the value of one for 2020 and 2021 and zero for 2019 in columns 3–4. The mean of the dependent variable at the bottom of columns 1–2 is expressed in liters. Standard errors, in squared brackets, are clustered at the household level. FDR-adjusted p-values (q-values) for pre-specified hypothesis in parentheses. The last two rows of the table report the p-values and q-values for the pre-specified hypothesis of the difference in the effectiveness of the two treatments. *** significance at the 1% level, ** at the 5% level, * at the 10% level.

where $Standard_i$ and Cap_i are dummies taking the value of one if customers are assigned to the standard information treatment and the standard information with cap treatment, respectively, and zero otherwise. The coefficients β_1 and β_2 reveal the effect of receiving the social information with and without cap indication, compared to not receiving the report.

Panel estimates of the effect of the waste report on monthly waste disposal are reported in Table 2. The social information program significantly reduces waste disposal by about 4 liters per month (Column 1). Given an average waste disposal of 73.7 liters per month for control households in the treatment period, this effect corresponds to a reduction of about 5%. Column 2 displays the treatment effects, separated by type of treatment. The norm nudge alone has a larger effect than the social norm augmented with the cap. While the standard report decreases unsorted waste disposal by 6%, the report informing about the cap decreases disposal by 4%. The difference between the two coefficients is statistically significant. These results are robust to MHT correction, as shown in the table through the FDR-adjusted p-values (q-values) reported in parentheses.

We explore the dynamics over time of treatment effects. Fig. 2 plots the effect of receiving the standard and the standard with cap treatments, relative to the control group receiving nothing, over the study period. The figure suggests that the program's impact builds up over time, particularly after the delivery of two reports over a short time span between the end of 2020 and the beginning of 2021. After peaking in the spring of 2021, the impact of the program persists until the end of our observation period in October 2021.¹⁷

Our results are robust to changes in the specification and sample. First, we replicate the analysis at the weekly rather than at the monthly level. Results, provided in Columns 1 and 2 of Appendix Table A.2, confirm the magnitude of the average treatment effect of Table 2. Second, we run our main specification on the sub-sample of customers for which we have data on disposal over the entire study period, i.e. 34 months. This restriction generates a balanced panel of 25,548 customers observed for the entire period. This is done in Columns 3–4 of Appendix Table A.2. The results are qualitatively confirmed, albeit slightly larger.

5.1.2. Impact on exceeding the cap

We analyze the effect of the intervention on the probability of exceeding the yearly cap, which we denote as the extensive margin of waste disposal. We estimate Eqs. (1) and (2), where y_{it} is a dummy equal to one if household i exceeded the threshold in the year t and 0 otherwise, and $Post$ is a dummy variable equal to 0 in 2019 and 1 in 2020 and 2021. Since exceeding the threshold may only occur once yearly, we organize the data as a yearly panel in this specification. h_t are year fixed-effects and g_i household fixed-effects.

The program reduces the risk of exceeding the cap by 1.2 percentage points (Column 3 of Table 2). Considering that 8.9% of control households exceed the cap in the treatment period, the effect corresponds to a 13.5% decrease. While the standard treatment is more effective than the cap treatment in reducing waste volume (Column 2), it is as effective as the cap treatment in reducing the probability of passing the threshold (Column 4). From these findings, we could infer that the cap intervention is less effective than

¹⁷ We also examine the evolution of the level of disposals by treatment over time (Appendix Figure A.2). The relative decline in the treatment groups appears to be also a decline in absolute levels.

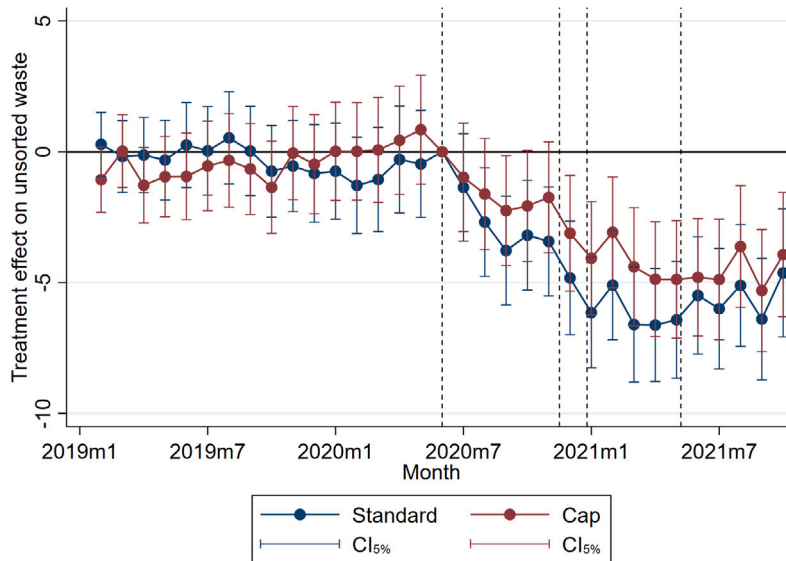


Fig. 2. Treatment effect dynamics.

the social comparison intervention for households (far) below the cap, while they are equally effective among households closer to the cap. To provide further support to this statement, in the next section we will compare the relative performance of the cap and standard treatments for households differing in their position relative to the cap.

Our results are robust to MHT correction and changes in the observation period. Specifically, the yearly-panel specification we adopt does not precisely capture the start and end of the program. First, the program was launched in July 2020, and considering the whole of 2020 as a treated period, as we do in our main specification, leads to underestimating the effect of the treatment. Second, the study period runs until October 2021. This may lead again to an underestimation of the probability of exceeding the cap in 2021, since such likelihood increases over the course of the year.¹⁸ A monthly-level specification allows us to precisely delimit the treatment period and account for the trend in cumulative disposals over the year. Hence, we complement the analysis above with one where the outcome is the probability of exceeding the “theoretical” cap in the month, or monthly allowable volume (which is equal to the cap divided by 12), using specifications similar to (1) and (2). Results are shown in Columns 5–6 of Appendix Table A.2 and confirm the significance and magnitude of the treatment effects. Appendix Figure A.4 shows how the shares of customers exceeding the theoretical monthly cap change over time by treatment.

We now examine whether the report influences the intensive margin beyond the cap, i.e., the volume of unsorted waste exceeding the cap. While changes in behavior below the cap do not produce monetary benefits, customers save €0.05 for each liter-reduction in disposal above the cap. We estimate Eqs. (1) and (2), where y_{it} is the cumulative waste that household i disposes of beyond the cap in the year t . For households not exceeding the cap, the dependent variable is set to zero. Appendix Table A.3 shows the regression results for the whole sample, dominated by a majority (over 90%) of households not exceeding the cap (Columns 1–2); and for the sub-sample of households that exceeded the cap in the year prior to the launch of the program (Columns 3–4). We find no treatment effects on either sample.

5.1.3. Heterogeneous effects

We look at the heterogeneous treatment effects along two pre-specified dimensions: pre-treatment unsorted waste disposal and having passed the cap in the pre-treatment year. We estimate the following equation:

$$y_{it} = \beta_1 \text{Treat}_i * \text{Post}_t + \beta_2 \text{Treat}_i * \text{Post}_t * X_i + \beta_3 \text{Post}_t * X_i + h_i + g_t + \varepsilon_{it} \quad (3)$$

To capture the first dimension (X_i), we create a dummy variable that is equal to one for households with pre-treatment unsorted waste disposal above the sample median and zero otherwise. Table 3 reports the results. Households with high unsorted waste disposal curb waste by 8.5 liters more than those with low disposal (Column 1). Given an average monthly post-treatment disposal of 73.7, this corresponds to an 11.6% reduction. We detect no significant reduction nor a boomerang effect among households with below-median baseline disposal.

When we distinguish between the two types of treatments, we confirm the stronger reaction of households with high unsorted waste disposal compared to those with low disposal (Column 2). We find a significant positive effect of the cap treatment within the

¹⁸ See Appendix Figure A.3.

Table 3
Heterogeneous treatment effects.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
X:	Monthly Disposal High Pre-Treat Disposal		Pr. Exceeding cap		Monthly Disposal Exceeded cap (2019)		Pr. Exceeding cap	
Treat*Post	0.450 [0.398] (0.151)		−0.001 [0.001] (0.195)		−3.118*** [0.439] (0.001)		−0.007*** [0.002] (0.001)	
Treat*Post*X	−8.515*** [0.989] (0.001)		−0.023*** [0.005] (0.001)		−6.570** [2.932] (0.026)		−0.056*** [0.012] (0.001)	
Standard*Post		0.121 [0.448] (0.271)		−0.002 [0.002] (0.095)		−3.736*** [0.502] (0.001)		−0.008*** [0.002] (0.001)
Cap*Post		0.776* [0.468] (0.065)		−0.000 [0.002] (0.324)		−2.502*** [0.509] (0.001)		−0.006*** [0.002] (0.003)
Standard*Post*X		−9.270*** [1.141] (0.001)		−0.022*** [0.006] (0.001)		−7.432** [3.451] (0.029)		−0.053*** [0.014] (0.001)
Cap*Post*X		−7.757*** [1.131] (0.001)		−0.025*** [0.006] (0.001)		−5.698* [3.271] (0.061)		−0.058*** [0.014] (0.001)
Observations	1,499,733	1,499,733	140,799	140,799	1,499,733	1,499,733	140,799	140,799
Number of hh	46,933	46,933	46,933	46,933	46,933	46,933	46,933	46,933
P-val(Std=Cap) X=0		0.151		0.159		0.0137		0.349
q-val(Std=Cap) X=0		(0.095)		(0.095)		(0.015)		(0.175)
P-val(Std=Cap) X=1		0.0339		0.878		0.362		0.793
q-val(Std=Cap) X=1		(0.03)		(0.293)		(0.175)		(0.271)

Note: This table reports panel estimates of the heterogeneous effect of the report on monthly volume of disposal and on the probability of exceeding the cap in the year. The study period is from January 2019 to October 2021. Households with high pre-treatment disposal are above the median yearly disposal in 2019. The model includes individual and period fixed effects. Periods are months in columns 1-2-5-6 and years in columns 3-4-7-8. Post takes the value of one from July 2020, and zero before in columns 1-2-5-6; and one for 2020 and 2021 and zero for 2019 in columns 3-4-7-8. The mean of the dependent variable at the bottom of columns 1-2-5-6 is expressed in liters. Standard errors, in squared brackets, are clustered at the household level. FDR-adjusted p-values (q-values) for pre-specified hypothesis in parentheses. The last rows report the p-values and q-values for the pre-specified hypothesis of the difference in the effectiveness of the two treatments in the sub-groups. *** significance at the 1% level, ** at the 5% level, * at the 10% level.

households with below-median baseline disposals, possibly suggesting a boomerang effect. The cap treatment performs significantly worse compared to the social treatment within the sub-samples of households with high pre-treatment disposal.

In terms of the extensive margin, the treatment is only effective in reducing the likelihood of surpassing the threshold in households with high pre-treatment disposals (Column 3). The two treatments do not affect the probability of exceeding the cap differently, in particular for households with above-median pre-treatment disposal ($p = 0.878$).

For the second dimension of heterogeneity, we distinguish between households with yearly disposals above or below the cap in 2019. The former group comprises about 9.7% of the total sample. The intervention effectively reduces disposal in both sub-groups, but we detect a stronger reaction among households that exceeded the cap in the pre-treatment year. These households react to the report by curbing disposals by 6.6 liters, or 13%, compared to the control group, twice as much as those who did not exceed the cap in 2019 (Column 5).

While both reports appear similarly effective in curbing disposals for those who exceeded the cap in 2019 (Column 6, $p = 0.362$), the standard report appears more effective than the cap one for those who did not exceed the cap ($p = 0.014$). This is consistent with the overall difference in treatment effects found in Column 2 of Table 2, given that more than 90% of the sample lies in this group. The report significantly reduces the risk of disposing above the cap among both groups of households, with a stronger effect among those who exceeded the cap in 2019 (Column 7). The two versions of the report do not significantly differ in their effects on the likelihood of exceeding the cap across both groups of households (Column 8).

In an exploratory analysis, we further examine the heterogeneity of treatment effects by baseline disposal. We focus on the sub-samples of high depositors, proxied either by being in the top 20% of the disposal distribution at baseline or by having exceeded the cap at baseline. We compute the median baseline disposal within these sub-samples, and test the heterogeneity of treatment effects between users below and above such median values. The rationale for this analysis is that below-median households within these sub-samples of high depositors may be particularly close to the cap, and thus be most responsive to the cap treatment. Appendix Table A.4 shows that the two treatments perform similarly among users close to the cap, who are the below-median depositors in these sub-samples, while the cap treatment performs significantly worse than the standard one among above-median ones.

The boomerang effect that we report in Table 3, along with the last piece of evidence in Table A.4, suggests that very low and very high depositors mainly drive the cap's lower performance compared to the standard treatment. While the two sub-samples react similarly when receiving information on the cap on top of the social comparison, the mechanisms behind these responses are likely to be different. Low depositors may be induced to slack off by the cap information. High depositors, on the contrary, may be discouraged by it.

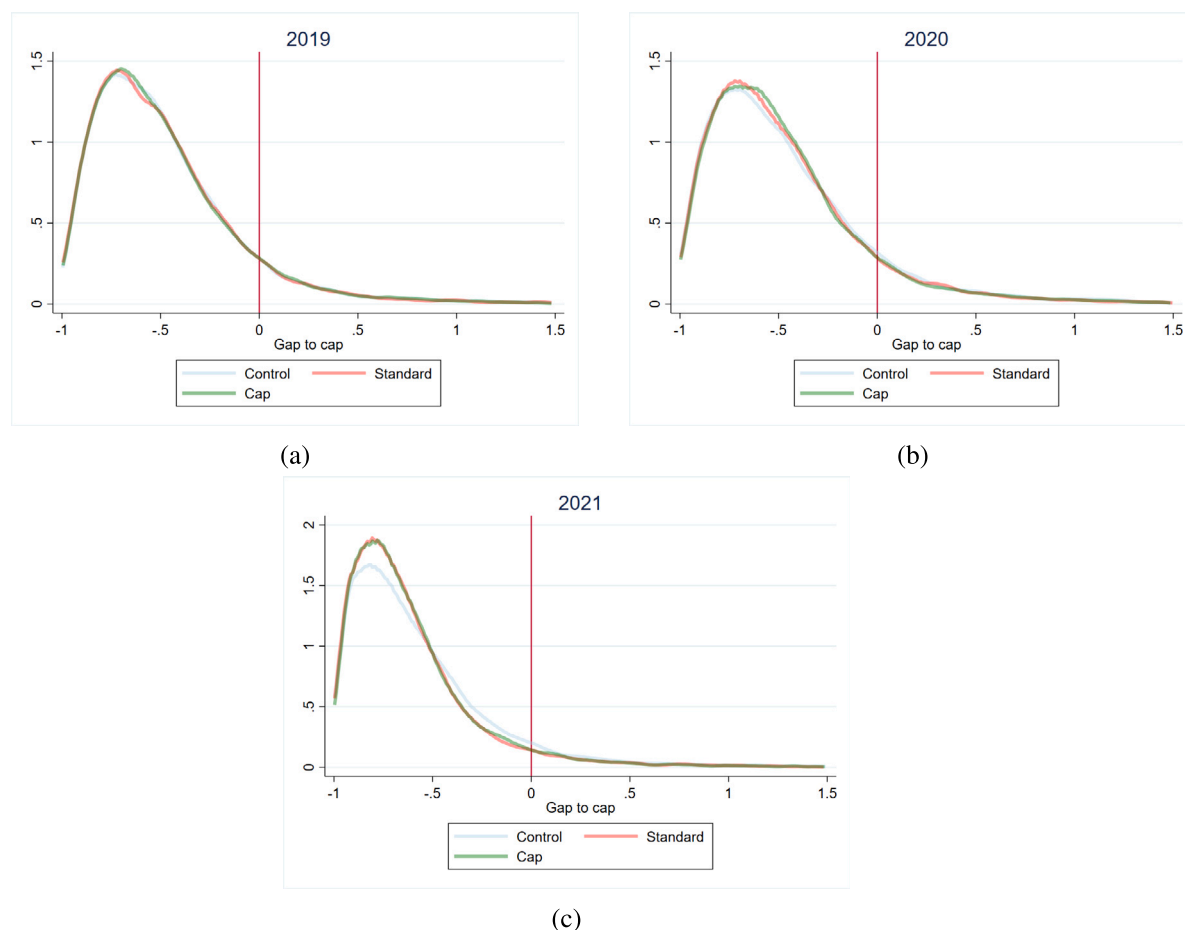


Fig. 3. Gap to the cap, by treatments and years. **Note:** the figures show the density functions of cumulative yearly disposal as a difference from the cap, expressed as a share of the cap in different years.

Results from pre-specified analysis are robust to MHT. Results are also robust to changes in how we compute the dependent variable in the analysis of volumes. In particular, we normalize the dependent variable using the individuals' cap. Such change makes the results on the intensive and extensive margin of disposal more readily comparable. The average and heterogeneous treatment effects are robust to this change (Appendix Table A.5).¹⁹

To further characterize how treatment effects vary along the distribution of yearly disposals, we plot the distribution of average cumulative disposals in the different treatments for the three years we observe in our data (Fig. 3). We present the yearly cumulative disposal as a percentage deviation from the annual cap. Points to the left of the vertical red lines indicate annual disposal below the cap, while points to the right indicate disposal above the cap. As expected, we do not detect any difference in the distributions of control and treated families before the intervention (Panel a). Differences between the three conditions are more evident in Panels (b) and (c). As already mentioned above, low-disposal households, to the left tail of the distribution, do not react to the intervention. Households with very high disposal, to the far right of the distribution, are similarly unresponsive, consistent with the lack of treatment effects on the volume of disposals exceeding the cap (Appendix Table A.3). We detect the largest changes in the middle of the distribution. Specifically, among treated households, we observe a reduction in the share of households lying below and just above the cap, particularly in 2021, and an increase in the share of households lying around the median of the distribution, relative to the distribution for the control group. This seems to confirm the results presented in Table 3, where stronger treatment effects are found among above-median disposal households.²⁰ Finally, we detect no evidence of bunching in the disposal distribution below the cap, which would indicate strategic sorting of users to avoid paying per piece for additional disposals. Our data may, however, not be adequate to detect bunching, given the small number of observations around the cap.²¹

¹⁹ In the heterogeneous analysis in Column 3, we distinguish households with high and low pre-treatment disposal using the distribution of pre-treatment levels as a share of individuals' cap.

²⁰ Appendix Figure A.6 shows the cumulative distribution functions which confirm the same results.

Table 4
Treatment intensity effects on weight and quality of waste.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
<i>Panel A:</i>	Unsorted waste log weight		Sorted waste log weight All materials		Paper	Cardboard	Plastic	Glass and Cans
Post*Int treat	−0.160*** [0.052]		0.513*** [0.131]		0.551** [0.215]	0.552* [0.281]	0.481*** [0.178]	2.442 [1.589]
Post*Int treat (std)		−0.184 [0.261]		0.587** [0.241]				
Post*Int treat (cap)		−0.143 [0.256]		0.457* [0.251]				
Avg weight (tonnes)	4.790	4.790	1.417	1.417	1.185	0.935	0.928	5.293
P-val (Int(std)=Int(cap))		0.935		0.758				
<i>Panel B:</i>	Sorted waste quality log score							
Post*Int treat			0.078 [0.054]		0.201** [0.095]	0.196*** [0.062]	−0.175* [0.102]	−0.624 [1.353]
Post*Int treat (std)				0.021 [0.144]				
Post*Int treat (cap)				0.121 [0.120]				
Avg. Quality score			2.215	2.215	2.020	2.420	2.036	2.688
P-val (Int(std)=Int(cap))				0.679				
Observations	3,081	3,081	3,477	3,477	1,007	1,103	1,038	329
N. Of routes	105	105	411	411	129	67	131	84

Note: This table reports panel estimates of the effect of the intensity of treated households along the route on weight of unsorted and sorted waste (Panel A) and quality of sorted waste (Panel B), overall and by different materials. “Int treat”, “Int treat (std)” and “Int treat (cap)” are the average (across collection points) volume of unsorted waste disposed of by households in the (pooled) treatment, standard and cap treatments as a share of the total volume disposed of by all households in the study sample in each collection point. The unit of analysis is a route-day. Post takes the value of one from July 2020, and zero before. The period considered is from January 2020 to October 2021. In Panel A, the dependent variable is the natural logarithm of the weight of unsorted and sorted waste collected along a route in a day. In Panel B, the dependent variable is the natural logarithm of the average quality score of the sorted waste along the route in a day. The model includes routes and month-fixed effects. Models in columns 1–2 also include material fixed effects. The mean of the dependent variable is expressed in liters at the bottom of Panel A and in a score ranging from 1 to 3 at the bottom of Panel B. Standard errors, in squared brackets, are clustered at the route level. P-values for the hypothesis indicated are reported at the bottom of each panel. *** significance at the 1% level, ** at the 5% level, * at the 10% level.

The pre-analysis plan for this study includes a third dimension of heterogeneity: the quarter of reference of the report. As mentioned in Section 3, implementation issues affecting the delivery timing of the reports prevent us from credibly evaluating this aspect. We nonetheless run the pre-registered specification, interacting the treatment with the quarter of reference of the report. The effect of the standard treatment on the volume of disposals is significantly stronger than that of the cap treatment in all but the first quarter of the second year (Appendix Table A.6) ($p=0.171$).

5.2. Behavioral responses

We have established that the report is effective in reducing unsorted waste volume and helping households keep their annual waste below the contractual cap. We now analyze other dimensions affected by the program that have important environmental implications.²²

5.2.1. Impact on the weight and quality of sorted and unsorted waste

From an environmental perspective, the reduction in the volume of waste disposal induced by the program is an important outcome only if it is associated with a reduction in the quantity of waste. The effectiveness of the program on both the volume and the weight of waste is achieved only under the assumption that households do not change their bag-filling behavior. If each 30-liter bag of unsorted waste is filled with the same quantity of waste before and after the program, the reduction in the volume of waste implies a reduction in the quantity of waste. However, this may not be the case. On one hand, the treatment, by encouraging a reduction in the number of disposals, may lead users to fill each bag with more waste. In this case, the reduction in nominal volume would not correspond to a reduction in the quantity of waste produced. On the other hand, if the treatment caused a reduction in the quantity of unsorted waste produced, households would take longer to fill out each bag. The longer time needed to accumulate the same volume of unsorted waste may result in increased inconvenience of in-home storage, due, for instance, to stronger smells. As a result, households may dispose of bags containing less waste, and thus reduce the frequency of disposals by less than would be possible given the reduction in the quantity of waste produced. In the first scenario, the amount of waste per disposal

²¹ Studies finding evidence of bunching in public economics typically employ several million observations from administrative tax records (Saez, 2010; Mortenson and Whitten, 2020).

²² The analysis that follows is not pre-specified.

would increase, and our treatment effects based on volume would overestimate the actual reduction in the quantity of waste. In the second scenario, the opposite would be the case. Distinguishing between these two scenarios is important from an environmental perspective, as waste weight and composition are more relevant than nominal volume.

Another important outcome of the program that is worth evaluating is its effect on the quantity of sorted waste. Reducing the volume and weight of unsorted waste may require behavioral changes, from avoiding the purchase of products with a lot of packaging, re-using products instead of disposing of them, and, most importantly, increasing sorting. The report can increase households' efforts in sorting waste directly and indirectly. First, households can reduce the disposal of unsorted waste, which is targeted by the report, by increasing sorted waste. This is an indirect effect of the report. Second, the report also directly affects sorted waste, because the report's tips section provides suggestions on how to improve sorting and directly stresses its importance.

Finally, from an environmental perspective, it is crucial to analyze whether a reduction in unsorted waste and an increase in sorted waste comes at the expense of a lower quality of sorting.

To analyze the effect of the program on these additional outcomes we turn to truck-route-level analysis.²³ Recall that routes are a sequence of collection points followed by trucks that collect specific materials (unsorted, paper, cardboard, glass and plastic). At the end of the truck's route, an operator weights and, in the case of sorted waste, rates the quality of the truck's content. We estimate the following equation:

$$y_{rsd} = \beta IntTreat_r * Post_t + h_s + g_r + n_t + \varepsilon_{rsd} \quad (4)$$

where y_{rsd} is the natural logarithm of the total weight of waste of type s collected along route r in date d .²⁴ Types of waste are: unsorted and sorted. The latter comprises paper, cardboard, plastic, glass and cans. $Post$ is a dummy variable that becomes one after the delivery of the first report, i.e., July 2020; h_s is the material fixed-effect; g_r is the route fixed-effect, and n_t is the month-by-year fixed-effect.

$IntTreat_r$ is a continuous variable that measures the intensity of exposure of the route r to the treatment, based on where households are expected to dispose of their waste. We compute $IntTreat_r$ as follows. First, for each collection point c along the route r , we calculate the volume of unsorted waste disposed of in the collection point c from the treated households (N) in the pre-treatment period ($\sum_{i=1}^N volume_i^c$), as a share of the volume of unsorted waste disposed of in the collection point by all households ($N + J$) in the pre-treatment period ($\sum_{i=1}^N volume_i^c + \sum_{j=1}^J volume_j^c$). This measure gives us the intensity of treatment exposure at the collection point c :

$$IntTreat_c = \frac{\sum_{i=1}^N volume_i^c}{\sum_{i=1}^N volume_i^c + \sum_{j=1}^J volume_j^c} \quad (5)$$

Given that the truck route follows a fixed sequence of collection points, we take the average of the collection points (K)' treatment intensity exposure over each truck route to have a measure of the treatment intensity at the route level.²⁵ This is our unit of analysis for sorted waste:

$$IntTreat_r = \frac{1}{n} \sum_{c=1}^K IntTreat_c \quad (6)$$

Table 4 shows regression results for the unsorted waste weight (Panel A, Columns 1–2). We find that as the share of treated users increases along a given route, the weight of unsorted waste collected by trucks significantly decreases, regardless of the type of treatment. This exploratory analysis provides evidence that the program contributed to reducing the weight, not just the volume, of unsorted waste.²⁶

Table 4 also reports results for the impact of the intervention on the quantity of recycled waste. We find that the intensity of the intervention affects the weight of sorted waste (Panel A, Column 3). In particular, a 10-percentage points increase in treatment intensity, from an average of 0.5 to 0.6, is associated with a 5.1% increase in the weight of sorted waste along the route.

The effect is not different by treatment (Column 4). The reduction in the disposal of unsorted waste thus appears to go hand in hand with an increase in the weight of sorted waste. We replicate this analysis separately for each type of sorted material: paper, cardboard, plastic, glass and cans (Columns 5 to 8). The point estimates are positive for all materials but statistically significant only for paper, cardboard, and plastic. The differential effect of the program on the specific materials can be due to a combination of factors. First, the tips in the report might have targeted specific materials. Second, the margins of improvements vary by type of

²³ Individual-level data do not allow us to investigate treatment effects on waste weight and quality because these outcomes are only observed at the route level.

²⁴ We employ the logarithm of the weight as it better performs than the level measure, in particular in the sorted waste analyses. This may be due to the dispersion of the dependent variable.

²⁵ As an example, in the sample of routes used to analyze the effect of the program on sorted waste, the share of waste disposed of by treated households in collection points along the route is 0.5 on average and ranges from 0 to 0.92. The average intensity of the two types of treatments along the routes calculated in the pre-treatment period is 0.28 and 0.25 for the standard and the cap report, respectively. The intensity varies by route. There are routes where none of the households were treated and routes where the majority of them received the report. As described in Section 4, routes differ in the number of collection points they cover. As the number of collection points increases, the intensity converges to 0.66, which is the percentage of treated households in the program (Appendix Figure A.5). On the contrary, routes with a small number of collection points display a higher dispersion.

²⁶ The differences in the empirical approaches do not allow us to quantitatively compare the decrease in unsorted waste volume estimated in Table 2 and the decrease in weight in Table 4.

materials. For example, while the percentage of glass sent for recycling is already quite high in Italy (78% in 2019), plastic has a recycling rate of only 45% (Pettinao et al., 2019).

To evaluate the program's impact on the quality of sorted waste, we estimate Eq. (4), where y_{irt} is now the natural logarithm of the average quality of sorted waste of truck i , running route r and month t . The quality is measured using a 3-point scale. Results are reported in Panel B of Table 4. We find no evidence of a lower quality of the sorted waste when we analyze all materials jointly (Column 3). When analyzing each material separately, we find that collection quality improves for paper and cardboard, while it decreases for plastic as treatment intensity increases. The negative effect of plastic may be explained by the higher complexity of recycling this material: not all types of plastic can be recycled, and users attempting to recycle more plastic may sort by mistake non-recyclable plastics.

Appendix Figure A.7 shows the dynamics of treatment effects for the quantity of unsorted and sorted waste and the quality of sorted waste. The figure provides support to the identifying common trend assumption.

In a robustness check, we repeat the analysis of the weight of unsorted and sorted waste and the quality of sorted waste, restricting the sample to the routes that are observed at least once both in the pre and post-treatment periods. This is done for the pooled model with all materials in Appendix Table A.7 (Columns 4 and 7). Results are consistent with the ones presented above. We also change the operationalization of the independent variable using the average share of treated households along the route instead of the average share of volume disposed of by treated households. Results are consistent (Appendix Table A.7, Columns 2, 5, and 8). Finally, we estimate the outcomes in levels. Results are similar, although less precisely estimated (Appendix Table A.7, Columns 3, 6, and 9).

To conclude this section, we must consider how the empirical strategy that we use may affect our estimates. In particular, our choice to include in the analysis only routes observed multiple times may lead us to underestimate the treatment effects. This would be the case if the treatment caused a change in routes due to its impact on the quantity of waste. For example, the increase in the quantity of sorted waste caused by the treatment may have resulted in shorter routes, as trucks filled out after fewer collection points. These routes, most affected by the treatment, would be excluded from the analysis given our inclusion criteria. We have suggestive evidence that this indeed may have occurred in the sample of sorted waste: the average number of collection points covered by a route is 46 at baseline and 44 in the experimental period, a statistically significant difference ($p = 0.019$). We should, therefore, consider our estimates of the impact of the program on sorted waste as a lower bound of the treatment effects on waste sorting.

5.2.2. Impact on access to waste collection centers

The hybrid PAYT system may induce customers to reduce unsorted waste by exploiting the opportunity to access WCC. In WCC, people can dispose of bulky items that do not fit in unsorted waste collection points. In addition, WCC can be used to dispose of items that are more correctly disposed of in dedicated bins, such as electronics.

We explore the treatment effects on the probability of accessing and the number of accesses to WCC in Appendix Table A.8, using a household-month specification like in 1 and 2. The treatment has a positive but insignificant impact on the likelihood of visiting these centers in the month (Column 1). However, households in the cap treatment are weakly significantly more likely to visit WCC than the control group (Column 2). No impact is detected on the number of monthly visits (Columns 3–4).

5.2.3. Impact on littering and illicit disposal

Finally, in Appendix Table A.9, we analyze the effect of the intervention on illicit disposals proxied by littering around the collection points. We estimate the following equation:

$$y_{ct} = \beta_1 Post_t + \beta_2 IntTreat_c * Post_t + g_c + n_t + \varepsilon_{ct} \quad (7)$$

where y_{ct} measures the average cleanliness of the collection point c in week t , and is computed as the natural logarithm of the 4-point scale rating of the collection point c .²⁷ $Post$ is a dummy variable that becomes one after the delivery of the first report; g_c is the collection point fixed effect, and n_t is a week of the year fixed effect. $IntTreat_c$ is a continuous variable that measures the intensity of treatment in the specific collection point c , as described in Eq. (5). The value ranges from 0 to 0.99, and the average is 0.6.

We do not detect any increase in littering that would have resulted in a lower quality score of the collection points. Neither the treatment overall (Column 1), nor the two versions of the report analyzed separately (Column 2), have any impact on the cleanliness of the collection points. We cannot exclude that the program increased leakage to unregulated areas, as we have no data on them.

²⁷ Given the irregular frequency of the evaluation of the collection points, with some collection points being evaluated more than once a day, while others only once a week, we organize the data as a weekly panel.

6. Mechanisms

One of our main findings is the different effectiveness of the cap compared to the standard treatment on unsorted waste disposal. This differential effect can be explained by two possible reasons. First, users may be misinformed or have misbeliefs about their cap and their expected distance from it. Second, users may know this information, but be inattentive to it. Hence, the cap treatment, in principle, could work through the provision of information and correction of misbeliefs; or could serve as a reminder, offering the cap as a salient alternative reference point to the one provided by the social information. A better understanding of which mechanism is in place would help us derive possible welfare implications of the intervention. If the cap information increases awareness, then the resulting decisions should reflect the users' preferences to a greater extent, and thus improve welfare. If, instead, the cap treatment affects decisions through the provision of a salient, potentially arbitrary reference point, then it may, in principle, shift consumers' decisions away from their preferences under full information, with potentially negative consequences on their welfare.

By embodying information on the tariff structure, the cap treatment allows consumers to better understand the economic costs of higher disposal volumes. If users care about economic savings, this information may motivate them to keep their disposals below the threshold. The literature on the effectiveness of PAYT schemes confirms that economic incentives matter for curbing waste production (Bueno and Valente, 2019; Colussi et al., 2022). In our setting, the relevance of this information varies depending on the volume of disposal relative to the cap. For example, users without any previous experience of exceeding the cap may value this information more than users who have passed the cap before. The former may have little awareness of the level of the cap and hence be highly responsive to this information. Second, users far below the cap, who face a zero marginal cost of disposal, should perceive lower incentive to further curb their disposals compared to users closer to the cap on both sides. The relevance of the economic incentives is, therefore, larger for users close to the cap. Finally, users far above the cap may not be able or willing to respond to the economic incentives built into the tariff.

The social norm represents a reference point for individuals, but so does the cap. The cap treatment adds an alternative reference point to the social norm, which users may measure their behavior against and strive to conform to. The volume of disposal relative to the cap is again crucial in affecting the relevance of this reference point. For users with disposal volumes below the cap, which constitute the majority of households, the salience of the reference point provided by the cap should induce an increase in disposal: seeing that the level of disposal, which the utility has deemed adequate for the household, is large relative to the household's current level of disposal may induce a reduced effort in curbing unsorted waste. The opposite should hold for users with disposal volumes above or just below the cap.

A comparison of the relative performance of the cap and standard treatments, however, does not allow us to be conclusive on which mechanism is at work. Based on the considerations above, the two mechanisms produce similar predictions on which treatment should be more effective in curbing unsorted waste on different types of users. Both the information and salience mechanisms predict that the cap treatment outperforms the standard one among users close to the cap on both sides, and possibly for users far above the cap; and underperforms relative to the standard one for users disposing below the cap and below what is provided by the social norm, as in this case two pieces of information, rather than one, encourage an increase in disposal.

Empirically, we find some support for the theoretical predictions above. The cap treatment is associated with a boomerang effect among low-disposal users, while the standard one is not. Other findings are instead at odds. The cap treatment is never more effective than the standard one, even among users who should be more responsive to the tariff information, such as those near the cap or far above it; or those with above-median baseline disposal volumes. The analyses presented so far do not yet allow us to distinguish which mechanism may be more relevant in our setting.

To distinguish between information provision and reference point salience, we therefore rely on additional data, and perform new exploratory analyses. Specifically, we extend our data and analysis to the post-treatment period, from November 2021 to December 2022. From November 2021, customers in both the cap treatment and the control group started receiving the standard report. By examining the behavior of users who first received the cap treatment and then received the standard treatment in the post-treatment period, we can analyze the persistence of the message conveyed by the cap treatment after its removal. Since salience effects are typically short-lived, while information should remain, if salience were the main channel we would expect the differential effect of the cap treatment to disappear after its removal. The literature on reference points confirms that, when such reference points are arbitrary, they have only short-lived effects on behavior (Ariely et al., 2003; Kahneman, 1992). On the other hand, any understanding of the tariff and cap gained in one year may still be relevant the following year since the cap is fixed for each household as long as its composition or health status does not change.²⁸

For this analysis, we focus on customers belonging to the standard and cap treatments and split the study window into three non-overlapping sub-periods: pre-treatment (before July 2020); treatment (July 2020–October 2021); post-treatment (October 2021–December 2022) periods. We run a model similar to Eq. (2). Results are reported in Appendix Table A.10. We confirm that customers in the cap treatment dispose of higher volumes of unsorted waste than those in the standard one over the experimental period. This effect persists in the post-experimental period when the cap information is no longer available in the report. The point estimate is even larger in the post-experimental than in the experimental period, although the difference between the coefficients for the two periods is not statistically significant. This result suggests that the effect of the cap treatment is more likely to work through learning about the tariff scheme, rather than through increased salience of the reference point.

²⁸ This strategy is similar to the one used by Chetty et al. (2009) for a similar purpose.

Having established that increased awareness of the tariff scheme is likely to be behind the effect of the cap treatment, we now provide some explanations of our empirical findings that are at odds with the theoretical predictions above. Our results indicate that the information on the economic incentives of waste reduction never makes the cap treatment more effective than the standard one, even among users for whom such incentives should be more relevant. The standard treatment outperforms the cap one for most users. We consider different explanations for this finding.

First, it is possible that the incentives provided by the tariff scheme that we study are simply not strong enough to elicit effort on the part of users to curb disposals. The fact that households do not sort just below the cap indicates the limited influence of economic considerations on disposal volumes. A hybrid PAYT scheme, such as the one we focus on, creates a discontinuity in the marginal price of disposals. The marginal price is zero below the threshold and positive above it. If economic incentives were strong and households could perfectly control their disposals, we should observe bunching just below the notch created by the tariff scheme. The lack of bunching at the cap may be due to the features of the specific tariff that we study. The cap may be too generous and the marginal price above the cap may be too low to compensate households for the effort required to limit their disposals.²⁹ In any case, this mechanism does not explain why the cap treatment performs worse than the standard one, as at most it would predict a similar effectiveness of the two treatments.

Second, the cap treatment may not strengthen the effect of the social information because the cumulative effect of multiple nudges is lower than the sum of the effects of each nudge in isolation. Bonan et al. (2020) report that additional nudges produce small marginal gains when they reinforce existing ones; and Bonan et al. (2024) provide evidence of the reduced effectiveness of multiple nudges due to the high load that they impose on individuals' cognitive ability and attention. Similar to the previous explanation, this one would also predict that adding the information on the cap to the social information would not improve the latter's effectiveness, not that it would reduce it.

Finally, the cap treatment may reduce the effectiveness of the social information because of crowding out. Specifically, the cap treatment, by making salient the extrinsic incentives tied to waste reduction, may crowd out users' intrinsic motivation to preserve the environment and to conform to pro-environmental norms of behavior (Rode et al., 2015; Bowles and Polania-Reyes, 2012; Bénabou and Tirole, 2006; Pellerano et al., 2017; Sudarshan, 2017). If simply mentioning the extrinsic incentives crowds out any intrinsic motivation to reduce waste production, then the crowding-out mechanism should affect all users, regardless of their baseline level of disposal or experience with exceeding the cap. When economic incentives are strong enough, their influence on behavior may offset that of crowding out. This explanation would account both for the lower effectiveness of the cap treatment relative to the standard one for most users, and for their similar effectiveness only among users facing the stronger economic incentives to remain below the cap. Crowding-out could also explain the persistent difference between the standard and cap treatments, as existing evidence demonstrates how intrinsic motivation, once crowded out, cannot be brought back through the removal of the extrinsic incentives (Gneezy and Rustichini, 2000a).

7. Conclusions

Our results show that a treatment based on a social norm alone is significantly more effective than one highlighting the tariff cap in curbing the volume of unsorted waste disposals. The two treatments are equally effective in reducing the likelihood of exceeding the cap, and neither leads to any reduction in disposal volume beyond the cap. Both treatments are more effective for households with high disposals at baseline. Although we are limited in our ability to examine the dynamic effects of the treatments, we can note that the standard treatment is never less effective than the cap one.

The results confirm the effectiveness of social information in shifting behavior toward the descriptive norm displayed in the report, even among users who, thanks to their low disposal volumes, do not benefit in economic terms from doing so. Moreover, the report has persistent effects even in a context where the opportunities for technological investments are limited, as is the case for waste. Households appear to achieve a reduction in disposal through behavioral changes, such as increasing the quantity of sorted waste. Households increase their effort in sorting and acquiring new habits over time, contributing to the persistent effectiveness of the intervention. The changes we detect are not accompanied by negative externalities in terms of reduced quality of sorting or littering.

The welfare implications of our findings are nuanced. Providing consumers with information that increases their awareness of the consequences of their decisions improves the quality of their choices and their welfare as a result. However, if economic information crowds out individuals' intrinsic motivation to preserve the environment, then such information may backfire. This effect may occur particularly if consumers intrinsically care about environmental conservation. This is especially true if the economic incentives faced by consumers are not strong enough to offset the crowding-out effects (Gneezy and Rustichini, 2000b).

Our study has limitations. First, we conduct our RCT in a setting with very high levels of sorting, indicating high environmental concerns among citizens. It is unclear how our results would generalize in a less virtuous setting. Second, the tariff that we study is characterized by very generous caps and low price-rate for disposals above the cap. It would be interesting to investigate the robustness of our results to changes in the tariff. Finally, our analysis of the interaction between the cap and the norm nudges, particularly its dynamics, is limited by implementation constraints. This remains an interesting direction for further research.

²⁹ We acknowledge that we may have too few observations around the cap to be able to detect bunching. Also, we cannot rule out that households, even treated ones, may be unable to sort below the cap by perfectly controlling their level of disposal. The absence of strategic bunching, which should occur when consumers face block rate schemes, is also common for other resources like electricity, natural gas, water, and whenever consumers cannot predict consumption with precision (Alberini et al., 2022).

CRedit authorship contribution statement

J. Bonan: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **C. Cattaneo:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **G. d'Adda:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **A. Galliera:** Writing – review & editing, Validation, Data curation, Conceptualization. **M. Tavoni:** Writing – review & editing, Validation, Supervision, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Additional figures and tables

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.jeem.2025.103124>.

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AI techniques for urban planning

Using machine learning to understand causal relationships between urban form and travel CO₂ emissions across continents

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ABSTRACT

Climate change mitigation in urban mobility requires policies reconfiguring urban form to increase accessibility and facilitate low-carbon modes of transport. However, current policy research has insufficiently assessed urban form effects on car travel at three levels: (1) *Causality* – Can causality be established beyond theoretical and correlation-based analyses? (2) *Generalizability* – Do relationships hold across different cities and world regions? (3) *Context specificity* – How do relationships vary across neighborhoods of a city? Here, we address all three gaps via causal graph discovery and explainable machine learning to detect urban form effects on intra-city car travel, based on mobility data of six cities across three continents. We find significant causal effects of urban form on trip emissions and inter-feature effects, which had been neglected in previous work. Our results demonstrate that destination accessibility matters most overall, while low density and low connectivity also sharply increase CO₂ emissions. These general trends are similar across cities but we find idiosyncratic effects that can lead to substantially different recommendations. In more monocentric cities, we identify spatial corridors – about 10–50 km from the city center – where subcenter-oriented development is more relevant than increased access to the main center. Our work demonstrates a novel application of machine learning that enables new research addressing the needs of causality, generalizability, and contextual specificity for scaling evidence-based urban climate solutions.

Significance statement

Car travel is one of the activities emitting the most greenhouse gas emissions in cities. Urban planning strategies can reduce urban car travel and thus mitigate climate change. How urban development impacts traveled distances is a long-standing problem that has been primarily studied via correlation-based studies in individual cities. Our study based on causal methods offers evidence that certain strategies, such as increasing accessibility to the city center, hold across six cities on three continents. We also show how to adapt strategies to the specifics of each city, thus offering a new approach of relevance to city governments, transportation planning researchers, and the climate change mitigation community.

Introduction

Cities are responsible for 70% of the world's CO₂ emissions¹ and by 2050 nearly 70% of the earth's population will live in urban areas². These urban areas have a pivotal role in defining how humanity will solve the climate crisis. The largest CO₂ emitter in cities next to the building sector is urban transport, being responsible for 3 GtCO₂-eq per year³. For promoting sustainable urban transport, altering physical infrastructure – buildings, streets, and relevant points of interest, which together characterize urban form – is widely accepted to be a key leverage point. Such infrastructure modifications are estimated to have stronger influence than personal or social factors⁴, as also emphasized by the IPCC⁵. Yet, it is currently unclear how to translate the IPCC's generic, national-level policies, such as more urban densification, into location-specific actions implemented by municipalities.

Three main bottlenecks hinder the uptake of urban planning initiatives that can effectively reduce urban car travel and induced CO₂ emissions: *causality*, *generalizability*, and *context specificity*.

First, urban planning decisions require an understanding of how urban form causes car travel emissions. A literature body spanning several decades has studied the impact of urban form on traveled distances, respectively described by the '6Ds of compact development' and the metric 'vehicle kilometers traveled' (VKT). The 6Ds describe the destination accessibility, density, distance to transit, diversity, design, and demographic properties of a given location⁶. Most prior studies conclude that destination accessibility, described by the distance of a trip origin to the city center (or sub-centers) has the strongest effects on VKT^{6–11}. This feature is followed by density measures, such as population (or job) density^{6,8–15}, which reduce VKT with higher densities. Socio-demographic variables, such as the average income of an area, are also found to have a stronger association, mostly with negative^{8,11,12,16} and few with positive^{9,17} correlations. Neighborhood design, and specifically the number and density of road intersections, reduces GHG emissions from car travel^{6,10,13,14,17}. Land use diversity, such as land use mix ratios, or proximity to transit, also reduces GHG emissions slightly^{6,8,12,14,17}.

However, the *causality* of these effects remains uncertain and only few studies have considered that some of the 6Ds might be dependent of each other^{18,19} – risking to bias effect estimates¹⁸ and causing skepticism on the general impact of urban form¹⁴. Causal dependencies across the 6Ds arise as features such as destination access influence car travel on the metropolitan scale, while other 6Ds operate on a neighborhood level. Hence, the effects of features like street design or density on travel are likely dependent on their location relative to the center²⁰ – a question insufficiently investigated by previous research^{6,8–10,12,13,21}. Some mixed method approaches better reflect the causal mechanisms via (quasi-)longitudinal study designs, combining questionnaires and interviews of residents before and after urban form changes with geographical analysis^{7,20,22}. However, such approaches are cost-intensive, hardly representative for all locations of a city, and not scalable to many cities around the globe. Here, novel big data methods, such as causal graph discovery, can now approximate such dependencies based on observational data^{23,24}. Recent examples in the context of urban transport include the analysis of using graph discovery methods to understand causal drivers of urban form on mode choice^{19,25,26} or subway ridership²⁷.

Second, scaling city-specific recommendations requires an understanding of what may hold across certain cities – *generalizability* – and what is specific to the local context. Yet, previous work on urban form and car mobility has mostly focused on one^{8–10,12,15} or two cities⁷ or several of the same country^{6,13,14,16,17,28}. Using more diverse sets of cities from varying countries with different sizes, densities, and centralities could support distinguishing findings holding general or local relevance.

Third, effective urban planning policies require location-specific recommendations that consider and leverage the unique spatial characteristics of a city – *context specificity*. Previous literature has progressed from single city-wide effect measures of the 6Ds^{6,14} to uncovering nonlinear behaviors of individual effects, such as⁸. However, only little work was able to assign urban form effects to specific locations of a city, limiting their applicability for neighborhood-specific policy advice and real-world implementation. Recently, explainable machine learning methods enable the investigation of effects at individual locations. A case study in Berlin, for example, demonstrated that location-specific analysis allows the identification of areas with disproportionately high travel emissions due to low accessibility⁹.

Here, we address all three gaps and conduct a spatially explicit, cross-city analysis of the causal effects of urban form on travel-related CO₂ emissions across 6 six cities on three different continents. Our contributions are three-fold: (1) We establish a directed-acyclic graph (DAG) representing car distance traveled for commute and a subset of the 6Ds at the trip origin to develop a causal understanding of how urban form impacts VKT across all considered cities. (2) We analyze how individual features contribute to VKT and resulting trip emissions per city, using causal Shapley values derived from training a supervised machine learning model. (3) Finally, we demonstrate how analyzing location-specific causal effects of urban form on trip emissions enables us to discover new urban planning strategies.

Results

Causal urban form effects partially confirm previous assumptions

Using causal graph discovery, we find that destination accessibility, density, and design have a direct effect on VKT, while no significant direct effect is measured for income. In contrast with previous work, we observe inter-dependencies between several urban form features, enabling more nuanced urban planning decisions based on distinct cause-effect relationships. Fig. 1 summarizes our findings.

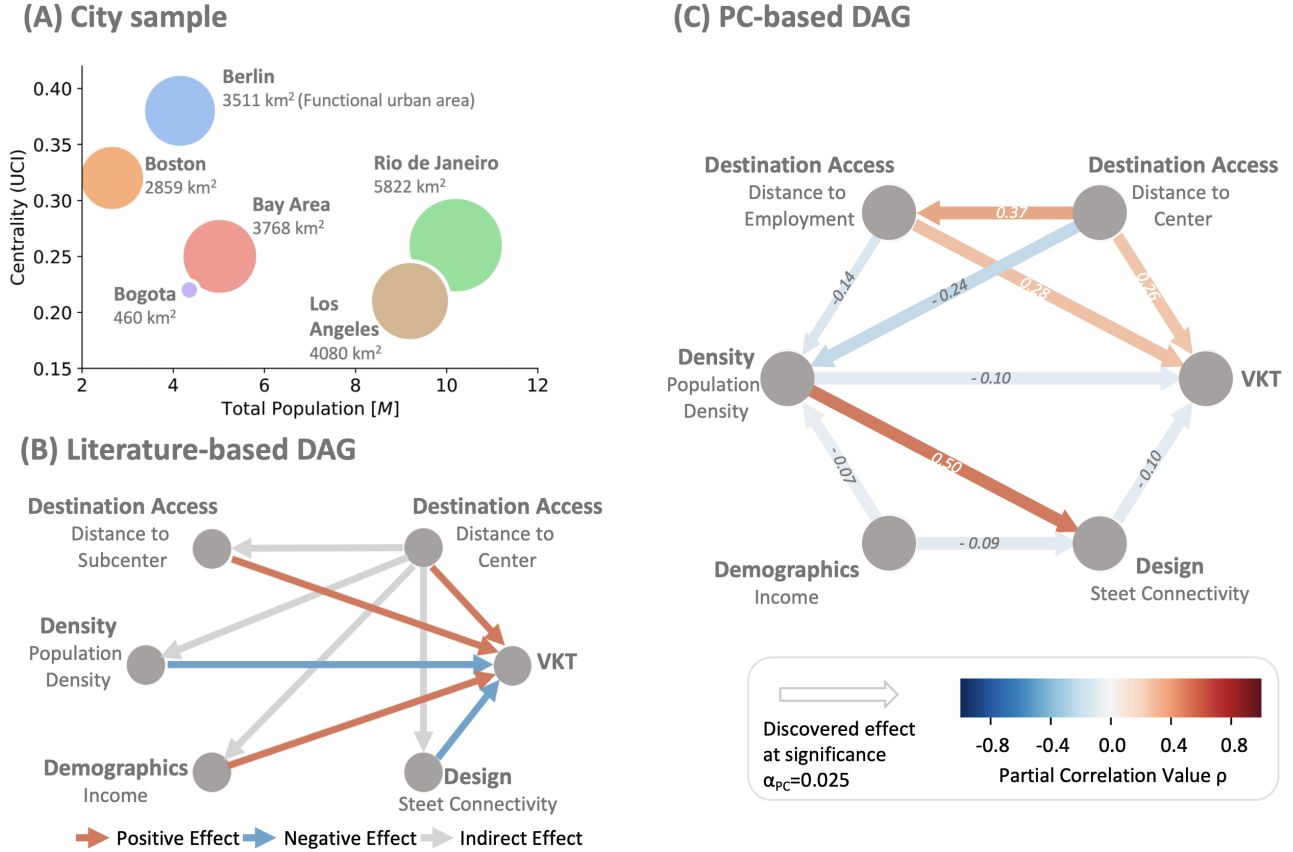


Figure 1. Comparison of causal graphs of the 6Ds of compact development on vehicle kilometers traveled (VKT) based on observational data across six cities. *Panel A:* Characterization of the cities Berlin (blue), Boston (orange), Los Angeles (brown), Bay Area (red), Rio de Janeiro (green), and Bogotá (purple) according to their centrality, measured by the urban centrality index on the y-axis (where values close to 0 indicate a more poly-centric distribution of jobs and values close to 1 indicate more mono-centric concentration), their total population count on the x-axis in million [M] and functional urban area size (dot size in km²). *Panel B:* Causal directed-acyclic graph (DAG) displaying the relationships between Destination Accessibility, Density, Design, Demographics, and VKT from previous work. The coloring denotes a direct positive (red), direct negative (blue), and indirect (gray) effect. *Panel C:* Causal DAG based on the causal discovery with the PC algorithm using a robust partial correlation (Robust ParCorr) conditional independence test at a significance level $\alpha_{PC} = 0.025$ (right). The arrow indicates the direction of the causal effect, while the coloring denotes a particular partial correlation value (see Methods, Causal Graph Discovery), indicating the causal strength of the effect between two nodes. No arrow between two nodes (e.g. between Demographics and VKT) indicates that no significant direct relationship was found between the two variables.

To examine the causal relationship between urban form variables and VKT, we utilize data from six cities with varying area, population density, and centrality, measured by the urban centrality index (see Urban Centrality Index in Methods), as shown in Fig. 1, A. We apply the conditional independence test-based causal discovery framework²⁹, specifically the PC (Peter-Clark) algorithm^{30,31}, to an equally pooled sample of 1542 traffic assessment zones (TAZ) across all cities. The framework aims at detecting and orienting edges between nodes in a DAG using conditional independence tests. In our case, the nodes represent

the target variable (VKT) and a subset of the 6Ds (see Feature Engineering in Methods for inclusion criteria). It also indicates a measure of causal strength of the dependency between two variables via the partial correlation value ρ . The discovered DAG can be interpreted as possibly causal for the analyzed data and constructed variables under certain assumptions (see Causal Graph Discovery in Methods for further details). Thus, our DAG allows for stronger statements towards causality than correlation-based studies²⁴. We report the discovered DAG in Fig. 1, C. The DAG is compared with a graph that consists of a similar subset of the 6Ds, which was derived from previous relevant studies (refer to SI, Table 5), as shown in Fig. 1, B.

Our PC-based DAG partly coincides with the literature-based DAG, but also exhibits noteworthy differences. Previous work has found all urban form features to have a direct effect on VKT. In previous studies, VKT typically correlates positively (red arrows) with distance to the center, distance to sub-centers and demographics (measured by mean income). VKT correlates negatively (blue arrows) with density and design. Additionally, some quasi-longitudinal studies recognized the different spatial scales of features and a resulting indirect link between distance to the center on all other urban form variables (gray arrow). In our study, we observe that lower distances to the main center and employment, higher population density, and street connectivity all have decreasing direct effects on VKT with partial correlation value ρ ranging between -0.1 and 0.28 . However, we cannot find a significant effect on VKT of demographics (measured by mean income).

In addition, and importantly, we can measure for the first time relationships between urban form features. We find that distance to the main center strongly affects distance to employment ($\rho = 0.37$) and population density ($\rho = -0.24$), but we do not find significant indirect effects of distance to the center on other variables. We also find that distance to employment is negatively linked to population density ($\rho = -0.14$) and population density is strongly positively linked to street connectivity ($\rho = 0.50$). We observe that income negatively affects density ($\rho = -0.07$) and connectivity ($\rho = -0.09$), reflecting that higher-income households tend to be located in less dense areas.

Trends generalize across cities but effect magnitudes differ

When comparing urban form effects across cities (see Fig. 2), we find that distance to the main center and distance to accessible jobs have stronger effects on trip emissions than density and connectivity. Yet, very low density and low connectivity increase emissions and should be avoided. While effects follow similar trends across cities, we measure differences in magnitudes that arise due to varying city sizes but also due to different spatial distributions of jobs and housing.

For the analysis of travel-related emissions, we convert observed travel distances to trip emissions (see SI, Location-specific emission factors). We first examine how well urban form explains trip emissions across cities. Here, we train a supervised, tree-based machine learning (ML) model in five cities and generalize to a sixth unseen city. We only consider features with a direct causal effect on the target to improve generalization performance. Then, we analyze the effect of individual urban form features on trip emissions at every location. For this, we calculate causal Shapley values³², which incorporate the variable relationships from the learned DAG (for further details, see Methods, Modelling, Model Generalization and Interpretation).

Overall, our ML model can capture the variation in trip emissions up to 84% in Berlin, 62% in Boston, 41% in Rio de Janeiro, 26% in the Bay Area, 51% in Bogotá, and 21% in Los Angeles (refer to SI, Table 6). Trip emissions can be best explained in the mono-centric cities of our sample.

The individual feature analysis via causal Shapley values reveals that distance to the center has the highest effect across the analyzed 6Ds. Shorter distances between trip origins and the center translate into lower CO₂ emissions. However, the feature distance to the center exerts non-linear effects that strongly increase between 22 km (Berlin) and 55 km (Bay Area) across all cities. The relative location to the center of a trip origin can affect emissions from +500 gCO₂ in Bogotá up to +1100 gCO₂ per trip in Berlin, respectively +24.7% and +53% relative to city average. Decreasing effects start from -100 gCO₂ (Bay Area) down to -320 gCO₂ (Berlin) per trip, respectively -3.4% and -15.5% relative to city average. We find that in cities with longer distances to the center, the slope increases slower (compare the Bay Area and Bogotá). Yet, different magnitudes in increasing effects result not only from different city sizes but possibly also from where citizens who live far away from the center travel to. Here, more diverse destinations of trips starting very far away from the center tend to have smaller effect magnitudes (refer to SI, Fig. 8). Additionally, the long tail of the Bay Area can be explained by the fact that we only define one center in downtown San Francisco. When defining four centers (including San Francisco, Oakland, Fremont and San Jose) the effect aligns closer with Boston and Los Angeles (compare SI, Fig. 23).

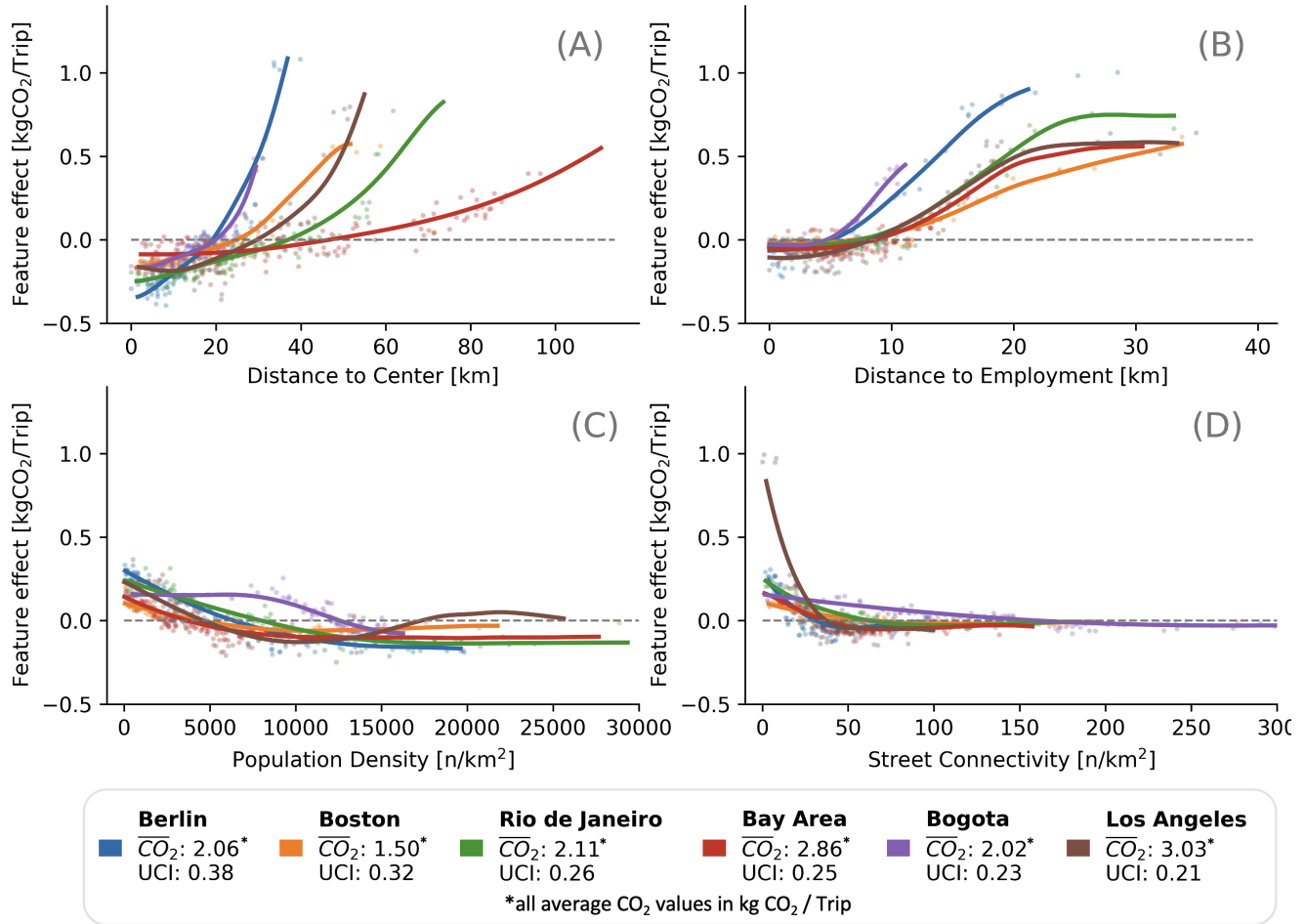


Figure 2. Comparison of causal Shapley effects on VKT for each significant urban form feature across cities. Causal Shapley scatter plots are visualized for the features: distance to the center (A), distance to employment (B), population density (C), and street connectivity (D). Every dot of a given color represents a traffic assignment zone (TAZ) in a city. The solid lines represent a fit over all samples of a city. Feature effects are displayed relative to the city's average emission per trip in kgCO₂ (dotted line). Average trip emissions for each city ($\overline{CO_2}$) and urban centrality index (UCI) are provided in the legend to contextualize effect magnitudes.

Distance to employment overall has slightly decreasing effects on VKT and related emissions for areas closer to job opportunities. This feature is nonetheless important, as we find that locations far away from jobs have strongly increasing effects on trip emissions beyond 6–7 km in Bogotá and Berlin, and beyond 10 km in Rio de Janeiro and US-based cities. This implies that depending on the location of accessible jobs, trip emissions can increase between +550 gCO₂ (Bogotá) and +900 gCO₂ (Berlin), respectively +27.2% to +26.6% relative to city average.

For population density, we find that low population density corresponds to increasing effects between +400 gCO₂ (Berlin) and +110 gCO₂ (Boston), respectively +19.4% and +7.3% relative to city average. For higher densities, we find smaller, mixed effects between –50 gCO₂ and –160 gCO₂ (–3.3% and –7.7% relative to city average) per trip in Boston, the Bay Area, Rio de Janeiro, and Berlin. Two outlier cities display opposite trends, Bogotá and Los Angeles. In Bogotá, we find that the model allocates an increasing effect of +200 gCO₂ (+9.9% relative to city average) for densities up to +8000 people per km². This might occur due to the overall very high densities in Bogotá, requiring the model to strongly extrapolate (compare SI, Table 4). In Los Angeles, we measure slightly increasing effects for very high densities beyond 17k people per km². Whether this is due to a lower model fit or particularly relevant in more polycentric cities requires further investigation with a focus on travel close to the center, as these trip origins mostly lie very close to downtown Los Angeles (refer to SI, Fig. 9).

When analyzing street connectivity, we observe only small decreasing effects between –30 gCO₂ (Bogota) and –140 gCO₂ (Los Angeles) per trip for higher densities across all cities, respectively –1.5% and –4.6% relative to city average. Increasing effects appear below 20 to 45 intersections per km² for all cities apart from Bogotá. While the increasing effects stay below

+300 gCO₂ per trip for most cities, in Los Angeles, we observe some outliers with strong increasing effects of up to +1000 gCO₂ (+33.3%) per trip for very low densities. The outliers appear to be mostly very large TAZ with few intersections, which induce disproportionally low connectivity values, as analyzed in SI, Fig. 10.

Which urban form effect matters most depends on specific locations within cities

TAZ-level causal Shapley values also enable us to discover specific locations across all cities (see SI, Individual feature effects for effect maps), in which the lack of density, instead of the distance to the center increases trip emissions most. This points to particular planning opportunities for lowering commuting trip emissions of peripheral communities, based on sub-center development.

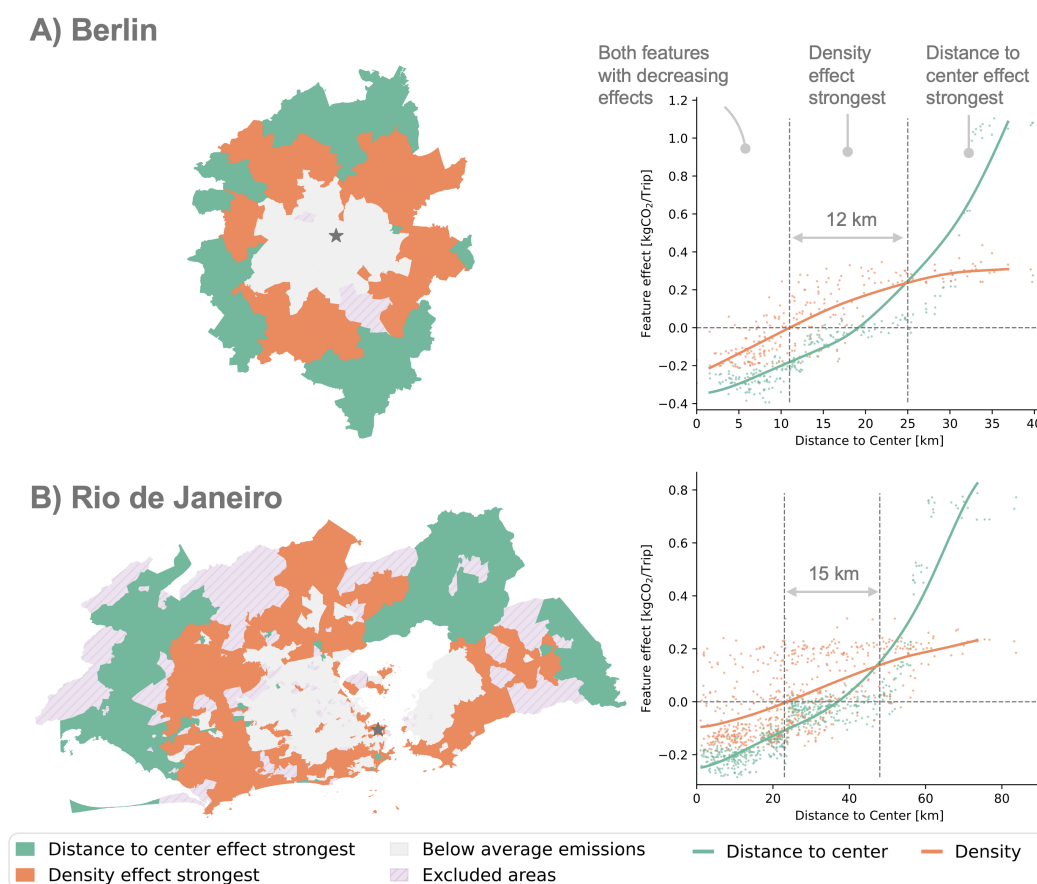


Figure 3. Location-specific urban form effects reveal corridors where density matters more than accessibility. *Left panels:* The map shows whether population density (orange) or distance to center (green) increase VKT most at Traffic Assignment Zones (TAZ) with emissions above the city average. Areas below average city emissions are coded in gray and purple areas correspond to TAZs excluded due to data cleaning. Results are shown for Berlin (A) and Rio de Janeiro (B). *Right panels:* The scatter plots display for the respective city how the effects of both features evolve depending on the location of the TAZ relative to the center. Per color, every dot represents a traffic assignment zone (TAZ) in a city. The solid lines represent a fit over all samples of the city. Feature effects are displayed relative to the city's average emission per trip in kgCO₂ (horizontal dotted line). Vertical dotted lines reveal corridors where density increases emissions more than the distance to the center.

For all locations with above-mean trip emissions, we examine if the measured causal Shapley effect of distance to the center or population density is larger, as shown in Fig. 3. This reveals which of the two features are driving trip emissions the most and should be prioritized in low-carbon urban planning strategies.

Across all cities, we find specific locations where a lack of density is increasing emissions more strongly than the distance to the center. In monocentric cities, this difference unfolds around the center creating donut-shaped corridors, where first density, and after which it is the effect of distance to center that drives most trip emissions. In more polycentric cities, the effects are less spatially clustered, except in the very outskirts where the distance to the center always increases emissions most.

We display in Fig. 3 the differences in Berlin and Rio de Janeiro, as examples for these two cases with high model accuracy (the results for all remaining cities can be found in the SI, Threshold effects of distance to center and population density, Fig. 24).

In Berlin and Rio de Janeiro, we find TAZ in which a lack of density has a higher increasing effect on emissions than the distance to the center. In Berlin, we find that close to the center, most locations exhibit below-average travel emissions (marked in gray) and both features have decreasing effects. As density decreases with longer distances from the center, it starts to have an increasing effect after 11 km from the center (see the evolution of the orange line). At these locations, the effect of distance to the center is still negative and decreases emissions. At 23 km, the distance to the center starts having a positive effect, and at 28 km, it becomes larger than the effect of density. This creates a 12 km buffer where density is more important than accessibility, and where the maximum differential between both effects is 300 gCO₂ per trip, at 20 km distance to the center. In Rio, we find similar yet less strong effect differences. Close to the center, we find that most areas have decreasing effects for both features. Yet, some areas in the proximity of the center also display increasing effects of density, like Alto da Boa Vista or the main harbor of the city. In Rio, density starts having increasing effects for most locations after 26 km, while the distance to the center starts having an increasing effect only after 45 km. At 51 km, the effect of distance to center becomes higher than the effect of density, resulting in a buffer of 15 km with a maximum effect differential of 150 gCO₂.

Discussion

Improving accessibility, avoiding low density and low connectivity

By considering relationships between urban form and trip emissions via causal graph discovery and causal Shapley values, we find that accessibility of the center is most important for reducing trip emissions. We also find that low density and low connectivity should be avoided as they strongly increase emissions.

The importance of high accessibility implies that new housing should be preferably located as close to the center as possible (compare decreasing effects in Fig. 2, A). This recommendation is valid for all analyzed cities. With greater distances to the center, trip emissions increase disproportionally and alternative strategies become more important. In more mono-centric cities, we find city-specific corridors between 10–50km located between the inner city and the outskirts, where low-carbon planning strategies should prioritize local density over access to the center. In these areas low density is driving high trip emissions even more than low access. Here, creating secondary urban centers that increase density could help to reduce trip emissions for citizens who cannot or do not want to live closer to the center. Beyond observed corridors, the lack of access to the main center becomes so strong that car trips should be avoided if possible. While the avoidance of car trips reduces emissions everywhere in the city, it is most effective, yet most difficult, in the very outskirts. Here, possible strategies to reduce individual car travel include transit-oriented development (initiating mode shifts), ride-sharing initiatives (increasing vehicle occupancy), and telecommuting (avoiding trips).

We also find across cities all that long distances to jobs increase emissions and mostly affect peripheral locations (compare increasing effects in Fig. 2, B). While generating additional employment opportunities at the outskirts might alleviate those effects, they can come at the risk of inducing new car travel, as the city outskirts are less accessible via public transport and less congested, thus particularly prone to car usage. Hence, additional measures, such as increased public transport accessibility or ride-pooling offers should accompany such planning considerations.

Location-specific differences call for spatially-explicit analyses

Our work emphasizes an existing bottleneck for climate change mitigation in cities, where municipalities must implement sustainable planning policies, yet lack the tools to adequately prioritize strategies and locations. Big data with high spatial resolution have a clear potential to fill this gap – as our work demonstrates. We show how generic urban planning strategies like ‘compact development’ can be translated into city-specific radii (compare where effects lines cross the zero line in Fig. 2, A) and how different urban form effects can even be compared and prioritized at specific locations (see Fig. 3).

The pressing climate crisis requires solutions to be modeled in more than just six cities. We call for more comparative research that can further discover possible generalizable trends. This research would support generating city typologies where recommendations can be replicated, similar to³³. At the same time, it would specify how such trends should be modulated within cities according to idiosyncratic urban form effects. However, while open data on urban form has increased dramatically^{34,35}, scaling the framework is constrained by the scarce availability of open and harmonized data on travel patterns, urban functions and socio-demographics at high resolution. Our results show the importance of looking at more cities: indeed, trip emissions can be explained well in more monocentric cities, like Berlin or Boston, with an accuracy of up to 81%; yet, in other more poly-centric cities, like Los Angeles or the Bay Area, we get less clear results. This implies that there must exist other relevant factors. Such factors could include access to sub-centers of specific functions (such as work, commercial, leisure) or car connectivity between sub-centers. Those could not be modeled here mostly due to a lack of consistent available data across all cities.

In addition, more work covering cities from the Global South and in different developing stages is primordial. This is necessary as, for example, cities with disproportionately high densities such as Bogotá require the model to extrapolate if little comparable cities are available for pattern recognition (see Fig. 2, C). With more cities from the Global South such density effects could be more robustly assessed and may inspire novel transport strategies. Relevant strategies to reduce car commute emissions could include the installation of shared ride pooling services in peripheries that often struggle to be economically viable in low-dense, low-demand suburban areas in the Global North³⁶. Similarly, further comparisons between mature and fast-growing cities would broaden the existing set of recommendations, as outlined in the Transport Chapter of the 6th IPCC assessment report³⁷. This would enable research to better specify differences in their specific planning needs, such as re-think strategies in mature cities, like the 15-minute concept, versus the avoidance of lock-in decisions in fast-growing cities.

Steering low-carbon urban transformation with causal science

Via causal graph discovery, we demonstrate that urban form features are not independent, but rather interconnected. This provides empirical evidence that confirms previous hypotheses made in the literature about possible causal relationships between urban form and travel^{22,38}. Our findings highlight that changes to one urban form dimension, such as density, are interdependent with others, such as the distance to the center. We strongly believe that reflecting such dependencies in analyses should become standard to ensure effective prioritization of planning efforts.

Yet, we acknowledge that while the graph discovery minimizes required assumptions about if and how different urban form features are interlinked, it comes at the cost of other assumptions, such as that variable relationships are continuous and linear. These are made very explicit in Methods, Causal Graph Discovery. Yet, the obtained graph is influenced by them and results should be interpreted considering them (see SI, Causal Graph Discovery, Assumptions). In comparison to the existing (quasi-)longitudinal, mixed methods study design, our approach is representative of all locations of a city and scalable across continents. This enables us to compare cities within and across. Yet, our approach cannot capture all relevant dimensions. For example, we only proxy residential self-selection effects via income and find no significant direct effect when modeled across all cities. While influence on trip emissions has been found to be smaller than of urban form⁸, representing socio-demographic and attitude-based-residential-self selection most accurately would require additional mixed-method study designs, like^{22,38}, which could incorporate our findings and further validate it for a local context.

Conclusion

Our findings demonstrate the importance of causal and spatially explicit urban form analysis to derive a location-specific but generalizable understanding of climate change action. Across cities, we find that: (1) Distance to the center and to jobs reduces urban travel emissions most, followed by increased density and better street connectivity. This implies that center densification within city-specific radii is most effective for low-carbon urban travel. (2) Subcenter-oriented development in suburban spatial corridors between about 10-30km from the city center could further reduce emissions, especially in monocentric cities, like Berlin or Boston. (3) For the more poly-centric urban areas, like Los Angeles and the Bay Area, the chosen urban form features can only partially explain trip emissions, requiring additional climate policies.

This work is a starting point for future work at the intersection of big spatial data, causality, and climate change research – highly relevant for urban planners, municipalities, and researchers alike. Our results demonstrate that big data approaches help to translate prevalent national-scale scenarios for climate change mitigation from the IPCC to local-level recommendations. Analyzing urban form relationships via causal graph discovery makes system dependencies explicit, revealing where interventions may be most effective. The analysis via causal Shapley values allows to incorporate causal system relationships, and conjointly enables us to visualize effects spatially in maps where hotspots for actions can be identified. The resulting insights and visualizations are of high relevance for interdisciplinary urban design and citizen participation throughout the planning process. For researchers, the obtained results open up new opportunities, such as modeling urban form interventions via causal inference methods which can utilise the discovered DAG. Prospective modeling of the (treatment) effects of existing and future urban planning policies will improve the quality of evidence-based policy-making by a substantial margin. More broadly, as cities are complex systems³⁹ our approach can initiate an integrated, systems-thinking approach to urban planning, as proposed by⁴⁰, allowing municipalities and urban planners to better understand cause-effect mechanisms in spatially highly contextualized settings.

Methods

Data

Datasets For mobility data, we use various data sources from previous peer-reviewed studies. In Boston, Los Angeles, the Bay Area, Rio de Janeiro, and Bogotá, we use origin-destination tables for traffic demand based on call detail records (CDR) aggregated on TAZ as used in^{41–45}. In Berlin, we utilize origin-destination tables based on GPS signals of navigation systems from various sources, including connected cars, floating cars and commercial car fleets, cleaned and calibrated as in a previous study⁹.

For all cities, urban form data is extracted from OpenStreetMap (OSM)⁴⁶, while center definitions as well as population density, income and employment data are collected from region-specific sources as no harmonized data source could be obtained. The definition of centers are derived from Google Maps⁴⁷, similar to⁴⁸. For the US cities, population count and household income data from the United States Census Bureau⁴⁹ as of 2013 are used. For Rio de Janeiro, population count and average household income per capita data are obtained from the Access to Opportunities Project (AOP) for the year 2010⁵⁰. The data are aggregated by H3 hexagonal cells at a resolution of 9. In Bogotá, population data is adopted from⁵¹ and socioeconomic stratification on the block level as developed in⁴⁵ is used as a proxy for income. In Berlin, population data on a 100mx100m grid is derived from⁵² and filled up at the boundaries with population density data from⁵¹. Income data on the household level is obtained from the commercial provider AXCIOM as used in⁹ and filled up with data from⁵³ at the boundaries. Employment data, defined by number of jobs per TAZ, is derived from the Smart Location Database⁵⁴ for the US cities and in Rio de Janeiro from the AOP project⁵⁰. In Berlin and Bogotá, no open employment data could be obtained and employment locations are inferred from all work destinations derived from the SrV mobility survey 2017⁵⁵ and Bogotá mobility survey 2015 respectively⁵⁶.

Cleaning From all mobility datasets only trips in the morning hours between 6 and 10 am that start and end within the boundary of a city are considered. For the boundary definition, we adopt the functional urban area definition⁵⁷ as this recognizes the total city area and its surrounding commuting zone. At the outskirts, we consider all TAZ which overlap at least 50% with the boundary. For Rio de Janeiro, we adopt the official boundary of Rio's 'urban concentration area' defined by Brazil's statistics Office⁵⁸ as recommended by local knowledge of one of the manuscript's co-authors as it better reflects Rio de Janeiro's commuting catchment area.

The mobility data from the US cities, Rio de Janeiro and Bogotá are further cleaned and calibrated as in previous studies, which includes assigning mean number of trips from CDR records to TAZ. For Berlin, the same cleaning procedure as in⁹ is applied and individual trip origins and destinations are aggregated to zip codes (in the following we adopt the wording TAZ across all cities to describe the spatial unit of analysis) to match the other data sources. Additionally, only TAZ are considered that have at least ten trip origins to construct a meaningful average and TAZ with an airport are removed from the sample, as this study focuses on commuting.

Target variable – VKT and Trip emissions To derive travel emissions, we transform mean travel distances to emissions using location specific emissions factors (refer to SI, Location specific emission factors). For the US cities, Rio de Janeiro, and Bogotá the mean travel distances per TAZ are calculated by creating uniformly random samples of trip origins and destinations on the road network. For each TAZ, we sample the number of points starting and ending within the TAZ's boundaries. To reduce errors we only sample onto residential or tertiary roads, as we assume that no trips start on highways, primary or secondary roads. To calculate travel distances, we calculate the shortest path along the street network from origin to destination and average travel distances per TAZ. In Berlin, we similarly average the travel distances of all trips starting within a TAZ.

Feature Engineering We develop five urban form features across all cities to represent four of the 6Ds. We define the features based on what has been used most frequently across previous work and for which data is available across all cities, compare Table 5. Our features represent destination accessibility, measured by distance to center and employment, density, measured as population density, demographics, measured by income, and design, represented via street network connectivity. We choose to exclude the diversity dimension, due to data restrictions and as previous studies only associated with it (if at all) only small effects in the context of car travel and as it is more relevant for promoting active travel^{6,14}. As everyone in our study has already decided to use the car, we also exclude distance to transit, which primarily influences mode choice, but hardly car travel distance^{4,59}. Table 1 summarises the features.

We acknowledge that previous work has emphasized the significance of addressing residential self-selection by including socio-demographic factors and travel attitudes^{38,60,61}. Since detailed data on travel-related attitudes is not available across all cities, we can only control for the effects of residential self-selection that can be proxied via the socio-demographic variable income, similar to^{8,9}.

D-Variable	Feature	Description
Destination Accessibility	Distance to city center	Distance from TAZ center to main city center.
Destination Accessibility	Distance to employment	Weighted average distance from TAZ center to 1% of all jobs.
Density	Population density	Number of inhabitants divided by area of TAZ.
Demographics	Income	Average household income per TAZ.
Design	Street connectivity	Number of intersections divided by area of TAZ.

Table 1. Predictive features of urban form based on the 6Ds of compact development

Modelling

Urban Centrality Index We measure the centrality of an urban area adopting the urban centrality index⁶². It controls for differences in areas and shape of a city and assigns based on the spatial distribution of jobs a value between 0 (extrem polycentric) and 1 (extrem monocentric) to define a city’s centrality.

Causal Graph Discovery To test the hypotheses that urban form affects mobility behavior and to examine the causal relationship between the considered variables in more detail, we apply causal graph discovery. Causal graph discovery is typically based on either constrained- or score-based algorithms. While the former uses conditional independence tests to obtain a graph, the latter defines graph discovery as a structure learning problem, where the graph that maximises some score is selected out of the space of possible graphs. In addition, hybrid approaches that combine both also exist (for an overview and a comparison of different algorithms, refer to^{24,63}).

For our problem setting, we adopt a conditional independence-based causal discovery framework, here the PC (Peter-Clark) algorithm^{30,31}, which identifies spurious correlations (e.g. resulting from indirect links or common drivers) among the included variables. It determines the presence and absence of edges and their orientation in a DAG using conditional independence tests among all observed variables and VKT. The PC algorithm assumes independent and identically distributed (*iid*) data and can handle linear and nonlinear variable dependencies, depending on the chosen conditional independence test. A detailed introduction to the method can be found in²⁴. To summarize, the PC algorithm starts from a fully connected undirected graph and consists of three phases: (1) The *skeleton phase* uses conditional independence tests to learn the skeleton of adjacencies of the causal graph. If two variables X and Y are found to be independent conditional on a (possibly empty) set of other variables $\mathbf{Z}$, then the edge between X and Y is removed. The algorithm efficiently selects these conditioning sets to avoid iterating through all possible ones. (2) In the *collider orientation phase* all *collider motifs* of the form $X \rightarrow Y \leftarrow Z$ where X and Z are non-adjacent are detected. These orientations can be inferred because these motifs are only compatible with a particular pattern of (conditional) (in-)dependencies. (3) The final *orientation phase* uses graphical rules based on the assumption of acyclicity to orient as many remaining unoriented edges as possible. Some edges may not be oriented (represented as oo in the graph) such that the result of the PC algorithm is often a set of graphs, called the Markov equivalence class, that cannot be distinguished by conditional independence testing alone.

Regarding the choice of a conditional independence test, we assume variable relationships to be continuous and linear with potentially non-gaussian marginal distributions and, hence, select a robust version of the partial correlation independence test where the variables X, Y, Z are first transformed to have normal marginal distributions before applying the standard partial correlation test with an assumed t -null distribution. We also test an alternative conditional independence test that assumes multivariate, continuous variables with more general nonlinear dependencies together with a permutation-based test, but with less detection power for linear dependencies, called CMiknn⁶⁴. The results of the five fold validation with CMiknn can be found in SI, Additional results, Fig. 5.

Next to discovering a DAG, we use the framework to examine a measure of the strength of an observed causal dependency between an X and Y by investigating the partial correlation value ρ derived from the selected conditional independence tests in the PC algorithm’s skeleton phase at the maximal p-value over all considered conditioning sets $\mathbf{Z}$. This partial correlation value between two nodes can be seen as a qualitative estimator of causal strength.

The PC algorithm assumes the Causal Markov Condition, Faithfulness and Causal Sufficiency. The first indicates that a statistical dependence between two variables is the result of an underlying causal connection. Faithfulness states that statistical independence indicates the absence of any causal connection, and causal sufficiency implies that the analyzed variables include all common causes. Here we have to relax the causal sufficiency assumption as not all causes of travel distance can be measured or are freely available as open data. This means that any detected edge could still be rendered as spurious if a relevant common cause was included in the analysis. On the contrary, detecting an absence of a link does not require the causal sufficiency assumption. In addition, we assume the following about our variable relationships: first, we expect that none of the urban form features can be caused by the target VKT. Second, we assume that income differences (as a proxy for socio-demographics and behavioral attitudes) can affect both urban form (via residential self-selection) and travel behavior, but cannot be caused

by urban form. Third, as previous studies^{18,22} have frequently mentioned the indirect effect of distance to the city center on other variables, we assume that distance to city center cannot be caused by other variables. These assumptions constrain the PC algorithm's inference and lead to more stable results.

To calculate the DAG, we use a balanced sample of 1542 TAZ. As some cities have more TAZ than others, the samples are pooled equally from all cities to remove city-specific biases. To improve the robustness of the approach, we randomly sample five rounds with different seeds and only report links that are consistently present across all rounds. When the orientation of a link varies, we adopt the orientation of most appearances (refer to SI, Additional results, Fig. 4). We standardize the features per city by subtracting the mean and scaling to unit variance to remove city-specific hidden confounding, such as differences in gas prices, city sizes or network lengths.

Model Generalisation To analyze how much of the overall variation in VKT and related emissions can be explained by urban form, we adopt a 6-fold, city-wise cross-validation procedure. We train a Gradient Boosting Decision Tree Regression Model (GBDT), using the XGBOOST Python library⁶⁵, on five cities and predict VKT in the unseen 6th city. We choose a GBDT model, as it can represent non-linear dependencies, is robust against feature multicollinearity⁸, and has been shown to perform best with data in tabular format in a similar problem setting⁶⁶. We evaluate the generalization performance using the coefficient of determination (R²), the mean absolute error (MAE), and root mean squared error (RMSE).

Model Interpretation To analyse heterogeneity in urban form effects, we calculate causal Shapley values on the prediction test set, as proposed by Heskes et al. (2020)⁶⁷. Causal Shapley values are based on (marginal) Shapley values⁶⁸, which solve an attribution problem where the prediction score of a model is distributed to its individual features. This is calculated by taking the weighted average across all possible feature combinations, also called coalitions, to evaluate how much a prediction changes when a feature is part of a coalition S versus when it is not $\bar{S}$.

Estimating the prediction in the absence of a feature sparked a debate among scholars about which probability distribution is the right one to draw from (for further reference, see for example⁶⁹), questioning the suitability of Shapley values, especially when correlated features are present. While different solutions were proposed^{70–73}, we adopt causal Shapley values which estimate the prediction based on sampling from an interventional conditional distribution instead of the previously used observational conditional distributions. For this, causal Shapley values aim to incorporate the relationships of a causal DAG, however, the current implementations of causal Shapley only consider a causal chain. A causal chain is a sequential representation of a DAG that defines a partial causal ordering, refer to Figure 2 in⁶⁷). By doing so, causal Shapley values break the dependence between the features in the coalition S and the remaining features, allowing to obtain meaningful feature attributions that reflect the underlying causal structure when explaining a model. Causal Shapley values require a causal chain as an input. In the chain, one feature can only cause subsequent features of the chain and the target, while information about missing edges is inferred from the data based on conditional independencies. Based on the discovered DAG, we adopt the order *distance to center* $\rightarrow$ *distance to employment* $\rightarrow$ *population density* $\rightarrow$ *street connectivity*.

In comparison to the partial correlation value ρ of the causal graph discovery, causal shapley values do not quantify the strength of dependencies between features, but allocate only an importance to the direct effect of a feature on the target, considering inter-feature relationships. For analysing spatially explicit urban form effects, the properties of causal Shapley values are of high use. They allow (1) to keep the desirable property of marginal Shapley values to calculate effects for individual samples (which translate to individual locations) and (2) to reflect causal relationships between our features and the target via causal chain graphs (see SI, Comparison of Causal and Marginal Shapley values, Fig. 6).

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Data and code availability

For all openly available data used in this study references are provided in Methods, Datasets. Upon publication, the code of this work will be provided as a freely accessible git repository here: <https://github.com/wagnerfe/xml4uf>.

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Supplementary Information

Additional methods material

Location specific emission factors

Location specific emission factors are approximated based on official statistics about vehicle fleet numbers (share of small-medium and large cars) in the US⁷⁴, Germany⁷⁵ and Latin America⁷⁶ (note that due to a lack of data availability for Bogotá, we assume Bogotá to have a similar share of car types than Brazil) and respective emissions factors, see summary Table 2. Shares of vehicle types are derived for US cities from , Berlin from , and Rio and Bogotá from . Mapping of car categories to small-medium and large car is shown in Table 3, whereas well-to-wheel CO₂ intensity factors for small-medium and large cars are derived from the International Energy Agency⁷⁷. We acknowledge that this approximates only internal combustion engine car emissions and does not consider for example uptake of electric vehicles in those countries.

Location	Share small-medium cars	Emission factor [gCO ₂ eq/km]	Share large cars	Emission factor [gCO ₂ eq/km]	Combined Emission factor [gCO ₂ eq/km]
Germany	0,74	148	0,26	211	164,33
United States	0,19	148	0,81	211	199,07
Latin America	0,64	148	0,36	211	170,68

Table 2. Location specific emission factors per kilometer

Latin America		Germany		US	
Categorie	Mapping	Categorie	Mapping	Categorie	Mapping
Subcompact	small	Mini	Small	Crossover	large
Mid-size	medium	Kleinwagen	Small	Pickup	large
Compact	medium	Kompaktklasse	lower-medium	Small car	small
Full size	large	Mittelklasse	lower-medium	SUV	large
SUV	large	Obere Mittelklasse	lower-medium	Midsized car	medium
Compact SUV	large	Oberklasse	large	Luxury car	large
Microcar	small	SUV	large	Van	large
Pickup	large	VAN	large	Large Car	large
Luxury car	large	Utilities	-		
light commercial	-	Sonstige	-		
Sport car	large				
campervan	large				
minivan	medium				
large van	large				
other	-				
not defined	-				

Table 3. Mapping of country specific car types

Feature distribution

Feature distributions across all cities are summarised in Table 4.

City	Feature	Mean	σ	q25	q75
Berlin	Distance to Center	14166.5	9257.0	7093.0	18376.4
	Distance to Employment	5149.0	5672.8	1201.3	7052.8
	Population Density	6339.1	5726.0	1251.2	9619.7
	Street Connectivity	37.2	24.1	19.4	50.9
Boston	Distance to Center	15544.0	11206.2	7149.0	21457.4
	Distance to Employment	6607.9	6975.2	1909.0	9384.2
	Population Density	4255.7	4741.0	914.7	6071.7
	Street Connectivity	69.6	46.2	31.5	102.1
Los Angeles	Distance to Center	23761.7	11785.2	14769.8	32594.3
	Distance to Employment	9403.5	6450.0	4438.5	13201.5
	Population Density	4923.3	3918.4	2481.0	6372.8
	Street Connectivity	44.7	17.7	33.9	55.5
Bay Area	Distance to Center	41713.4	28089.8	18229.6	67897.9
	Distance to Employment	7311.2	5608.9	3334.6	9715.7
	Population Density	4433.1	4579.8	1965.1	5372.2
	Street Connectivity	56.0	26.6	40.5	68.5
Rio de Janeiro	Distance to Center	26148.5	16562.4	12763.6	34840.1
	Distance to Employment	7269.3	6696.3	2867.7	9329.7
	Population Density	8518.4	6697.4	3091.5	12248.7
	Street Connectivity	63.1	39.3	34.2	85.5
Bogotá	Distance to Center	13827.1	6536.4	7917.3	18521.2
	Distance to Employment	3977.9	2510.9	1940.0	5660.9
	Population Density	12248.2	2982.3	11179.4	14259.5
	Street Connectivity	159.9	96.5	91.2	213.3

Table 4. Feature distribution per city. Provided are the feature average, the standard deviation (σ), the 25th (q25) and 75th (q75) quantile.

Causal Graph Discovery

Urban form effect in previous work

Urban form effects in previous work. The literature review was conducted via google scholar, arxiv and semantic scholar with a focus on quantitative or mixed methods approaches, urban car travel and the 6D framing. The resulting list is not exhaustive and aims to summarize the most relevant previous work. Across the examined studies we find distance to center and to jobs having positive correlations across all studies that included the feature (note that some studies calculated distance to subcenter or job accessibility instead of distance to jobs. For job accessibility a negative correlation with VKT aligns with a positive correlation of distance to jobs with VKT, as high access implies short distances). Population density was found to have negative correlations and in one study no clear effect could be found. Across all studies that included street connectivity, either measured as intersection density, network connectivity, road density or number of 4 way intersection count, negative correlations with VKT were found. For income, in 6 cases positive and in 2 cases negative correlations were found. We interpret this as an overall positive correlation with VKT in Fig. 1 of the main manuscript. Additionally, some studies^{18,20,22} have pointed out that distance to center indirectly affects all other urban form features, reflected as an indirect link Fig. 1 of the main manuscript. We also note that one study pointed out a potential indirect link between density and distance to subcenters/job centers, see Fig. 1 in²⁰.

Location	Destination Accessibility	Density	Design	Demographics	Reference
Oslo	Distance to CBD (+) Distance to sub-center (+)	Population Density (-) Job Density (-)		Income (+)	8
Oslo	Distance to CBD (+) Distance to local CBDs (+)	Population Density (-) Job Density (-)		Income (+)	7
Stavanger	Distance to CBD (+)	Jobs/Capita Density (+)		Income (+)	
Montreal		Population Density (-)		Income (+)	12
US cities	Distance to CBD (+)	Job Density (-) Population Density (-)	Network Connectivity (-)		13
US cities	Distance to CBD (+) Job Accessibility (-)	Job Density (x) Population Density (-)	Intersection Density (-) 4-way Intersection (-)		6
US cities	Distance to CBD (+) Job Accessibility (-)	Job Density (x) Population Density (-)	Intersection Density (-) 4-way Intersection (-)		14
Berlin	Distance to CBD (+)	Population Density (x)		Income (-)	
	Distance to sub-center (+)				9
Washington	Distance to CBD (+)		Street Conectivity (-)	Income (+)	10
US cities	Distance to Jobs (+)	Population Density (-)		Income (+)	16
Germany	Distance to Jobs (+)	Commercial Density (-)	Road Density (-)	Income (-)	17
Chicago	Distance to CBD (+)	Population Density (-)			15
Switzerland		Population Density (-) Job Density (-)			28

Table 5. Effects of Destination Accessibility, Density, and Demographics in previous work For every study it is marked whether the feature was (among others) included and a positive observed effect on VKT is marked with (+), a negative with (-) and no clear effect found with (x).

Causal DAG based on robust partial correlation conditional independence test across all seeds

As we create a balanced sample of 1542 TAZ, representing each city equally, we can calculate a DAG five times with a random sample of different seeds as shown in Fig. 4 and create a summary graph, considering only consistently present links. This implies that we do not report the link from income to distance to employment in seed 4. Additionally, we report the link from distance to employment to population density, as it is present in all sampling rounds, but the direction is not solved only one time, see seed 4.

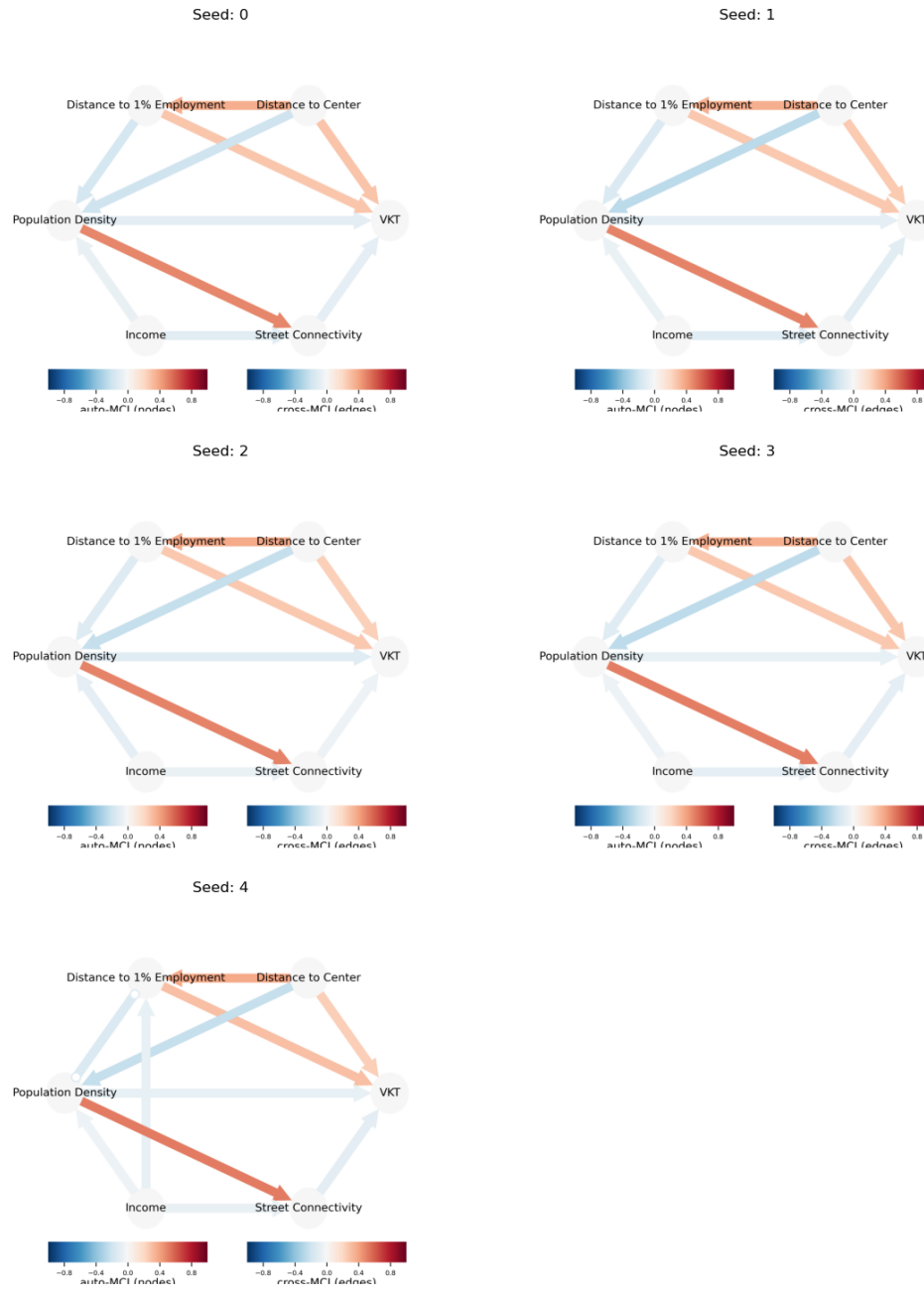


Figure 4. Causal DAG based on robust partial correlation conditional independence test across five seeds. Edges whose direction cannot be oriented are represented as $\leftrightarrow$ in the graph.

Causal DAG based on cmiknn conditional independence test across all seeds

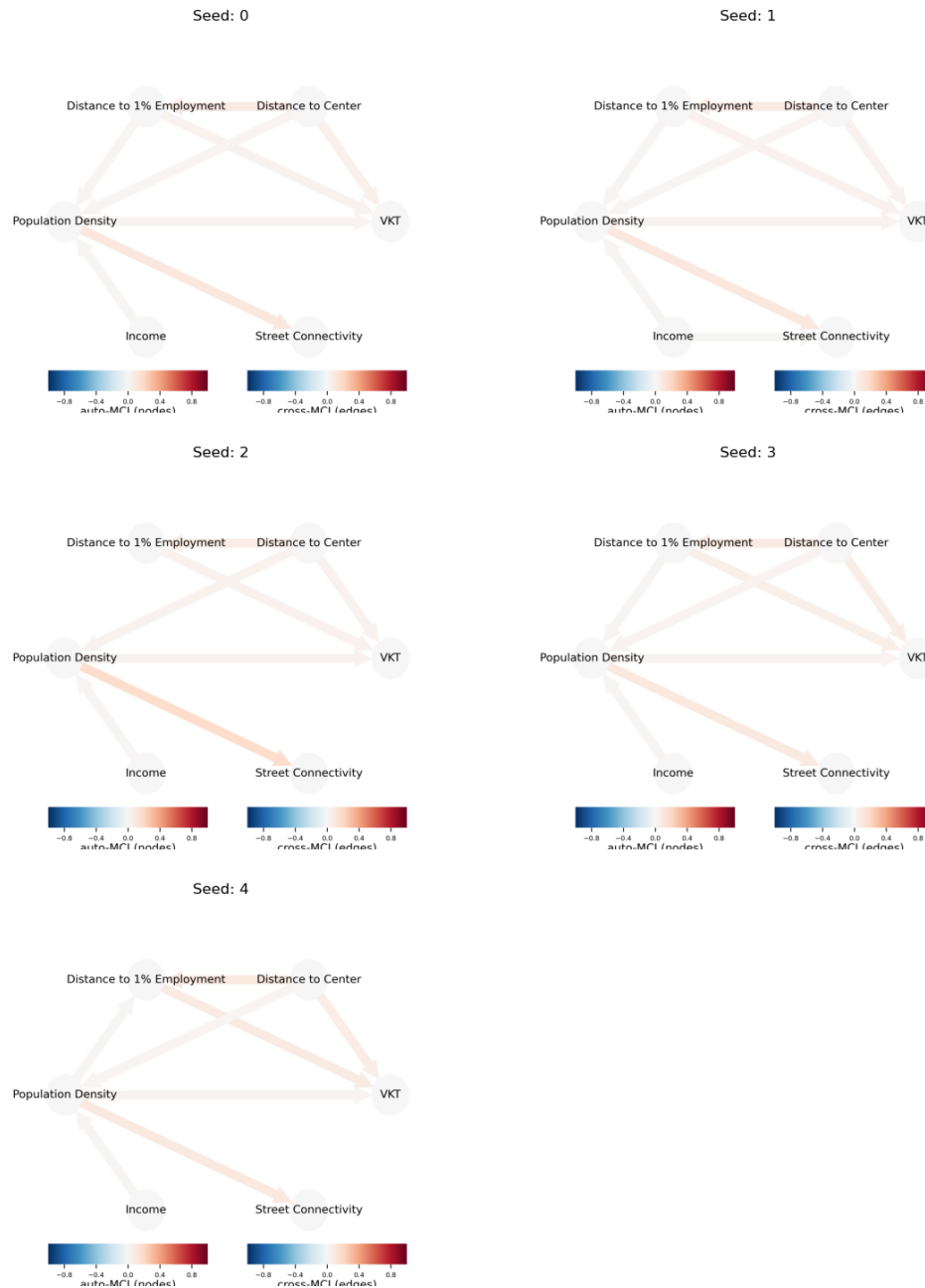


Figure 5. Causal DAG based on cmiknn conditional independence test across five seeds.

When using cmiknn conditional independence test, we also measure a direct effect of distance to center, distance to employment and density on VKT, but we do not find a significant link between street connectivity and VKT. Differences in indirect feature links are observed in seed 2 and seed 4 between distance to employment and density as well as between income and street connectivity which is only present in one out of 5 sampling rounds.

Discussion of causal graph assumptions

One important assumption (which has also been present in previous studies), is the choice and definition of included 6Ds. The feature choice was constrained by data availability and modelling dimensionality. Our features are proxies for measurable and non-measurable urban form and demographic differences in cities. As dimensionality affects link detection power⁷⁸, we aimed at finding a minimal set of representative features yet recognize that this comes at the cost of not accurately describing urban form. Further, the 6Ds have been defined in various ways in the past. Here, we chose definitions that, to our knowledge, represent the true effect of one feature in a most meaningful way. For example, as the zip code sizes vary within a city, we scaled all density features per area of zip code. Yet, this scaling can affect the resulting DAG and requires interpreting all remaining results only on the basis of our definitions.

Another key assumption is the choice of conditional independence (CI) test. We acknowledge that we observe both linear and non-linear dependencies between the analyzed variables (see SI Fig. ??). This implies that using a CI test that supports both linear and non-linear dependencies (e.g. GPDC, CMiknn^{64,78}) might be best suited for the analysis. Yet, they come at the cost of having a lower detection power for linear links, and hence true linear, but smaller effects might be overlooked. We acknowledge that this is a current shortcoming of the method and hence, provide the DAG of Fig. 1 also calculated with CMiknn CI test, displayed in SI Fig. 5. Future work can compare different graph discovery algorithms to get a more robust estimate of the true DAG.

Model Interpretation

Model generalization

We find that all 6Ds with a direct causal effect on VKT hold predictive information on car commute distances when generalizing towards an unseen city. When training a model in five cities on all features with a direct causal effect on the target and predicting in an unseen 6th city, we can show that the variation in VKT can be explained up to 84% in Berlin, 62% in Boston, 51% in Bogotá, 21% in Los Angeles, 41% in Rio de Janeiro, and 26% in the Bay Area, as shown in Table 6.

city	R2 Train 5 cities	R2 Test 1 city	MAE [km]	RMSE [km]	$\overline{\text{VKT}}$ [km]	σ [km]
Berlin	0.42	0.84	1.81	2.52	12.53	9.18
Boston	0.41	0.62	1.22	1.59	7.56	3.25
Los Angeles	0.55	0.21	2.22	3.33	15.24	3.74
Rio de Janeiro	0.42	0.41	2.59	3.73	12.38	4.86
Bay Area	0.47	0.26	1.90	2.55	14.35	2.97
Bogotá	0.41	0.51	1.75	2.11	11.84	3.03

Table 6. Results of a 6-fold, city-wise cross-validation procedure to analyze how much of the variation in VKT can be explained by urban form. The generalization performance is provided for each city representing the test set, using the R2 score, the mean average error (MAE) and the root mean square error (RMSE). Additionally, the average VKT of the city is provided for reference.

When training in five cities and predicting in a 6th city (for more details see Methods, Model Generalization), the Mean Average Error Ranges (MAE) from 1.75 km in Bogotá to 2.59 km in Rio, while the Root Mean Square Error (RMSE) varies between 1.59 km in Boston and 3.73 km in Rio de Janeiro. While the high R2 score in Berlin is also due to the very high standard deviation of VKT, it also shows that given our model and data, the variation in VKT can be better explained by the urban form in more mono-centric cities, such as Berlin or Boston.

Comparison of Causal and Marginal Shapley Values

The comparison of marginal and causal Shapley values for an example location in Berlin is shown in Fig. 6. It highlights how causal shap (green bars) allocates most importance to distance to center and removes importance from other features like employment, density or street connectivity for this location in comparison to marginal shapley values (pink bars).

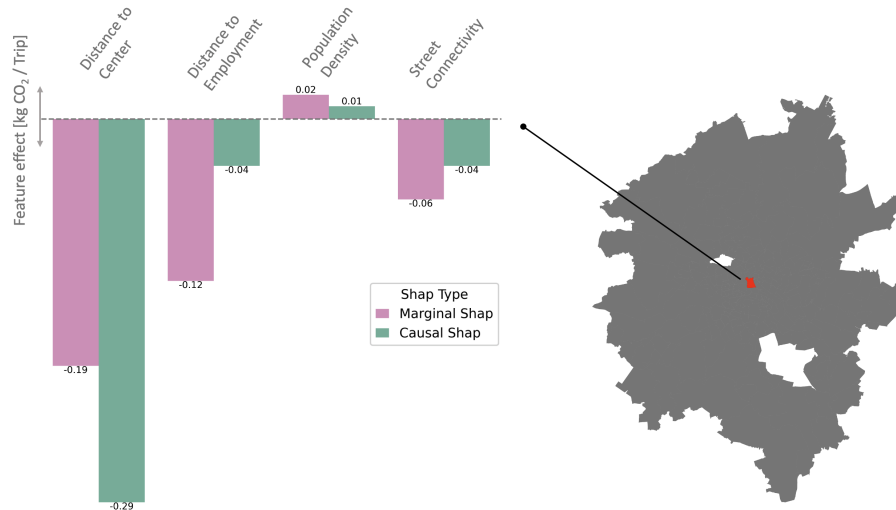


Figure 6. Comparison of causal and marginal Shapley values Comparison of the differences in feature importance for traditional marginal (pink) and causal (green) causal Shapley values for an example location in Berlin.

Relative feature importance per city

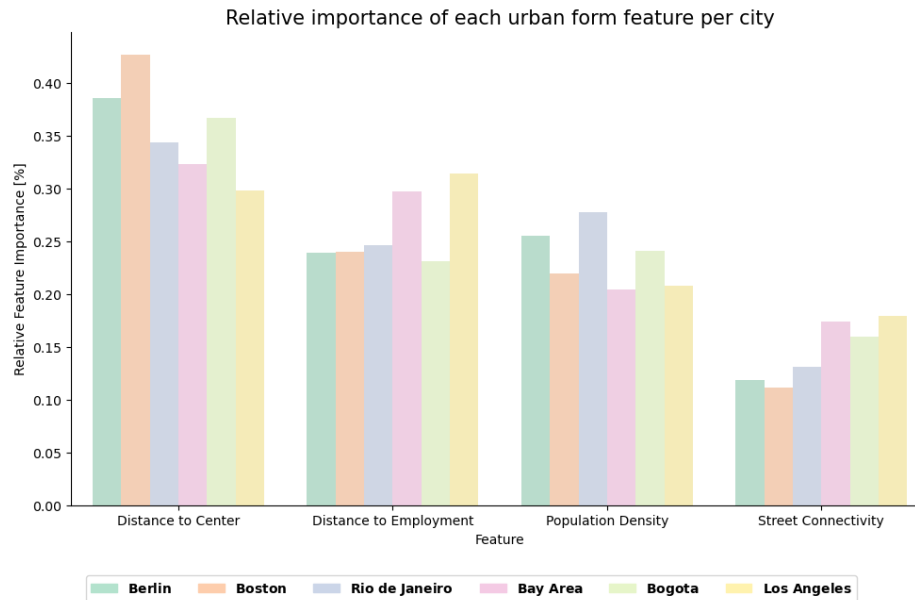


Figure 7. Relative feature importance per city For each city we calculate the relative feature importance based on the mean absolute causal shapley values per feature.

Destinations of areas with high emissions due to long distances to the center

To further assess why the effect of distance to center follows different magnitudes, we analyze where trips go to from all locations with feature effects (causal Shapley values) of above 150 gCO₂ due to their location relative to the center. To do so, we define 5 km rings around the city center and calculate the percentage of how many trips starting in locations in the very outskirts end in each ring, as shown in Fig. 8. We find that in Berlin and Bogotá, most trips also from remote locations travel to locations close to the city center (compare Fig. 8 descending slope with higher distance to the center). Yet, in other cities, especially in the Bay Area, Boston and Rio, there are other destinations than the center that attract many trips. In the Bay Area (red) the peak at 60 to 65 km marks San Jose, while in Boston, we find many destinations in Gloucester at 35km distance from the center and in Rio de Janeiro we find many destinations in Santa Cruz in the west of the municipal boundaries at 45 km to the center.

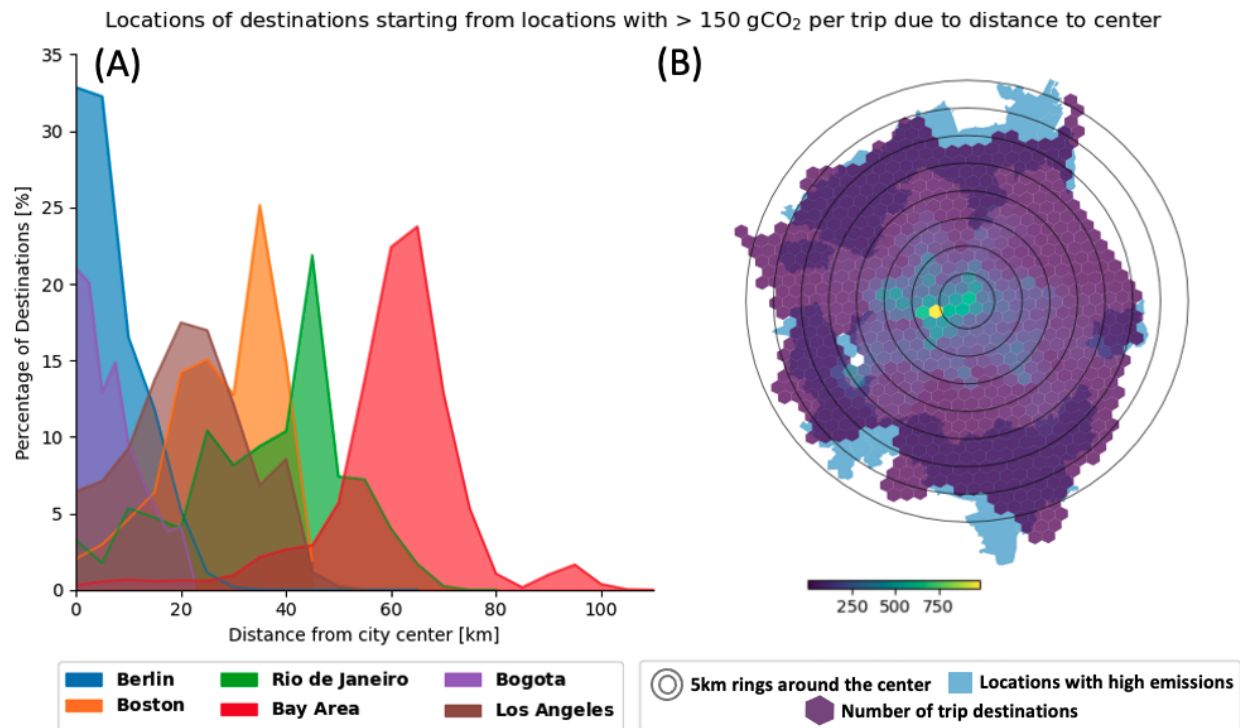


Figure 8. Destinations of locations with high emissions due to their location relative to the city center Panel A: Percentage of destinations in 5km rings around the city center. Panel B: Exemplary visualization of 5km rings (black), locations with >150 gCO₂ emissions (blue) and trip destinations in hexagons, where yellow indicates many destinations and purple few.

Areas with very high population densities in Los Angeles

To better understand at which locations in Los Angeles causal Shapley values turn positive for high population densities, we plot all locations with population density values over 17k people per km^2 in Fig. 9. We find that most locations are located very close to downtown, in the neighbourhoods Koreatown and Westlake, as well as some in the neighborhood Panorama City.

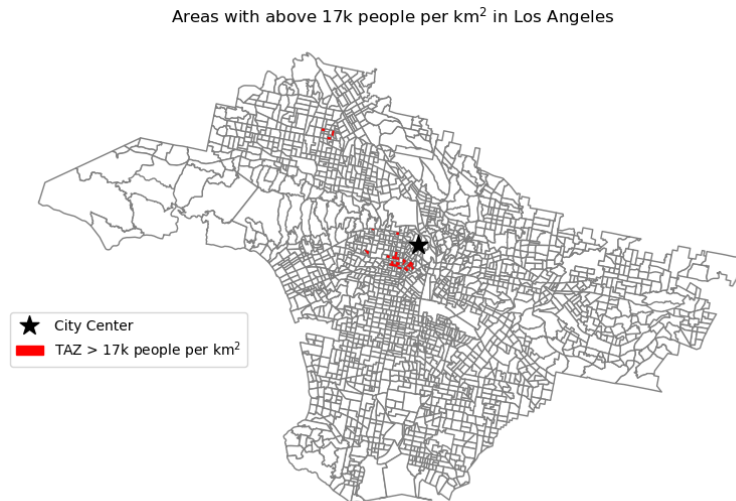


Figure 9. Locations with very high population densities in Los Angeles Areas with high population densities marked in red, while the city center is marked with a black star.

Areas with very low street connectivity values in Los Angeles

To better understand at which locations in Los Angeles we receive very high causal Shapley values for low street connectivities, we plot all locations with street connectivity values below 10 intersections per km^2 in Fig. 10. We find that most locations are located at the outskirts, such as in Topanga State Park, Malibu Creek State Park, Chino Hills State Park but also at the port in Long Beach.

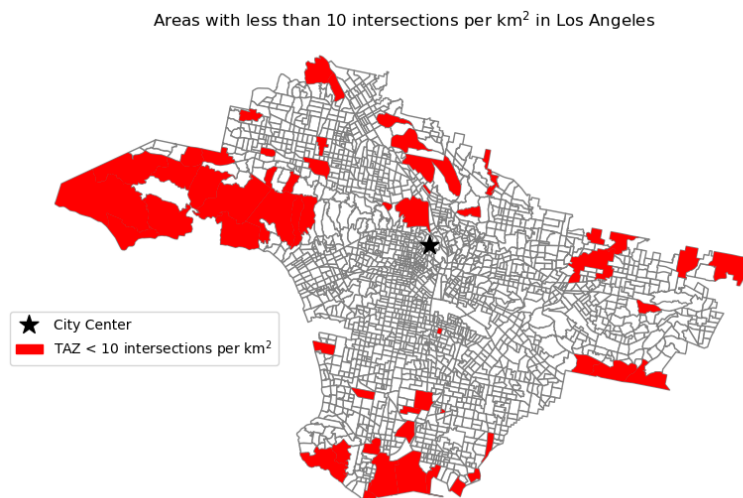


Figure 10. Locations with very low street connectivity in Los Angeles Areas with low street connectivity values are marked in red, while the city center is marked with a black star.

Individual feature effects per city

The following displays the causal Shapley effects, summarized in Fig. 2 as individual plots per city.

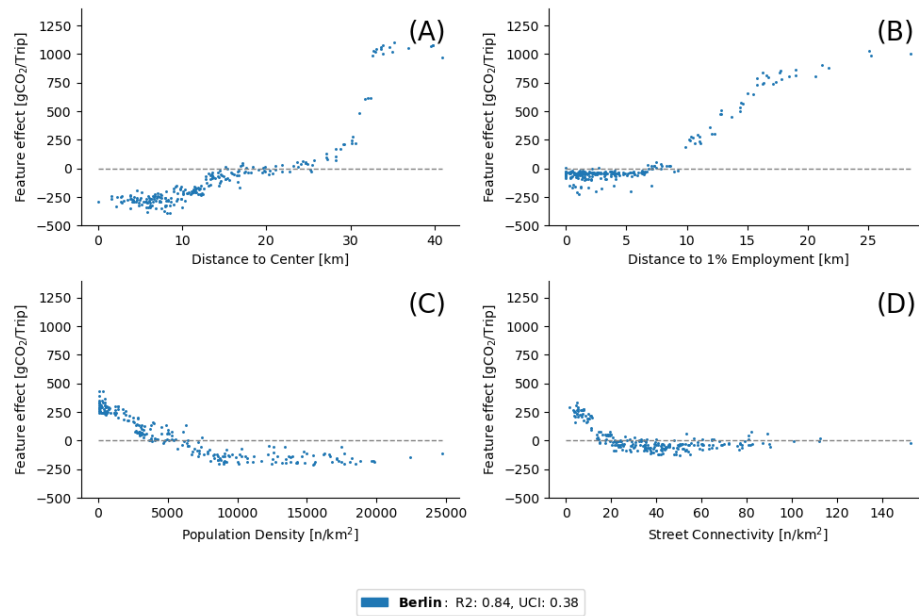
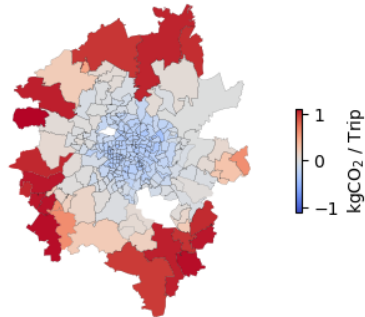
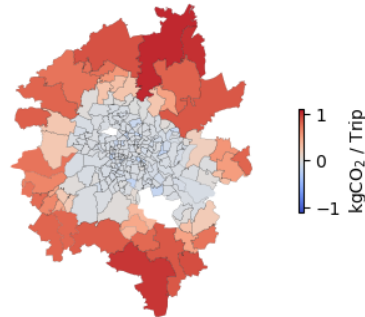


Figure 11. Causal Shapley effects over feature distributions in Berlin

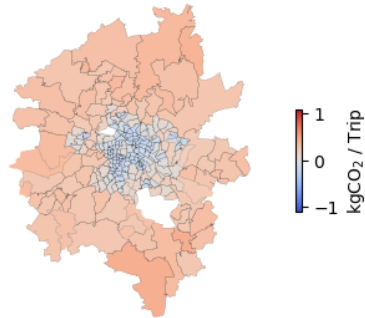
Distance to Center



Distance to Employment



Population Density



Street Connectivity

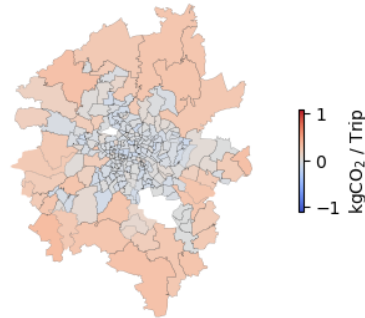


Figure 12. Causal Shapley effects spatially in Berlin

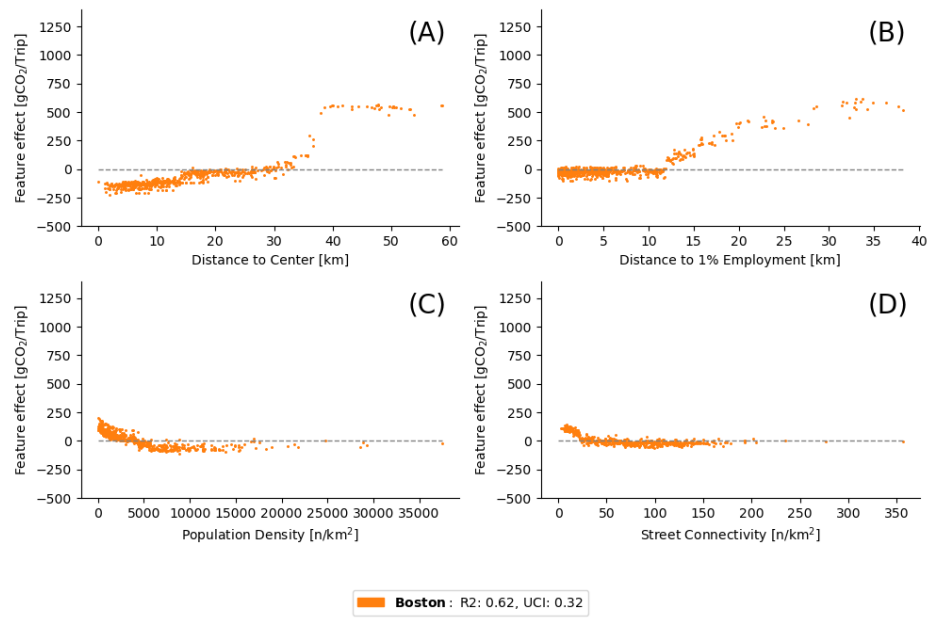


Figure 13. Feature effects in Boston

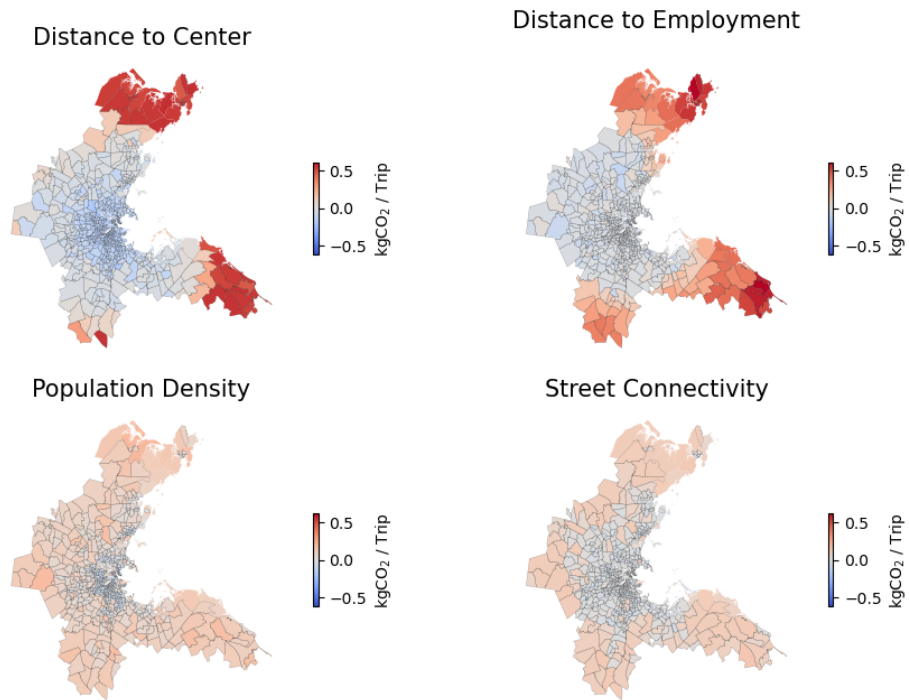


Figure 14. Causal Shapley effects spatially in Boston

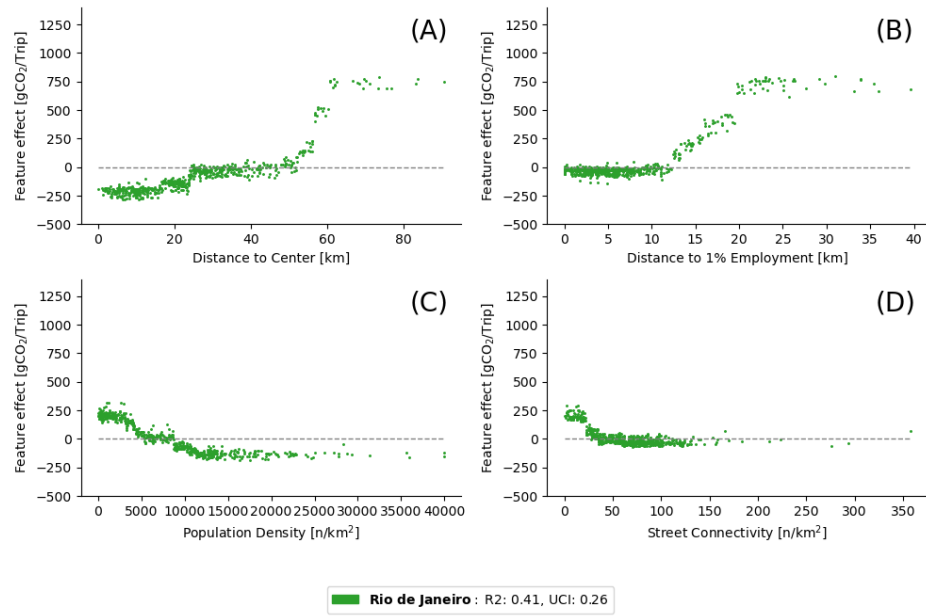


Figure 15. Feature effects in Rio de Janeiro

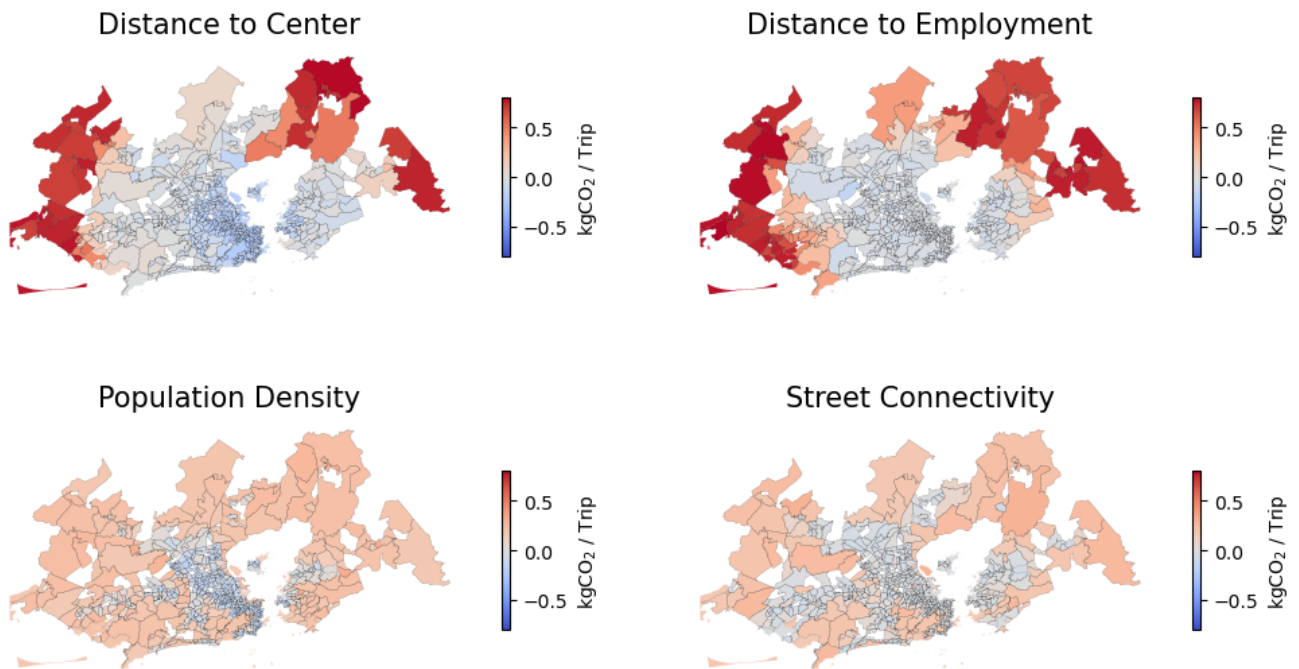


Figure 16. Causal Shapley effects spatially in Ro de Janeiro

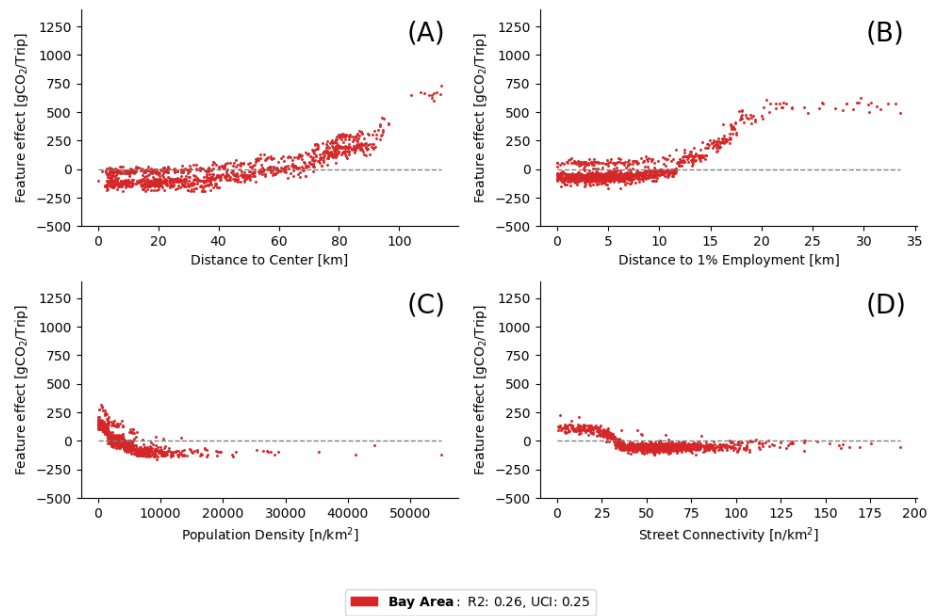


Figure 17. Feature effects in the Bay Area

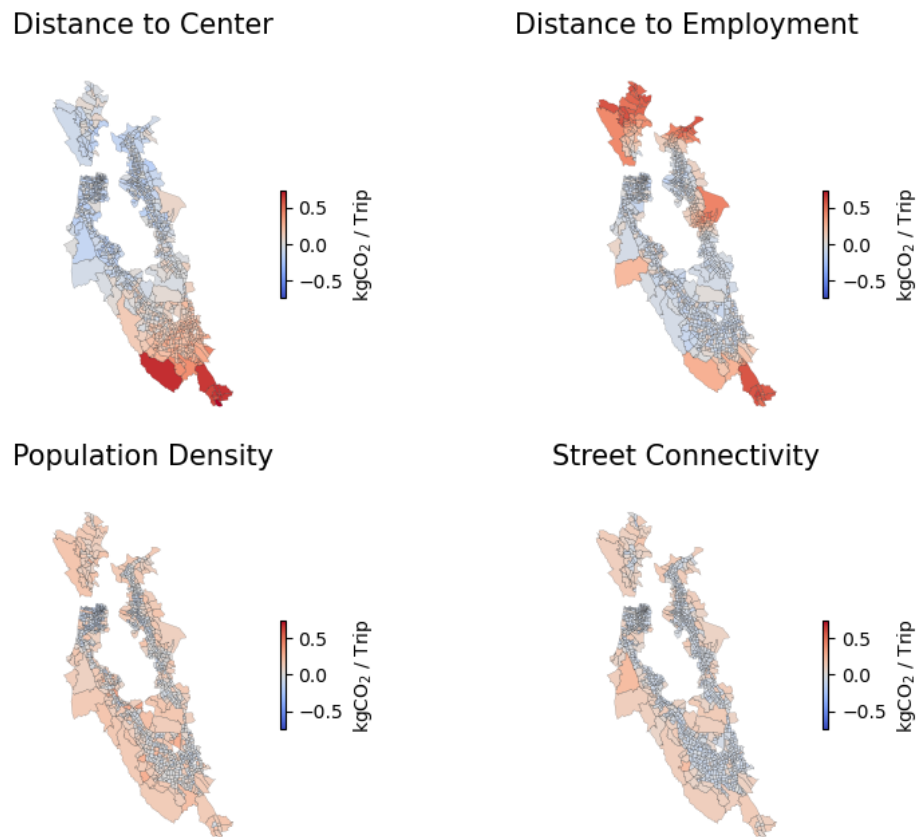


Figure 18. Causal Shapley effects spatially in the Bay Area

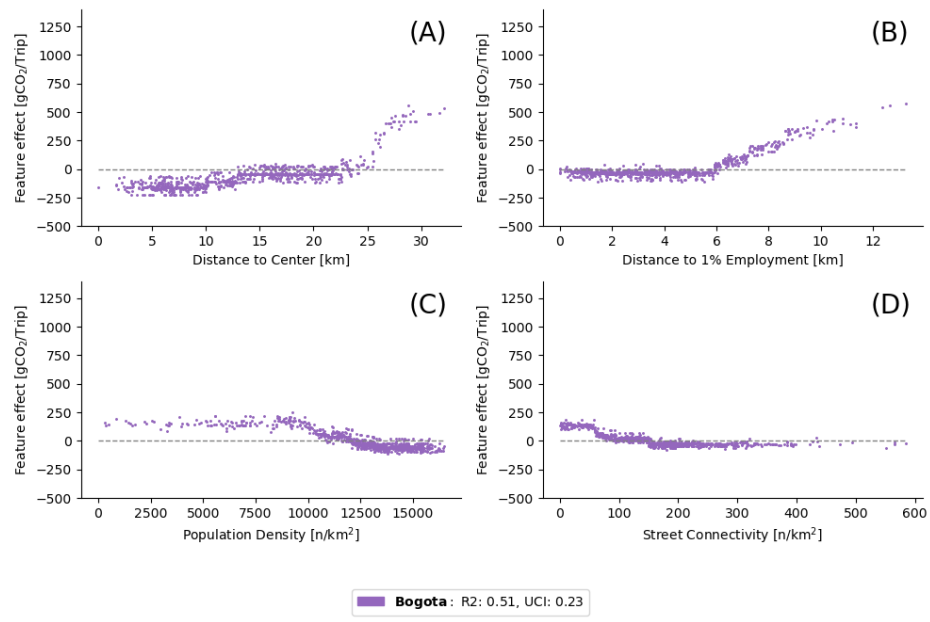
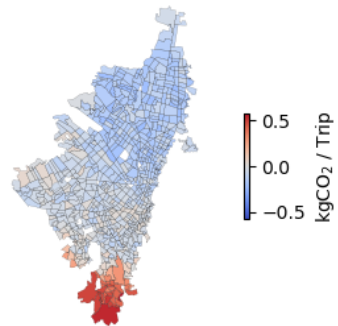
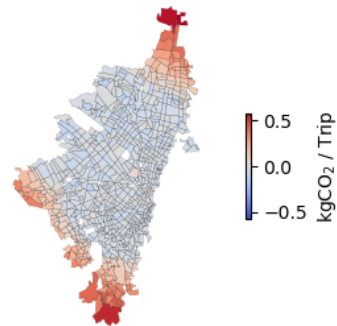


Figure 19. Feature effects in Bogotá

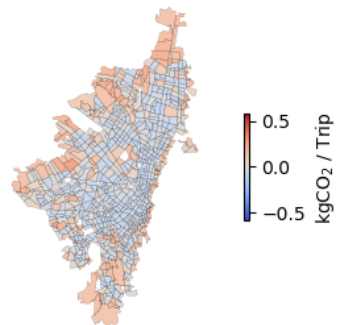
Distance to Center



Distance to Employment



Population Density



Street Connectivity

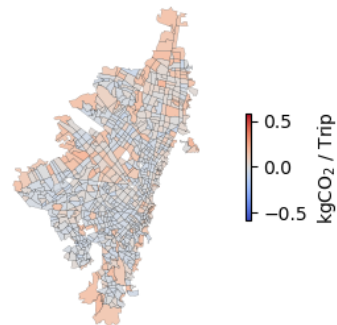


Figure 20. Causal Shapley effects spatially in Bogotá

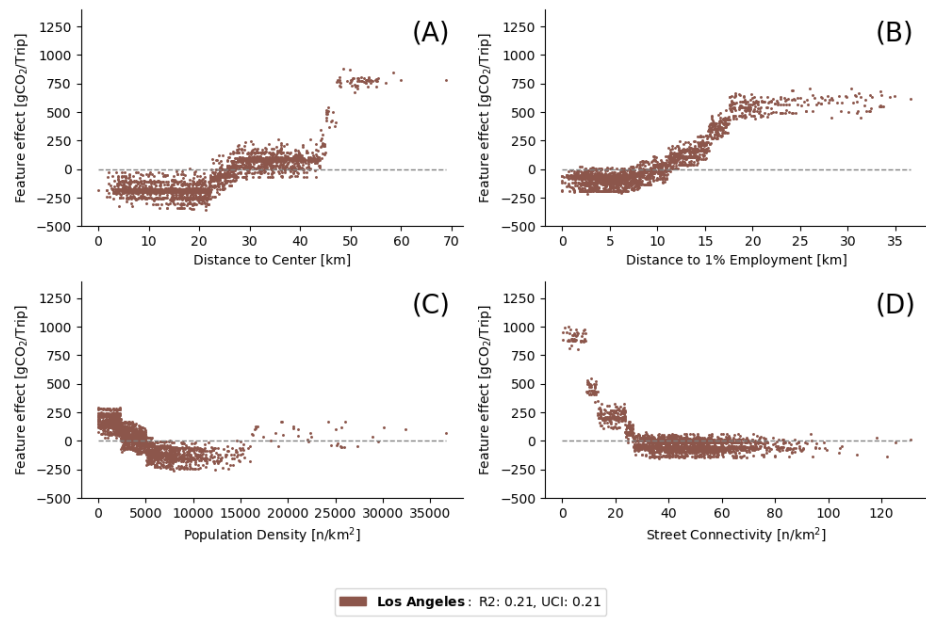


Figure 21. Feature effects in Los Angeles

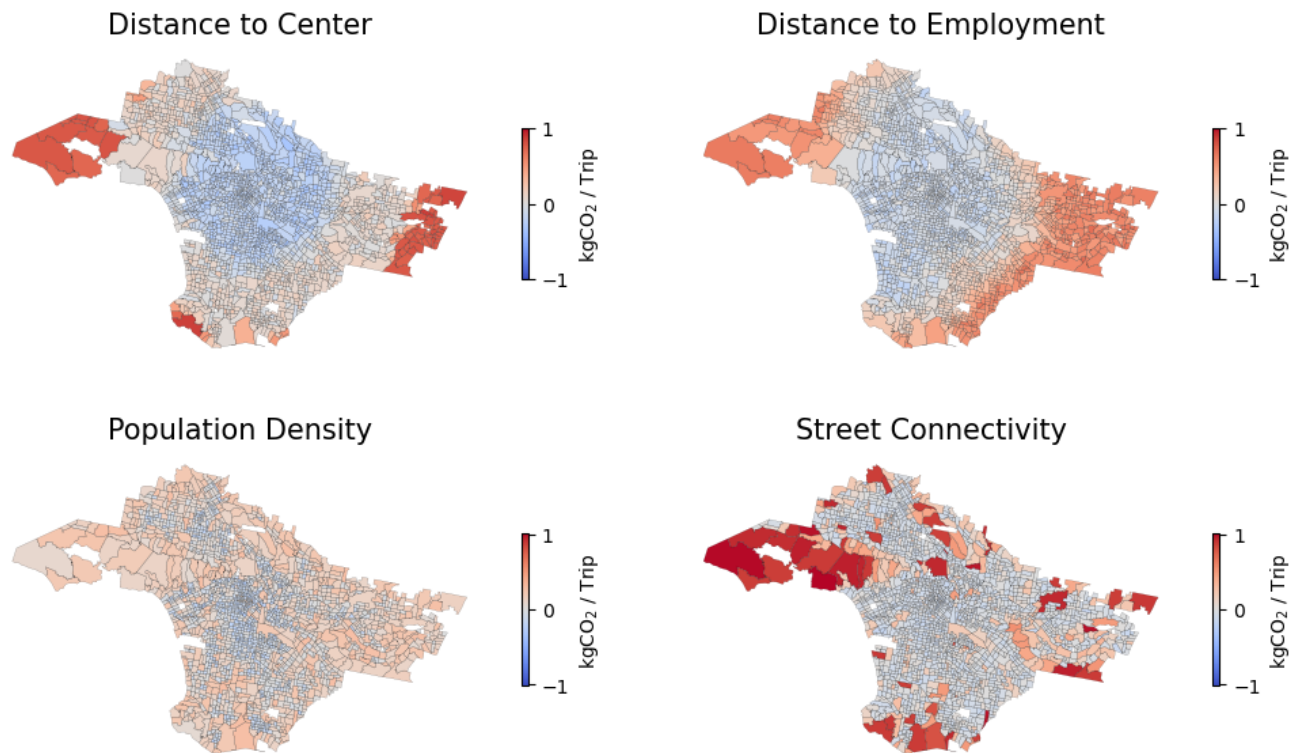


Figure 22. Causal Shapley effects spatially in Los Angeles

Individual feature effects in the Bay Area with 4 centers

The following displays the causal Shapley effects, when considering 4 centers in the Bay Area, located in Downtown San Francisco, San Jose, Fremont and Oakland.

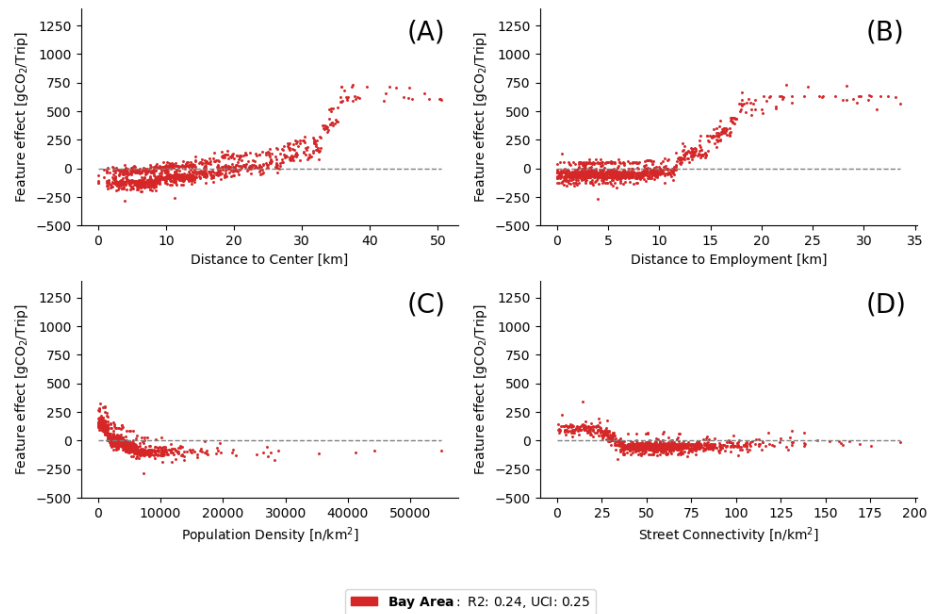


Figure 23. Causal Shapley effects over feature distributions in Berlin

Threshold effects of distance to center and population density

Spatially explicit differences in urban form effects of density and accessibility, displayed in remaining four cities, A) Boston, B) Bay Area, C) Bogotá and D) Los Angeles.

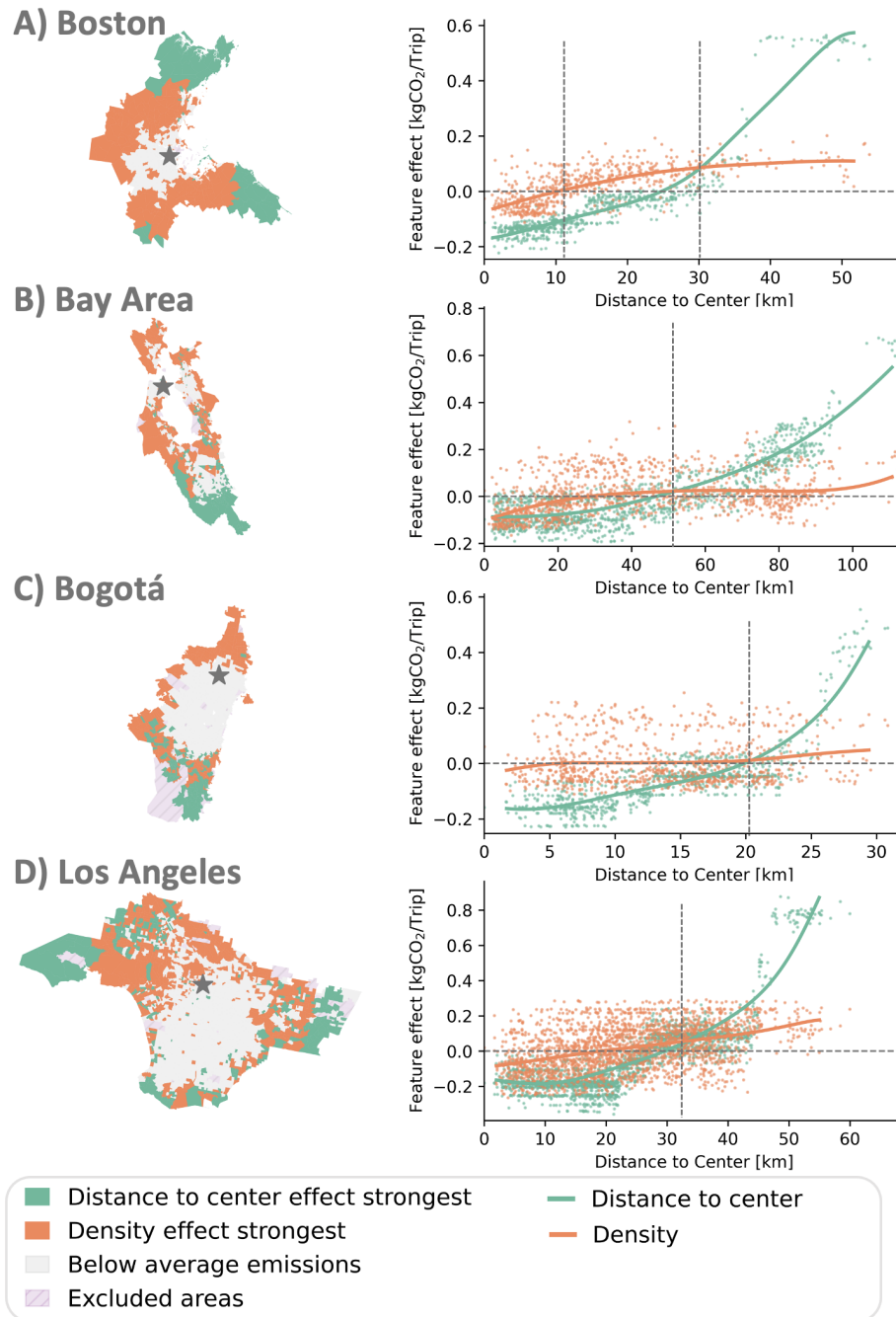
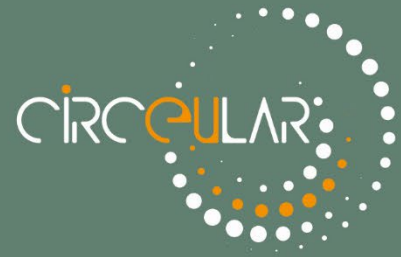


Figure 24. Threshold effects in Boston, Bay Area, Bogotá and Los Angeles For all locations with above mean trip emissions the map on the left visualizes if density (orange) or distance to center (green) are contributing more to trip emissions. The scatter plots on the right highlight the effects of both features over distance to center.



Consumer perspectives on digitalisation as a potential enabler of the CE



DELIVERABLE 4.4

WP4 Interim Report - preliminary results from the Circular Consumption Survey

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Disclaimer

This report was written as part of the CircEULAR project under EC grant agreement 101056810. The information, documentation and figures available in this deliverable were written by the CircEULAR project consortium and do not necessarily reflect the views of the European Commission. The European Commission is not liable for any use that may be made of the information contained herein.

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CircEular

Developing circular pathways for an EU low-carbon transition

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Version	Date	Issued by	Description	Summary of changes
1	26/03/2025	Eoin Grealis, Henrike Rau	First draft	n/a
2	15/04/2025	Eoin Grealis, Henrike Rau	Final draft	Inclusion of additional Italian data



Executive Summary

This CircEULAR deliverable consists of a preliminary report and summary of the initial findings from a pan-European survey of circular consumption practices (CCPs) i.e. practices which on the balance of probability lead to less resource intensive consumption and support moves towards a circular economy. The *Circular Consumption Survey* was conducted in five European countries with a broad geographical spread namely, the United Kingdom, Germany, the Netherlands, Italy and Lithuania. Nationally representative samples were selected based on age, sex, level of education, and region. Over 1,000 respondents from each country were surveyed and asked to provide information on the incidence, and frequency of their engagement with various CCPs as well information on the importance or otherwise of various factors affecting their (non)-willingness to engage in these practices in the future.

In addition to activity levels, standardised social variables were collected to facilitate statistical and segmentation analyses of socio-economic and demographic factors for both engagers and non-engagers in CCPs. Data on material stocks and existing competences was collected to examine existing opportunities for engagement while data on meaning, motivational and cultural factors as well as views on circular citizenship were collected to assess their potential impact on both current and future engagement.

The purpose of the data collection can be summarised as the intention to gather information on:

- (i) past and current engagement in CCPs,
- (ii) socio-economic, motivational and material factors that impact the adoption of CCPs, and
- (iii) indicators concerning future engagement in CCPs.

Data collected from the survey will be combined with insights from the biographical consumption interviews to perform iterative content analysis which combined with statistical and segmentation analyses will yield insights into the acceptance and adoption factors associated with CCPs and potential consumer groups.



Keywords

circularity, circular consumption survey, practice theory, digitalisation, mobility, buildings, household services, representative survey, attitudes, motivations, material conditions, skills, competences, meanings

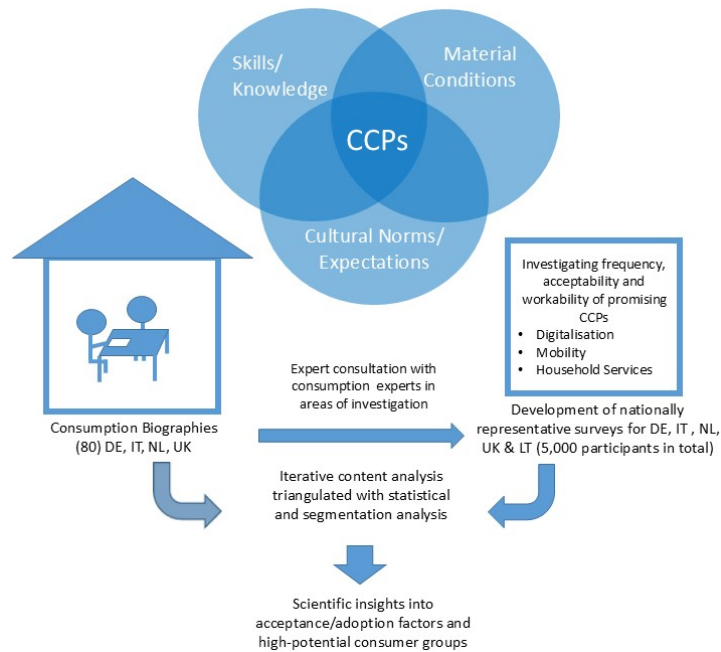


Figure 1: Circular Consumption Research Design (Grealis & Rau 2023a)



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Acronyms/Abbreviations

FAs	Focus Areas
CCPs	Circular Consumption Practices
CircEular	Developing circular pathways for an EU low-carbon transition
EU	European Union
NUTS	Nomenclature of territorial units for statistics
UN	United Nations
Varname	Variable name
WP	Work Package

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Definitions and Clarifications

Circular Consumption Practices

We understand Circular Consumption Practices (CCPs) to be practices that have the potential to increase circularity such as reducing overall consumption, extending the useful life of products and avoiding waste. CircEular is primarily concerned with promising higher-impact consumption practices that are likely to make a substantial positive contribution to circularity (e.g. voluntary carlessness or ‘car shedding’) compared to lower-impact activities like recycling that nevertheless require significant amounts of time, energy and effort.

It is acknowledged in this and other CircEular publications that there may be specific circumstances, contexts and/or instances where a practice which is assumed to be circular, may not in fact contribute to increased total circularity or that while increasing material circularity, a practice leads to adverse environmental outcomes e.g. the repair/refurbishment of a particularly inefficient heating systems, or a production process that increases localised toxicity. There are also likely instances where reduced consumption in one area results in increases in total consumption elsewhere, due to rebound and/or backfire effects (Druckman et al. 2011). However, the focus of the study is to assess the instance, frequency, enablers and barriers of/to CCPs which have the greatest *potential* to contribute to circularity rather than to assess, calculate and or affirm the circularity of a particular practice in every context.

Elements of Practices

By their very nature, different CCPs require different (infra-)structures, skills and competences. Moreover, they have diverse meanings ascribed to them by those who continually reproduce them. As we investigate different CCPs across the three Focus Areas (FAs), differential weight is placed on investigating these elements of practice due to the differential weight of importance each element holds in the performance of those practices.

Unit of analysis

While the broader unit of analysis for profiling engagement, acceptance and adoption of CCPs is the household, we asked individual respondents about their attitudes to CCPs and the meanings they associated with performing them. Acquiring detailed information on all household members would have been unduly onerous on respondents and would have consumed a considerable amount of the time allocated to the survey. Asking respondents to report on the number of children in the household by age group and the presence of dependents was deemed to be a feasible alternative that yielded sufficient amounts of information about the household.

Enablers and barriers of circular practices

Enablers and barriers are factors that affect the attractiveness and feasibility of particular circular practices, including motivational factors (e.g., values, norms, perceptions), contextual factors (e.g., availability of products and services), and cultural factors (reflecting differences between regions and countries).

Commoning

To assess the potential for high-impact CCPs, we have included questions that aim to capture the extent to which sharing/commoning practices and collaboration among residents form a regular part of participants’ lives (Huber, 2022).



Quantitative Stock Measures

While we have included both stock and use variables to assess the resource and material requirements for individual CCPs, it is recognised that survey respondents may not be able to reliably quantify less tangible use variables at short notice (e.g. the number of online second-hand purchases per annum, or the annual number of non-work trips taken over 100km). Where possible, we have attempted to frame such questions in a simplified accessible manner both to aid recall and reduce the memory burden for respondents. Already available regional and national statistics concerning CCPs have been used to complement survey data.

Material Conditions

Material conditions from a practice perspective include the available infrastructure from which one is practically able to draw on.

Survey Notes

Sample Size

The target sample size was 1,000 respondents in each participant country. This follows conventional standards as the minimum number of respondents to canvass where the target population is over 1 million (European Commission, 2025), which was the case for all 5 participant countries. A sample size of 1,000 returns a margin of error (which quantifies the range within which the true population parameter is expected to lie) of + or - 3.1 % for maximum variability (0.5) at the 95% confidence interval typically required for statistical significance.

Weights

The *Circular Consumption Survey* contains data from respondents selected to be nationally representative of the population in terms of age, gender, education and region. This is facilitated by the calculation and inclusion of normalised probability weights in the data set which sum to 1 for each country. These weights can facilitate country comparison when reporting means and relative frequencies but only when the analysis is confined within each country. Simple cross-country pooled analysis using the provided weights should not be used as while the sample sizes are similar, population sizes vary significantly. Such analysis would require the calculation of population level weights. Probability weights should also not be directly used with statistical models which rely on equal probability sampling or IIA (independence of irrelevant alternatives) assumptions.

Variable labels

To increase usability and ease of handling, summary variable labels have been provided for each variable in the data set which are described in Appendix B. However, all data analysis should be conducted and interpreted with reference to the full version of the question which was presented to respondents of the survey. The full version of the questionnaire is provided in Appendix D.



Likert-Ordering

Likert-scaled variables were collected which included a mixture of 4-, 5- and 7-point scales covering attitudinal & willingness statements, frequency of CCP engagement, service ratings, frequency of engagement and estimations of social capital. All Likert variables were collected by presenting respondents with a numerical scale ordered from positive to negative (in terms of contribution to circularity) ordered left to right. From a science communication it is understood that authors of future reports and other users of the data may wish to recode particular Likert variables such as those that cover frequency of engagement in certain practices, where higher coded values relate to lower levels of frequency. However, for reasons of consistency, in this report, all Likert variables have been reported as collected.

Randomisation

Of the Likert question collected 110 were collected in 18 question sets. Where responses were grouped as part of a single question theme, e.g., on the importance of various factors for engagement in a particular circular consumption practice. In all cases the order of questions was randomised to limit the impact of any order effects on data quality.

Ethics

All survey data was collected anonymously through a sub-contracted third-party, with no ethical issues or points of concern identified. Also, no “personal data” was collected according to the definition of the General Data Protection Regulation (European Union, 2018). The survey design was approved by the LMU Ethikkommission (Projekt Nr.: 24-0905) as having no requirement for ethical consultation. While it is noted that with modern technological advances the potential to identify individual respondents from any published survey is increasing, the omission of more highly disaggregated geographical data from the finalised survey secures the data against “reasonable” attempts to identify, link or infer the identity of survey respondents, as per the recommendations of the European Data Protection Board (EDPB) following the previous principles developed by the Article 29 Working Party (European Data Protection Board, 2020).

Household Income

Households were asked to select their monthly net household income after taxes and benefits from 11 income bands. To ensure that respondents were able to reasonably estimate their income and respond within a reasonable timeframe, fixed equal width income bands (500 increments for bands 1-8 and 1000 increments for bands 9-11) were provided as answer options. While country-specific deciles would have returned a more accurate representation of the income distribution and allowed for easier direct cross-country comparison, the burden it would have placed on the respondents in terms of income estimation was deemed too onerous.

Italian Survey Data

During the data review, it was discovered that respondents in Italy with the lowest levels of education were under-sampled. This occurred due to the inadvertent omission of the lowest of seven education categories in the Italian survey, which led to a corresponding over-sampling of individuals with higher education levels. To address this issue, an additional 320 respondents were surveyed in Italy, and normalized probability weights were recalculated for the entire Italian sample (1,409 observations).



As a result, the unweighted Italian sample contains a disproportionately higher number of respondents with higher levels of education compared to population quotas (see Section 2: Quotas & Table 2). Consequently, the probability weights for Italian respondents span a wider range to ensure nationally representative estimates.

Due to the additional respondents, Italians now comprise 25% of the total sample, whereas respondents from the United Kingdom, Germany, the Netherlands, and Lithuania each represent approximately 18%–19%. Accordingly, unweighted results reported in each table should be interpreted with this distribution in mind.

While an unweighted sample more closely resembling the weighting quotas could have been facilitated by dropping observations, for completeness, in this report, the descriptives for all respondents are reported.

Section 1: Introduction

This report presents selected descriptive results derived from the nationally representative *Circular Consumption Survey* conducted across five countries: the United Kingdom (UK), Germany (DE), the Netherlands (NL), Italy (IT), and Lithuania (LT). The survey collects data on current levels of circular consumption practices (CCPs), that is, practices which on the balance of probability contribute to greater levels of circularity. Specifically, it collects data on potential high impact practices in the CircEULAR focus areas (FAs) of mobility, buildings & household services, and digitalisation, with a focus on practices such as car sharing and carless-ness, commoning and online second-hand trading.

Following the methodological overview and a description of the data collection and validation process, the report highlights key descriptives starting with socio-economic and demographic characteristics. It subsequently summarises and highlights by country a number of selected variables which outline current levels of engagement in selected high-impact CCPs across all five participant countries as well as examining the levels of willingness of current non-engagers to take up CCPs in the future if certain conditions are met. Summary and highlighted data are also provided for variables covering respondents' stated importance of potential enablers, barriers and opportunities to/for engagement, including relevant competences, current material conditions, and prevailing structures. Data is also collected on motivational factors and the meanings and values associated with certain CCPs that may act as either barriers or enablers to engagement in CCPs and circular citizenship behaviours.

Regarding the survey's execution, methodological considerations such as sample size, representative quotas, weighting procedures, language considerations, and ethical considerations are also detailed in the survey notes, with a view to providing data which may be used to accurately reflect the broader population of each surveyed country.

The report concludes with a summary of areas of potential investigation and provides a number of appendices, including variable labels and summary statistics on all 250 variables as well as details on the representativeness quotas. This mid-term assessment serves as a foundational analysis, offering preliminary insights that will be further explored in subsequent stages of research.



Section 2: Methodological Overview

Data Collection

Following the finalisation of the data collection frame, the *Circular Consumption Survey* was collected during the months of October and November 2024 across the United Kingdom, Germany, the Netherlands, Italy and Lithuania with an additional 320 respondents surveyed in Italy in March 2025. Pilot versions of the survey were conducted in advance in each country, with adjustments being made before full launch where necessary. In total, 5,651 observations were collected with nationally representative quotas and weights assigned on the basis of age, gender, education, and region. For ease of use and transparency, tables and figures in this report describe the unweighted survey results and in text reported percentages are always rounded to the nearest whole number.

Table 1: Number of survey respondents by country

Country	No. of Respondents	Percent
United Kingdom	1,053	18.65
Germany	1,100	19.43
Netherlands	1,081	19.13
Italy	1,409	24.93
Lithuania	1,008	17.84
Total	5,651	

The dataset itself comprises 66 question sets, resulting in a total of 250 variables. It includes 127 Likert-scale variables using a mix of 4-, 5- and 7-point scales to capture attitudinal and willingness statements, frequency of CCP engagement, service ratings, and social capital. In addition to these attitudinal measures, the dataset collects key socio-demographic information, including age, gender, education, region, main activity, monthly household income (in bands), household composition, tenure and rural-urban classification.

It also covers material conditions such as living space and dwelling type, providing an overview of respondents' living situations as well as recording materials stocks for key variables of interest related to the focus areas of the CircEULAR project (Grealis and Rau, 2023). Examples include private car ownership and the number and type of alternative mobility tools owned by the household (e.g., bicycles).

Quotas

To provide the opportunity to report outcomes at a national level, nationally representative samples in each country were selected in terms of age, gender, level of education and region (NUTS¹ level), i.e. the standardised key variables for capturing socio-economic, demographic and cultural variations within the population. Respondents were chosen to match specific characteristics (e.g., gender balance, age distribution) and are not clustered within groups. The primary source data used to generate quotas for each country were the latest available regional population statistics by age and gender (Eurostat, 2024b) and the population by educational attainment level, sex and age (Eurostat, 2024a). For the United Kingdom, statistics data from the Office for National Statistics (England and Wales), the Scottish census, and the Northern Ireland Statistics and Research agency were used. The representativeness quotas for all countries are reported in

¹ Nomenclature of territorial units for statistics: see <https://ec.europa.eu/eurostat/web/nuts>



Appendix A. While more targeted representativeness criteria for specific variables of interest such as carless households would undoubtedly result in more accurate estimates for target variables, they would also result in a significant increase in complexity and associated costs without significantly improving the representativeness of the survey for all other variables.

Language

The survey was translated from English into four different languages through a collaborative process involving consultation with data collection partners. Native speakers with research experience were engaged to ensure cultural and contextual relevance for each translation. Although great care was taken to maintain consistency across languages, there may still be instances where responses are not precisely comparable due to subtle nuances and variations in meaning between languages. The full questionnaire in English is included in Appendix 2 while the survey in all languages is published with the survey's accompanying documentation.

Section 3: Data Validation

Duration and distribution

The average completion time for the *Circular Consumption Survey* was 24 minutes and 59 seconds across all countries. All response times lower than 15 minutes were excluded as responses under this lower limit were deemed to include a high risk to data quality due to an increased likelihood of insufficient cognitive processing, insufficient reading time and random or patterned responses due to survey fatigue. Times under 15 minutes were also not observed during preliminary piloting.

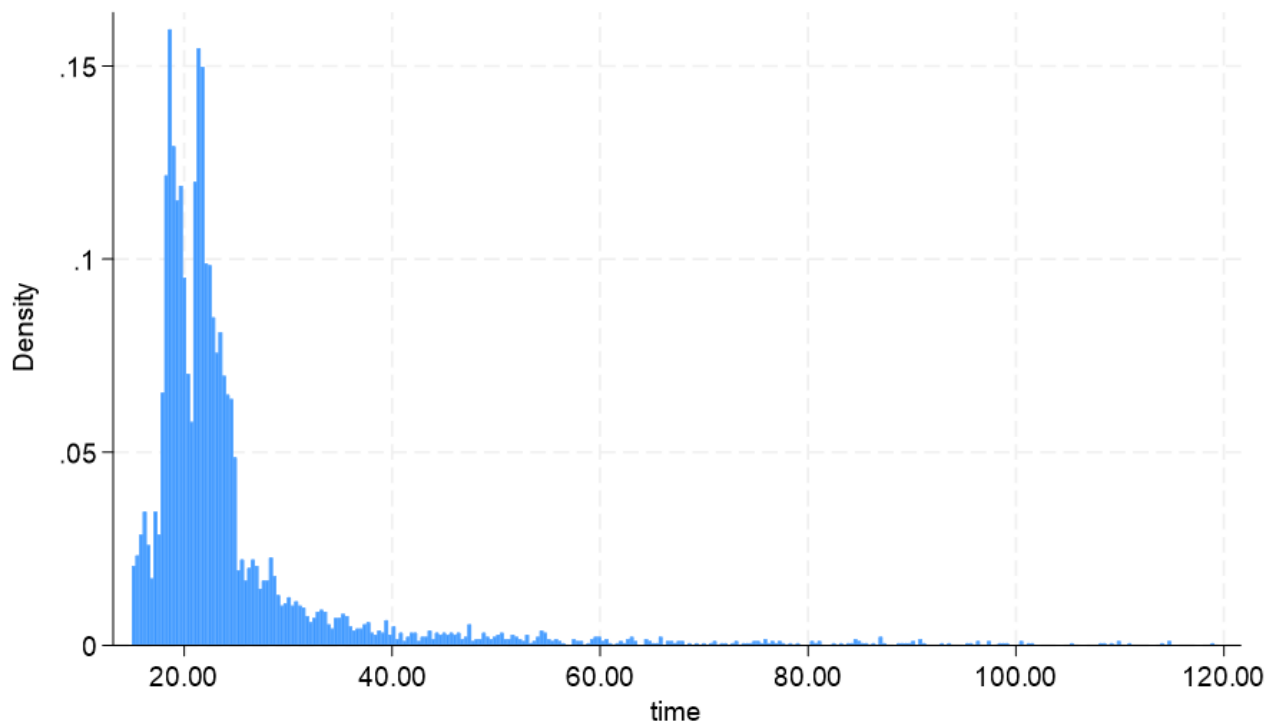


Figure 2: Distribution of survey response times for all respondents



A bimodal distribution of response times was observed (Figure 2). While this was somewhat anticipated due to certain cohorts being required to complete fewer questions, the precise reason for this distribution is unclear, though it is likely influenced by several factors. Primarily, there seems to be an age effect. Older respondents (those 60+) typically took longer to complete the survey, but the distribution of their response times followed a more normal distribution, possibly due to fewer interruptions. By contrast, those under 30 completed the survey more quickly and although the bimodal distribution was still present, it was less pronounced. While bimodal distributions can result from various factors such as differences in respondent familiarity, device usage, survey length, and attention levels, we theorize that in this case, the primary cause is two distinct clusters corresponding to participant age groups and those who took a break during completion of the survey and those who did not.

Living Space

During the piloting phase it was observed that inconsistent responses were submitted in the United Kingdom sample for the question “Approximately how much living space does your current home have?” (varname: *sqmtre*). This problem was somewhat anticipated due to the fact that in the United Kingdom historically, properties have been categorised and marketed according to the number of bedrooms rather than the calculated floor space which was often unavailable. In the pilot, respondents were asked to submit their floor space in sq. feet to account for the fact that while official statistics report in metric, imperial measurements are still in common use. However, this returned numerous implausible entries on the lower end of the scale. An attempt to remedy this was undertaken in the full launch by highlighting to respondents the requirement to estimate their floor space in square metres. While this had the effect of more easily identifying less plausible entries, ultimately the significant number of rounded entries suggests that many respondents did not have the accurate information to hand and simply guessed. More generally, across all countries, where less plausible (i.e. very low) estimates were returned, there is a possibility that those in existing sharing arrangements such as house shares interpreted the question as purely relating to their own private living space in the residence e.g. their private unit/room in a shared living situation. As such, any analysis undertaken which relies on living space estimates in particular should be treated with caution.

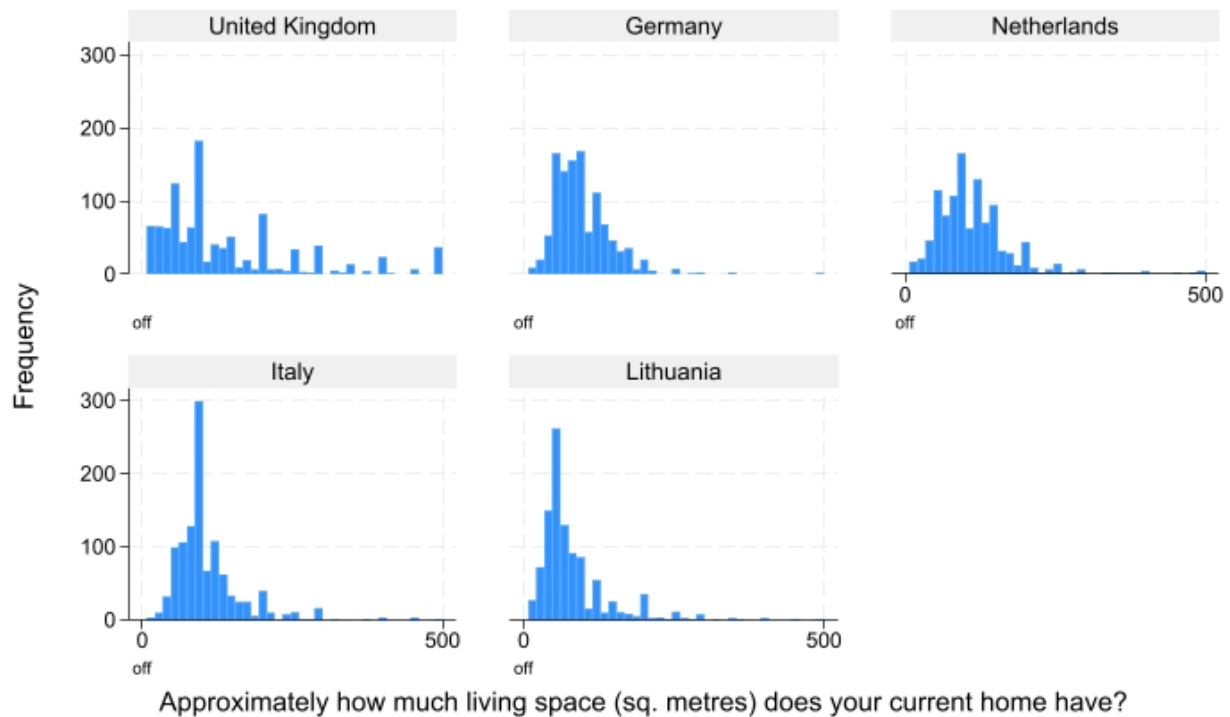


Figure 3: Unweighted distribution of living space by country

Responding Effort

To provide consistency and avoid confusing the participant, Likert-question sets typically cover similar themes with similar if not identical response options. In the *Circular Consumption Survey*, the response options were also consistently presented from left to right, positive to negative. Given the large amount of Likert-scale variables recorded, the data was tested for insufficient effort responding (Hong et al., 2020). Evidence of straight lining (continually choosing the same answer option on the same scale) was detected within some question sets, with 15% of respondents choosing the same response category for the first set of nine, 7-point Likert variables. This rose to 22% for the final set of nine 7-point Likert question variables. This is somewhat anticipated as logically consistent responses from respondents will automatically result in some straight lining. Additionally, as respondents got tired towards the end of the survey their responding effort would be expected to drop. Across the sixty-one 7-point Likert variables which were posed to all respondents, straight-lining dropped to 2.5% of the sample, with the distribution of responses to all 7-Point Likert questions (primarily value and attitudinal questions) posed to all respondents presenting as normal and slightly right (negatively) skewed (Figure 4). This distribution was consistent across all countries.

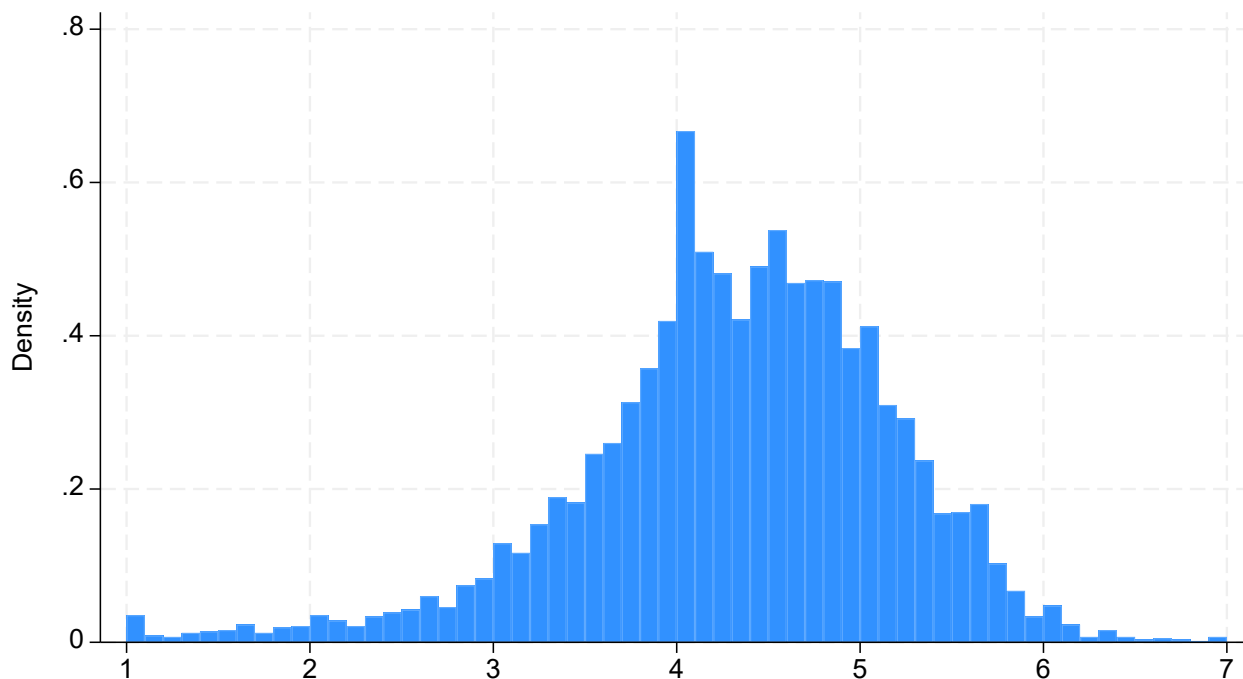


Figure 4: Distribution of responses to all 7-Point Likert questions posed to all respondents

Given that all responses completed under 15 minutes were eliminated from the final data set and the issue was not specific to any of the weighting characteristics and no discernible pattern was identified, no additional observations were removed from the raw data set for lack of responding effort. Researchers should however be aware of such results and in each case consider the suitability or otherwise of including respondents who consistently selected the same response option.

Representativeness

The unweighted distribution of age group, gender, education (Table 2) and region (Table 3) closely aligns with the representativeness quotas outlined in Appendix A for categories in each country with the exception of the education quotas for Italy, the reasons for which are outlined in the Italian survey data note above.

Table 2: Unweighted tabulation of Gender, Age Group & Education by country

	UK		DE		NL		IT		LT	
Gender (%)	P	<i>s</i>	P	<i>s</i>	P	<i>s</i>	P	<i>s</i>	P	<i>s</i>
Male	49	49	49	49	50	49	49	49	46	46
Female	51	51	51	51	50	51	51	51	54	54

	UK		DE		NL		IT		LT	
Age Group (%)	P	<i>s</i>	P	<i>s</i>	P	<i>s</i>	P	<i>s</i>	P	<i>s</i>
16 - 29	23	22	16	14	22	21	17	18	19	19
30 - 39	16	15	16	15	15	12	13	12	16	17



40 – 49	16	16	15	15	14	15	16	16	15	16
50 – 59	16	15	19	20	17	19	19	17	17	18
60 – 69	13	16	16	20	15	17	15	16	16	16
70+	16	16	18	19	17	16	20	21	17	15

Education/Training	UK		DE		NL		IT*		LT	
ISCED-Level %	P	s	P	s	P	s	P	s	P	s
Level 0-2	19	18	23	24	24	24	37	26	12	12
Level 3-4	40	41	48	48	38	38	44	38	48	50
Level 5-8	41	41	29	28	38	38	19	36	41	38

Where *P*= population share and *s* = unweighted sample percentage

* See survey note on Italian survey data

Table 3: Unweighted shares of all 39 NUTS1 Regions by country

Regions NUTS1			
% Share	Population Share		Sample share
East England UK	9		9
East Midlands UK	9		8
London UK	13		14
North East UK	4		4
North West UK	11		10
Northern Ireland UK	3		3
Scotland UK	8		8
South East UK	14		14
South West UK	9		9
Wales UK	5		5
West Midlands UK	9		9
Yorkshire & the Humber UK	8		9
Baden Württemberg DE	13		13
Bayern DE	16		16
Berlin DE	5		5
Brandenburg DE	3		3
Bremen DE	1		1
Hamburg DE	2		2
Hessen DE	8		8
Mecklenburg-Vorpommern DE	2		2
Niedersachsen DE	10		10
Nordrhein-Westfalen DE	22		22
Rheinland-Pfalz DE	5		4
Saarland DE	1		1
Sachsen DE	5		5
Sachsen-Anhalt DE	3		2
			% Share diff



Schleswig-Holstein DE	4	4	0
Thüringen DE	3	3	0
North NL	10	11	-1
East NL	21	22	-1
West NL	48	46	2
South NL	21	22	-1
North-West IT	28	27	1
North-East IT	20	19	1
Centre IT	21	22	-1
South IT	20	22	-2
Islands IT	11	9	2
Capital region LT	29	29	0
Central and Western LT	71	71	0

Section 4: Socio-economic and demographic data

The majority of the socio-economic and demographic variables collected were drawn from the EU's guidelines for standardised key social variables (SKSV) (European Union, 2019, European Union, 2021). Key socio-economic, demographic and contextual information about survey respondents was collected to later serve as potential explanatory variables for material conditions that affect people's capacity to engage in CCPs across the three FAs. Some variables were combined to reduce the burden for respondents, e.g., collecting the number of children in distinct age categories together rather than requiring respondents to fill out a completed household grid. A combination of individual- and household-level socio-economic and demographic variables included gender, age, the presence of a partner, children, and other dependents in the household. Additional socio-economic data included tenure status, net estimated household disposable income band (defined as after tax and benefits are applied) and activity status of the respondent. To provide some basis for assessing the material conditions of the household's residence and local context in terms of local infrastructure etc., respondents self-reported their residence type and the level of urbanity.

Household Size

Table 4 presents the distribution of household sizes across all five countries. Single, two- and three-person households respectively make up around 80% of the sample. Larger households (5+ members) are relatively rare, with just 288 households (5.4%) falling into this category. Across all countries, the unweighted mean sample household size was above the mean household size reported by Eurostat a total sample mean of 2.46 above the European average of 2.3 (Eurostat, 2023).

Table 4: Sample Household size by Country

Household Size	Country					Total
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	
1	251	319	247	195	154	1166
2	399	450	488	492	383	2212
3	182	199	157	366	223	1127
4	145	107	136	278	155	821



5	54	18	41	58	57	228
6	10	6	7	17	22	62
7	10	1	3	3	7	24
8	2	0	1	0	2	5
9	0	0	0	0	1	1
10	0	0	1	0	4	5
Total	1053	1100	1081	1409	1008	5651
Mean	2.46	2.16	2.33	2.69	2.72	2.46
Eurostat (2023)/ Office for National Statistics (2025)	2.36**	2.0	2.1	2.2	1.9	

*see survey note on Italian survey data

**Figures for the UK based on information from the Office for National Statistics (2025)

While the United Kingdom, Germany and the Netherlands returned values within 0.22 of the mean household size reported by Eurostat (2023) mean household sizes from Italy and Lithuania were notably higher with survey respondents from those countries coming from larger households than the reported national averages to the order of 0.4 and 0.8 persons respectively.

The Italian and Lithuania samples returned the highest average household sizes, at 2.64 and 2.72 members, respectively, while the German sample returned the smallest average household size of 2.16 members (Figure 5).

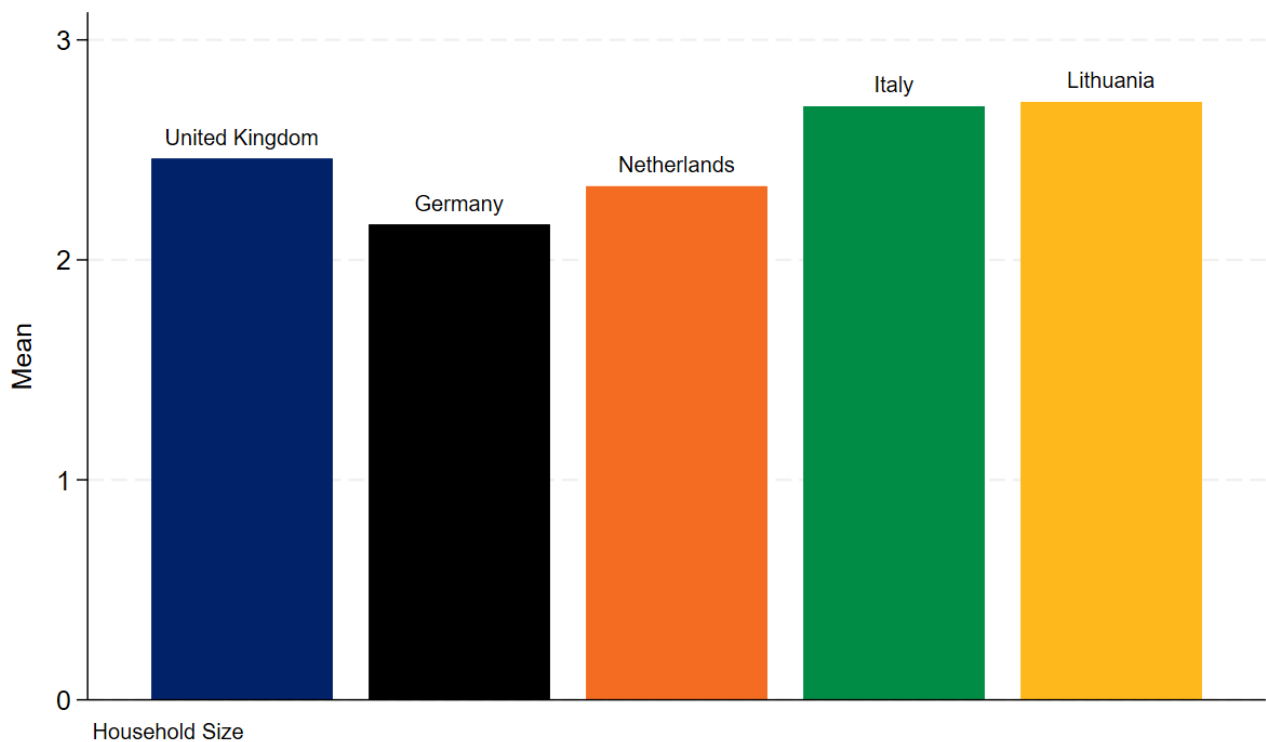


Figure 5: Mean household size by country



It should be noted however that as household size was not a representativeness quota, such differences are not entirely unanticipated. The sampling of larger households than the true mean is likely due to issues such as coverage (e.g. the loss of older single-person households from sampling frames due to relocation/death and the difficulty in acquiring younger single-person households due to early life mobility) and higher non-response rates (Eurostat, 2010) resulting in lower levels of participation from certain types of single-person households. Certain households may be less likely to respond due to factors such as lower levels of social integration and an absence of other household members who might encourage and support participation by supplying information which the individual respondent cannot readily access or recall (Johansson-Tormod and Klevmarken, 2022).

Income & Activity Status

Household disposable income bands (after tax plus benefits) across all countries followed a left-skewed truncated distribution (Figure 6), with some bunching in the highest income categories.

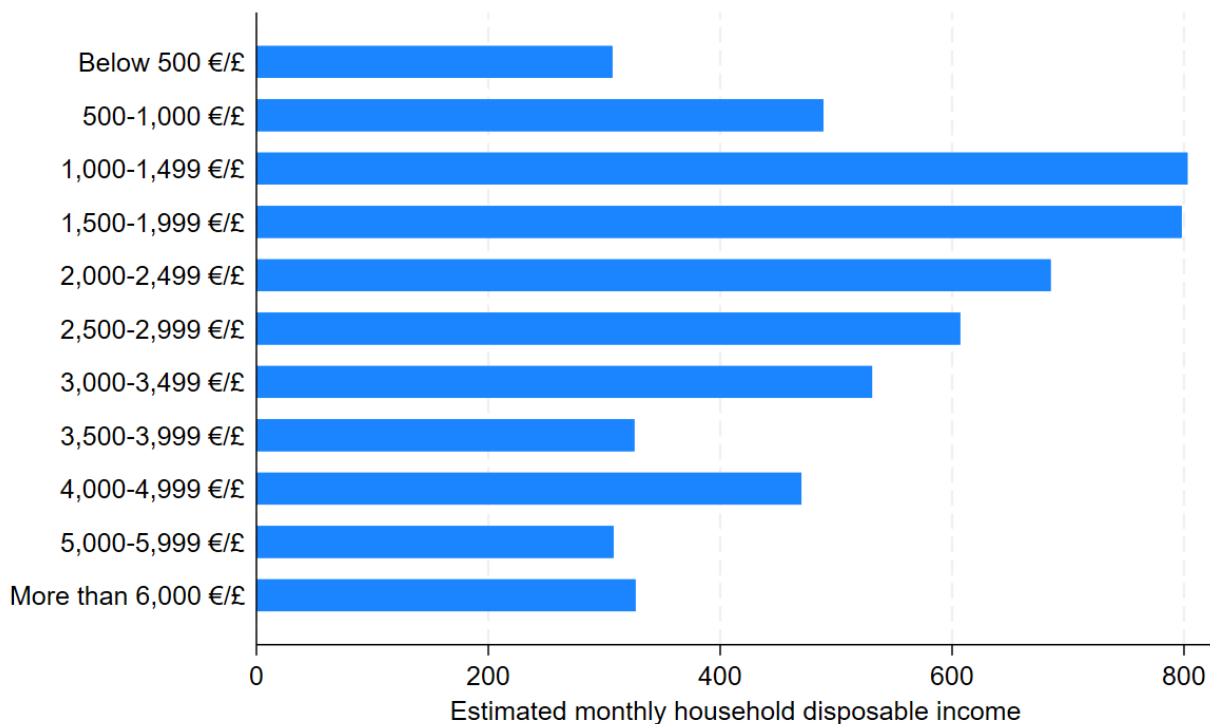


Figure 6: Income distribution across all 11 bands for monthly disposable household income

On a per country basis, Figure 7 shows that household income distributions for survey respondents in the United Kingdom, Germany, and the Netherlands exhibit greater levels of bunching at the higher end compared to Italy and Lithuania. In contrast, Italian and Lithuanian respondents display a more pronounced skew toward the lower income brackets, with a noticeable clustering in the lower- and middle-income brackets. This pattern reflects broader economic differences between these countries, due to disparities in wages, cost of living, labour market structures, differential marginal tax band rates and the stepped distribution of two-income households in each country likely resulting in unexpected distributions in individual income bands e.g. in the 3,500-3,999-income band.

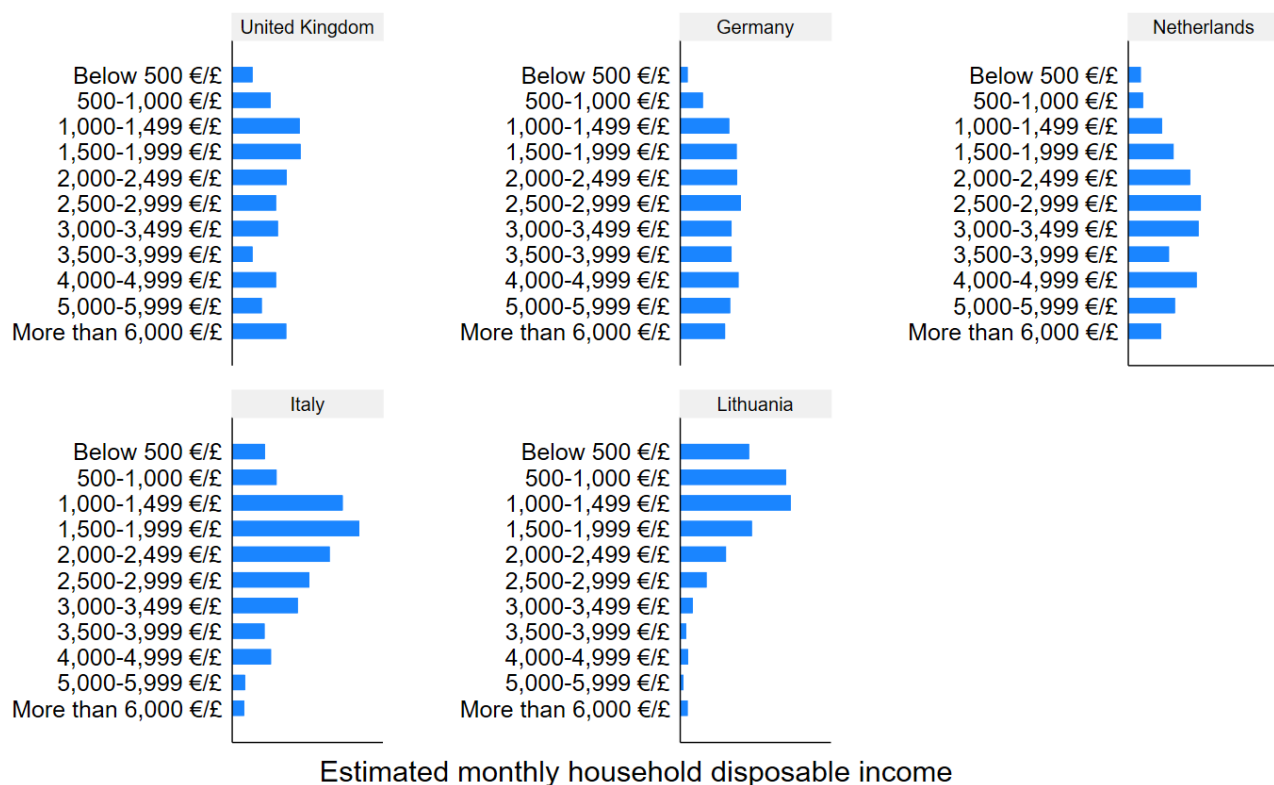


Figure 7: Self-estimated monthly disposable household income by participant country

Tenure, Urbanity & Dwelling

Regarding tenure, average levels of home ownership both with and without an outstanding mortgage were 64% across the sample, with predictably lower levels of ownership for Germany (45%). Interestingly, the Dutch sample contained a relatively high share of owners with outstanding mortgages, compared to the other four participant samples which could perhaps be due to earlier life stage mortgage acquisition but warrants further investigation. In terms of tenancy, German respondents reported the highest levels of tenancy at the market rate, contrasting with respondents from the Netherlands who reported the highest levels of rent at a reduced market rate and respondents from Lithuania reporting the highest levels of rent-free tenancy.

Table 5: Sample tenure status by country

Please describe your Tenure/Residential Status.	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Owner no outstanding mortgage	464	305	124	771	512	2176
	44.06	27.73	11.47	54.72	50.79	38.51
Owner with outstanding mortgage	207	194	583	281	159	1424
	19.66	17.64	53.93	19.94	15.77	25.20
Tenant with rent at market rate	224	537	161	191	197	1310
	21.27	48.82	14.89	13.56	19.54	23.18
Tenant with rent at reduced rate	103	46	200	47	26	422
	9.78	4.18	18.50	3.34	2.58	7.47



Tenant, Rent free	55 5.22	18 1.64	13 1.20	119 8.45	114 11.31	319 5.65
Total	1053	1100	1081	1409	1008	5651

*see survey note on Italian survey data
Note: First row lists *frequencies* and second row lists *column percentages*

In terms of activity status, similar levels of employment were observed in the United Kingdom, Germany, the Netherlands and Italy. Lithuania respondents reported a higher level of both employment and unemployment relative to the other four participant countries. The sample collected in Lithuanian also returned a commensurately low number of respondents who described their activity status as “retired”. This is likely due to a number of factors including a 4–6-year lower life expectancy in Lithuania (77.6 in 2023) in comparison to the other four countries (Eurostat, 2025) and by the slight under-representation of those in the higher age group category (see Table 2). Other potential reasons include differences in interpretation, structure and social provision in the “Retired” category with only 40% of persons leaving the labour market 6 months after reaching retirement age (Valstybės duomenų agentūra (State Data Agency), 2024).

Table 6: Sample activity status by participant country

What is your main activity status?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Employed	558 52.99	655 59.55	568 52.54	717 50.89	649 64.38	3147 55.69
Unemployed	52 4.94	29 2.64	21 1.94	145 10.29	108 10.71	355 6.28
Retired	296 28.11	277 25.18	270 24.98	334 23.70	63 6.25	1240 21.94
Unable to work due to long-standing health problems	63 5.98	43 3.91	117 10.82	8 0.57	40 3.97	271 4.80
Student, pupil	48 4.56	35 3.18	45 4.16	82 5.82	74 7.34	284 5.03
Fulfilling domestic tasks	14 1.33	43 3.91	38 3.52	95 6.74	50 4.96	240 4.25
Compulsory military or civilian service	0 0.00	0 0.00	0 0.00	0 0.00	2 0.20	2 0.04
Other	22 2.09	18 1.64	22 2.04	28 1.99	22 2.18	112 1.98
Total	1053 100.00	1100 100.00	1081 100.00	1409 100.00	1008 100.00	5651 100.00

*see survey note on Italian survey data
Note: First row lists *frequencies* and second row lists *column percentages*

Respondents’ self-reported level of urbanity is displayed in Table 7. While the subjective definitions seemed to have performed well for the United Kingdom and Germany, most noticeably, respondents from the largest urban areas in the Netherlands did not consider themselves to be resident in “a big city” despite the fact that the Netherlands is the participant country with the highest population density. This was likely due to



translation difficulties and terminology with specific population-level interpretations attached to certain terms such as “Een metropool”. Additionally, while Lithuania is the participant country with the lowest population density, it reports the lowest number of respondents living in the lowest two urbanity categories. Single-country and cross-country analyses using urbanity should thus be carefully handled with reference to the original translations and the respondent distributions.

Table 7: Self-reported level of urbanity in respondents’ residential area

How would you describe the area where your residence is located?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
A big city	221	284	27	200	385	1117
	20.99	25.82	2.50	14.19	38.19	19.77
The suburbs or outskirts of a big city	236	205	147	147	65	800
	22.41	18.64	13.60	10.43	6.45	14.16
A large town	209	185	165	220	308	1087
	19.85	16.82	15.26	15.61	30.56	19.24
A small town	232	192	346	566	131	1467
	22.03	17.45	32.01	40.17	13.00	25.96
Rural Area or village	155	234	396	276	119	1180
	14.72	21.27	36.63	19.59	11.81	20.88
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

Focusing on dwelling type, survey respondents from the United Kingdom and the Netherlands reported similar levels (75-78%) of individual housing (detached, semi-detached and terrace), with a greater proportion of terraced housing reported by respondents from the Netherlands (Table 8). In contrast, survey respondents in Germany, Italy and Lithuania reported much greater levels of apartment dwelling (54-58%).

Table 8: Dwelling type by country

Which dwelling type do you live in?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Detached house	249	294	133	413	375	1464
	23.65	26.73	12.30	29.31	37.20	25.91
Semi-detached house	331	124	200	141	40	836
	31.43	11.27	18.50	10.01	3.97	14.79
Terraced house	222	42	465	75	17	821
	21.08	3.82	43.02	5.32	1.69	14.53
Apartment	223	635	270	766	561	2455
	21.18	57.73	24.98	54.36	55.65	43.44
Other (e.g. Mobile Home/Trailer, Boathouse, Dormitory, Adjacent Housing/Bedsit, Tiny House etc.)	28	5	13	14	15	75
	2.66	0.45	1.20	0.99	1.49	1.33
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*



Across all countries surveyed, the mean age of respondents was 49, with 51% percent of the sample reporting their gender as female. More than half of all respondents (62%) reported living with a partner while 31% of all households reported the presence of children.

Section 5: Mobility, carless-ness, and car sharing

This section reports data relating to current engagement in mobility-related CCPs such as carless-ness, levels of car sharing, and active mobility. Stated levels of willingness to engage in car sharing and car shedding where sharing services would be available as well as information on existing structures and competencies for public, active, and multi-modal mobility also feature.

Car ownership and carless-ness

Regarding car ownership, respondents were asked “How many cars does your household have? (including leased and company-cars).” This facilitated the later reporting of “ownership type” for each car, i.e., whether it was privately owned, leased, or a company car².

Most respondents (52%) reported being part of a one-car household, with a further quarter of respondents (26%) belonging to a two-car household (Table 9). Carless households made up 17% of the total sample with over a fifth of respondents in the United Kingdom (21%) and Lithuania (23%) reporting non-ownership of a car by the household.

Table 9: Number of cars per household by participant country.

No. of cars owned by household	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
0	225	197	146	144	236	948
	21.37	17.91	13.51	10.22	23.41	16.78
1	532	582	632	750	452	2948
	50.52	52.91	58.46	53.23	44.84	52.17
2	242	271	249	434	259	1455
	22.98	24.64	23.03	30.80	25.69	25.75
3	36	37	41	67	42	223
	3.42	3.36	3.79	4.76	4.17	3.95
4	12	8	9	12	12	53
	1.14	0.73	0.83	0.85	1.19	0.94
5	6	5	4	2	7	24
	0.57	0.45	0.37	0.14	0.69	0.42
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

² While the term “possession type” would have been more accurate, it was decided that this would be potentially confusing for participants and had the potential to slow response times.



Concerning car type, survey respondents were asked about details for each car reported, i.e., whether it was a conventional, hybrid, or electric vehicle. Only 6% of respondents reported having an electric car (Table 10), with 12% reporting hybrid use (see Table 11).

Table 10: Number of respondents reporting an electric car by country

Number of Electric Cars in Household	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
0	957	1024	1003	1370	973	5327
	90.88	93.09	92.78	97.23	96.53	94.27
1	84	67	73	34	31	289
	7.98	6.09	6.75	2.41	3.08	5.11
2	11	9	5	4	4	33
	1.04	0.82	0.46	0.28	0.40	0.58
3	1	0	0	1	0	2
	0.09	0.00	0.00	0.07	0.00	0.04
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

Table 11: Number of respondents with a hybrid car by participant country

Number of Hybrid Cars in Household	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
0	874	1025	950	1181	935	4965
	83.00	93.18	87.88	83.82	92.76	87.86
1	152	70	124	206	64	616
	14.43	6.36	11.47	14.62	6.35	10.90
2	23	5	7	21	9	65
	2.18	0.45	0.65	1.49	0.89	1.15
3	4	0	0	1	0	5
	0.38	0.00	0.00	0.07	0.00	0.09
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

Moving on to ownership status, only 6% of the sample reported a leasing arrangement (Table 12), with just 5% of respondents mentioning a company car (Table 13).



Table 12: Number of respondents reporting having a leased car by participant country

Number of Leased Cars in Household	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
0	957	1050	990	1360	946	5303
	90.88	95.45	91.58	96.52	93.85	93.84
1	90	40	85	44	59	318
	8.55	3.64	7.86	3.12	5.85	5.63
2	4	9	5	5	3	26
	0.38	0.82	0.46	0.35	0.30	0.46
3	2	1	1	0	0	4
	0.19	0.09	0.09	0.00	0.00	0.07
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

Table 13: Number of respondents reporting having a company car by participant country

Number of Company Cars in Household	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
0	1018	1039	990	1368	969	5384
	96.68	94.45	91.58	97.09	96.13	95.28
1	32	55	85	39	34	245
	3.04	5.00	7.86	2.77	3.37	4.34
2	3	6	4	1	5	19
	0.28	0.55	0.37	0.07	0.50	0.34
3	0	0	2	0	0	2
	0.00	0.00	0.19	0.00	0.00	0.04
4	0	0	0	1	0	1
	0.00	0.00	0.00	0.07	0.00	0.02
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

Car sharing and car shedding

All respondents were asked to state whether they had access to car sharing services in their local area. The share of respondents who reported the availability of commercial sharing options was 28% while 20% reported informal car sharing opportunities and 9% community options. At least one car sharing option was reported as being available in the local area by 45% of respondents (Table 14).



Table 14: At least one car-sharing option available reported by country

At least one car sharing option available in my local area.	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
No Sharing available	583	668	583	851	408	3093
	55.37	60.73	53.93	60.40	40.48	54.73
At least one sharing option available	470	432	498	558	600	2558
	44.63	39.27	46.07	39.60	59.52	45.27
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

Of the 2,558 respondents who reported the availability of car sharing services, 73% of respondents reported that they either rarely (27%) or never (45%) use them, with weekly (11%) or monthly (11%) use the most common frequency levels reported for what may be subjectively deemed as regular use (Table 15). The distribution of frequency across participant countries was largely similar, with the greatest level of non-use of available options reported in Germany (61% “Never” and 21% “Rarely”).

Table 15: Frequency of use of car sharing by country with at least one sharing option available

How often do you use car sharing?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Daily	46	9	29	30	33	147
	9.79	2.08	5.82	5.38	5.50	5.75
Weekly	69	37	39	65	71	281
	14.68	8.56	7.83	11.65	11.83	10.99
Monthly	52	32	40	75	76	275
	11.06	7.41	8.03	13.44	12.67	10.75
Rarely	119	90	119	135	232	695
	25.32	20.83	23.90	24.19	38.67	27.17
Never	184	264	271	253	188	1160
	39.15	61.11	54.42	45.34	31.33	45.35
Total	470	432	498	558	600	2558
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

Out of 5,651 respondents, 3,093 reported no availability of car sharing options. These respondents were then asked how likely it would be that they would use car sharing if it was available (1= “Yes, very likely” to 7= “No, very unlikely”; Figure 8).

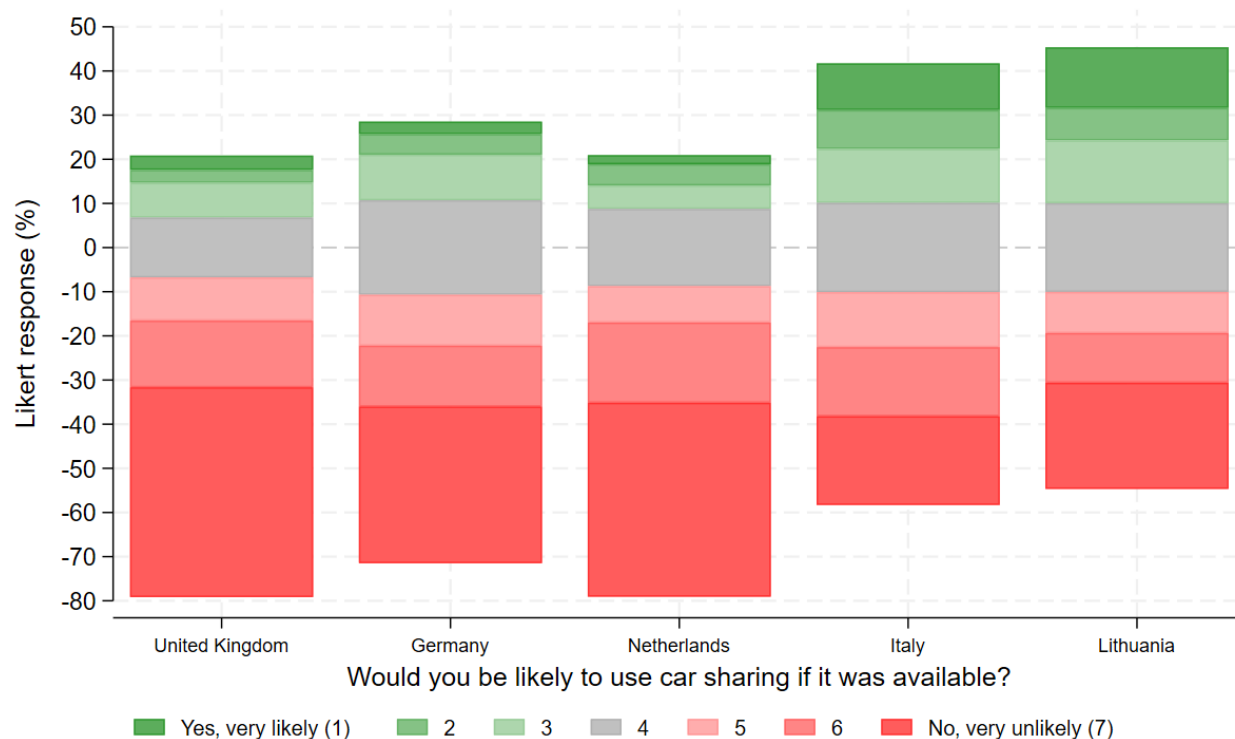


Figure 8: Percentage shares of likelihood of using car sharing if it was available.

Very low levels of likelihood of using car sharing (where none was currently available) were reported across all participant countries, with only 14, 18 and 12% of respondents rating their likelihood from 1-3 in the United Kingdom, Germany and the Netherlands respectively. Noticeably higher rates of likelihood were reported in Italy and Lithuania. However, across all respondents, 59% rated their likelihood level between 5-7, with 34% reporting their likelihood as “No, very unlikely (7)” (Table 16).

Table 16: Reported likelihood of using car-sharing if it was available.

Would you be likely to use car sharing if it was available?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Yes, very likely (1)	19	19	12	90	56	196
2	3.26	2.84	2.06	10.58	13.73	6.34
3	17	31	28	75	30	181
4	2.92	4.64	4.80	8.81	7.35	5.85
5	46	69	31	104	58	308
6	7.89	10.33	5.32	12.22	14.22	9.96
7	79	143	102	172	82	578
No, very unlikely (7)	13.55	21.41	17.50	20.21	20.10	18.69
1	57	77	48	106	38	326
2	9.78	11.53	8.23	12.46	9.31	10.54
3	88	92	106	133	46	465
4	15.09	13.77	18.18	15.63	11.27	15.03
5	277	237	256	171	98	1039

	47.51	35.48	43.91	20.09	24.02	33.59
Total	583	668	583	851	408	3093
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

Respondents were then asked about the potential of car sharing to result in 'car shedding'. This question was only asked of those respondents who reported car use and currently did not have any car-sharing options available in their local area. Here, a cross-country profile similar to likelihood of car sharing (Figure 8) emerged, with higher levels of likelihood to shed their car reported by respondents in Italy and Lithuania (Figure 9).

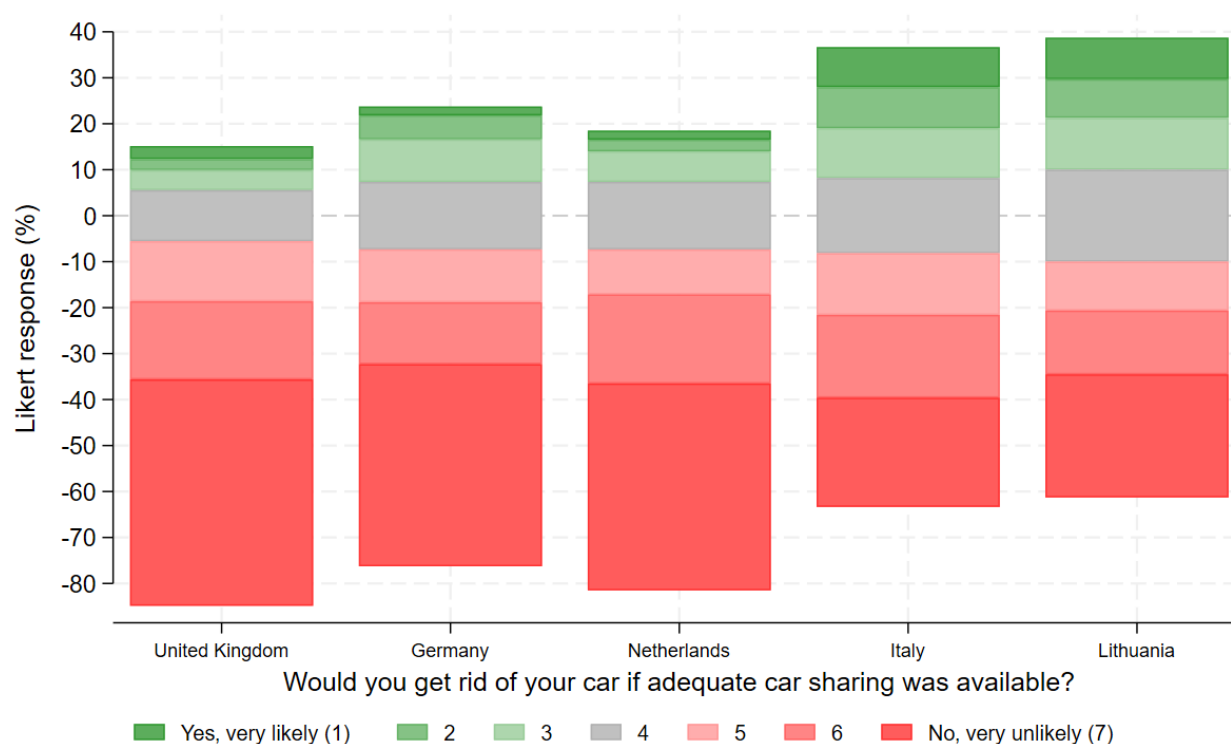


Figure 9: Likelihood to shed car if adequate car sharing was available.

The overall likelihood of car shedding reported was low, with 66% of respondents choosing scale points between 5-7, including 37% selecting "No, very unlikely (7)" (Table 17).

Table 17: Likelihood of shedding car with adequate car-sharing by country

Would you get rid of your car if adequate car sharing was available?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Yes, very likely (1)	13	11	10	68	28	130
2	2.83	1.92	1.96	8.68	9.03	4.93
3	11	30	13	70	26	150



	2.40	5.24	2.54	8.94	8.39	5.69
3	20	53	34	85	35	227
	4.36	9.25	6.65	10.86	11.29	8.61
4	51	84	75	128	62	400
	11.11	14.66	14.68	16.35	20.00	15.17
5	60	66	50	105	33	314
	13.07	11.52	9.78	13.41	10.65	11.91
6	78	77	99	141	43	438
	16.99	13.44	19.37	18.01	13.87	16.62
No, very unlikely (7)	226	252	230	186	83	977
	49.24	43.98	45.01	23.75	26.77	37.06
Total	459	573	511	783	310	2636
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

Public, Active, and Multi-Modal Transport

To provide a basis for assessing existing structures and local conditions impacting respondents' capacity to reduce their car use, they were asked to rate their local transport provision on a 7-point scale from "Very good (1)" to "Very poor (7)".

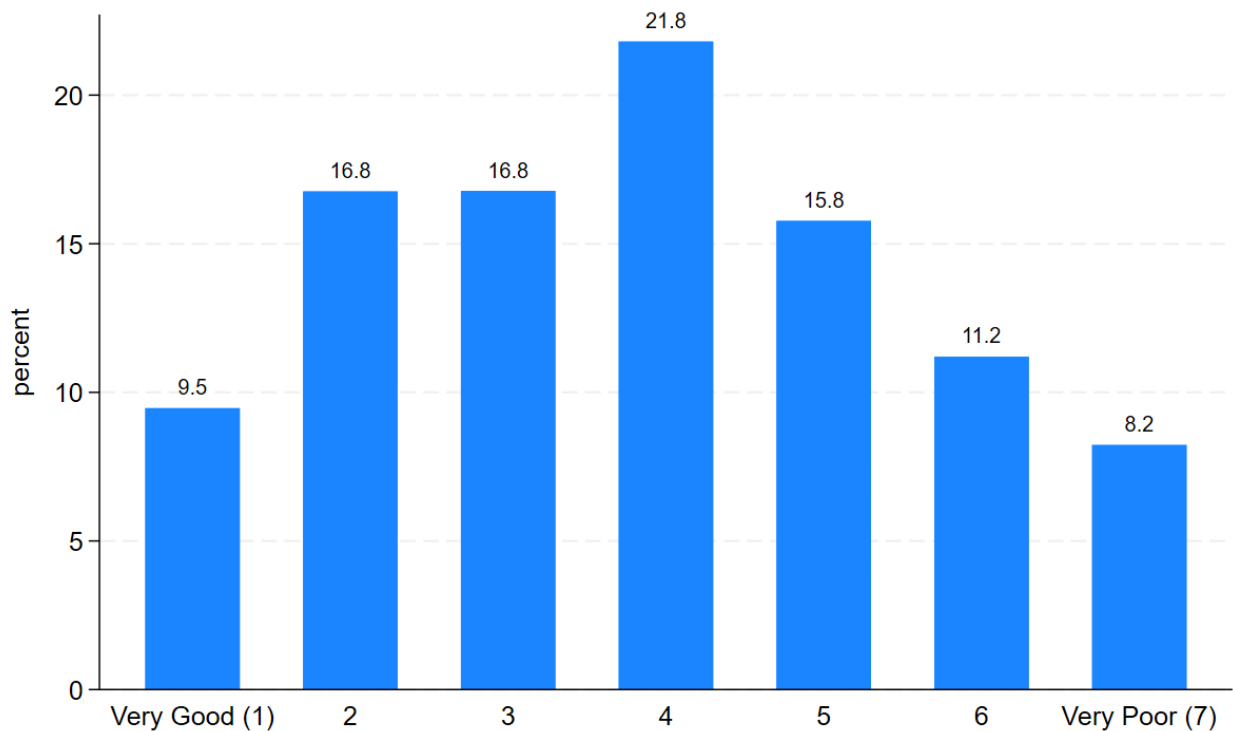


Figure 10: How would you rate the current public transport provision in your local area?



While 22% of respondents rated their public transport provision neither positively nor negatively (with a rating of 4), 43% gave their local area public transport provision a positive rating (1-3) while 35% chose a negative rating (5–7).

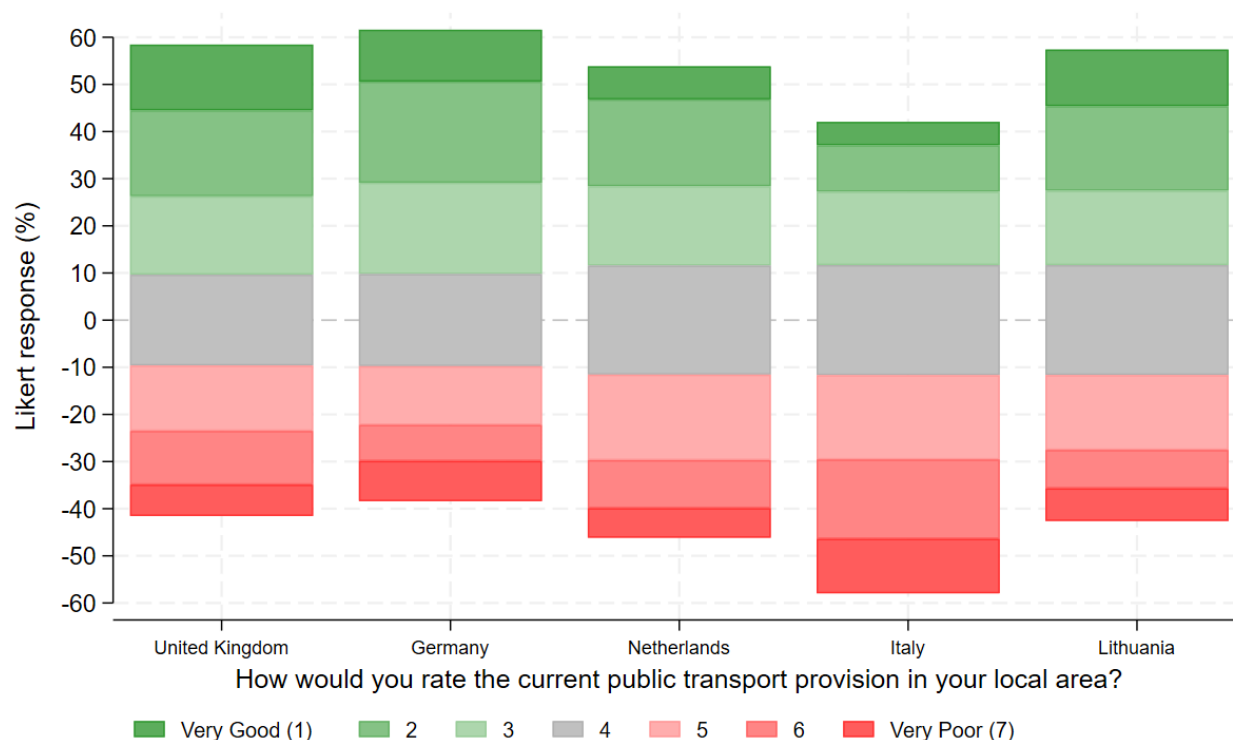


Figure 11: Local public transport provision rating by country

While the distribution of local public transport ratings was similar across all countries surveyed, Italian respondents rated their local transport provision more negatively (Figure 11): just 30% selected scores between 1 and 3, compared to 47% for all other respondents (Table 18).

Table 18: Public transport rating by country

How would you rate the current public transport provision in your local area?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Very Good (1)	147	121	76	70	121	535
	13.96	11.00	7.03	4.97	12.00	9.47
2	192	236	199	139	181	947
	18.23	21.45	18.41	9.87	17.96	16.76
3	175	213	182	219	159	948
	16.62	19.36	16.84	15.54	15.77	16.78
4	203	215	250	329	235	1232
	19.28	19.55	23.13	23.35	23.31	21.80
5	146	137	196	252	160	891



	13.87	12.45	18.13	17.89	15.87	15.77
6	120	84	110	237	82	633
	11.40	7.64	10.18	16.82	8.13	11.20
Very Poor (7)	70	94	68	163	70	465
	6.65	8.55	6.29	11.57	6.94	8.23
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

In terms of active mobility, considerable differences emerged between respondents in participant countries. The mean number of bicycles reported by United Kingdom respondents was just 0.69, contrasting with anticipated high levels of reported bicycle ownership in the Netherlands at 2.35 bicycles per household (Figure 12 & Table 20).

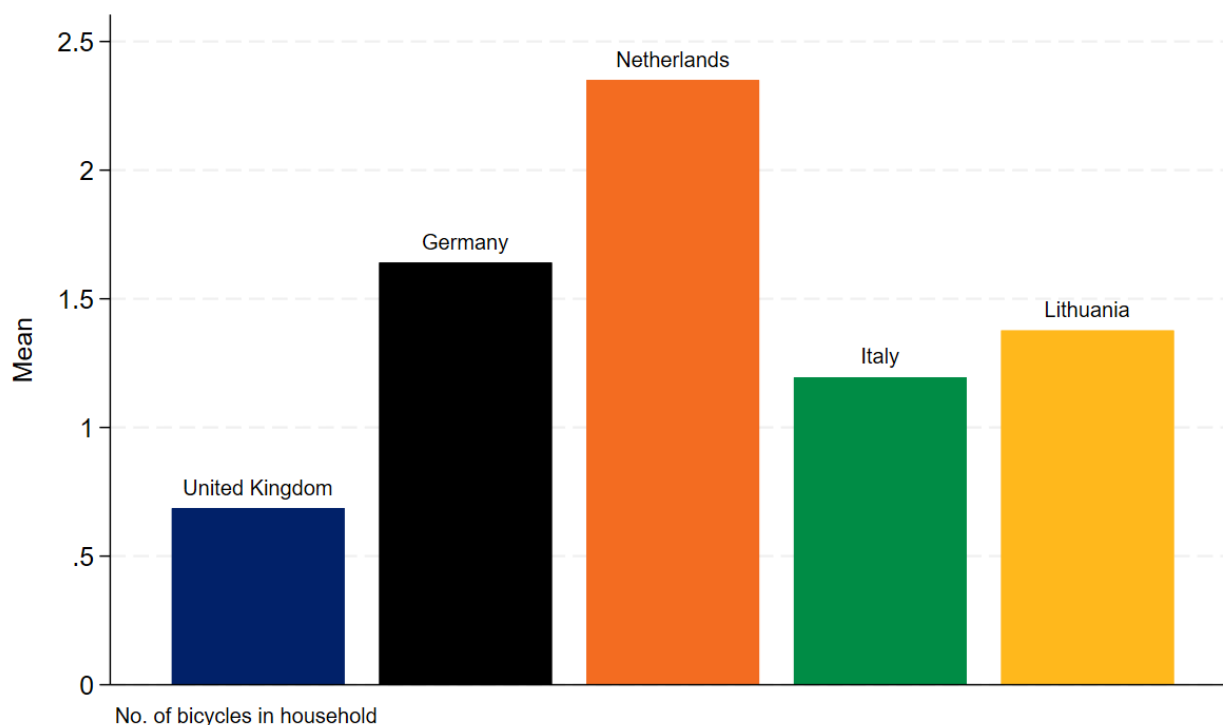


Figure 12: Mean number of bicycles per household for all respondents

This disparity is largely due to very high number of respondents in the United Kingdom (60%) who stated that the household does not own a bicycle, contrasting with the Netherlands where only 11% of respondents reported no bicycle ownership (Table 19). Overall, almost 36% of respondents reported that their household does not own a bicycle.

Table 19: Reported number of households who do not own a bicycle by country.

Household does not own a bicycle.	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Not selected	419	796	960	825	642	3642



Selected	39.79 634 60.21	72.36 304 27.64	88.81 121 11.19	58.55 584 41.45	63.69 366 36.31	64.45 2009 35.55
Total	1053 100.00	1100 100.00	1081 100.00	1409 100.00	1008 100.00	5651 100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

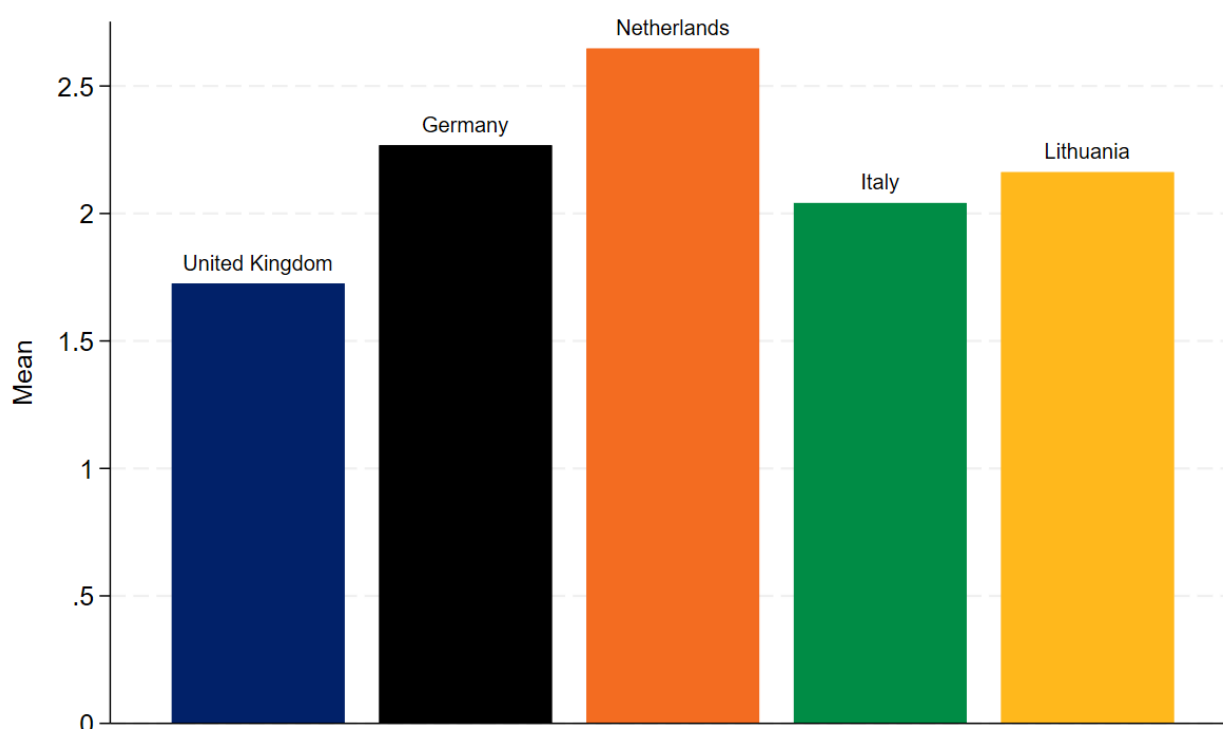


Figure 13: Mean number of bicycles per household those who report owning at least one bicycle.

When looking only at households who did report bicycle ownership (Figure 13), the contrast was less pronounced. Respondents in the United Kingdom reported bicycle ownership averaging 1.73 bicycles per household, compared to 2.65 in the Netherlands (Table 20).

Table 20: Mean number of bicycles per household for all respondents and for those who report owning at least one bicycle.

How many bicycles	Country				
	United Kingdom	Germany	Netherlands	Italy*	Lithuania
Mean	0.67	1.64	2.35	1.20	1.38
Mean (at least one bicycles)	1.73	2.27	2.65	2.04	2.16

*see survey note on Italian survey data



In terms of regularity of bicycle use among those who reported household bicycle ownership, 36% of respondents reported that they themselves rarely or never cycle, with a further 14% reporting that they cycle on a monthly basis. The remaining 51% of respondents reporting cycling on a weekly (32%) or daily (18%) basis (Table 21).

Table 21: Bicycle use by country

How often do you cycle?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Daily	47	138	330	75	58	648
	11.22	17.34	34.38	9.09	9.03	17.79
Weekly	127	297	379	251	127	1181
	30.31	37.31	39.48	30.42	19.78	32.43
Monthly	71	96	94	122	137	520
	16.95	12.06	9.79	14.79	21.34	14.28
Rarely	97	213	110	274	276	970
	23.15	26.76	11.46	33.21	42.99	26.63
Never	77	52	47	103	44	323
	18.38	6.53	4.90	12.48	6.85	8.87
Total	419	796	960	825	642	3642
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

Respondents from the Netherlands and Germany report the highest frequency of bicycle use, with 75% and 55% reporting weekly or daily use. Lower levels of frequency of use were reported by respondents from the United Kingdom, Italy, and Lithuania who reported daily or weekly use levels of 41%, 40% and 29% respectively (Figure 14).

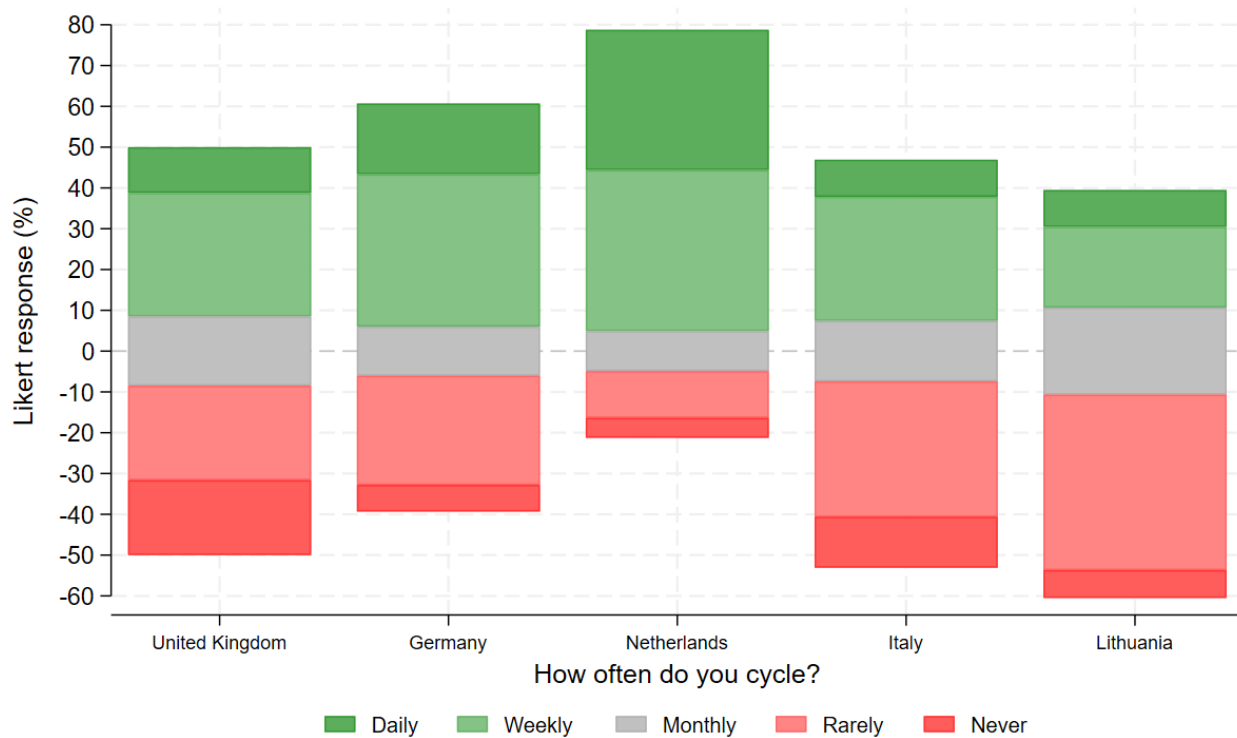


Figure 14: How often do you cycle?

Section 6: Commoning & repair

Living space sharing and downsizing

This section describes the current rate of sharing and/or commoning of living spaces reported by respondents. Participants were asked if they currently share a kitchen, bathroom, basement, garden, utility room, or entrance/hallway with a non-family member. All respondents were also asked if they would be willing to permanently share those spaces (where applicable) with non-family members. Overall, levels of reported space sharing were low across all countries, with 73% of respondents stating that they did not share any of the living or residential spaces described. The rate of space sharing was the highest in Lithuania with 39% of respondents reporting they shared at least one of the listed spaces. In contrast, only 17% of respondents from the Netherlands reported sharing at least one of the listed spaces (Table 22). Respondents from the Netherlands also reported the lowest level of space sharing for all categories apart from entrances and hallways with Lithuania reporting the highest rates in all categories apart from gardens.



Table 22: Current level of space sharing reported by respondents

Do you currently share.....?	Country					
% of total respondents who reported sharing the follow areas.	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Kitchen	83	55	58	125	138	459
	7.88	5.00	5.37	8.87	13.69	8.12
Bathroom	80	63	48	112	134	437
	7.60	5.73	4.44	7.95	13.29	7.73
Basement	44	118	43	104	156	465
	4.18	10.73	3.98	7.38	15.48	8.23
Garden	137	119	65	230	100	651
	13.01	10.82	6.01	16.32	9.92	11.52
Utility room	67	82	25	68	95	337
	6.36	7.45	2.31	4.83	9.42	5.96
Entrance/hallway ³	136	211	146	200	235	928
	12.92	19.18	13.51	14.19	23.31	16.42
I currently do not share any spaces	829	793	895	970	611	4098
	78.73	72.09	82.79	68.84	60.62	72.52
Total respondents	1053	1100	1081	1409	1008	5651

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row shows the independent *percentage of total respondents for each area*.

The type of space to be shared mattered greatly in this context. Somewhat higher levels of sharing were reported in what might be commonly interpreted as less private areas such as entrances (16%) and gardens (12%), contrasting with low shares for more private areas such as kitchens (8%) and bathrooms (8%). Current structural arrangements as well as cultural norms and prescriptions regarding public and private spaces are likely to be the primary drivers for these differences.

Participants were then asked about their level of willingness to permanently share those spaces with non-family members where applicable, with answer options ranging from “Very willing” (1) to “Not at all willing” (7). Respondents from the Netherlands reported the lowest willingness to permanently share space across all categories despite reporting the second highest average living space per household member (Table 23).

Table 23: Willingness to permanently share spaces with non-family members.

Would you be willing to share your space with non-family member?	Country					
Mean Likert response 1-Very Willing to 7-Not at all willing	United Kingdom	Germany	Netherlands	Italy*	Lithuania	
Kitchen	5.93	6.09	6.20	5.89	5.83	
Bathroom	6.03	6.26	6.31	6.03	5.91	
Basement	5.18	4.93	5.69	5.12	5.24	
Garden	4.88	4.55	5.54	4.54	5.27	
Utility room	5.25	4.65	5.99	5.49	5.31	
Entrance/hallway	5.27	4.76	5.43	5.36	5.29	
Mean reported living space per household member**	68.83	50.82	57.83	46.94	35.28	

*see survey note on Italian survey data

**see note on living space in Section 3: Data validation

³ The category entrance/hallway was not defined further and followed the respondent’s interpretation



In terms of willingness to downsize, 28% of respondents stated a willingness level of 3 or better, with almost 56% of respondents returning a score of 5-7. In fact, 32% of all respondents stated that they were “Not at all willing (7)” to move to a smaller home if it was readily available.

Table 24: Willingness to move to a smaller home

Extent of willingness to live in a smaller home if one was readily available	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Very willing (1)	123	82	116	122	81	524
	11.68	7.45	10.73	8.66	8.04	9.27
2	100	102	91	104	52	449
	9.50	9.27	8.42	7.38	5.16	7.95
3	106	153	103	168	79	609
	10.07	13.91	9.53	11.92	7.84	10.78
4	173	171	159	250	170	923
	16.43	15.55	14.71	17.74	16.87	16.33
5	98	122	122	208	134	684
	9.31	11.09	11.29	14.76	13.29	12.10
6	124	123	124	180	120	671
	11.78	11.18	11.47	12.78	11.90	11.87
Not at all willing (7)	329	347	366	377	372	1791
	31.24	31.55	33.86	26.76	36.90	31.69
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

The distribution of willingness to downsize was similar in all participant countries (Figure 15), with Lithuania reporting the lowest average willingness to move which may be related to those respondents also reporting the lowest living space per household member (Table 23)

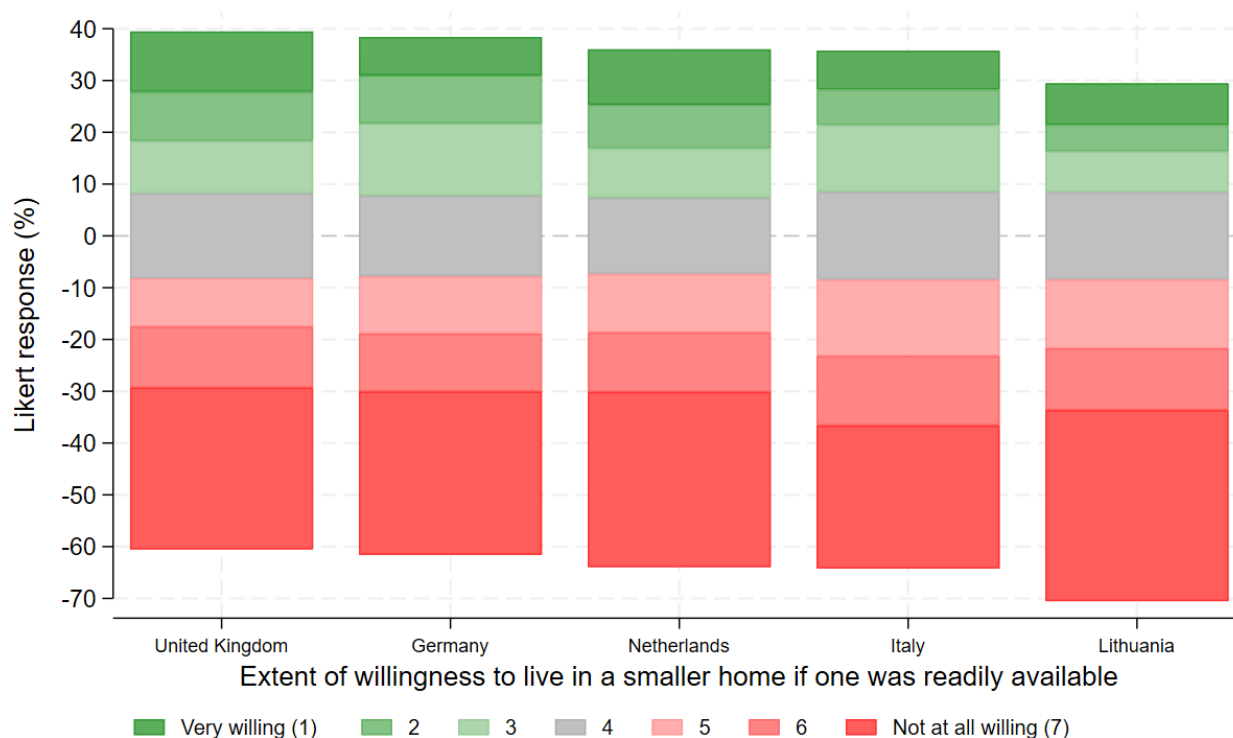


Figure 15: Extent of willingness of respondents in all countries to live in a smaller home if readily available.

Borrowing and Lending

Respondents were asked if they ever borrowed any of the following items from their neighbour: car, E-bike, bicycle, tools, electronic devices, kitchen appliances, or other smaller household items. Low levels of borrowing (less than 11%) were reported across all categories, with tools (30%) being a notable exception. Respondents from all countries reported borrowing rates for tools of 22% or higher.

Table 25: Level of borrowing reported by respondents by participant country

Which of the following items have you borrowed at some stage from your neighbours?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Car	78	89	110	99	74	450
	7.41	8.09	10.18	7.03	7.34	7.96
E-bike	30	42	29	45	34	180
	2.85	3.82	2.68	3.19	3.37	3.19
Bicycle	61	72	81	66	78	358
	5.79	6.55	7.49	4.68	7.74	6.34
Tools	307	432	445	294	223	1701
	29.15	39.27	41.17	20.87	22.12	30.10
Electronic/digital device	50	71	70	35	74	300
	4.75	6.45	6.48	2.48	7.34	5.31
Kitchen appliances	60	102	82	120	48	412
	5.70	9.27	7.59	8.52	4.76	7.29
Other smaller household items	75	138	145	122	104	584
	7.12	12.55	13.41	8.66	10.32	10.33



None of these	654	559	551	919	631	3314
	62.11	50.82	50.97	65.22	62.60	58.64
Total	1053	1100	1081	1409	1008	5651

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row shows the independent *percentage of total respondents for each item*.

Respondents were then asked about their level of lending for the same items. While overall levels of lending could also be described as relatively low (15% for all categories, except for tools at 37%), respondents consistently reported slightly higher levels of lending rather than borrowing (Table 26). Such differences may be due to poor recall and social desirability biases and/or asymmetrical interactions where people may lend to many but borrow from few.

Table 26: Level of lending reported by respondents by participant country

Which of the following items have you lent at some stage to your neighbours?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Car	90	99	119	108	116	532
	8.55	9.00	11.01	7.67	11.51	9.41
E-bike	35	48	45	40	46	214
	3.32	4.36	4.16	2.84	4.56	3.79
Bicycle	71	88	113	85	128	485
	6.74	8.00	10.45	6.03	12.70	8.58
Tools	393	465	495	347	318	2018
	37.32	42.27	45.79	24.63	31.55	35.71
Electronic/digital device	86	99	111	79	119	494
	8.17	9.00	10.27	5.61	11.81	8.74
Kitchen appliances	98	137	112	178	95	620
	9.31	12.45	10.36	12.63	9.42	10.97
Other small household items	118	202	189	170	139	818
	11.21	18.36	17.48	12.07	13.79	14.48
None of these	553	499	482	811	478	2823
	52.52	45.36	44.59	57.56	47.42	49.96
Total	1053	1100	1081	1409	1008	5651

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row shows the independent *percentage of total respondents for each item*.

Respondents from Lithuania reported the highest levels of lending in the car, E-bike, bicycle, and electronic devices categories. While respondents from Italy reported the highest levels of non-engagement (none of these) in both borrowing (65%) and lending (58%), they did report the highest levels of lending in the category of kitchen appliances (13%).

Repair Activity

Respondents were asked about their engagement in repair activities in the categories of car, bicycle, mobile phone, digital devices, clothing, furniture, shoes and household appliances. They were first asked if they carried out repair activities themselves before being asked if they purchased repairs in those categories. Overall, 73% of respondents reported engaging in at least one self-repair activity (Table 27). While 27% reported not engaging in any self-repair activity, this differed substantially across countries, with only 20% of



respondents from Lithuania reporting no self-repair activity compared to 33% of respondents from the United Kingdom. The most common self-repair activity reported was clothes mending (44%), with respondents from the Netherlands reporting the highest level (52%). The lowest levels of self-repair activity related to mobile phone repairs (14%) and shoe repairs (15%).

Table 27: Level of self-repair activity reported by respondents by participant country

Do you perform.....?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
minor car repairs	265 25.17	278 25.27	237 21.92	340 24.13	330 32.74	1450 25.66
bicycle repairs	218 20.70	480 43.64	557 51.53	393 27.89	369 36.61	2017 35.69
mobile phone repairs	126 11.97	207 18.82	102 9.44	188 13.34	187 18.55	810 14.33
repairing other digital devices	145 13.77	206 18.73	154 14.25	202 14.34	196 19.44	903 15.98
clothes mending	457 43.40	533 48.45	495 45.79	600 42.58	421 41.77	2506 44.35
furniture repairs	263 24.98	449 40.82	312 28.86	447 31.72	356 35.32	1827 32.33
shoe repairs	138 13.11	155 14.09	138 12.77	234 16.61	160 15.87	825 14.60
household appliance repairs	289 27.45	329 29.91	316 29.23	297 21.08	359 35.62	1590 28.14
None of these	351 33.33	269 24.45	299 27.66	410 29.10	202 20.04	1531 27.09
Total	1053	1100	1081	1409	1008	5651

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row shows the independent *percentage of total respondents for each item*.

When asked about the purchase of repair services, overall, 82% of respondents reported purchasing at least one repair service (Table 28). While 18% reported not purchasing any of the listed repair services, this again differed substantially across countries. Only 10% of respondents from the Netherlands reported no repair service purchase, compared to 28% of United Kingdom respondents. The most common repair service category reported was minor car repairs (51%), with respondents from the Dutch sample reporting the highest levels of repair service purchase across all categories, except for household appliance repair service purchase levels reported by respondents from Italy (43%).

Table 28: Level of repair service purchase activity reported by respondents by participant country

Do you purchase any of these repair services?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
minor car repairs	474 45.01	614 55.82	671 62.07	713 50.60	437 43.35	2909 51.48
bicycle repairs	122 11.59	332 30.18	497 45.98	276 19.59	180 17.86	1407 24.90
mobile phone	384 36.47	447 40.64	690 63.83	593 42.09	509 50.50	2623 46.42



other digital devices	305	437	616	500	432	2290
	28.96	39.73	56.98	35.49	42.86	40.52
clothes mending	129	236	354	258	151	1128
	12.25	21.45	32.75	18.31	14.98	19.96
furniture	159	186	320	224	174	1063
	15.10	16.91	29.60	15.90	17.26	18.81
shoe repair	246	469	509	436	364	2024
	23.36	42.64	47.09	30.94	36.11	35.82
household appliances	345	405	456	612	299	2117
	32.76	36.82	42.18	43.44	29.66	37.46
None of these	300	161	107	311	160	1039
	28.49	14.64	9.90	22.07	15.87	18.39
Total	1053	1100	1081	1409	1008	5651

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row shows the independent *percentage of total respondents for each item*

Section 7: Digitalisation and second-hand trading

This section describes data considering the contribution of digitalisation towards engagement in CCPs more generally, and extensions to the useful lifespan of products through second-hand trading in particular. Initially reporting on variables addressing digital competency levels, the section then reports on respondents' perceived impact of digitalisation on their rate of consumption across various categories before focusing on digitalisation's role as a potential enabler of reuse activity through the medium of online second-hand trading.

Material Conditions, Skills and Competences

Respondents were asked to self-assess the quality of their internet access on a 5-point scale ranging from 1= "Excellent" to 5= "No access" (Figure 16). Respondents from Lithuania reported the highest shares across all countries for the "Excellent", "Poor" and "No access" categories which suggests that they experience a larger level of structural inequality in terms of internet access compared to their counterparts from the other four countries.

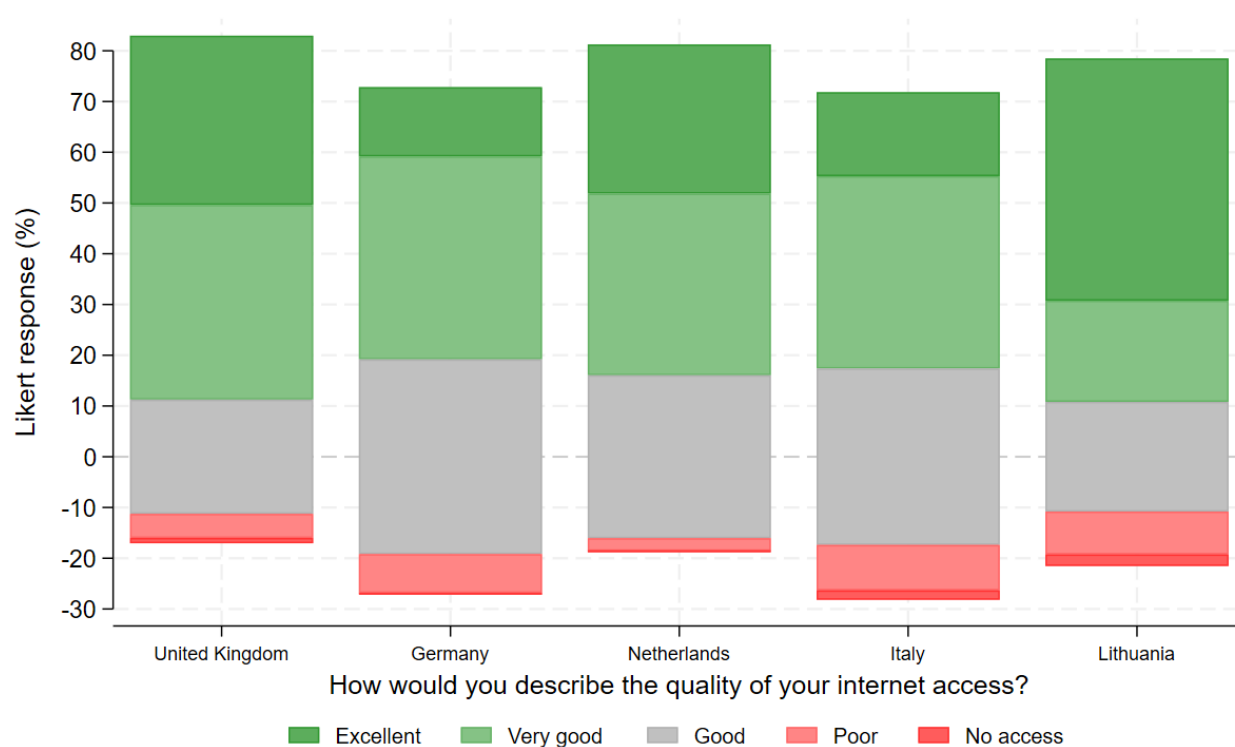


Figure 16: Respondent rating of quality of internet access by country

While overall, 92% of respondents assess the quality of their internet access as good or better, there are a number of reasons to treat the results with caution as there is a strong possibility of some self-selection bias occurring in terms of the profile of available survey respondents. Additionally, given that the categories are exclusively subjective, responses may be skewed against the backdrop of differential historical development paths and the pace of roll-out of technological improvements in different countries.

Table 29: Respondent rating of internet access by country.

How would you describe the quality of your internet access?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Excellent	351	150	318	233	481	1533
	33.33	13.64	29.42	16.54	47.72	27.13
Very good	404	440	387	534	201	1966
	38.37	40.00	35.80	37.90	19.94	34.79
Good	237	422	347	490	218	1714
	22.51	38.36	32.10	34.78	21.63	30.33
Poor	50	84	27	126	85	372
	4.75	7.64	2.50	8.94	8.43	6.58
No access	11	4	2	26	23	66
	1.04	0.36	0.19	1.85	2.28	1.17
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*



Concerning smart-phone use, just under 92% of respondents reported use of a smartphone to access the internet, with only 95 of the 5,651 respondents reporting non-ownership of a smart phone (Table 30). Noticeably, the number of respondents in the United Kingdom reporting non-ownership of a smart phone was almost twice the overall mean, contrasting with the lowest level of non-ownership reported by respondents from Italy.

Table 30: Smartphone use to access the internet by country

Do you use a smartphone to access the internet?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Yes	941 89.36	1003 91.18	998 92.32	1272 90.28	924 91.67	5138 90.92
No	80 7.60	72 6.55	70 6.48	123 8.73	73 7.24	418 7.40
I don't have a smartphone	32 3.04	25 2.27	13 1.20	14 0.99	11 1.09	95 1.68
Total	1053 100.00	1100 100.00	1081 100.00	1409 100.00	1008 100.00	5651 100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

Respondents were also tasked to use a 5-point scale (1 = “Very often” to 5 = “Never”) to report the frequency with which they asked others for help (Figure 17) and how often they were approached for help when solving digital/IT problems (Figure 18). The intent was to indirectly capture an indication of respondents’ digital competency.

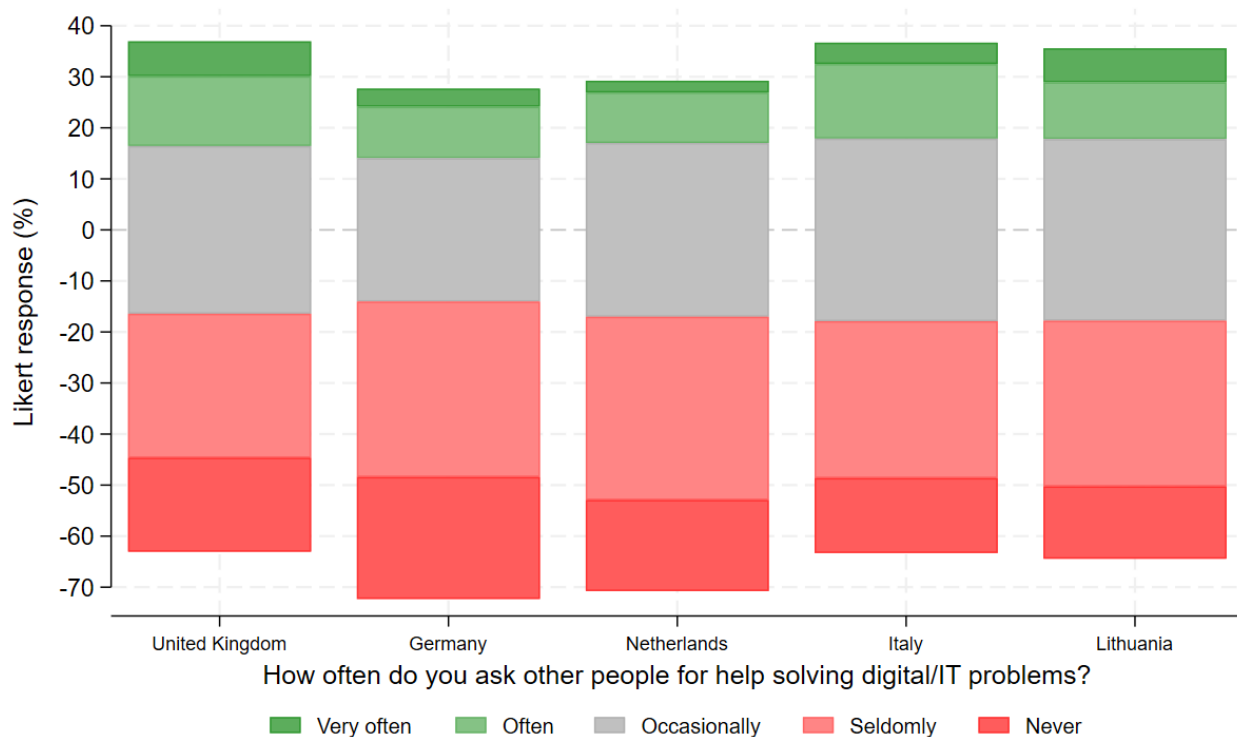


Figure 17: Frequency of asking other people for help solving digital/I.T problems.



Overall, respondents reported a slightly higher frequency of being asked for help (Table 31) rather than asking for help (Table 32), which suggests a possible recall and social desirability bias.

Table 31: Frequency of being asked for help with I.T problems by country

Do people ask for your help when solving digital/IT problems?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Very often	117	57	30	151	143	498
	11.11	5.18	2.78	10.72	14.19	8.81
Often	148	155	138	290	194	925
	14.06	14.09	12.77	20.58	19.25	16.37
Occasionally	308	320	336	493	372	1829
	29.25	29.09	31.08	34.99	36.90	32.37
Seldomly	222	283	278	235	182	1200
	21.08	25.73	25.72	16.68	18.06	21.24
Never	258	285	299	240	117	1199
	24.50	25.91	27.66	17.03	11.61	21.22
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

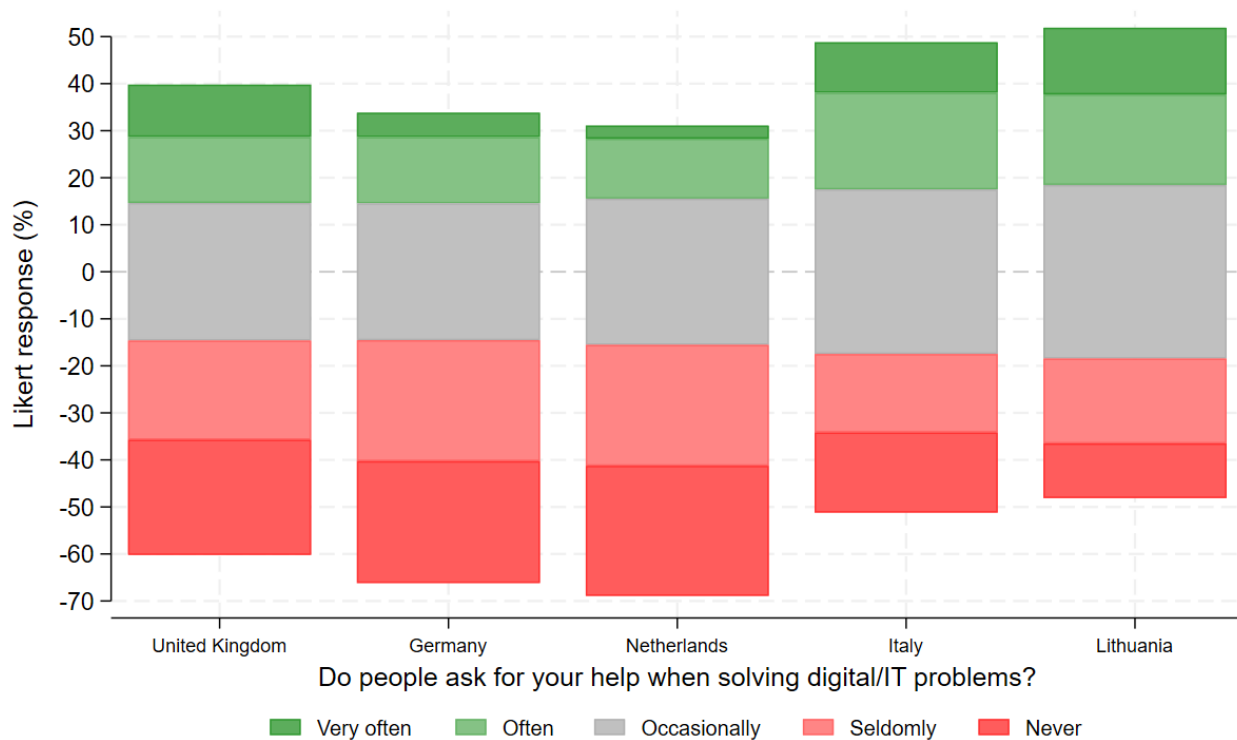


Figure 18: Frequency of others asking for your help when solving digital/I.T problems



Slightly higher rates of collaboration/exchange were reported by respondents in Italy and Lithuania, with lower levels of exchange reported in the Netherlands and Germany.

Table 32: Frequency of others asking for I.T help by country

How often do you ask other people for help solving digital/IT problems?	Country					Total
	United Kingdom	Germany	Netherlands	Italy*	Lithuania ^a	
Very often	72	39	25	59	67	262
	6.84	3.55	2.31	4.19	6.65	4.64
Often	144	111	107	206	112	680
	13.68	10.09	9.90	14.62	11.11	12.03
Occasionally	346	309	368	504	359	1886
	32.86	28.09	34.04	35.77	35.62	33.37
Seldomly	297	378	388	433	327	1823
	28.21	34.36	35.89	30.73	32.44	32.26
Never	194	263	193	207	143	1000
	18.42	23.91	17.85	14.69	14.19	17.70
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

When both responses are combined (with scoring order recoded and reversed for asking for help from others) and taken as a proxy of digital competency, the distribution of the resultant 5-point scale (1 = high competency, 5 = low competency) is largely normal, with a slight leftward skew (Figure 19).

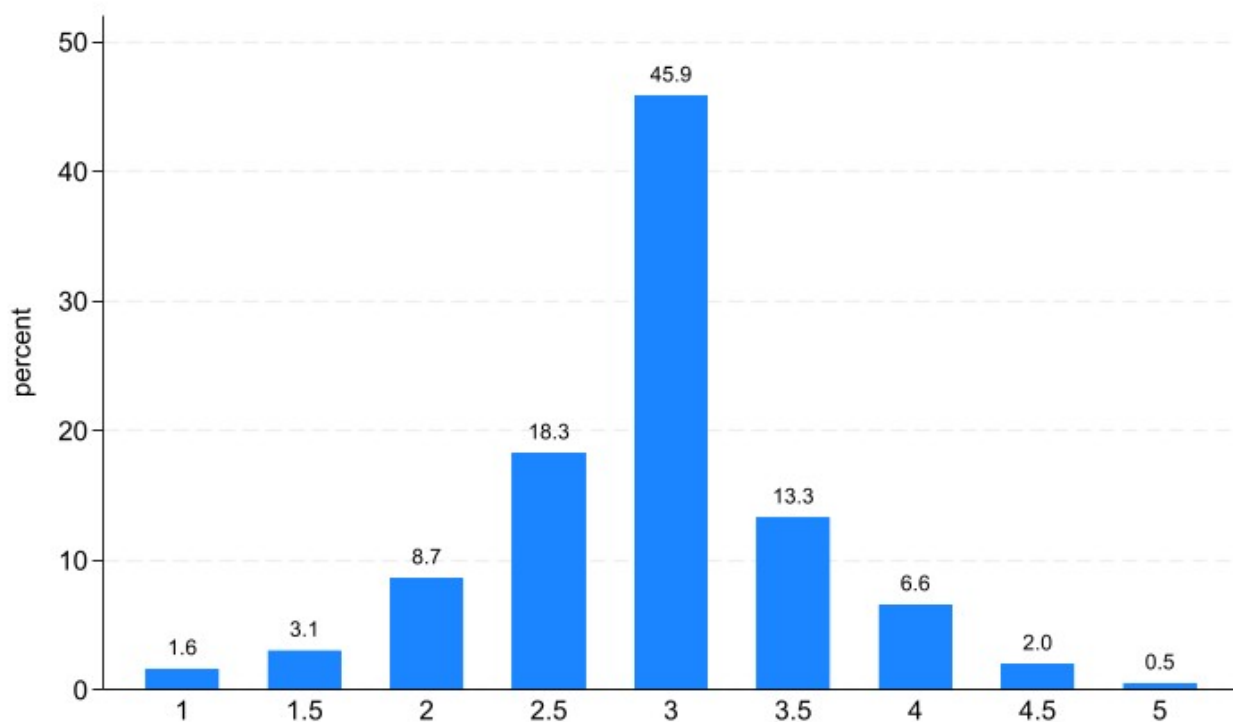


Figure 19: Distribution of combined measure of digital competency



Perceived impacts on consumption

Respondents were asked to use a 7-point scale to indicate how digitalisation has impacted their consumption in the areas of travel, energy use, media consumption and the amount of household goods. Across all categories, on average respondents reported marginal increases in levels of consumption.

However, data concerning the impact of digitalisation on the amount of travel was normally distributed, with 28% of respondents feeling that it had increased the amount of travel (1-3) and 28% reporting a decreasing effect (5-7; Table 33). There were slight differences across countries, with 34% and 38% of respondents in Italy and Lithuania respectively reporting that their amount of travel had increased compared to just 19% of respondents from Germany (Figure 20). Conversely, 30% of respondents from Germany reported that digitalisation had decreased the amount of travel they do, compared to just 24% in the Netherlands.

Table 33: Perceived impact of digitalisation on amount of travel by country

How do you feel digitalisation has affected the amount you travel?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Largely increased (1)	70	26	28	108	106	338
	6.65	2.36	2.59	7.67	10.52	5.98
2	80	72	56	173	115	496
	7.60	6.55	5.18	12.28	11.41	8.78
3	114	113	140	199	158	724
	10.83	10.27	12.95	14.12	15.67	12.81
4	519	564	594	501	360	2538
	49.29	51.27	54.95	35.56	35.71	44.91
5	134	139	137	218	143	771
	12.73	12.64	12.67	15.47	14.19	13.64
6	63	86	67	118	64	398
	5.98	7.82	6.20	8.37	6.35	7.04
Largely decreased (7)	73	100	59	92	62	386
	6.93	9.09	5.46	6.53	6.15	6.83
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

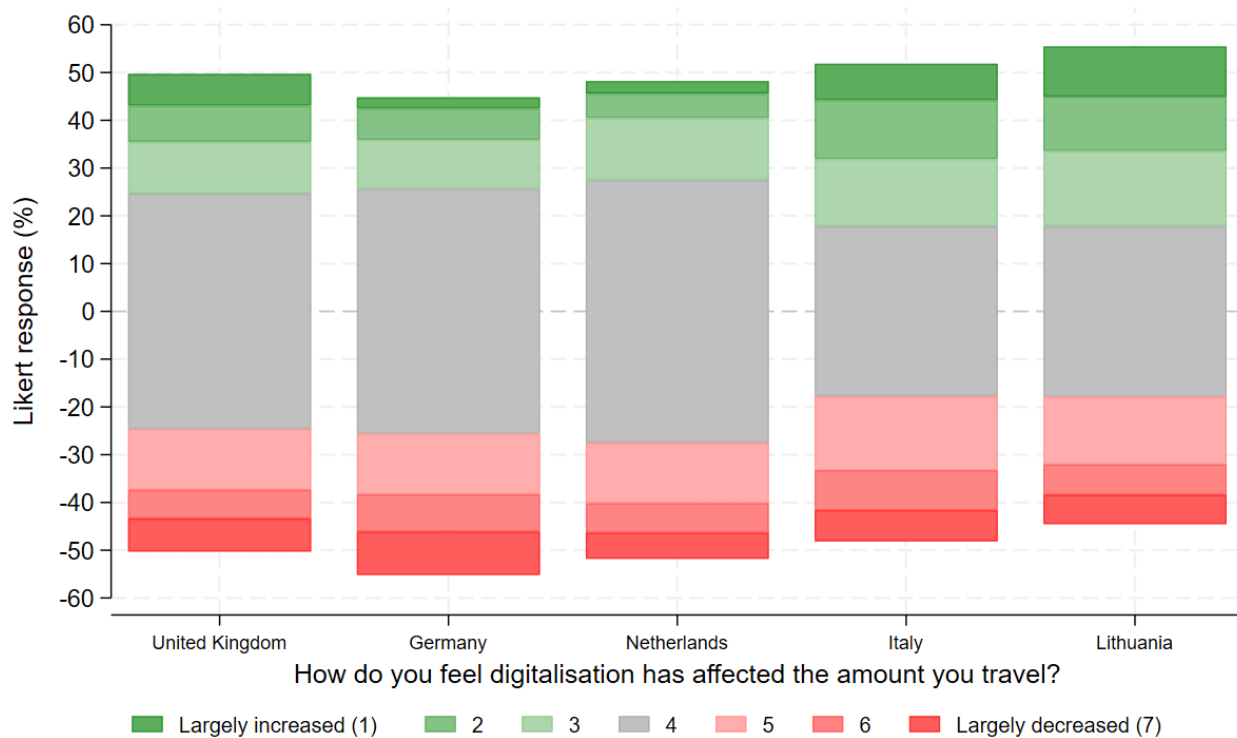


Figure 20: Perceived impact of digitalisation on the amount of travel

Respondents were then asked to assess the impact of digitalisation on their energy consumption. Overall, 39% of respondents felt that digitalisation had increased their energy consumption (1-3) while 21% felt that it had decreased their energy use (5-7) (Table 34).

Table 34: Perceived impact of digitalisation on energy consumption by country

How do you feel digitalisation has affected the amount your energy use at home?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Largely increased (1)	91	43	44	136	126	440
2	8.64	3.91	4.07	9.65	12.50	7.79
3	121	104	94	198	113	630
4	11.49	9.45	8.70	14.05	11.21	11.15
5	209	247	189	283	201	1129
6	19.85	22.45	17.48	20.09	19.94	19.98
7	425	507	512	469	337	2250
Largely decreased (7)	40.36	46.09	47.36	33.29	33.43	39.82
	133	108	136	175	123	675
	12.63	9.82	12.58	12.42	12.20	11.94
	42	53	60	104	73	332
	3.99	4.82	5.55	7.38	7.24	5.88
	32	38	46	44	35	195



	3.04	3.45	4.26	3.12	3.47	3.45
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

In terms of differences reported across countries, just 30% of respondents from the Netherlands felt that digitalisation had increased their energy consumption, compared to 44% of respondents from Italy (Figure 21). There was less variation between countries in terms of respondents who reported that digitalisation had largely decreased their energy consumption, with 23% of Lithuanian respondents reporting a decrease compared to just 18% of respondents from Germany.

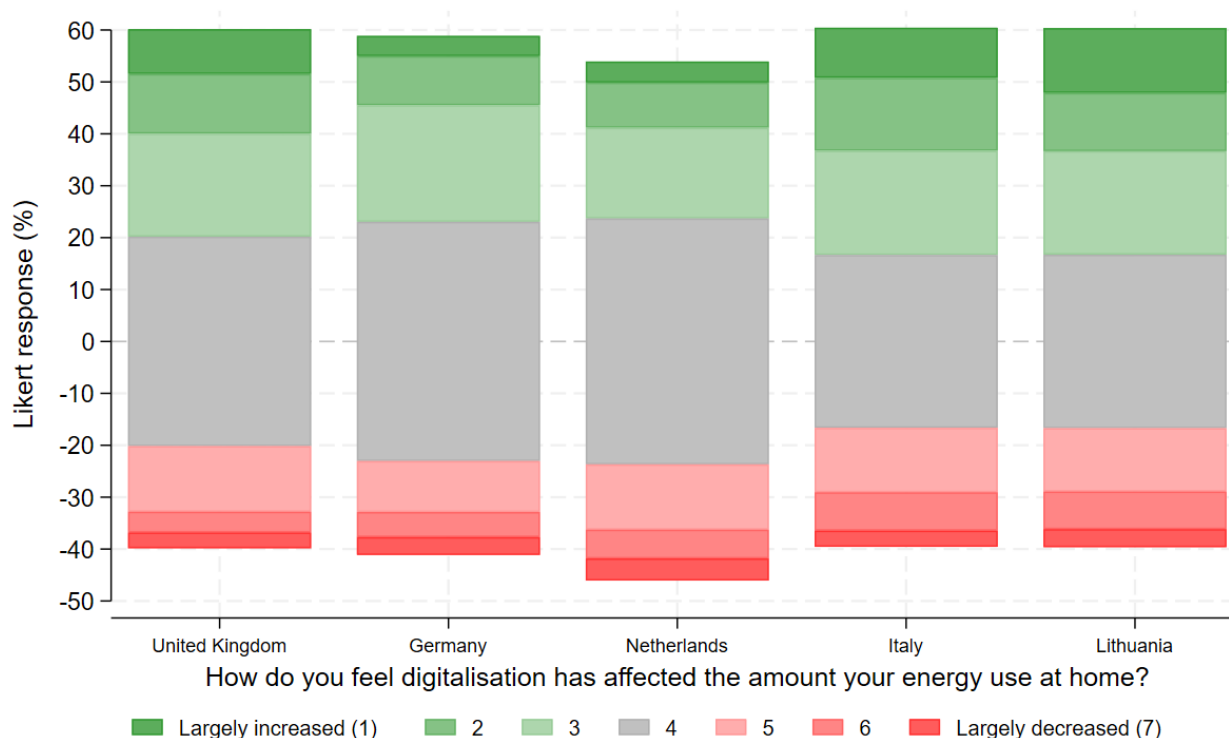


Figure 21: Perceived impact of digitalisation on energy consumption

With regards to media consumption, the majority of respondents (50%) reported an increase, defined as 'what you read, watch or listen to'. In contrast, only 18% felt that digitalisation had decreased their media use.

Table 35: Perceived impact of digitalisation on media consumption by country

How do you feel digitalisation has affected your media consumption?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Largely increased (1)	185	112	100	176	183	756
2	17.57	10.18	9.25	12.49	18.15	13.38
3	194	210	183	240	124	951
4	18.42	19.09	16.93	17.03	12.30	16.83
5	199	253	249	244	174	1119
6	18.90	23.00	23.03	17.32	17.26	19.80
7	323	392	386	417	291	1809
Largely decreased (7)	30.67	35.64	35.71	29.60	28.87	32.01
	88	72	97	190	114	561
	8.36	6.55	8.97	13.48	11.31	9.93
	37	29	36	97	63	262
	3.51	2.64	3.33	6.88	6.25	4.64
Total	27	32	30	45	59	193
	2.56	2.91	2.78	3.19	5.85	3.42
	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

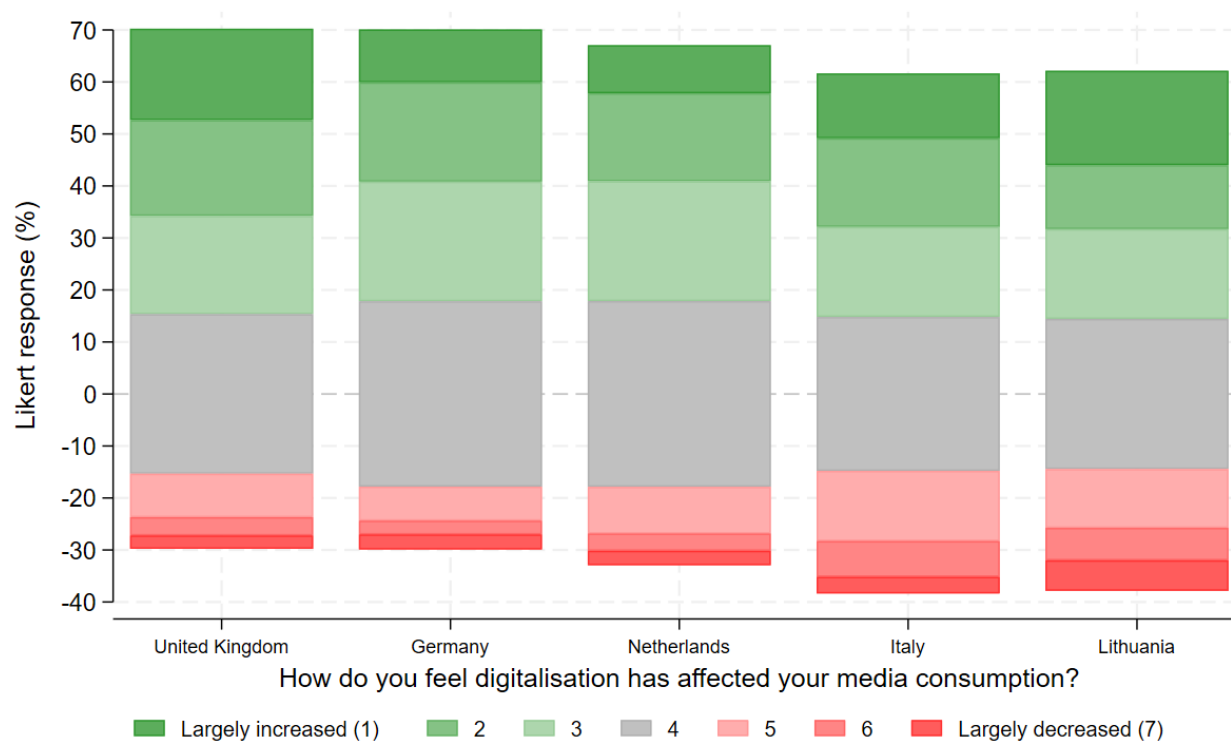


Figure 22: Perceived impact of digitalisation on media consumption

The distribution profile was largely similar across countries. However, there were noticeably more respondents in Italy (24%) and Lithuania (23%) who stated that they felt digitalisation had decreased their



media consumption (5-7), compared to the number of respondents in Germany (12%), the United Kingdom (14%) and the Netherlands (15%) who felt that way (Figure 22).

Finally, in terms of the perceived impact on the consumption of household goods, 35% of respondents felt that digitalisation had increased their consumption of household goods (1-3) while 21% felt that their consumption had decreased (5-7) (Table 36).

Table 36: Perceived impact of digitalisation on consumption of household goods by country

How has digitalisation affected the amount of household goods/services you buy?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Largely increased (1)	93	38	32	115	137	415
	8.83	3.45	2.96	8.16	13.59	7.34
2	106	82	74	170	121	553
	10.07	7.45	6.85	12.07	12.00	9.79
3	172	184	169	279	178	982
	16.33	16.73	15.63	19.80	17.66	17.38
4	493	576	583	511	344	2507
	46.82	52.36	53.93	36.27	34.13	44.36
5	113	114	122	190	123	662
	10.73	10.36	11.29	13.48	12.20	11.71
6	41	63	58	97	62	321
	3.89	5.73	5.37	6.88	6.15	5.68
Largely decreased (7)	35	43	43	47	43	211
	3.32	3.91	3.98	3.34	4.27	3.73
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

While the distribution was similar across countries for those who felt that digitalisation had decreased their consumption, differences between respondents who felt consumption had increased were more pronounced. A considerably larger share of respondents in Italy (40%) and Lithuania (43%) reported increases in the consumption of household goods compared to Germany (28%) and the Netherlands (25%) (Figure 23).

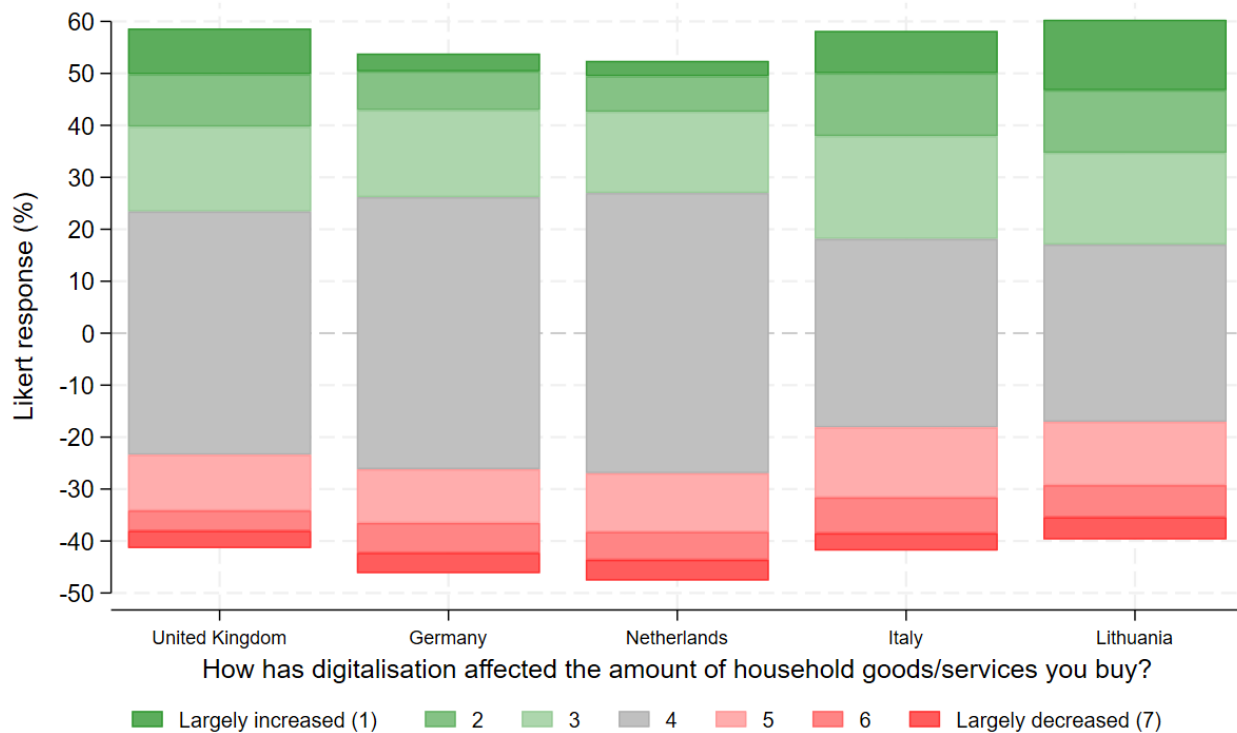


Figure 23: Perceived impact of digitalisation on the amount of household goods/services purchased

Contribution to second-hand trading

Engagement in second-hand trading can extend the useful lifespan of products and has the potential to contribute to a more circular economy by slowing the rate of extraction of raw materials and reducing associated resource consumption. Respondents in the survey were initially asked about their engagement in second-hand trading before being asked about the role of digitalisation in facilitating the re-circulation of goods by buying, selling, or the non-market acquisition and disposal of second-hand items by collecting free items or the registering online of items they wish to simply give away. Initially, participants were asked if they preferred to buy second-hand rather than new. Here, 27% of respondents (somewhat) agreed compared to 46% who rather disagreed. Figure 24 shows that the distribution was right-skewed with a greater number of respondents strongly disagreeing with the statement than those who strongly agreed.

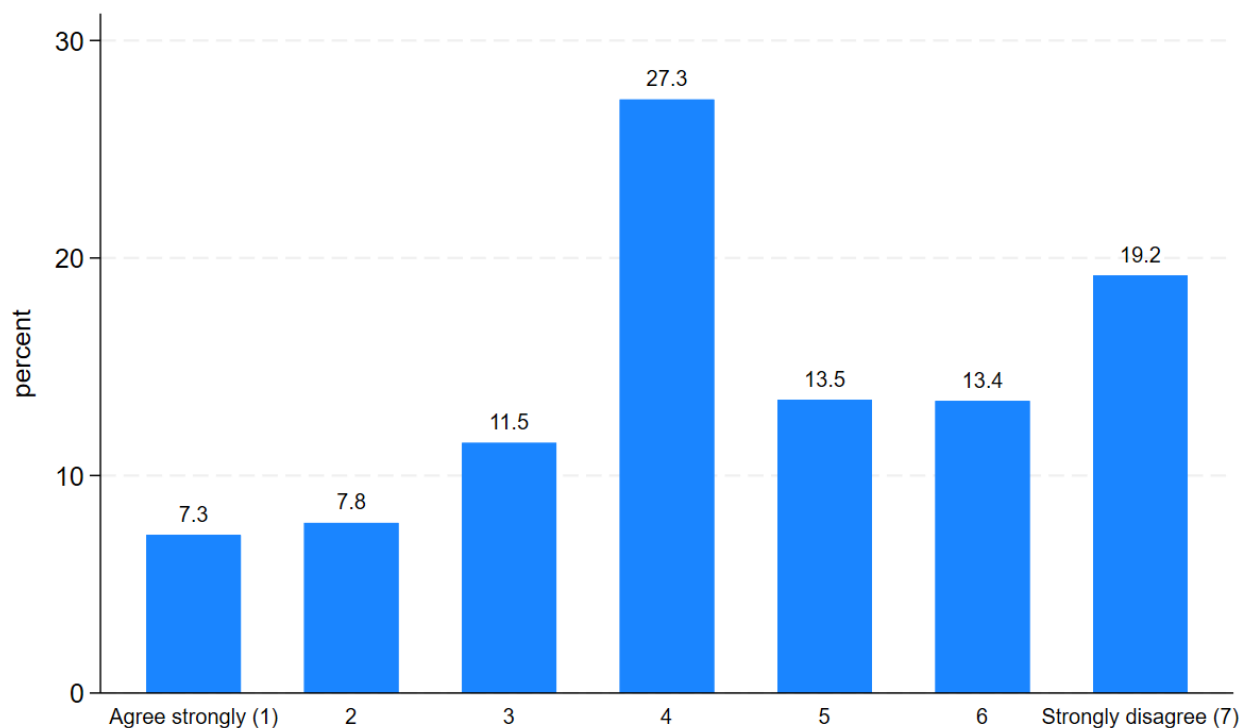


Figure 24: 7-point distribution of preference for second-hand goods for all respondents.

The distribution of preference for buying second-hand was largely similar across countries (Figure 25), with marginally lower levels of preference (values 1-3) reported by respondents in Italy (23%) compared to Germany (26%), the Netherlands (27%), the United Kingdom (29%) and Lithuania (30%) (Table 37).

Table 37: Level of agreement with preference for buying second-hand by country.

I prefer to buy second-hand rather than new.	Country					
	United Kingdom	Germany	Netherlands	Italy	Lithuania	Total
Agree strongly (1)	94	64	72	73	108	411
	8.93	5.82	6.66	5.18	10.71	7.27
2	103	81	87	102	69	442
	9.78	7.36	8.05	7.24	6.85	7.82
3	110	137	133	148	122	650
	10.45	12.45	12.30	10.50	12.10	11.50
4	292	282	303	369	296	1542
	27.73	25.64	28.03	26.19	29.37	27.29
5	121	141	137	246	117	762
	11.49	12.82	12.67	17.46	11.61	13.48
6	128	141	161	211	118	759
	12.16	12.82	14.89	14.98	11.71	13.43
Strongly disagree (7)	205	254	188	260	178	1085
	19.47	23.09	17.39	18.45	17.66	19.20
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

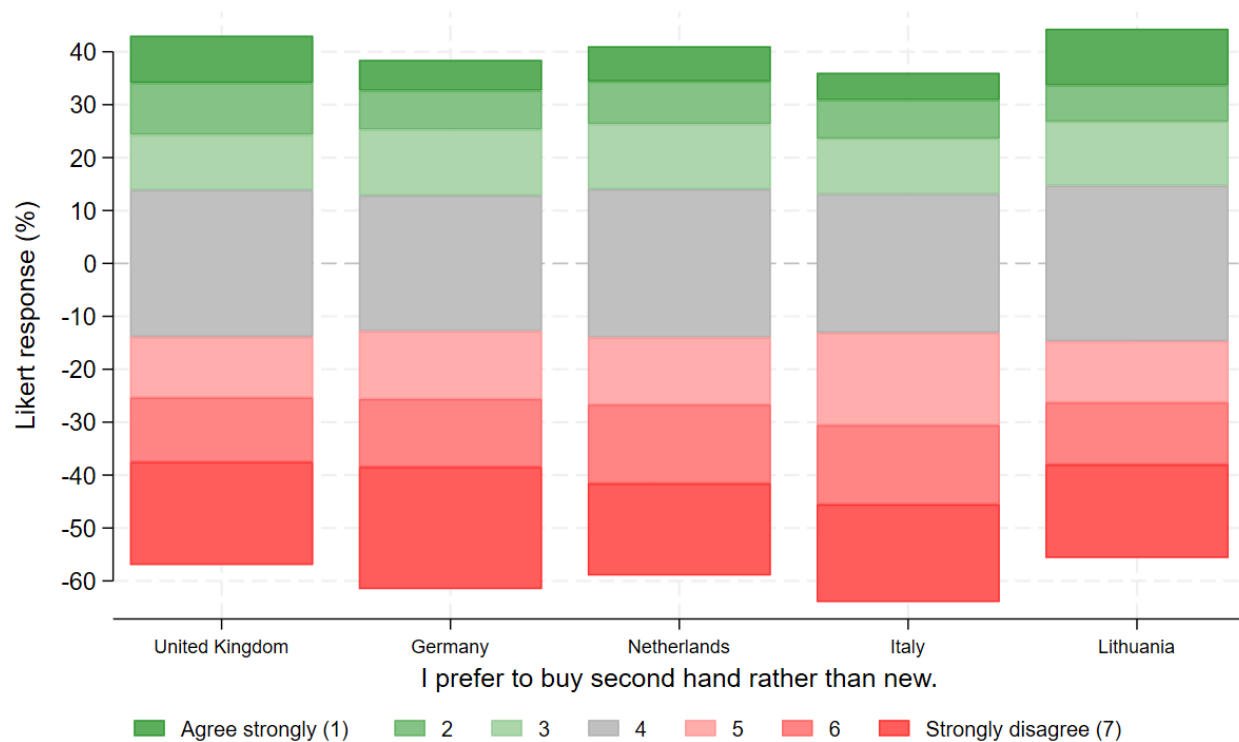


Figure 25: Respondent preference for buying second-hand by country.

In terms of stated second-hand purchase activity, 76% of respondents reported acquiring second-hand goods online at least at some point with 24% stated that they had never acquired any second-hand goods online. However, only 16% of respondents described themselves as acquiring second-hand goods online “Very often” (4%) or “Often” (12%) with the largest group of respondents stating that they acquired second-hand goods online “Occasionally” (32%) (Table 38).

Table 38: Rates of online second-hand good acquisition by country

How often do you buy/collect/acquire goods found online?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Very often	72	34	30	48	70	254
	6.84	3.09	2.78	3.41	6.94	4.49
Often	143	137	112	161	123	676
	13.58	12.45	10.36	11.43	12.20	11.96
Occasionally	314	327	401	416	358	1816
	29.82	29.73	37.10	29.52	35.52	32.14
Seldomly	272	307	301	397	282	1559
	25.83	27.91	27.84	28.18	27.98	27.59
Never	252	295	237	387	175	1346
	23.93	26.82	21.92	27.47	17.36	23.82
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*



While respondent distribution was largely similar across countries, 20% and 19% of respondents from the United Kingdom and Lithuania respectively reported that they bought second-hand goods online “very often” or “often” in contrast to 13% of respondents from the Netherlands.

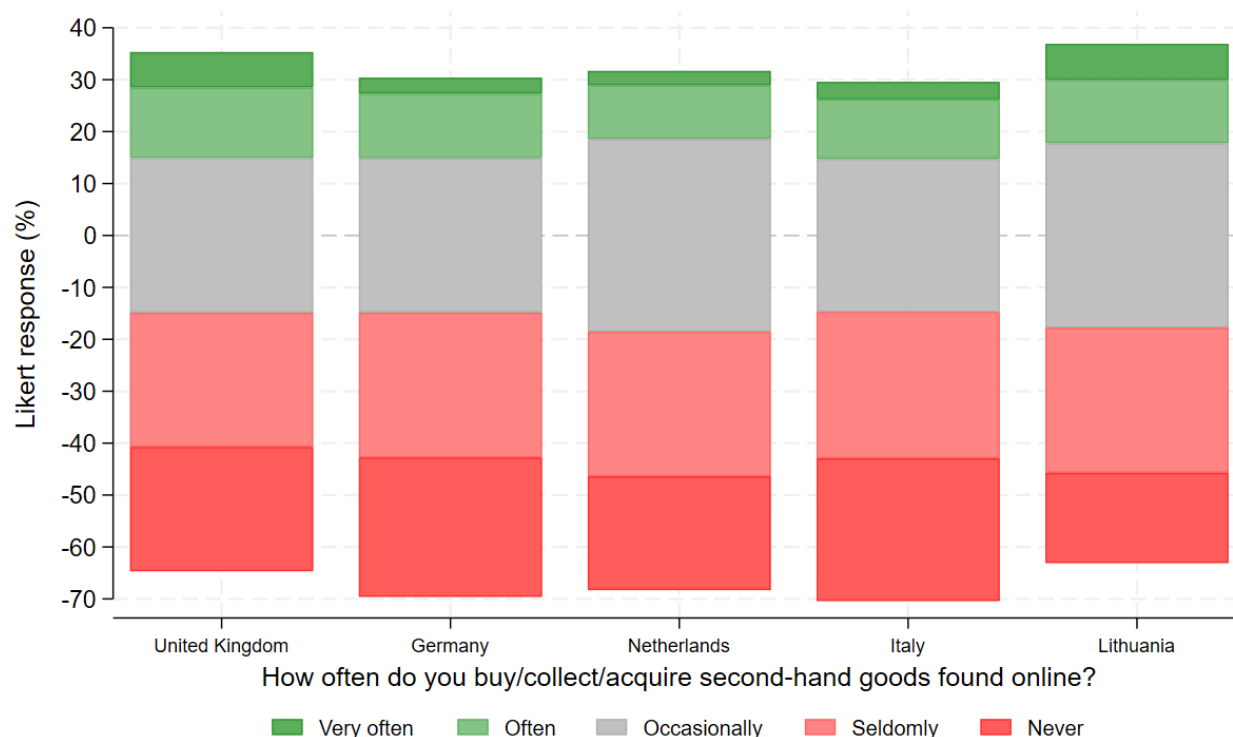


Figure 26: Respondent stated frequency of acquisition of second-hand goods online by country.

Respondents were then asked to indicate how often they sold or gave away items online. Slightly higher rate of disposal versus acquisition were reported with 81% of respondents indicating that they had disposed of second-hand items online at some point with 26% of respondents reporting their frequency as “Very often” or “Often” (Table 39).

Table 39: Rates of online second-hand good disposal by country

How often do you sell/give away unwanted items/items you no longer need online?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Very often	118	67	60	86	97	428
	11.21	6.09	5.55	6.10	9.62	7.57
Often	223	194	234	258	155	1064
	21.18	17.64	21.65	18.31	15.38	18.83
Occasionally	329	404	422	447	344	1946
	31.24	36.73	39.04	31.72	34.13	34.44
Seldomly	184	235	190	293	254	1156
	17.47	21.36	17.58	20.79	25.20	20.46
Never	199	200	175	325	158	1057



	18.90	18.18	16.19	23.07	15.67	18.70
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

Again, respondent distribution was largely similar across countries, however 32% of respondents from the United Kingdom reported that they sold second-hand goods online “Very often” (11%) or “Often” (21%) compare to 24% of respondents from Germany (Figure 27).

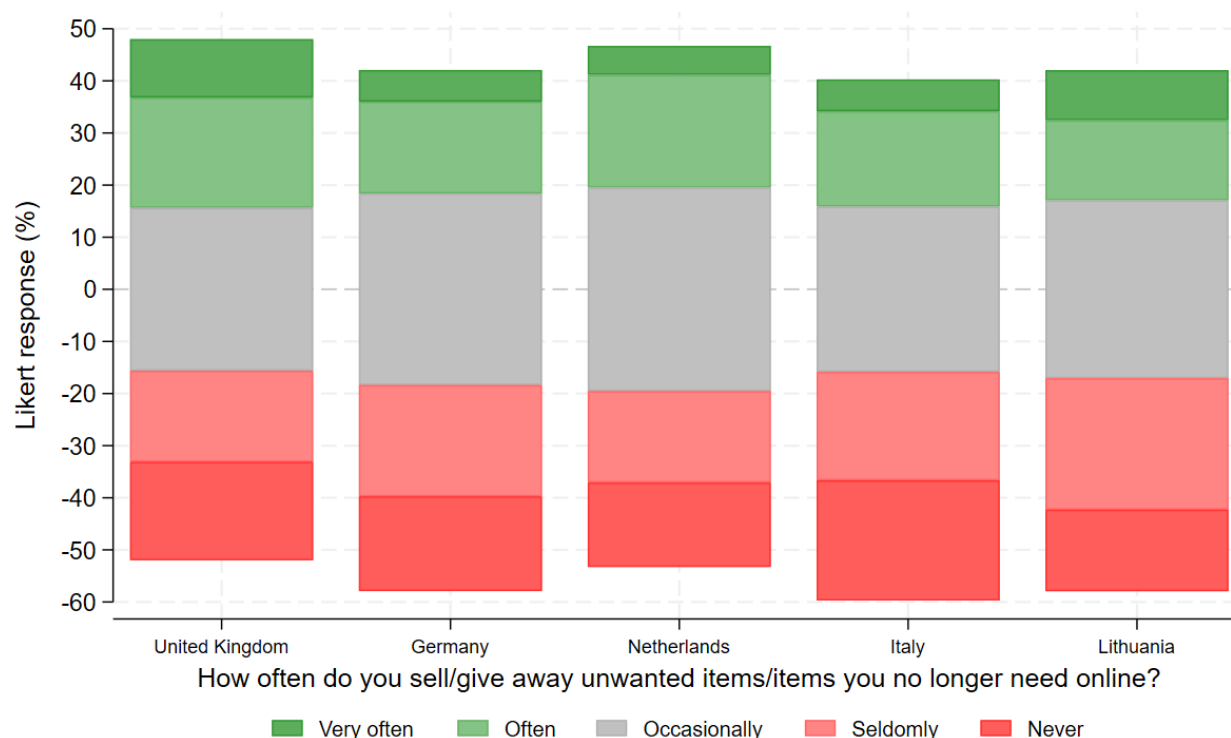


Figure 27: Respondent stated frequency of disposal of second-hand goods online by country.

While 18% of respondents had reported that they never disposed of second-hand goods online, the remaining respondents were asked if offering goods online allowed them to “sell/give away things more easily than other methods e.g. flea markets, car boot sales etc.”. Overall, 74% of the remaining respondents reported that offering goods online made it easier to sell/give away goods compared to 26% who answered “No” with a similar split reported across all countries (Table 40).

Table 40: Perceived impact of online offering on ease of good disposal by country

Does offering goods online allow you sell/give more easily than other methods?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Yes	598	666	701	757	672	3394
	70.02	74.00	77.37	69.83	79.06	73.88



No	256	234	205	327	178	1200
	29.98	26.00	22.63	30.17	20.94	26.12
Total	854	900	906	840	850	4350
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

Notably, respondents from the United Kingdom reported the lowest level of agreement (70%) with the statement of being more easily able to dispose of goods online, having previously indicated higher levels of activity in both the acquiring and disposing of goods. Respondents from Lithuania reported the highest level of agreement at (79%) (Figure 28).

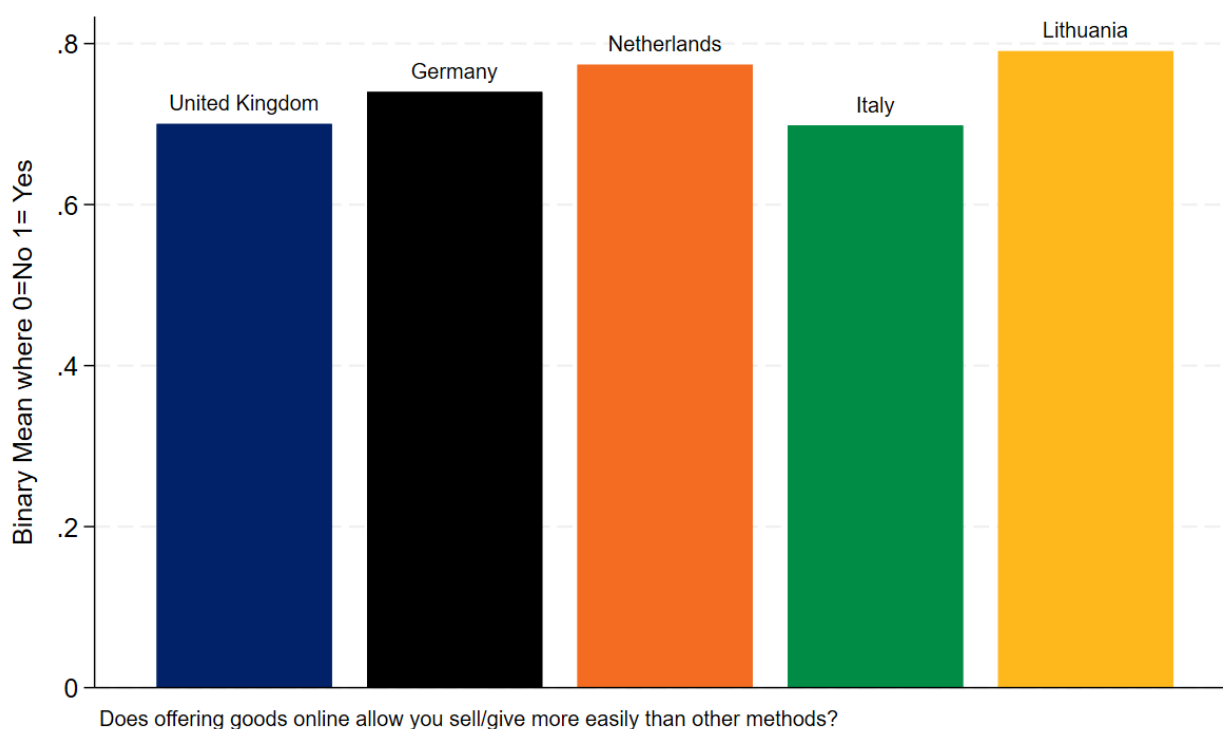


Figure 28: Share of respondent agreement with being able to dispose of goods more easily online.

Finally, respondents were asked how often they bought items that they ultimately don't use or need. Just 11% of respondents reported that this happened "Very often" or "Often" with 30% reporting that it occurred occasionally and 42% reporting that this seldomly occurred (Table 41).

Table 41: Frequency of buying unwanted items by country

How often do you buy things you ultimately don't need/use?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Very often	48	20	17	18	46	149



	4.56	1.82	1.57	1.28	4.56	2.64
Often	109	73	67	150	82	481
	10.35	6.64	6.20	10.65	8.13	8.51
Occasionally	287	287	404	426	304	1708
	27.26	26.09	37.37	30.23	30.16	30.22
Seldomly	419	554	448	526	400	2347
	39.79	50.36	41.44	37.33	39.68	41.53
Never	190	166	145	289	176	966
	18.04	15.09	13.41	20.51	17.46	17.09
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

Note: First row lists *frequencies* and second row lists *column percentages*

The remaining respondents who stated that this occurred seldomly or more often were then asked as to whether this happened less often if they bought items online, with 28% and 31% answering “Yes” and “No” respectively and 41% reporting no difference (Table 42).

Table 42: Respondents agreeing with the statement that buying items they ultimately don’t need happens less often when they buy something online.

Does this happen less often when you buy something online?	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Yes	222	219	202	335	342	1320
	25.72	23.45	21.58	29.91	41.11	28.18
No	256	364	337	281	220	1458
	29.66	38.97	36.00	25.09	26.44	31.12
The same	385	351	397	504	270	1907
	44.61	37.58	42.41	45.00	32.45	40.70
Total	863	934	936	1120	832	4685
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

Section 8: Circular Citizenship

Even when individuals are motivated to adopt CCPs, they may encounter contextual barriers that limit their ability to do so. Rather than passively waiting for systemic changes, individuals may actively try to contribute to such changes by encouraging other actors to take steps that enhance the feasibility and appeal of circular consumption. This form of engagement is referred to as *circular citizenship*. This final section presents a summary of descriptive findings from survey responses related to circular citizenship. The aim is to assess the extent to which individuals engage in actions that seek to influence systemic factors, rather than solely modifying their own consumption behaviour.

Respondents were asked about their opinions about engaging in actions to influence distinct groups (i.e., governments, businesses, and people around them) to protect the environment by reducing the use of resources. Respondents were informed that efforts to protect the environment would include using fewer



new resources and materials, using existing products for longer, reusing materials and recycling, i.e., actions which on the balance of likelihood lend themselves towards greater levels of circularity.

With regard to actions to pressure government to protect the environment, reported action frequencies were low with 30% stating that they never engaged in such action and over 55% of respondents reporting rating the frequency of their action at a value of 5-7 on a 7-point Likert scale of “Frequently (1)” to “Never (7)” (Table 43).

Table 43: Respondent frequency of actions to pressure the government by country

Actions to pressure the gov.- e.g. protesting or signing petitions etc..	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Frequently (1)	80 7.60	36 3.27	17 1.57	57 4.05	68 6.75	258 4.57
2	82 7.79	78 7.09	37 3.42	94 6.67	65 6.45	356 6.30
3	129 12.25	146 13.27	73 6.75	166 11.78	136 13.49	650 11.50
4	204 19.37	216 19.64	227 21.00	311 22.07	287 28.47	1245 22.03
5	131 12.44	91 8.27	100 9.25	215 15.26	151 14.98	688 12.17
6	127 12.06	134 12.18	160 14.80	235 16.68	114 11.31	770 13.63
Never (7)	300 28.49	399 36.27	467 43.20	331 23.49	187 18.55	1684 29.80
Total	1053 100.00	1100 100.00	1081 100.00	1409 100.00	1008 100.00	5651 100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

Respondents from the United Kingdom and Lithuania reported engaging in actions to pressure the government more frequently with 28% and 27% reporting frequency values of 1-3 while 24% and 23% of respondents reported similarly in Germany and Italy. This was in notable contrast to the 12% of respondents in the Netherlands who reported frequency values between 1-3 while 43% of respondents reported that they had never engaged in such actions.

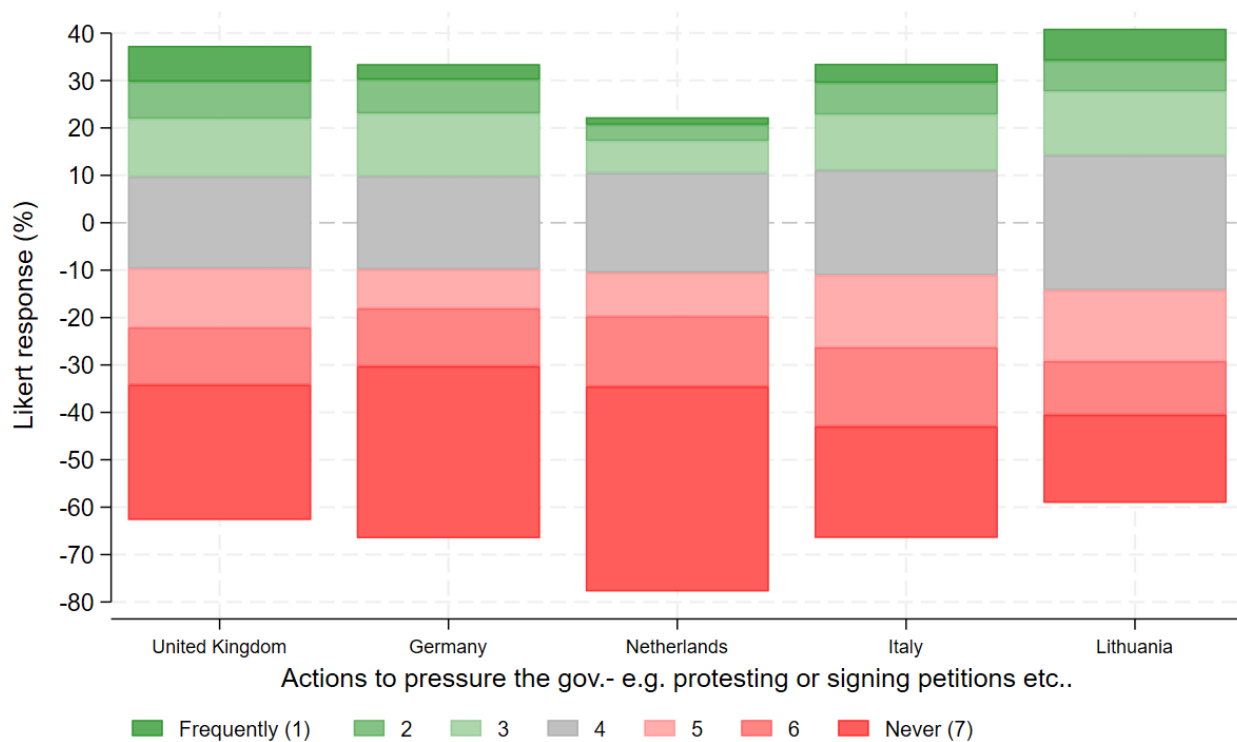


Figure 29: Distribution of frequency of respondent actions to pressure the government by country

A similar pattern was observed when respondents recalled the frequency of their actions to influence businesses to protect the environment. Across all countries, 31% of respondents reported that they never engaged in such actions with 56% reporting a frequency value of between 5 and 7 (Table 44).

Table 44: Respondent frequency of actions to influence businesses by country

Actions to influence businesses- e.g. investing in sustainable businesses	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Frequently (1)	74	22	18	52	71	237
	7.03	2.00	1.67	3.69	7.04	4.19
2	71	72	32	73	81	329
	6.74	6.55	2.96	5.18	8.04	5.82
3	117	138	75	178	142	650
	11.11	12.55	6.94	12.63	14.09	11.50
4	213	215	237	332	302	1299
	20.23	19.55	21.92	23.56	29.96	22.99
5	116	100	118	212	133	679
	11.02	9.09	10.92	15.05	13.19	12.02
6	128	131	154	210	106	729
	12.16	11.91	14.25	14.90	10.52	12.90
Never (7)	334	422	447	352	173	1728
	31.72	38.36	41.35	24.98	17.16	30.58
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*



A total of 29% of respondents from Lithuania reported frequency values of 1-3 in terms of actions to pressure businesses to protect the environment while slightly lower numbers of respondents in the United Kingdom (25%), Italy (22%) and Germany (21%) reported similarly. Again, this was in notable contrast to the 12% of respondents in the Netherlands who reported frequency values of 1-3 while 41% of respondents from the Netherlands reported that they had never engaged in such actions (Figure 30).

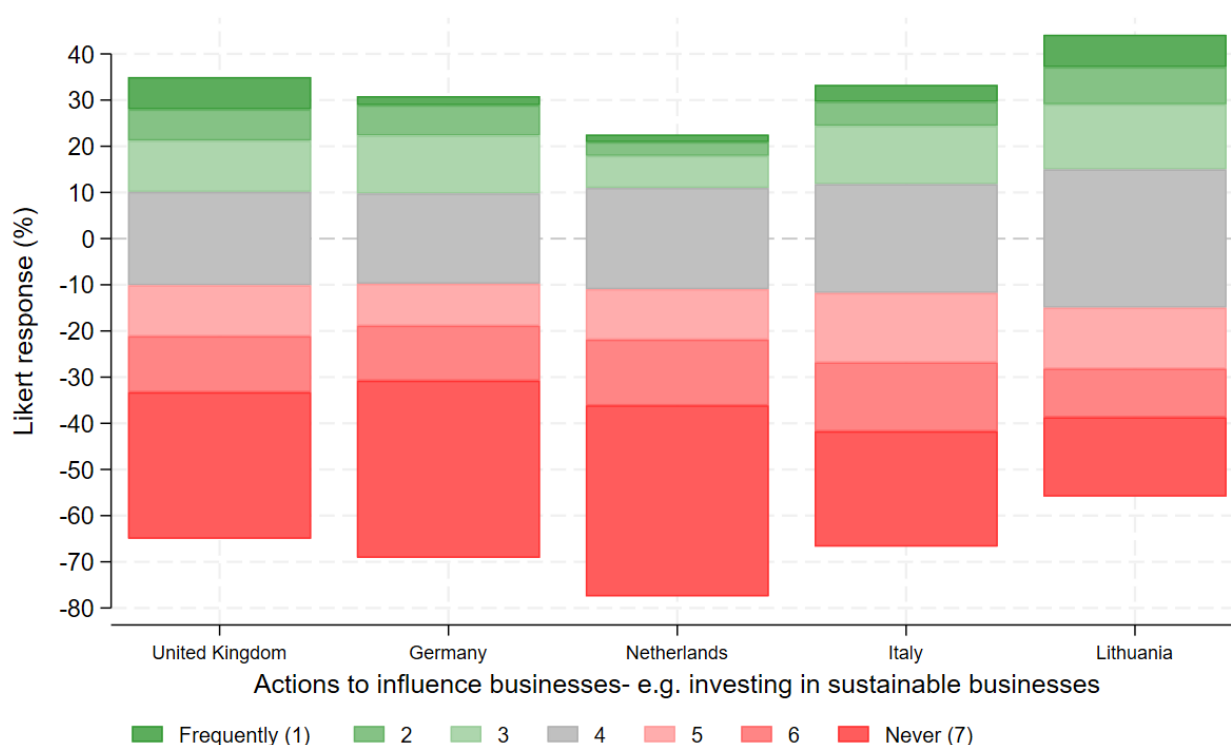


Figure 30: Distribution of respondent frequency of actions to pressure businesses by country

Finally, respondents were asked about the frequency of their actions to influence the people around them (e.g. family and friends) to protect the environment. Notably, a greater number of respondents reported engaging in such actions at least once, with only 22% of respondents stating that they had never engaged in such action.

Table 45: Respondent frequency of actions to influence people around them by country

Actions to influence people around you- e.g. inform friends and family	Country					
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	Total
Frequently (1)	85	26	14	74	91	290
2	8.07	2.36	1.30	5.25	9.03	5.13
3	102	83	44	147	88	464
4	9.69	7.55	4.07	10.43	8.73	8.21
5	158	166	101	258	153	836
6	15.00	15.09	9.34	18.31	15.18	14.79
7	236	234	258	364	315	1407
Never (7)	22.41	21.27	23.87	25.83	31.25	24.90
	130	126	118	212	158	744



	12.35	11.45	10.92	15.05	15.67	13.17
6	120	126	178	153	104	681
	11.40	11.45	16.47	10.86	10.32	12.05
Never (7)	222	339	368	201	99	1229
	21.08	30.82	34.04	14.27	9.82	21.75
Total	1053	1100	1081	1409	1008	5651
	100.00	100.00	100.00	100.00	100.00	100.00

*see survey note on Italian survey data

Note: First row lists *frequencies* and second row lists *column percentages*

A total of 34% of respondents from Italy reported frequency values of 1-3 in terms of actions to encourage people around them to protect the environment, followed by 33% of respondents from both the United Kingdom and Lithuania and 25% of respondents from Germany. Again, participants from the Netherlands differed substantially, with just 15% of respondents choosing values of 1-3 and 34% reporting that they had never engaged in such actions (Figure 31).

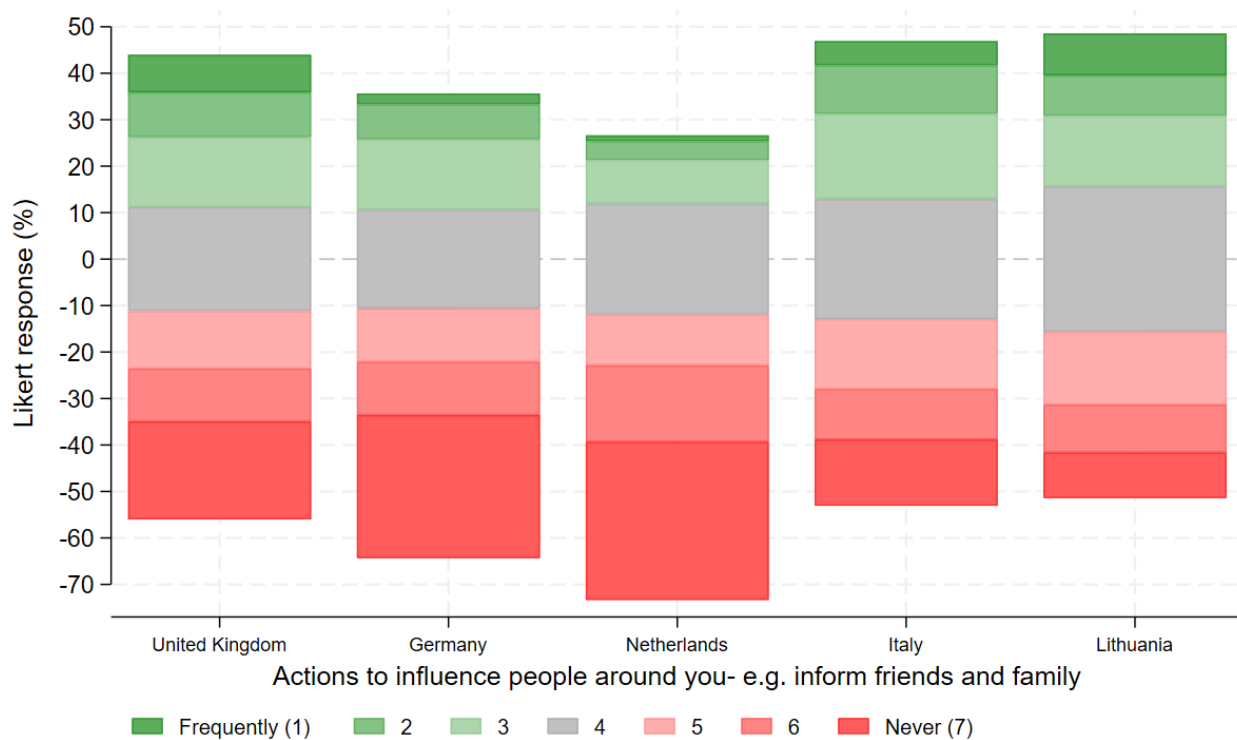


Figure 31: Distribution of respondent frequency of actions to encourage others around you by country

Across the three target groups for circular citizenship behaviours (governments, businesses, and people around them), respondents from the Netherlands consistently reported the lowest average levels of engagement while conversely, participants from Lithuania reported the highest average frequency of engagement (Table 46).



Table 46: Mean frequency of engagement buy country.

Mean frequency of engagement on scale of “Frequently (1)” to “Never (7)” of...	Country					Total
	United Kingdom	Germany	Netherlands	Italy*	Lithuania	
Actions to pressure the gov.- e.g. protesting or signing petitions etc..	4.71	5.04	5.50	4.82	4.47	4.91
Actions to influence businesses- e.g. investing in sustainable businesses	4.85	5.16	5.46	4.86	4.34	4.94
Actions to influence people around you- e.g. inform friends and family	4.40	4.89	5.25	4.25	4.06	4.56
Total mean	4.65	5.03	5.40	4.54	4.29	4.79
Total N	1053	1100	1081	1409	1008	5651

*see survey note on Italian survey data

Concluding Summary

The *Circular Consumption Survey* collected detailed information on respondents’ engagement in several potentially high-impact CCPs across the United Kingdom, Germany, the Netherlands, Italy, and Lithuania. While it is encouraging to see a considerable number of respondents engaging in such practices, there is also clear evidence to suggest that the majority of respondents either do not engage or engage infrequently and/or at a very low level. Low levels of engagement could, and perhaps should, be viewed as an opportunity as there is clear room for expansion in terms of both frequency and wider dispersion of CCPs such as carlessness, commoning, borrowing, lending, repairing and extending the useful life of products by engaging in second-hand markets. However, practices shape and reflect localized structural and material conditions, existing skill sets, norms, expectations, and values of those who engage, which poses a number of challenges concerning effective measures to boost their uptake.

Further analysis will focus on identifying specific cohorts of both engagers and non-engagers using socio-economic and demographic data to better understand the factors that shape participation in CCPs. This will include examining the influence of personal values, social norms, and other potential explanatory variables that may drive or inhibit engagement. Outputs from the survey will be combined with consumption biographies from the United Kingdom, Germany, the Netherlands, and Italy to provide more detailed insights into the relative importance of various aspects of individual and collective (non-)engagement, including clearly identifiable enablers and barriers. These findings will contribute to the identification of high-potential groups and the development of targeted strategies to enhance participation in CCPs.



Appendix A: Representativeness quotas

The following tables represent the representativeness quota targets for *Circular Consumption Survey*. It should be noted that in terms of region, while regional information was gathered in the Netherlands, Italy, & Lithuania at NUTS2 level, the representativeness quotas for all countries were set at NUTS1 level.

UNITED KINGDOM

Education/Training		
ISCED-Level	%	
Level 0-2	19	Primary education
		Lower secondary education
Level 3-4	40	Upper secondary education
		Post-secondary non-tertiary education
Level 5-8	41	Short-cycle tertiary education
		Bachelor's or equivalent level
		Master's or equivalent level
		Doctoral or equivalent level

Age Group	%
16 - 29	23
30 - 39	16
40 - 49	16
50 - 59	16
60 - 69	13
70+	16

Region	
ITL1	%
South East	14
London	13
North West	11
East England	9
West Midlands	9
South West	9
Yorkshire and the Humber	8
Scotland	8
East Midlands	7
Wales	5
North East	4
Northern Ireland	3

Gender	%
Male	49
Female	51



Sources:

Office for National Statistics (ons.gov.uk)

Northern Ireland Statistics and Research Agency (nisra.gov.uk)

Scotland's Census (scotlandscensus.gov.uk)

Eurostat (europa.eu/eurostat)

International Territorial Levels (ITLs) have been established by the United Kingdom as a mirror to the previous Eurostat NUTS system

GERMANY

Education/Training			
ISCED-Level	%		Description
Level 0-2	23		(Noch) kein allgemeiner Schulabschluss
			Haupt- / Volksschulabschluss
			Realschul- oder gleichwertiger Abschluss (Mittel-, Handelsschule, polytechnische Oberschule)
Level 3-4	48		Fachhochschulreife (Fachabitur)
			Allgemeine Hochschulreife (Abitur)
Level 5-8	29		Bachelorabschluss oder gleichwertiges Niveau
			Masterabschluss oder gleichwertiges Niveau
			Dokortitel oder gleichwertiger Abschluss

Age Group	%
16 - 29	16
30 - 39	16
40 - 49	15
50 - 59	19
60 - 69	16
70+	18

Region (NUTS1)	%
Baden-Württemberg	13
Bayern	16
Berlin	5
Brandenburg	3
Bremen	1
Hamburg	2
Hessen	8
Mecklenburg-Vorpommern	2
Niedersachsen	10
Nordrhein-Westfalen	22
Rheinland-Pfalz	5



Saarland	1
Sachsen	5
Sachsen-Anhalt	3
Schleswig-Holstein	4
Thüringen	3

Gender	%
Male	49
Female	51

Sources:

Statistisches Bundesamt (destatis.de)

Eurostat (europa.eu/eurostat)

NETHERLANDS

Education/Training		
ISCED-Level	%	
Level 0-2	24	Basisonderwijs
		VMBO, onderbouw HAVO/ VWO
Level 3-4	38	Bovenbouw HAVO/ VWO
		MBO
Level 5-8	38	HBO
		WO
		Doctoraal of gelijkwaardig niveau

Age Group	%
16 - 29	22
30 - 39	15
40 - 49	14
50 - 59	17
60 - 69	15
70+	17

Region (NUTS1)	%	
North	10	Drenthe
		Friesland
		Groningen
East	21	Flevoland
		Gelderland
		Overijssel
West	21	North Holland
		South Holland
		Utrecht



		Zeeland
South	48	Limburg
		North Brabant

Gender	%
Male	49.7
Female	50.3

Sources:

Centraal Bureau voor de Statistiek (cbs.nl)

Eurostat (europa.eu/eurostat)

ITALY

Education/Training		
ISCED-Level	%	
Level 0-2	36.7	Scuola primaria
		Scuola secondaria di primo grado
Level 3-4	44.1	Scuola secondaria di secondo grado
		Istruzione post secondaria non terziaria
Level 5-8	19.2	Laurea triennale o titolo equivalente
		Laurea magistrale o titolo equivalente
		Dottorato di ricerca o titolo equivalente

Age Group	%
16 - 29	17
30 - 39	13
40 - 49	16
50 - 59	19
60 - 69	15
70+	20

Region (NUTS1)	%	
North-West	28	Valle d'Aosta
		Liguria
		Piemonte
		Lombardia
North-East	20	Trentino-Alto Adige
		Veneto
		Friuli Venezia-Giulia
Centre	21	Emilia-Romagna
		Toscana
		Umbria
		Marche



		Lazio
South	20	Abruzzo
		Molise
		Campania
		Puglia
		Basilicata
		Calabria
Islands	11	Sicilia
		Sardengna

Gender	%
Male	49
Female	51

Sources:

Istituto Nazionale di Statistica (istat.it)

Eurostat (europa.eu/eurostat)

LITHUANIA

Education/Training		
ISCED-Level	%	
Level 0-2	12	Pradinis ir žemesnis
		Pagrindinis (nebaigtas vidurinis)
Level 3-4	48	Vidurinis
		Profesinis (profesinė mokykla, vidurinis su profesine kvalifikacija)
Level 5-8	41	Aukštesnysis (technikumas, aukštesnioji mokykla) arba neuniversitetinis aukštasis (kolegija)
		Universitetinis aukštasis – bakalauro laipsnis
		Universitetinis aukštasis – magistro laipsnis ar jam prilygstanti profesinė kvalifikacija
		Doktorantūros arba lygiavertis lygis

Age Group	%
16 - 29	19
30 - 39	16
40 - 49	15
50 - 59	17
60 - 69	16
70+	17



Region (NUTS1)	%	
Capital region	29	Vilnius
Central and Western Lithuania	71	Alytus
		Kaunas
		Klaipėda
		Marijampolė
		Panevėžys
		Šiauliai
		Tauragė
		Telšiai
		Utena

Gender	%
Male	46
Female	54

Sources:

Oficialiosios statistikos portalas
(osp.stat.gov.lt)

Eurostat (europa.eu/eurostat)

Appendix B: Variable names and summary labels

Variable	Variable Label
Number	Number
time	Survey completion time
country	Country
gender	Please state your gender.
birthyear	In which year were you born?
dwelling	Which dwelling type do you live in?
region_UK	Which region do you live in?
region_DE	In welchem Bundesland leben Sie?
region_NL	In welke regio woon je?
region_IT	In quale regione vive?
region_LT	Kuriame regione gyvenate?
educ_UK	What is your highest level of education?
educ_DE	Welchen höchsten Bildungsabschluss haben Sie?
educ_NL	Wat is je hoogste opleidingsniveau?
educ_IT	Qual è il suo livello di istruzione più alto?
educ_LT	Koks j?s? aukš?iausias išsilavinimas?
hhincome	Monthly estimated household income. (after tax and including social benefits)
partner	Do you live with a partner?
hhsz	Household Size
num_child	Number of Children



numchild_0_4	Number of Children 0-4
numchild_5_9	Number of Children 5-9
numchild_10_17	Number of Children 10-17
numchild_18_25	Number of Children 18-25
depend_child_90	No child under the age of 25
depend_adult	Number of adult dependants living in household
depend_adult_0	No adult dependents living in household
tenure	Please describe your Tenure/Residential Status.
actvstat_UK	What is your main activity status?
actvstat_DE	Wie würden Sie Ihre Hauptbeschäftigung beschreiben?
actvstat_NL	Wat is je recente activiteitsstatus?
actvstat_IT	Qual è lo stato di attività recente?
actvstat_LT	Kokia yra naujausia j?s? aktyvumo b?sena?
residence	How would you describe the area where your residence is located?
bio_val	It is important to me to take care of; and live in harmony with; nature.
alt_val	It is important to me to help others and that others are treated fairly.
ego_val	It is important to me to have wealth; possessions; influence and status.
hed_val	It is important to me to have fun and have a good time
jic_val	I like to be prepared for every eventuality in life.
UA_val_1	I feel uneasy in unfamiliar situations.
UA_val_2	I prefer clear rules and guidelines.
UA_val_3	Society should minimise risks.
UA_val_4	I am comfortable with uncertainty.
nocar	No. of cars owned by household.
nocar_0	No car owned by Household
carnum1_1	Car No 1. Electric
carnum1_2	Car No 1. Hybrid
carnum1_3	Car No 1. Conventional
carnum1_4	Car No 1. Owned
carnum1_5	Car No 1. Leased
carnum1_6	Car No 1. Company Car
carnum2_1	Car No 2. Electric
carnum2_2	Car No 2. Hybrid
carnum2_3	Car No 2. Conventional
carnum2_4	Car No 2. Owned
carnum2_5	Car No 2. Leased
carnum2_6	Car No 2. Company Car
carnum3_1	Car No 3. Electric
carnum3_2	Car No 3. Hybrid
carnum3_3	Car No 3. Conventional
carnum3_4	Car No 3. Owned
carnum3_5	Car No 3. Leased
carnum3_6	Car No 3. Company Car
carnum4_1	Car No 4. Electric
carnum4_2	Car No 4. Hybrid



carnum4_3	Car No 4. Conventional
carnum4_4	Car No 4. Owned
carnum4_5	Car No 4. Leased
carnum4_6	Car No 4. Company Car
carnum5_1	Car No 5. Electric
carnum5_2	Car No 5. Hybrid
carnum5_3	Car No 5. Conventional
carnum5_4	Car No 5. Owned
carnum5_5	Car No 5. Leased
carnum5_6	Car No 5. Company Car
ptrating	How would you rate the current public transport provision in your local area?
multimod	Regular journeys- Do you sometimes combine modes of transport? (P&R- Bike etc.?)
carfrquse	How often do you use your car?
prknorm	Where do you normally park your car when at home?
parkfee	Do you pay a fee where you normally park at home? (e.g. per hour/week/year)
regjour	Would you know how to do your regular journeys if suddenly left without car?
wyuscar_c	Rate the importance of cost for you using a car.
wyuscar_tt	Rate the importance of travel time for you using a car.
wyuscar_cv	Rate the importance of convenience for you using a car.
wyuscar_td	Rate the importance of the transport of dependents for you using a car.
wyuscar_lk	Rate the importance of a lack of alternative means (e.g P.T) for you using a car
carlntrip_cm	In general- could you commute without using a car?
carlntrip_rs	In general- could you do your regular shopping without using a car?
carlntrip_le	In general- could you do your hobbies/leisure activities without using a car?
carlntrip_hl	In general- could you travel for holidays without using a car?
carlntrip_ff	In general- could you care for friends and family without using a car?
nocarfut_c	Rate the importance of cost for not owning a car in the future.
nocarfut_tt	Rate the importance of travel time for not owning a car in the future.
nocarfut_nd	No longer needed (e.g. care duties) - Importance for not owning car in future.
nocarfut_vi	Rate the importance of viable alternatives for not owning car in the future.
nocarfut_vr	Virtual interaction removing need - Importance for not owning car in the future.
nocarfut_er	Rate the importance of environmental factors for not owning car in the future.
willnocar	Would you get rid of your car if viable alternatives were available?
carprev	Did you own a car previously?
nocar_c	Importance of cost for HH's non-ownership of a car.
nocar_tt	Importance of travel time for HH's non-ownership of a car.
nocar_cv	Importance of convenience for HH's non-ownership of a car.
nocar_nd	Importance of no-need to transport dependents for non-ownership of a car.
nocar_vi	Importance of availability of viable alternatives for HH's non-ownership of car.
nocar_sf	Importance of safety for HH's non-ownership of a car.
nocar_er	Importance of environmental concerns for HH's non-ownership of a car.
shar_avl_cl	Commercial Car Sharing (e.g. rental/share companies) - Available in local area.
shar_avl_cy	Community Car Sharing (e.g. car clubs) - Available in local area.
shar_avl_in	Informal Car Sharing (e.g. friends and family) - Available in local area.
noshare	No Car Sharing options available locally.



share_use	How often do you use car sharing?
shareif	Would you be likely to use car sharing if it was available?
wdshedcar	Would you get rid of your car if adequate car sharing was available?
onlintrv_pt	Do you normally use online services for public transport? (train- bus etc.)
onlintrv_pk	Do you normally use online services for paying for parking?
onlintrv_cs	Do you normally use online services for short-term car rental/ car sharing?
onlintrv_tx	Do you normally use online services for Taxi/Ride sharing services?
onlintrv_mc	Do you normally use online services for bicycle/scooter/e-bike rental.
cycnum_1	Number of bicycles owned by Household (All types)
cycnum_0	Household does not own a bicycle.
cycnum_s	Number of standard bicycles owned by Household
cycnum_c	Number of cargo bicycles (electric or non-electric) owned by Household
cycnum_e	Number of electric bicycles owned by Household
cycnum_o	Number of other bicycles (i.e. folding bikes etc.) owned by Household
cycling	How often do you cycle?
flynum_1	Number of return flights in the last year
flyno_90	I don't fly.
mob_pa1	Car ownership and use cause serious environ. & soc. problems.
mob_pa2	(Serious) environ. and soc. problems are due to car ownership and use.
mob_se1	I feel capable of living my life without owning a car.
mob_se2	I feel confident that I can live my life without owning a car if I want to.
mob_oe1	If I don't own a car; I can help reduce environ. and soc. problems.
mob_oe2	I can contribute to reducing environ. & and soc. problems by not owing a car.
mob_pn1	I feel a personal responsibility to live my life without owning a car.
mob_pn2	I feel morally obliged to live my life without owning a car.
mob_desc_nat	In my country most people do not own a car.
mob_desc_imp	Most people important to me do not own a car.
mob_dyn_nat	In my country more and more people do not own a car.
mob_dyn_imp	More and more people important to me do not own a car.
sqmtre	Approximately how much living space (sq. metres) does your current home have?
shrd_sc	Do you have use of/access to a place for leaving items neighbours might want.
shrd_sw	Do you have easy use of/access to a shared workspace?
shrd_slr	Do you have easy use of/access to a shared laundry room?
shrd_sg	Do you have easy use of/access to a shared garden?
shrd_pl	Do you have easy use of/access to a to a public library?
shrd_cg	Do you have local groups promoting sharing/swapping/second hand trade?
onplat	Are you familiar with any online 2nd-hand trading platforms (inc. local area)?
knwneig	How well do you know your immediate neighbours in your street/building?
ncon_cb	Would you contact your neighbours in case of: Car breakdown?
ncon_ec	Would you contact your neighbours in case of: Emergency care? (e.g. child)
ncon_hs	Would you contact neighbours: Care of house while away? (e.g. plants etc.)
ncon_sc	Would you contact your neighbours in case of: Security concerns?
ncon_it	Would you contact your neighbours in case of: I.T. problems?
cfborw_cr	How comfortable-asking your neighbour to lend you their car?
cfborw_eb	How comfortable-asking your neighbour to lend you their E-bike?



cfborw_bi	How comfortable-asking your neighbour to lend you their bicycle?
cfborw_to	How comfortable-asking your neighbour to lend you their tools?
cfborw_di	How comfortable-asking your neighbour to lend you their electronic device?
cfborw_ki	How comfortable-asking your neighbour to lend you their kitchen appliance?
cfborw_ot	How comfortable-asking your neighbour to lend you other small HH items?
currshr_ki	Currently share a kitchen with non-family member?
currshr_ba	Currently share a bathroom with non-family member?
currshr_bs	Currently share a basement with non-family member?
currshr_gn	Currently share a garden with non-family member?
currshr_ur	Currently share a utility room with non-family member?
currshr_eh	Currently share an entrance/hallway with non-family member?
currshr_no	I currently do not share any of these spaces.
doborw_cr	Have you ever borrowed your neighbour's car?
doborw_eb	Have you ever borrowed your neighbour's e-bike?
doborw_bi	Have you ever borrowed your neighbour's bicycle?
doborw_to	Have you ever borrowed your neighbour's tools?
doborw_di	Ever borrowed an electronic device from your neighbour?
doborw_ki	Ever borrowed a kitchen appliance from your neighbour?
doborw_ot	Ever borrowed other smaller household items from your neighbour?
doborw_no	I have not borrowed any of these items from my neighbour.
dolend_cr	Have you lent your neighbour your car?
dolend_eb	Have you lent your neighbour your E-bike?
dolend_bi	Have you lent your neighbour your bicycle?
dolend_to	Have you lent your neighbour your tools?
dolend_di	Have you lent your neighbour an electronic device?
dolend_ki	Have you lent your neighbour a kitchen appliance?
dolend_ot	Have you lent your neighbour other smaller household items?
dolend_no	I have not lent any of these items to my neighbour
rprself_cr	Do you perform minor car repairs?
rprself_bi	Do you perform bicycle repairs?
rprself_mp	Do you perform mobile phone repairs?
rprself_di	Do you perform repairs on other digital devices? (not mobile phones)
rprself_cl	Do you perform clothes mending?
rprself_fr	Do you perform furniture repairs?
rprself_sh	Do you perform shoe repairs?
rprself_ha	Do you perform household appliance repairs?
rprself_no	I don't do any of the repairs listed myself.
rprserv_cr	Do you purchase minor car repairs?
rprserv_bi	Do you purchase bicycle repairs?
rprserv_mp	Do you purchase mobile phone repairs?
rprserv_di	Do you purchase repairs on other digital devices?
rprserv_cl	Do you purchase clothes mending services?
rprserv_fr	Do you purchase furniture repair services?
rprserv_sh	Do you purchase shoe repair services?
rprserv_ha	Do you purchase household appliance repairs?



rprsrv_no	I don't purchase any of these repair services.
wudshr_ki	Willing to permanently share your kitchen with non-family member?
wudshr_ba	Willing to permanently share your bathroom with non-family member?
wudshr_bs	Willing to permanently share your basement with non-family member?
wudshr_gn	Willing to permanently share your garden with non-family member?
wudshr_ur	Willing to permanently share your utility room with non-family member?
wudshr_eh	Willing to permanently share entrance/hallway with non-family member?
wudmv	Extent of willingness to live in a smaller home if one was readily available
wudmvbe_1	Willing to live in a smaller home - Saving on running costs.
wudmvbe_2	Willing to live in a smaller home - Ease of moving.
wudmvbe_3	Willing to live in a smaller home - Being able to stay in my neighbourhood.
wudmvbe_4	Willing to live in a smaller home - Lower cleaning burden.
wudmvbe_5	Willing to live in a smaller home - Environmental factors.
wudmvbe_6	Willing to live in a smaller home - Altruism(e.g. those in greater need).
wudmvif_1	Less willing to live in a smaller home - Cost/expense.
wudmvif_2	Less willing to live in a smaller home - Inconvenience of moving.
wudmvif_3	Less willing to live in a smaller home - Unlikely able to stay in neighbourhood.
wudmvif_4	Less willing to live in a smaller home - Unwillingness to reduce available space
wudmvif_5	Less willing to live in a smaller home - Attachment to home/neighbourhood.
build_pa1	Living in a large home causes important environ. & soc. problems.
build_pa2	(Serious) environ. & social problems are due to people living in large homes.
build_se1	I feel capable of living in a small home or sharing living spaces.
build_se2	I feel confident I can live in a small home or share living spaces if I want to.
build_oe1	If I live in a small home/share living space; I reduce environ. & soc. problems
build_oe2	Can contrib. to reducing env. & soc. probs. living in small home/sharing space.
build_pn1	I feel a personal responsibility to live in a small home or share living spaces.
build_pn2	I feel morally obliged to live in a small home or share living spaces.
build_desc_nat	Most people live in a small home or share living spaces.
build_desc_imp	Most people important to me live in a small home or share living spaces.
build_dyn_nat	More and more people live in a small home or share living spaces.
build_dyn_imp	More and more people important to me live in a small home/share living spaces.
netaccq	How would you describe the quality of your internet access?
smtphuse	Do you use a smartphone to access the internet?
onlinepay	Do you personally pay bills or purchase goods and services online?
dghlpgiv	Do people ask for your help when solving digital/IT problems?
dghlpask	How often do you ask other people for help solving digital/IT problems?
sechand	I prefer to buy second hand rather than new.
buysec	How often do you buy/collect/acquire second-hand goods found online?
sellsec	How often do you sell/give away unwanted items/items you no longer need online?
sellbcon	Does offering goods online allow you sell/give more easily than other methods?
noneed	How often do you buy things you ultimately don't need/use?
digneed	Does this happen less often when you buy something online?
digicons_t	How do you feel digitalisation has affected the amount you travel?
digicons_rg	How do you feel digitalisation has affected the amount your energy use at home?
digicons_m	How do you feel digitalisation has affected your media consumption?



digicons_hg	How has digitalisation affected the amount of household goods/services you buy?
dgenable_bs	Banking and shopping online. In the last few years has it become:
dgenable_bi	Searching for information online. In the last few years has it become:
dgenable_ls	Searching for local services online. in the last few years has it become:
dgenable_bc	Basic communication (e-mail- video/voice) in the last few years has it become:
ccb_gov	Actions to pressure the gov.- e.g. protesting or signing petitions etc..
ccb_busi	Actions to influence businesses- e.g. investing in sustainable businesses
ccb_cit	Actions to influence people around you- e.g. inform friends and family
ccb_se	I feel capable of engaging in the actions above to influence other groups.
ccb_oe	If I engage in actions above to influence groups- I reduce env. & soc. problems.
ccb_pn	I feel a personal responsibility to engage in actions above to influence others.
ccb_desc_nat	Most people in my country engage in the actions above to influence other groups.
ccb_desc_imp	Most people close to me engage in the actions above to influence other groups.
ccb_dyn_nat	More and more people in my country engage in actions to influence other groups.
ccb_dyn_imp	More and more people close to me engage in actions to influence other groups.
ccb_pa	The current level of resource use causes serious env. & soc. problems.
ccb_ar	I feel partly responsible- env. & soc. probs. arising from current resource use.
pweight	Normalised Probability Weight



Appendix C: Circular Consumption Survey descriptives

This appendix contains a summarised table of the number of observations, mean, standard deviation, min and max values for all numerical, binary and ordinal variables. Summary descriptives for strictly categorical variables (e.g. dwelling, region, tenure, and activity status) which do not provide insight have been removed. Additionally, the means and standard deviations for variables for which non-response values were coded numerically (e.g. “non-selected” = 0 or “None of these” = 90) have also been removed for multi-punch variables (see Appendix D) as responses to these questions are coded sequentially rather than binarily.

Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
time	5651	24.591	11.251	14.95	119.083
country	5651	3.039	1.379	1	5
gender	5651	1.514	.5	1	2
birthyear	5651	1974.401	17.449	1931	2008
dwelling	5651			1	5
region UK	1053			1	12
region DE	1100			1	16
region NL	1081			1	12
region IT	1409			1	20
region LT	1008			1	10
educ UK	1053	4.287	1.837	1	8
educ DE	1100	4.785	1.522	1	8
educ NL	1081	3.859	1.45	1	7
educ IT	1409	3.651	1.647	1	7
educ LT	1008	4.221	1.566	1	8
hhincome	5651	5.518	2.805	1	11
partner	5651	.623	.485	0	1
hhsiz	5651	2.483	1.223	1	10
num child	4485	1.642	.951	1	8
numchild 0 4	1064	.558	.655	0	5
numchild 5 9	1042	.607	.654	0	3
numchild 10 17	1154	.906	.746	0	4
numchild 18 25	969	.627	.793	0	6
depend adult	573	1.295	.61	1	6
depend adult 0	4485	.872	.334	0	1
tenure	5651	2.165	1.182	1	5
actvstat UK	1053			1	97
actvstat DE	1100			1	97
actvstat NL	1081			1	97
actvstat IT	1409			1	97
actvstat LT	1008			1	97
residence	5651	3.14	1.417	1	5
bio val	5651	3.157	1.801	1	7
alt val	5651	3.098	1.827	1	7
ego val	5651	4.156	1.676	1	7
hed val	5651	3.252	1.816	1	7
jic val	5651	3.224	1.746	1	7
UA val 1	5651	3.834	1.705	1	7
UA val 2	5651	3.169	1.785	1	7
UA val 3	5651	3.326	1.707	1	7
UA val 4	5651	4.37	1.676	1	7
nocar	4703	1.458	.687	1	5



nocar 0	5651	.168	.374	0	1
carnum1 1	4703	.055	.228	0	1
carnum1 2	4703	.219	.598	0	2
carnum1 3	4703	2.204	1.225	0	3
carnum1 4	4703	.912	.283	0	1
carnum1 5	4703	.102	.421	0	2
carnum1 6	4703	.081	.481	0	3
carnum2 1	1755	.048	.214	0	1
carnum2 2	1755	.143	.489	0	2
carnum2 3	1755	2.348	1.131	0	3
carnum2 4	1755	.886	.318	0	1
carnum2 5	1755	.082	.382	0	2
carnum2 6	1755	.18	.697	0	3
carnum3 1	300	.047	.211	0	1
carnum3 2	300	.067	.32	0	2
carnum3 3	300	2.433	1.047	0	3
carnum3 4	300	.84	.367	0	1
carnum3 5	300	.107	.435	0	2
carnum3 6	300	.267	.835	0	3
carnum4 1	77	.039	.195	0	1
carnum4 2	77	.117	.428	0	2
carnum4 3	77	2.312	1.127	0	3
carnum4 4	77	.883	.323	0	1
carnum4 5	77	.039	.253	0	2
carnum4 6	77	.221	.754	0	3
carnum5 1	24	.083	.282	0	1
carnum5 2	24	.167	.565	0	2
carnum5 3	24	2.083	1.248	0	3
carnum5 4	24	.833	.381	0	1
carnum5 5	24	.042	.204	0	1
carnum5 6	24	.375	1.013	0	3
ptrating	5651	3.842	1.735	1	7
multimod	5651	.381	.486	0	1
carfrquse	4703	1.575	.817	1	5
prknorm	4703			1	3
parkfee	4703	.148	.355	0	1
regjour	4703	.825	.38	0	1
wyuscar c	4703	3.106	1.68	1	7
wyuscar tt	4703	2.595	1.677	1	7
wyuscar cv	4703	2.469	1.692	1	7
wyuscar td	4703	3.25	1.945	1	7
wyuscar lk	4703	3.116	1.794	1	7
carlntrip cm	4703	3.976	2.107	1	7
carlntrip rs	4703	3.863	2.039	1	7
carlntrip le	4703	3.84	1.92	1	7
carlntrip hl	4703	4.3	2.04	1	7
carlntrip ff	4703	4.33	1.933	1	7
nocarfut c	4703	3.146	1.793	1	7
nocarfut tt	4703	3.152	1.833	1	7
nocarfut nd	4703	3.757	1.889	1	7
nocarfut vi	4703	3.275	1.799	1	7
nocarfut vr	4703	4.576	1.868	1	7
nocarfut er	4703	3.71	1.813	1	7



willnocar	4703	4.242	1.988	1	7
carprev	948	.402	.491	0	1
nocar c	948	2.922	1.924	1	7
nocar tt	948	3.89	1.92	1	7
nocar cv	948	3.787	1.925	1	7
nocar nd	948	3.771	2.006	1	7
nocar vi	948	3.371	1.934	1	7
nocar sf	948	3.635	1.961	1	7
nocar er	948	3.671	1.938	1	7
shar avl cl	5651	.277	.447	0	1
shar avl cy	5651	.194	.592	0	2
shar avl in	5651	.616	1.212	0	3
noshare	5651			0	90
share use	2558	3.954	1.231	1	5
shareif	3093	5.007	1.903	1	7
wdshedcar	2636	5.215	1.844	1	7
onlintrv pt	5651	4.105	2.188	1	7
onlintrv pk	5651	4.585	2.199	1	7
onlintrv cs	5651	5.473	1.972	1	7
onlintrv tx	5651	5.093	2.067	1	7
onlintrv mc	5651	5.537	1.955	1	7
cycnum 1	3642	2.235	1.335	1	9
cycnum 0	5651	.356	.479	0	1
cycnum s	3267	1.9	1.175	0	9
cycnum c	949	.116	.418	0	6
cycnum e	1652	.908	.902	0	5
cycnum o	960	.336	.802	0	6
cycling	3642	2.764	1.266	1	5
flynum 1	2484	2.767	3.431	1	50
flyno 90	5651			0	90
mob pa1	5651	4.128	1.758	1	7
mob pa2	5651	4.342	1.763	1	7
mob se1	5651	4.416	2.041	1	7
mob se2	5651	4.308	2.016	1	7
mob oe1	5651	4.221	1.911	1	7
mob oe2	5651	4.343	1.911	1	7
mob pn1	5651	4.952	1.88	1	7
mob pn2	5651	5.139	1.844	1	7
mob desc nat	5651	5.37	1.621	1	7
mob desc imp	5651	5.417	1.75	1	7
mob dyn nat	5651	4.972	1.669	1	7
mob dyn imp	5651	5.388	1.711	1	7
sqmtre	5651	107.349	74.139	8	500
shrd sc	5651	.174	.38	0	1
shrd sw	5651	.152	.359	0	1
shrd slr	5651	.188	.391	0	1
shrd sg	5651	.274	.446	0	1
shrd pl	5651	.617	.486	0	1
shrd cg	5651	.3	.458	0	1
onplat	5651	.537	.499	0	1
knwneig	5651	2.261	.926	1	4
ncon cb	5651	2.668	1.08	1	4
ncon ec	5651	2.71	1.125	1	4



ncon hs	5651	2.472	1.131	1	4
ncon sc	5651	2.344	1.031	1	4
ncon it	5651	3.004	1.029	1	4
cfborw cr	5651	3.323	.948	1	4
cfborw eb	5651	3.265	.963	1	4
cfborw bi	5651	3.047	1.047	1	4
cfborw to	5651	2.464	1.086	1	4
cfborw di	5651	2.995	1.017	1	4
cfborw ki	5651	2.857	1.071	1	4
cfborw ot	5651	2.749	1.092	1	4
currshr ki	5651			0	1
currshr ba	5651			0	2
currshr bs	5651			0	3
currshr gn	5651			0	4
currshr ur	5651			0	5
currshr eh	5651			0	6
currshr no	5651			0	90
doborw cr	5651			0	1
doborw eb	5651			0	2
doborw bi	5651			0	3
doborw to	5651			0	4
doborw di	5651			0	5
doborw ki	5651			0	6
doborw ot	5651			0	7
doborw no	5651			0	90
dolend cr	5651			0	1
dolend eb	5651			0	2
dolend bi	5651			0	3
dolend to	5651			0	4
dolend di	5651			0	5
dolend ki	5651			0	6
dolend ot	5651			0	7
dolend no	5651			0	90
rprself cr	5651			0	1
rprself bi	5651			0	2
rprself mp	5651			0	3
rprself di	5651			0	4
rprself cl	5651			0	5
rprself fr	5651			0	6
rprself sh	5651			0	7
rprself ha	5651			0	8
rprself no	5651			0	90
rprserv cr	5651			0	1
rprserv bi	5651			0	2
rprserv mp	5651			0	3
rprserv di	5651			0	4
rprserv cl	5651			0	5
rprserv fr	5651			0	6
rprserv sh	5651			0	7
rprserv ha	5651			0	8
rprserv no	5651			0	90
wudshr ki	5651			1	90
wudshr ba	5651			1	90



wudshr bs	5651			1	90
wudshr gn	5651			1	90
wudshr ur	5651			1	90
wudshr eh	5651			1	90
wudmv	5651	4.764	2.031	1	7
wudmvbe 1	1582			1	90
wudmvbe 2	1582			1	90
wudmvbe 3	1582			1	90
wudmvbe 4	1582			1	90
wudmvbe 5	1582			1	90
wudmvbe 6	1582			1	90
wudmvif 1	4069			1	90
wudmvif 2	4069			1	90
wudmvif 3	4069			1	90
wudmvif 4	4069			1	90
wudmvif 5	4069			1	90
build pa1	5651	4.839	1.782	1	7
build pa2	5651	4.982	1.771	1	7
build se1	5651	4.634	1.927	1	7
build se2	5651	4.542	1.924	1	7
build oe1	5651	4.863	1.828	1	7
build oe2	5651	4.971	1.82	1	7
build pn1	5651	5.265	1.781	1	7
build pn2	5651	5.366	1.736	1	7
build desc nat	5651	4.694	1.677	1	7
build desc imp	5651	5.141	1.739	1	7
build dyn nat	5651	4.558	1.724	1	7
build dyn imp	5651	5.122	1.737	1	7
netaccq	5651	2.199	.951	1	5
smtphuse	5651			1	3
onlinepay	5651	2.051	1.051	1	5
dghlpgiv	5651	3.297	1.22	1	5
dghlpask	5651	3.463	1.059	1	5
sechand	5651	4.49	1.801	1	7
buysec	5651	3.543	1.111	1	5
sellsec	5651	3.239	1.178	1	5
sellbcon	4594	.739	.439	0	1
noneed	5651	3.619	.952	1	5
digneed	4685			1	3
digicons t	5651	3.999	1.432	1	7
digicons rg	5651	3.684	1.383	1	7
digicons m	5651	3.359	1.502	1	7
digicons hg	5651	3.753	1.359	1	7
dgenable bs	5651	2.526	1.557	1	7
dgenable bi	5651	2.459	1.52	1	7
dgenable ls	5651	2.728	1.505	1	7
dgenable bc	5651	2.552	1.513	1	7
ccb gov	5651	4.91	1.816	1	7
ccb busi	5651	4.938	1.798	1	7
ccb cit	5651	4.559	1.788	1	7
ccb se	5651	4.338	1.709	1	7
ccb oe	5651	4.308	1.713	1	7
ccb pn	5651	4.486	1.752	1	7



ccb desc nat	5651	4.468	1.587	1	7
ccb desc imp	5651	4.664	1.679	1	7
ccb dyn nat	5651	4.242	1.593	1	7
ccb dyn imp	5651	4.627	1.676	1	7
ccb pa	5651	3.623	1.759	1	7
ccb ar	5651	4.098	1.755	1	7
pweight	5651	1	.208	.401	1.871



Appendix D: Questionnaire

Appendix D below provides the complete order and structure and of the *Circular Consumption Survey* in the English language which was released in the United Kingdom. This was the base version from which the survey in all other languages was translated. All questions presented to respondents are highlighted in blue with the response type and question screening conditions (if any) highlighted in grey above each question. It should be noted that while the **response numbers** described in the middle column “Response No.” can be used to interpret the screening conditions, they **should not be used for coding purposes** as some variable names and value labels (codes) have been altered in the process of data cleaning. **All data processing and interpretation should be made with reference to the *Circular Consumption Survey* codebook** accompanying the published data.

Variable name	Response No.	Questions and Section Titles
		Language: English
		Section 0: Screening
		Response type & Conditions: Single Punch
gender		Please state your gender.
	01	male
	02	female
	03	diverse
	99	prefer not to say
		Response type & Conditions: Numeric input, check routine 4 numbers, years 1906-2006
age		In which year were you born?
	01	----
		Question Type: Single Punch
dwelling		Which dwelling type do you live in?
	1	Detached house
	2	Semi-detached house
	3	Terraced house
	4	Apartment
	5	Other (e.g. Mobile Home/Trailer, Boathouse, Dormitory, Adjacent Housing/Bedsit, Tiny House etc.)
		Response type & Conditions: Single Punch
region		Which region do you live in?
	01	East England
	02	East Midlands
	03	London
	04	North East
	05	North West
	06	Northern Ireland



	07	Scotland
	08	South East
	09	South West
	10	Wales
	11	West Midlands
	12	Yorkshire and the Humber
	13	
	14	
	15	
	16	
	17	
	18	
	19	
	20	
		Response type & Conditions: Single Punch
educ		What is your highest level of education?
	01	Primary education
	02	Lower secondary education
	03	Upper secondary education
	04	Post-secondary non-tertiary education
	05	Short-cycle tertiary education
	06	Bachelor's or equivalent level
	07	Master's or equivalent level
	08	Doctoral or equivalent level
		Response type & Conditions: Single Punch
hhincome		Monthly estimated household income (after tax and including social benefits)
	01	Below 500 GBP
	02	500-999 GBP
	03	1,000-1,499 GBP
	04	1,500-1,999 GBP
	05	2,000-2,499 GBP
	06	2,500-2,999 GBP
	07	3,000-3,499 GBP
	08	3,500-3,999 GBP
	09	4,000-4,999 GBP
	10	5,000-5,999 GBP
	11	More than 6,000 GBP
		Section 1: Sociodemographics. Please complete the following:
		Response type & Conditions: Single Punch
partner		Do you live with a partner? (married or unmarried)



	01	yes
	00	no
		Response type & Conditions: Numeric input
hhsz		How many people - including yourself - currently live in your household?
	01	_____
		Response type & Conditions: only if hhsz > 1 Numeric
no_child		How many children under the age of 25 currently live in your household?
	01	No child
	02	1 child
	03	2 children
	04	3 children
	05	4 children
	06	5 children
	07	6 children
	08	7 children or more
		Response type & Conditions: only if nochild Code2-8, numeric input
depend_child		What age is / are your child / children? Please enter the number of children per age group.
	01	_____ child / children under 5 years of age
	02	_____ child / children aged 5 to under 10 years
	03	_____ child / children aged 10 to under 18 years
	04	_____ child / children aged 18 to 25 years
	90	No child under the age of 25
		Response type & Conditions: Only if hhsz > 1 Numeric
depend_adult		Do adult dependants live in your household, e.g. older people, people with disabilities, special needs or people who are otherwise unable to live independently?
	01	yes: _____ person(s)
	00	no
		Response type & Conditions: Single Punch
tenure		Please describe your Tenure/Residential Status.
	01	Owner with no outstanding mortgage
	02	Owner with outstanding mortgage
	03	Tenant with rent at market rate
	04	Tenant with rent at reduced rate
	05	Tenant, Rent free
		Response type & Conditions: Single Punch
actvstat		What is your main activity status?



	01	Employed
	02	Unemployed
	03	Retired
	04	Unable to work due to long-standing health problems
	05	Student, pupil
	06	Fulfilling domestic tasks
	07	Compulsory military or civilian service
	97	Other
		Response type & Conditions: Single Punch
residence		How would you describe the area where your residence is located?
	01	A big city
	02	The suburbs or outskirts of a big city
	03	A large town
	04	A small town
	05	Rural Area or village
		Section 2: Values & Uncertainty
		Response type & Conditions: Single Punch per row, statements in rows, randomize
		To what extent do you agree with the following statements
bio_val	01	It is important to me to take care of, and live in harmony with, nature
alt_val	02	It is important to me to help others and that others are treated fairly
ego_val	03	It is important to me to have wealth, possessions, influence, and status
hed_val	04	It is important to me to have fun and have a good time
jic_val	05	I like to be prepared for every eventuality in life
UA_val_1	06	I feel uneasy in unfamiliar situations
UA_val_2	07	I prefer clear rules and guidelines
UA_val_3	08	Society should minimise risks
UA_val_4	09	I am comfortable with uncertainty
		Response type & Conditions: Answers in columns
	01	Fully agree (1)
	02	
	03	
	04	
	05	
	06	
	07	Fully disagree (7)
		Section 3: Mobility
		Response type & Conditions: Numeric, maximum of 5



nocar		How many cars does your household have? (including leased and company-cars)
	01	_____ car(s)
	00	No car
		Response type & Conditions: S per row, only if in nocar Code 1 was mentioned; show following questions depending on number of cars in nocar
carnum1-5		For each car, please indicate the type and the ownership status:
		Type: Electric / Hybrid / Conventional
		Ownership status: Owned / Leased / Company Car
		Response type & Conditions: Single Punch
pstrating		How would you rate the current public transport provision in your local area?
	01	Very Good (1)
	02	
	03	
	04	
	05	
	06	
	07	Very Poor (7)
		Response type & Conditions: Single Punch
multimod		For your regular journeys do you sometimes combine different modes of transport (e.g. such as park and ride systems, cycling or other active travel and public transport use)?
	01	Yes
	00	No
		Response type & Conditions: Single Punch, only if nocar = Code 1
carfrquse (if nocar = 0)		How often do you use your car?
	01	Daily
	02	Weekly
	03	Monthly
	04	Rarely
	05	Never
		Response type & Conditions: Single Punch, only if nocar = Code 1
prknorm (if nocar = 0)		Where do you normally park your car when at home?
	01	private space
	02	semi-private/shared



	03	public (e.g. on-street parking)
		Response type & Conditions: Single Punch, only if nocar = Code 1
parkfee (if nocar = 0)		Do you pay a fee where you normally park your car when at home (e.g. per hour/week/month/year).
	01	Yes
	00	No
		Response type & Conditions: Single Punch, only if nocar = Code 1
regjour (if nocar = 0)		If you suddenly had to do your regular journeys without the use of a car, would you know how to do this? (i.e. through public transport, cycling, walking other modes, car sharing, etc.)
	01	Yes
	00	No
		Response type & Conditions: only if nocar = Code 1, Single Punch per row, statements in row randomize
(if nocar = 0)		Rate the importance of the following reasons for you using a car
wyuscar_c	01	Cost
wyuscar_tt	02	Travel time
wyuscar_cv	03	Convenience
wyuscar_td	04	Transport of dependents
wyuscar_lk	05	Lack of alternative means (e.g. no public transport route)
		Response type & Conditions: Answers in columns
	01	Very Important (1)
	02	
	03	
	04	
	05	
	06	
	07	Not at all important (7)
		Response type & Conditions: only if nocar = Code 1, Single Punch per row, statements in row randomize
(if nocar = 0)		In general, could you do the following tasks without using a car?
carIntrip_cm	01	Commuting
carIntrip_rs	02	Regular shopping
carIntrip_le	03	Hobbies & leisure activities
carIntrip_hl	04	Travelling for holidays
carIntrip_ff	05	Care for friends and family
		Response type & Conditions: Answers in columns
	01	Very easily (1)



	02	
	03	
	04	
	05	
	06	
	07	With great difficulty (7)
		Response type & Conditions: only if nocar = Code 1, Single Punch per row, statements in row randomize
(if nocar = 0)		How important are the following factors for not owning a car in the future?
nocarfut_c	01	Cost
nocarfut_tt	02	Travel time
nocarfut_nd	03	Car no longer needed (e.g. for dependents)
nocarfut_vi	04	Viable alternatives become available
nocarfut_vr	05	Virtual interaction removes the need for travel
nocarfut_er	06	Environmental reasons
		Response type & Conditions: Answers in columns
	01	Very Important (1)
	02	
	03	
	04	
	05	
	06	
	07	Not at all important (7)
		Response type & Conditions: only if nocar = Code 1, Single Punch
willnocar (if nocar = 0)		Would you get rid of your car if viable alternatives were available?
	01	Definitely Yes (1)
	02	
	03	
	04	
	05	
	06	
	07	Definitely Not (7)
		Response type & Conditions: only if nocar = Code 0, Single Punch
carprev (if nocar = 1)		Did you own a car previously?
	01	Yes
	00	No
		Response type & Conditions: only if nocar = Code 0, Single Punch per row, statements in row randomize



(if nocar = 1)		How important are the following factors for your household's non-ownership of a car?
nocar_c	01	Cost
nocar_tt	02	Travel time
nocar_cv	03	Convenience
nocar_nd	04	No need to transport dependents (children, elderly relatives etc.)
nocar_vi	05	Viable alternatives available
nocar_sf	06	Safety
nocar_er	07	Environmental concerns
		Response type & Conditions: Answers in columns
	01	Very Important (1)
	02	
	03	
	04	
	05	
	06	
	07	Not at all important (7)
		Response type & Conditions: Multi Punch
		Are any of the following car sharing options available in your local area?
shar_avl_cl	01	Commercial (e.g. rental companies/agencies)
shar_avl_cy	02	Community (e.g. car clubs)
shar_avl_in	03	Informal (e.g. friends and family)
noshare	90	None [Conditions: Single Punch]
		Response type & Conditions: only if share_avl = Code 1-3, Single Punch
share_use (If noshare = 0)		How often do you use car sharing?
	01	Daily
	02	Weekly
	03	Monthly
	04	Rarely
	05	Never
		Response type & Conditions: only if noshare ==0, Single Punch
shareif (If noshare = 1)		Would you be likely to use car sharing if it was available?
	01	Yes, very likely (1)
	02	
	03	
	04	
	05	
	06	



	07	No, very unlikely (7)
		Response type & Conditions: only if nocar = 0 & noshare = 1, Single Punch
wdshedcar (if nocar = 0 & noshare = 1)		Would you get rid of your car if adequate car sharing was available?
	01	Yes, very likely (1)
	02	
	03	
	04	
	05	
	06	
	07	No, very unlikely (7)
		Response type & Conditions: Single Punch per row, statements in row randomize
		Do you normally use online services for any of the following activities?
onlintrv_pt	01	Using public transport (e.g. train, bus, tram etc)
onlintrv_pk	02	Paying for parking
onlintrv_cs	03	Short-term car rental/ car sharing
onlintrv_tx	04	Taxi/Ride sharing services
onlintrv_mc	05	bicycle/scooter/e-bike rental
		Response type & Conditions: Answers in columns
	01	Yes, very often (1)
	02	
	03	
	04	
	05	
	06	
	07	No, very seldomly (7)
		Response type & Conditions: Numeric
cycnum		How many bicycles are owned by your household?
	01	___ bicycle(s)
	00	Household does not own a bicycle.
		Response type & Conditions: Only if cycum = Code 01, Numeric
		Please select the number of bicycles owned by your household by type:
cycnum_s	02	Standard (drop down numeric)
cycnum_c	03	Cargo (Electric or non electric) (drop down numeric)
cycnum_e	04	Electric (drop down numeric)
cycnum_o	05	Other (drop down numeric)
		Response type & Conditions: Only if cycum = Code 01, Single Punch



cycling		How often do you cycle?
	01	Daily
	02	Weekly
	03	Monthly
	04	Rarely
	05	Never
		Response type & Conditions: Numeric, Single Punch
		How many return flights did you make in the last 12 months?
flynum	01	_____ [drop down numeric 1-9 and 10 and more]
flyno	90	I don't fly. [Single Punch]
		Response type & Conditions: Single Punch per row, statements in row randomize
		Please indicate to which extent you agree with the following statements.
mob_pa1	01	Car ownership and use cause serious environmental and social problems.
mob_pa2	02	(Serious) environmental and social problems are due to car ownership and use.
mob_se1	03	I feel capable of living my life without owning a car.
mob_se2	04	I feel confident that I can live my life without owning a car if I want to
mob_oe1	05	If I don't own a car, I can help reduce environmental and social problems.
mob_oe2	06	I think I can contribute to reducing environmental and social problems by not owning a car.
mob_pn1	07	I feel a personal responsibility to live my life without owning a car.
mob_pn2	08	I feel morally obliged to live my life without owning a car.
mob_desc_nat	09	In the UK most people do not own a car.
mob_desc_imp	10	Most people important to me do not own a car.
mob_dyn_nat	11	In the UK more and more people do not own a car.
mob_dyn_imp	12	More and more people important to me do not own a car.
		Response type & Conditions: Answers in columns
	01	Fully agree (1)
	02	
	03	
	04	
	05	
	06	



	07	Fully disagree (7)
		Section 4: Living Spaces, Sharing and Repair
		Response type & Conditions: Numeric
sqmtre		Approximately how much living space (in square meter) does your current home have?
	01	___m ²
		Response type & Conditions: Single Punch per row
		Do you have use of/have easy access to any of the following in your residential area?
shrd_sc	01	Swap corner (a place for leaving items your neighbours might want/need)
shrd_sw	02	Shared workspace
shrd_slr	03	Shared laundry room
shrd_sg	04	Shared garden
shrd_pl	05	Public Library
shrd_cg	06	Community groups promoting sharing/swapping/second-hand trade
		Response type & Conditions: Answers in columns
	01	Yes
	00	No
		Response type & Conditions: Single Punch
onplat		Are you familiar with any online second-hand trading platforms, including in your local area?
	01	Yes
	00	No
		Response type & Conditions: Single Punch
knwneig		How well do you know your immediate neighbours in your street/building
	01	Very Well (1)
	02	
	03	
	04	Not at all well (4)
		Response type & Conditions: Single Punch per row, statements in row randomize
		How likely would you be to contact your neighbours for help with the following?
ncon_cb	01	Car breakdown
ncon_ec	02	Emergency care (e.g. of child)
ncon_hs	03	Care of house while away (e.g. watering plants)
ncon_sc	04	Security concerns
ncon_it	05	I.T. problems
		Response type & Conditions: Answers in columns
	01	Very likely (1)



	02	
	03	
	04	Not at all likely (4)
		Response type & Conditions: Single Punch per row, statements in row randomize
		How comfortable would you be asking your neighbour to lend you the following items?
cfborw_cr	01	Car
cfborw_eb	02	E-bike
cfborw_bi	03	Bicycle
cfborw_to	04	Tools
cfborw_di	05	Electronic/digital device
cfborw_ki	06	Kitchen appliances
cfborw_ot	07	Other small household items (e.g. utensils cookware etc)
		Response type & Conditions: Answers in columns
	01	Very comfortable (1)
	02	
	03	
	04	Not at all comfortable (4)
		Response type & Conditions: Multi Punch
		Do you share the following spaces with a non-family member (e.g. tenant, housemate, neighbour, or other)? (Tick all that apply)
currshr_ki	01	Kitchen
currshr_ba	02	Bathroom
currshr_bs	03	Basement
currshr_gn	04	Garden
currshr_ur	05	Utility room
currshr_eh	06	Entrance/hallway
currshr_no	90	None of these [Response type & Conditions: Single Punch]
		Response type & Conditions: Multi Punch
		Which of the following items have you borrowed at some stage from your neighbours? (Tick all that apply)
doborw_cr	01	Car
doborw_eb	02	E-bike
doborw_bi	03	Bicycle
doborw_to	04	Tools
doborw_di	05	Electronic/digital device
doborw_ki	06	Kitchen appliances
doborw_ot	07	Other small household items (e.g. utensils cookware etc)



doborw_no	90	None of these [Response type & Conditions: Single Punch]
		Response type & Conditions: Multi Punch
		Which of the following items have you lent at some stage to your neighbours? (Tick all that apply)
dolend_cr	01	Car
dolend_eb	02	E-bike
dolend_bi	03	Bicycle
dolend_to	04	Tools
dolend_di	05	Electronic/digital device
dolend_ki	06	Kitchen appliances
dolend_ot	07	Other small household items (e.g. utensils cookware etc)
dolend_no	90	None of these [Response type & Conditions: Single Punch]
		Response type & Conditions: Multi Punch
		Which of the following repair activities do you personally carry out? (Tick all that apply)
rprself_cr	01	minor car repairs
rprself_bi	02	bicycle repairs
rprself_mp	03	mobile phone repairs
rprself_di	04	repairing other digital devices (tablets, laptop etc.)
rprself_cl	05	clothes mending
rprself_fr	06	furniture repairs
rprself_sh	07	shoe repairs
rprself_ha	08	household appliance repairs
rprself_no	90	None of these [Response type & Conditions: Single Punch]
		Response type & Conditions: Multi Punch
		Which of the following repair services do you purchase? (Tick all that apply)
rprserv_cr	01	minor car repairs
rprserv_bi	02	bicycle repairs
rprserv_mp	03	mobile phone
rprserv_di	04	other digital devices (tablets, laptop etc.)
rprserv_cl	05	clothes mending
rprserv_fr	06	furniture
rprserv_sh	07	shoe repair
rprserv_ha	08	household appliances
rprserv_no	90	None of these [Response type & Conditions: Single Punch]
		Response type & Conditions: Single Punch per row, statements in row randomize



		Where applicable, would you be willing to permanently share the following spaces with a non-family member (tenant, housemate, neighbour, or other)?
wudshr_ki	01	Kitchen
wudshr_ba	02	Bathroom
wudshr_bs	03	Basement
wudshr_gn	04	Garden
wudshr_ur	05	Utility room
wudshr_eh	06	Entrance/hallway
		Response type & Conditions: Answers in columns
	01	Very willing (1)
	02	
	03	
	04	
	05	
	06	
	07	Not at all willing (7)
	90	Not applicable
		Response type & Conditions: Single Punch
wudmv		To what extent would you be willing to live in a smaller home if one was readily available in your area?
	01	Very willing (1)
	02	
	03	
	04	
	05	
	06	
	07	Not at all willing (7)
		Response type & Conditions: only if wudmv Code 1-3, Single Punch per row, statements in row randomize
wudmvbe (if wudmv = 1,2 or 3)		Please rate the importance of the following factors (if applicable) for being more willing to live in a smaller home.
	01	Saving on running costs
	02	Ease of moving
	03	Being able to stay in my neighbourhood
	04	Lower cleaning burden
	05	Environmental factors
	06	Altruism (e.g. wanting those in greater need to have sufficient space)
		Response type & Conditions: Answers in columns



	01	Very Important (1)
	02	
	03	
	04	
	05	
	06	
	07	Not at all important (7)
	90	Not applicable
		Response type & Conditions: only if wudmv Code 4-7, Single Punch per row, statements in row randomize
wudmvif (if wudmv = 4,5,6 or 7)		Rate the importance of the following factors (if applicable) for being less willing to live in a smaller home.
	01	Cost/expense
	02	Inconvenience of moving
	03	Unlikely to be able to stay in neighbourhood
	04	Unwillingness to reduce available space
	05	Emotional attachment to home/neighbourhood
		Response type & Conditions: Answers in columns
	01	Very Important (1)
	02	
	03	
	04	
	05	
	06	
	07	Not at all important (7)
	90	Not applicable
		Response type & Conditions: Single Punch per row, statements in row randomize
		Please indicate to which extent you agree with the following statements.
build_pa1	01	Living in a large home causes important environmental and social problems.
build_pa2	02	(Serious) environmental and social problems are due to people living in large homes.
build_se1	03	I feel capable of living in a small home or sharing living spaces.
build_se2	04	I feel confident that I can live in a small home or share living spaces if I want to.
build_oe1	05	If I live in a small home or share living spaces, I reduce environmental and social problems.



build_oe2	06	I think I can contribute to reducing environmental and social problems by living in a small home or sharing living spaces.
build_pn1	07	I feel a personal responsibility to live in a small home or share living spaces.
build_pn2	08	I feel morally obliged to live in a small home or share living spaces.
build_desc_nat	09	In the UK, most people live in a small home or share living spaces.
build_desc_imp	10	Most people important to me live in a small home or share living spaces.
build_dyn_nat	11	In the UK, more and more people live in a small home or share living spaces.
build_dyn_imp	12	More and more people important to me live in a small home or share living spaces.
		Response type & Conditions: Answers in columns
	01	Fully agree (1)
	02	
	03	
	04	
	05	
	06	
	07	Fully disagree (5)
		Section 5: Digitalisation and second-hand trading
		Response type & Conditions: Single Punch
netaccq		How would you describe the quality of your internet access
	01	Excellent
	02	Very good
	03	Good
	04	Poor
	05	No access
		Response type & Conditions: Single Punch
smtphuse		Do you use a smartphone to access the internet?
	01	Yes
	02	No
	03	I don't have a smartphone
		Response type & Conditions: Single Punch
onlinepay		Do you personally pay bills or purchase goods and services online?
	01	Very often
	02	Often



	03	Occasionally
	04	Seldomly
	05	Never
		Response type & Conditions: Single Punch
dghlpgiv		Do people ask for your help when solving digital/IT problems? E.g. setting up and connecting networked devices, installing software, syncing or transferring data etc.
	01	Very often
	02	Often
	03	Occasionally
	04	Seldomly
	05	Never
		Response type & Conditions: Single Punch
dghlpask		How often do you ask other people for help solving digital/IT problems? E.g. installing and setting up apps on your phone, syncing or transferring data, resetting passwords, changing the settings on your devices. etc
	01	Very often
	02	Often
	03	Occasionally
	04	Seldomly
	05	Never
		Response type & Conditions: Single Punch
sechand		To what extent do you agree with the following statement: "I prefer to buy second-hand rather than new"
	01	agree Strongly (1)
	02	
	03	
	04	
	05	
	06	
	07	Strongly Disagree (7)
		Response type & Conditions: Single Punch
buysec		How often do you buy/collect/acquire second-hand goods found online?
	01	Very often
	02	Often
	03	Occasionally
	04	Seldomly
	05	Never



		Response type & Conditions: Single Punch
sellsec		How often do you sell/give away unwanted items or items you no longer need online?
	01	Very often
	02	Often
	03	Occasionally
	04	Seldomly
	05	Never
		Response type & Conditions: only if sellsec Code 1-4, Single Punch
sellbcon (if sellsec != "never")		Does offering goods online allow you to sell/give away things more easily than other methods e.g. flea markets, car boot sales etc.?
	01	Yes
	00	No
		Response type & Conditions: Single Punch
noneed		How often do you buy things you ultimately don't need/use?
	01	Very often
	02	Often
	03	Occasionally
	04	Seldomly
	05	Never
		Response type & Conditions: Only if noneed Code 1-4, Single Punch
digneed (if noneed != "never")		Does this happen less often when you buy something online?
	01	Yes
	02	No
	03	The same
		Response type & Conditions: Single Punch per row, statements in row randomize
		How do you feel digitalisation has affected the following:
digicons_e	01	The amount you travel
digicons_f	02	The amount of energy you use at home
digicons_m	03	Your media consumption (i.e. what you read, watch or listen to)
digicons_hg	04	The amount of household goods/services you buy
		Response type & Conditions: Answers in columns
	01	Largely increased (1)
	02	
	03	



	04	
	05	
	06	
	07	Largely decreased (7)
		Response type & Conditions: Single Punch per row, statements in row randomize
		In the last few years has it become harder or easier for you to do the following online?
dgenable_bs	01	Banking & online shopping
dgenable_bi	02	Searching for information
dgenable_ls	03	Finding local services
dgenable_bc	04	Basic communication (e-mail, video/voice calling etc.)
		Response type & Conditions: Answers in columns
	01	Much Easier (1)
	02	
	03	
	04	
	05	
	06	
	07	Much Harder (7)
		Section 6: Circular Citizenship
		Response type & Conditions: Text, own page
		Finally, we would like to understand your opinions about engaging in actions (i.e doing things) to influence other groups (other people, governments, businesses) to protect the environment by reducing the use of resources. This includes using fewer new resources and materials, using existing products for longer, reusing materials and recycling. With other groups we mean the government, businesses, and people around you, such as your friends and family.
		Response type & Conditions: Single Punch per row, statements in row randomize
		Please indicate how often you engage in the following actions that aim to urge other actors to reduce the use of resources.
ccb_gov	01	Actions to pressure the government, e.g. protesting, signing petitions, emailing officials, participating in public assemblies or hearings.



ccb_busi	02	Actions to influence businesses, e.g. investing in sustainable businesses, giving input for product/service design, speaking up in the organisation you work for.
ccb_cit	03	Actions to influence people around you, e.g. inform friends and family why and how to reduce the use of resources, or motivating them to change their behaviour
		Response type & Conditions: Answers in columns
	01	Frequently (1)
	02	
	03	
	04	
	05	
	06	
	07	Never (7)
		Response type & Conditions: Single Punch per row, statements in row randomize
		Next, please indicate to which extent you agree with the following statements about these actions to influence other groups (government, businesses, and people around you, such as your friends and family)
ccb_se	01	I feel capable of engaging in the actions above to influence other groups.
ccb_oe	02	If I engage in the actions above to influence other groups, I reduce environmental and social problems.
ccb_pn	03	I feel a personal responsibility to engage in the actions above to influence other groups.
ccb_desc_nat	04	In the UK, most people engage in the actions above to influence other groups.
ccb_desc_imp	05	Most people close to me engage in the actions above to influence other groups.
ccb_dyn_nat	06	In the UK, more and more people engage in the actions above to influence other groups.
ccb_dyn_imp	07	More and more people close to me engage in the actions above to influence other groups.
		Response type & Conditions: Answers in columns
	01	Fully agree (7)
	02	
	03	
	04	
	05	
	06	
	07	Fully disagree (1)



		Response type & Conditions: Single Punch per row, statements in row randomize
		Lastly, please indicate to which extent you agree with the following statements.
ccb_pa	01	The current level of resource use causes serious environmental and social problems.
ccb_ar	02	I feel partly responsible for environmental and social problems arising from the current use of resources.
		Response type & Conditions: Answers in columns
	01	Fully agree (7)
	02	
	03	
	04	
	05	
	06	
	07	Fully disagree (1)
		Response type & Conditions: End of Interview

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Digital transformation as an enabler of the CE

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Digital transformation in the Shared Socioeconomic Pathways



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Digital transformation refers to the widespread use of digital technologies in ways that reshape societal and economic activity, with significant impacts on sustainable development and climate challenges — both for better and for worse. Using statistical models calibrated to historical evidence in 62 countries across 12 world regions, we project future digital transformation within the Shared Socioeconomic Pathways (SSPs), adding contextual richness to this scenario framework used extensively in global climate research. In some scenarios, we find a pervasive and prolonged digital divide with up to 45% of the assessed population by mid-century still residing in countries with relatively low levels of digital transformation despite ever-deepening digitalisation in wealthier countries. We set out six use cases for how our explicit representation of digital transformation within the SSPs enables quantitative assessment of digitalisation's impact on energy, emissions, climate policy, and Sustainable Development Goals. We also discuss challenges with using empirically calibrated models to project digital transformation given its rapid evolution and socioeconomic implications.

The digital era is changing norms in communication, business and investment, policy reform and social interaction. Digitalisation is the use of data and digital technologies¹, ranging from the internet, cloud computing, and social media platforms to automation, digital twins, and artificial intelligence. Digitalisation improves process and system efficiency, enables data-driven decision-making, and enhances effective monitoring and reporting of climate-related action². On the flip side, digital technologies may also amplify climate-related and other environmental risks, as well as societal risks. These include the displacement of workers due to automation, the spread of misinformation, heightened cybersecurity vulnerabilities, increased electricity consumption from expanding information and communication technology (ICT) infrastructure and a rapid increase in electronic waste and other environmental footprints (energy, water, critical minerals)³.

Digital transformation means the increasing penetration of, and dependence on, digital technologies across economic sectors, government and public services, and societal functions¹, including information dissemination. The speed and extent of digital transformation varies globally, but with a clear general trajectory towards both widening applications and deepening dependence^{4,5}.

Scenario assessments help explore and understand potential futures for digital transformation and its implications for climate change mitigation and adaptation⁶. In turn, this facilitates proactive climate risk mitigation, helping society adapt to new realities while ensuring the benefits of digitalisation are widely accessible. This aligns with the Intergovernmental Panel on Climate Change (IPCC) Working Group III report^{7,8}, which emphasises

that digitalisation supports decarbonisation only if appropriately governed. The EU's twin transition agenda⁹ further reinforces the entwined green and digital transitions while taking key actions to prevent tensions between them. Similarly, the German Advisory Council on Global Change (WBGU)¹⁰ underscores the urgent need for formative political action to ensure that digitalisation serves sustainable development and that a growing digital divide is contained. The importance is also reflected in the Global Digital Compact's emphasis on aligning digital cooperation with sustainability goals (e.g. addressing digital divides)¹¹.

Projecting alternative futures for digital transformation is more complex than in other clearly defined sectors with tangible outputs. As a general-purpose technology with applications across sectors, activities and scales, digitalisation poses unique measurement challenges. There is no single consistent way to quantify physical output, performance or levels of digital transformation. A range of different proxy variables have been proposed in current and historical assessments including: ICT infrastructure (e.g. the number of secure internet servers, installation of industrial robots or robot intensity); access and use (e.g. individuals using the internet, number of devices, broadband and mobile subscriptions); innovation and economic activities (e.g. the number of patents, ICT service exports); knowledge and literacy (e.g. ICT skills); and composite metric-based indicators such as the E-Government Development Index (EGDI) (Supplementary Table 1). Though introduced for other purposes, these variables are also useful for exploring potential future digital transformation within the framework of Shared Socioeconomic Pathways (SSPs).

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The SSPs define different reference scenarios for global and regional socioeconomic development based on five narratives that span a range of plausible futures and examine resulting challenges and opportunities for climate mitigation and adaptation. The five SSPs are defined by different assumptions on high-level drivers of change: economic growth (GDP), demographics (population), and urbanisation rates. A wide range of additional elements are characterised in both narrative and quantitative forms by numerous studies^{12–14} that interpret the implication of the five SSP narratives for the energy system, land use change, pollution and health, and greenhouse gas (GHG) emissions (Table 1).

More recently, several studies have extended the SSP narratives and their constituent elements to assess implications for governance¹⁵, extreme poverty¹⁶, gender inequality¹⁷, income inequality¹⁸, net migration and remittances¹⁹, structural change²⁰, the human development index²¹ and armed conflict risk^{22,23}, which involve highly nonlinear phenomena. Resulting ‘SSP extension variables’ are typically based on statistical relationships observed historically with SSP drivers and elements that can then be used to generate future projections based on how these drivers and elements change under the different SSP storylines. All these SSP extensions are designed to enrich the SSP narratives and strengthen their usefulness without altering their fundamental architecture or quantitative interpretation.

Despite how widespread digitalisation is today and its anticipated role as a transformative force shaping economic and social life, it is not explicitly mentioned in the SSP narratives. (One small exception is a mention of digitalisation in the SSP5 narrative with reference to global institutions and coordination²⁴).

This remarkable omission is evident both in the SSP storylines and in their quantitative elements and interpretations, including the thousands of scenarios using the SSP framework that were reviewed in the IPCC’s recent 2022 assessment²⁵. As a dimension of technological change, digitalisation is implicitly included in the broader context of technological development that varies across the SSPs (Table 1), but this is concerned primarily with energy-related innovation that has a more direct bearing on GHG emissions.

Digital transformation introduces significant GHG mitigation opportunities and challenges through the economic and social activities it enables, as well as its direct energy consumption footprint. The lack of quantitative elements in the SSP framework makes it difficult to assess the enabling or exacerbating effect of digitalisation in uncertainty analyses of climate mitigation futures, including those used to inform policies for achieving national net-zero commitments under the Paris Agreement.

In this study, we assess global trends in digital transformation and explore alternative plausible futures within the SSP framework. We model the historical relationship between socioeconomic and demographic variables (our independent variables) and digital transformation measured by a widely-used UN index²⁶ (our dependent variable), across countries and through time. These statistical models guide our projections of future digital transformation, taking into account variation across the SSP storylines.

As an extension to the SSP framework, our quantitative projections show relative differences in the pace and depth of digital transformation between countries in an uncertain long-term future. Coupled to interpretive narratives informed by an expert workshop, our projections enrich the plausible futures characterised by the SSPs and expand their applicability to assess the implications of digitalisation for energy use, material consumption, GHG emissions, and the achievability of climate targets.

The fast-moving pace and varied application of digital technologies make it hard to anticipate future digital transformation, particularly in the long-term²⁷. These uncertainties are magnified by the potential for disruptive technological breakthroughs such as generative AI, or even future artificial general intelligence (AGI)²⁸.

Despite these uncertainties, the highly consequential nature of digitalisation for climate change invites initial efforts to fill a knowledge gap that can be critiqued and strengthened within the large SSP community²⁹. We contribute our results as an enabling framework, including six defined use cases for further quantitative analysis of GHG mitigation and adaptation

challenges affected directly or indirectly by digitalisation under the societal, economic and demographic influences on global development explored by the SSPs. An important stream of further analysis would specifically examine future discontinuities with observed historical trends, building on initial analytical work in this area³⁰.

Results

Digital transformation historically

Given its extensive scope and complexity, digital transformation and its dimensions can be conceptualised in many ways. We use the UN’s EGDI²⁶ as our dependent variable. The EDGI combines information from three subindices measuring: ICT infrastructure, access, and use; digital skills proxied by human capital; and online service availability and accessibility (Supplementary Table 4). Compared to other indices or measures summarised in Supplementary Table 1, the EGDI has better representativeness by covering multiple dimensions of digital transformation, and provides broader temporal and spatial coverage.

Using the EGDI as a measure of digital transformation, we show historical trends aggregated to 12 world regions common to global SSP modelling. Our aggregations use population-weighted averages for countries in each region (Fig. 1a). Over the period to 2020, the digital transformation level of North America is generally higher than that of the other 11 regions, with the Pacific OECD catching up and Sub-Saharan Africa the lowest.

We tested a range of socioeconomic and demographic factors as predictors (Supplementary Table 5) of country-level digital transformation using a panel dataset of 62 countries over the period 2003–2020. Our econometric model shows that digital transformation historically can be explained by GDP per capita, R&D expenditure, and population size as independent variables with fixed entity (country) effects to control for unobserved heterogeneity (see ‘Methods’ and Supplementary Table 6), such as trust and cultures.

These independent variables in our model proxy the economic capacity (GDP/capita), technological innovation (R&D) and market demand (population) that drive digital transformation. As well as controlling for the wide variation in country size in our sample, the population variable proxies not just aggregate demand for digital services but also the availability of human capital.

Future digital transformation within the SSP framework

Using country-level projections for the three independent variables in our model, we project digital transformation levels to 2050 under each of the five SSP narratives. We limit our projections to 2050 as uncertainties amplify over longer time periods, particularly for fast-changing phenomena like digitalisation. However, our model can be used to project out to 2100 if needed to link digital transformation to long-term carbon budgets (see use case discussions and Supplementary Fig. 1).

Our projections of digital transformation go beyond the 0–1 range over which the historical EGDI is normalised, so they should not be interpreted as future values of the EGDI (Supplementary Table 4). However, our measure of digital transformation serves the same function in showing variation between countries and over time (‘Methods’ and Supplementary Table 10). As with the EGDI, absolute values of digital transformation are hard to interpret as they are based on a basket of different subindices and indicators. It is more meaningful to interpret quantitative changes in a relative sense: for example, digital transformation in Sweden is 0.94 in 2020, increasing to 1.25 by 2050, which is in the top percentile of all 62 countries worldwide in our sample. Higher values of digital transformation imply more ICT technologies and infrastructure, stronger human capital and digital skills, and more widespread access to digital services.

Our projections of digital transformation show disparities across storylines as expected (Fig. 1b; Supplementary Fig. 1 and Supplementary Excel Sheet 4 for other regional projections). SSP3 (‘Regional Rivalry’) shows the lowest level and SSP5 (‘Fossil-fuelled Development’) the highest, aligning with its storyline of rapid economic and technological progress.

Table 1 | Summary of basic SSP elements²⁴ relevant to digital transformation and proposed extension to include digital transformation explicitly

Storyline element	SSP1	SSP2	SSP3	SSP4	SSP5
Main Dimensions of Uncertainty Varied and Quantified in SSP Framework					
Economy growth	High in LIC, MIC, medium in HIC ^a	Medium, uneven	Slow	Low in LIC, Medium in other countries	High
Population growth	Relatively low	Medium	High; Low in Rich OECD	Relatively High; Low in Rich OECD	Relatively low
Education	High	Medium	Low	V. low-low; Medium in Rich OECD/uneq.	High
Urbanisation level	High	Medium	Low	High; Medium in Rich OECD	High
Trade	Moderate	Moderate	Strongly constrained	Moderate	High
Technology development	Rapid	Medium, uneven	Slow	Rapid in high tech economies and sectors; Slow in others	Rapid
Technology transfer	Rapid	Slow	Slow	Little within countries to poorer population	Rapid
Energy technological change	Directed away from fossil fuels, toward efficiency and renewables	Some investment in renewables but continued reliance on fossil fuels	Slow tech change, directed toward domestic energy sources	Diversified investments including efficiency and low-carbon sources	Directed toward fossil fuels; alternative sources not actively pursued
Carbon intensity	Low	Medium	High in regions with large domestic fossil fuel resources	Low/Medium	High
Energy intensity	Low	Uneven, higher in LICs	High	Low/Medium	High
Relative digital transformation level	Medium-High	Medium-Low	Low	Medium-Low	High
Digital inequality (divide) between countries ^b	Medium-Low	Medium-Low	High	High-Medium	Low

SSP1 'Sustainability' and SSP5 'Fossil-fuelled Development' represent relatively optimistic trends for human development focused on green growth and energy-intensive economic growth, respectively. SSP3 'Regional Rivalry' (a fragmented world of resurgent nationalism) and SSP4 'Inequality' are more pessimistic, with SSP2 'Middle of the Road' providing a moderate pathway in which future trends broadly follow their historical pattern.

^aHIC, MIC, LIC = high-, medium-, low-income countries.

^b% countries/population in very low or low digital transformation categories.

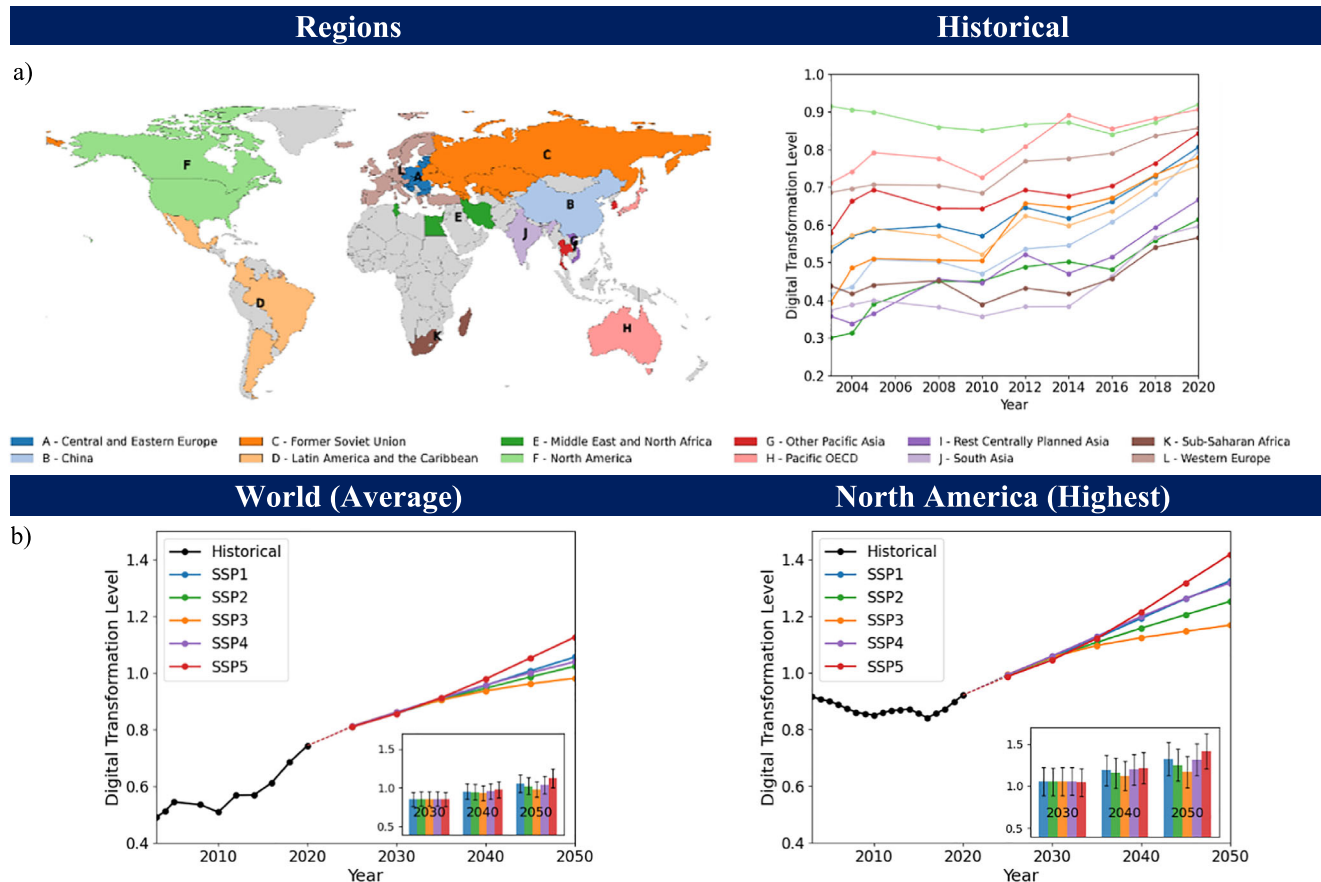


Fig. 1 | Relative digital transformation level of 12 world regions. **a** Historical digital transformation level based on the E-Government Development Index (EGDI) with representative countries shown for each region, and **b** Projected digital transformation levels up to 2050 for world average (population-weighted) and North America as an example region. Countries shown in grey on the map were not

included in the direct analysis. Solid lines show central estimates. The inset highlights digital transformation levels at 3 selected years, along with upper and lower bounds representing 95% confidence intervals for the predicted value based on the uncertainty in estimated coefficients. This shows modest differentiation across SSPs over the long term (see text for discussion).

North America demonstrates the highest level of digital transformation, generally above the population-weighted world average, based on 62 countries representing 12 regions with available data. Using North America's 2020 digital transformation level (0.92) as a benchmark, we can use our projections to estimate when other world regions will reach or surpass that level under different scenario assumptions. In an SSP2 future, for example, regions will 'catch up' by 2025 (Pacific OECD, Western Europe), by 2035 (centrally planned Asia, former Soviet Union), or by 2050 or later (Latin America, Middle East). The longest lag is for Sub-Saharan Africa, which surpasses North America's 2020 digital transformation level only by 2085. It is important to note that for Sub-Saharan Africa, the Middle East and North Africa, and Other Pacific Asia, as presented in Supplementary Fig. 1, the subset of countries included in the analysis represents less than 70% of each region's total GDP when compared to the 180 countries dataset used for out of sample generalisation projections (Supplementary Information—Supplementary Table 14). Within this subset, Sub-Saharan Africa and Other Pacific Asia are more strongly represented by countries with relatively higher GDP per capita, while the Middle East and North Africa are primarily represented by countries with lower GDP per capita. As such, projections for these regions should be interpreted with some caution due to limitations in regional coverage.

Ranking the twelve regions by their 2050 digital transformation levels in SSP3 and SSP5 shows both convergence and divergence (Fig. 2). The two highest and the two lowest ranked regions remain unchanged by 2050 (North America and Pacific OECD, and Middle East and Sub-Saharan Africa, respectively). Despite Sub-Saharan Africa being represented by countries with relatively high GDP per capita—potentially leading to an

overestimation of its digital transformation ranking—it consistently ranks lowest across scenarios, suggesting that the overall regional ranking remains valid. Some regions, such as South Asia, show a significant change in rank by 2050 (to sixth in SSP3 but tenth in SSP5). This is primarily due to the slower population growth assumed for South Asia under the SSP5 assumptions. These relative changes in digital transformation levels over time between regions can be used in various ways as reference points or modifiers when assessing the implications of digital transformation for GHG mitigation and adaptation challenges (see 'Discussion').

Uneven digital transformation across world regions

We use percentile categories¹⁵ to group countries into five categories from very low to very high digital transformation level based on the distribution of projected values from 2020 to 2050 across all the assessed countries. A country is classified as relatively 'very high' if its digital transformation value exceeds the 90th percentile (>1.22)—meaning its level is in the top 10% of all observed values regardless of scenario (Supplementary Table 11). By mid-century, the proportion of countries categorised as having low (blue) or very low (light blue) levels of digital transformation ranges from 9.7% (under SSP5 'Fossil-fuelled Development') to 29% (under SSP3 'Regional Rivalry') (see Fig. 3a and Supplementary Table 12). This translates into 5–45% of the population of the 62 countries in our sample living with relatively low levels of digital transformation in 2050. Conversely, the share of the population in countries with high (orange) or very high (red) levels of digital transformation ranges from 15 to 53%.

The average differences between SSPs shown in Fig. 3 can strongly exacerbate underlying inequalities if these are a salient feature of the SSP

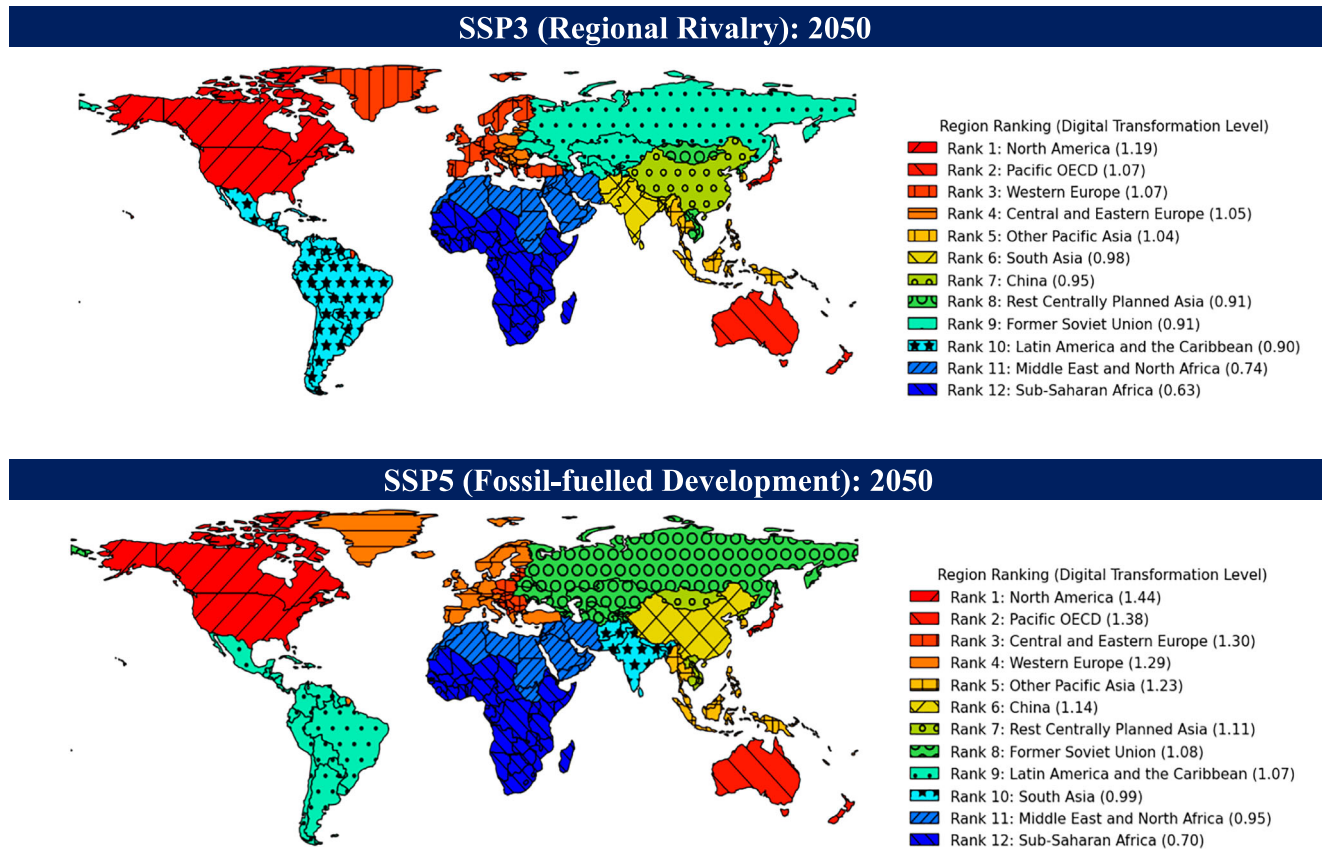


Fig. 2 | Digital transformation by 2050. Regional ranking under SSP3 (Regional Rivalry) and SSP5 (Fossil-fuelled Development) scenarios based on projections for 62 representative countries. The values in parentheses in the legend represent the digital transformation levels corresponding to their respective ranks. For Sub-Saharan Africa, the Middle East and North Africa, and Other Pacific Asia, the

countries included in the analysis account for less than 70% of each region's total GDP when compared to the full 180 country dataset (see Supplementary Information). In this subset, Sub-Saharan Africa and Other Pacific Asia are predominantly represented by countries with higher GDP/capita, while the Middle East and North Africa are represented by countries with lower GDP/capita.

storylines—as with SSP3. Figure 3b shows that among the 45% of the assessed population with low or very low levels of digital transformation under SSP3 assumptions, none are in countries with average GDP per capita over \$50,000, and the majority are in countries with GDP per capita between \$20,000–\$50,000. These trends in the digital divide between high-income and low-income countries are generally consistent across different SSPs, although varying in magnitude.

These results for our 62-country sample (Fig. 3) are biased towards countries with data availability. To provide a full projected global picture, we extend our dataset to 180 countries, but with caution in interpreting these out-of-sample projections (see Supplementary Tables 13 and 14, Supplementary Fig. 8, for approach and limitations). By mid-century, under SSP3 assumptions, we find that 47% of all countries and 35% of the world's population (~3.5 billion) in 180 countries (see Supplementary Fig. 2a) have access to very low or low levels of digital transformation compared to the other countries.

Digital transformation as an extension to the SSP narratives and elements

The SSPs comprise both qualitative narratives (or storylines) and quantitative drivers, elements, and other variables. Our quantitative projections of digital transformation in each of the SSPs are summarised in Table 1 alongside the most relevant SSP elements, including demographics, economic development and technological change²⁴.

For example, SSP3 'Regional Rivalry' is characterised by relatively weak digital transformation and high digital inequality—a digital divide—in which a significant proportion of the population (~45%) remains at low or very low levels of digital transformation. We also show how digital

inequality interacts with income inequality across SSPs with different economic growth and convergence assumptions. For example, SSP3 has the highest proportion of the population facing digital inequality even in countries with higher GDP per capita (using USD 20,000 as a threshold). This is consistent with a storyline in which economic growth does not automatically translate into digital progress, with digital stagnation exacerbating socioeconomic inequalities.

Drawing on insights from an expert workshop on digital and climate futures (see 'Methods'), we also provide qualitative interpretations of these projections that emphasise how digital transformation interacts with other aspects of the SSP narratives (Supplementary Table 2). As an example, in the SSP4 ('Inequality') narrative, digitalisation amplifies the high-growth global knowledge economy with rapid structural change among 'winning' countries, firm types, and population segments, but with strong negative effects on job losses, skills displacement, and income polarisation as well as the concentration of power undermining political agency.

Discussion

Digitalisation is not currently represented within the SSP framework. Our quantitative projections of digital transformation levels across countries and time allow the impacts of digitalisation on GHG mitigation and adaptation challenges to be modelled and assessed consistently and comparatively across SSPs. This adds an important new dimension to the characterisation of reference or baseline scenario uncertainty in global development relevant to climate futures. Explicit representation of digital transformation also improves the SSP framework's wider policy relevance beyond climate, in line with recommendations by O'Neill⁶. Digital transformation is an integral element of Sustainable Development Goals (SDGs)³¹ on innovation, labour

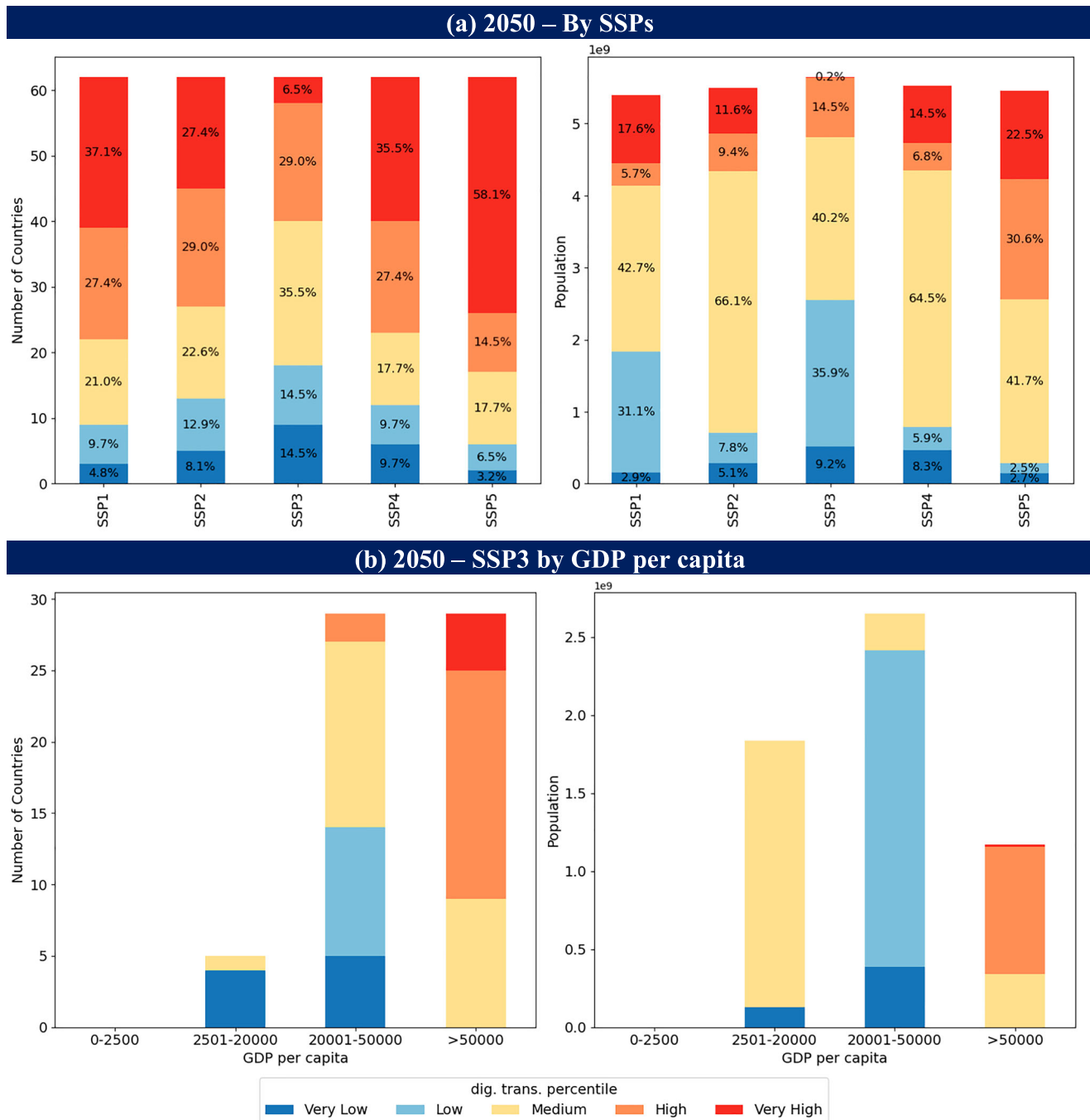


Fig. 3 | Number of countries and population by digital transformation level in 2050 based on our 62-country sample. a SSP1-5 **b** SSP3 by GDP per capita. The percentile-based categorisation is based on the 2020–2050 digital transformation

level: Very high (>90th percentile), high (>75th and ≤90th percentile), medium (>50th and ≤75th percentile), low (>25th and ≤50th percentile), very low (≤25th percentile), see Supplementary Table 11.

markets, and accessible infrastructure (SDG8,9), and a cross-cutting enabler of many other goals, including those on education and cities (SDG4,11).

Here we set out five use cases for how our projections can enrich understanding of GHG mitigation pathways and policies, with an illustrative sixth use case for GHG adaptation (Table 2).

Assessing direct energy and material consumption and resulting GHG emissions from ICT infrastructure

The data centres, networks and devices that comprise ICT infrastructure have a direct energy consumption footprint estimated at 1000 TWh in 2023, equivalent to 4% of global electricity use³². This is projected to increase rapidly in the next 5 years in some locations³³ due to energy-intensive

training and inference of generative AI, including large language models. The material needs of ICT infrastructure are small relative to bulk material flows globally, but account for significant shares of certain critical minerals, including rare earths like indium, gallium and germanium³⁴. Our long-term projections of digital transformation levels can be coupled to analyses of the energy and/or material consumption of the continuing expansion of ICT infrastructure across countries and regions under SSP storylines. For example, the marginal effect of digital transformation on energy demand growth observed historically (controlling for other drivers of demand) could be estimated across different time periods and regions. Resulting elasticities of ICT energy demand to deepening digital transformation in turn would enable longer-term projections under different scenario assumptions,

Table 2 | Applications of projected digital transformation levels within the Shared Socioeconomic Pathways (SSPs)

Use case	Quantitative elements needed for assessment
1. Assessing direct energy and material consumption and resulting GHG emissions from ICT infrastructure.	Digital Transformation within SSPs [our projections]. Energy and material intensity or incremental expansion of ICT infrastructure. SSP variables include C intensity of electricity and the global distribution of manufacturing and infrastructure.
2. Assessing the indirect impact of specific digital applications (e.g. teleworking) on energy consumption and resulting GHG emissions through changes in behaviour, economic activity, or societal functions.	Digital Transformation within SSPs [our projections]. Indirect impact assessment of net energy-reducing (substitution, efficiency, optimisation) and net energy-increasing (rebound, induced demand) effects of specific digital applications. SSP variables on technological change, economic growth, plus specific variables related to the use of digital applications (e.g. for teleworking: share of services in economic output, urbanisation, travel distances).
3. Assessing the indirect impact (enabling effect) of digitalisation as a general-purpose technology on energy consumption and resulting GHG emissions.	Digital Transformation within SSPs [our projections]. Statistical relationships between digitalisation and economy-wide (or industry sector) energy demand, controlling for country characteristics. SSP variables on country characteristics (e.g. GDP, trade intensity, economic structure).
4. Assessing the interaction between digital transformation and the stringency of climate policy required to reach emission reduction targets.	Digital Transformation within SSPs [our projections]. Levels of carbon price or other measures of climate policy for reaching defined climate stabilisation targets (e.g. 2 °C) or emission targets (e.g. net-zero). SSP variables on country characteristics affecting policy capacity (e.g. government effectiveness) and digitalisation (e.g. R&D intensity).
5. Informing global initiatives to ensure universal and equitable access to digital transformation opportunities as part of the SDG agenda.	Digital Transformation within SSPs [our projections]. Linkages between digitalisation and SDG outcomes. Metrics of digital divide by socioeconomic group, marginal cost of expanding access to ICT infrastructure.
6. Assessing digital climate services for adaptation planning.	Digital Transformation within SSPs [our projections]. Measures of climate impact and adaptation planning or resilience strategies (e.g. drought frequency and intensity, climate impact on agricultural yields, agricultural diversification, improved access to markets). Links between digital climate services and adaptation planning (e.g. weather and climate prediction tools, yield modelling tools, geospatial analysis of climate vulnerabilities, ICT availability to farmers).

including those in the SSPs. Existing SSP variables refine this analysis by contextualising the carbon intensity of electricity and manufacturing activities across different regions (Table 2). Insights on future energy consumption and GHG emissions from ICT infrastructure across countries under SSP storylines, as well as the extent of dependence on rare earth materials, water or recoverable electronic waste, inform policymakers concerned with resource uncertainties and resilience linked with digital trends.

Assessing the indirect impact of specific digital applications (e.g. teleworking) on energy consumption and resulting GHG emissions through changes in behaviour, economic activity or societal functions

Digitalisation impacts energy consumption and GHGs indirectly by influencing or changing household and firm behaviour and so the structure of social and economic activity. Compared to direct impacts, indirect impacts are larger in magnitude, more uncertain, and harder to model for methodological reasons, including difficulties in clearly defining system boundaries^{35,36}. Impacts can be net energy-reducing (through substitution, efficiency, optimisation) or net energy-increasing (through rebound, induced demand)³⁷. Our projections of the relative levels of digital transformation across different regions provide a means of scaling and extrapolating estimates of indirect impacts from specific digital applications. For example, Hook et al.³⁸ synthesised data showing that teleworking results in a net reduction in overall energy use in transport and buildings sectors ranging from −15% to −0.01% accounting for variation in study design,

context, and geography. These estimates of indirect impacts of energy can be combined with SSP variables capturing heterogeneity in relevant adoption conditions across countries (Table 2) to project future indirect impacts of specific digital applications on energy, consistent with SSP storylines. This helps understand their contribution to mitigation goals or the mitigation challenges they pose.

Assessing the indirect impact (enabling effect) of digitalisation as a general-purpose technology on energy consumption and resulting GHG emissions

Econometric models identify relationships between digital transformation and energy demand across the whole economy or in industrial sectors. For example, Briglauer et al.³⁹ found a small but significant negative elasticity of CO₂ emissions with respect to broadband connections in OECD countries over the period 2002–2019. Kopp et al.⁴⁰ found that a 10% increase in firms' ICT investments was associated with a 0.29% decrease in emissions, with a stronger effect in higher-income countries. These statistical models of the aggregate energy impacts of digitalisation typically control for variation in country size, development stage, trade relationships, and other factors explaining energy demand or GHG emissions. A general finding is that additional digitalisation reduces energy demand at the margins, with a stronger effect in more developed economies. These elasticities identified historically can be integrated with our projected levels of digital transformation across different regions to understand the future economy-wide impact of digitalisation for mitigation goals within different SSPs (Table 2).

Assessing the interaction between digital transformation and the stringency of climate policy required to reach emission reduction targets

By design, SSP reference scenarios assume no additional or new climate policies, and vary widely in GHG emission trends resulting from SSP drivers and other elements. This allows climate policy assumptions to be layered in to identify the stringency required to achieve net-zero or other defined emission reduction or climate stabilisation targets under different SSP uncertainties²⁵. As digitalisation will have significant direct and indirect impacts on energy demand, varying across sector and region, digital transformation will interact with climate policy assessments as both enabler and potential exacerbator. Our projected digital transformation levels allow this to be explored explicitly and quantitatively, including by specifying the relationship between the extent of digitalisation and the carbon pricing levels (or the de-risking of finance) needed to achieve net-zero targets. SSP variables related to governance conditions and effectiveness¹⁵ provide additional context, helping to tailor policy insights to the specific capacities of different regions⁴¹ (Table 2).

Informing global initiatives to ensure universal and equitable access to digital transformation opportunities as part of the SDG agenda

Digital transformation plays a fundamental but complex role in progressing towards SDGs^{31,42}. Global modelling analyses quantify the synergies and trade-offs of different strategies across the SDGs⁴³ but have not been able to include the interacting effects of digitalisation. Our projected digital transformation levels allow analysis of relationships between SDG indicators and digitalisation across countries under SSP storyline uncertainties. An important example is the digital divide between countries and over time that is shown clearly in our projections (Fig. 3). Modelling the progression of this divide, and how it can be strategically tackled through digital access and infrastructure investments can improve understanding policy capacity (and coherence) to address specific SDG concerns associated with digitalisation (Table 2).

Assessing digital climate services for adaptation planning

Effective climate change adaptation depends not only on traditional resilience strategies but also on the use of digital technologies to improve responsiveness and decision-making. Our example use cases for SSP-consistent projections of digital transformation levels have emphasised impacts on GHG mitigation challenges and opportunities (via energy demand and GHG emissions). However, there are many examples of digital applications both strengthening adaptation planning to climate impacts⁴⁴ (e.g. early warning systems for extreme weather events) but also adversely affecting resilience (e.g. over-dependence on digital infrastructure, digital divides). Our projections can be used to explore how digitalisation influences climate change, adaptive capacity and adaptation planning. For example, empirical studies that show how farmers' practices are affected by access to accurate weather prediction models or real-time information on market prices for agricultural commodities can be coupled to our projections of how the underlying digital capacities to access and use such tools vary across countries and time (Table 2). This adds a new dimension to SSP-consistent analysis of climate adaptation challenges while emphasising how marked regional variation in digital transformation interacts with the geography of climate impacts. The digital divide potentially adds an additional vulnerability to impact hot spots already subjected to multiple climate stressors⁴⁵.

The digital transformation level projects change in future digital infrastructure, activities, and services, as well as the capacity, including human capital, to support increasing digitalisation. While high digital transformation has the potential to enable sustainable development and net-zero transition pathways, it does not guarantee such outcomes. Digitalisation has its own energy and resource consumption footprint, exacerbated by high carbon intensities of electricity in some futures (e.g. SSP5). Digitalisation also has powerful adverse as well as beneficial impacts across

application domains and economic sectors, from governance and societal interactions to industrial processes, jobs and livelihoods.

There are two important limitations and considerations for our SSP-consistent projections of digital transformation. The first concerns uncertainty; the second concerns endogeneity.

Projections based on econometric models using panel data assume that historical relationships observed between variables will hold in the future. While these models can often account for dynamic changes in the short term, uncertainties compound and amplify over the long term. This is particularly the case for digital transformation given its fast-moving innovation cycles, speed of deployment, and potential for surprises²⁷. Our main projections only run to 2050 and emphasise uncertainty around our central estimates.

Some of these uncertainties relevant to digitalisation are represented in the SSP framework and the quantitative projections of drivers, elements and extension variables in the different SSPs. These include rates of technological change and economic growth, and between-country inequalities (Table 1) that indirectly flow through into our projections via their impact on the independent variables in our model.

However, additional uncertainties are specific to digitalisation, particularly those related to breakthroughs in AI⁴⁶ that may result in discontinuous change or even systemic disruption³⁰, rather than the smooth path-dependent trajectories projected by our historically calibrated panel models using future GDP, population, and R&D intensity trends.

Against these smooth trajectories, the effects of AI, generative AI, or other digital advances not captured in historical relationships can be explored using sensitivity analysis, sector-specific projections, or further what-if scenario analysis—all of which can be nested within the SSP framework's long-term variation of macro uncertainties relating to the economy, demography, urbanisation, and technological change.

These issues of uncertainty are arguably less fundamental than issues of endogeneity. Our approach treats digital transformation as an internally consistent outcome of socioeconomic development already characterised by different SSPs. However, it is not only an outcome. Digital transformation is also a driver or amplifier of socioeconomic uncertainty, as our analysis of the digital divide compounding income inequality shows. At the same time, digitalisation can contribute to productivity gains and accelerate economic growth.

This two-way endogenous relationship—digitalisation as both driver and outcome of change—was also emphasised in our expert workshop mapping of linkages between digital transformation and SSP elements (Supplementary Table 3).

As our approach takes the SSP framework as given—both as a set of future narratives and as derived demographic and economic variables used in our modelling—we do not capture the feedback effects of digital transformation on social and economic development. The same limitation applies (by design) to climate impacts on the socioeconomic development pathways, which determine GHG emissions but do not co-evolve with the resulting changes in climate.

Other SSP extensions, such as gender inequality and the rule of law, also face this endogeneity problem as they both impact and are impacted by socioeconomic development. As with our projections of digital transformation, the value of these SSP extensions is in making important uncertainties explicit in order to open up further avenues for policy-relevant analysis (see our use cases). What is distinctive about digital transformation, however, is the speed and magnitude of its potential disruptiveness.

As an example, digital transformation as a driver of change may undermine governance institutions and political agency through misinformation, unchecked market power of tech companies, and social polarisation under assumptions of weak global oversight³. Generative AI could turbocharge this challenge to the governance landscape necessary for concerted action on global commons problems like climate change, highlighting risks similar to the tragedy of the commons⁴⁷. To some extent, this is captured implicitly in the SSP3 storyline of fragmentation, divergence, and weakened global institutions. But could AI accelerate and amplify this effect

to the point at which it destabilises the fundamental socioeconomic assumptions and relationships on which the SSP framework is built? This eventuality is explored by Carlsen et al.³⁰ in the case of a breakthrough on AGI²⁸. Resulting systemic disruption could require a reimagining of a wholly new scenario architecture for understanding future uncertainties relevant to climate goals.

Methods

Our methodology (Supplementary Fig. 3) begins with the pre-selection of independent variables hypothesised to have a relationship with our digital transformation dependent variable. We then build stepwise regression models testing the predictive ability of each independent variable (Supplementary Table 5), yielding a viable historical model for SSP-consistent future projections. Our emphasis in the specification of this historical model is to identify independent variables for which SSP-consistent projections either already exist (e.g. GDP growth as a core SSP driver) or can be estimated indirectly through their observed associations with SSP drivers or elements (e.g. R&D intensity as a function of GDP growth). We can then couple our viable historical model to SSP-consistent projections of the independent variables to estimate within-country change over time in digital transformation in each of the five SSP pathways. Finally, we propose simple narratives to help interpret these quantitative projections of digital transformation, drawing on stakeholder input collected from an expert workshop.

Historical data

Our dependent variable is the EGDI²⁶, which we use as an indicator of digital transformation across diverse countries. Published by the UN, the EDGI has the advantage of broad representativeness (extending beyond ICT infrastructure) and the availability of panel data, both in terms of year and country coverage. It combines three components—the telecommunication infrastructure index, the human capital index and the online service index—into a weighted average of normalised scores (Supplementary Table 4). The EGDI is not designed to capture development in an absolute sense; rather, it aims to provide a comparative performance rating of countries. This is consistent with the purpose of our study. The EGDI consists of components that assess the readiness of the digital economy, including infrastructure, human capital, and the prevalence and acceptance of online services. For model estimation, we use data for 62 countries for which there are no missing observations for any variables over the timeframe 2003–2020.

To present historical data (and projected results), we group countries into 12 world regions, matching those commonly used by the global Integrated Assessment Models used in quantitative analyses of SSPs (Supplementary Fig. 4). We use population-weighted averages to aggregate digital transformation from countries to world regions. Some regions are represented by a small number of countries—for example, Sub-Saharan Africa is represented by two countries that tend to have a higher GDP per capita than the regional average. This is further detailed in Supplementary Fig. 4 and Supplementary Information. To expand country coverage, we conducted out-of-sample generalisation based on 180 countries instead of the original 62. However, since the model was trained on only 62 countries, we present these extended 180 country results only as Supplementary Information, with potential limitations of this generalisation discussed and visualised.

Our independent variables are a range of country-level economic, technological and sociodemographic characteristics associated with digital transformation, drawing primarily on data from the World Bank (Supplementary Table 5).

Historical model

We use stepwise panel data regression to add or remove independent variables systematically based on criteria including statistical significance ($p < 0.05$) and hypothesised associations with the dependent variable (Supplementary Table 5). Multicollinearity between independent variables was a persistent problem, particularly with GDP per capita and other

Table 3 | Fixed effect model—digital transformation (EGDI) historically

Independent variables	VIF (multicollinearity)	Coefficient	p value
GDP per capita, PPP (2017)	3.807 (<5)	1.04e-05	0.0000
Population	1.099 (<5)	0.0472	0.0001
R&D expenditure (% of GDP)	3.997 (<5)	8.296e-10	0.0003

economic measures. We use a variance inflation factor (VIF) threshold of <5, iterating between alternative model specifications to find a good model fit with clear interpretability. We test and compare ordinary least squares, fixed effects (fixed entity or fixed time), and random effect models. We use the Breusch-Pagan Lagrange Multiplier test and the Hausman test to statistically justify the appropriateness of each model, supported by theoretical considerations (Supplementary Table 6).

We select a fixed effect model as our preferred final viable model with the form shown in Eq. (1). The overall model has an $R^2 = 0.777$ (F-statistic = 86.279, $p < 0.01$), with coefficients given in Table 3. The independent variables are GDP per capita, population, and R&D intensity (Supplementary Table 6).

$$\text{Digital Transformation}_{it} = \alpha_i + \beta_1 \text{GDP}_{it} + \beta_2 \text{Pop}_{it} + \beta_3 \text{R\&D}_{it} + \varepsilon_{it} \quad (1)$$

in which α_i represents the fixed effect for country i , ε_{it} is the error term for country i at time t , β_1 = coefficient for GDP per capita, PPP (2017), β_2 = coefficient for population, β_3 = coefficient for R&D expenditure (% GDP).

We validated our model fitted to 2003–2020 observations using the 2022 dataset as a test year to compare actual versus projected values. Overall, the projection error remained below 3%, and regional rankings were unchanged or in two cases differed by one rank. Details are provided in Supplementary Fig. 7 and Supplementary Table 7. We conduct additional global sensitivity analysis on the explanatory variables using permutation importance and moment-independent importance measure (see Supplementary Table 8). This shows GDP per capita to be the most influential variable on model projections of digital transformation. This is consistent with expectations given the role of economic growth in driving both supply of digital infrastructure and demand for digital services, as well as enabling human capital (the three constitutive elements of the EGDI).

SSP-consistent projections

In our future projections we refer to ‘digital transformation levels’ as our dependent variable to distinguish it from the historical EGDI which has a scale of 0–1. Our future projections are not constrained by this cap (Supplementary Table 10).

We project future changes in relative levels of digital transformation in line with the five SSPs using projected future values of our independent variables extracted from the SSP Public Database or its extension explorer⁴⁸. However, not all independent variables have projected future SSP data available, e.g. R&D expenditure (Eq. (1) and Supplementary Table 5). In such cases, we follow the approach used by Leimbach et al.²⁰ which uses historical regression to explain non-SSP variables as a function of variability in core SSP elements, particularly GDP. The steps and models involved in this procedure, including robustness checks, are shown in Supplementary Fig. 3 (Step 4) with results and robustness checks in Supplementary Fig. 5 and Supplementary Table 9.

Our SSP-consistent projections of digital transformation levels are limited by their reliance on historical relationships with predictors (GDP per capita, population, R&D expenditure) and fixed entity effects. They do not capture uncertainties not evident in the historical observations such as the impact of crises or disruptive innovations (e.g. AI growth).

Our projections run from 2020 to 2050 at 5-year intervals with indicative extended projections to 2100 in Supplementary Fig. 1. Within the SSP framework and its quantification, most of the SSP elements are modelled by

using historical data from 1980 to 2015, with projections extending from 2020. We use 2020 as a calibration point to align observations with the projected data. This alignment updates the SSP data for consistency with recent trends, an approach also utilised in Hoy et al.⁴⁹. Full details of the alignment procedure are in Supplementary Fig. 6.

We categorise digital transformation levels into percentiles-based group using the projected distribution of digital transformation across all scenarios from 2020 to 2050, with the cut-off for each category stated in Supplementary Table 11. The five categories are defined as: very high (>90th percentile), high (>75th and ≤90th percentile), medium (>50th and ≤75th percentile), low (>25th and ≤50th percentile), and very low (≤25th percentile). A country with a score or level above 90th percentile is classified as ‘very high’, meaning its digital transformation level is higher than 90% of all country-year scores across 2020–2050 period. Countries in the ‘very low’ category fall within the lowest 25%. This categorisation is used to analyse the distribution of countries and their populations under different scenarios, along with their associated GDP per capita.

SSP narratives

O'Neill et al.²⁴ is the principal reference point for SSP narrative descriptions. Since the SSP narratives nor derived quantifications capture digitalisation trajectories, we interpret our projections of relative digital transformation level alongside the storylines described in O'Neill et al.²⁴ and extend these storylines specifically for digitalisation (Supplementary Table 2). For this, we draw on insights from stakeholders at an expert workshop on digitalisation and climate narratives (Supplementary Table 3). The workshop⁵⁰ was held on May 13–14, 2024 and brought together 35 researchers and practitioners working on digitalisation's impacts on energy, the economy, markets, society, and governance.

Data availability

Data are provided within the Supplementary Information files. The Python code (standard regression analysis) used in this study is available from the corresponding author upon request.

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Author contributions

Y.V.F. led the analysis and wrote the main manuscript text. C.W. contributed to the conceptualisation, methodology, discussion of use cases, advisory support and writing. M.A. and H.C. provided advisory support on the analysis, use cases and writing. S.J. contributed to the initial discussion of the conceptualisation and use cases. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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