Present and Future of Circular Economy in Europe

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EXECUTIVE SUMMARY

Despite efforts to increase circularity, to date, the European economy remains highly linear. To sustain our lifestyle, we need 18 tonnes of materials per person per year, 1.5 of which are landfilled. The raw material consumption keeps increasing, the waste production remains high, and the level of material recovery is low: only about 12% of materials are "circled".

This linear extractive economy is a key driver of environmental pollution and contributes to 6 out of 9 planetary boundaries being breached [1], [2], [3]. Resource extraction and use are responsible for about half of the global greenhouse gas emissions and 90% of the loss in biodiversity and water stress. Those issues are worsened by plastic pollution.

The overexploitation of natural resources is expected to worsen as material use is projected to double by 2050 [4]. The electrification of the economy will increase the demand for critical raw materials, such as lithium. The associated pollution leads to significant impacts on health and economic loss, thus calling for urgent societal changes.

The Circular Economy (CE) is critical to reducing resource consumption and achieving net zero by 2050. The CE is a regenerative model that reduces material use, prolongs products' lifetime, reuses and recycles resources rather than disposing of them as waste, designs out pollution, and regenerates natural systems. CE strategies aim to narrow (use less), slow (use longer), close (use again), and regenerate (make clean) material flows.

This paper explores the present and future of the circular economy in Europe, through the lens of the EU net-zero objective. Our goal is to understand the relative contribution of CE strategies to the EU's target-emission pathways, across sectors and products. To do so, we use the EUCalc model to simulate the long-term strategies of the EU towards 2050 and their impacts on greenhouse gas emissions and material demand.

As of today, the EU policies only include milder improvements around circularity for the years to come and miss the 2050 net-zero target. In the baseline scenario, which builds on existing policies, the EU economy improves mainly on recycling rates and energy efficiency. However, little is done on the other principles of CE, such as narrowing, slowing and regenerating material flows. As a result, GHG emissions are only reduced by about 60% with respect to the 1990 level.

A systemic shift in production and consumption patterns towards a more circular economy would allow us to both reach net zero and reduce material demand by half. Following the European Green Deal, The European Commission is currently revisiting and strengthening its environmental policies. It is therefore likely that the deployment of CE actions will accelerate, across all four ways of managing flows in a circular way. This acceleration is necessary to reach the net-zero target by reducing the number of travels and owned appliances, improving the material efficiency and the share of recycled materials, and switching to regenerative construction materials (e.g., timber and natural fibres).

However, we need to keep in mind that this is not a silver bullet, as even with all these drastic changes in place, the demand for some materials will still increase. There are trade-offs between decarbonization and material use, especially around lithium and graphite: the technological changes will still require large amounts of these two materials, raising questions about the environmental and human impacts of extracting them. In addition, there are more planetary boundaries than climate change to address, which will require higher regulatory efforts.

While these drastic changes may seem unrealistic now, we need to realize that, up until the

end of the 19th century, our economy was already mostly circular. We now need to find back the equilibrium between resource management and progress, “transition back” to a more circular economy, and close the circle.

KEY TAKEAWAYS

1. Circular economy strategies are crucial to limit the impingement upon planetary boundaries and social foundations.
2. While legislative and operational efforts around circular economy are being implemented, the European economy is still mostly linear.
3. Current CE strategies and policies are not enough for the European economy to reach net zero by 2050.
4. A systemic shift in production and consumption patterns towards a more circular economy would allow us to both reach net zero and reduce material demand by half.
5. The demand for some critical raw materials such as lithium and graphite will still increase while transitioning towards net zero.

1 WHY IS A CIRCULAR ECONOMY NECESSARY?

Our current linear "take-make-waste" economy is driving our breaching of the planetary boundaries, such as climate change, water scarcity, and biodiversity loss [1], [2], with the associated erosion of our social foundations. We are currently over the safe operating space in 6 out of 9 planetary boundaries [3], notably due to the extraction and use of natural resources:

- **Material use in products is responsible for about half of global greenhouse gas (GHG) emissions** [5], [6]. These emissions stem from (i) the energy used to power extraction and process machineries, and transport for minerals and fossil fuels, and (ii) chemical reactions used in the production of materials.[4] Materials-related GHG emissions also include waste management contributing to about 5% of total GHG emissions in 2016 due to methane released in landfills and waste incineration [8].
- **The extraction and use of natural resources drive over 90% of global biodiversity loss and water stress** [6]. The permanent conversion of forests to agriculture, mining, and energy infrastructure is responsible for 27% of global forest loss [9].[5] Besides deforestation, mining activities can lead to water and air pollution, threatening ecosystems and human health – see e.g., [11], [12], [13], [14].
- **"Novel entities", e.g., plastics, threaten the integrity of Earth system processes** [15]. Novel entities are defined as "new substances […] that have the potential for unwanted geophysical and/or biological effects" [16]. They include, for instance, plastics and synthetic chemicals. Plastic pollution, especially in the marine environment, now poses a planetary boundary threat: the pollution is ubiquitous, not readily reversible, and has severe negative impacts on ecosystems [17], [18]. By posing a threat to the biosphere integrity and raising concerns about human health issues, novel entities also increase the risks on the other boundaries [15].

We are currently on track to increase, rather than decrease, material use and waste production. Material use is projected to double by 2050 [4]. For instance, the global demand for lithium is expected to increase by a factor of 18 in 2030 and by a factor of 90 in 2050, in particular due to the electrification of the economy [19].[6] Meanwhile, the World Bank estimates that global waste generation will increase from 2.01 billion tonnes in 2016 to 3.40 billion tonnes in 2050 [8]. The associated pollution calls for urgent societal changes: the world could lose about 10% of total economic value by mid-century if climate change stays on the currently-anticipated trajectory [21], and the cost of climate change mitigation increases with each year of inaction [22].

The Circular Economy (CE) is a solutions framework that can allow us to limit and start reversing our impingement of the planetary boundaries [23]. The CE can be defined as a regenerative model that reduces material use, prolongs products' lifetime, reuses and recycles resources rather than disposing of them as

[4] The most emission-intense materials are metal, chemicals and cement, accounting for, respectively 7.8, 6.3 and 2.6 % of global emissions, excluding the use of the resulting products (scope 3 down-stream) [7].

[5] To further explore this issue, see the E4S white paper "Pricing and Restoring Natural Capital: A Case Study on Mining and Vegetation" [10], in which a mechanism is proposed to fund and restore vegetation loss.

[6] This increase in material needs raises concerns of potential supply disruption in the European Union (EU), as the EU largely depends on the import of many raw materials. Several critical materials – such as cobalt, graphite, and lithium – face a high risk of supply disruption [20].

waste, designs out pollution, and regenerates natural systems. CE strategies have the potential to reverse the current overshoot of several planetary boundaries, e.g., climate change, land system change, nitrogen cycle, phosphorus cycle, and ocean acidification [24]. By reducing material use, CE directly cuts GHG emissions from mineral extraction, material production, and waste management, while recycled materials are less carbon-intensive than virgin materials [25].[7] As such, the largest potential GHG reductions through circularity come from materials (plastics, metals, cement), food (via waste reduction, improved packaging, nutrient recycling), construction (via material substitution, efficient design, space-sharing, reuse and recycling of components), mobility (car sharing, extended lifetime, improved end of life), and waste management [26]. Specifically in the EU, circular strategies around steel, plastics, aluminium, and cement could reduce industrial emissions by 56% by 2050 [27].[8]

The Circular Economy also has significant socio-economic benefits. Material circularity can accelerate decarbonisation and lower its costs, especially in hard-to-abate sectors such as chemicals [7], [25], [28]. Further, a CE can diminish Europe's dependency on imported materials and increase supply chain resilience, hence ensuring a technically and politically feasible transition. Finally, CE policies could lead to a net GDP gain and employment creation by relying on labour-intensive activities.[9] In the EU, the adoption of CE could increase GDP by almost 0.5% by 2030 while creating almost 700'000 jobs [30]. This transition could especially benefit vulnerable groups by providing new employment opportunities that do not require tertiary education [31].

However, the path to a CE in the EU is fraught with challenges. Past societal choices create a lock-in in the linear economy: institutional preferences, existing infrastructures, consumption habits, and company culture all slow down the adoption of CE actions [2]. While successful CE supply chains tend to be local, the economic efficiency via *economies of scale* favours large plants that deliver a wide area. As a result, the collection systems to reuse and recycle products would have to cover vast distances, making some circular business models prohibitively expensive [32]. The limited presence of circular business models is exacerbated by inconsistent policies and prices that do not reflect the true cost of extracting resources and polluting [2], [33], [34]. Further complexities include the lack of consumer awareness and weak cooperation throughout the supply chain [33]. Finally, the CE transition entails structural changes in the labour market: waste management, services, and repair and installations sectors will gain jobs while mineral extraction, construction, and electronics sectors will likely lose jobs. This shift highlights the need for education and training policies to support the transition [30].

This paper explores the present and future of the circular economy in Europe, through the lens of the EU net-zero objective. Given the large GHG emissions from material use, the European Commission has put the circular economy at the core of the EU strategy for a net-zero economy [35], [36]. Our objective is to understand the relative contribution of CE strategies to the EU's target-emission pathways, across sectors and products. As decarbonisation will require critical raw materials, such as lithium, we will explore how CE actions can help us find the equilibrium between decarbonising faster and at the same time reducing material demand.

[7] For instance, the carbon-intensity of recycled vs virgin materials is: 0.4 vs 2.3 tCO2/t for steel, 0.3 vs 13.5 tCO2/t for aluminium, and 0.4 vs 2.4 tCO2/t for plastics.

[8] Further studies assessing the impacts of circular actions on GHG emissions are reported in Table A1 in the Section A1 of the Appendix.

[9] See Laubinger et al. (2020) for a review of the consequences on the labour market of a transition to a CE [29].

The rest of this paper is organized as follows. We first introduce the CE principles and strategies in Section 2. We then review the current state of CE in the EU by looking at existing regulations, historical trends, and emerging business models (Section 3). Finally, in Section 4, we assess the role played by CE actions in the official decarbonisation pathways of the EU, their impacts on GHG emissions and material use.

2 PRINCIPLES OF THE CIRCULAR ECONOMY

The circular economy (CE) is a regenerative model that reduces material use, prolongs products' lifetime, reuses and recycles resources rather than disposing of them as waste, designs out pollution, and regenerates natural systems. Despite its rapid rise in popularity, the concept is not new. Prior to the advent of single-use plastic bottles in the 1970s, returnable glass bottles were a common practice.[10] Before the invention of synthetic fertilisers at the beginning of the 20th century, agriculture relied on circular strategies such as recycling animal manure, crop rotation to restore soil fertility, and nitrogen fixation by legumes. Even today, indigenous communities keep on reusing products and using waste as resources, e.g., using natural waste for their clothing and fallen natural materials for dyeing [38]. Some of these practices are regaining popularity as several countries, such as France, have now planned to re-introduce a returnable deposit system, circular agricultural strategies are supported in the EU's action plan on organic farming [39], and several companies offer clothes made of recycled plastics and recovered cotton [40].

Circular-economy strategies are strategies that narrow, slow, close, and regenerate economic flows. The academic literature builds on two principal frameworks to conceptualize the circular economy: the Flow Framework [41] and the R Frameworks [42]. In this paper, we focus on the Flow Framework, which proposes four strategies for resource cycling:

1. **Narrow flows (use less)**: using fewer resources to achieve the same purpose, i.e., resource efficiency [41].

2. **Slow flows (use longer)**: designing long-life goods and extending the lifetime of products to prolong their utilisation and slow down the flow of resources [41].

3. **Close flows (use again)**: managing waste as a resource to close the loop between post-use and production, resulting in a circular flow of resources [41]. Using waste as a resource is the last option if either narrowing or slowing flows is not possible.

4. **Regenerate flows (make clean)**: prioritising regenerative resources to produce goods and services through regenerative material and energy management, designing out waste, and excluding toxic chemicals from production processes [43].[11]

Table 1 summarises how the Flow Framework relates to the R Frameworks. The R Frameworks (10, 5 or 3 Rs) propose strategies for a zero-waste economy – detailed in Table 1 – and prioritise reducing before reusing and recycling. Recycling alone is the tail end of a linear economy and the 10 R framework generally orders the R drivers in decreasing order of efficiency. For more information, see Section A2 of the Appendix.

[10] See The History of Plastic Bottles [37].

[11] As this aspect is not strictly related to the fundamental strategies of cycling resources, it is not included in the R Frameworks. However, a circular economy would not be sustainable without flow regeneration, which includes regenerative water management, regenerative material management, regenerative energy management, designing out waste, and excluding toxic chemicals from production processes.

Table 1 - Circular-economy frameworks and strategies		
Flow Framework	**10R Framework**	**Illustrative strategies**
Narrow	**Refuse**	Refuse to produce waste and use virgin and hazardous materials in the design process [44], buy and use less, refuse packaging waste and shopping bags [45], [46]
	Rethink	Increase the usage rate of products, e.g., participate in the sharing economy [47]
	Reduce	Use less material per unit of production, "dematerialise" product design (e.g., [42], [48], [49]), use purchased products less frequently [42]
Slow	**Reuse**	Reuse by another consumer of a discarded product for the same purpose [47]
	Repair	Repair and maintenance of a defective product to use it again with the same purpose [47]
	Refurbish	Restore an old product to bring it up to date [47]
	Remanufacture	Use parts of a discarded product in a new one with the same function [47]
Close	**Repurpose**	Use a discarded product or its parts in a new product with a different function [47]
	Recycle	Process waste materials to convert them into reusable materials
	Recover	Incinerate waste with energy recovery [47]
Regenerate		Shift to renewable and bio-based resources, replace freshwater with rainwater and wastewater [43]

Notes. This table summarises the circular economy strategies between the Flow (Bocken et al.,2016) [41] and R Frameworks (Reike et al., 2018) [42]. It is adapted from Brown et al. (2021) [43] and Kirchherr et al. (2017) [47].

3 STATUS OF CIRCULAR ECONOMY IN EUROPE: REGULATIONS, TRENDS, AND BUSINESS MODELS

3.1 CIRCULAR-ECONOMY POLICIES WITHIN EUROPE

Given the potential of CE strategies to reduce GHG emissions and negative externalities, in recent years the European Commission has promoted the concept of a more circular EU economy, especially in light of its net-zero ambitions. In this section, we will describe the current regulatory frameworks to advance a circular economy, as a background for the subsequent exploration of the role of CE in a transition to net-zero.

The EU legislators have made regulations and directives on CE topics since 1994.[12] Figure 1 reports the timeline of when the current legislations on CE topics in the EU came into force, with a reference to the four main categories of CE actions, namely narrow, slow, close and regenerate. A regulation or directive is colour-referenced with a specific resource flow if its text includes aspects of that resource flow.

New legislation on the circular economy in the EU will be implemented in the near future. Since 2019, the European Commission has put the circular economy at the centre of its legislative strategy, proposing new regulations and directives that are currently being scrutinised by the Parliament and Council. These new proposals are part of the European Green Deal, a policy framework published in 2019 to reach climate neutrality by 2050. The European Green Deal, together with the Circular Economy Action Plan (2020), plans to address issues around critical raw materials, biobased, biodegradable and compostable plastics, microplastics, repairing of goods, textile products, and eco-design for sustainable products. The European Commission also disposes of a set of tools and instruments that help apply these legislative packages, such as the EU Ecolabel, the European Circular Economy Stakeholder Platform and the Level(s) application for sustainable buildings.[13] All directives and regulations are described in Section A3 of the Appendix – including other legislations related to circular economy that we did not consider here.

While the focus of most legislations in force in the EU is on closing and regenerating flows, they also promote narrowing and slowing:

1. Narrowing flows: Only 4 out of the 13 considered legislations mention aspects of narrowing flows, by introducing requirements for using less materials and producing less waste.

2. Slowing flows: Strategies to slow flows are mentioned in 8 out of 13 of the considered legislation, such as the Ecodesign Directive and the Directive on end-of-life vehicles, which include products' reuse.[14]

3. Closing flows: When legislating on CE, the EU authorities have focused on waste management and recycling (11 out of 13 of the considered legislation). A turning point was marked by the Waste Framework Directive in 2008 (and amended in 2023). It sets standards on when waste material can cease to be "waste" and be considered a secondary product, promotes quality

[12] A regulation is a binding legislative act that must be applied in its entirety across the EU. A directive is a legislative act that sets out a goal that EU countries must achieve, though it is up to the individual countries to make their own laws on how to reach this goal. For more information, see the types of EU legislation.

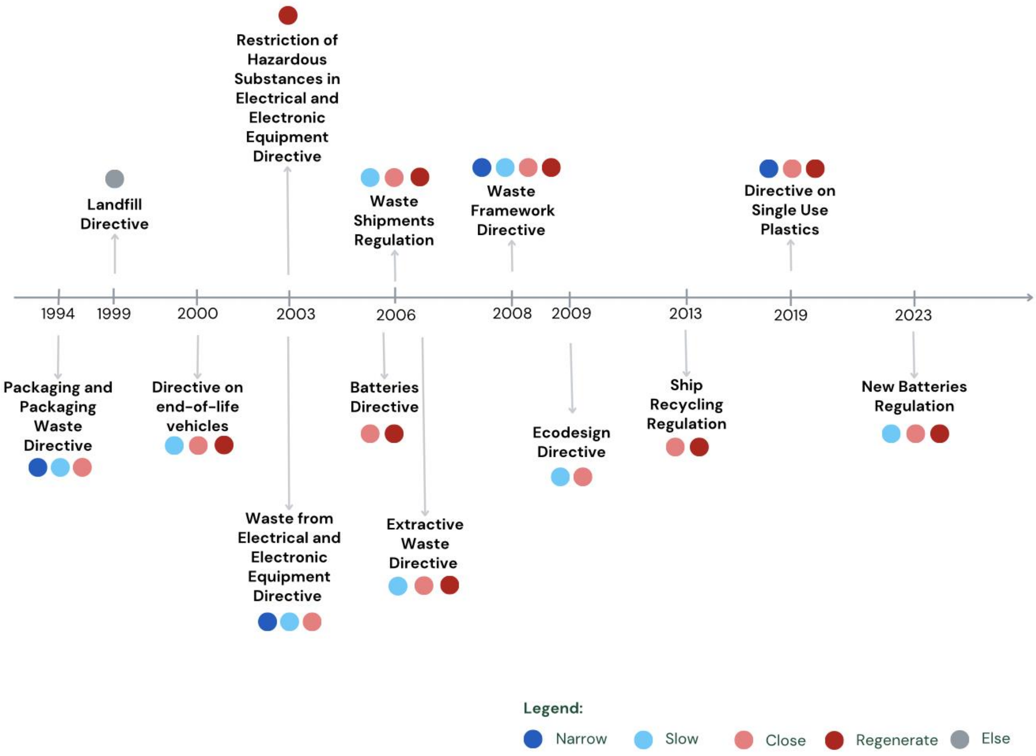
[13] For more information, see the European Commission Circular Economy policy overview.

[14] In 2023, the European Commission submitted a new proposal to update the Directive on end-of-life vehicles. The initiative proposes to enhance circularity in the design and production of vehicles, requiring car manufacturers to provide detailed instructions for dismantlers on how to replace and remove parts, hence facilitating the reuse of components.

standards for recycling, and requires separate collection systems for at least paper, metal, plastic, and glass.

4. Regenerating flows: 9 out of the 13 considered legislations introduce elements to regenerate flows, as they restrict the use of certain toxic materials and regulate the treatment of hazardous waste[15] – such as the Regulation on the registration, evaluation, authorisation and restriction of chemicals (REACH) which came into force in 2007, and revised since then to regulate nanomaterials

Figure 1 - Timeline of the main EU legislations around the circular economy



Notes. This figure reports the timeline for EU directives and regulations around the circular economy. Each legislative package has a colour code that refers to one or more of the four flows of circular economy, namely narrow, slow, close and regenerate.

The EU legislation sets future targets on slowing, closing and regenerating flows for EU states, but not narrowing. The various legislative packages – mainly directives – set targets around CE for the past and coming years up to 2035. Some examples of these targets are the minimum share of waste materials, including paper, metal, plastic and glass, that must be prepared for reusing and recycling (by weight), which goes from 55% in 2025 to 65% in 2035, in the Waste Framework Directive. Other legislative packages that report targets on collecting, reusing and recycling, are the Packaging and Packaging Waste Directive (share of packages that must be recycled), the Landfill Directive (share of waste that can be landfilled), the Waste Electrical and Electronic Equipment Directive (share of electrical equipment that must be recycled), the New Batteries Regulation (share of waste batteries that must be recycled), and the Directive on single-use plastics (share of plastic bottles that must be recycled). Table A2 in the Appendix reports the main objectives and targets for each legislation, with the related target years.

[15] Hazardous waste is waste with one or more hazardous properties such as explosiveness, ecotoxicity, and carcinogenicity. See the Waste Framework Directive for a detailed list.

Box 1: Circular Economy Policies in Swizerland.

Switzerland has long lagged behind in putting circular economy on its political agenda. At the federal level, the issue of circular economy – even if not using the “circular economy” concept – entered the political agenda in 2012 through the popular initiative "For a Sustainable Economy Based on Efficient Resource Management (Green Economy)". This initiative called for the inclusion in the Swiss Constitution of an article stating the commitment of the Swiss authorities (Confederation, cantons and communes) to developing a sustainable economy based on the efficient management of resources, namely by encouraging the closure of material life cycles and ensuring that economic activity does not deplete natural resources or damage the environment. Moreover, the initiative asked for Switzerland's "ecological footprint" to be reduced by 2050 so that, extrapolated to the world's population, it does not exceed one planet equivalent. Described as over-ambitious by the government, which wanted to avoid excessive and rapid changes in production and consumption patterns, the initiative was finally rejected in 2016.

Nonetheless, a parliamentary initiative is currently underway to promote these principles. Meanwhile, the topic continued to gain traction in European neighbours countries, and numerous parliamentary interventions on various aspects of the circular economy were proposed in Switzerland. For example: in 2017, a postulate titled "Study tax incentives and other measures to stimulate the circular economy to seize its opportunities"(postulate VonLanthen 17.3505) and in 2018, a postulate titled "For the removal of obstacles to the efficient use of resources and the establishment of a circular economy" (postulate Noser 18.3509). Since 2019, a multitude of parliamentary interventions have converged to create a cross-party parliamentary initiative to revise the Environmental Protection Act (EPA; RS 814.01) – the initiative "Developing the Circular Economy in Switzerland". Its main objective is for the Confederation and the cantons to preserve natural resources and commit to reducing environmental impact throughout the life cycle of products. As of our current writing (February 2024), the project has been adopted both by the National Council and the Council of States, with only slight divergences. This is an important first step to establishing the circular economy in Switzerland. Yet, the implementation of these new legal provisions remains to be done – and the potential of these new provisions to lead to actual change on the ground will have to be carefully evaluated.

Simultaneously, several initiatives to promote a circular economy are happening at the cantonal level and in the cities. For instance, in September 2022, the canton of Zurich became the first Swiss canton to explicitly anchor the circular economy in its constitution (article 106a), while Geneva pioneered by committing to the principles of industrial ecology and waste reduction at the source in its constitution in 2012 (see article 161). Other cantons are also adopting roadmaps (e.g., Fribourg and Geneva).

The Swiss legislation currently includes some aspects of closing flows, though narrowing and slowing receive less attention. The waste management principles already enshrined in the EPA (since 1983) are compatible with the circular economy hierarchy: avoid waste creation, recover, and only last dump (see art. 30 EPA). However, when it comes to concretizing these principles, until now, the Swiss regulatory framework and its application tended to focus primarily on closing material flows, in particular by improving recycling, while less focusing on narrowing or slowing these flows. A genuine circular economy policy means giving priority to reducing and slowing material flows. Moreover, public policies in favour of the circular economy need to move away from their compartmentalisation within environmental public policies to adopt a more systemic view on the transformation of production and consumption patterns, for example by adapting certain aspects of product legislation, of the fiscal policy, warranty and repair issues, etc. On this issue, compared to the European Union, Switzerland has been shyer in leading the adoption of the circular economy as a central framework to guide the development of the country’s regulatory framework.

For a full discussion of the state of the circular economy in Switzerland, see Brunner, D. & Moussu, N. (2023) L’économie circulaire – Agir pour une Suisse durable. Lausanne, Savoir Suisse, Presses polytechniques et universitaires romandes [50].

3.2 HOW CIRCULAR IS THE EU ECONOMY?

Did the EU legislations effectively lead to a more circular EU economy? In this section, we report the status and main trends around CE for the European Union 27 Member States (EU27), along the four CE flows reported above, namely narrow, slow, close, and regenerate.

Figure 2 reports how the EU economy extracts, uses and recycles material (figures from 2022). Each year virgin materials (in the figure, "Direct material inputs") are either extracted from the natural environment in the EU ("Natural resources extracted") or imported ("Imports"). These virgin materials, together with the materials that are recycled within the economy, are used as inputs in production and consumption activities ("Processed materials"). Specifically, these materials are either exported, lost in the environment ("Dissipative flows"), burned for our energy needs, e.g., fossil fuels – which produce emissions ("Emissions to air") –, or used to make goods ("Material use"). Examples of these goods are buildings, infrastructures, and durable goods in general - such as cars, industry machinery, or household appliances. Each year, new goods are added to the economy's material stock ("Material accumulation"), and old materials are removed from the stock as buildings are demolished and durable goods disposed of as waste ("Waste treatment"). Once materials become waste, they can be either incinerated, landfilled, or recovered. Recovery operations can be differentiated between energy recovery (not reported here), backfilling[16] and recycling[17].

Despite its ambitions, the EU economy has not been able to narrow its resource flows, as the use of virgin materials and production of waste remain high. Figure 2 shows that in 2022 the EU has extracted around 5.5 billion tons of materials (or 12.4 tonnes per capita) and processed around 8 billion tons (or 18.26 tonnes per capita). This figure has kept increasing for the past few years, as shown in Figure A1 of the Appendix. Approximately half of the consumption is of non-metallic minerals, which include sand, gravel, limestone and fertiliser minerals (8.97 tonnes per capita in 2022), while metal ores, such as iron, nickel and copper, have a minor share (1.76 tonnes per capita in 2022).

The amount of materials that we dispose of as waste remains high, at 1.8 billion tons in 2022 (3.94 tonnes per capita), and has been increasing in the past years, except during COVID when it decreased sharply – see Figure A1 in the Appendix. Most of the waste generated comes from the industry, with mining and construction producing, respectively, 1.67 and 2.25 tonnes of waste per capita in 2018. Households' waste has remained constant through the years, at around 0.52 tonnes per capita (even during COVID).

While the EU has made some progress in reusing products, making an overall assessment on slowing slows remains difficult due to the lack of data. Preparing waste for reuse is the process of checking, cleaning and repairing products that have become waste so that they can be reused without any other pre-processing.[18] For example, waste reuse includes computers and smartphones that became waste, and were then checked, cleaned, repaired and resold (e.g., refurbished smartphones). The quantity of products prepared for reuse has increased in recent years, especially for electrical and electronic devices, followed by large equipment – see Figure A2 in the Appendix. However, data on the different categories of reused products and second-

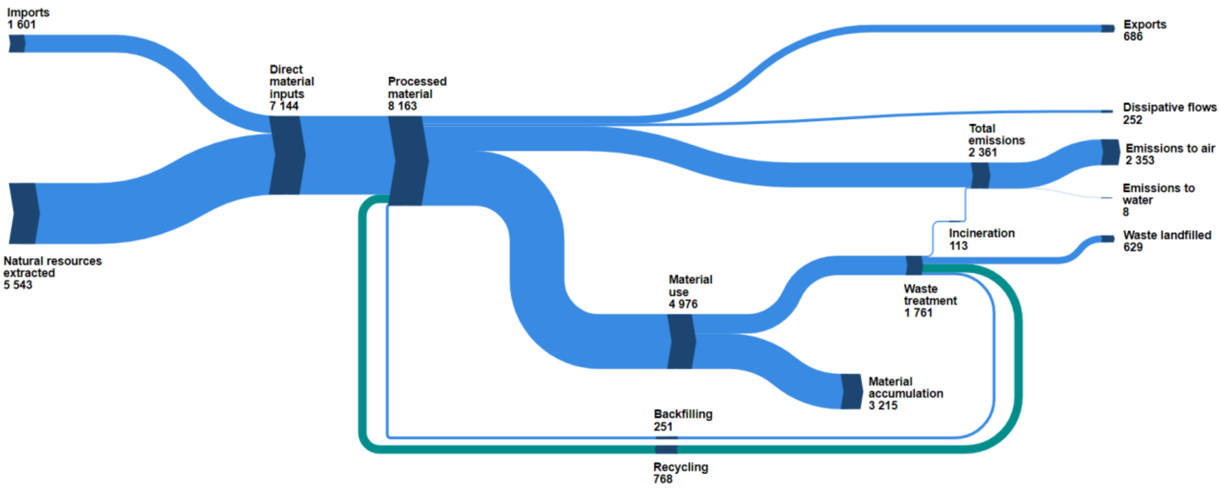
[16] Backfilling is a recovery operation where the waste soil that is removed during the excavation of foundations, ground bearing slabs or other groundworks, is reused to support and strengthen the structure of slabs, roadways, walkways and other groundwork elements (Eurostat).

[17] In the Waste Framework Directive, the definition of recycling is broader than in the 10 R Framework: recycling is any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes (Eurostat).

[18] This category does not include reuse, repair and cleaning of items which never became waste (like second-hand markets or services for phone repairing for individuals).

hand market is currently missing, thus making difficult to assess whether Europe has effectively slowed its material flows.

Figure 2 - Material Flows for the EU in 2022



Notes. This figure is a Sankey diagram reporting the material flows for the EU27 in 2022. The width of the flows reflects the volume of materials, which are in million tonnes. The definitions of the nodes (dark blue) can be found in the text and the metadata of the Material Flow Account by Eurostat. Source: Eurostat, material flow diagram.

Though the EU has improved in closing flows via recovery and recycling, it still landfills around 40% of its waste and only around 12% of materials are "circled". In 2022, out of 1.8 billion tons of material that became waste, 36% was landfilled (Figure 2). Of the remaining waste materials, about 58% was recovered, by either backfilling (14%) or recycling (44%). The level of material recovery is low when considering that recycled and backfilled materials are only about 12% of the materials processed. This circular material use rate has only mildly increased in the past years, as shown in Panel (b) of Figure A3 in the Appendix. When diving into the most GHG-emitting sectors, the level of recycling is encouraging – 69% for aluminium, 61% for copper, and 75% for iron –, but the loop is far from closing due to material loss in products at end-of-life and exports of secondary materials [51].

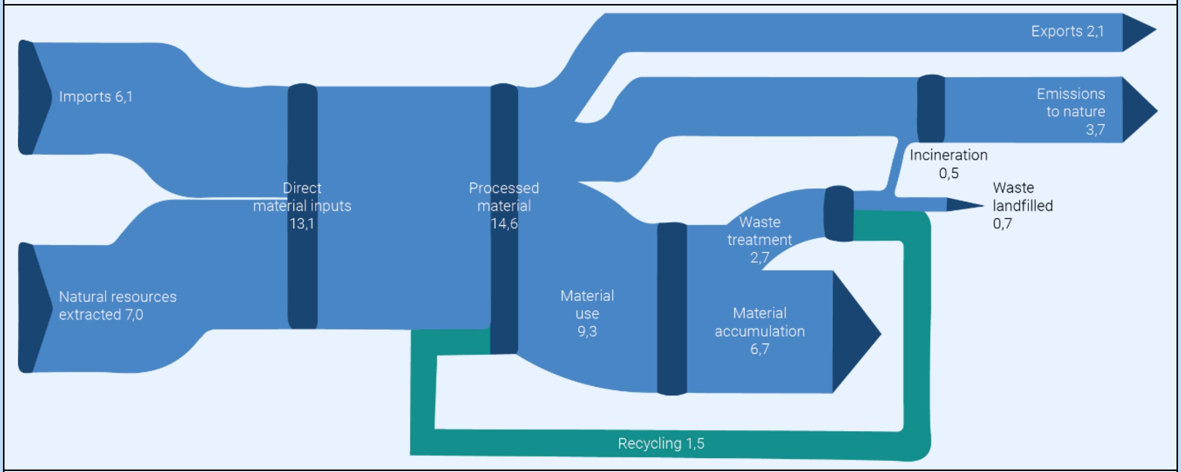
While the EU has been producing more renewable energy, its energy supply still largely relies on fossil fuels, and it continues to produce hazardous chemical waste. Regenerate flows require prioritising regenerative resources to produce goods and services through regenerative material and energy management, designing out waste, and excluding toxic chemicals from production processes. The EU has been using more and more renewable sources to produce energy, e.g., geothermal, hydro, tide, wind, solar and ambient heat, as the share of energy supply produced with renewables increased from 11.35% in 2010 to 17.96% in 2021 – see Figure A4 in the Appendix. However, this share remains low compared to the share of energy produced with oil and petroleum products (31.35%) and natural gas (24.28%). Furthermore, the industries in the EU should progress in excluding and reducing the use of toxic chemicals. The generation of hazardous chemical wastes, which include spent chemical catalysts, chemical preparation wastes, and other chemical wastes [52], has remained approximately constant through the years to around 35 kilograms per capita – figure A4 in the Appendix. This needs to be reduced to improve human health and wider environmental eco-systems.

Box 2: Material Flows in Switzerland

Concerning material flows, the situation in Switzerland is quite comparable to Europe. There is a low circularity rate and waste levels are high, even higher than in Europe. The diagram below illustrates the main material flows that traverse the Swiss economy and society, along with exchanges with the rest of the world and the environment. Most of these flows contribute to the increase in the physical stock of society (infrastructure and durable goods), while the remainder is either discarded into the environment, exported, or recovered through material recovery activities. This proportion of recovered materials is considered the "material circularity rate" of Switzerland, representing the flow of materials derived from waste recovery and reused in the economy as a percentage of the total domestic material consumption. The circularity rate stood at approximately 14% in 2021 (Federal Statistical Office – Circular material use rate), although other estimates based on different methodologies place it much lower (less than 7% for Circle Economy [53]).

Regardless of the chosen estimate, it is essential to note that this rate only accounts for the recycling and valorisation of materials from waste and does not reflect all circular economy strategies related to the entire lifecycle of objects (such as reuse or repair). However, it serves to draw attention to the waste issue in Switzerland. Indeed, more than 80 to 90 million tons of waste are produced annually in the country (2020 figures), a quantity that has continued to grow since the 1980s.

Figure 3 - Material Flows per person for Switzerland in 2018



Notes. This figure is a Sankey diagram reporting the material flows for Switzerland in 2018, per person. The width of the flows reflects the volume of materials, which are in tonnes. The following flows are based on estimates: Waste treatment, Incineration, Waste landfilled, and Recycling. For reasons of readability, balancing items that allow for the consideration of e.g., air exchange during the combustion process, are not shown here. To ensure the consistency of the diagram, the mass of emissions to nature is deduced from the other flows and does not correspond to the actual mass published in the material flow accounts (6.5 tonnes per person). Source: FSO – Environmental accounts – Material flow accounts, [54]

3.3 Circular business models

While to date our economy is still largely linear, we are witnessing an increasingly vibrant ecosystem of circular business models that are driving the transition. This section outlines different types of business models and the drivers and limitations for increasing the adoption of these models.

The transition to circular business models is driven by a variety of factors, including:

1. **Regulatory Pressures:** As outlined above, governments and regulatory bodies including the EU are implementing stricter regulations and policies to encourage sustainable practices, including waste reduction targets, extended producer responsibility (EPR) laws, and incentives for adopting circular economy principles.

2. **Resource Scarcity:** As traditional linear business models rely on extracting finite resources and generating waste, companies are realizing that the availability and cost of resources can become a significant risk. Adopting circular models allows companies to reduce dependence on virgin resources by recycling and reusing materials, mitigating the impact of resource scarcity [55].

3. **Changing Consumer Preferences:** Consumers are increasingly prioritizing sustainable products and services. They are more conscious of the environmental impact of their purchases and prefer companies that demonstrate a commitment to sustainability [56]. Adopting a circular business model allows companies to meet these evolving consumer demands and gain a competitive edge.

4. **Cost Savings and Efficiency:** Circular business models can lead to cost savings through improved resource efficiency and reduced waste management costs [57]. By adopting practices such as recycling, remanufacturing, and product life extension, companies can optimize resource use, extend the lifespan of products, and reduce the need for raw material extraction.

5. **Reputation and Brand Value:** Embracing circular practices can enhance a company's reputation and brand value. By demonstrating a commitment to sustainability and responsible resource management, companies can attract environmentally conscious consumers, investors, and employees, which can positively impact their market position and long-term success [56], [58].

Circular models can enhance a company's resilience by diversifying supply chains, reducing cost and dependence on volatile commodity prices, and building stronger relationships with customers product innovation and through product stewardship. Additionally, transitioning to a circular economy often requires innovative solutions and collaboration across sectors, fostering opportunities for growth and new business models. However, these drivers vary depending on the geographical location, the sector and the value chain, as well as the specific circumstances of each company.

The emergence and the scaling of circular business models also face various barriers and challenges, including:

1. **Upfront Investment and Financial Constraints:** Shifting to circular business models often requires significant upfront investments in terms of technology, infrastructure, and process redesign [32], [59]. Smaller companies or those with limited financial resources may find it challenging to bear these costs, especially if they are already operating on thin profit margins.

2. **Complex Supply Chains:** Transitioning to circular models often necessitates changes in supply chain management. Companies may need to establish new partnerships, secure reliable sources of recycled or reused materials, and develop reverse logistics systems. Managing these complex supply chains can be challenging, particularly for larger organizations with diverse and global operations [32].
3. **Regulatory and Policy Barriers:** While some regulations and policies promote circular economy principles, others may inadvertently hinder the transition. A lack of harmonization or conflicting policies can create barriers or uncertainties for companies seeking to adopt circular business models [60]. Clear and supportive regulatory frameworks are essential to facilitate the transition.
4. **Limited Market Demand and Customer Awareness:** The demand for circular products and services may still be limited in some markets. Customers may be unfamiliar with the concept or unwilling to pay a "green premium" for circular products. Generating sufficient market demand and educating customers about the benefits of circularity can be a challenge for companies [60], [61].
5. **Cultural and Organizational Resistance:** Resistance to change within organizations can be a significant barrier. Defining a clear CE strategy, allocating the necessary resources, defining roles and targets, as well as educating employees are key to fostering a culture and organizational practices that support a transition to circular business models [62].
6. **Technical and Technological Limitations:** The availability and maturity of technologies required for circularity can be a limitation. For certain industries or products, for example, textile-to-textile or electronics recycling, suitable technologies may not yet exist or may be prohibitively expensive.

Overcoming these barriers and limitations requires a combination of supportive policies, financial incentives, cross-sector collaboration, and awareness-building efforts. Governments, industry associations, and non-profit organizations play a crucial role in providing guidance, facilitating knowledge-sharing, and creating an enabling environment for the transition to circular business models [55].

Despite these barriers and limitations, we are witnessing an increasingly vibrant ecosystem of CE business models, across CE strategies, industries and levels of maturity. Some examples are reported in Table 2.

Table 2 - Illustration of CE business models	
Refuse	Lush Cosmetics offers package-free products, encouraging customers to avoid unnecessary packaging and reduce waste. They provide a range of cosmetics, skincare, and personal care items with minimal or no packaging, promoting a more sustainable approach to consumption.
Rethink	Philips Lighting (now Signify) has redesigned its lighting products to focus on energy-efficient LED lighting solutions. Their products are designed to be long-lasting, recyclable, and free of hazardous substances.
Reduce	Miles is a digital car-sharing platform that enables users to access vehicles on-demand, reducing the need for private car ownership. By promoting shared mobility, Miles optimizes vehicle utilization, leading to resource savings.
Reuse	Loop is an initiative developed by TerraCycle that enables consumers to purchase products in reusable packaging. After use, the packaging is collected, cleaned, and refilled, reducing single-use waste.
Repair	Fairphone is a smartphone manufacturer that focuses on ethical sourcing and repairability. They design their phones with modular components, making it easier for users to repair and replace specific parts rather than replacing the entire device.
Refurbish	Backmarket is an online marketplace that contributes to the circular economy by refurbishing and reselling electronics. By extending the lifespan of electronic devices, they reduce e-waste and promote a more sustainable approach to consumption.
Remanufacture	Xerox's Green World Alliance program remanufactures toner cartridges and other printing supplies. They collect used cartridges, refurbish them, and reintroduce them into the market, reducing waste and conserving resources.
Recycle	TOMRA Systems is a company that develops advanced recycling systems, including reverse vending machines that collect and recycle used beverage containers. They help automate and optimize the recycling process.
Recover	Anaergia is a company that specializes in recovering energy from organic waste through anaerobic digestion. They convert organic waste, such as food scraps and agricultural residues, into biogas for energy generation.
Regenerate	Patagonia has developed the Regenerative Organic Certification, which focuses on regenerative agricultural practices that enhance soil health, biodiversity, and ecosystem resilience.

4 THE FUTURE OF THE CIRCULAR ECONOMY IN EUROPE

Given the large emission footprint of materials, the European Commission has put CE at the heart of the EU strategy for a net-zero economy [36], [63]. However, while CE has the potential to create substantial economic and environmental benefits, the actual implementation and impacts of CE actions in the EU remain uncertain. In this section, we explore whether our current efforts are enough to reach the net-zero objectives, the role of CE in reaching these objectives, and what could be viable steps to adjust our strategies and correct course.

A large body of literature has studied the impacts of CE strategies on GHG emissions and material use. For example, Material Economics (2018) estimates that CE strategies around steel, plastics, aluminium, and cement could reduce industrial emissions by 56% by 2050 [27].[19] Closer to our work, Ciacci et al. (2020) focus on the evolution of copper demand – forecasted to grow in electric vehicles and charging infrastructure, considering the EU target of cutting GHG emissions by 50% in this sector by 2050 [64]. They find that, in three out of four scenarios, secondary production of copper would be insufficient to comply with the emission target, even when combined with aggressive recycling, moderate decarbonization of electricity, and energy efficiency improvements. However, these studies – and most of the literature – analyse sectors one at a time, independently of what is happening in the rest of the economy.

In the following, we evaluate CE strategies within the context of decarbonization pathways, using a system-dynamic model called EUCalc. EUCalc allows us the simulate the impacts of detailed technological and lifestyle changes whilst taking into account the complex non-linearities happening in the whole economy.[20] This approach will allow us to better understand the potential synergies and trade-offs when CE strategies happen simultaneously in society.

4.1 THE EU 2050 LONG-TERM STRATEGY

The EU sets out its vision to achieve climate neutrality in its 2050 long-term strategy (LTS). Recognizing that the transition towards climate neutrality is an urgent challenge, the EU explored several pathways to reach net-zero GHG emissions in 2050 [65], [66]. The starting point is the *LTS Baseline*, which reflects the policies and 2030 targets agreed in the EU as of November 2018.[21,22] These measures are projected to reduce emissions by only about 60% with respect to 1990, failing to meet the EU commitment to climate neutrality (see Figure 4). Hence, the European Commission investigated several alternative and more ambitious pathways to reach net zero [65], [66]. In this paper, we consider three scenarios based on these pathways:

- **The *Life* scenario portrays a Europe with ambitious behavioural changes**, e.g., healthier and flexitarian diets, fewer appliances and vehicles owned

[19] Other similar papers are summarized in Table A1 in the Appendix

[20] Please refer to the European Calculator website for a description of the EUCalc model and detailed documentation. The model also includes an online interface to explore decarbonization pathways and visualise the associated environmental and socio-economic impacts.

[21] The measures include a reformed EU emission trading system, Effort Sharing Regulation, 2030 targets for energy efficiency and renewable, and legislations on vehicles carbon efficiency and on land and forests. Following the European Green Deal, some legislations were revised to meet the higher climate ambition. For instance, the minimum share of renewable in the 2030 energy mix was raised from 32% to 42.5% in the 2023 revision of the Renewable Energy Directive.

[22] It goes without saying that emission targets can be missed. For example, Kalmykova et al (2015) find that implemented policies have failed to significantly reduce resource consumption in Sweden, while waste generation has largely outpaced improvements in recycling [67]. Furthermore, Tol (2021) points out that the EU climate policies may be more expensive than initially anticipated, and therefore more difficult to implement [68].

thanks to the development of the sharing economy, lower temperature in buildings, and longer product lifetimes. This scenario is based on the EU 1.5LIFE pathway [66].[23]

- **The *Tech* scenario portrays a Europe with ambitious technological changes**, e.g., more efficient energy systems, better-insulated buildings, electrified vehicle fleet, increased material efficiency in industry, and the deployment of carbon capture technologies. This scenario is based on the EU 1.5TECH pathway [66].

- **The *Tango* scenario assumes a shift in production and consumption patterns towards a more circular economy** and combines the most ambitious behavioural and technological changes of the *Life* and *Tech* scenarios.

We simulated the *LTS Baseline*, *Life*, *Tech*, and *Tango* scenarios using the EUCalc model. The detailed assumptions are described in Costa et al. (2019) [69] and the results can be reproduced using the EUCalc's web interface. Figure 4 displays the evolution of GHG emissions in Europe for each pathway, and the detailed GHG emissions per sector are reported in Table A3 in the Appendix.

Our results show that Europe will have to adopt drastic technological and behavioural changes to reach net zero by 2050:

- The *LTS Baseline* shows that, with current policies, the EU is far from reaching net zero – in the figure, the red line does not cross the zero line. Driven by the Renewable Energy Directive and the Energy Efficiency Directive, GHG emissions strongly decrease in buildings (-76% in 2050 w.r.t 2015) and energy supply (-73%). However, emissions in manufacturing remain high (-22.5%), especially due to hard-to-abate industries such as steel, cement, and chemicals.

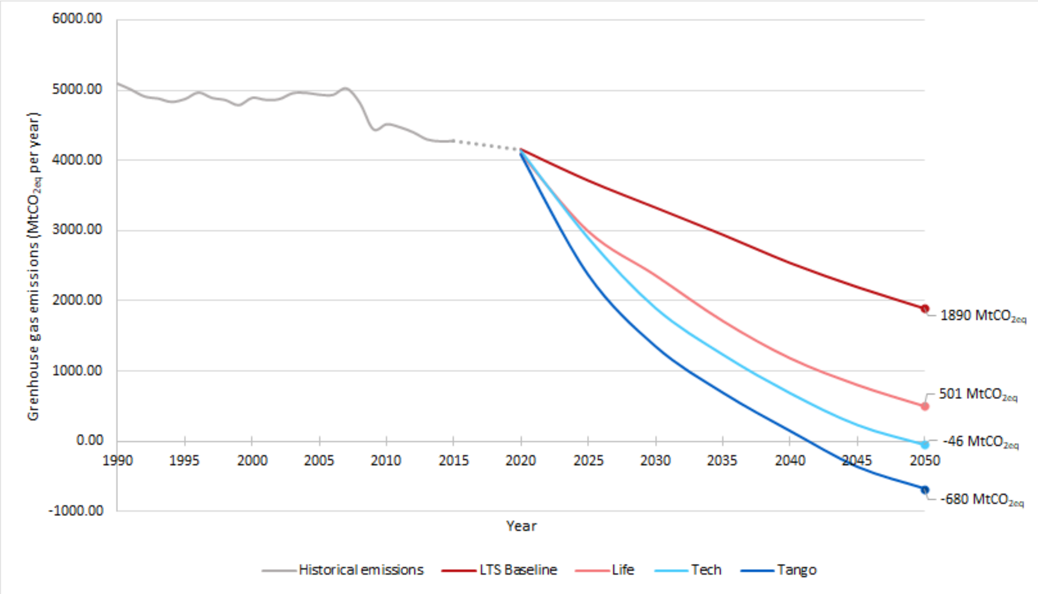
- The *Life* scenario highlights that, even with drastic behavioural changes, the EU will not be able to achieve net zero in 2050 (pink line). Still, the reduction in distance travelled, the increased share of public transportation, and the adoption of car sharing decrease emissions in transport by 73% in 2050 with respect to 2015. In addition, emissions in agriculture decrease by 61% due to the adoption of healthier diets and the reduction of food waste.

- In the *Tech* scenario, Europe is reaching net zero around 2050, with ambitious technological changes and significant GHG reductions in buildings (-90%), transport (-88%), and manufacturing (-65%) in 2050 with respect to 2015, thanks to increased material efficiency and a switch toward less carbon-intensive materials. However, climate neutrality is only achieved thanks to the massive deployment of carbon capture and storage technologies, which remove 520 $MtCO_{2eq}$ per year in 2050.[24]

- In the *Tango* scenario, combining drastic behavioural and technological allows the EU to reach net zero already by 2040. The lifestyle changes would speed up and facilitate the transition, contributing to more than 20% of the overall GHG required for net zero in the *Tango* scenario [69].

[23] The EU 1.5LIFE scenario considers stronger technological changes than the *Life* scenario and is thus more ambitious. In the *Life* scenario, technological changes follow the ones of the *LTS Baseline*, allowing us to pinpoint the impacts of behavioural changes.
[24] The deployment of carbon capture and storage technologies remains uncertain. To further explore this issue, see the E4S white paper "Carbon removal, net zero, and implications for Switzerland" [70].

Figure 4 - Evolution of GHG emissions in Europe for decarbonization pathways



Notes. This graph presents the evolution of territorial GHG in Europe (EU27, UK, Switzerland) for 4 scenarios. The *LTS Baseline* reflects the current policies and targets agreed upon in the EU (European Commission, 2018a; European Commission, 2018b) [65], [66]. The *Life* scenario portrays a Europe with ambitious lifestyle changes. The *Tech* scenario portrays a Europe with ambitious technological changes. The *Tango* scenario combines both lifestyle and technological changes. The reference year is 2015, i.e., historical emissions are calibrated until 2015 and simulated between 2020 and 2050. Source: The results were simulated using the EUCalc model and can be reproduced using EUCalc's web interface.

4.2 CIRCULAR STRATEGIES FOR NET-ZERO PATHWAYS

Each of these scenarios is based on assumptions notably on the evolution of CE strategies in the coming years. In what follows, we discuss these assumptions to map out the deployment of CE strategies in the EU.

In the *LTS Baseline* scenario, recycling and energy efficiency significantly improve. The EU has planted the seeds for a clean energy transition, as illustrated by the Energy Efficiency and Renewable Energy directives that aim to improve energy efficiency improvement and reach 42.5% renewable energy by 2030. These efforts are expected to carry on to 2050. For instance, eco-label could help increase appliance efficiency by 65% by 2050, moderately less than in the *Tango* scenario (89%). CE policies, e.g., the Waste Framework Directive, can also significantly improve recycling rates: 58% secondary steel, 72% secondary aluminium, and 80% secondary paper by 2050.

However, the *LTS Baseline* scenario still lacks commitments around other aspects of CE, namely to narrow, slow, and regenerate flows. For example, the average distance travelled keeps growing (+18% by 2050 with respect to 2015), the number of appliances owned by households increases (e.g., 2.3 computers in 2050 vs 1.7 in 2015) while the lifespan of appliances remains at the 2015 level, and non-regenerative resources such as steel and cement remain predominant in the construction of buildings.

In the *Tango* scenario, the widespread adoption of CE strategies in all sectors unlocks the full potential of GHG reduction needed to reach net zero. Some of these strategies are described below and detailed in Table 3:

1. **Narrowing flows:** In the transport sector, teleworking and more local leisure and services are projected to reduce the average distance travelled by about 8% by 2050 with respect to the 2015 level, and the development of

car-sharing platforms and services increases the average car occupancy from 1.6 in 2015 to 2.75 in 2050. In buildings, sharing and leasing strategies reduce the number of appliances owned by households. More efficient product design that increases durability while facilitating repair and disassembly reduces the purchase frequency of electronic equipment by 30%. In manufacturing, smarter product design and the reduction of overspecification and production waste increase the material efficiency of steel by 33%, cement by 20%, and aluminium by 14%. Finally, the use of plastic packaging and consumer food waste also significantly decrease, by 40% and 75%.

2. **Slowing flows:** Thanks to sharing and repair strategies, appliances are replaced less frequently. For example, the lifespan of washing machines and computers increases by, respectively, 10% and 30% [71].

3. **Closing flows:** Material recirculation boosts recycling rates, increasing the shares of secondary steel from 39% in 2015 to 70% by 2050, aluminium from 57% to 79%, and paper from 54% to 90%.

4. **Regenerating flows:** In *Tango*, regenerative resources such as timber replace 20% of steel and 60% of concrete in building construction, while natural fibres supplant 20% of chemicals in renovated surfaces. In addition, the industry sector increases the production of geopolymers-based cement from 11% to 20%. At the same time, the share of production of renewable energy increases from 64% to 75%. Finally, the deployment of organic farming practices allows the replacement of synthetic fertilisers by organic ones.[25]

[25] The E4S white paper "*Threats to Nitrogen Fertilizer, Opportunities to Cultivate Sustainable Practices?*" explores how to shift towards more sustainable agricultural practices while maintaining a viable level of food supply [72].

Table 3 - Circularity strategies in Europe by 2050 in the *LTS Baseline* and *Tango* scenarios

Flow	Sector	Action	2015	2050 pathways	
				Baseline	***Tango***
Narrow	Transport	Average passenger distance travelled (pkm/year)	12'466	15'120	11'521
		Average car occupancy (person/vehicle)	1.6	1.6	2.75
	Buildings	Number of appliances per household: ● washing machines ● computers	0.9 1.7	0.95 2.3	0.8 1.3
		Appliances efficiency	-	+65%	+89%
	Industry	Material efficiency (material used to the supplied material): ● Steel ● Cement ● Aluminium		+19% +12% +8%	+33% +20% +14%
		Use of plastic packaging (kg/cap/year)	30	34	18
	Food	Consumer food waste (kcal/cap/day)	515	390	130
Slow	Buildings	Extension of appliances lifetime (w.r.t. 2015): ● washing machines ● computers		0% 0%	+10% +30%
Close	Industry	Share of recycled material (%): ● secondary steelmaking[26] ● aluminium ● paper	39% 57% 54%	58% 72% 80%	70% 79% 90%
Regenerate	Buildings	Material substitution: ● Steel by timber in buildings ● Concrete by timber in buildings ● Chemicals by natural fibres in renovated surfaces		3.5% 10% 3.5%	20% 60% 20%
	Industry	Geopolymers-based cement (%)	0%	11%	20%
	Energy	Share of renewable electricity production (%)	28%	64%	75%
	Agriculture	Synthetic fertiliser use (kg/ha)	150	200	0

Notes. The table presents some circularity indicators in Europe (EU27, UK, Switzerland) for two future pathways. The *LTS Baseline* reflects the current policies and targets agreed upon in the EU (European Commission, 2018a; European Commission, 2018b) [65], [66]. The *Tango* scenario portrays a Europe with ambitious lifestyle and technological changes. Note that the values present the average in Europe but there is significant heterogeneity at the country level. Source: The results were extracted from the EUCalc model and can be accessed via the EUCalc's web interface. More details are available in the specific documentations of the Lifestyle (Costa et al., 2020) [73], Buildings (Kockat & Wallerand, 2020) [74], Transport (Taylor et al., 2020) [75], Manufacturing (Warmuth et al., 2020) [76], Energy (Gyalai-Korpos et al., 2019) [77], and Agriculture and land-use (Baudry et al., 2019) [78] modules.

[26] In Europe, steel is produced with two main processes: basic oxygen furnace (BOF) and electric arc furnace (EAF). BOF is a method of primary steelmaking that transforms iron into steel (scrap is added to control the temperature of the process). EAF is a method of secondary steelmaking that converts scrap iron into steel.

4.3 MATERIAL CONSUMPTION AND NET-ZERO PATHWAYS

The impacts of the technology and behavioural changes go far beyond reducing emissions. In this section, we will consider the effects of such changes on material consumption and highlight potential trade-offs that may arise.

Today, the materials that are most widely used in strategic sectors in the EU are aluminium, copper, nickel, silicon metal, and manganese. The European Commission has addressed the issue of sourcing raw materials for its production process [19]. The Commission identified 51 Critical Raw Materials (CRM), which are materials of high economic importance and exposed to high supply risk. Among these CRM, the Commission has identified 26 Strategic Raw Materials (SRM) which are extensively used in 15 technologies that are strategic for the EU. These technologies include lithium-ion batteries, wind turbines, solar photovoltaics, and robotics.[27] Specifically, lithium, graphite, cobalt, nickel, and manganese, are extensively used in lithium-ion batteries. Rare-earth elements, like dysprosium, neodymium, praseodymium and terbium, are used in magnets in traction motors, wind turbines and ICT technologies. Platinum is used in fuel cells, electrolysers and ICT technologies. The SRM that are used in most technologies today are aluminium and iron ore (used in all 15 considered technologies), copper, nickel, silicon metal (14 technologies), and manganese (13 technologies).

The materials that will see the largest increase in demand in the coming years are lithium, graphite, cobalt, nickel, and rare-earth elements like neodymium and dysprosium. Carrara et al. (2023) estimate the increase in demand for strategic materials between now and 2050 due to the net-zero transition [19]. In Europe, the demand for graphite and lithium in 2050 will be, respectively, 22 and 18 times larger than what it is today.[28] Though to a lower degree, the demand for nickel and cobalt will also increase – respectively 14 and 4 times of what it is today. Among the rare-earth elements, neodymium and dysprosium will be the ones in highest demand in 2050, which is projected to be 4 times more than what it is today. Finally, copper and aluminium will continue to be largely used, and their demand will increase by, respectively, 8 and 5 times compared to today.

In our scenario, technological changes strongly increase the demand for materials such as lithium and graphite. Figure 5 displays the mineral demand in Europe in 2050 for the *LTS Baseline*, *Life*, *Tech*, and *Tango* scenario, with respect to the 2015 level. The detailed mineral demand for each pathway is reported in Table A4 in the Appendix. The mineral demand in 2050 in the *Tech* scenario increases by a factor of 19 for lithium, 7 for graphite, 2 for copper, and 3 for nickel.[29] Indeed, low-carbon technologies such as electric vehicles, renewables, and batteries require more minerals than their alternatives.

However, lifestyle changes could significantly alleviate the pressure on these and other materials. The decrease in distance travelled and the development of car sharing are key to partially compensate for the increase in mineral

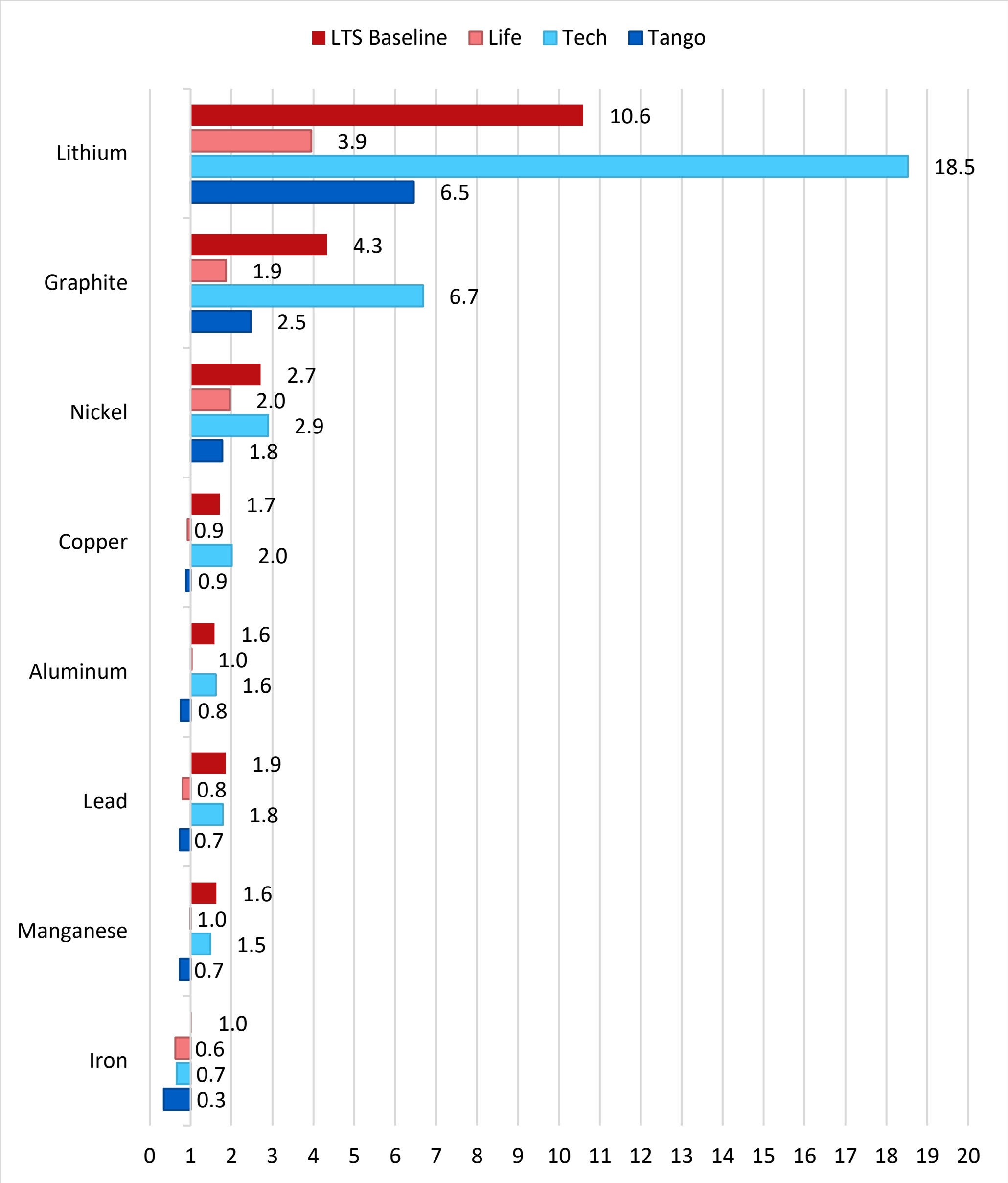
[27] These technologies are li-ion batteries, fuel cells, electrolysers, wind turbines, traction motors, solar photovoltaics, heat pumps, h2-dri, data transmission networks, data storage and servers, smartphones, tablets and laptops, additive manufacturing, robotics, drones, space launchers and satellites.

[28] These numbers are averages across the two scenarios presented in the report, namely high and low demand scenarios.

[29] The difference between our results and those of Carrara et al. (2023) [19] can be explained by the difference in scope of studies: for instance, Carrara et al. (2023) include data servers, robotics, and drones in their analysis, while these technologies are not represented in EUCalc. On the other hand, the EUCalc model includes the construction of buildings and several appliances such as washing machines, fridges, and TV that are out of the scope of Carrara et al. (2023). See Table 10 in Raffray (2020) for the mineral decomposition of technologies included in EUCalc [79].

demand due to the electrification of the vehicle fleet. As a result, in the *Life* scenario, the demand for lithium "only" increases by a factor of 4 in 2050 with respect to the 2015 level while the demand for graphite and nickel double. For other materials such as copper, the demand stays close to 2015 values.

Figure 5 - Mineral demand in Europe in 2050 w.r.t. 2015 level



Notes. This graph shows the mineral demand in 2050 for four transition pathways with respect to the 2015 level. A value of 1 means that the demand in 2050 is the same as in 2015. The *LTS Baseline* reflects the current policies and targets agreed in the EU (European Commission, 2018a; European Commission, 2018b) [1], [2]. The *Life* scenario portrays a Europe with ambitious lifestyle changes. The *Tech* scenario portrays a Europe with ambitious technological changes. The *Tango* scenario combines both lifestyle and technological changes. The scope includes the mineral needs for passenger and freight transport (e.g., cars, trucks, buses, trains, planes, ships), appliances (e.g., computers, TV, fridges, dishwashers), energy supply technologies (e.g., PVs, wind turbines, hydropower plants, nuclear, coal and gas power plants, batteries). For more information, please refer to Raffray (2020) [79]. Source: The results were simulated using the EUCalc model and can be reproduced using EUCalc's web interface.

Combining both lifestyle and technological changes drives down the overall material demand, especially in hard-to-abate sectors. In the *Tango* scenario, thanks to improved material efficiency and the switch to regenerative resources, the production of steel decreases by 46% in 2050 compared to 2015, and enhanced recycling rates further reduce the demand for iron (-65%).[30] Circular strategies also lead to a reduction in the demand for aluminium (-24%), lead (-27%), and copper (-11%). These reductions more than compensate for the increase in demand for lithium, graphite, and nickel: the total material demand decreases by 56% in 2050 compared to 2015.

These predictions on material demand highlight trade-offs behind decarbonization pathways. The *Tango* scenario leads to the lowest GHG emissions and demands for aluminium, copper, iron, nickel, manganese, and lead. However, the lowest demands for lithium and graphite are achieved in the *Life* scenario. In addition, less water is withdrawn from the environment in the *Life* scenario.[31] Hence, there are no perfect pathways: the implementation of decarbonization strategies depends on societal choices, ideally supported by multicriteria analysis and factors that influence the supply and trade of resources, such as the geopolitical situation.

Only a systemic perspective allows us to properly evaluate the impacts of decarbonization and circular actions. The effects of decarbonization actions are non-linear, as illustrated in Figure 5. For example, while the demand for aluminium increases in the *Tech* scenario (+61%) and remains constant in the *Life* scenario, the combination of both lifestyle and technological changes in the *Tango* scenario results in the lowest aluminium demand (-24%). In the *Tech* scenario, the gains in product and material efficiency and more efficient building design reduce the aluminium need for appliances and building construction but do not compensate for the increased aluminium demand for electric vehicles. By contrast, in the *Tango* scenario, the reduced ownership and use of products and vehicles unlock the full potential of mineral savings. This has some important implications:

1. **Policy-makers should carefully plan the transition to maximise the synergies between policies**. Systemic thinking needs to be encouraged to avoid situations such as plastics end-of-life: since the EU Landfill Directive drives plastic waste from landfill to incineration, the emissions associated with plastic incineration trend in the opposite direction of the EU targets [80]. The proposed EU regulation on the design and end-of-life management of cars is a step in the right direction to manage plastics more efficiently: it calls for car makers to provide detailed instructions on how to dismantle vehicles and aims for 25% recycled plastics in new vehicles.[32]

2. **For companies, business models can only be sustainable in light of the overall context**. For instance, car producers that transform their vehicle fleets from fossil-fuel to electric vehicles without considering a decrease in their sales risk to worsen material criticality, while the actual decrease in GHG emissions would depend on the carbon intensity of the electricity mix and the vehicle lifetime. Indeed, the GHG emissions from assembling electric vehicles exceed those of internal combustion engine vehicles due to the emissions from producing batteries. These extra emissions are only compensated when the vehicles are used if the electricity is produced by renewable sources and if the lifetimes of vehicles and batteries are sufficient [81]. Since customers' choices and buying patterns are affected by dynamically changing legislations and incentives, the whole ecosystem plays a role in the transition towards net zero.

[30] Steel is an alloy – i.e., a mixture – of iron and carbon.
[31] You can explore these trade-offs using EUCalc's web interface.
[32] For further information, see Circular economy: improving design and end-of-life management of cars for more resource-efficient automotive sector.

4.4 LIMITATIONS AND FUTURE WORK

Our work and results rely on certain assumptions and therefore bear some limitations. We will briefly discuss them here, including how we plan to address them in future work.

In our simulation, the uptake of new technologies is governed by technology-adoption curves, which bear some uncertainties. For example, the sales of electric vehicles follow a "s-shaped" trajectory.[33] The rate of technology adoption is subject to uncertainties and could be underestimated. In addition, the model only includes technologies that are mature enough.[34] The emergence of new technologies could alter our results, for instance by substituting one critical raw material by another resource. In future research, we will assess the robustness of our findings under different technological scenarios.

Our analysis only considers "territorial emissions", i.e., the emissions that take place within the EU. Our results do not include the emissions stemming from imported goods and services, i.e., "consumption-based" emissions. Accounting for consumption-based emissions is crucial to assess the entire GHG footprint of European lifestyles. Indeed, when adjusted for trade, the EU CO_2 emissions significantly increase, by about 20% in 2021.[35] To provide a more comprehensive assessment of the impacts of CE strategies, we aim to integrate consumption-based emissions into our modelling framework.

Moreover, a comprehensive assessment of the environmental impacts of CE strategies should consider all planetary boundaries. In this white paper, we focused on one planetary boundary, namely climate change. Expanding the scope of our analysis is necessary for understanding the broader implications of CE strategies. In future work we will consider other planetary boundaries, such as biodiversity loss and plastic pollution. By evaluating the EU's footprint on a global scale, we aim to identify priority areas for intervention, pinpoint potential trade-offs, and promote more sustainable consumption and production patterns.

This white paper did not explore in detail some of the sectoral barriers hindering the implementation of CE strategies, such as the investment costs for the CE transition. In future work, we will address this topic by studying the capital and operating expenditures related to applying CE practices, across sectors. Our goal will be to identify those sectors where the transition will be too costly to take place without the aid of public subsidies, and advise related policy making.

Finally, our analysis does not address the socio-economic impacts and equality considerations of the transition. This includes assessing the potential job losses and gains and the need for re-skilling and training programs to facilitate this transition. Additionally, we did not consider the distributional effects of CE strategies on different societal groups. We will explore these issues in future work, with the aim of advising policymakers to mitigate inequalities and promote an inclusive transition to a more circular economy.

[33] S-shape curves are commonly used to represent the adoption of technologies. First, new technologies only reach early adopters and the adoption rate is slow. Then, adoption rapidly rises before flattening out when market saturation is reached.

[34] More precisely, EUCalc includes technologies with a technology readiness level of at least 5, i.e., technologies that are validated in relevant environment.

[35] You can read the Our World in Data article "How do CO2 emissions compare when we adjust for trade?" by Hannah Ritchie to explore the difference between territorial and consumption-based emissions around the world [82].

5 Conclusions

While the EU economy has improved on some aspects of circularity, such as recycling, it is still very much linear. We have seen how circular economy strategies can be classified around four main flows, namely narrow (reduce), slow (reuse), close (recycle), and regenerate. In the past 10 years, the main improvements have been around second-life applications of products' parts and recycling.[36] Such progress could be partly attributed to the regulatory packages that the EU authorities have put in place to promote circularity, such as the Waste Framework Directive, the Directive on Single-use Plastics and the New Batteries Regulation. Yet, the EU economy remains mostly linear today, with an increasing consumption of raw materials and waste production, a low rate of recycled inputs in the production of raw materials, a high reliance on non-regenerative energy sources, and a long-lasting production of hazardous chemical wastes.

However, an increasingly vibrant ecosystem of circular business models is building up. The adoption of such circular models is driven by regulatory pressures, resource scarcity, changing consumer preferences towards more sustainable products, cost savings thanks to resource efficiency, and potential gains in reputation. Circular models can also enhance a company's resilience by diversifying supply chains. Nonetheless, the emergence and the scaling of circular business models are still hampered by various barriers such as the significant investment required to shift model, the complexity of supply chain, limited customer awareness, and resistance to change within organizations. Overcoming these limitations requires a combination of supportive policies, financial incentives, cross-sector collaboration, and awareness-building efforts.

Looking ahead, CE strategies are key to reduce the impingement of planetary boundaries and the associated impacts on human health. Strategies to narrow, slow, and close flows improve material efficiency and reduce waste, which can lead to large reductions in emissions. The largest potential GHG reductions through circularity come from product design, material recycling and efficiency, reducing food waste, improving packaging, and promoting the sharing economy and second-life application in the transportation sector. Moreover, circularity actions can start to reverse the current overshoot of several of the other planetary boundaries, e.g., land system change, nitrogen cycle, phosphorus cycle, and ocean acidification.

As of today, the EU policies only include milder improvements around circularity for the years to come and missed the 2050 net-zero target. To map out the deployment of circularity actions in the EU in the coming years, we used the model EUCalc to study the official long-term strategy of the EU towards 2050. In the official baseline scenario, which builds on existing policies prior to the European Green Deal, the EU economy improves mainly on recycling rates and energy efficiency. However, little is done on the other flows of CE, such as narrowing, slowing and regenerating. In combination with other policies outside the definition of CE, this set-up leads to missing the 2050 net-zero target by a large margin.

In a more ambitious scenario, the EU implements CE actions to narrow, slow and regenerate flows in the sectors of transport, buildings, industry, food, agriculture and energy. Following the European Green Deal, The European Commission is currently revisiting its policies around environmental pressures, including the ones on critical raw materials, bio-based and biodegradable plastics, repairing of goods, textile products, and eco-design for sustainable products, to strengthen its transitioning measures and reach net zero by 2050. It is therefore likely that the deployment of CE actions will accelerate, across all four ways of

[36] Specifically, there was an increase in waste prepared for re-use, and an increase in the share of waste that gets recycled (and consequently reducing the share that gets landfilled).

managing flows in a circular way. This acceleration is described in an alternative scenario that respects the net-zero target. This scenario improves on narrowing flows, for example by increasing the average car occupancy and material efficiency, and by reducing the use of plastic packaging. In addition, it contributes to slowing flows by extending the lifetime of appliances and closing flows by increasing recycling more than in the baseline scenario. Finally, it regenerates flows by implementing material substitutions in buildings and phasing out synthetic fertilisers.

Furthermore, these ambitious measures would alleviate the expected increase in demand for materials, such as lithium, graphite and aluminium. The materials that are considered strategic for the development of key technologies in the EU are aluminium, copper, nickel, silicon metal, and manganese. Looking ahead, the materials that will see the largest increase in demand by 2050 are lithium, graphite, cobalt, nickel – which are key for batteries – and rare-earth elements like neodymium and dysprosium – which are used to build magnets. In the ambitious scenario mentioned above, the increase in demand for materials driven by technological changes, especially of lithium and graphite, is alleviated by large behavioural change. Circular strategies even lead to a reduction in the demand for iron and aluminium. Overall, the total material demand decreases by 56% in 2050 compared to 2015.

While in this alternative the EU reaches net zero, a significant share of the GHG emitted to sustain our lifestyle is embodied in trade and products made outside of the EU. Circular strategies contribute in solving this issue by reducing the dependence on imports. However, trade-offs between decarbonization and material use still emerge, especially around lithium and graphite: the technological changes will still require large amounts of these two materials, raising questions on the environmental and human impacts of extraction and conversion of these materials.

In addition, there are more planetary boundaries than climate change to address, which will require higher regulatory efforts. Climate change is just one of the nine planetary boundaries. A recent study by the Stockholm Resilience Centre shows that we are currently exceeding six out of nine of these boundaries, and calls for immediate actions to intensify the efforts in radically transforming our economy [3]. This transformation will require systemic changes around the adoption of CE strategies, both in the short and medium term. On top of what is described above in the more stringent scenario, in the short term the EU should pass legislation with rules and incentives for manufacturers to facilitate product disassembly and recycling, implement waste-reduction campaigns for consumers, move subsidies from oil and gas to companies that are embracing circular business models, map out the sectoral impacts on employment and retraining needs of the CE transition, and increase investments in recovery and recycling technologies based in the EU. In the long term, the EU, in cooperation with other regions, should price raw materials correctly to include their externalities, implement subsidy and education programs for workers that will be reallocated due to the CE transition, re-think and increase the robustness of the supply chain of sensitive industries, and essentially eliminate single-use packaging.

The way ahead for CE in the EU thus strongly depends on how binding the new regulations will be, and the intensity of external geo-political and business pressures. Some of the current barriers to implementing a more circular economy are high costs for businesses and individuals, limitations of material and energy flows across boundaries (i.e., trade to recycle), high path dependencies and lock-in, new discoveries of raw materials (e.g., oil), and imprecise measurements of CE actions. To which degree the EU economy will become more circular will depend on how effectively new legislations will be able to address these barriers, and therefore on the political will of the new European Commission and Parliament. Furthermore, it will also depend on external factors outside the control of EU authorities, such as the state of critical raw materials in foreign markets. For example, the role of China in the world economy in the coming future will be pivotal for the CE agenda, as it disposes of a legislative and infrastructure framework that will enable to scale circular-economy practices (e.g., recycling facilities for lithium-ion batteries). While the adoption of CE depends mainly on political, economic and social factors, it hardly depends on technological progress. Many of the technological solutions we need already exist, and the core issue is that of investing and deploying these at scale in a compressed time frame to both meet demand and react to changing consumers' behaviour.

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APPENDIX

A1 GHG IMPACTS OF CIRCULAR ECONOMY ACTIONS

Table A1: Overview of estimated GHG impacts of circular economy actions

Study	Sector	Scope	Main Circular Economy Actions	GHG reduction
SYSTEMIQ, 2022 [83]	Plastics	EU	• Elimination of unnecessary plastics • Mechanical and chemical recycling • Material substitution	-33% by 2030, -65% by 2050 w.r.t. 2020
Agora Industry, 2022 [25]	Steel, Plastics, Aluminium, Cement, Construction, Mobility	EU	• Increase material efficiency and reduce waste • Increase product lifetime • Increase material reuse and recycling rates • Reduce vehicle weight and size • Material substitution	-10% by 2030, -34% by 2050 (239 $MtCO_{2eq}$) w.r.t. 2018
Den et al., 2020 [84]	Buildings	EU	• Efficient design to reduce material needs, use recycled materials, and extend buildings' lifetime • Reuse existing building structures and materials, or recycle • Intensify the use of existing building space (reduce space per inhabitant, optimise use of space, etc.) • Improve resource efficiency of production processes	-61% (130 $MtCO_{2eq}$)
Material Economics, 2018 [27]	Steel, Plastics, Aluminium, Cement, Mobility, Construction	EU	• Reduce material use during building construction, increase reuse of building components • Increase car sharing, optimise car design to increase lifetime and reduce maintenance • Reduce material-production waste • Increase recycling of materials	-56% by 2050 (296 $MtCCO_{2eq}$) w.r.t. to baseline scenario
Ellen MacArthur Foundation, 2015 [85]	Mobility, Food, Buildings	EU	• Increase car sharing, share of electric vehicles, and car recycling • Reduce food waste, close nutrient loop, emphasise local food supply chain • Increase renewable energy and energy efficiency	-83% by 2050 w.r.t. 2012
Circle Economy, 2021 [86]	Housing, Food, Mobility, Consumables	World	• Reduce floor space, travel, vehicle use, food waste and excess food consumption • Efficient design of buildings, vehicles, and products • Reuse materials and products; improve waste management • Sustainable food production	-39% by 2032 w.r.t. 2018
Ellen MacArthur Foundation, Material Economics, 2019 [87]	Steel, Aluminium, Plastics, Cement, Buildings, Food Mobility	World	• Eliminate waste from building/vehicle designs, construction, and food waste • Prolong buildings/vehicles' lifetime, Car sharing • Reuse products, components, and materials • Implement regenerative agriculture	-40% from Industry (3.7 $GtCCO_{2eq}$) and -49% from Food (5.6 $GtCCO_{2eq}$) by 2050 w.r.t. baseline scenario
IRP, 2020 [4]	Mobility, Buildings, Materials	G7 countries	• Efficient building design, reuse of building components • Car sharing; extend vehicle lifetime • Material substitution; enhance end-of-life recovery and recycling of materials	-35% in House (250 $MtCCO_{2eq}$) -40% from cars (305 $MtCCO_{2eq}$) in 2050 with vs without material efficiency

Notes. This table presents an overview of the potential GHG emissions savings found in the literature.

A2 CIRCULAR-ECONOMY STRATEGIES AND ENABLERS

This section reports more specific information on the circular-economy strategies mentioned in Section 2.

1. Narrow flows

Narrowing flows means using fewer resources in the production process to achieve the same purpose, i.e. resource efficiency [41]. In the R Frameworks, the actions within narrowing flows are refuse, reduce and rethink. Specifically, the concept "reduce" can be either producer or consumer oriented. For producers, reducing means using less material per unit of production or "dematerializing" product design (e.g. [48]). For consumer behaviours, participating in the sharing economy (e.g. carpooling) and using purchased products less frequently (e.g. using the car less) can also be classified as reducing actions [42]. Also "refuse" refers to both consumers and producers. For consumers, refuse means buy and use less, especially refusing using packaging waste and shopping bags [45], [46]. For producers, refuse means refusing to produce waste and use virgin and hazardous materials in the design process [44].

2. Slow flows

Slowing flows means designing long-life goods and extending the lifetime of products so to extend their utilisation and thus slow down the flow of resources [41]. In the R Frameworks, the actions that lead to slowing down the resources' flows are reuse, repair, refurbish and remanufacture. In the definitions of the European Commission, which we will use later on, reuse means any operation by which products (not yet waste) are used again for the same purpose for which they were conceived (Eurostat). Repairing, refurbishing and remanufacturing also play a large role in stretching products' lifetime. The difference between refurbishing and remanufacturing is that, while refurbished products "only" need to maintain certain standards, remanufactured products must revert back to the conditions of the original product. These actions can vary significantly across countries because of differences in culture, consumer acceptance and availability of skilled labour.[37] While these actions are expanding rapidly in certain sectors, such as vehicle components and digital printers [88], Wieser and Tröger (2018) show that around 80-90% of phones are still bought new, thus highlighting the existence of relevant social and psychological barriers in buying used [89].

3. Close flows

Closing flows means managing waste as a resource to close the loop between post-use and production, resulting in a circular flow of resources [41]. Use waste as a resource is the last option if narrowing or slowing flows are not possible. The actions of the R Frameworks related to closing the flows are recycle, recover and repurpose.

Recycling can take place either within an organisation, i.e., use a product's waste as input in the production process of the same or another product, in a cooperation across organisations, i.e. eco parks, or at the market level, i.e. sending waste streams or buying secondary inputs on the market [90], [91]. Following Bocken et al. (2016), recycling processes can be split into 4 main levels, the first one being the most circular and the last one being the least circular. Primary recycling is about using a product's waste as an input in the production of a similar product, as in the process known as "upcycling", which aims at preserving the properties of a resource [92]. Secondary recycling, or "downcycling", consists in obtaining products of lower standards [93]. Tertiary recycling relates to process used products with chemicals, with the aim to obtain core materials that can be reused to rebuild the same products, such as the recycling of LIBs. Finally, quaternary or "thermal" recycling is using

[37] For example, a survey by Greenpeace (2016) shows that Chinese and South Koreans use repair services for their phones twice more than Germans and Americans. Another London-based study by Cole and Gnanapra gasam (2017) shows that the main cause is lack of awareness in repair options and high cost of repair compared to buying new. Today, the main barriers for companies to invest in refurbishment and remanufacturing facilities are lack of skilled labour force and low consumer acceptance.

waste to produce energy, which is not considered as a CE-acceptable policy by Bocken et al. (2016) as it does not completely close the loop (waste needs to be burned).

Recovering can have different meanings, from collecting, disassembling, sorting and cleaning products for utilisation [94] to the extraction of materials from end-of-life composites, and capturing energy from waste (e.g., energy recovery [49], [95]). The European commission defines recovery as any operation by which waste is used to replace other materials that fulfil a function in a plant or in the wider economy (Eurostat).

Finally, repurposing means reusing discarded goods or components adapted for another function for second-life applications [42]. Some examples are transforming defective microchips into jewellery, glass bottles into mugs and using dismissed car batteries to power buildings [96].

4. Regenerate flows

Regenerate flows means prioritising regenerative resources to produce goods and services. As this aspect is not strictly related with the fundamental strategies of cycling resources, it is not included in the main circular-economy actions of the R Frameworks.

One of the main aspects of regenerating flows is regenerative water management. This strategy aims at replacing freshwater with rainwater and regenerated wastewater whenever possible, for example to recharge underground aquifers or as an input for permaculture.[38] Another main strategy is regenerative material management, which supports the use of bio based, reusable and non-critical materials in production processes. Examples are 3D printing, which can reduce by half the energy demand for small plastic-made products [97], and reducing rare elements such as neodymium and praseodymium in the electric cars' engines [98]. A third strategy for prioritising regenerative resources is regenerative energy management, which consists in three main courses of action. First, using renewable energy whenever possible – solar and wind do not have any technological barriers, only social and political ones [99]. Second, electrifying combustion engines, which cancels combustion and related emissions and increases efficiency [100]. Third, moving from centralised to decentralised energy systems, which have much less emissions and are more efficient [101], [102]. The final component of regenerating flows is designing out waste. There are policies that can reduce waste, such as CE design, which reduce waste via making it easier to disassemble products, traffic management or sourcing food locally whenever possible, given the local production capacity [103]. There are also other policies that can cut waste completely, such as banning single use packaging or packaging all together.

Circular-economy strategies can be enabled by 5 core enabling elements, namely design for the future, rethink business models, incorporate digital technologies, collaborate for joint value creation, and strengthen and advance knowledge [43]:

1. **Design for the future:** designing products to allow future repair, disassembling and easy recycling, by intervening on types of materials used, building components and systems. Another aspect is designing products in such a way that consumers feel more long-term attachment to the products they buy, and thus are reluctant to throw them away.

2. **Rethink the business model**: shifting the value proposition from selling products to service-based models, considering the lifetime of the products, e.g., refurbishment and servitisation [104], [105], [106].

3. **Incorporate digital technologies**: using digital technologies to enable circular actions, e.g., smart meters to track resource consumption and waste, and digital platforms to support enhanced second-life uses, such as secondary marketplaces.

[38] Concretely, rather than being drained into the sewage system, rainwater could be recovered via rainwater harvesting, greywater and wastewater systems (e.g. Espíndola et al., 2018).

4. **Collaborate for joint value creation**: collaborations between firms and governments is an important enabler of CE. As an example of private-public collaboration that enabled CE in Switzerland, the cities of Bern and Basel used Circle Economy's City Scan Process to identify best case-specific strategies for CE. Finally, take-back programs are a good example of CE-enabling collaborations between companies that sell the products and consumers who can give them back after use if they are functioning well.

5. **Strengthen and advance knowledge**: unclarity of definitions and lack of consensus in the literature is a large barrier to the implementation of CE policies. The knowledge about CE is fragmented across stakeholders and there is therefore a general distrust about CE solutions and low awareness by firms. This is why data sharing about materials, processes and in general about CE, possibly via online platforms, will be key [107]. With this regard, frameworks such as the Circle Economy's Key Elements, Ellen MacArthur Foundation's Butterfly Diagram (more general) or the European Union's Circular Economy Monitoring Framework (about data) can be useful enablers. Finally, an important enabler of CE is education on the matter, both through schools and vocational training. The (mostly mental) barriers of consumers to buy second-hand products could also be addressed by designing products for sustainable behaviour, a new branch of design which aims at convincing consumers to product return, rental or reuse [108].

A3 EUROPEAN LEGISLATION ON CIRCULAR ECONOMY

Packaging and Packaging Waste Directive 94/62/EC (1994, amended 2018, 2021, 2022): covers both design and waste management of all packaging types, from industrial to commercial, and household. Specifically, it states the types of packaging that can be placed on the EU market, with requirements on the manufacturing, composition, and reusable or recoverable nature of the packaging. It also describes the specific measures for management and prevention of packaging waste.[39]

Landfill Directive 1999/31/EC (1999, amended 2020): sets operational requirements for landfilling to protect both human health and the environment. First, it states that waste that can be used for either recycling or material recovery cannot be landfilled. Second, it sets the maximum share of municipal waste to be landfilled at 10% by 2035, while introducing rules for monitoring municipal waste and guidelines for what to do if targets are not met.[40]

Directive on end-of-life vehicles 2000/53/EC (2000): it prevents the use of certain heavy metals in the manufacturing of new vehicles, and it sets targets for the end of life of vehicles and their components. Specifically, the collection of vehicles must be carried out at suitable treatment facilities, parts and components must have suitable coding and information for both consumers and treatment organisations. In addition, it sets specific targets for reuse, recycling and recovery performance. This Directive is complemented by the Directive on the type-approval of motor vehicles regarding their reusability, recyclability and recoverability. In 2023 the Commission submitted a new proposal for a Regulation on end-of-life vehicles.

Waste from Electrical and Electronic Equipment (WEEE) Directive 2002/96/EC (2003, amended in 2012): prevents the creation of WEEE and sets rules and targets on the retrieval of raw materials from WEEE for re-use, recycle and recovery. It also makes it easier for countries to fight against illegal waste exports. This directive works in parallel with the Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS) Directive 2002/95/EC (2003, amended in 2017), which restricts the use of specific hazardous substances in electrical and electronic equipment.

Extractive Waste Directive 2006/21/EC (2006): it sets rules to either prevent or reduce adverse effects of the management of extractive waste on the environment and any resultant risks to human health. Specifically, it requires the introduction of extractive waste management in the design phase, it sets specific rules on the management of extractive waste, and it promotes reusing, recovery and recycling of extractive waste and the reduction of cyanide compounds in tailing ponds.

Batteries Directive 2006/66/EC (2006) and New Batteries Regulation (2023). The directive prevents batteries and accumulators that contain hazardous waste from being placed on the market, and sets specific rules and targets for collection, treatment, recycling and disposal of waste batteries and accumulators. The regulation adds targets on recovery and replacement and will apply the requirements of the directive in the same way across all EU states.

Waste Shipment Regulation 1013/2006 (2006, amended in 2021): sets rules to reduce the trade in hazardous waste between countries, in line with the Basel Convention. It also introduces new rules on EU waste exports in general and makes it easier to transport waste for recycling or reuse in the EU.

Waste Framework Directive 2008/98/EC (2008)[41]: sets standards on when waste material can cease to be "waste" and be considered

[39] For example, it sets the targets for recycling for all packaging types, which are 55% for all packaging at present date, and which will increase to 65% and 70% in, respectively, 2025 and 2030.

[40] It also states that only treated waste can be landfilled, and that hazardous and inert waste must be directed to specific landfills (if no other recycling options are available).

[41] The first Waste Framework Directive dates back to 1975, and the one of 2008 is the current version of it. For simplicity, we treated it as it was introduced in 2008.

a secondary product, promotes quality standards for recycling, and requires separate collection systems for at least paper, metal, plastic, and glass. It also requires additional monitoring of the process that sends waste from production to disposal or recovery (cradle to grave) and bans the mixing of hazardous waste with either other categories of hazardous waste or non-hazardous waste. In 2023, the Commission proposed an amendment of the Waste Framework Directive to introduce mandatory and harmonised Extended Producer Responsibility (EPR) schemes for textiles in all EU Member States.

Ecodesign Directive 2009/125/EC (2009, amended in 2012, 2019 and 2021): it requires manufacturers of energy-using products to reduce the energy consumption and other negative environmental impacts of their products. From 2021, it includes requirements to enhance the reparability and recyclability of appliances. It works together with the Energy Labelling Regulation 2017/1369 (2017), which regulates the type of information products must report on their energy performance.

Ship Recycling Regulation 1257/2013 (2013): it implements the Hong Kong Convention by setting rules on the recycling of ships. It brings requirements for recycling facilities, prohibits the use of hazardous materials on ships (asbestos or ozone-depleting substances) and introduces an inventory for hazardous waste materials on ships to promote clean recycling.

Directive on single-use plastics 2019/904/EC (2019): it forbids single-use plastic products, such as cotton bud sticks, cutlery, plates, straws, stirrers, and food and beverage containers, to be placed on the EU market when alternatives are available. For other single-use plastic products, it promotes reducing consumption through awareness-raising measures, introduces design and labelling requirements, and a Extended Producer Responsibility scheme with waste-management and clean-up obligations for producers.

Other directives that can be related to the circular economy but that we have not reported here are the Plastic Bags Directive, the Clean Vehicles Directive, the Directive on integrated pollution prevention and control, the Directive on the disposal of polychlorinated biphenyls and polychlorinated terphenyls, the Sewage Sludge Directive, the Directive on waste containing persistent organic pollutants, the Directive on waste oil, the Industrial Emission Directive, and the Medium Combustion Plant Directive.

Table A2 - Main circular-economy targets of EU legislation

Legislation	Objective	Target (%)	Year
Waste Framework Directive	Minimum share of municipal waste materials (paper, metal, plastic and glass) that must be prepared for reusing and recycling (by weight)	50	2020
		55	2025
		60	2030
		65	2035
	Minimum share of non-hazardous construction and demolition waste that must be prepared for reusing, recycling, and other material recovery (by weight)	70	2020
Packaging and Packaging Waste Directive[42]	Minimum share of all packaging waste that must be recycled (by weight)	65	2025
		70	2030

[42] There are more targets for packaging waste of single materials, namely plastic, wood, ferrous, aluminium, glass, paper and cupboard, which we have not reported here for brevity.

Landfill directive	Maximum share of municipal waste that can be landfilled (by weight)	10[43]	2035
Waste Electrical and Electronic Equipment Directive	Minimum share of waste of temperature-exchange and large equipment that must be recovered (by weight)	85	From 2018
	Minimum share of waste of temperature-exchange and large equipment that must be prepared for reusing and recycling (by weight)	80	From 2018
	Minimum share of waste of screens, monitors, and equipment containing screens that must be recovered (by weight)	80	From 2018
	Minimum share of waste of screens, monitors, and equipment containing screens that must be prepared for reusing and recycling (by weight)	70	From 2018
	Minimum share of waste of small equipment and small IT and telecommunication equipment that must be recovered (by weight)	75	From 2018
	Minimum share of waste of small equipment and small IT and telecommunication equipment that must be prepared for reusing and recycling (by weight)	55	From 2018
	Minimum share of waste of lamps that must be recycled (by weight)	80	From 2018
New Batteries Regulation	Minimum share of waste portable batteries that producers must collect	45	2023
		63	2027
		73	2030
	Minimum share of waste batteries for light means of transport that producers must collect	51	2028
		61	2031
	Minimum share of waste lead-acid batteries that enter recycling that must be returned to the economy (by weight)	75	2025
		80	2030
	Minimum share of waste lithium-based batteries that enter recycling that must be returned to the economy (by weight)	65	2025
		70	2030
	Minimum share of waste nickel-cadmium batteries that enter recycling that must be returned to the economy (by weight)	80	2025
	Minimum share of other waste batteries that enter recycling that must be returned to the economy (by weight)	50	2025
	Minimum share of cobalt, copper, lead, and nickel in the battery that must be recovered	90	2027
		95	2031
	Minimum share of lithium in the battery that must be recovered	50	2027
		80	2031
Directive on single-use plastics	Minimum share of plastic bottles up to 3 litres that must be collected separately for recycling (by weight per year)	77	2025
		90	2029
	Minimum share of recycled plastic in PET plastic bottles (by number of bottles)	25	2025
		30	2030

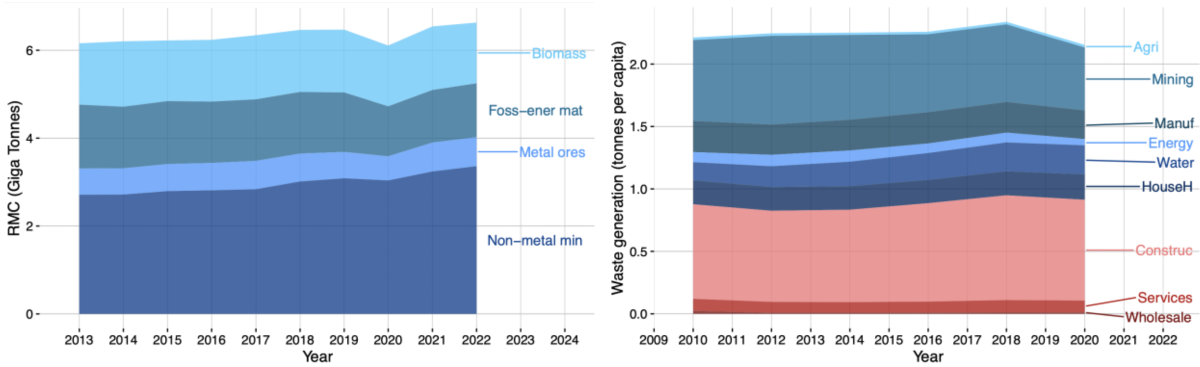
Notes. This table reports the targets developed in EU directives and legislations on CE topics. This table is an extension of the table presented in the report of the World Bank Squaring the Circle.

[43] If the deadline is postponed, member states shall take the necessary measures to reduce by 2035 the amount of municipal waste landfilled to 25 % or less of the total amount of municipal waste generated (by weight).

A4 ADDITIONAL DATA ON THE STATUS OF CIRCULAR ECONOMY IN EUROPE

Figure A1 - Trends in raw material consumption and waste generation in the EU27

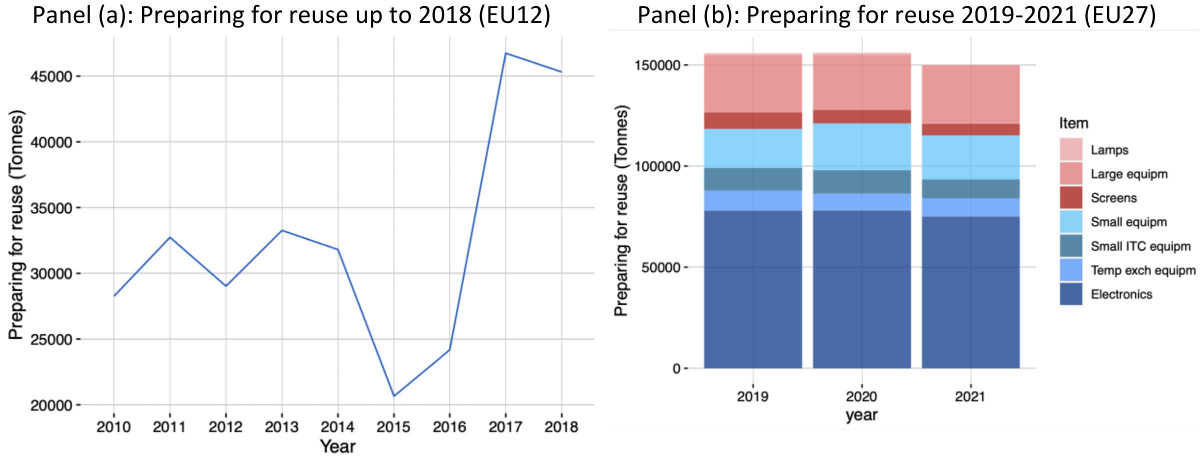
Panel (a): Raw material consumption   Panel (b): Waste generation



Notes. This graph reports trends of raw material consumption and waste generation per capita for the EU27. Raw material consumption, or material footprint, (panel a) is the demand for the extraction of materials induced by consumption of goods and services within a geographical reference area. It is the sum of domestic extraction and total imports in raw materials equivalents, net of the total exports in raw materials equivalents. The overall raw material consumption is split between fossil-energy materials/carriers ("Foss-ener mat"), metal ores (gross ores) ("Metal ores"), biomass ("Biomass") and non-metallic minerals ("Non-metal min"). Waste generation (panel b) is the total waste generated including major mineral wastes. The overall waste generation is split between Economic Activities in the European Community (NACE) plus households. They are Wholesale of waste and scrap ("Wholesale"), Services (except wholesale of waste and scrap) ("Services"), Construction ("Construction"), Households ("HouseH"), Water supply; sewerage, waste management and remediation activities ("Water"), Electricity, gas, steam and air conditioning supply ("Energy"), Manufacturing ("Manuf"), Mining and quarrying ("Mining") and Agriculture, forestry and fishing ("Agri"). Source: Eurostat.

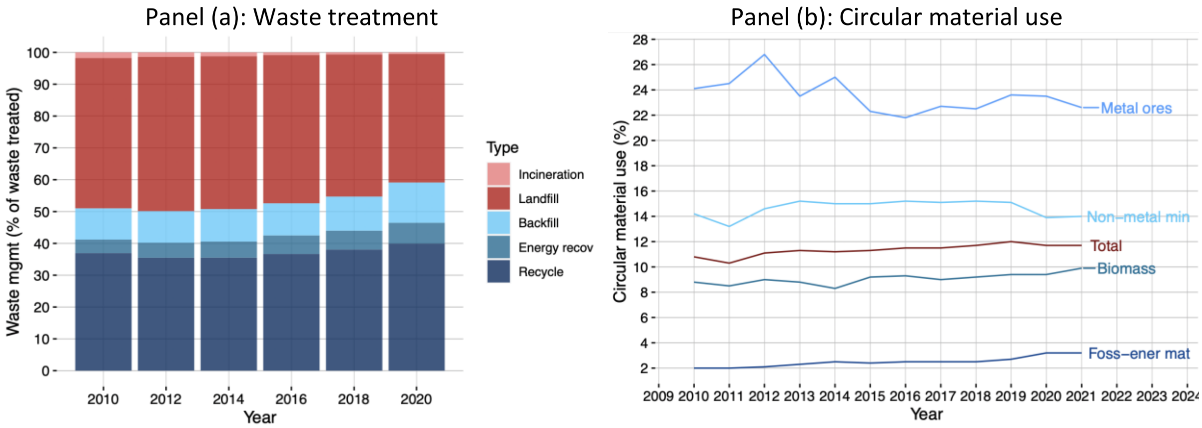
Figure A2 - Preparing for reuse

Panel (a): Preparing for reuse up to 2018 (EU12)   Panel (b): Preparing for reuse 2019-2021 (EU27)



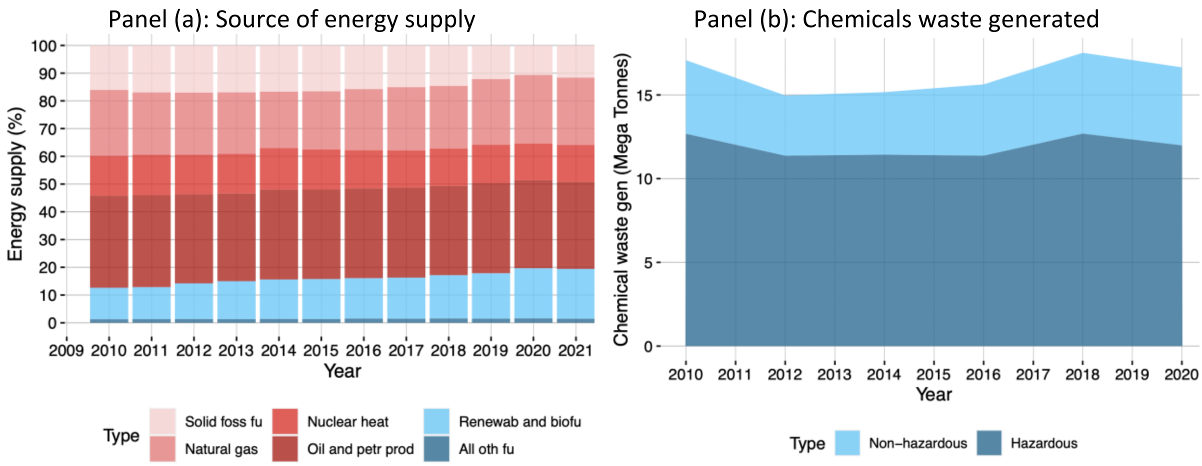
Notes. This figure reports trends in preparing for reuse of all products. As it is defined by Eurostat, preparing for reuse is the process of checking, cleaning and repairing products that have become waste so that they can be reused without any other pre-processing. This category does not include reuse, repair and cleaning of items which never became waste. In addition, to follow the new legislative packages, in 2018 Eurostat changed the definition of the items that are declared waste and prepared for reuse. Thus, panel (a) shows the general trend of all items that are being repaired to be reused up until 2018 for EU12, which includes Austria, Belgium, Cyprus, Finland, France, Germany, Ireland, Latvia, Netherlands, Poland, Portugal, Sweden. Panel (b) shows the trend for preparing for reuse for 2019-2020 for EU27, with the split of the new categories of items. They include Large equipment (any external dimension more than 50 cm) ("Large equipm"), Lamps, ("Lamps"), Small equipment (no external dimension more than 50 cm) ("Small equipm"), Small IT and telecommunications equipment (no external dimension more than 50 cm) ("Small ITC equipm"), Screens, monitors, and equipment containing screens having a surface greater than 100 cm2 ("Screens"), Temperature exchange equipment ("Temp exch equipm"), Waste arising only from separate collection of EEE (6 categories methodology defined in WEEE directive) ("Electronics"). Source: Eurostat.

Figure A3 - Trends in waste treatment and circular material use in the EU27



Notes. This figure reports trends in waste-treatment operations and circular material use. Panel (a) reports the percentages of the total treated waste that get incinerated and landfilled (red), and recovered, through backfilling, energy-recovery and recycling operations (blue). Panel (b) reports the circular material use rate, also called 'Circularity rate', which measures in percentage the share of material recycled and fed back into the economy - thus saving extraction of primary raw materials. It is defined as the ratio of the circular use of materials (U) to the overall material use (M). The overall material use is measured by summing up the aggregate domestic material consumption (DMC) and the circular use of materials (M = DMC + U). Total (red) is the total rate for the EU27, while the other ones are the specific rates for fossil-energy materials / carriers ("Foss-ener mat"), metal ores (gross ores) ("Metal ores"), biomass ("Biomass") and non-metallic minerals ("Non-metal min"). Source: Eurostat.

Figure A4 - Trends in renewable energy and chemical wastes in the EU27



Notes. This figure reports the trends in renewable energy and chemical wastes for the EU27. Panel (a) reports the split of energy supply by source, namely Solid fossil fuels ("Solid foss fu"), Natural gas ("Natural gas"), Nuclear heat ("Nuclear heat"), Oil and petroleum products (excluding biofuel portion) ("Oil and petr prod"), Renewables and biofuels ("Renewab and biofu") and All other fuels ("All oth fu"), which includes Manufactured gases, Electricity, Heat, Peat and peat products, Oil shale and oil sands, and Non-renewable waste. Panel (b) reports the chemicals waste generated in kilograms per capita, with the split between non-hazardous and hazardous waste. Source: Eurostat.

A5 Detailed Simulation Results

Table A3 - GHG emissions in Europe ($MtCO_{2eq}$)					
Sector	**2015**	**2050**			
		Baseline	***Life***	***Tech***	***Tango***
Sectoral emissions					
Agriculture	486	402	188	376	180
Buildings	901	250	220	86	81
Transport	1266	670	346	158	120
Industry	846	655	482	296	231
Energy supply	1134	307	68	27	13
Negative emissions					
Land Use and Land Use Change	-363	-389	-798	-469	-797
Biogenic carbon captured	0	-5	-5	-520	-507
Net Total Emissions					
	4270	1890	501	-46	-680

Notes. The table presents the sectoral greenhouse gas emissions in Europe (EU27, UK, Switzerland) in 2015 and for four future pathways in 2050. The *LTS Baseline* reflects the current and planned policies and targets agreed in the EU (European Commission, 2018a; European Commission, 2018b) [65], [66]. The *Life* scenario portrays a Europe with ambitious lifestyle changes. The *Tech* scenario portrays a Europe with ambitious technological changes. The *Tango* scenario combines both lifestyle and technological changes. The reference year is 2015, i.e., historical emissions are calibrated until 2015 and simulated between 2020 and 2050. Source: The results were simulated using the EUCalc model and can be reproduced using EUCalc's web interface.

Table A4 - Material demand in Europe (in thousands of tonnes)					
Material	**2015**	**2050**			
		Baseline	***Life***	***Tech***	***Tango***
Aluminium	46'079	73'001	47'361	74'286	34'956
Copper	3'959	6'792	3'671	7'926	3'522
Graphite	104	451	195	696	257
Iron	186'865	191'351	117'193	122'241	64'821
Lead	188	350	151	336	138
Lithium	8	85	32	149	52
Manganese	731	1'193	726	1'087	539
Nickel	233	630	455	674	414

Notes. The table presents the mineral demand in Europe (EU27, UK, Switzerland) in 2015 and for four future pathways in 2050. The *LTS Baseline* reflects the current and planned policies and targets agreed in the EU (European Commission, 2018a; European Commission, 2018b) [65], [66]. The *Life* scenario portrays a Europe with ambitious lifestyle changes. The *Tech* scenario portrays a Europe with ambitious technological changes. The *Tango* scenario combines both lifestyle and technological changes. The scope includes the mineral needs for passenger and freight transport (e.g., cars, trucks, buses, trains, planes, ships), for appliances (e.g., computers, TV, fridges, dishwashers), energy supply technologies (e.g., PVs, wind turbines, hydropower plants, nuclear, coal and gas power plants, batteries). For more information, please refer to Raffray (2020) [79]. Source: The results were simulated using the EUCalc model and can be reproduced using EUCalc's web interface.