DELIVERABLE 6.1

Pathway Narratives and Model Parameterisation

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Executive Summary

As a key outcome of the CircEUlar project, a set of circular economy (CE) driven net-zero pathways are being co-developed together with stakeholders using a light version of the so-called “Story and Simulation” approach. This document describes three narratives about utilizing CE strategies as a lever to reach net-zero greenhouse gas emissions. Each of the three CE narratives relies on one of the so-called “Narrow-Slow-Close” circular economy approaches, respectively with actions in three focus areas *Mobility*, *Buildings and Household Services*, and *Digitalisation* receiving special attention. The so-called R-strategies map to the broader Narrow-Slow-Close framework and depict specific CE actions in a more nuanced way.

The narratives integrate societal transformation towards circularity in three main ways: (i) dematerialization and a transition to a service-based economy to achieve smarter utilisation of material stocks limit their growth; (ii) lifetime extension of material stocks via repair, maintenance, reuse and repurposing of products and infrastructure; and (iii) waste treatment and recycling.

The elements of the CircEUlar narratives have been turned into initial model parameterisations, following a similar process that was used in the development of the Shared Socio-economic Pathways (SSPs). Specifically, elements of the narratives are mapped to sets of parameters in the models used for the pathway quantifications.

Keywords

Narratives, pathways, modelling, circular economy, GHG emissions, net-zero targets

Contents

Abbreviations

AI	Artificial Intelligence
B2C	Business to Consumer
BAU	Business As Usual
BIM	Building Information Management
C	Consumption
CAD	Computer Aided Design
CC	Climate Change
CE	Circular Economy
CircEUlar	Developing circular pathways for a EU low-carbon transition
EE	Energy Efficiency
EU	European Union
GHG	Greenhouse Gas
ICT	Information and Communication Technology
IPCC	Intergovernmental Panel on Climate Change
LCD	Liquid Crystal Display
NA	Not Applicable
NDCs	Nationally Determined Contributions
MSW	Municipal Solid Waste
P	Production
P2P	Peer to Peer
R-strategies	Reduce, Reuse, Recycle, etc.
SAS	Story and Simulation
SSPs	Shared Socio-economic Pathways
TV	Television
WP	Work Package

Pathway Narratives and Model Parameterisation

Introduction

Development process

As a key outcome of the CircEUlar project, a set of circular economy (CE) driven net-zero pathways are being co-developed together with stakeholders using a light version of the so-called “Story and Simulation” approach (SAS) (Alcamo 2008). The development process comprises five steps. First, the project consortium has developed an initial set of qualitative goals and narrative elements for the pathway development process which were shared with stakeholders in a workshop in March 2024 to gather feedback on the narratives. The stakeholders were tasked to revise the narratives in three groups on the so-called focus areas of CircEUlar which are (i) Mobility, (ii) Buildings and Household Services, and (iii) Digitalisation. Second, the first quantitative pathways are in the process of being developed based on the narrative sketches which will be presented in the following sections of this document. Third, stakeholders will be confronted with these initial quantitative pathways in a second series of stakeholder meetings to gather further feedback on the pathways. Fourth, stakeholder input will guide the revision of the narratives and model-based pathway quantifications in the remainder of the project. Fifth, the CircEUlar narratives and quantitative pathways will ultimately be shared with stakeholders and pathway users in a series of outreach activities.

The CircEUlar narratives, co-developed with stakeholders, integrate societal transformation towards circularity in three main ways: (i) dematerialization and a transition to a service-based economy to achieve smarter utilisation of material stocks limit their growth; (ii) lifetime extension of material stocks via repair, maintenance, reuse and repurposing of products and infrastructure; and (iii) waste treatment and recycling. In addition to stakeholder input, the narratives make use of the empirical insights on circular provision of goods and services as well as circular consumption practices which are generated as part of WP3 and WP4, respectively. These insights emerge from case studies, interviews and surveys in different European countries and regions, “upscaled” to a level suitable for model-based analysis. The narrative descriptions, together with sets of circular economy strategies, are described in the sections following the introduction.

The elements of the CircEUlar narratives have been turned into initial model parameterisations, following a similar process that was used in the development of the Shared Socio-economic Pathways (SSPs, cf. (Riahi, van Vuuren et al. 2017)). Specifically, elements of the narratives are mapped to sets of parameters in the models used for the pathway quantifications and “ordinal qualifiers”. Ultimately, the qualifiers are translated into model parameterisations that specifically fulfil the needs of the involved models. This process is documented in a set of tables in the Section on *Model Parameterisations*. The numerical values will be made available with the open-source release of the modelling tools and an open access database to make the full workflow transparent and traceable. An illustration of the process is shown in Figure 1.

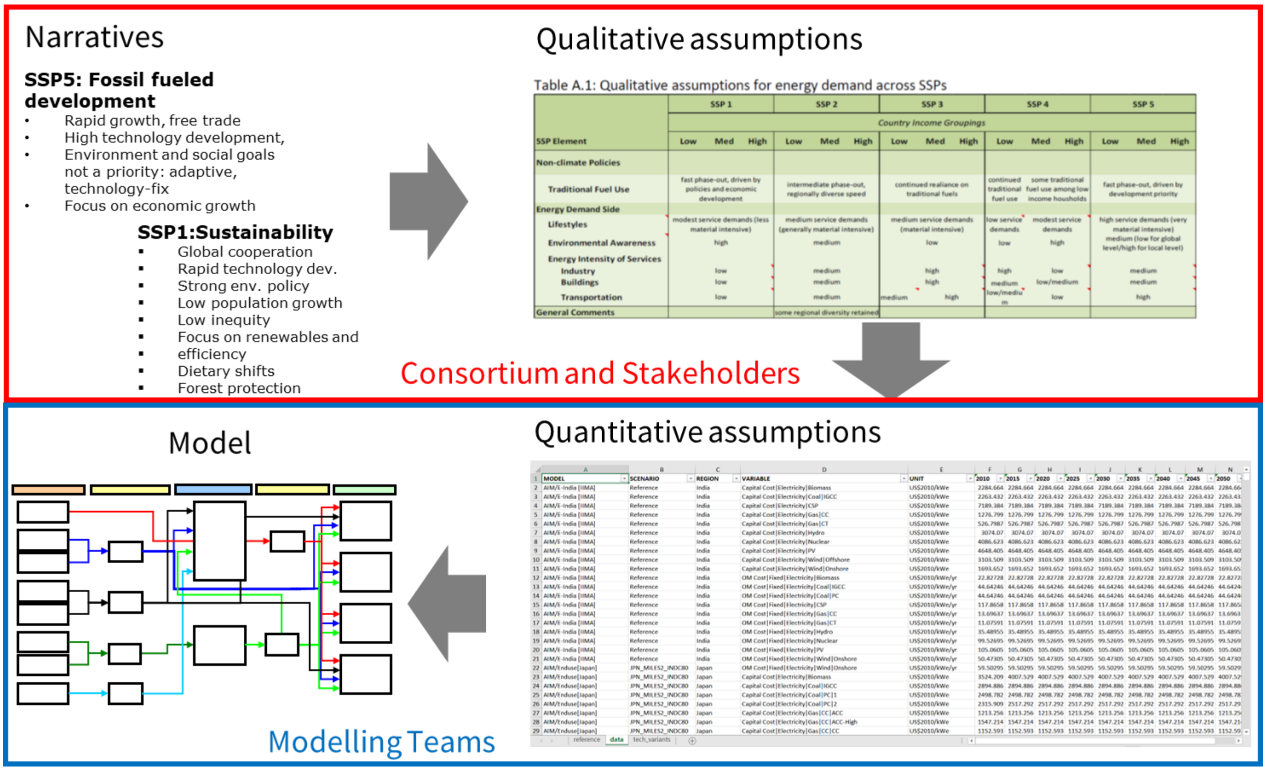

Figure 1: Process of translating narratives into quantitative pathways for the example of Shared Socio-economic Pathways. Illustration material based on (Riahi, van Vuuren et al. 2017) and (Krey, Guo et al. 2019).

Narrative and Pathway Concept

Climate policy and energy efficiency are two other key aspects of net-zero pathways, in addition, to the CE dimension. In particular, the literature points to energy efficiency as having many connections to CE frameworks; yet, energy efficiency does not fully map to circularity (Wiedenhofer, Wieland et al. 2025).

Based on these considerations, we distinguish three key pathway dimensions, (i) the Circular Economy (CE) dimension, (ii) the Energy Efficiency (EE) dimension, and (iii) the Climate Change (CC) dimension that are combined in the quantitative analysis. Each of the three dimensions has several narrative variants which are listed below.

- Circular Economy (CE)
    - Current Efforts: No CE-focus (CE counterfactual)
    - Narrow: focus on reducing material stock buildup
    - Slow: focus on keeping material stocks in use for longer
    - Close: focus on recycling and recovering materials at end-of-life
    - Circular: Integrated Narrow-Slow-Close focus
- Energy Efficiency (EE)
    - Current efforts: No EE focus (EE counterfactual)
    - EE focus
- Climate Change (CC)

- Current Policies (climate counterfactual)
- CC focus: NDCs + net-zero targets + 1.5/2°C

The narrative descriptions in this document focus on drivers of the Circular Economy while the Energy Efficiency and Climate Change dimensions build on existing narratives from the literature.

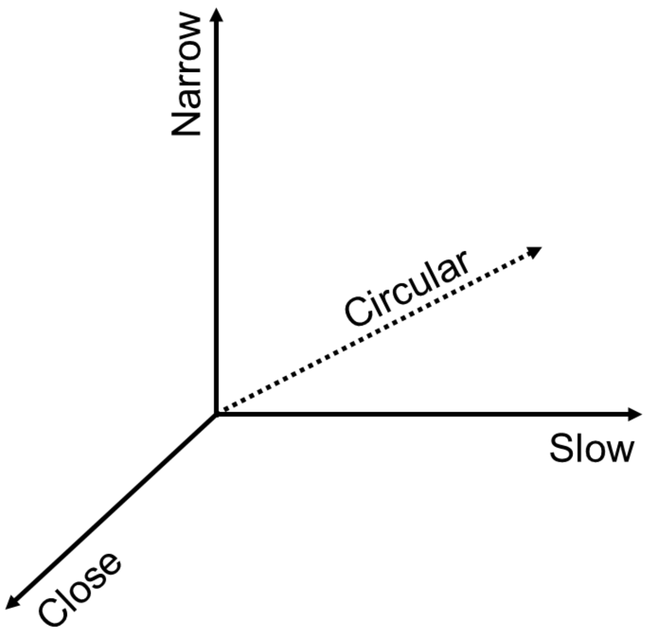

Figure 2: Circular economy narrative variants (see Box on Narrow-Slow-Close Framework).

The following sections describe the three narratives about utilizing CE strategies as a lever to reach net-zero GHG emissions. Each of the three CE narratives relies predominantly on one of the so-called *narrow*, *slow* and *close* approaches, respectively. Each narrative consists of four sections – the *Overall approach*, and descriptions of actions in the three focus areas *Mobility*, *Buildings and Household Services*, and *Digitalisation*, where we distinguish between actions and developments on the Consumption and Production side.

The "Narrow-Slow-Close" circular economy framework is a concept that describes a transition from the traditional linear economy model (take-make-dispose) to a circular economy model (Stahel W 1994, Bocken, de Pauw et al. 2016). The so-called R-strategies map to the broader Narrow-Slow-Close framework and depict specific CE actions in a more nuanced way. The box below includes additional information about the Narrow-Slow-Close framework and its relationship to the R-strategies.

Digitalisation is understood as an enabler for implementing CE strategies in Mobility, and Buildings and Household Service as well as the infrastructure of the ICT sector (Creutzig, Simoes et al. 2024). In the table below, the enabling function of *Digitalisation* is included under the *Mobility*, and *Buildings and Household Services* sections while the infrastructure dimension is discussed under the heading *Digitalisation (ICT Sector)*.

Table 1 below summarizes the CE narrative variants at large and the development in the three focus areas in tabular form.

Table 1: Summary of pathway narratives in tabular form.

	Narrow	Slow	Close
Overall	The emphasis of action is on narrowing material cycles to improve circularity and reduce GHG emissions. The R-strategies *refuse*, *rethink*, and *reduce* receive particular attention.	The emphasis of action is on slowing material cycles to improve circularity and reduce GHG emissions. The R-strategies *reuse*, *repair*, *refurbish*, *remanufacture* and *repurpose* receive particular attention.	The emphasis of action is on closing material cycles to improve circularity and reduce GHG emissions. The R-strategies *recycle* and *recover* receive particular attention.
Mobility	Digitalisation provides virtual substitutes for physical travel (e.g., teleworking, teleconferencing). Digital mobility services reduce private vehicle dependency particularly in cities. Digital platforms connect mobility users with available public, shared, and active transport modes to provide multi-modal 'mobility-as-a-service' as a flexible, convenient alternative to vehicle ownership. Consumer preferences push for changes in firms' business models towards service provision	More readily accessible information and technical support enable user-led repair and reconditioning of vehicles and micro-mobility technologies (bikes, scooters, drones). Increased use of shared vehicle fleets incentivises mobility providers to optimise vehicles for efficient maintenance and repair, including modular replacement or refurbishment of key components. Retrofitting of electric drive trains allows continued use of existing vehicles. Repair and refurbishing businesses are established.	A focus on increasing recycling and recovery of materials from transport infrastructure, in particular road infrastructure, reduces new materials for construction. Digital product passports tracking and sorting technologies facilitate disassembly of vehicles in the scrapyard for improved recovery and recycling of materials, including critical battery materials. Firms specialized in recycling are established and scaled up
Buildings and Household Services	Urban planning makes cities the most attractive choice for the majority of population. Mobility needs decrease and reduce the need for road and parking infrastructure. More flexible housing arrangements support "rightsizing" for different stages of peoples' lives. For building use, digital platforms enable sharing of space to increase overall occupancy rates. Single-function consumer products (e.g., books, clocks, TVs) are all substituted by digital services, dematerializing daily lives. Consumer preferences push for changes in firm's business models towards service provision (e.g., rental or sharing of appliances). Programs and incentives to encourage consumers to generate less waste.	For building use, shift towards flexible, reconfigurable space enables reuse and repurposing (e.g., office to residential conversions), supported by urban planning and policy reforms in favour of densification. Digital platforms enable more reuse (second hand trading) and refurbishment, reconditioning of consumer goods, thereby increasing their lifetime (incl. devices, clothes). Repair and refurbishing businesses for appliances are established.	Standardization of single-use packaging and improving source-separated waste collection via incentive schemes for consumers increases recovery and recycling yields. For building demolition and dismantling, building information models (BIM) identify material components (by location, volume, design) to enable disassembly and recycling. Firms specialized in recycling household devices are established and scaled up

Digitalisation (ICT Sector)	ICT consumer devices, particularly smartphones, become ubiquitous as universal interfaces for accessing cloud-based services. Although this supports dematerialisation in other sectors, ICT devices increase in both number and aggregate material footprint. Concerns over social and environmental impacts of critical minerals, as well as supply chain risks, drive continuous improvements in material efficiency, material simplification, and miniaturisation.	Consumption norms shift towards more use of second-hand or reconditioned digital devices, and away from novelty-seeking purchases of latest released ICTs. Widespread access to and use of repair cafes, shops, and information resources. Redesign of ICT infrastructure and devices embeds circularity principles to enable more repair, remanufacturing, and reuse of components. Product-service business models create strong incentives for producers to design, manage, and repurpose hardware over its full lifecycle.	Widespread access to and use of e-waste recycling facilities along with regulatory policy improve recycling rates of ICT devices. Collection, processing, and recycling facilities for ICT devices become widely accessible, with strong economic incentives for e-waste recovery and reuse.

For the climate dimension, we build on existing concepts used in the pathways literature instead of developing new narratives from scratch. Notably, we use two levels of climate policy ambition defined in the literature. On the one hand “Current Policies” which describes a future in which currently implemented climate policies continue to exist, their targets are met and the level of ambition is extrapolated equivalently (Riahi, Schaeffer et al. 2022, Guivarch 2023). On the other hand, “CC focus” describes a future in which near-term goals of the Nationally Determined Contributions (NDCs) are met, furthermore the net-zero targets of countries are implemented and then a transition to the long-term goals of the Paris Agreement, 1.5 and 2°C respectively, is followed.

Finally, for the energy efficiency dimension we define a counterfactual that implements current efforts and an “EE focus” variant which follows ambitious efficiency targets as in the so-called “Low Energy Demand” (LED) scenario by (Grubler, Wilson et al. 2018).

Socio-economic development

Taking the Shared Socio-economic Pathways (SSPs) as the basis to describe the socio-economic developments of the CircEUlar net-zero pathways is imperative to ensure that they are compatible with literature on climate change mitigation, impacts and adaptation and can easily be used in the context of IPCC assessments. At the same time, using identical socio-economic projections across scenarios that rely on alternative circular economy strategy combinations is essential so that outcomes are directly comparable with each other. Therefore, socio-economic projections of the SSP2 “Middle-of-the-Road” pathway will be used across all CircEUlar pathways. To explore the sensitivity of the scenario analysis insights to varying socio-economic conditions, the combined Narrow-Slow-Close scenario may also be implemented based on SSP1 “Sustainability” socio-economic projections given that the SSP1 narrative is very much compatible with a focus on circular economy measures.

Box: Narrow-Slow-Close framework and R-strategies

Following the Circularity Gap Report[a], Narrow, Slow and Close strategies (Figure 3) can be described as follows. They also map to the frequently used R-strategies that describe more specific CE actions (Figure 4).

Narrow: Use less

Narrow strategies reduce material and energy use. Currently, material use is highly inefficient and ineffective; we can deliver similar social outcomes by using much less and phasing out fossil fuels, for example. This doesn’t mean being worse off, but rather focussing on using materials efficiently: think in terms of riding a bike instead of driving a car, eating less meat and living in a space that suits your needs. Using less is a core tenet of the circular economy – yet currently, the threshold for sustainable consumption, 8 tonnes per person, is being surpassed by 1.5 times.

Slow: Use longer

Slow strategies aim to keep materials in use for as long as possible, for example through design for durability and repairability. A more circular economy is also a slower one: materials, components and products—and even buildings and infrastructure— are made to last. This will lower material demand in the long run, in essence also serving to narrow resource flows.

Close: Use again

Close strategies aim to cycle and reuse materials at their highest value: they maximise the volume of secondary materials re-entering the economy, ultimately minimising the need for virgin material inputs and therefore also narrowing flows. Of course, virgin materials will always be needed to a degree: all materials degrade and can’t be cycled infinitely, use energy, and require blending with virgin materials to maintain strength and functionality.

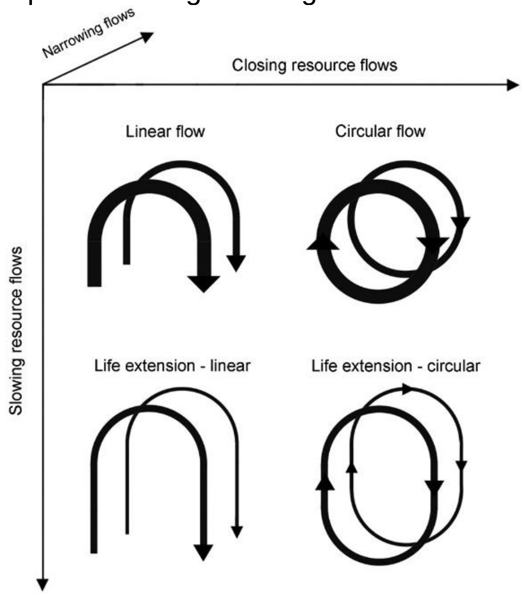

Figure 3: Categorization of linear and circular approaches for reducing resource use (Bocken, de Pauw et al. 2016).

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

Figure 4: Circularity strategies with the production chain, in order of priority (adapted from (Potting, Hekkert et al. 2017)).

Narrative 1 – Narrow focus

Motivation

Citizens/consumers as well as firms accept that significant action on climate change mitigation and improved circularity are critically important. They are willing, under the right conditions, to achieve ambitious goals in these domains by changing consumption practices, thus diminishing the cultural inertia towards existing habits. At the same time, they demand and are willing to enforce high quality regulation on consumer rights, data privacy and related areas; they also have high levels of trust in both governmental and non-governmental institutions. The transition from ownership to sharing is perceived as enhancing well-being while maintaining the same or improving the level of utility in services. Digitalisation and its accompanying services are equally accessible across all segments of society. Through a change in business models, firms shift from a strong focus on producing and selling goods to becoming providers of services.

Overall approach

The emphasis of action is on narrowing material cycles to improve circularity. The R-strategies *refuse*, *rethink*, and *reduce* receive particular attention, also having positive impact on the reduction of waste generation. The provision of the necessary physical or digital infrastructure, a radical change in firms' business models and a high willingness of consumers to switch to a more service-based economy allows for higher utilisation of capital stocks via sharing approaches and therefore decreased production levels to provide the same (or even higher) levels of services. Complementary consumer protection and service industry regulations are introduced to ease the transition creating enforceable standards for customer service and consumer rights while existing consumer protections which may encourage waste are reviewed.

European perspective and global context

Demonstrated effective consumer protections and industry standards foster a high level of trust in European and international institutions which leads to global cooperation.

Role of different actors

Consumers are willing to change behaviour with an emphasis on demanding high quality services instead of owning goods. They are well educated about the environmental consequences of their consumption decisions through methods like labelling on products or infographics. Many industrial firms transform from being providers of goods into integrated service providers. As changes are enabled via pervasive digitalisation, regulators impose stronger policies on digital consumer service rights aiming to protect consumers against anti-competition and misuse of consumer data. Governments promote policies that encourage shared resource utilisation (such as enhancing public transportation), while discouraging individual ownership (through measures like imposing higher taxes on cars or implementing urban planning that minimizes reliance on personal vehicles).

Mobility

A fundamental shift in the social contract and the corresponding role of governments enable a pronounced reduction in personal motorized mobility.

Consumption (C)

Digitalisation provides virtual substitutes for physical travel (e.g., teleworking, teleconferencing, e-services, e-retail). Government redirection of investments towards public transportation provides a viable substitute for cars, with frequent service and extensive coverage both within urban centres and suburban regions. This is complemented with the digital mobility services that reduce private vehicle dependency particularly in cities. Digital platforms connect mobility users with available public, shared, and active modes to provide multi-modal ‘mobility-as-a-service’ as a flexible, convenient alternative to vehicle ownership. As a result, vehicle ownership per capita falls with car-free households in cities rising across all demographic groups. Urban planning and design for 15-minute city concepts are supported by increasingly sophisticated agent-based simulations of population movements in digital twins of cities. Resulting pedestrian- and bicycle-friendly urban environments lead to a shift towards active mobility modes. Infrastructure for these transport modes is improved to be more convenient and safer. In addition, through initiatives such as receiving compensation for biking to work, gaining additional days off, or participating in employer-provided bike leasing programs, individuals are motivated to opt for more active modes of transportation. The attractiveness of urban environments thus increases and shift preferences from suburban to urban dwellings. Shared mobility options are granted privileges in traffic, including access to lanes typically reserved for buses and taxis. People are better informed on the environmental impacts of their mobility choices.

Production (P)

Digitalisation in automotive manufacturing includes control and monitoring systems to improve material efficiency of production lines, reducing material waste. Digital design practices support material simplification of components (for easier end-of-life recovery) and pervasive adoption of lightweighting, with widespread diffusion of 3D printing of components from single material substrates. To further reduce the material footprint of the remaining vehicle stock, as a result of the service-based approach to mobility, the average size of light duty vehicles is reduced significantly as vehicles do not need to serve all potential use cases of a single user. The automotive sector modifies the currently prevalent business model, with many producers becoming integrated service providers. By becoming the owners of the vehicle stock, vehicle producers have an incentive to design vehicles to last for longer, to be repaired as needed. The need for personalization and overspecification in several aspects of the vehicles is reduced, shifting attention strongly towards performance and efficiency.

Key CE strategies:

- *Refuse*: Substitution of physical travel for work, retail and public services (e.g., teleworking, e-health & e-education, e-retail) resulting in reduced air and road travel (C)
- *Rethink*: Increase sharing of cars and rides enabled by P2P and B2C platforms (P, C)
- *Rethink*: Mode shift towards active mobility such as walking and biking (C)
- *Rethink*: Light motorized forms of mobility (e.g., e-scooters, e-bikes) displace more material-intensive forms of mobility in certain applications (P, C)
- *Rethink*: Investment into public transport and creating minimum public transport distance/travel time standards for point-to-point travel, inducing modal shifts from private to public transport (P)
- *Rethink*: Facilitating/promoting “slow” travel (e.g., recent example of incentive in the European Erasmus programme) (C)
- *Rethink*: Data-driven optimisation of traffic flows (P)
- *Rethink / Redesign*: Design, automation & additive manufacturing in vehicle production to improve material efficiency, increase lifetime and reduce process waste (P)
- *Reduce*: Enable the deployment of electric cars (C) which require less non-renewable energy resources over the lifetime of vehicles (but needing of critical raw material) and less maintenance
- *Reduce*: Reduce travel activity (pkm) and number trips via better urban form/planning (C, P)

Buildings and Household services

Urban planning is a key entry point that makes urban environments the most attractive choice across the larger part of populations. Urban planning systems streamline bureaucracy, accelerate decision-making, and enhance effectiveness through the integration of AI models for developing low-carbon strategies for cities. Mobility needs are also reduced with more compact, walkable cities becoming the aspirational norm reducing the need for road and parking infrastructure.

Consumption (C)

For building use, digital platforms enable sharing of space to increase overall occupancy rates on a per m^2 basis in both residential and commercial sectors. Short- and long-term rental of rooms and facilities/appliances in homes and offices becomes normalised, with digital platforms providing assurance, trust, user-provider profile matching, and handling financial exchanges with an economically feasible business model.

For consumer goods, single-function consumer products including books, print media, maps, clocks, TV and sound systems are all substituted by digital services. Daily life dematerialises and declutters.

Production (P)

Downsizing of apartments and more flexible building designs with shared spaces lead to overall lower floor space area per capita. Urban planning focuses on densification of cities and avoids urban sprawl which also fosters the trend towards lower total floor space and due to its mobility implications reduces the need for construction of road infrastructure and parking spaces. A shift towards light-weight construction practices such as wood-based construction leads to a reduction of material stocks of energy-intensive materials like steel and concrete.

Digitalisation of building design and construction practices enables greater material efficiency with components rightsized (avoiding over-specification), substitution away from high carbon intensity materials including concrete, and increasing offsite manufacturing of high specification components for rapid assembly on site during construction. To support flexible use of buildings, digitally-enabled design also supports reconfigurable, multi-purpose spaces and building infrastructure. Building information models (BIMs) as an extension of 3D computer-assisted design (CAD) diffuse out of leading architectural and design practices throughout the industry. BIMs enable design optimisation and provide a dynamic record of building material composition through design, construction and operation phases across the lifecycle of a building.

Key CE strategies:

- *Rethink*: Increase shared, flexible, multi-occupancy usage of building floor space enabled by digital platforms, including through new ‘real estate as a service’ business models (P, C)
- *Rethink*: Sharing living space through co-housing and co-working/common service spaces/ larger households with solutions for existing as well as new developments (C)
- *Rethink*: Preference for living in urban environments and shift from single-family housing to multi-family, mixed-use housing (C, P)
- *Rethink*: Adapt urban planning to focus on existing urban tissues (e.g., urban consolidation such as adding new stories or infill development) instead of furthering urban sprawl and/or suburban development (P)
- *Rethink*: Appliance and tool sharing (e.g., common washing machines), avoiding stock accumulation (e.g., number of TVs per dwelling) (C)
- *Reduce*: Use of BIM in building design & construction to optimise material efficiency, avoid over-specification, and enable offsite manufacturing (P)

- *Reduce*: Automation & monitoring of on-site construction practices (e.g., 3D printing, drones, laser scanners) to reduce construction waste (P)
- *Reduce*: Shift to alternative construction materials (e.g., wood-based or clinker substitutes) in buildings to substitute more energy-intensive materials (P)
- *Reduce*: Avoid acquisition of second homes (e.g., holiday houses) that are not inhabited most of the time, particularly relevant for touristic locations (C)
- *Reduce*: As a result of shared mobility being widely adopted, the number of vehicles in use is reduced and therefore less road and in particular parking infrastructure is needed (P)
- *Reduce*: Reduce packaging from e-commerce (P, C), reduce the use of plastic bottles and products wrapped in plastic (P, C), reduce food waste (C)
- Refuse: Material substitution e.g., plastics by bioplastics (P)

Digitalisation (ICT sector)

Pervasive digitalisation acts as an enabler for reducing material footprints in other sectors, most notably in provision of mobility services, buildings and household services. At the same time, digitalisation requires the expansion of ICT infrastructure, which presents challenges for promoting circularity within the ICT sector.

Consumption (C)

Digitalisation enables a dematerialisation of service provision and consumption as more and more goods are accessed through product-service systems, access or usage-based models (incl. subscription services, pay-as-you-go), and sharing platforms. These enabling effects of digitalisation are picked up under the focus areas for mobility and buildings (including consumer goods). In the ICT sector, consumer devices - particularly smartphones - become ubiquitous as universal interfaces for accessing cloud-based services. Although this supports dematerialisation in other sectors by helping to dematerialize and declutter daily life, ICT devices increase in both number and aggregate material footprint. However, consumer culture shifts away from frequent replacement and upgrading of numerous ICT devices and towards fewer high quality multi-functional devices.

This is facilitated by institutions with appropriate levels of regulation and enforcement of (i) digital consumer service rights (e.g., fair access to digital markets, effective rights to reject online profiling, equity of rights and responsibilities for consumers and producers in both the physical and digital spheres), (ii) anti-trust measures to safeguard consumers against anti-competitive markets, (iii) clear regulation on the ownership of consumer data, (iv) a framework of fundamental digital rights which cannot be waived by agreement.

Production (P)

In the ICT and electronic equipment sector, concerns over social and environmental impacts of critical minerals, as well as supply chain risks, drive continuous improvements in material efficiency, material simplification (redesigning products for component recovery), and miniaturisation. This includes both infrastructure (data centres, networks, servers) and the manufacture of digital devices (phones, computers, peripherals). However, overall ICT infrastructure still expands significantly in a pervasively digitalising world. Efforts are underway to standardize data collection within the ICT sector to track and monitor the emissions and energy demand of the sector which is primarily fulfilled by renewable energy sources.

Key CE strategies:

- *Refuse*: Discourage unnecessary purchases (buying new devices) or device usage – “digital detox” (C) as well as promotion/marketing of new products without significant upgrades (P)
- *Refuse*: Avoid unnecessary data streaming or storage needs, e.g., delete duplicate media, refuse to stream for views boosting (P, C)
- *Rethink / redesign*: Improve transparency of sustainability labelling of digital devices to inform consumer decision making on GHG and material footprints (P, C)
- *Rethink / redesign*: Increase utilisation rates of ICT devices (e.g., monitors, projectors, networks) (C)
- *Rethink / redesign*: Promote the use of multifunctional devices or wearables to decrease the amount of bulk and speciality materials (P), although the inclusion of active components (such as integrated circuits) is anticipated to rise.
- *Rethink*: Providing public digital services to ensure a fair access to digital markets (C, P)
- *Reduce / redesign*: Design lightweight devices with improved longevity, repairability, modularity, disassembly and recycling potential, thus avoiding obsolescence (P)
- *Reduce*: Source and utilise secondary raw materials in ICT infrastructure (P)
- *Reduce:* Localise computing & promote micro-data centres to reduce data network and transmission footprint (P, C)
- *Reduce*: Consolidate data centres (P), to reduce the amount of hardware used at each physical location
- *Reduce*: Improve efficiency of data exchange and streaming protocols (e.g., wide-spread adoption and further development of Web Sustainability Guidelines (P)

Narrative 2 – Slow focus

Motivation

Proficiency of both producers and consumers in repairing, refurbishing, and remanufacturing items and utilizing digital applications supporting these practices is highly advanced. Qualified installers and repairers possess extensive know-how in these areas. There is a cultural shift towards valuing the longevity of items, emphasizing repair or repurposing over purchasing new ones, including policy frameworks that incentivise this behaviour. User needs are addressed case-by-case to determine the optimal course of action at the end of an item's lifespan, whether it be repair or replacement with a new one. Servitisation results in firms being the owners of durable goods, providing incentives for design for lightweighting, reparability and longer lifetimes.

Overall approach

The emphasis of action is on slowing material cycles to improve circularity and reduce GHG emissions. The R-strategies *reuse*, *repair*, *refurbish*, *remanufacture* and *repurpose* receive particular attention. Emphasizing repair and maintenance might sustain the utilisation of outdated, less efficient technologies, potentially resulting in increased energy consumption, emissions, and impeding necessary technological advancements. For example, prolonging the service life of a fridge may be disadvantageous over replacing it with a smart fridge that is more energy efficient and can make optimal use of green electricity. Downside risks are emissions of remaining goods overcompensate resource and emissions savings on the manufacturing side. These risks need to be handled by regulation to harvest the benefits of slowing material cycles.

European perspective and global context

A key benefit of the Slow focus is reducing the dependency on imports through utilizing existing products and infrastructure longer. Countries and regions like the EU with high in-use stocks have an advantage over developing countries which have yet to build up stocks. This may perpetuate global inequality.

Role of different actors

Consumers value used items more and invest extra efforts to preserve and maintain them; ownership still plays an important role. Producers shift to repair, remanufacturing, and maintenance services. Producers invest in technologies and research to increase the maximum life time of the new products put on the market. They also find innovative ways to repurpose existing goods and infrastructure for the transition. Policy makers penalize raw material consumption and waste generation and incentivise the preservation of existing products and structures where it aligns with climate goals. Robust regulations clarify intellectual property rights concerning repair manuals and repaired, refurbished, or remanufactured products, and promote extended producers' responsibility. Retrofitting and repurposing existing buildings and spaces is supported by stricter regulation.

Mobility

Consumption (C)

More readily accessible information and technical support via digital platforms support user-led repair and reconditioning of vehicles and micro-mobility technologies (bikes, scooters, drones). Incentives for repair and maintenance of goods can shift consumer preferences from replacement to repair while creating value added within the country compared to the region a replacement good would come from.

Production (P)

Increased use of shared vehicle fleets (enabled by digital platforms) incentivises mobility providers to optimise vehicles for efficient maintenance and repair, including modular replacement or refurbishment of key components. Turning roads into bus lanes, bike lanes and urban green spaces incentivises a shift to public and non-motorized modes of transport. Retrofitting existing vehicles with electric drive trains and switching the internal combustion engines to run on sustainable fuels reduces material needs for manufacturing new vehicles while reducing operational emissions during the remaining lifetime.

Key CE strategies:

- *Reuse*: Develop reuse markets through digital platforms & exchanges for vehicle components (P)
- *Reuse*: Retrofitting internal combustion engine (ICE) vehicles, especially trucks and buses but also boats and ships, with electric drive trains, including batteries and pantographs preserving the vehicle structure (P)
- *Reuse*: Converting existing/remanufacturing motors of heavy trucks to run on more sustainable fuels, e.g., hydrogen (P)
- *Reuse / Rethink*: Design batteries to be reusable and increasing lifetime of batteries to avoid material needs/environmental impacts of manufacturing for electrification of transport (P)
- *Reuse*: Converting roads to public transport (e.g., bus lanes), bike lanes and urban green spaces (P)
- *Repair / Rethink*: Simplification of material composition (e.g., reduced use of multiple alloys) enables component disassembly and replacement (P)
- *Repair*: Enable predictive maintenance to replace the fixed term repair scheduling and scrapping (C)
- *Repair*: Improved maintenance and development of low-carbon transport infrastructure (e.g., railways) to make operations more reliable and encourage mode shifting (P)
- *Reuse:* Enable smart driving which could extend the lifetime for reuse, e.g., tire wear, break wear (C)

Buildings and Household services

Consumption (C)

For building use, shift towards flexible, reconfigurable space enables reuse and repurposing (e.g., office to residential conversions), supported by urban planning and policy reform in favour of densification. Digital platforms enable increased reuse (second-hand trading) and refurbishment, reconditioning of consumer goods (incl. devices, clothes). More established local repair mechanisms and more economic reverse logistics systems covering larger areas (urban and rural) provide repair guarantee to customers building a relationship of trust between them and service providers. In addition, there is a reliable supply of spare parts for repairing. Such mechanisms and support policies incentivise consumers to repair and properly maintain goods instead of buying new products, thereby prolonging use phases and reducing waste.

Production (P)

A general focus on retrofitting and repurposing existing buildings and spaces instead of new construction reduces primary material inputs significantly with a strong emphasis on thermal retrofits to make existing buildings fit for a low-carbon future. Where new buildings and spaces are built, they are designed in a modular and reconfigurable way from the start to enable easy repurposing throughout their lifetime. Building information models from design and construction stage are integrated into building operation and maintenance, enabling lifetime extensions of key building components. Digital platforms facilitate information flows and exchange of building components as well as consumer goods. A pervasive shift from single-use packaging to reusable packaging e.g., relying on Deposit Return Systems, reduces the need for virgin materials, recycling and waste treatment. Extended producer responsibility policies are further revised to be more inclusive, including through supporting small medium enterprises (SMEs).

Key CE strategies:

- *Reuse*: Develop reuse markets through digital platforms & exchanges for building components and consumer goods (P)
- *Reuse*: Via thermal retrofitting allow continued use of existing buildings with a low carbon footprint (P)
- *Reuse / Repurpose*: Reusing building stocks, e.g. outside urban areas, which are currently less and less in use. This can be facilitated by home office and digital services (P, C)
- *Reuse*: Give the right price signals for consumers to choose refurbished appliances and equipment (C)
- Reuse: Integrate reuse/refurbishment into public procurement contracts (C)
- *Reuse*: Promote reuse instead of single-use packaging via Deposit Return Systems (DRS) and Extended Producer Responsibility Schemes (C, P)
- *Repair*: Use of BIM from building design stage, digital twins, IoT sensors to improve maintenance and to extend lifetime of key components (P)
- *Repurpose / redesign*: Redesign or repurpose existing buildings for new uses to avoid new construction (and land use) as much as possible (e.g., older people in repurposed homes supported by younger residents (P)
- *Repurpose / redesign*: Design new buildings for flexible use to promote future repurposing and adaptations (e.g., rooms in houses being easily changed for different purposes) (P)
- *Repair*: Extend the lifetime of buildings and appliances with improved design, maintenance, and refurbishment via incentives (e.g., repair support subsidies, modular design easily enabling replacement of spare parts, service maintenance contracts which could preventively diagnose repair needs) (P)

Digitalisation (ICT Sector)

Consumption (C)

Consumption norms shift towards more use of second-hand or reconditioned digital devices, and away from novelty-seeking purchases of latest release ICTs. Widespread access to and use of repair cafes, shops, and information resources.

Production (P)

Redesign of ICT infrastructure and devices embeds circularity principles to enable more repair, remanufacturing, and reuse of components. Planned obsolescence becomes illegal. Product-service business models create strong incentives for producers to design, manage, and repurpose hardware over its full cradle-to-grave lifecycle.

Key CE strategies:

- *Reuse, repair, refurbish, remanufacture, repurpose*: Implement product-as-a-service models (to use rather than own devices) with producers responsible for lifecycle management (P, C)
- *Reuse, repair, refurbish, remanufacture, repurpose*: Digital product passports and/or blockchain using a standardized, interoperable software for transparent tracking of device components and materials (P)
- *Reuse*: Expand and quality assure second-hand marketplaces, stores, exchanges for digital devices (P, C)
- *Repair*: Provide cost-effective repair services, with increased facilities and skills training (e.g., improved decision-making via AI in repair services by analysing product information including age, brand, type, and repair history, suggesting appropriate actions and locating technicians as needed) (P)
- *Repair*: Implement right-to-repair laws, and laws against planned obsolescence (P)
- *Repair*: Repairing manuals and tutorials on public access platforms along with easy access to spare parts (C, P)
- *Repair*: 3D printing of spare parts for repair of appliances (P, C)
- *Repurpose:* Develop 'adaptive reuse' business models (e.g. LCDs as TVs) (P, C)
- *Repurpose*: Repurposing servers (5-year lifespans)[1] and other hardware in traditional (retired) data centres (P)
- *Refurbish*: Installation of software updates, hardware dissembles and replacement (P, C)

1 https://www.datacenterdynamics.com/en/analysis/re-use-refurb-recycle-circular-economy-thinking-and-data-center-it-assets/

Narrative 3 – Close focus (recycling)

Motivation

In a world with geopolitical tensions, national security and sovereignty considerations shape policy making. With supply chains being less integrated globally and the objective to reduce or avoid dependencies on material and energy imports from other geopolitical blocks, domestic mining of resources and enhanced efforts to recycle bulk and critical materials to keep them in use within the economy as long as possible are cornerstones of the implementation strategy.

Overall approach

The emphasis of action is on closing material cycles to improve circularity. The R-strategies *recycle* and *recover* receive particular attention. Efforts focus on minimizing landfilling, waste incineration, and primary material extraction, but material flow rates in society (and thus economic activity) may increase.

European perspective and global context

The EU collaborates with strategic partners to guarantee access to primary resources but is in competition with other regions and reduces supply chain dependence on those.

Role of different actors

Efforts focus on producers/firms and on technological development to keep materials within the economy as much as possible. Consumer action is required to some degree (e.g., acceptance of products designed for recycling, standardized packaging) to maximize recycling yields. To facilitate this, there is a need for increased incentives to correctly recycle occasional use items, as well as transparent traceability in processed recyclables to establish and uphold public confidence in the system. Source waste segregation and source-separated waste collection provides cleaner feedstock for recovering and recycling materials.

Mobility

Consumption (C)

Consumers broadly support changes in vehicle design for increased recyclability as well as us buying and using vehicles – both motorized and non-motorized – built from recycled rather than virgin materials.

Production (P)

A focus on increasing recycling and recovery of materials from transport infrastructure, in particular road infrastructure, reduces construction waste and helps reducing materials that are currently mostly derived from fossil fuels (e.g., bitumen/asphalt as a by-product of oil refining).

Digital product passports facilitate disassembly in the scrapyard for improved recovery and recycling of materials. This includes battery materials needed for the electrification of transport.

Digital provenance, tracking and sorting technologies (e.g., sensors, AI visual recognition systems) help automate disassembly, separation and recycling of vehicle components at end-of-life (e.g., aluminium). Improved separation is enabled by narrow strategies that redesign products for material simplification to enable mixed recyclates[2] to keep quality, properties and value comparable to virgin materials.

Key CE strategies:

- *Recycle*: Automation of sorting and separation technologies for end-of-life vehicles to boost recycling rates (P)
- *Recycle*: Design batteries suitable for recycling and build up efficient battery recycling facilities to reduce reliance on primary specialty materials for transport electrification such as lithium or cobalt (P)
- Recycle: Implement unified battery passports for EVs that facilitates trade among regions and enhance recyclability (P)
- *Recycle/recover*: Increased asphalt and construction waste recovery and recycling in transport infrastructure (P)

Buildings and Household services

Consumption (C)

Improving source-separated waste collection, by introducing incentive schemes for consumers, increases recycling yields. For consumer goods, digital product passports (incl. QR codes and RFID tags) attached to materials, components and final products help identify high-value material components for disassembly and recycling, incentivised by smart ‘pay-as-you-throw’ waste collection systems. Consumers benefit from enhanced product labelling that provides comprehensive information on concepts like recyclability and recycled content within the product.

Production (P)

On the production side, design for high recyclability (e.g., ability to separate several parts of a given good to recycle them separately) becomes the new standard. In addition, increasing recycling rates from buildings, consumer goods and packaging at end-of-life is a key focus. For building demolition and dismantling, building information models (BIM) identify material components (by location, volume, design) to enable disassembly and recycling and creating a market for these materials. Landfilling and incineration become more expensive. Standardization of single-use packaging allows easier waste separation and therefore higher recycling rates. Potential to reduce virgin material in closed-loop recycling depends on material/product traits, substitution rates, and economic viability.

Key CE strategies:

- *Recycle*: Expansion of waste management infrastructure for WEEE (waste electrical and electronic equipment) to collect, disassemble, and recycle consumer goods (P)
- *Recycle*: Use of BIM (for building end-of-life) and digital product passports (consumer goods end-of-life) to increase recycling rates of high-value material components (P)
- *Recycle:* Utilize smart bins to monitor household waste sorting and employ advanced recycling technologies to address material complexity, thereby increasing recycling rates (P, C)
- *Recycle*: Recycling materials from buildings at end-of-life for new construction focusing on local treatment options (P)

[2] recyclate: raw material sent to, and processed in, a waste recycling plant or materials recovery facility (https://www.wordnik.com/words/recyclate).

- *Recycle/Redesign*: Design buildings for deconstruction (instead of demolition) to promote future reuse and recycling of materials (P)
- *Redesign:* design products to allow for separate recycling of different components (P)
- *Recycle*: Standardise packaging to ease recycling (P)
- *Recycle*: Incentivise source-separated collection systems including Deposit Return Systems (DRS) and Extended Producer Responsibility Schemes covering different materials to reduce the level of contamination thereby increasing the quality of the materials after collection (C, P)
- *Recycle*: Enhance recyclate marketability via political interventions, like setting targets for their use in products, and offering economic incentives (P)

Digitalisation (ICT Sector)

Consumption (C)

Widespread access to and incentives to use e-waste recycling facilities.

Production (P)

Collection, processing, and recycling facilities for ICT devices become widely accessible, with strong economic incentives for e-waste recovery and reuse.

Key CE strategies:

- *Recycle*: Digital product passports enable device recovery for e-waste value streams (P)
- *Recycle*: Improved technology for 'urban mining' (e.g., pyrometallurgical, hydrometallurgical and biohydrometallurgical recovery) (P)
- *Recycle*: Incentivise collection and recycling of 'hibernating' stocks of stored, unused devices (C)
- *Recycle*: Safe device disassembly before disposal (C, P)
- *Recycle*: Expansion of waste management infrastructure for ICT collection & recovery (e.g., e-waste pre-processing facilities to perform sorting, dismantling, shredding, compression, concentration) (P)
- *Recycle*: Knowledge transfer on waste management and recycling from developed to developing countries (P)

CE Narrative Summary

Based on the above narrative descriptions, a summary table for each of the three focus areas is presented below that mirrors the structure of the model parameter tables that follow in the next section.

Table 2: Summary table for Mobility focus area.

Parameter/Indicator	Circular Economy									
	No	reason	Narrow	reason	Slow	reason	Close	reason	Combined	reason
Total motorized travel demand (personal kilometer per person)	High	continue with focus on private EVs	Low	better urban planning and digitisation remove need for travel	Medium		High		Low	Narrow dominates
Electric bus penetration	Low	focus on private EVs	Medium	reduced private car use requires faster expansion of public transport offers, based on new electric busses	High	accelerated electrification and expansion of bus fleet through retrofitting diesel busses	Low	focus on recycling of EV batteries	High	Narrow and Slow dominate, fast electrification of busses due
Public transport share *(PT mode share %)*	Low	focus on private EVs	High	reduced private car use, investments in public transport	High	higher acceptance for public transport, fossil-free and improved offerings	Low	still focus on private EVs	High	low private car use
Shared mobility (*out of total personalized mobility*); load factor for ldvs	Low	focus on private EVs	High	service-based transport based on high digitalisation	Medium	More readily accessible information and technical support via digital platforms	Low	still focus on private EVs	High	Narrow dominates, lower private ownership, lower car use, more dense cities
total number of ldvs	High	focus on private EVs	Low		Medium	longer lifespans for private cars, but not necessarily a reduction in car free households (?)	High	still focus on private EVs	High	lower private ownership
Teleworking (% reduction in commuting trips)	Low	some displacement of work commute, however majority of work commute recovers from post-COVID dip	High	consistent with substitution of physical travel for work, retail and public services	Medium	high digitization (?)	Low		High	Narrow dominates
Active travel modes (% mode share)	Low	focus on private EVs	High	Mode shift towards active mobility such as walking and biking	Medium	Converting roads to public transport (e.g., bus lanes), bike lanes and urban green spaces	Low	Focus on private EVs	High	Narrow and Slow dominate
Average material intensity of LDVs	High	current trends of bigger EVs continue	Low	LDVs mainly used for long-distance travel and shared mobility leading to right-sizing of vehicles for trips	High	Longer lifespans of existing vehicles which are heavier than lightweighting approaches	NA	depends if recyceable batteries require more weight or if they can be added to lighter vehicles.	Low	Narrow dominates
Vehcile class distribution (% heavy duty vehicles): average vehicle weight	High	current trends of bigger EVs continue	Low	smaller vehicles for urban vehicles escpecially	NA	depends if Retrofitting existing vehicles adds more weight	High	current trends of bigger EVs continue	Low	Narrow dominates
Light motorized forms of mobility (e.g., e-scooters, e-bikes) (% mode shift from LDVs to 2/3 wheelers)	Low	current trends of LDVs continue	High	Light motorized forms of mobility displace more material-intensive forms of mobility in certain applications	Medium	Digital platforms support user-led repair and reconditioning of vehicles and micro-mobility technologies	Low	current trends of LDVs continue	High	Narrow and Slow dominate
(EV) Battery lifetime	Default	current trend	Default		High	Design batteries to be reusable and increasing lifetime of batteries to avoid material needs/environmental impacts	Default		High	Slow dominates
Vehicle lifetime	Default	current trend	Low	high usage of shared EVs mean lower life cycles	Medium-High	Repair / Rethink, reuse strategies allow for a longer vehicle life time	Default		Medium	Combination of Narrow and Slow
Air mode share (or AIR pkm)	BAU		Low	Substitution of physical travel for work, retail and public services	BAU		BAU		Low	driven by Narrow strategies
LDV mode share	High	focus on private EVs	Low	Demand reduction for LDV mode share due to teleworking, demand reduction	Low-Medium	e.g. Due to teleworking and rail/bus mode shift	High		Low	Narrow dominates
Energy intensity of travel demand (fuel consumed per pkm for Road modes/ldvs)	High		Low	Data-driven optimisation of traffic flows plus smart/eco driving techniques enabled by digitization	High		High		Low	Narrow dominates

Table 3: Summary table for Buildings and Household Service focus area.

Parameter/Indicator	Circular Economy									
	No	reason	Narrow	reason	Slow	reason	Close	reason	Combined	reason
Floor area per capita	High	in global comparison, floor area per capita in the EU is already high (though not as high as US and AUS) and rising	Low	sharing spaces and downsizing by moving or splitting housing units can potentially reduce the floor area per capita considerably	Medium	lifetime extension of existing buildings through renovation and revitalisation limits new floor area	High		Low	Narrow dominates
Building occupancy (share of daily/weekly time occupied)	Medium		High	Opening buildings for use during off-peak hours can increase building occupancy and reduce need for floor area	Medium		Medium		High	Narrow dominates
Household size	Low	Household sizes are are shrinking in the EU with a trend towards single-person households and lower birthrates	High	sharing spaces could involve increasing household sizes e.g. pensioners with students, WGs	Medium	revitalisation of an area can lead to larger household sizes	Low		High	Narrow and Slow dominate
Population density	Medium	Population density is increasingly concentrating in urban centres	High	Sharing spaces and downsizing by moving or splitting housing units can increase local population densities	Low	Renovating and revitalising rural building stock can slow/reverse increase in population density by locating people in sprawled areas	Medium		Medium	Combination of Narrow and Slow
Single-family house share of all building types	Medium		Low	Splitting housing units can reduce the demand for construction of single-family houses	High	Renovating existing building stock can slow the transition from single-family to multi-family buildings	Medium		Medium	Combination of Narrow and Slow
Building density (sprawl)	Medium		Low	increasing number of housing units in existing stock reduces need for new construction	Medium		Medium		Low-Medium	Combination of Narrow and Slow
Building lifetime	Medium		Medium		High	Renovating and revitalising existing building stock can extend their lifetime	Low	increased demand for recycled construction materials might motivate the premature demolition of buildings that have been out of use for some time	Medium	Combination of Narrow, Slow and Close
Material intensity (kg/m2)	Medium		Low	Optimized design can reduce the material intensity per floor area	Low	Reusing components in future construction can limit the amount of material needed to construct a new building	Medium	Closing loops does not necessarily reduce material intensity of buildings it only provides this material demand more efficiently	Low	Narrow and Slow dominate
Lightweighting materials	Medium	Some lightweighting is already applied when it is cost-efficient	High	Lower material demand	Low	Second-hand materials may not be fit for lightweighting techniques; lightweight material can have shorter lifetime	Medium		Medium	Combination of Narrow and Slow
Disassembly share of all demolition	Low		Low		High	Reusing components of abandoned buildings	Medium	With highly efficient and cost-effective recycling the incentive to employ labour intensive disassembly is lower	High	Slow dominates
Separation of demolition waste	Medium		Medium		Medium		High		High	Close dominates
Recyling share	Medium		Medium		Medium		High		High	Close dominates

Table 4: Summary table for Digitalisation focus area.

Parameter/Indicator	Circular Economy									
	No	reason	Narrow	reason	Slow	reason	Close	reason	Combined	reason
Data Centre Total Numbers	High	v rapid current growth, AI driven	Low	Consolidation, reduced demand for DCs	Medium	Existing DCs refurbed, lower demand for new DCs	High	no effect on new builds or refurbs, = No	Low	Narrow dominates
Data Centre Hyperscale Share	High	dominant current scale, reinforced by genAI	High	Material economies of scale in hyper DCs	Medium	Existing DCs refurbed, lower demand for new DCs	High	no effect on new builds or refurbs, = No	High	Narrow dominates
Data Centre Energy Efficiency (PUE)	Medium	improving fairly rapidly, new standards	High	rethinking designs improves cooling tech (natural heat sinks)	Medium	Aging infrastructure limits efficiency	Medium	no effect on new builds or refurbs, = No	High	Narrow dominates
Data Centre Material Intensity	High	low ec incentives for material efficiency	Low	rethinking designs	Medium	refurb = opportunity for more efficient materials	High	no effect on new builds or refurbs, = No	Low	Narrow dominates
Data Centre Lifetime	Low	rapid tech change, incentive for new builds	Medium	redesign for longevity & refurb	High	refurb	Low	no effect on lifetime, = No	High	Slow dominates
Data Centre Water Usage for Cooling	High	low ec incentives for water efficiency	Low	redesign for closed loop or 'free' cooling	Medium	refurb = opportunity for more efficient systems	High	no effect on new builds or refurbs, = No	Low	Narrow dominates
ICT Network Infrastructure Total Amount	Medium	rapid current growth, but DC location near demand centres	Medium	ltd opportunity to redesign mat efficiency of networks	Low	refurb or repurposing of existing networks	Medium	no effect on lifetime, = No	Low	Slow dominates
ICT Devices Total Numbers	High	v rapid current growth	Low	some opportunity for redesign + multifunctionality + sharing / leasing business models	Medium	refurb (modular devices) reduces demand for new	High	no effect on new builds or refurbs, = No	Low	Narrow dominates
ICT Devices Energy Efficiency	Medium	improving fairly rapidly, new standards	High	redesigns for efficiency	Medium	ltd or even slowing effect on more efficient new generations	Medium	no effect on new builds or refurbs, = No	High	Narrow dominates
ICT Devices Material Intensity	High	inc. critical minerals	Low	redesigns for mat efficiency + diversity of materials (reduce geopolitical risk)	Medium	refurb = opportunity for more efficient material use	High	no effect on new builds or refurbs, = No	Low	Narrow dominates
ICT Devices Lifetime	Low	current rapid turnover, innovation in new models drives short lifetimes	Medium	more futureproofed hardware designs	High	refurb for lifetime extensions	Low	no effect on new builds or refurbs, = No	High	Slow dominates
E-waste (all ICTs)	High	dominated by end-use devices	Medium	redesign for refurb (supports Slow)	Medium	refurb (modular devices) reduces demand for new + extends lifetimes	Low	improved value capture from recycling (e.g., critical minerals)	Low	Close dominates

Model Parameterisation

To develop quantitative pathways, the narratives described in the previous sections need to be translated into parametric input assumptions for the modelling tools used in the pathways development process. Here we follow the process established in the development of the SSPs (Riahi, van Vuuren et al. 2017) and present tables that map key model input parameters to the different circular economy narrative dimensions and assign ordinal attributes to them. This process allows establishing consistency across the different models used for the quantification of the CE-driven net-zero pathways while retaining flexibility for the modelling teams to choose parameter values that fit this structure and needs of the individual models.

Modelling tools

For the quantification of pathways, a suite of modelling tools is currently foreseen (see Table 5 and Figure 5). Detailed representations of circular economy strategies featured in industrial ecology modelling approaches - including dynamic Material and Energy Flow Analysis (MEFA), prospective Life-Cycle Assessment (LCA) and Multi-Regional Input/Output scenario (MRIO) modelling - are combined with global Integrated Assessment Models (IAMs) for economy-wide climate change mitigation analysis. These macro-level models are informed by detailed service-based (e.g., shared mobility) or sectoral models (e.g., building construction and renovation) to address production and consumption practices for reducing material throughput and improving the utilisation of material stocks. Taken together, the suite of modelling tools shown in Table 5 allows comprehensive coverage of interactions among different economic sectors and material stocks and flows (IAM MESSAGEix-GLOBIOM, dynamic MEFA model MISO2, MRIO model EXIOfutures, and CGE model JRC-GEM-E3), linking these to planetary boundaries related to material budgets (ERA), while also providing important entry points for analysing consumer-focused transformations including the adoption of new business models in service sectors (MESSAGEix-Materials, -Transport, -Buildings modules, GLANCE, GAINS, EUBUCCO). The combined suite of models allows addressing the biophysical implications of CE strategies in detail using industrial ecology methods but also look at the economic dimension that is addressed in the IAM and CGE modelling tools.

Table 5: Suite of complementary macro-level and sector-specific modelling tools used and developed in the CircEUlar project.

Model	Institution	Type (Sectors, Materials, …)	Region
MESSAGEix-GLOBIOM	IIASA	Integrated Assessment Model (energy supply, linked to energy end-use models, land use)	Global (12 regions)
+ MESSAGEix-Materials	IIASA	Energy-intensive industries at process level, incl. material flow/stock dynamics for selected sectors	Global (12 regions)
+ MESSAGEix-Transport	IIASA	Transport model with heterogenous consumer groups for the light-duty vehicles sector	Global (12 regions)
+ MESSAGEix-Buildings	IIASA	Building stock model (residential and commercial buildings)	Global (EU countries, ~30 other regions)
GLANCE-GAINS	IIASA	Appliance stock turnover model	Global (EU countries, 12 global regions)
GAINS	IIASA	Air pollution and GHG+ model incl. waste sector	Global (165 regions, 44 European countries)
EXIOfutures	NTNU	An environmentally extended MRIO monetary + hybrid (163 industries, 200 products) scenario simulation model based on EXIOBASE	Global (43/44 countries, 5 ROW regions)
MISO2	BOKU	Dynamic biophysical stock-flow model, mass-balanced (~16 materials), to be	Global (~170 countries)

		embedded into economy-wide material and energy flow analysis of circularity	
GLOMIS	BOKU	biophysical, stock-driven model for global mobility infrastructure	Global (~170 countries)
ERA	EMPA	Translation of planetary boundaries into resource budgets (materials or energy) to assess ecological resource availability (ERA)	Global (resource budgets can be allocated to regions/countries)
EUBUCCO	TUB	Machine-learning model of buildings and street networks drawing on open street map data	Europe (27+3 countries)
JRC-GEM-E3	JRC	CGE model (31 production sectors)	Global (38 regions)
IMUC - Integrated Model of Urban Circularity	INEGI	Machine-learning model integrating buildings, transport infrastucture, and socio-economic variables, analysing energy and materials implications.	Calibrated for 2 European cities (Porto, Berlin) – scalability to be assessed.

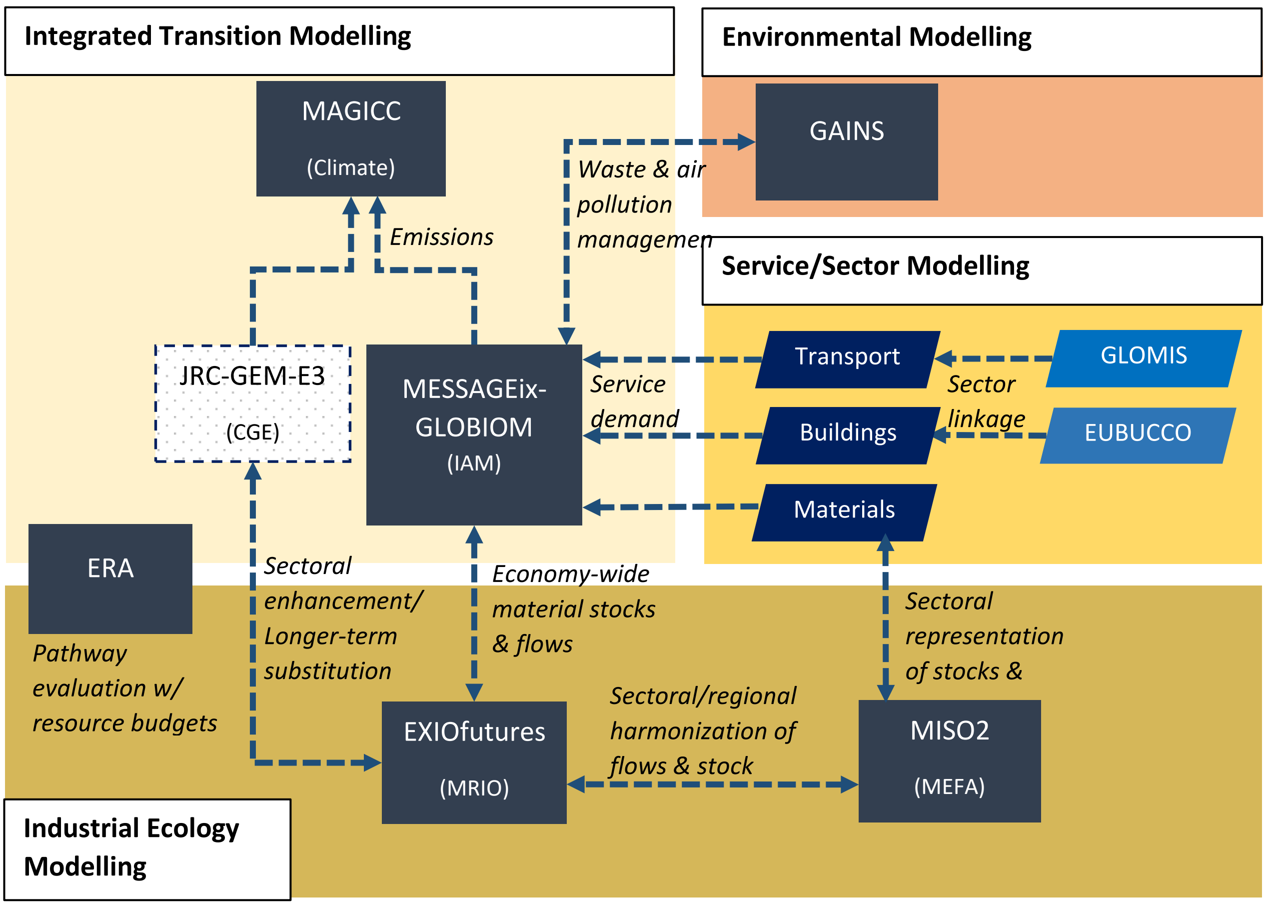

Figure 5: Overview of modelling tools employed in CircEUlar for the quantification of CE-driven net-zero pathways.

Parameter Tables

In the following we present the tables that assign qualitative ordinal attributes of parameter sets in individual models to the CE dimension of the narrative variants.

Table 6: Mapping table for the MESSAGEix-Buildings model.

Parameter/Indicator	Circular Economy				
	No	Narrow	Slow	Close	Combined
Buildings per-cap floor space reduction	No	Yes	No	No	Yes
Buildings increase in reuse of vacant buildings	No	Yes	No	No	Yes
Buildings shift to bio-based materials	No	Yes	No	No	Yes
Buildings shift to low-carbon materials	No	Yes	No	No	Yes
Buildings lifetime extension through improved design of new buildings	No	No	Yes	No	Yes
Buildings lifetime extension via renovation and repurposing of existing buildings	No	No	Yes	No	Yes
Buildings improved design for disassembly	No	No	No	Yes	Yes
Buildings increase in use of materials with high recycled content	No	No	No	Yes	Yes
Buildings increase in reuse of existing materials	No	No	No	Yes	Yes
Buildings increase in recycling of materials at the end-of-life	No	No	No	Yes	Yes

Table 7: Mapping table for the MESSAGEix-Transport model.

Parameter/Indicator	**Circular Economy**				
	No	Narrow	Slow	Close	Combined
Total (motorized) travel demand: *personal kilometer per person (pkm)*	High	Low	Medium	High	Low
Public transport share: PT mode share %	Default	High	High	Low	High
Shared mobility (out of total personalized mobility): average load factor for LDVs	Low	High	Medium	Low	High
total number of LDVs	Default	Low	Medium	High	High
Teleworking: % reduction in (commuting trips) pkm	Low	High	Medium	Low	High
Active travel modes (% mode share)	Default	High	Medium	Low	High
Light motorized forms of mobility (e.g., e-scooters, e-bikes): % mode share 2/3 wheelers	Default	High	Medium	Low	High
Vehicle lifetime (# of years)	Default	Low	Medium-High	BAU	Low-Medium
Air mode share (or AIR pkm)	Default	Low	BAU	BAU	Low
LDV mode share	High	Low	Low/Medium	High	Low

Energy intensity of travel demand (fuel consumed per pkm for Road modes/LDVs)	Default	Low	High	High	Low
Possible additions					
Electric bus (share of EV buses out of total Bus vehicles)	Low	Medium	High	Low	High
Average material intensity of LDVs	High	Low	High	Default	Low
Vehicle class distribution (% heavy duty vehicles): average vehicle weight	High	Low	Default	Default	Low

Table 8: Mapping table for the MESSAGEix-Materials model.
* Residual demand is demand not explicitly provided by the MESSAGEix-Buildings/-Transport/-Energy modules.

Parameter/Indicator	**Circular Economy**				
	No	Narrow	Slow	Close	Combined
Residual Demand*					
Plastics	High	Low	Medium	High	Low
Fertilizer	Medium-High	Low	Medium	High	Low
Steel	High	Low	Medium	High	Low
Cement	High	Low	Medium	High	Low
Aluminum	High	Low	Medium	High	Low
Recycling					
Chemicals	Default	Default	Default	High	High
Iron and Steel	Default	Default	Default	High	High

Cement	Default	Default	Default	High	High
Aluminum	Default	Default	Default	High	High

Table 9: Mapping table for the GLANCE-GAINS model.

Parameter/Indicator	**Circular Economy**				
	No	Narrow	Slow	Close	Combined
Sharing of appliances (e.g, washing machines)	Low	High	No	No	High
Substitution of PP & PS with BIO-PLA	No	High	No	High	High
Lifetime extension (first generation)	No	No	High	No	High
Life time extension (second generation)	No	No	Medium	No	Medium
Reuse of appliance	Low	No	High	No	High
WEEE collection rates	High	High	High	High	High
WEEE reuse - metals	Low	Low	Low	Medium	Medium
WEEE reuse - glass	No	No	No	Low	Low
WEEE reuse - PP, PS, PP	No	No	No	Medium	Medium
WEEE reuse - other plastics and materials	No	No	No	Low	Low
WEEE recycling/downcycling - metals	High	High	High	Medium	Medium

WEEE recycling/downcycling - glass	High	High	High	Medium	Medium
WEEE recycling/downcycling - PP, PS, PP	High	High	High	Medium	Medium
WEEE recycling/downcycling other plastics and materials	Low	Low	Low	Medium	Medium
WEEE incineration	Medium	Medium	Medium	Low	Low
WEEE landfill	Medium	Medium	Medium	Low	Low

Table 10: Mapping table for the GAINS model.

Parameter/Indicator	**Circular Economy**				
	No	Narrow	Slow	Close	Combined
Prevention of food waste generation at source	No	High	No	No	High
Prevention of plastic waste generation at source	No	High	No	No	High
Prevention of paper & cardboard waste generation at source	No	High	No	No	High
Source-separated waste collection	Medium	Medium	Medium	High	High

Recycling	Medium	Medium	Medium	High	High
Composting/anaerobic digestion	Medium	Medium	Medium	High	High
Landfill with gas recovery	Medium	Medium	Medium	High	High
Landfill waste diversion	Medium	Medium	Medium	High	High
Incineration with energy recovery	Medium	Medium	Medium	Medium	Medium

Table 11: Mapping table for the GLOMIS model.

Parameter/Indicator	**Circular Economy**				
	No	Narrow	Slow	Close	Combined
Modal split shift	Default	High	Low	Low	Default
Mobility reduction	Default	High	High	Low	Default
Lifetime extension	Default	Low	High	Low	Default
Car sharing rate	Default	High	Low	Low	Default
Fleet electrification	Default	High	Low	Low	Default
Increased recycling	Default	Low	Low	High	Default
Material substitution	Default	Low	Low	High	Default

Table 12: Mapping table for the MISO2 model.

Parameter/Indicator	**Circular Economy**

	No	Narrow	Slow	Close	Combined
MISO2 inflow-driven (running model)					
material use intensity	Default	High	Default	Default	High
stock lifetimes	Default	Default	High	Default	High
end-of-life recycling rate	Default	Default	Default	High	High
new scrap recycling rate	Default	Default	Default	High	High
increased process yields	Default	High	Default	Default	High

Table 13: Mapping table for EXIOFutures model.

Parameter/Indicator	**Circular Economy**				
	No	Narrow	Slow	Close	Combined
Buildings per-cap floor space reduction - Reduction in total building Final Demand	No	Yes	No	No	Yes
Buildings increase in reuse of vacant buildings - Reduction in total building Final Demand	No	Yes	No	No	Yes
Buildings shift to bio-based materials - Shift to bio-based materials used in building sectors	No	Yes	No	No	Yes
Buildings shift to low-carbon materials - Shift to low-carbon materials used in building sectors	No	Yes	No	No	Yes
Buildings lifetime extension through improved design of new buildings - Lifetime extension in new buildings	No	No	Yes	No	Yes

Buildings lifetime extension via renovation and repurposing of existing buildings - Renovation of buildings with increase in FD sector repair to extend lifetime of old buildings, and repurposing with changing part of capital stock from Non-res to residential, or similar.	No	No	Yes	No	Yes
Buildings improved design for disassembly - New building stock with higher disassembly yield	No	No	No	Yes	Yes
Buildings increase in use of materials with high recycled content - New building stock with new material with high recycling content	No	No	No	Yes	Yes
Buildings increase in reuse of existing materials - Increase in secondary flows (from old stocks) in the production of new buildings	No	No	No	Yes	Yes
Buildings increase in recycling of materials at the end-of-life - Increase of recycling rate of waste management of buildings at the end of life	No	No	No	Yes	Yes
Electric bus penetration - Change in the Interindustry Transactions Matrix (technology parameter)	Low	Medium	High	Low	High
Public transport share - Reduction of FD for private vehicles, increase in FD for public transport	Low	High	High	Low	High
Shared mobility share (out of total personalized mobility) - Reduction FD vehicles	Low	High	Low	Low	Low
Teleworking (share of commuting trips) - Reduction FD vehicles	Low	High	Low	Low	Low
Active travel modes - Reduction FD vehicles	High	High	High	High	High

Vehicle class distribution - Change in the Interindustry Transactions Matrix (technology parameter)	Low	High	Low	Low	Low
Material Intensity of vehicles - Change in the Interindustry Transactions Matrix (technology parameter)	Low	Medium	Medium	Medium	High
Electrification - Change in the Interindustry Transactions Matrix (technology parameter)	Low	Medium	High	Medium	Medium
Lightweight materials - Change in the Interindustry Transactions Matrix (technology parameter)	Low	Medium	Low	Medium	Medium

Table 14: Mapping table for JRC-GEM-E3 model.

Parameter/Indicator	**Circular Economy**				
	No	Narrow	Slow	Close	Combined
Car-sharing and optimization of the use of private vehicle stock	Low	High	Low	Low	High
Mode switching from private to public transport	Low	High	Low	Low	High
Material efficiency in the production of transport equipment	Low	High	Low	Low	High
Deployment of electric vehicles	Medium	High	High	Medium	High
Lifespan of existing vehicle stock	Low	Low	High	Low	High

Thermal retrofitting of buildings	Medium	Medium	High	Medium	High
Recycling in materials sectors (e.g. iron and steel)	Low	Low	Low	High	High
Mining and extraction of raw materials	High	Low	Medium	Low	Low

Table 15: Mapping table for IMUC model.

Parameter/Indicator	Circular Economy				
	No	Narrow	Slow	Close	Combined
Buildings Floors (average)	Low	High	NA	NA	High
Buildings Age (weighted average) - the higher the older	Medium	High	High	NA	High
Family size (average)	Low	High	NA	NA	High
Population density	Low	High	NA	NA	High
Subdivision index	Medium	High	NA	NA	High
Density of public transport stops (public transport stops by area)	Low	High	NA	NA	High
Surface to Volume ratio of buildings (average)	High	Low	Medium	NA	Low
Gross floor area of Housing Units (average)	High	Low	NA	NA	Low

Unemployment rate (SEC21)	Medium	Low	Low	Low	Low
Mixed Used Index	Low	High	NA	NA	High
House prices	High	Medium	Medium	NA	Medium
Diversity of Activities reached by Public Transport compared to maximum accessibility	Low	High	NA	NA	High
Diversity of Activities reached by Walking weighted by the number of activities	Low	High	NA	NA	High
Proportion energy certificates with highest energy efficient labels (A+ to B)	Medium	High	High	NA	High
Proportion of vacant residential units	High	Medium	Low	NA	Low
Ground Space Index (Building footprints/ ground area)	Low	High	NA	NA	High
Floor Space Index (GFA/ ground area)	Low	High	NA	NA	High
Years of education (SEC21)	Low	High	High	High	High

Ratio of dependent-age individuals to working-age individuals (between 25-65)	Medium	Low	Low	NA	Low

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