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Measuring environmental benefits of Circular Economy – Public report

Authors:
An Vercalsteren, Maarten Christis, Karolien Peeters (VITO), Philip Nuss, Jens Günther (UBA), Renato Marra Campanale (ISPRA)

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Contents

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Summary / Description

This report is the first output of an ongoing task in the European Topic Centre on Circular economy and resource use (ETC CE), that aims to contribute to the knowledge on the environmental potential of circular economy. It does so by developing a methodological framework that allows a quantitative analysis of the potential of CE to reduce environmental impacts i.e. climate change, air pollution and biodiversity loss. This report uses the Circular Material Use Rate (CMUR) as a case study to assess the environmental potential of different scenarios to reach the CMUR target as set out in the 2020 Circular Economy Action Plan (CEAP), i.e. to double the CMUR within a decade. It describes the methodology that is used, the scenarios that are defined to reach this doubling target, the results and insights, along with key messages following from the assessment.

1 Key messages

The assessment of the environmental benefits of different scenarios to reach the target of doubling the CMUR in the next decade leads to some interesting insights and take-aways. The key messages following from this case study are summarized here:

- Continuing the path of historical material efficiency gains as observed in the EU are not sufficient to achieve the EU´s CMUR doubling target. We are currently 'off-track' to meet the CMUR target in 2030 as the CMUR has hardly improved compared to the 2020 level.
- Fossil fuel phase out measures can contribute only to a small extent to increasing the CMUR, because of the relatively small share of fossil fuels in the total material use. These measures are in any case not sufficient to reach a doubling of the CMUR between 2020-2030. However, they can contribute significantly to tackling specific aspects of the triple planetary crisis, being climate change and air pollution.
- Enhanced recycling has a significant effect on the CMUR though not sufficient to double the CMUR. However, the potential effect on environmental impacts is relatively small. The recycling rates (i.e., waste sent to recycling as a share of total waste treatment) are already high for metals waste (84%[1]), and considerable for biomass waste (53%[1]), fossil-based waste (41%[1]), and non-metallic mineral waste (34%[1]). The materials with the highest environmental impacts per tonne (metals and biomass) already have high recycling rates. These recycling rates have already contributed significantly to lowering environmental impacts in the past, but there is limited scope for additional benefits given that the highest potential for increasing recycled amounts lies with the non-metallic minerals category[2] which has the lowest potential environmental benefits per tonne of recycled material. However, the methodology does not capture improvements towards higher-quality recycling of wastes already recycled now (see limitations to the methodology, section 4.5).
- A small potential for improving land use related biodiversity loss is found for enhanced recycling due to improved wood and organic waste management. Climate change and air pollution impacts linked to enhanced recycling in this assessment remain largely unchanged.
- The target of doubling the CMUR between 2020 and 2030 cannot be achieved with measures focussing on fossil fuel phase out and enhanced recycling alone. In total, the overall volume of materials consumed needs to decrease with 26% below the 2020-level or 1.6 Gton (e.g., via material efficiency and demand-side measures).
- Reducing primary non-metallic minerals use (e.g., via measures targeting resource-efficient construction, increasing buildings' durability, circular construction materials, etc.) is critical for increasing the CMUR (due to large volumes and current medium-level recycling rates). However, their relatively low environmental footprint intensity[2] (compared to other materials) limits their environmental impact reduction potential.
- A higher CMUR is not necessarily a guarantee for an equivalent reduction of environmental impacts. Careful considerations on which material groups to focus on are needed when wanting to increase CMUR and maximise the environmental benefits.
- Environmental impacts differ by raw material, related to both production and use of the materials. Phasing out fossil fuels is essential for tackling climate change, while a more sustainable use of metals can help to lower impacts on human health and increase resource security, and more sustainable sourcing and use of biomass helps to lower impacts on biodiversity.
- In addition to production-side changes, also demand-side changes are necessary to increase the CMUR while also lowering environmental impacts. Policy measures focussing on final

[1] The share is the amount of waste to recycling divided by the amount of waste treated (2020-data, EU27). To link the waste codes to the material categories, a correspondence matrix of waste codes to the four material flows is used.

[2] Overall, the environmental footprint intensity is low compared to the other material categories. However, within the non-metallic minerals some smaller categories (e.g., cement) do have a higher environmental footprint intensity.

consumption are necessary to reach the doubling target of the CMUR and additionally reduce environmental pressures/impacts.

- The approach comes with limitations (see section 4.5). In the specific context of this assessment, comprehensiveness was more important than level of detail. The results from the scenario modelling of the fossil fuel phase out and the enhanced recycling should be interpreted within this specific context, considering a number of limitations.

2 Introduction

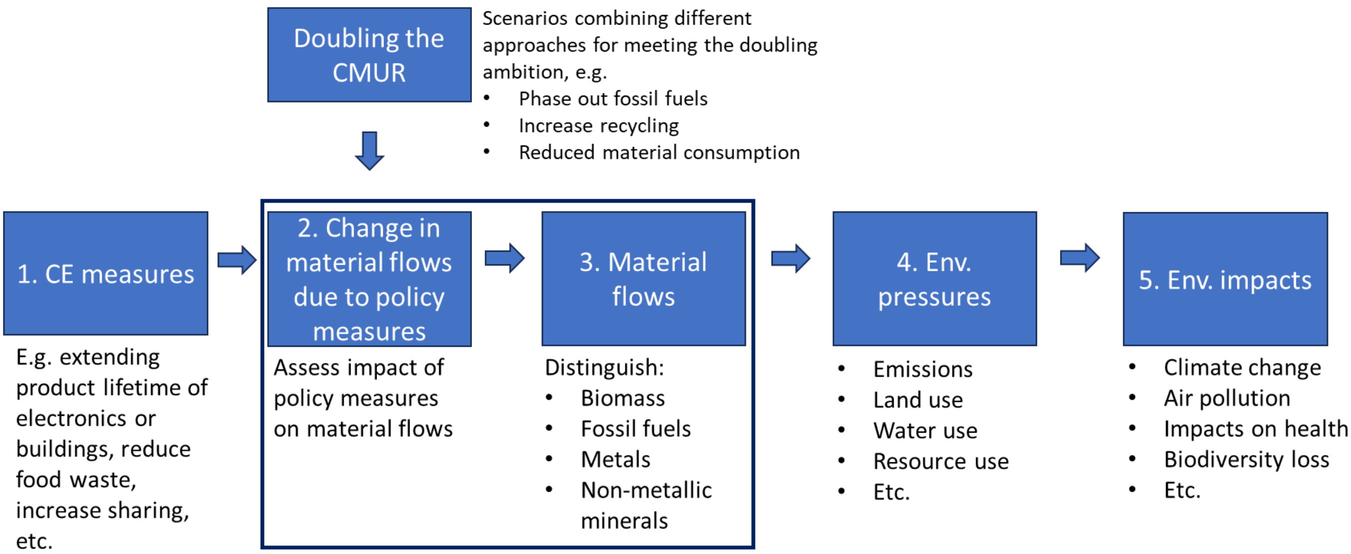
This report is the first result of a multi-annual activity with the overall objective of creating knowledge on measuring the environmental benefits of CE. Each part of the activity focusses on increasing the knowledge on the methodological steps needed to model these environmental benefits. The focus lies on climate change, biodiversity loss, and air pollution (the triple planetary crisis). This work aims to inform the debate on the future role of CE in reducing environmental pressures and impacts, to enhance positive environmental outcomes of CE and to inform policy makers around the integration of CE with multiple environmental policy arenas.

As a first step a methodological framework is developed that can be used to assess the environmental benefits of the circular economy towards biodiversity loss, pollution, and climate change. Such a methodological framework would roughly include the following steps, as illustrated in Figure 2-1:

- Identify and define the scope of CE measures;
- Translate these CE measures into changes in material flows;
- Quantify the environmental pressures;
- Calculate final impacts on climate change, biodiversity loss and pollution from the changes in environmental pressures.

Next, a case study is used to further refine the different steps in this methodological framework. The target set for the Circular Material Use Rate (CMUR) in the 2020 Circular Economy Action Plan (CEAP) is selected as a case study. The ambition as set out in the CEAP is to double the CMUR within a decade. The objective of this case study is to concretize the methodology and explore the potential environmental benefits from doubling the EU's CMUR. The analysis also offers insights on increasing the CMUR and how this could be achieved with the largest potential benefit for the environment.

Figure 2-1: Visualisation of the methodological framework



3 Background

3.1 The policy ambition to double the EU's circular material use rate

The Circular Economy Action Plan (CEAP), published in 2020, includes a non-legally binding target of doubling the circular use of materials in the coming decade[3]. Both the reduction of material use and increasing the demand and supply for secondary raw material can reduce demand for extraction of primary raw materials. This in turn would reduce the environmental impacts associated with the EU's production and consumption. The case study presented in this report is **an assessment of the environmental effects of meeting the ambition of the CEAP and the European Green Deal (EGD) to double the Circular Material Use Rate (CMUR) in the next decade.**

ESTAT data shows that the circular use of materials, expressed through the CMUR indicator, also referred to as the circularity rate, in the EU stood at 11.6%[4;5] in 2020. In terms of volume, this translates as around 0.8 billion tonnes of circular materials out of a total of 6.9 billion tonnes of material use. Although this value has increased by 0.9 percentage point since 2010, from 10.7%, and by 3.2 percentage points since 2004, from 8.4%, the current trend indicates that the EU target of doubling the CMUR will be very challenging to reach (ETC CE, 2023).

For the purpose of this report, it is assumed that meeting this non-legally binding target would mean **moving from 11.6%, the 2020 value for the EU27, to 23.2% in 2030**, as the CEAP defines neither a reference year nor a target value. Also, the target refers to the EU as a whole with no individual country-level targets set. Therefore, this analysis of the CMUR also focuses on the EU as a whole.

3.2 Description of the CMUR indicator

The CMUR[6] indicator is part of the EU's Circular Economy Monitoring Framework. It is used to monitor progress towards a circular economy on the thematic area of 'secondary raw materials'. This indicator is also one of the EEA's indicators on resource efficiency and waste (EEA, 2022). The CMUR measures the share of material recovered and fed back into the economy in overall material use:

$$\text{circular material use rate (CMUR)} = \frac{\text{circular use of materials}}{\text{overall use of materials}}$$

The circular use of materials (numerator) is approximated by the amount of waste recycled in domestic recovery plants, corrected by imports and exports. The overall use of material (denominator) is approximated by domestic material consumption (DMC), and additionally the circular use of materials is included to ensure that the rate ranges between 0 and 1. DMC is the total amount of material used directly in an economy as defined in economy-wide material flow accounts[7]. Instead of DMC, the raw material consumption (RMC) could be used as an indicator of overall material use. The RMC, however, is currently only available as a modelling estimate per Member State[8]. This report sticks to the methodological choices made by Eurostat.

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3 The Circular Economy Action Plan (CEAP) (EC, 2020) states, "[…] *the EU needs to accelerate the transition towards a regenerative growth model that gives back to the planet more than it takes, advance towards keeping its resource consumption within planetary boundaries, and therefore strive to reduce its consumption footprint and double its circular material use rate in the coming decade*".

Source: Eurostat databases Circular material use rate by material type: [env_ac_curm] (last update: 14/11/2023).

5 The 2020 data is affected by the economic slowdown due to COVID-19.

6 Eurostat metadata of the CMUR: [env_ac_cur].

7 Eurostat metadata of economy-wide material flow accounts of which the DMC is a derived indicator: [env_ac_mfa].

8 Eurostat uses DMC as a proxy indicator. The RMC is only available as an estimate and would imply potentially an overestimate of the CMUR.

A higher circularity rate value means that more primary raw materials are substituted by secondary ones thus reducing the environmental impacts of extracting primary material unless the substitution effect is overcompensated by an increase in the use of virgin materials.

Data sources that define both the numerator and the denominator of the CMUR are identified as the best proxies among official statistics of the European Statistical System. Data are available for the whole EU economy and by material category – biomass[9], metal ores[10], non-metallic minerals[11] and fossil energy carriers/materials[12] (Eurostat, 2018).

The CMUR components are DMC, waste recycling, notably recycling, RCV_R ([13]), and international trade in waste bound for recovery (IMP_W[13] and EXP_W [13]). The rate stems from the ratio between circular use of materials (U) and overall material use (DMC + U).

The formula for the CMUR is:

$$\mathrm{CMUR} = \frac{\mathrm{U}}{\mathrm{DMC + U}} = \frac{(\mathrm{RCV\_R} - \mathrm{IMP_w} + \mathrm{EXP_w})}{\mathrm{DMC} + (\mathrm{RCV\_R} - \mathrm{IMP_w} + \mathrm{EXP_w})}$$

The CMUR is developed making use of different European statistics, all of them provided by Eurostat. The components of the CMUR by material category are based on the following.

- The **DMC** component is directly available, and provided in the material flow categories, from the economy-wide material flow accounts (Eurostat, 2022).
- The **U** component, the circular use of materials, is calculated based on the amount of waste recycled in domestic recovery plants, RCV_R, derived from waste statistics[14], minus imported waste destined for recovery (IMP_W) and plus exported waste destined for recovery abroad (EXP_W) [15].
    - The component for recycling, **RCV_R**, is derived from the Treatment of waste by waste category, hazardousness and waste operations dataset[16] (Eurostat, 2023c). The statistic is provided through a waste category classification, requiring a conversion to the material categories to derive the RCV_R at a material category level. The conversion factors from

9 Biomass records material flows from the environment to the economy related to the human appropriation of cultivated and non-cultivated biomass. While the latter, for example, wild fish catch, hunting and gathering, logging from natural forests, can be measured straightforwardly at the boundary between environment and economy, the former cannot and by convention the so-called harvest approach is introduced. Amounts harvested from cultivated biological resources are available from agriculture and forestry harvest statistics.

10 Metal ores records material flows from the environment to the economy related to the mining of metallic minerals performed through underground or open-cast extraction, seabed mining, etc.

11 Non-metallic minerals records material flows from the environment to the economy related to mining and quarrying of mineral material other than metals and fossil energy carriers such as stone, sand, clay, salt, etc. It refers not only to the extraction from a mine or quarry, but also the dredging of alluvial deposits, rock crushing and the use of salt marshes.

12 Fossil energy materials/carriers extraction records material flows from the environment to the economy related to extraction of solid, liquid and gaseous fossil mineral fuels through underground or open-cast mining, and the operation of crude oil and natural gas fields. Extraction of oil shale and sands is included.

13 RCV_R: the amount of waste recycled in domestic recovery plants. Waste recycled in domestic recovery plants comprises the recovery operations R2 to R11 as defined in the Waste Framework Directive 2008/98/EC; IMP_w: the amount of imported waste destined for recycling; EXP_w: the amount of exported waste destined for recycling abroad.

14 Eurostat metadata on waste generation and treatment: env_wasgt.

15 See the Eurostat manual: Circular material use rate — Calculation method — 2018 edition

16 This statistic is collected on the basis of the Waste Statistics Regulation (EC) No 2150/2002.

waste categories to material categories are provided by Eurostat[17]. The data is only available for every even year[18].

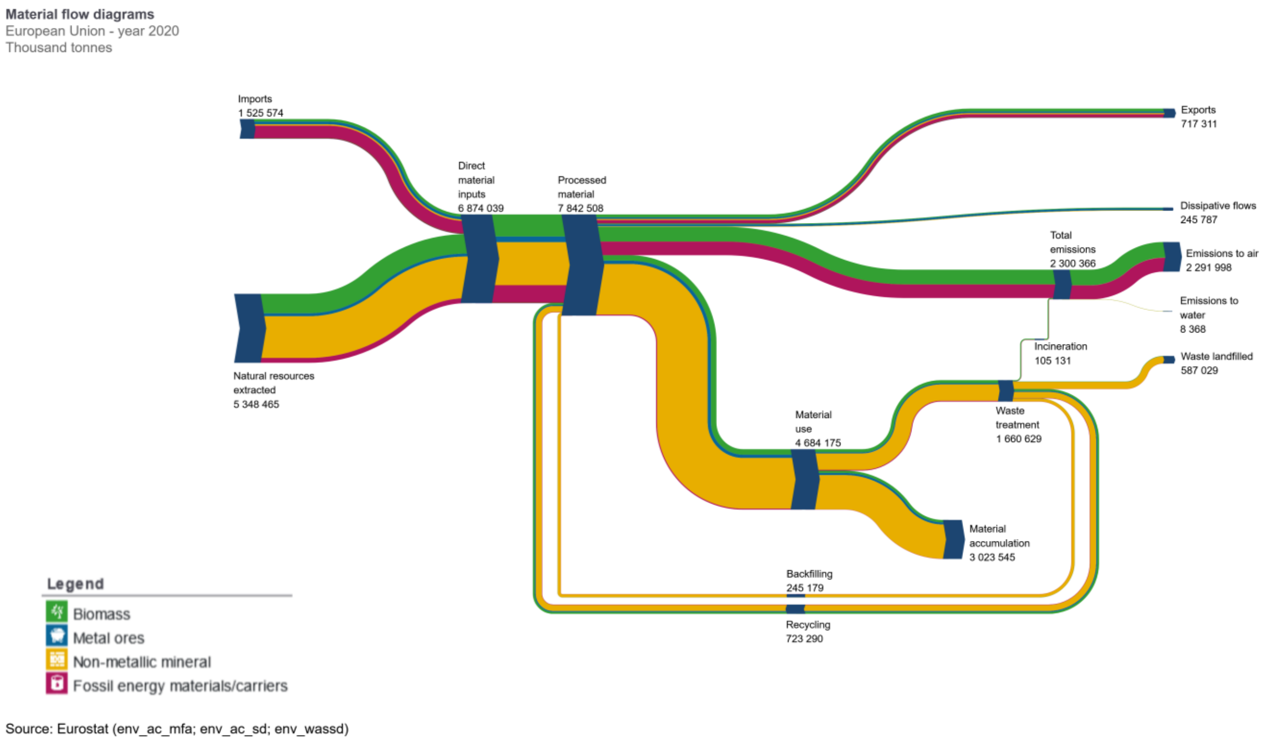
- The components **IMP**$_W$ and **EXP**$_W$ are approximated from the international trade in goods statistics (Eurostat, 2023b)[19]. A list of combined nomenclature (CN) codes used to approximate the imports and exports of waste destined for recycling is provided by Eurostat[20], together with their allocation to the four material categories.

There is a close link between the economy-wide material flow diagram (Figure 3-1; see also the assessment of the data presented by the 2020 Raw Materials Scoreboard[21]) and the CMUR. The diagram visualises the material flows captured by the components of the CMUR indicator. A Sankey diagram, in which the width of the arrow is proportional to the size of the flow, presents the (annual) flows of:

(1) resources extracted to make products or be used as a source of energy;
(2) materials and products flowing in and out of society (imports and exports); and
(3) materials and products discarded into the environment as residues, such as landfilled waste or emissions to air, or recovered and fed back into the economy.

Products with a longer life span and infrastructure such as buildings, roads and machinery are used over a long period during which they mount up in societies, increasing stocks, until they are eventually dismantled or taken out of use.

Figure 3-1 The material flow diagram for EU, 2020, thousand tonnes.



***Source**:* *Eurostat (2021) - ([env_ac_sd](env_ac_sd)) accessed January 2024.*

17 WStatR in MFA (europa.eu)

18 A gap filling (interpolation) and nowcasting methodology is developed by Eurostat to allow a yearly estimation of the CMUR.

19 Eurostat metadata on international trade in goods

20 cei_srm030_esmsip_CN-codes.pdf (europa.eu)

21 https://rmis.jrc.ec.europa.eu/uploads/scoreboard2021/indicators/ind12.pdf

The CMUR intuitively represents the size of the closing loop relative to the overall amount of materials entering the economy, although definitions, classifications, scope and treatment of imports and exports of waste differ for CMUR and the Sankey (Eurostat, 2023a).

3.3 CMUR trends in the EU

The CMUR can increase by *(1) boosting the amount of waste recycled and therefore kept in the loop (RCV_R)* and *(2) reducing the amount of primary raw material inputs into the EU-economy (DMC).* This can be supported via several policies that directly and indirectly help achieve this goal such as policies focussing on recycling, product design and material efficiency.

Enhanced recycling may be achieved, e.g., via technological improvements for better collection, sorting, and recycling as well as by product design for recycling (numerator in the CMUR equation). Recycling figures (RCV_R) vary between EU member states from, e.g., 0.26 tons per capita in Ireland to 6.41 tons per capita in Luxembourg[22] (all numbers for 2020).

Furthermore, policy measures targeting improved product durability, reusability and reparability, material/technological substitution (e.g., fossil energy carriers by metal-based renewable energy systems), and demand-side changes (e.g., lower per-person floor space, product sharing, less meat consumption) can lead to **improved materials efficiency** and **reduced materials consumption** (denominator in the CMUR equation) (ETC CE, 2023). DMC figures vary widely in EU member states from around 7.7 tons per capita in Italy to 45.0 tons per capita in Finland[23] (all numbers for 2020).

A CMUR corresponding with the EU doubling target of approximately 23.4% by 2030 has already been achieved (or exceeded) today by two EU-countries, namely the Netherlands and Belgium.
The Netherlands (NL) have constantly achieved a CMUR around 25 to 29% over time due to high waste recycling and low DMC as a result of large exports of semi-finished and finished goods (the DMC is a measure of apparent consumption of raw materials meaning that exports are subtracted from domestic extraction and imports) (Figure 3-2). The year with the highest CMUR in NL was 2016. The Netherlands has especially high recycling rates for some of the biggest waste streams (e.g., construction & demolition waste, other mineral wastes, soils, mineral wastes from waste treatment and combustion wastes) and the country's accumulation in material stocks is with 2.6 tons per capita (in 2022)[24] the smallest. In Belgium, a CMUR of 23% or higher has been measured during 2020 and 2021. Again, this is the result of relatively high waste recycling and backfilling and low domestic material consumption (Figure 3-2). However, both examples also highlight an important constraint for increasing the level of circularity, namely (1) the large fraction of materials accumulated in in-use material stocks[25]; (2) the large amounts of materials used for energy purposes[26] (fossil energy carriers, bioenergy, and the use of biomass for feed and food purposes).

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22 https://ec.europa.eu/eurostat/databrowser/view/env_wassd__custom_10964815/default/table?lang=en

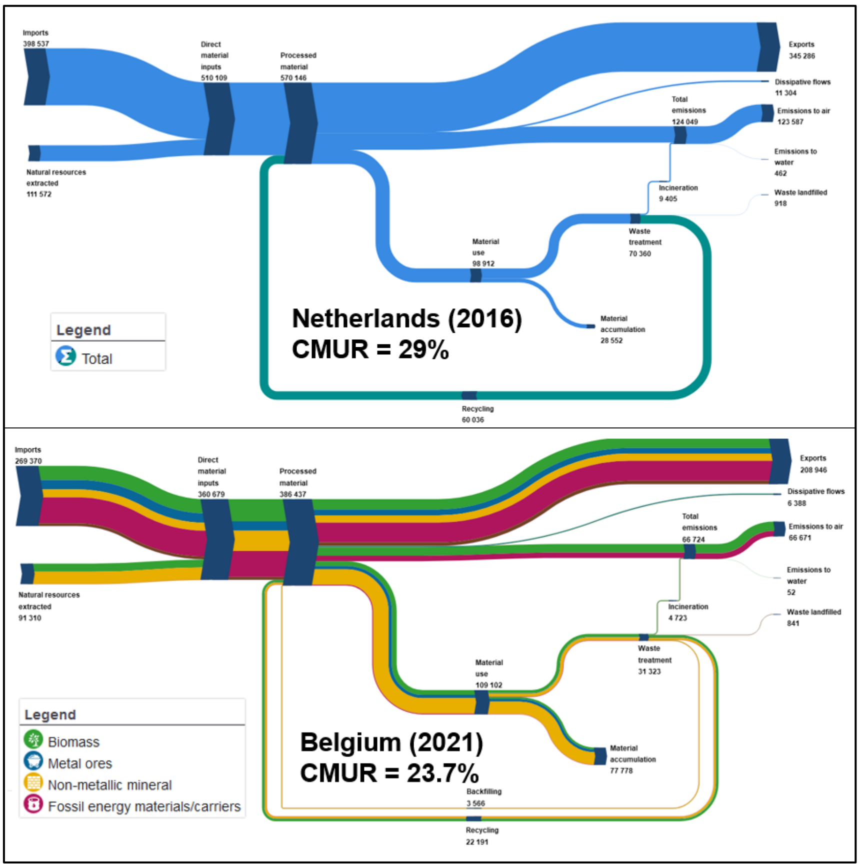
23 https://ec.europa.eu/eurostat/databrowser/view/env_ac_mfa__custom_10964843/default/table?lang=en

24 https://ec.europa.eu/eurostat/databrowser/view/env_ac_sd__custom_11907011/default/table?lang=en

25 Material accumulation is a proxy for net additions to stocks (NAS) in the CE Sankey diagram. Expanding material stocks can limit material loop closing because new materials added to stocks in the form of long-living products/goods and infrastructure are not immediately available for recycling (**add link to CML material stock growth indicator once available: https://www.eea.europa.eu/en/circularity/thematic-metrics/materialsandwaste).

26 Using materials in a dissipative manner, e.g., combustion for energy production or in products with inherently dissipative properties (e.g., pigments in paints or material-losses in tire abrasion and wear) makes them usually inaccessible for recovery and recycling.

Figure 3-2 Material flows in the Netherlands* (2016) and Belgium (2021) leading to a CMUR above the EU doubling target.



*Note that a disaggregation into individual raw material categories is not possible for the Netherlands due to a lack of available data.

A small number of studies has estimated possible future CMUR figures based on simple "what-if" estimations (ETC CE, 2023) and more elaborate scenario studies or dynamic stocks and flows models (Haas et al., 2016; Dittrich et al., 2021). For example, (Haas et al., 2016) estimated that the level of circularity of the global economy could increase from around 7% in 2025 to 21–34% through a range of strategies including, e.g., halting stock growth (non-metallic minerals), ecodesign and local material flow management, fossil fuel phase out (reduction of demands for fossil energy carriers/materials), the prevention of food waste and cascading biomass/wood use (biomass). In Germany, (Dittrich et al., 2021) find that enhanced recycling could increase the CMUR from currently around 11.7% to 21.8%. In addition, a variety of technical options exist to increase recycling in scenarios towards a greenhouse gas neutral and resource efficient Germany. Finally, a study by the ETC CE examined the influence of variations in DMC and waste recycling on the CMUR at EU-level and highlighted that only a combination of both recycling and input reductions would allow the EU to achieve the doubling target until 2030 (ETC CE, 2023).

3.4 Relationship between the CMUR and environmental impacts

The European Commission (EC) hopes with its CMUR doubling target to also lower overall environmental implications in the EU. One method for assessing the environmental impacts of material use is the method developed by Cabernard et al. (2019) and applied in the IRP GRO 2024 report (UNEP IRP, 2024) which uses the REX3 MRIO database[27] and which is also applied and explained in more detail in the ETC CE report 'Analysis of the CMUR and the doubling target' (ETC CE, 2023). This method assesses the environmental impacts of material extraction and the processing of materials to the point that they are 'ready to be used'

[27] REX3 MRIO database: https://zenodo.org/records/10354283

by the manufacturing industry[28]. The assessment covers the environmental impact categories of the Environmental Footprint methodology, endorsed by the European Commission.

Figure 3-3 shows the historical trend (between 2010 and 2022) of the material use, expressed in DMC, in Europe and the impacts related to these 'ready to be used' materials in terms of climate change, particulate matter, and biodiversity loss. The weighted environmental impact in terms of 'Environmental Footprint' is also added to the graph. The amount of material used experienced growth from 2010 to 2011, followed by a sharp decline in 2012. This is followed by a steady trend in volume through 2016 after which the trend increases with an exception in 2020 and 2022. Particulate matter has a similar trend, but more pronounced: the increase after 2016 is larger compared to the increase in the volume of material use. The same is true for climate change, but less pronounced compared to particulate matter. This downward trend in 2011-2016 is also present in the environmental footprint of 'ready to be used' materials. However, after 2016 the environmental footprint increased again with an exception in the year 2020. Land-use related biodiversity loss follows a different pattern which is more closely related to the trend in the use of biomass materials, and less to the overall trend in material use.

Figure 3-3 Historical trend of environmental impacts of raw materials used in the EU-27, 2010-2022. Data in Table 3-1.

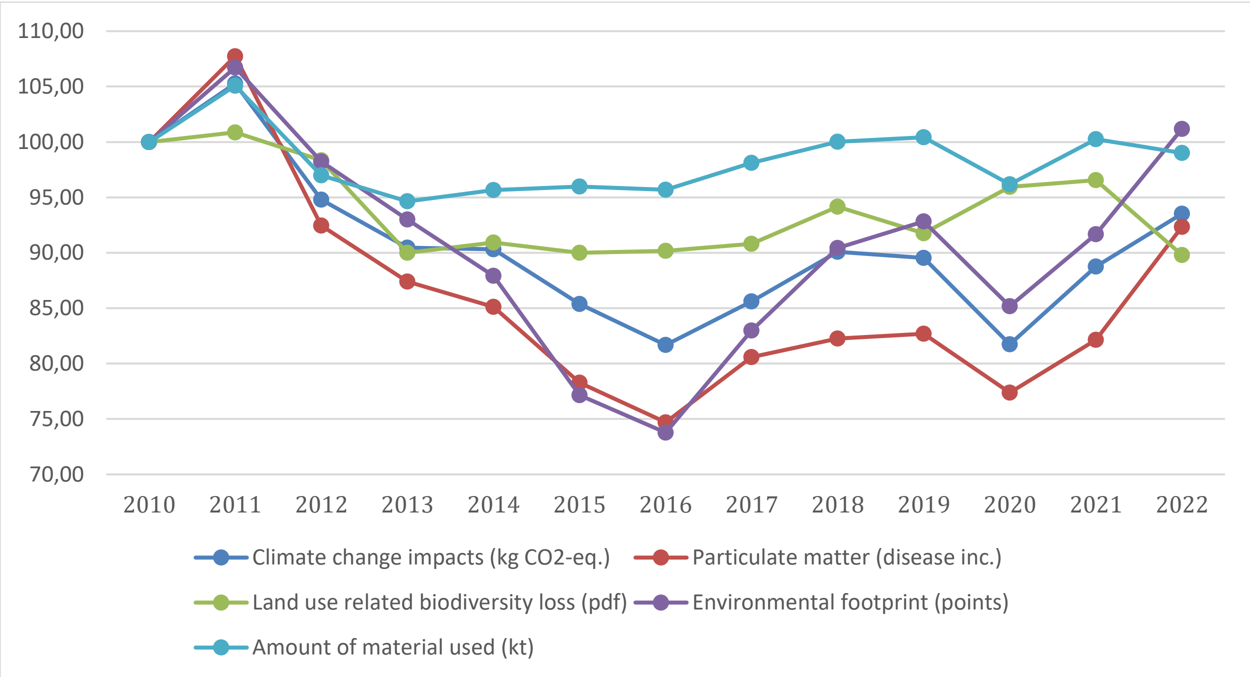


Table 3-1 Historical trend of environmental impacts of raw materials used in the EU-27.

	Climate change impacts	Particulate matter	Land use related biodiversity loss	Environmental footprint	Amount of materials used (DMC)
	(kg CO_2-eq.)	*(disease inc.)*	*(pdf)*	*(points)*	*(in kilotons)*
2010	3.09E+12	5.54E+05	7.32E-03	6.39E+08	6.40E+06
2011	3.25E+12	5.97E+05	7.38E-03	6.81E+08	6.72E+06
2012	2.93E+12	5.12E+05	7.20E-03	6.27E+08	6.20E+06

28 Environmental impacts linked to the further processing of ready-for-use materials into final products, i.e., final demand, covering household and government consumption, and investment by households and industry, are grouped into the additional remaining economy category – for example, assembly activities. Impacts that occur during household activities such as emissions from driving a car or heating are grouped under the direct impacts of household activities category.

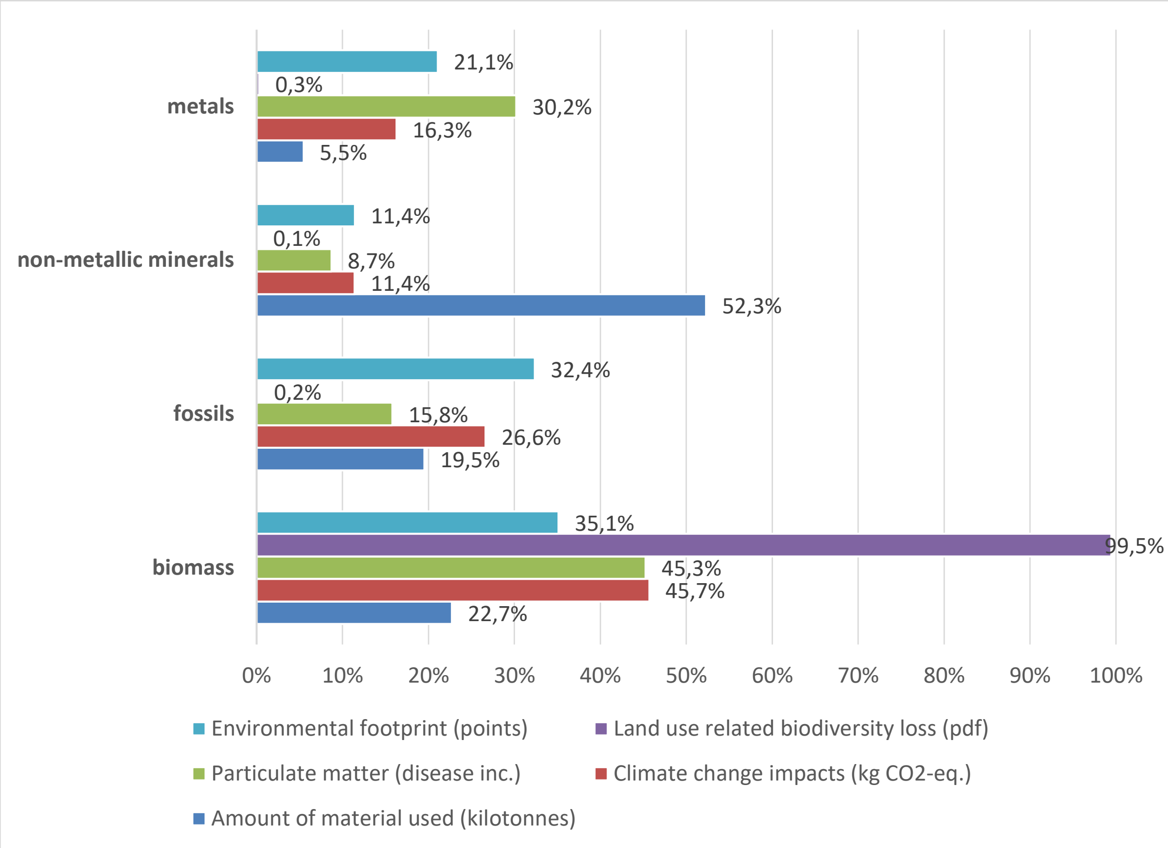
2013	2.79E+12	4.84E+05	6.59E-03	5.94E+08	6.05E+06
2014	2.79E+12	4.71E+05	6.65E-03	5.61E+08	6.12E+06
2015	2.64E+12	4.33E+05	6.59E-03	4.93E+08	6.14E+06
2016	2.52E+12	4.14E+05	6.60E-03	4.71E+08	6.12E+06
2017	2.65E+12	4.46E+05	6.65E-03	5.30E+08	6.28E+06
2018	2.78E+12	4.55E+05	6.89E-03	5.77E+08	6.40E+06
2019	2.77E+12	4.58E+05	6.72E-03	5.93E+08	6.42E+06
2020	2.53E+12	4.28E+05	7.02E-03	5.44E+08	6.15E+06
2021	2.74E+12	4.55E+05	7.07E-03	5.85E+08	6.41E+06
2022	2.89E+12	5.11E+05	6.57E-03	6.46E+08	6.33E+06

Data source: own calculation based on ESTAT FIGARO database (2024-edition), ESTAT Air Emission Accounts (last update: 13/12/2024), ESTAT Material Flow Accounts (last update: 07/08/2024), and EXIOBASE v3.8.2. The land-use related biodiversity loss footprint data of EU-27 is from IRP GRO 2024.

In Figure 3-4 the amounts of materials used in the EU are split up between the four different material types. Likewise, the environmental impact, in terms of climate change, particulate matter, biodiversity and environmental footprint, related to these material types ('ready to be used') is split over the same categories of materials.

Looking at the **amounts of raw materials used** in the EU, it shows that non-metallic minerals (e.g., used for construction and infrastructure) account for about half of all materials used, followed by biomass and fossil fuels, and metal ores having a much lower contribution. However, when looking at the cradle-to-gate **environmental footprint** (i.e., until the factory gate where "ready to be used materials" are available for subsequent products) this order is considerably different. Biomass is with 35% responsible for the largest share of overall environmental impacts followed by fossils (32%), metal ores (21%), and non-metallic minerals (11%). The same conclusions hold when looking specifically to climate change and particulate matter: the impact of ready to be used non-metallic minerals on climate change and particulate matter is significantly lower than the other material types. The ready to be used materials account for around 80% of the total environmental impacts (from a footprint perspective) with the remainder stemming from the rest of the economy and direct impacts by households. The picture is slightly different for biodiversity impact. Again, the impact of non-metallic minerals is very low (almost negligible) compared to their contribution in terms of volume, but it is mainly biomass production that contributes to the land-use-based biodiversity loss (99%), followed by metals (0.3%) and fossils (0.2%).

Figure 3-4 Amounts and environmental impacts of raw materials used in the EU-27, distinguishing the 4 material categories (2022)



Source: Based on EEA Briefing (2023) https://www.eea.europa.eu/publications/how-far-is-europe-fr and ETC CE report (ETC CE, 2023). Update for 2022 based on ESTAT FIGARO database (2024-edition), ESTAT Air Emission Accounts (last update: 13/12/2024), ESTAT Material Flow Accounts (last update: 07/08/2024), and EXIOBASE v3.8.2. The land-use related biodiversity loss footprint data of EU-27 is from IRP GRO 2024.

The insights following from Figure 3-4 illustrate that increasing the level of circularity, as measured by the CMUR indicator, does not necessarily lead to lower environmental impacts. This is confirmed by looking at country-specific levels of CMUR compared to the Consumption Footprint Indicator[29]. The level of environmental impacts depends, for example, on the individual material mix used by countries (e.g., depending on the type of energy produced/used and products produced/consumed) and the overall magnitude of material and energy demand.

[29] CMUR at country level is available via ESTAT Circular Material Use Rate database [cei_srm030]. The environmental footprint at country level is available from the EEA's European Consumption Footprint indicator.

4 Methodological approach and scenarios

4.1 Introduction

This study aims to refine the methodological approach using the CMUR target as a case study, and as such look at the environmental implications of achieving the EU CMUR doubling target between 2020 and 2030.

The method used builds on an analysis carried out by the ETC CE in 2023 to investigate how changes in the numerator (circular use of materials) and denominator (overall use of materials) of the CMUR equation can affect the overall level of circularity in the EU (ETC CE, 2023).
For this case study, three scenarios are defined to reach the CMUR target in 2030, with measures focussing on:

1. Fossil fuel phase out
2. Enhanced recycling
3. Reduced material consumption

BOX: Multi-Regional Input-Output modelling approach

Multi-regional Input-Output modelling is used to model the scenarios. This is a top-down approach, it starts from a macro perspective, sets Europe in a global context, and as such this approach gives a comprehensive picture of the EU at an aggregated macro-economic level. The approach comes with some limitations, such as the impossibility of drawing conclusions on a product level. In the specific context of this assessment, comprehensiveness was more important than level of detail. The environmentally extended multi-regional input-output (EE-MRIO) model EXIOBASE was used (Stadler et al., 2021).

According to the scenarios defined in the study, alterations are applied to the use of fossil energy carriers (against the background of fossil fuel phase out), changes in recycling, and overall reductions in material requirements (DMC) as a result of circular economy measures. For each scenario, the parameters of the CMUR equation are varied using a range of different combinations that would allow achieving the CMUR doubling target. No dynamic stock and flow model is used in this analysis. Changes are modelled via adjustments in the Multi Regional Input-Output (MRIO) tables of EXIOBASE using the methodological approach developed by (Donati et al., 2020). Changes to environmental pressures and impacts are estimated for climate change, air pollution and biodiversity loss applying an input-output analysis (i.e., calculating the EU-27 final demand footprint) using the modified MRIO-tables.

By incorporating explicit exogenous technological and demand change, it is possible to model direct and indirect effects of demand in a what-if scenario, but not to model the dynamic response of an economy, such as macro-economic price changes or systemic rebound effects (Wiebe et al., 2018). The use of expert-knowledge in the form of exogenous assumptions is considered superior to relying on formal methods to represent behaviours that make technological change endogenous (Wiebe et al., 2018) due to its transparency (Donati et al., 2020). This approach gives the modeller a maximum degree of freedom, but also the responsibility of ensuring that the changes implemented are consistent in both a mathematical and a contextual way. Annex 1 discusses more in detail the methodology used to calculate the environmental impacts.

The following sections explain how the three scenarios are defined and implemented in the methodological framework.

4.2 Fossil fuel phase out

Scenario definition

The 'Fit for 55' package targets a reduction of net EU greenhouse gas emissions to 55% below 1990 levels by 2030 and making the EU climate neutral by 2050[30]. The baseline is the existing 2030 climate and energy legislative framework, consisting of agreed climate and energy targets as well as the main policy tools to implement these (Emission Trading System (ETS), Effort Sharing Regulation (ESR), Renewable Energy Directive, Energy Efficiency Directive, CO_2 emissions Performance Standards for Cars and Vans and the LULUCF Regulation)[31]. This translates into the need for a gradual reduction of fossil energy carrier inputs, i.e., lowering fossil energy carriers/materials in DMC. We followed a combination of the ALLBNK-scenario ([30]) (most ambitious one) and the Global Energy and Climate Outlook (GECO)[32] modelling results (2022-edition). The ALLBNK scenario takes the scope 3 approach to assess the greenhouse gas (GHG) target ambition. The ETS scope covers the sectors: power, industry, all aviation and navigation and road transport and buildings. Medium intensification policies are applied to energy efficiency policies and to the renewable energy sector policies. Transport measures include the medium intensification policies covering CO_2 standards in road transport and measures improving transport system efficiency and a high intensification of renewables for aviation and maritime fuel mandates. For non-CO_2 policies the high intensification policies are considered. The GECO modelling presents an updated view on the implications of energy and climate policies around the world. Current climate policy pledges and targets imply a rapid decline in GHG emissions, but there remains both an implementation gap in adopting policies aligned with countries' mid-term Nationally Determined Contributions and Long-Term Strategies, and a collective ambition gap in reducing emissions to reach the Paris Agreement targets of limit global warming to well below 2 °C and pursue efforts to 1.5 °C.

For the fossil fuel phase out scenario in this study, it is assumed that **fossil energy carrier inputs are reduced by 34% until 2030** (ETC CE, 2023). Using this value would **increase the CMUR to 12.2% by 2030** (compared to 11.6% in 2020).

Scenario modelling

In order to calculate environmental impacts of this scenario in EXIOBASE, assumptions are made on investments in renewable energy capacity and shifts in demands to other energy carriers (e.g., renewables such as wind, biomass, hydro and solar) based on the EU Fit-for-55 policy scenarios[33]. This scenario also covers energy efficiency gains.

The scenario follows the fossil fuel phase out as presented by the EU Reference Scenario (EC, 2020). It is one of the European Commission's key analysis tools in the areas of energy, transport, and climate action. It allows policymakers to analyse the long-term economic, energy, climate and transport outlook based on the policy framework in place in 2020. This scenario can provide policymakers with a comprehensive analytical basis against which they can assess new policy proposals. The EU Reference Scenario 2020 is the baseline scenario on which specific policy scenarios and variants used to assess options informing the policy initiatives in the European Green Deal package adopted by the European Commission in July 2021 have been developed. In this assessment, the modelling is aligned with the ALLBNK-scenario as described in the impact assessment report (EC, 2020).

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30 The scenario is aligned with SWD(2020) 176 final.

31 An overview of challenges and recommendations to achieve the climate targets for 2030 and 2050 by the European Scientific Advisory Group on Climate Change can be found at: https://climate-advisory-board.europa.eu/reports-and-publications/towards-eu-climate-neutrality-progress-policy-gaps-and-opportunities

32 https://joint-research-centre.ec.europa.eu/scientific-activities-z/geco_en

33 https://energy.ec.europa.eu/data-and-analysis/energy-modelling/policy-scenarios-delivering-european-green-deal_en

The modelling assumes three main changes compared to the 2020-situation:

- **Investments in additional capacity for renewable energy.** Additional capacity for producing renewable energy is required in 2030. In 2020 the net installed capacity in EU27 based on wind (onshore and offshore), solar, bioenergy and other renewables, nuclear and fossil fuels sum up to 896 GW. In the ALLBNK-scenario the capacity is increased to 1,369 GW by 2030, with large increases in capacity for wind, solar and bioenergy (Fig. 29 in (EC, 2020)). The capacity for nuclear and fossil fuels is decreased. We assume that the additional capacity is installed equally in the 2020-2030 period. The investments into renewable energy technologies do not only involve investment into the technology itself, but the projects need to be planned (other business activities), insured, foundations and other infrastructure need to be built (construction) and the new technology needs to be connected to the grid (construction and electrical machinery and apparatus). Therefore, the total investment costs are spread across several products/industries in the gross fixed capital formation vector.

  We choose to add four renewable energy sectors to the EXIOBASE model: wind, solar, hydro and bioenergy. The structure of the input (i.e., the input of materials and services into these renewable energy sectors) of these sectors is taken from the GEME3 model. Note that these sectors are very capital intensive and require only small amounts of intermediary inputs compared to the fossil-based sectors. It is assumed that these renewable energy sectors are capital intensive requiring limited material input. Only the bioenergy sector requires agricultural inputs (ca. 0.25 euro per euro output). Service inputs like maintenance and repair are modelled as well.

- **Shifts in the demand for energy and electricity by industries and households toward renewable energy.** Shifts in demand for energy products from fossils to renewables is based on the SAM GEME3 Energy Tables from GECO (2022-edition). The change 2020-2030 is modelled into EXIOBASE showing a shift away from the use of coal, crude oil, oil products and gas towards electricity. In turn, the electricity production changes towards more renewables. The shifts are available per sector group, allowing for a varying and detailed modelling per sector group.

- **Energy efficiency by industries and households.** Making use of the changes derived from the SAM GEME3 Energy tables this not only includes a shift towards the use of renewable energy, but it also includes energy efficiency gains presented by a lower energy demand by multiple sectors and households in 2030.

As a result of the shifts towards renewable energy and the energy efficiency gains, the direct emissions of each sector in the model are also modified. Both the emissions from fuel combustion and the process emissions are modified following the emission data from the GECO modelling results. We assumed the change is equal to the difference between the 2020 and 2030 tables.

4.3 Enhanced recycling

Scenario definition

In 2020 a total of 2.0 Gt waste materials were treated in the EU27 consisting of 14% biomass, 5% metals, 76% non-metallic minerals, and 4% fossil energy carriers. Not all these waste flows can be fully recycled given existing technologies and market conditions. **Around 40% of all wastes treated in 2020 are sent to recycling and (potentially) fed back into the EU economy.** It is relevant to mention that there is a gap between the volume of waste sent to recycling and the volume of waste that is actually recycled, due to losses in the pretreatment steps (dismantling, sorting, etc.) and recycling process. The 2020 recycling rates as mentioned in Table 4-1 might overrepresent the actual recycling rates due to the accuracy of the data (for example: a recycling rate of 100% might be an overestimate).

The information on the generation of waste cannot be directly linked to the information on the treatment of waste for several reasons. The generation of waste concerns the waste produced in the country, the treatment of waste, the amount of waste treated in the country, so differences can occur due to import and export of waste. Moreover, the generation of waste includes the waste produced by waste treatment activities (sorting, composting, incineration), whereas the treatment table only includes the final treatment. Waste treatment is a process which takes time and in the meanwhile some of the weight might be lost (drying). Also, waste undergoes dismantling and sorting between generation and (final) treatment. A discarded vehicle may not be displayed as such in waste treatment data, but instead the materials it was composed of, like metal, glass, textiles etc. In short, waste generation figures are generally higher than waste treatment figures.

However, several studies have examined the potentials for increased recycling of various waste streams (e.g., Trinomics, 2020; EEA, 2020) and comparisons of different EU countries highlight that recycling potentials differ among them.

In this study, we base the total amount of waste generated that can be diverted to recycling on a mix of literature estimates, country comparisons, and expert opinions by the EEA as highlighted in Table 4-1.

Table 4-1 Eurostat waste categories, split into material categories, and assumed maximum recycling rates

Code	WASTE (Labels)	2020 Recycling rate (RCV_R/env_wasttrt)	Assumption on recyclability*	Rationale for assumption
Total	Total waste	40%	69%	
W011	Spent solvents	42%	90%	5 countries report a RR > 90%
W012	Acid, alkaline or saline wastes	82%	90%	10 countries report a RR > 90%
W013	Used oils	82%	90%	11 countries report a RR > 90%
W02A	Chemical wastes	42%	90%	4 countries report a RR > 90%
W032	Industrial effluent sludges	35%	90%	4 countries report a RR > 90%
W033	Sludges and liquid wastes from waste treatment	45%	90%	7 countries report a RR > 90%
W05	Health care and biological wastes	1%	34%	LV reports highest RR of 34%
W061	Metal wastes, ferrous	100%	100%	2020 recycling rate
W062	Metal wastes, non-ferrous	100%	100%	2020 recycling rate
W063	Metal wastes, mixed ferrous and non-ferrous	100%	100%	2020 recycling rate
W071	Glass wastes	98%	98%	2020 recycling rate
W072	Paper and cardboard wastes	98%	98%	2020 recycling rate
W073	Rubber wastes	68%	90%	6 countries report a RR > 90%
W074	Plastic wastes	71%	90%	7 countries report a RR > 90%
W075	Wood wastes	46%	90%	4 countries report a RR > 90%
W076	Textile wastes	72%	90%	7 countries report a RR > 90%
W077	Waste containing PCB	50%	70%	6 countries report a RR > 70%
W081	Discarded vehicles	100%	100%	all MS report 100%
W0841	Batteries and accumulators wastes	97%	100%	14 MS report 100%
W091	Animal and mixed food waste	72%	95%	11 MS report RR>95%
W092	Vegetal wastes	94%	95%	12 MS report RR>95%
W093	Animal faeces, urine and manure	87%	100%	13 MS report 100%
W101	Household and similar wastes	15%	70%	Better separation and sorting
W102	Mixed and undifferentiated materials	51%	70%	Better separation and sorting
W103	Sorting residues	16%	25%	4 countries report a RR >25%
W11	Common sludges	60%	90%	6 countries report a RR > 90%
W121	Mineral waste from construction and demolition	78%	96%	Trinomics study
W12B	Other mineral wastes (W122+W123+W125)	9%	33%	This is mainly mining waste - very dependent on specific case. PL only MS with a RR>30%
W124	Combustion wastes	35%	90%	5 countries report a RR > 90%
W126	Soils	36%	80%	5 countries report a RR > 80%

Code	WASTE (Labels)	2020 Recycling rate (RCV_R/env_wasttrt)	Assumption on recyclability*	Rationale for assumption
W127	Dredging spoils	8%	80%	4 countries report a RR > 80%
W128_13	Mineral wastes from waste treatment and stabilised wastes	80%	90%	6 countries report a RR > 90%

**Note that these are only first theoretical estimates which should be further improved in the future. Methods to derive waste treatment figures might vary by country as Member States are free to decide on the data collection methods. Recycling rates might include overestimates because the reporting might not deduct losses during recycling processes. RR: recycling rate.*

According to this first estimation, a **theoretical maximum of around 69% of all waste could be recycled in the future**, e.g., through a mix of technological developments such as better collection, sorting and market incentives for recycling. Using this value in the CMUR calculation implies that the **level of circularity could increase further to 21.0% in 2030** (compared to 11.6% in 2020), including the effect of the fossil fuel phase out scenario.

Scenario modelling

In order to calculate environmental impacts in EXIOBASE, assumptions are made on shifts in demands for primary to secondary materials based on Table 4-1 and a 1:1 substitution[34] for primary materials. Seven shifts are modelled. The increased demand for secondary materials is modelled via an increase in specific waste management activities to supply the additional secondary materials. Based on the categories from Table 4-1, three waste management sectors are added to the EXIOBASE model presenting secondary wood (EXIOBASE sector 51), secondary rubber and plastics (EXIOBASE sector 60) and other waste management activities (EXIOBASE sector 94). To improve the modelling quality, three new sectors are generated, and the input structure is derived as the (weighted) average of all EU27 sectors.

In this assessment, we assume a 1:1 substitution rate in which 1 kg of waste sent to recycling replaces 1 kg of primary materials.

The seven shifts included in the modelling are:

- The increased chemical wastes (W01-05) sent to recycling, from 12.3 million tons to 22.8 million tons substitute the demand for chemicals (EXIOBASE sector 57, petroleum refinery). The increased waste management activities are presented by EXIOBASE sector 94.
- The increasing volume of rubber and plastic waste (W073+074) sent to recycling, from 10.0 million tons to 12.7 million tons substitute the demand for primary rubbers and plastics (EXIOBASE sector 59, plastics basic). The increased waste management activities are presented by the specific EXIOBASE sector on secondary rubber and plastics (EXIOBASE sector 60, re-processing of secondary plastic into new plastic).
- The increased volume of wood (W075) sent to recycling, from 18.5 to 36.2 million tons, substitute primary wood (EXIOBASE sector 50, manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials). The increased waste management activities are presented by the specific EXIOBASE sector on secondary wood (EXIOBASE sector 51, re-processing of secondary wood material into new wood material).
- A small increase in the volume of textiles waste (W076) sent to recycling from 1.0 to 1.3 million tons, substituting textiles production (EXIOBASE sector 47, manufacture of textiles). The increased waste management activities are presented by EXIOBASE sector 94.
- A small increase waste containing PCB and batteries and accumulators (W077+0841), from 1.4 to 1.5 million tons, substitutes primary electronic products (EXIOBASE sector 88, manufacture of electrical machinery and apparatus n.e.c.). The increased waste management activities are presented by EXIOBASE sector 94.

[34] Note that this is likely an overestimation which, however, was used as no data on the actual share of materials substituted were available.

- A large increased volume of organic waste (W09+101) sent to recycling, from 83.0 to 141.6 million tons, substituting primary biomass (EXIOBASE sector 62, P- and other fertilisers). The increased waste management activities are presented by EXIOBASE sector 94.
- A large increase in the volume of mineral wastes (W10-12, excl. 101) sent to recycling, from 536.9 to 1,022.4 million tons, substituting primary minerals (EXIOBASE sector 32 and 33, quarrying of stone, sand, and clay). The increased waste management activities are presented by EXIOBASE sector 94.

In terms of volume, the largest shift is linked to mineral waste, followed by food waste. The other shifts present only smaller changes in terms of volumes. However, the changes are applied in monetary IO-tables meaning the volumes are converted into prices. Based on the quantities of waste sent to recycling, see above, and the EU27 production quantities from Eurostat[35], a share is derived representing the (primary) production reduction potential due to the substitution effect. The reduction in primary production is modelled via a reduced (intermediate and final) demand. The substitution is modelled via an increased (intermediate and final) demand for secondary materials. This assumes 1:1 substitution rate. Based on this monetary substitution, the largest shifts are for organic waste (29 billion euro), rubber and plastic waste (19 billion euro), and wood waste (16 billion euro).

Based on the above assumptions, this scenario should be considered as an upper limit of the potential of enhanced recycling. Several factors are set at a more optimistic value, some even beyond the feasibility range (e.g., the 1:1 substitution rate).

BOX: Optimisation of enhanced recycling

As indicated already in the methodological approach, there are some key assumptions made when it comes to the modelling of enhanced recycling. Two aspects are of great importance in that matter: the accuracy of the data on recycling rates, which are most likely now overestimations, and the quality of recycling which is not captured in the modelling.

The recycling rates, as presented in Table 4-1, are most likely overestimations. Looking for example at textile waste, the current recycling rate (as share of reported treated textile waste) is indicated to be 72% in 2020 (data from Eurostat) and an estimated maximum recycling rate of 90% is expected by 2030. This number represents the share of separately collected textiles that are sent to recovery (recycling). A large amount of textile waste is, however, not separately collected today and as such not recovered (ETC CE, 2024)

Moreover, it is important to note that the reported amounts directed to recycling include all kinds of recovery (excluding energy recovery), not only fibre-to-fibre recycling. In 2020, only 1% (or even less) was fibre-to-fibre recycling. The main share were open-loop recycled products, like cleaning rags, or even thermo-mechanical recycling of textile waste to create syngas. Quality of recycling is therefore another important aspect that could, when further optimised, influence the environmental potential of enhanced recycling.

Summarized, the approach applied for this assessment does not capture differences in the quality of secondary and primary materials. It also cannot assess the potential of improving the quality of the recycled materials. While the first is likely to overestimate the environmental benefits, the latter is likely to underestimate the benefits of the enhanced recycling scenario.

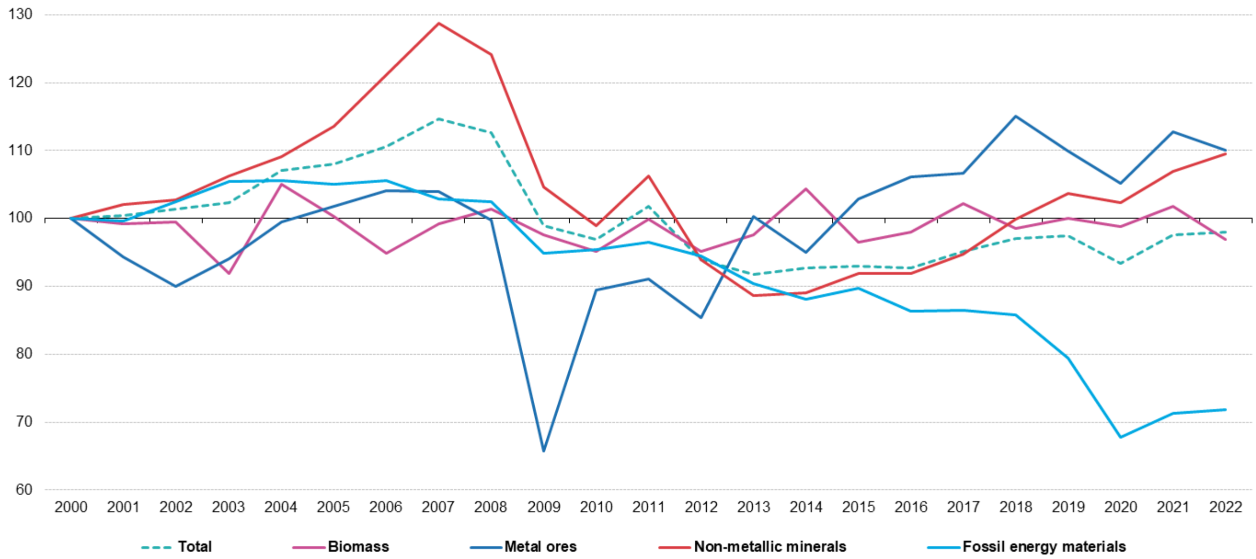
35 https://ec.europa.eu/eurostat/web/prodcom/database

4.4 Reduced material consumption

Scenario definition

Looking at the historical trend of Domestic Material Consumption (DMC) for the EU, this has slightly decreased from 2000 until 2022 largely due to a drop in the domestic consumption of fossil energy materials (Figure 4-1). On the other hand, the use of non-metallic minerals and metal ores has increased. The use of biomass has stayed roughly constant.

Figure 4-1 Development of domestic material consumption by main material category, EU, 2000-2022 (ESTAT data[36])

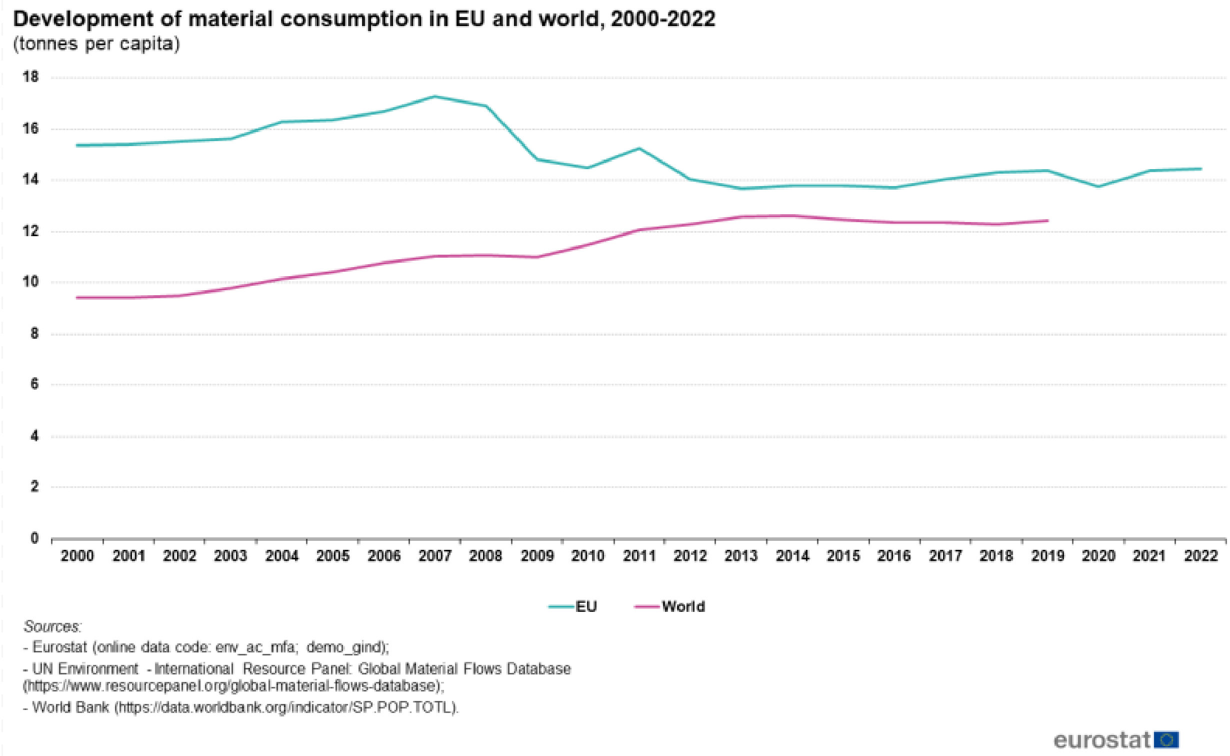


The efficiency with which materials are converted into economic output can be expressed by the *material intensity* (MI), calculated as the ratio of material used and gross domestic product (GDP). In 2020, the EU's DMC was around 6.1 Gt while its GDP was around EUR 12.5 trillion, resulting in a MI of 0.49 kg/EUR.

Figure 4-2 highlights the EU´s material consumption in comparison to the global average. Overall, the DMC of the EU decreased from more than 15 tons per capita in 2000 to approximately 14 tons per capita in 2022 (ca. 6.5% decrease over 22 years). At the same time, global material extraction steadily increased from 9.4 tons per capita to slightly above 12 tons per capita.

36 https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Development_of_domestic_material_consumption_by_main_material_category,_EU,_2000-2022.png

Figure 4-2 Development of material consumption in the EU and globally from 2000-2022 (Source: ESTAT[37] and IRP MFA[38] database)



However, if the pace of the decreasing trend of DMC in the EU from around 6.6 Gt in 2000 to about 6.5 Gt in 2022 (a reduction of ca. 0.1% per year) would be continued to 2030, this would not be sufficient to reach the CMUR doubling target by the EU. The fossil fuel phase out scenario would already reduce the DMC from 6.2 Gt in 2020 to 5.8 Gt in 2030 (DMC reduction of 6% compared to 2020). Adding the enhanced recycling scenario further reduces the DMC to 5.2 Gt in 2030 (DMC reduction of 15% compared to 2020). For doubling the CMUR, the DMC needs to be reduced to ca. 4.6 Gt in 2030 (DMC reduction of 26% compared to 2020).

It is thus clear that a third scenario is required to further reduce material consumption to a level that is sufficient to reach the CMUR doubling target. Circular Economy policy and related measures will play an important role in this. Policy approaches and measures to lower the DMC more significantly than what has been observed looking at past trends include policy measures such as improved product durability, reusability, upgradability, and repairability to increase energy and resource efficiency. Policy measures supporting sustainable consumption/lifestyle changes, e.g., lower per-person floor space or product sharing, lead to more intensive use of existing products requiring fewer materials for the same products/for meeting needs. This **reduced material consumption scenario needs to further reduce DMC from 5.2 Gt to 4.6 Gt** between 2020 and 2030 (approximately 12.3%), i.e. a reduction of the DMC of 642 million tons on top of the other two scenarios **to reach a CMUR of 23.2%.**

37 https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Development_of_material_consumption_in_EU_and_world,_2000-2022.png

38 https://www.resourcepanel.org/global-material-flows-database

Scenario modelling

The impact of the reduced material consumption scenario cannot be assessed following the same modelling approach as for the other two scenarios. To estimate the potential environmental effects of CE interventions focusing on reducing material consumption, two different approaches are followed:

- Literature review focusing on studies that assess the effect of circular interventions on material use and environmental impacts. Despite differences in scope, methods, and assumptions, the reviewed literature consistently demonstrates that the circular economy plays a pivotal role in climate change mitigation and reduction of other environmental impacts (ETC CE, 2024). A brief overview of relevant literature and a summary of the findings is reported further in this section.
- Building on the methodology developed in (ETC CE, 2023) where environmental impacts are calculated for ready to be used materials, distinguishing 4 different material categories – metals, non-metallic minerals, fossil fuels and biomass. First, different options are defined to reach the additionally required reduction in DMC, divided over the 4 material categories. A literature review is done to check if the targeted reduction of DMC is feasible or not. In a second step the environmental impact reduction induced by this reduced consumption, for each of the material categories, is calculated following the defined options. This approach, the defined options and results are discussed further in this section.

Box: The methodology 'Ready-to-be-used materials' from Cabernard et al. (2019)

In essence, this methodology allows to disaggregate the total environmental footprint from EU27 final demand into a share allocated to ready to be used materials and fuels, the remaining economy, and direct impact from households. All environmental impacts of production networks up to the point of the defined ready-for-use materials and fuels are allocated to one of the resource groups. The other environmental impacts are allocated to a remaining economy group. The impact from households (direct impacts, e.g., emissions from natural gas for heating at home) are allocated to the household category.

The method is applied to the "target perspective". In this perspective the impacts are attributed to the "target", which in this case are the (self-defined) ready-for-use materials and fuels aggregated into the four material categories, including the upstream supply network (Cabernard et al., 2019). The environmental impacts downstream the supply networks are not allocated to the material categories. These downstream emissions are critical mainly for fossil resources as their combustion causes the vast majority of global emissions (a minor part is allocated to biomass through decomposition) (Cabernard et al., 2019).

The material categories are approximated by the resource groups according to a matching sectoral output.

- Biomass is defined by the output of the sectors: agriculture, forestry, fishing, food processing industries, manufacture of wood and pulp production;
- Metals are defined by the output of the sectors: mining of metal ores, and the basic metal production (i.e., the production of iron and steel, aluminium, lead, zinc, tin, copper, other non-ferrous metals and the casting of metals);
- Non-metallic minerals comprise the output of the sectors: mining of non-metallic minerals, the production of fertilisers and the manufacture of mineral products; and
- Fossils include the output of the extraction of fossils industries, the petroleum refineries, chemical industries and the production of plastics and rubbers;

The assessment and discussion focus on the contribution of four material resource groups (metals, non-metallic minerals, fossils, and biomass) to the environmental impacts. If relevant, addition details per material category are included.

Approach based on literature review

A limited set of publications are reviewed which include an assessment or estimate of the reductions in materials use and environmental impact linked to specific circular interventions.

Circularity Gap Report

In a global context, **the Circularity Gap Report estimates that circular interventions may cut global GHG emissions by 39% and virgin resource use by 28%** (Circle Economy, 2021). Examples for such interventions include, e.g., shared mobility concepts, reductions in overall per-capita floor space, increasing the durability of buildings, or switching to healthy diets (Table 4-2). The information summarized in Table 4-2 is taken directly from (Circle Economy, 2021), except the last column where the intervention is linked to the intervention types (scenarios) defined in this study. Note that changes to the energy system (intervention 1 in our study) is part of the background system in the circularity gap report and not explicitly highlighted in Table 4-2. Together, the **combined interventions are estimated to almost double the global level of circularity[39] from 8.6% today to 17% in 2050.**

Table 4-2 GHG emissions savings from interventions examined in (Circle Economy, 2021) (global level)

Intervention	Societal need	GHG emissions savings (Gt CO2-eq)	Materials reduction (Gt)	*Intervention type (this study)**
"Natural" housing solutions	Housing	6.5	3.1	*3*
Sustainable food production	Nutrition	3.4	0.7	*3*
Resource efficient construction	Housing	3.4	4	*3*
Reduce floor space	Housing	3.2	8.4	*3*
Reduce travel	Mobility	2.4	2	*3*
Healthy diet	Nutrition	2.1	3.4	*3*
Increase housing durability	Housing	2.1	5.3	*3*
Resource efficient housing	Housing	2	0.9	*3*
Improve vehicle utilization	Mobility	1.8	1.6	*3*
Circular vehicles	Mobility	1.5	3.3	*2*
Vehicles durability	Mobility	1.3	2.2	*3*
Reduction excess consumption	Nutrition	1.3	0.4	*3*
Vehicle design improvements	Mobility	1.2	1.2	*3*
Circular construction materials	Housing	1.1	3.5	*2*
Chemicals free	Consumables	1	2.5	*3*
Clean cooking stoves	Nutrition	1	0.5	*3*
Efficient design & use of consumer products	Consumables	0.3	0.8	*3*
Circular consumables	Consumables	0.3	0.5	*2*
Efficient design & use of ICTs	Communications	0.2	0.3	*3*
Circular healthcare system	Healthcare	0.2	0.3	*2*
Durable consumer products	Consumables	0.2	0.3	*3*

*Note that the shift in the energy system (intervention 1 "fossil fuel phase out") has already been accounted throughout all interventions in the CGR 2021. It is not always possible to clearly relate the listed interventions to scenario 2 or 3 in our study.
Source: Figure 4 (Interventions Vortex) in (Circle Economy, 2021).

From Table 4-2 it is clear that CE interventions related to housing have most potential in terms of GHG mitigation and material reduction, followed by mobility and nutrition. CE interventions focused on housing thus are the most effective when aiming to reduce climate change impact and at the same time reducing

39 Note that the Global Circularity Metric derived in the 2021 CGR report is based on a mixture of EU-data for material flows and the Exiobase MRIO tables as a primary source of waste generation and treatment data. Methodological differences exist. The global circularity rate is therefore not directly comparable with the Eurostat CMUR. However, both indicators approximate the amount of waste entering the economy as a share of total material input.

our overall material use. With regard to other environmental impact categories such as air pollution, land use change, freshwater use, and acidification, the CGR 2023 (Circle Economy, 2023) provides figures, again at global level (Table 4-3). This highlights that the shift to a more circular economy (via the above-mentioned interventions) also has beneficial effects with regard to lowering other environmental impacts of which for this report especially climate change, atmospheric aerosol loading, and land use are relevant as they relate to the "triple planetary crisis" in focus.

Table 4-3 Additional environmental impact savings until 2050 due to CE measures (see Table 4-2 for examples investigated) as highlighted in the (Circle Economy, 2023) CGR 2023 (global level).

Impact category	Climate change	Ocean acidification	N cycle (air)	P soil	Atmospheric aerosol loading	Freshwater use	Land-system change	Material footprint
Unit	ppm	CO3+	Mt/yr	Mt/yr	AOD	Mm3/year bluewater	Mkm2 loss of forest covered area	Gt
Baseline	1018.5	3.1	98.9	34.8	0.03	1.6	23.61	95.1
Combined scenario	510.7	1.6	59.8	22.6	0.02	1.5	-6.9	63.2
Percentage change	-50%	-48%	-40%	-35%	-33%	-6%	-129%	-34%

The level of ambition (i.e., the detailed changes modelled within each consumption domain) is summarized in more detail in the CGR series. The measures examined in the CGR series include interventions that go beyond the Nationally Determined Contributions (NDCs) of countries (i.e., existing pledges within climate protection). These can also well go beyond what different actors might consider to fall within the realm of CE-policies. In a nutshell, assumed changes in the three sectors causing the largest impacts include (Source: Taken from the CGR methodological document 2023[40]):

Housing:

- Energy use is reduced between 6% and 25%.
- Low-carbon construction: doubling the use of wood in new housing, and a reduction of 15% in the use of steel, aluminium and cement.
- Light-weighting and reduced material needs: 15% reduction in the use of steel for new construction (substitution with wood) and 18% reduction in the use of concrete.
- 50% reduction of the construction sector's transportation requirements.
- Substitution of 18% of cement and manufactured metallic and mineral products for construction with stone, brick, sand and clay.
- Elimination of the incineration of C&DW in all world regions.

Food:

- 50% reduction in food waste globally.
- Healthy diets: eliminated the caloric intake of low nutrition foods like sugars and sugary beverages, and substituted this intake with fruits, vegetables and nuts.
- 50% reduction in the transportation of selected food products.
- Chemical N and P fertilisers were eliminated to represent an organic agriculture system.

Mobility:

40 Circle Economy. (2023). The circularity gap report 2023: Methods (v 1.0). Amsterdam: Circle Economy. Retrieved from: CGRi website

- Car-free lifestyle: penetration of these changes affects 40% of the urban population and 10% of the rural population.
- The reduction in passenger kilometres travelled by private car was partially substituted by bikes, and walking (modelled as a reduction of 30% of total passenger kilometres) and partially substituted by car sharing (70% of the total passenger-kilometres reduction).
- 50% of passenger cars and 100% of the public transport fleet is electrified in all five world regions.
- Vehicle design and lightweighting: Metals for private cars and vans were reduced by 50%, and steel, copper, and aluminium for trains, were reduced by 17%.
- Energy shift: phase-out of 75% of the electricity produced with fossil energy carriers: coal, coke, gas, oil and oil derivatives.

The examples from the CGR report illustrate that a high ambition level is required in order to reduce DMC (with 28%) and increase the CMUR (from 8.6 to 17%) (and reduce the environmental impact) on a global level by 2050. If we need to reduce the DMC in Europe by an additional 12.3% to meet the CMUR target, ambitious interventions will also be necessary on a European level. Focussing only on production-side measures will not be sufficient, additional gains need to come from demand-side measures.

Other studies did not explicitly calculate the CMUR, but provide possible ranges of environmental impacts savings due to CE-measures. The most relevant studies including their findings are summarized below.

Donati and colleagues

Another study which shows the potential of this type of strategies on a global level, i.e., product life time extension resp. resource efficiency, is documented in (Donati et al., 2020). Interventions aiming at extending the use of products or components distinguish reuse and remanufacturing on the one hand, and delayed product replacement on the other hand. Interventions targeting a reduced use of resources and improved performance during use are scrap diversion, yield loss reduction, process improvements, design improvements, use intensification and sharing. Both production-based and demand side-based measures are thus considered. In total, 37 specialized interventions are defined and all combined to assess the maximum reduction potential following the most optimal sequential processing of the interventions. All interventions are listed in detail in the annexes to (Donati et al., 2020).

The combined effect of all strategies leads to a **maximum impact reduction of 10.1% for climate change, 4.3% for land use and 12.5% for raw materials extractions used**. However, changes in the level of circularity (CMUR) were not modelled. Again, this shows the high ambition level of CE measures in order to have a significant effect on material consumption and environmental impacts. For example, the reduction potential of interventions related to delayed replacement is the most significant for all environmental impacts including material extraction. This assumes an increase in average lifetime of office buildings with 1.5 times in 32% of the market and a longer lifetime of all vehicles with a factor 2.3, which is quite challenging.

Material Economics

(Material Economics, 2019) estimates that CE actions can significantly reduce emissions from heavy industry by up to 56%, or 296 million tonnes of CO_2 equivalent (Mt CO_2 eq.) per year in the EU by 2050. The study looked at the effects of materials recirculation, product materials efficiency, and circular business models for the material categories steel, plastics, aluminium, and cement. Circular measures included in this assessment for materials recirculation are for example improved collection systems, avoiding contamination by additives or mixing of different qualities of materials, and producing materials of sufficient quality to really substitute the corresponding primary materials. More specifically for steel these measures are estimated to reduce the need for European primary steel production by 80% by 2050. Circular measures targeting more material efficient products include the reduction of materials discarded as scrap or waste in the manufacturing and construction processes, to use more advanced materials and construction techniques and to save materials by reducing over-specification and by tailoring individual products better to specific uses. For example, the use of high-strength steel is expected to potentially reduce material use by 30-40% in different applications, and reducing over-specification is estimated to lead to a 50% reduction of steel used in buildings. The last type of CE measures, related to circular business models, focus on increased utilisation and prolonged lifetime of products. One measure which is included in the assessment is the replacement of a large share of personal vehicles with a system of fleet-managed, shared vehicles. The latter is expected to require only 25% of the material inputs of the current system of individually owned cars.

Ramboll/Fraunhofer ISI/Ecologic

(Ramboll/Fraunhofer ISI/Ecologic, 2020)[41] indicate that implementing eight selected CE actions could reduce CO_2 eq. emissions related to construction, maintenance, and demolition of buildings by up to ca. 60%, avoiding 130 Mt of CO_2 eq. by 2050 compared to a 2015 baseline scenario. CE-measures investigated included product design (e.g., reduce overspecifications), use of alternative materials (e.g., innovative cement types or timber) during production processes, more sustainable consumption (i.e., optimization of space use in building), and demolition and waste management (e.g., reuse of steel and concrete).

Kennedy and colleagues

(Kennedy et al., 2022) explored the theoretical emissions reduction potential in the EU food and agriculture sector, finding that CE actions, including regenerative agriculture, could substantially save current emissions from this sector (this varies by CE-action, see respective report). CE-actions that were investigated included, e.g., the design phase (changes to the composition of food products, prevention of food loss etc.), alternative production systems (e.g., agroforestry or precision feeding livestock), preventing food waste generation, and end-of-life changes (e.g., industrial carbon capture in greenhouses, using food waste as feed, or insect-based feed). The by far largest emission reduction potentials were related to regenerative agriculture and dietary change.

Ellen Mc Arthur Foundation

On a global scale, the (Ellen MacArthur Foundation and Material Economics, 2019) found that CE-related activities could contribute to 45% of achieving the net-zero target, with the remainder stemming from energy-related activities. Focusing on five key areas—cement, plastics, steel, aluminium, and food—CE measures could reduce global GHG emissions by 40%, or 3.7 billion tonnes, equivalent to all transport-related emissions. CE measures included in this assessment relate to designing out waste and keeping products and materials in use (product reuse and materials recirculation). More concrete measures for the built environment include for example the ‘integration of durable, mixed-use buildings designed in a modular way and constructed with reused and non-toxic materials. Such building would be highly utilized, thanks to shared and flexible office spaces and flexible, smart and modular homes. This would be achieved by, for example, constructing buildings using only 50-60% cement compared to the current construction by reducing the cement content of concrete and using less concrete in the construction structure. Besides the improved design, less over-specification and the use of high-strength materials, also the industrialisation of construction processes such as prefabricated building elements and 3D printing has large potential for reducing material demand and on-site waste generation. Only focussing on the built environment, the defined CE measures could lead to a reduction of global CO_2-emissions related to the build environment by 38%. For the mobility system, CE measures could reduce global CO2-emissions even by 70% in 2050. CE measures defined for mobility include designing for lightweight vehicles, public and

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41 See also the EEA briefing: https://www.eea.europa.eu/themes/climate/cutting-greenhouse-gas-emissions-through/cutting-greenhouse-gas-emissions-through

private sharing of vehicles and designing for durability (modular and easy to maintain and repair) and for reuse and remanufacturing. CE measures considered in this assessment for the food system focus on food waste reduction through the full value chain (matching supply and demand in retail, use ugly fruits and vegetables as ingredients for food products, ensure any surplus edible food is redistributed for human consumption), nutrient-looping of by-products and green waste (composting), managed grazing (using livestock as a tool for building soil fertility) and regenerative cropland (set of techniques on arable land that reduce GHG emissions associated with different crop types and increase soil carbon capture). All measures combined are estimated to lead to a reduction of global CO2-eq. emission of 49% by 2050.

Conclusions

In conclusion, the literature review confirms the findings of the (CGR 2021) study that CE measures focusing on reduced material consumption could largely reduce the use of materials on a global scale and in Europe. Although not all studies quantify the reduction of the material consumption, or they apply another time horizon (e.g., 2050 instead of 2030), the reported reductions are of such high order of magnitude that it is safe to assume that a sufficient reduction of material consumption can be achieved to reach the required DMC reduction of 12.3% (or in absolute terms: 640 million tonnes) between 2020 and 2030 in order for Europe to reach a doubling of the CMUR. However, these reductions are the result of highly ambitious CE measures which also use a broad definition of CE. The set of CE actions modelled in the literature goes well beyond the currently adopted and proposed CE policies in the EU. Unfortunately, an assessment of the combined environmental benefits of the EU policies is currently not available. With the methodology applied in this report it is not feasible to quantify the effect of this scenario, however, following the literature review results it is assumed that the CMUR target of 23.2% will be reached, as a minimum.

The impact reduction for the reduced material consumption scenario is estimated using information from (Circle Economy, 2021, 2023). However, these estimates represent a combination of scenarios including national determined contributions (NDCs) (e.g., fossil phase out) and CE-changes across societal needs sectors (housing mobility, nutrition, consumables, healthcare) covering a mix of supply and demand-side changes related to enhanced recycling and reduced material consumption (different scenarios in our study) (Table 4-2).

Approach based on ready to be used materials methodology

As an alternative approach to estimate the environmental reduction potential of circular interventions in a reduced material consumption scenario, we apply the methodology developed in (ETC CE, 2023) where environmental impacts are calculated for ready to be used materials, distinguishing 4 different material categories – metals, non-metallic minerals, fossil fuels and biomass. This methodology allows to calculate the environmental impact per ton of metals resp. non-metallic minerals, fossil fuels and biomass used in Europe.

As a first step, different options are defined to reach the additionally required reduction in DMC, divided over the 4 material categories. The DMC-based material mix in 2020 and after the implementation of fossil fuel phase out and enhanced recycling is taken as a starting point (overview in Table 4-4).

Table 4-4: EU material mix in 2020 resp. 2030 considering implementation of (1) fossil fuel phase out scenario and (2) enhanced recycling scenario (as discussed in sections 4.2 and 4.3).

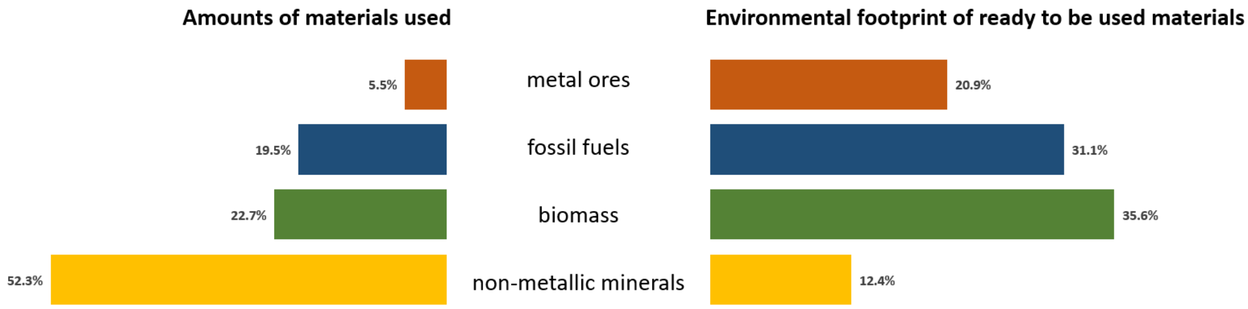
	2020			2030		
Material category	**DMC (Gton)**	**Material mix %**	**DMC (ton/cap)**	**DMC (Gton)**	**Material mix %**	**DMC (ton/cap)**
Total	***6.2***	***100%***	***13.8***	***5.2***	***100%***	***11.6***
Biomass	1.5	24%	3.3	1.4	27%	3.2

	2020			2030		
Material category	**DMC (Gton)**	**Material mix %**	**DMC (ton/cap)**	**DMC (Gton)**	**Material mix %**	**DMC (ton/cap)**
Metals	0.3	5%	0.7	0.3	6%	0.7
Non-metallic minerals	3.2	53%	7.2	3.1	53%	6.2
Fossil energy materials/carriers	1.1	18%	2.5	0.7	14%	1.6

**Assuming 468.7 million inhabitants in the EU in 2030*[42].

As is already discussed in section 3.4 and visualized in Figure 3-4, the non-metallic minerals have by far the highest share in the DMC of EU-27, but the environmental impact linked to ready to be used minerals is small (see also Figure 4-3). For the CMUR, as a volume-based indicator, the main leverage point for increasing the indicator are measures to decrease the DMC of non-metallic minerals. However, from an environmental perspective, the focus should be first on metals and on fossil energy materials/carriers and biomass products.

Figure 4-3: Amount and environmental footprint of the production of materials consumed in the EU-27, 2022



Source: EEA briefing How far is Europe from reaching its ambition to double the circular use of materials?[43] Update for 2022 based on ESTAT FIGARO database (2024-edition), ESTAT Air Emission Accounts (last update: 13/12/2024), ESTAT Material Flow Accounts (last update: 07/08/2024), and EXIOBASE v3.8.2.

As explained before, the DMC needs to be further reduced to ca. 4.6 Gt in 2030 to double the CMUR. This equals an additional reduction of the DMC of 642 million tons by 2030 compared to the 2020 level on top of the fossil fuel phase out scenario and enhanced recycling scenario. To define options on how to allocate this DMC reduction over the 4 material categories for this reduced material consumption scenario, a literature review has been done.

RESCUE-study (Germany) (Günther et al., 2019)

The RESCUE study outlines six potential pathways for Germany to achieve resource efficiency and GHG neutrality by 2050. It explores various levels of ambition in reaching GHG-neutrality, enhancing materials and energy efficiency, and promoting sustainable lifestyles. By 2050, GHG emissions could be reduced by 95% to 97% from 1990 levels. Net zero emissions may be attained through sustainable practices in agriculture and forestry. Additionally, primary raw material consumption is expected to decrease by 56% to 70% (compared to a base year of 2010), although demand for certain materials may rise. Circularity increases to 27-38% by 2050.

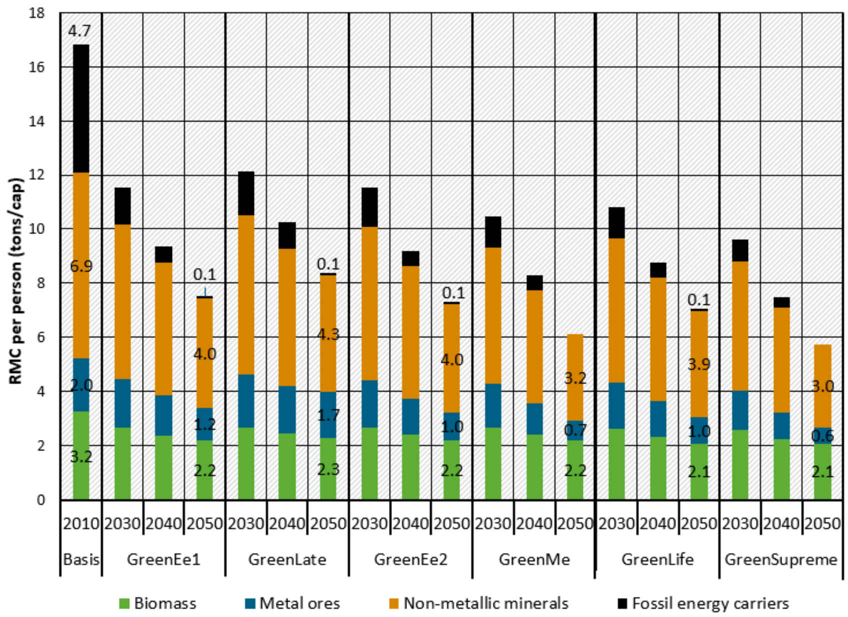
[42] https://ec.europa.eu/commission/presscorner/detail/fr/memo_05_96
[43] https://www.eea.europa.eu/publications/how-far-is-europe-from

The six scenarios include variations in energy efficiency, material use, and lifestyle changes[44]:

- *GreenEe1:* Focuses on ambitious energy efficiency improvements across all sectors, based on the earlier "Germany in 2050" project. Domestic production capacities and exports continue to increase.
- *GreenEe2:* Similar to GreenEe1 but assumes a balanced trade situation where imports and exports converge, leading to a decrease in domestic production capacities.
- *GreenLate:* The transition towards GHG neutrality starts later than in GreenEe, with less aggressive energy efficiency improvements. As a result, GHG reductions must happen more rapidly in a shorter time.
- *GreenMe:* Emphasizes ambitious improvements in material efficiency across sectors, focusing on recycling, increased use of durable products, light-weighting in transport, and reducing the demand for raw materials.
- *GreenLife:* Examines how lifestyle and behavior changes, alongside the energy and material efficiency measures from GreenEe and GreenMe, can further reduce GHG emissions. This includes scaling up trends like car-sharing and environmentally friendly habits.
- *GreenSupreme:* Combines the most effective measures from all previous scenarios, aiming for the highest level of GHG reduction and material consumption efficiency by 2050.

The material mix in 2010 (base year) and future years 2030, 2040, and 2050 is highlighted in Figure 4-4 (based on RMC per capita figures).

Figure 4-4: Material footprint (RMC) per person in the RESCUE scenarios (Source: (Günther et al., 2019))



The calculated range in material use (RMC per capita) in 2050 is given Table 4-5.

Table 4-5: RMC ranges in a GHG-neutral and resource-efficient Germany 2050 (Source: (Günther et al., 2019))

Raw material category	RMC in tons per capita in 2050	Measures
Biomass	2.1 – 2.3	Nutritional changes (less meat and dairy products), reduced food waste, biomass cascading use, more wood buildings, etc.

44 https://www.umweltbundesamt.de/en/topics/climate-energy/climate-protection-energy-policy-in-germany/rescue-resource-efficient-pathways-to-greenhouse

Raw material category	RMC in tons per capita in 2050	Measures
Metal ores	0.6 – 1.7	Enhanced recycling, eco-design, substitution, durable goods, materials efficiency, etc.
Non-metallic minerals	3.0 – 4.3	Spatial planning: reduced soil sealing, preservation before new construction of infrastructure and buildings, multi-family homes instead of single family homes, smaller apartments, material substitution, lightweight construction, (Down-)recycling, reuse.
Fossil energy carriers	0.0 – 0.1	Decarbonization, electrification, energy efficiency, etc.

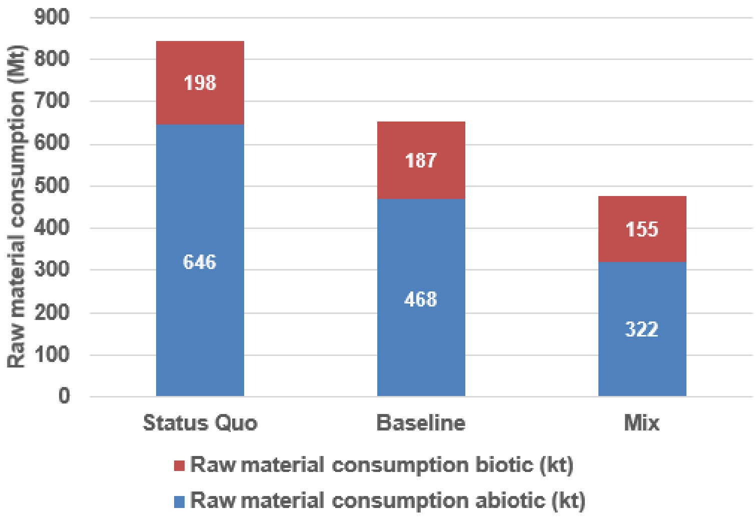
WWF-study: Circular Economy Model Germany (WWF, 2023)

The study "Modell Deutschland Circular Economy"[45] by WWF explores how Germany can transition to a circular economy, focusing on sustainable resource use. It highlights the importance of reducing waste, improving recycling, and designing products for longevity and reusability. The study outlines key sectors like construction, electronics, and packaging, providing recommendations for policy changes and industry practices that can promote circular economy principles. It emphasizes the environmental and economic benefits of shifting towards a more resource-efficient, waste-reducing system.

Three scenarios until 2045 have been modelled: (1) Status quo (continuation of already implemented measures), (2) Baseline (in addition to the status quo, a moderate implementation of CE measures, sustainable consumption, and technological development take place), and (3) Mix (an extensive mix of policy measures is implemented to make products more circular, shift toward sufficiency, and large technological developments). The base year refers to 2015 in the study.

Although no results by material category are presented in the study, a distinction is made by biotic and abiotic raw materials (Figure 4-5).

Figure 4-5: RMC developments until 2045 in the WWF Circular Economy Model Germany study (Source: (WWF, 2023)[455])



The use of biomass can be reduced to 155 Mt in 2045 assuming about 80 million inhabitants in Germany, this would equal about **1.9 tons biomass per capita** in the "mix-scenario" (approximately aligned with the RESCUE study). Abiotic raw materials use would equal with 322 Mt around 4.0 tons per capita and the total RMC per capita equals around 6 tons per capita in 2045.

UNEP IRP Global Resource Outlook (GRO2024) (global study) (UNEP IRP, 2024)

[45] https://www.wwf.de/nachhaltiges-wirtschaften/circular-economy/modell-deutschland-circular-economy

The Global Resource Outlook (GRO) 2024 by the UNEP International Resource Panel (IRP) examines a range of policy measures, including amongst them also resource efficiency, to reduce global resource use. This includes the following policy modules (UNEP IRP, 2024):

- Resource efficiency
  - Resource tax, revenue neutral ecological tax reform
  - Investment in resource efficiency innovation, demand shift
  - Efficient and sustainable settlements, shelter and building materials
  - More compact and sustainable urban form and transport modes
- Climate and energy
  - Price on carbon, early deployment of carbon removal technologies
  - Renewable energy, electrification, energy efficiency
  - Bioenergy limited to BECCCS[46] to avoid pressure on food prices
- Food and land
  - Nature protection and restoration, reduced water stress
  - Healthy diets with convergence to less average meat and dairy
  - Reduced food waste
- Just transition
  - Global resource and carbon dividend (equal per capita payment)
  - No net economic loss from sustainability transitions

In the GRO Sustainability Transition scenario global raw materials extraction is projected to slow down after 2030, peaking around 2045, and stabilizing at approximately 20% above 2020 levels by 2060 (UNEP IRP, 2024). The composition of resource use is expected to shift towards renewables, with food and fibre biomass extraction increasing by 40% by 2060. However, the global trend is not a good proxy for the EU´s evolution of raw materials use due to a global convergence in resource use (the global north has to reduce its resource demands while the global south shows an increase in resource uses.

The material footprint per capita across different income groups (low, lower-middle, upper-middle, and high income) varies for the years 2020, 2040, and 2060, as well as the global average:

- Low-income group: The material footprint per capita starts at a low baseline and shows a significant increase of 44% by 2060.
- Lower-middle-income group: Material consumption increases by 41% by 2060, indicating a similar trend of rising resource use as these economies grow and industrialize.
- Upper-middle-income group: The material footprint per capita remains relatively stable, showing a 1% decrease by 2060. This suggests that material consumption in these economies is approaching a saturation point, where growth in demand slows as efficiency improves.
- High-income group: High-income countries experience a notable 19% decline in material footprint per capita by 2060. This reduction reflects advancements in resource efficiency, circular economy practices, and shifting consumption patterns in developed economies.
- Global trend: At the global level, the material footprint per capita declines by 3% by 2060.

Resource scenarios for Austria (Haas et al., 2024a, 2024b; Meyer et al., 2024)

BOKU and WIFO published circular economy scenarios for Austria in 2024. The study examines the interaction between decarbonization- and CE-strategies in Austria's buildings, transport, and electricity sectors to achieve three key policy goals: carbon neutrality by 2040, reducing material consumption, and limiting annual land take. The study uses scenarios to evaluate the outcomes of different approaches over a time window from 2018 (base year) to 2040. A decarbonization-only scenario reduces material use by just 7% but presents significant risks, such as high green electricity demand, dependence on critical materials, and permitting challenges. A weak CE scenario fails to significantly mitigate these risks or achieve CE and land-use targets. In contrast, a strong CE scenario, which avoids further expansion of

[46] Bioenergy with carbon capture and storage

buildings and roads on unbuilt land, drastically reduces processed materials from 102 to 26 Mt/a, aligning with all three targets. This approach eases green electricity demand, supports decarbonization, and generates additional health and environmental benefits.

According to the study, DMC across the three sectors buildings, transport, and electricity[47] could be lowered depending on the scenario. Highest DMC numbers are found for scenario (A) decarbonization and lowest values for scenario (C) decarbonization and 'strong CE'. DMC numbers for scenario (B) decarbonization and 'weak CE' range in-between, closer to the high values:

- Fossil energy carriers: 0.08 – 0.30 tons per capita
- Biomass: 1.06 – 1.13 tons per capita
- Metals: 0.003 – 0.23 tons per capita
- Non-metallic minerals: 0.49 – 6.71 tons per capita

In comparison, per-capita DMC figures for the base year 2018 are: fossil energy carriers: 1.25 tons/capita, biomass 1.04 tons/capita, metals: 0.18 tons/capita, and non-metallic minerals: 6.38 tons/capita. Changes until 2040 for buildings include, e.g., the decarbonization of heating systems, improved thermal renovation rates, increased building insulation, lifetime extension of buildings, increased timber construction, and reduced heated floor space. Changes for transport include, e.g., vehicle fleet electrification, modal shifts, reduction of person kilometres driven, car sharing, and limited road network developments. Changes in the electricity sector cover the anticipated fossil phase out due to climate protection.

Global screening of current best practices (Dittrich et al., 2012)

(Dittrich et al., 2012) argue that based on current best practices in countries to lower their RMC (Table 4-6) and assuming the complete substitution of fossil fuels without increases of other materials might result in a level of **8 tonnes per capita by 2030**. This limit was also used in further environmental footprint analysis (Hoekstra and Wiedmann, 2014; O'Neill et al., 2018). The estimates as included in Table 4-6 are put forth for future raw materials use.

Table 4-6: Raw material use ranges based on current best practices as highlighted in Dittrich et al[48] (Dittrich et al., 2012)

Raw material category	Description	Value (tons per capita)
Biomass	Biomass consumption ranges from 1 to 22 tonnes per capita, with food-related activities being the largest contributor. Countries with low biomass use, like Kuwait, either import biomass or face insufficient diets. Higher consumption, over 5 tonnes, is linked to cattle-based or export-oriented agriculture. In contrast, nations like China and Italy, with around 2.2 tonnes per capita, exemplify efficient biomass use through domestic production and low consumption.	2.2
Fossil energy carriers	Fossil fuel consumption ranges from nearly zero to over 30 tonnes per person. Few countries with reliable energy supplies stand out, as most still rely heavily on oil, gas, or coal. However, Switzerland, Sweden, and Iceland are notable for their high shares of renewable energy, with fossil fuel consumption between 2 and 2.5 tonnes per capita. (Complete phase-out (substitution by other materials) assumed until 2030 in the decoupling analysis)	2.0 – 2.5 (0.0)
Metals	Metal consumption ranges from almost zero to over 30 tonnes per capita. Low consumption is found in the least developed and metal-importing countries, while high consumption occurs in metal-exporting nations. Japan stands out as a model of efficiency, with its 3R initiative (reduce, reuse, recycle) and an average metal use of 0.8 tonnes per capita.	0.8

[47] Note that for all other sectors (e.g., including food and agriculture) no change in relation to the reference scenario was modeled in the study by Haas and colleagues (Haas et al., 2024b).

[48] https://www.boell.de/en/content/green-economies-around-world-implications-resource-use-development-and-environment

Raw material category	Description	Value (tons per capita)
Non-metallic minerals	Mineral consumption ranges from 0.3 to 80 tonnes per capita. High consumption is seen in countries investing in infrastructure, while low levels are found in nations with minimal public infrastructure. In between, countries like the UK and the Netherlands, focused on maintenance rather than new construction, have relatively low consumption, around 4 to 5 tonnes per capita.	4.0 – 5.0

UNEP IRP decoupling analysis (UNEP IRP, 2014, 2011)

The UNEP International Resource Panel (IRP) sketches out a possible resource target of **6-8 tonnes per capita and year in 2050** based on different decoupling analysis conducted (UNEP IRP, 2014, 2011). This presents a target under which there would be convergence in raw materials use, i.e., developing countries would achieve a rising consumption of raw materials, while industrialized countries would need to reduce the intensity of the raw materials use (equitable use of natural resources). However, the report does not provide figures by raw material categories required for our assessment.

Global resource targets (Bringezu, 2015)

(Bringezu, 2015) outline a possible target corridor for raw material use of **3-6 tons per person until 2050** by assuming a necessary halving of global resource consumption (resulting in a low target value) or returning to the level of 2000 (resulting in a high target level). A level of **5 tons per capita** is suggested as "sustainable". This is based on an original proposal by Schmidt-Bleek (Schmidt-Bleek, 1992, 1994) which suggested "to halve global resource consumption while at the same time change the distribution between industrial and developing countries from 80:20 to 20:80 in order to reflect the relations between populations. This would allow developing countries to double their resource use within 50 years (increase it even 2.5 times within the first 40 years), while industrial countries would need to reduce their resource consumption by a factor of roughly 10 (87.5%)".

Table 4-7 summarizes the possible material use reductions as discussed in literature.

Table 4-7: Table of material use reductions proposed in the literature.

Material category	Future material use value (t/cap)	Indicator	Publication	Spatial scope	Temporal scope
Biomass	2.1 – 2.3	RMC	(Günther et al., 2019)	Germany	2050
	1.9	RMC	(WWF, 2023)	Germany	2045
	1.06 – 1.14*	DMC	(Haas et al., 2024b, 2024a; Meyer et al., 2024)	Austria	2040
	2.2	DMC	(Dittrich et al., 2012)	Current best practices (global screening)	2008
	3.0 (based on food)	TMR	(Lettenmeier et al., 2014) as cited in (Bringezu, 2015)	Finland	2050
	1.1 – 2.2	RMC	(Bringezu, 2015)	Global	2050
Metals	0.6 – 1.7	RMC	(Günther et al., 2019)	Germany	2050
	0.003 – 0.23*	DMC	(Haas et al., 2024b, 2024a; Meyer et al., 2024)	Austria	2040
	0.8	DMC	(Dittrich et al., 2012)	Current best practices (global screening)	2008
Minerals	3.0 – 4.3	RMC	(Günther et al., 2019)	Germany	2050
	*0.49 – 6.71**	DMC	(Haas et al., 2024b, 2024a; Meyer et al., 2024)	Austria	2040
	4.0 – 5.0	DMC	(Dittrich et al., 2012)	Current best practices (global screening)	2008
Fossil fuels	0.0 – 0.1	RMC	(Günther et al., 2019)	Germany	2050
	*0.08 – 0.30**	DMC	(Haas et al., 2024b, 2024a; Meyer et al., 2024)	Austria	2040
	2.0 – 2.5	DMC	(Dittrich et al., 2012)	Current best practices (global screening)	2008

Material category	Future material use value (t/cap)	Indicator	Publication	Spatial scope	Temporal scope
	0.0	DMC	(Dittrich et al., 2012)	Global	2030-2050

**The study modelled the sectors buildings, transport, and electricity in three scenarios until 2040, namely (A) decarbonization, (B) decarbonization and 'weak CE', and (C) decarbonization and 'strong CE'. For all other sectors (e.g., including agriculture/food) no changes in relations to the reference scenario were modelled.*

Note: Methodologically the difference in DMC and RMC is how trade flows are measured. In calculating the DMC, only the direct mass of trade flows in taken into account. While for RMC, also the material rucksack of trade flows is included. Via the raw material equivalents the direct mass of trade flows can be converted in its raw material equivalent to calculate the RMC. At EU-27 level, the difference between both is relatively small, except for the material category of metals. Therefore, in the further modelling in this report it is assumed that the future material use (RMC expressed in t/cap) is reasonable to be used as an approximate for DMC (in t/cap).

Based on the insights from the literature study and the assessment discussed in (ETC CE, 2023b), **three options for allocation of DMC reduction over the material categories** are tested to reach the targeted reduction of DMC following a reduced material consumption scenario, as presented in Table 4-8:

- In a first option the total required reduction is allocated to non-metallic minerals. As this material category has the highest share in EU-27 material consumption, reducing its use with 0.6 Gton can be expected to require the least effort.
- As a second option the material use reduction is allocated to the 4 material categories proportionally to the shares of material categories in the DMC in 2030, after implementation of fossil fuel phase out and enhanced recycling. However for some material categories the required reduction might not be feasible, for example for metals this can be questioned.
- Therefor, a third option takes into account the insights from other assessments reported in literature with regard to maximum potential and limits to reducing the use of specific types of materials. According to literature, the material use reduction potential of metals and fossil energy carriers is considered small and therefor set to zero in this option. The reduction potential of biomass is set to the limit of 2.3 tonnes per capita and the remaining reduction is allocated to non-metallic minerals.

Table 4-8: Three options for required DMC reduction according to the reduced material consumption scenario

	Option 1: 100% non-metallic mineral	Option 2: Proportional to 'current' share in DMC	Option 3: Following values proposed in literature
Biomass		-175 Mtonnes (27%)	-383 Mtonnes (60%, to 2.3 t/cap)
Metal ores		-39 Mtonnes (6%)	
Non-metallic minerals	-642 Mtons (100%)	-342 Mtonnes (53%)	-259 Mtonnes (40%, remainder to 5.6 t/cap))
Fossil energy materials/carriers		-87 Mtonnes (14%)	

4.5 Limitations to the methodology

Multi-regional Input-Output modelling (see Box on the Multi-Regional Input-Output modelling approach) is used to model the scenarios. This is a top-down approach, it starts from a macro perspective, sets Europe in a global context, and as such this approach gives a comprehensive picture of the EU at an aggregated macro-economic level. The approach comes with some limitations, such as the impossibility of drawing conclusions on a product level. In the specific context of this assessment, comprehensiveness was more important than level of detail. The results from the scenario modelling of the fossil fuel phase out and the enhanced recycling should be interpreted within this specific context, considering a number of limitations:

- The modelling does not account for any dynamic responses, meaning no rebound or induced effects where explicitly modelled. The modelling relies on static input-output analysis. Changes are included in the use and supply by industries and final demand and a limited number of 'new technologies' on energy production and recycling are added to the model to improve granularity. Other new and evolving technologies (e.g., steel production) are not included.

- The modelling of the fossil fuel phase out should be interpreted as major (predefined) changes from literature (e.g., Global Energy Climate Outlook and Fit-for-55-package). No dedicated or detailed energy modelling is included in this approach.
- For the modelling of recycling, the limitations come with the approach of using the waste treatment data. This approach does not capture any improvements in the quality of recycling, and also ignores that not all waste categorised as recycled is actually finally recycled. Assumptions on this are very coarse. The methodology does not capture improvements toward higher-quality recycling of waste already recycled now.
- The recycling rates should be interpreted as first theoretical estimates with limited accuracy. The assumptions on the increase in recycling rates are just based on expert judgement, with large uncertainties especially for some larger waste streams such as mining waste.
- Increasing recycling rates are modelled assuming a 1:1 substitution between primary and secondary materials. We note that a full conversion of waste sent to recycling into secondary materials and a 1:1 substitution between primary and secondary materials assumed in this assessment is overestimating the potential benefits and might be thwarted by lower efficiency levels.
- No modelling for the scenario on reduced material consumption, due to a lack in detailed assumption on how the reduction can be achieved.

5 Results: Environmental reduction potential

5.1 Introduction

For the three scenarios defined for the case of the CMUR target the environmental impact potential is assessed following the methodology and modelling approach as discussed in chapter 4. When discussing the results of this assessment, it is important to note that the effect of the scenarios on the CMUR resp. the environmental impacts is cumulated over the three scenarios, as presented in Table 5-1.

Table 5-1 Overview of scenarios defined and assessed in this study.

Scenarios	CMUR calculation	Modelling approach: EXIOBASE implementation
Fossil fuel phase out	Phase-out of fossil energy carriers by 34% until 2030. CMUR = 12.2%	Assumptions are made on investments in renewable energy capacity, lower energy demand following energy efficiency gains and shifts in demands to other energy carriers (e.g., renewables such as wind, biomass, hydro and solar) based on the EU Fit-for-55 policy scenarios
Fossil fuel phase out + Enhanced recycling	Increase of waste recycling to 69% by 2030, assuming the same amount of waste is generated in 2030 as in 2020. CMUR = 21.0%	Assumptions are made on shifts in demand to secondary materials (followed by an increased supply) based on Table 4-1, including a 1:1 substitution for primary raw materials
Fossil fuel phase out + Enhanced recycling + Reduced material consumption	**Additional 12.3% reduction in DMC is required**. CMUR = 23.2%	No implementation in EXIOBASE possible. Based on literature review resp. ready to be used materials methodology.

The **fossil fuel phase out scenario** is modelled as a reduction in the use of fossil energy carriers by 34% in 2030, being implemented as a reduction in the DMC-indicator. A reduction in the DMC, all other things equal, results in an increase in the CMUR from 11.6 to 12.2%. The relatively small increase results from the smaller share of fossil energy carriers in the DMC of only around 18% in 2020 and the increase in use of materials for energy infrastructure (short term).
The **scenario of enhanced recycling** is added via an increase of the volume of waste sent to recycling. In addition, the increased supply of secondary raw materials is assumed to equal a 1:1 substitution of primary raw materials. The waste sent to recycling is increased to 69% of the total waste treated. Around an additional 600 million tons of materials are send to recycling, and assuming a 1:1 substitution rate the DMC is reduced by the same amount. Following Table 4-1, the increase mainly encompasses non-metallic minerals and to a lesser extent biomass. The recycling rates for metals are already high and are assumed not to increase any further.
The **reduced material consumption scenario** introduces an additional reduction in DMC in order to reach the doubling target of 23.2%. Continuing from the other two scenarios, the required further reduction in DMC is an additional 12.3%. The three options as defined in Table 4-8 to allocate this additional DMC reduction over the four material categories are used to calculate the effect on the environmental impact via the ready to be used materials methodology.

The following paragraphs present and discuss the environmental reduction potential of the scenarios (following a cumulative approach), as calculated with the reported assumption and modelling approach and focussing on climate change, particulate matter (as a measure for air pollution) and land use based biodiversity impacts.

5.2 Fossil fuel phase out

Calculations for this scenario illustrate that measures related to fossil fuel phase out can help to reduce environmental impacts (large synergies for some) while also increasing the EU´s level of circular material use rate slightly (small synergies):

- The largest synergies exist with lowering climate change impacts, where calculations show a reduction potential of 18% compared to 2020 levels, followed by air pollution for which calculations show a reduction of 14% (both following the footprint perspective).
- This pathway doesn't seem to influence land use based biodiversity loss, as calculations show a very small increase of <1%. This is related to the slight increase in the biomass material footprint due to the energy transition which assumes increased demand for biomass required for bioenergy purposes.
- The effect on the CMUR is small, the CMUR only slightly increases from currently 11.6% to around 12.2%. This is not unexpected, as previous studies of the EEA and ETC-CE have illustrated already that this material category represents only a relatively small share in the DMC[49].
- The calculations demonstrate that the material footprints of metals and non-metallic minerals slightly increase, which is due to the additional investments in renewable energy capacity required for the energy transition.

The energy transition is the prerequisite for any further optimization of material flows and stocks in a circular economy transition. The stock of metals and non-metallic minerals in renewable energy systems is available for future recovery and recycling (while fossil energy carriers are dissipated during the combustion process and therefore no longer available for recovery/recycling).

5.3 Enhanced recycling (on top of previous scenario)

As already reported in par. 4.3.1, best-practice examples from EU countries and expert opinions point out that increasing waste recycling from currently 40% to around 69% by 2030 seems feasible (note that both values might be overestimations as explained in par. 0). Results show that the impact on the CMUR is, with an increase to 21%, quite significant[50]. Much of the increase in recycling rates will come from increased recycling of non-metallic minerals. While this has a profound impact on CMUR it has a somewhat more limited benefit on climate change and air pollution:

- Assuming enhanced recycling, from 40 to 69%, on top of fossil fuel phase out measures (see above) would have large benefits on the CMUR which could increase from the current 11.6% to around 21.0%.
- Using secondary materials is generally associated with lower environmental impacts than using their primary raw material counterparts. However, environmental impacts linked to enhanced recycling in this assessment remain largely unchanged. For climate change, air pollution, and land-use related biodiversity loss a limited effect is indicated by these calculations. This is because the highest potential for increasing recycling (in volumes) is related to non-metallic minerals such as construction and demolition waste and soil, while the recycling rates of metals and biomass are already relatively high and as such the potential volumes that could be recycled additionally are more limited. The recovery of non-metallic mineral materials has a large effect on the CMUR,

49 EEA briefing 'How far is Europe from reaching its ambition to double the circular use of materials: https://www.eea.europa.eu/publications/how-far-is-europe-from#:~:text=In%20this%20briefing%2C%20doubling%20the,%E2%80%94%20to%2023.4%25%20by%202030.

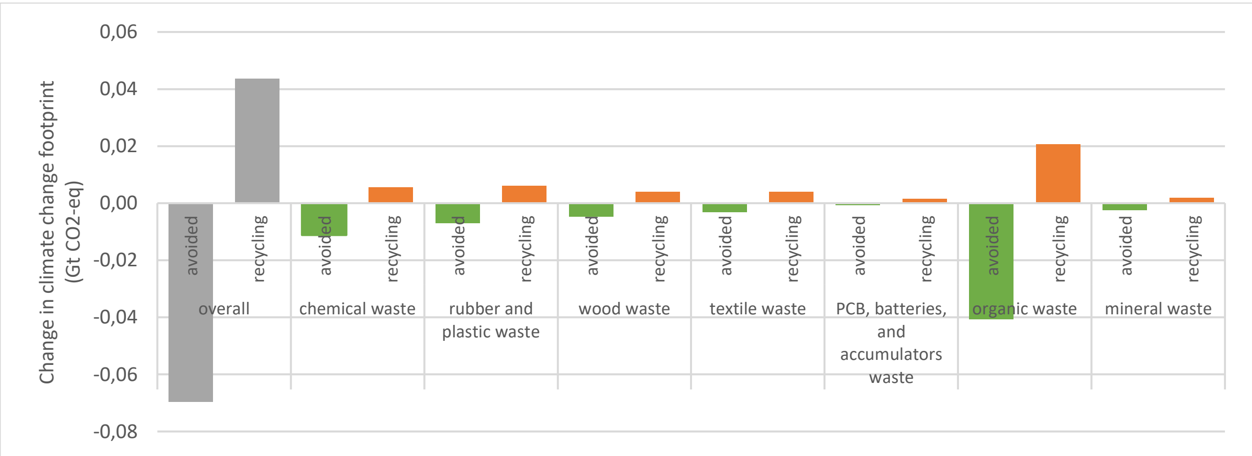
50 Bold assumptions underlying this statement: assuming all waste sent to recycling is converted into secondary materials and assuming a 1:1 substitution rate.

however the effect on environmental impacts is low[51]. The largest environmental benefit per tonne is linked to metals and fossil fuels, but their low share in the total waste limits their potential in this analysis.

- We note that a full conversion of waste sent to recycling into secondary materials and a 1:1 substitution between primary and secondary materials assumed in this assessment is overestimating the potential benefits and might be thwarted by lower efficiency levels.
- Rebound effects (e.g., (Castro et al., 2022)) are another aspect not considered in the modelling. Rebound effects could undermine the potential benefits.
- The modelling focuses on increased recycling activities and substitution of primary materials. Reduced demand for waste management activities, e.g., incineration and landfill, are not part of the modelling.

Figure 5-1 to Figure 5-3 detail the results from the modelling of the enhanced recycling intervention. Both the overall results (in grey) and the detailed results per waste category are shown. The avoided impacts are the result from a modelled reduction in (primary) production of materials (in green). The impacts resulting from recycling to produce the secondary materials are estimated (in orange). The largest reduction in climate change impacts results from a reduction in the production of fertilizers assuming an increased recycling of organic waste into fertilizer materials, followed by avoiding chemical waste production (i.e., a decrease in petroleum refinery production) and rubber and plastic production (i.e., a decrease in production of basic plastics). Similar results are available for air pollution, but with relatively larger gains and recycling impacts resulting from the mineral waste category. The largest gains and recycling impacts on land-use related biodiversity loss result from the categories wood waste, organic waste, and rubber and plastic waste. Note that the recycling impacts stem from an initial modelling prototype of an EU27 recycling sector. One consequence of this is the relatively high air pollution and biodiversity loss impact of recycling of organic waste compared to the avoided impacts of primary production of fertilizers. Adapting the input structure of this sector to specific waste streams would improve the quality of the modelling results. Also important to note when looking at these results is the fact that the modelling approach is not able to capture quality aspects of recycled materials. An improved quality of secondary materials by improving the collection, sorting and recycling processes is not taken into account.

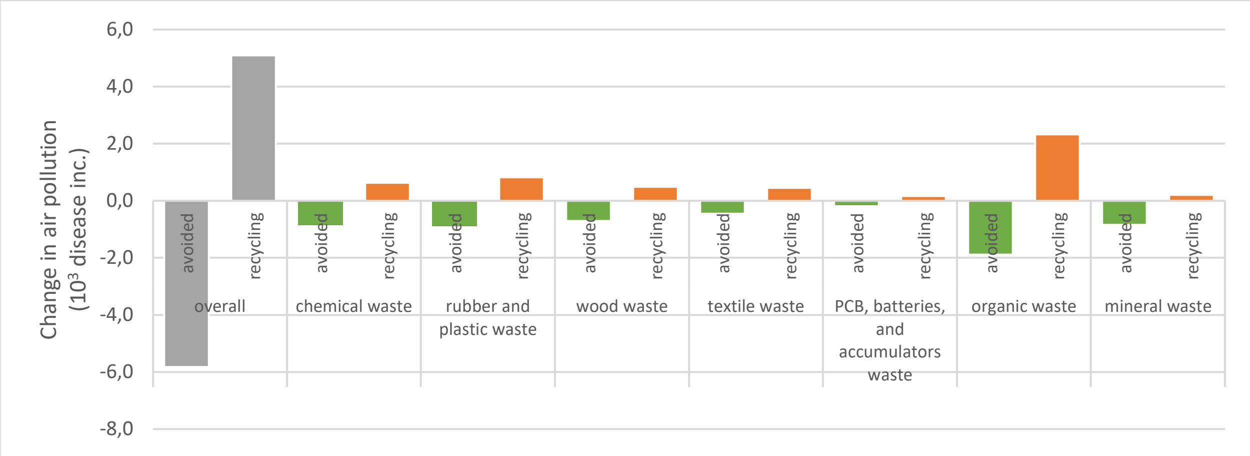
Figure 5-1: Climate change credits* due to avoided primary production respectively impact due to recycling of different materials.



**Note: Results based on a preliminary modelling assessment (see Section 4.5).*

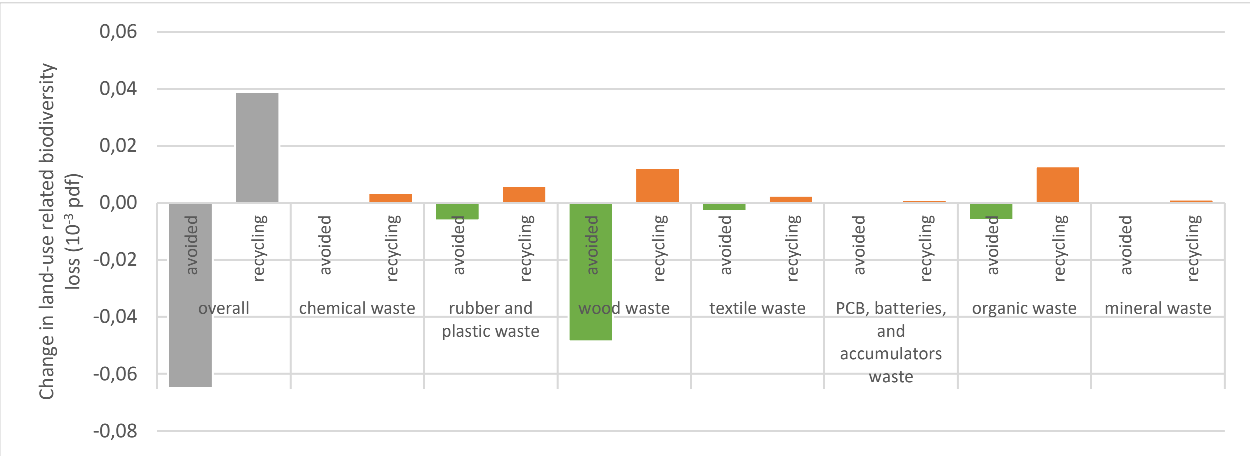
51 This is confirmed by other EEA-reports such as the EEA briefing 'How far is Europe from reaching its ambition to double the circular use of materials: https://www.eea.europa.eu/publications/how-far-is-europe-from#:~:text=In%20this%20briefing%2C%20doubling%20the,%E2%80%94%20to%2023.4%25%20by%202030.

Figure 5-2: Air pollution credits* due to avoided primary production respectively impact due to recycling of different materials.



**Note: Results based on a preliminary modelling assessment (see Section 4.5).*

Figure 5-3: Land-use related biodiversity loss credits* due to avoided primary production respectively impact due to recycling of different materials.



**Note: Results based on a preliminary modelling assessment (see Section 4.5).*

BOX: Check of the results based on LCA data

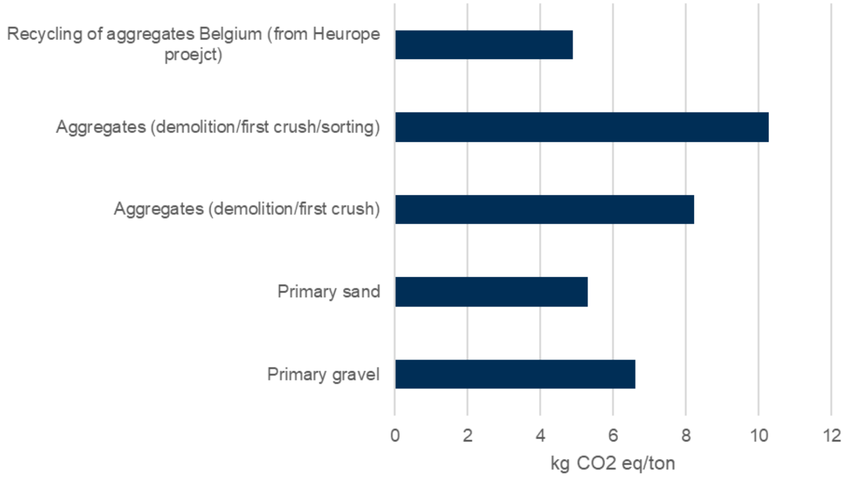
The IO-based modelling approach applied for this assessment is not able to distinguish between recycling of specific materials as only one average European recycling sector is defined in the model. To validate the results of this assessment, Life Cycle Assessment (LCA) data and results are used for non-metallic minerals waste resp. organic waste.

Recycling of non-metallic mineral waste

- <u>Construction and demolition waste</u>: concrete, bricks…

The graph below shows the climate change impact of the recycling of aggregates according to different data sources and recycling processes (demolition, first crushing and sorting resp. demolition and crushing without sorting). Data are taken from the Ecoinvent database (second and third bar) and from a Horizon Europe project where this is studied more in depth (first bar). The last two bars show the climate change impact for the extraction and production of sand and gravel, both materials are typically replaced by the recycled aggregates. Data are taken from the Ecoinvent database. The LCA-results confirm the conclusion that for climate change the impact of the recycling process is not per definition smaller than the avoided primary production impact.

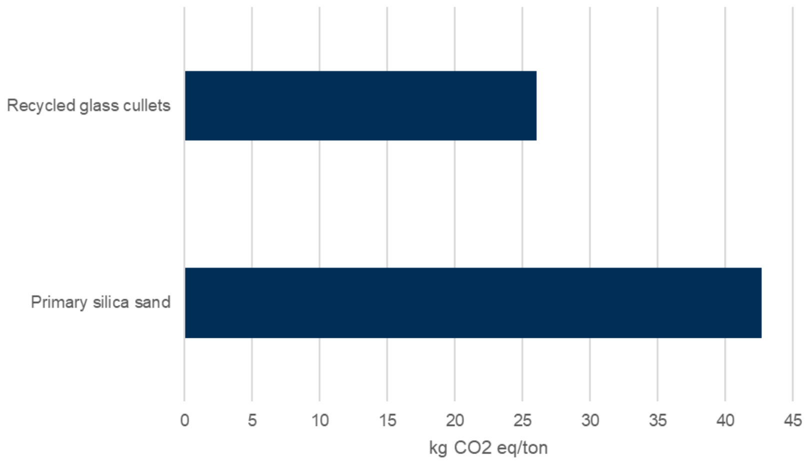
It is not always straightforward to define which type of materials is avoided by the recycling of a specific type of waste. For example, aggregates from recycled construction and demolition waste are typically used in the construction sector, however they don’t replace sand and/or gravel in all cases.



- <u>Glass waste</u>

The graph below presents the climate change impact of recycling of glass for use in glass wool insulation versus the impact of extraction and production, which is modelled by the production of 1 ton recycled glass cullets resp. the extraction and production of 1 ton silica sand (Ecoinvent data).

Important to note with these results is that the primary and secondary material (silica sand resp. recycled glass cullets) are not one-to-one replaceable. A rule of thumb is that 25-30% less energy is required for ‘production’ of glass cullets compared to primary material.



- <u>Excavated soil and rock (ESR) and dredging spoils (DDS):</u>

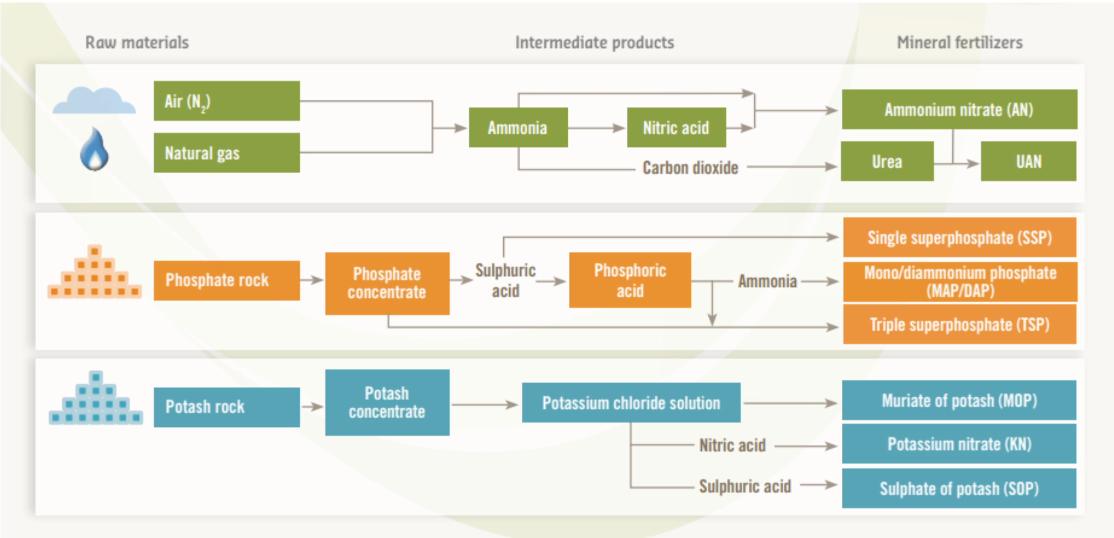
(Cristobal et al., 2024) studied the potential climate change impact reduction of increasing the level of ESR and DDS prepared for reuse and recycled, following different waste management scenarios. Their LCA-based assessment shows that sending more ESR and DDS to preparation for reuse and to recycling could lead to GHG reductions of up to 3.6 Mt CO_2 eq. (corresponding to 0.2 to 1% of net annual GHG emission reduction at EU level). These results are a combination of avoided landfill emissions, emissions from recycling and avoided emissions for replacing virgin materials. The LCA-results show that the waste hierarchy is respected for both flows, however for the individual pathways (i.e. preparing for reuse, recovery-backfill and recycling) the impacts of the process steps (generating, conditioning, transport and processing) are higher than the credits due to the material recovery although still lower than landfilling which is the currently dominating waste management path.

Recycling of organic waste

Typically, recycling of organic waste leads to compost which replaces NPK-fertilizer. For the primary material (fertilizer) production, different alternatives exist depending on the NPK-content:

- NH_3 via Haber-Bosh process
- H_3PO_4 via phosphate rock mining
- KCl via potash rock

The scheme below gives a schematic overview of the different mineral fertilizers and their primary production process.



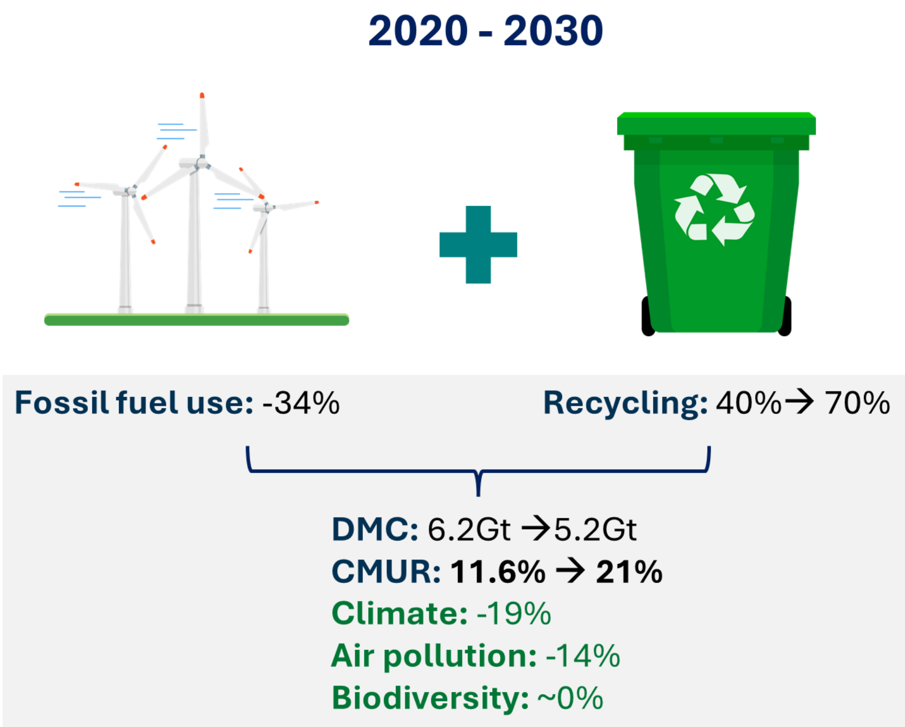
For the nutrient content in fresh compost/digestate assumptions are required as well. (WRAP (2016) assume the following:

- Nitrogen: 9.25 kg per tonne compost (mean of garden waste and garden/organic waste compost), 5 kg per tonne organic waste digestate.
- Phosphate (P_2O_5): 3.4 kg per tonne compost, 0.5 kg per tonne organic waste digestate

For the recycling of organic waste and the related overall environmental impact/benefit, it is important to take into account what type of waste management is replaced by the recycling. For example, the environmental benefit of diverting organic waste from landfill to recycling is much higher than diverting from energy recovery to recycling. (EEA, 2024) states that 70% of GHG-emissions of the EU waste sector are methane emissions from landfills, which mostly come from landfilling of organic waste.

Figure 5-4 presents the overall reduction that is achieved following the fossil fuel phase out and the enhanced recycling scenario as defined in this study. The CMUR significantly increases to 21%, mainly thanks to the enhanced recycling scenario, although not sufficiently to reach the doubling target. The potential cumulative effect of both scenarios on climate change is also considerable, i.e. a reduction of 19% can be reached. This is, as could be expected, mainly due to the fossil fuel phase out scenario. The cumulative reduction of air pollution is -14%, while the effect of both scenarios on land use based biodiversity loss is negligible.

Figure 5-4: Cumulative environmental impact potential of the fossil fuel phase out and enhanced recycling scenario

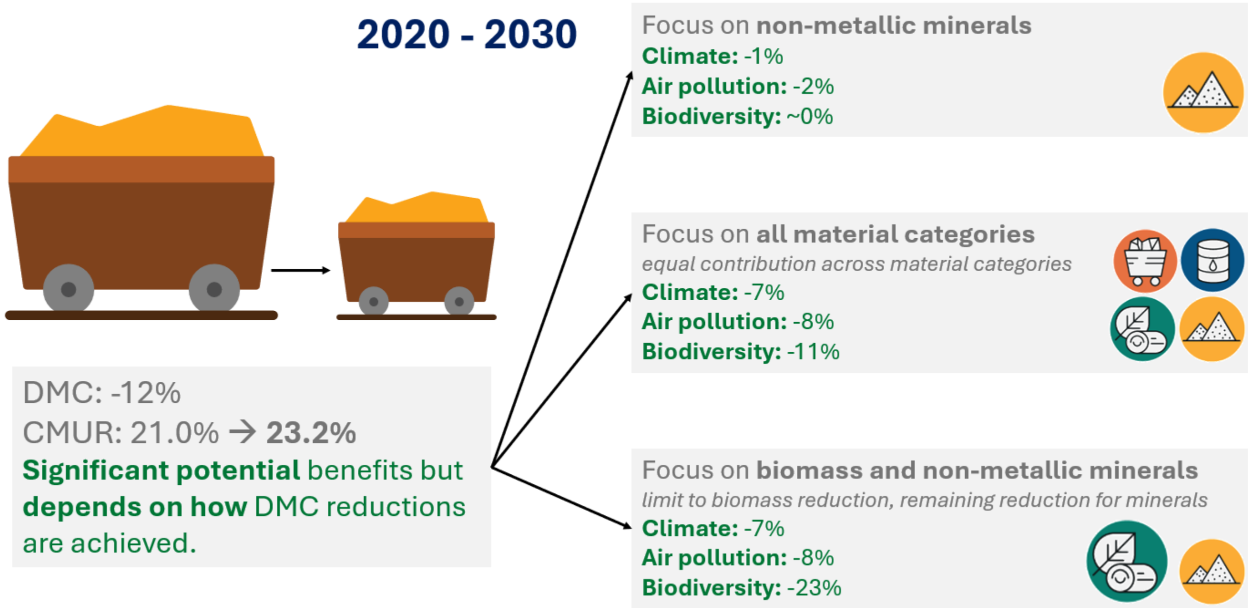


5.4 Reduced material consumption (on top of previous scenarios)

Quantification of environmental benefits of this scenario is only possible with the approach based on the ready to be used materials methodology. The results reported here are as such based on this approach. Annex 2 briefly presents the results of the **literature review approach**, so we refer to the annex for the reporting. The insights and conclusions following from the literature review confirm the results of the ready to be used materials approach as reported in this section.

The environmental benefits of the reduced material consumption scenario following the **ready to be used materials approach** are visually presented in Figure 5-5.
The three options for allocating the targeted DMC reduction over different material categories are separately assessed, to quantify the environmental benefits of each option individually. As the environmental impact of material categories can differ largely, the benefits of reducing material consumption targeting one or more specific material categories will also differ.

Figure 5-5: Additional environmental impact potential of the three options for DMC reduction in the reduced material consumption scenario



**Note: The environmental impact reduction stated in the figure is the additional reduction due to the reduced material consumption scenario.*

It is clear that altering non-metallic minerals use is critical for reducing the DMC and thus increasing the CMUR, as this material category has the highest share in EU-27 material consumption (highest volumes) so reducing its use can be expected to require the least effort. However, their relatively low environmental footprint intensity limits their environmental impact reduction potential. On top of the measures related to fossil fuel phase out and enhanced recycling, only an additional reduction of -1% respectively -2% and 0% is gained for climate change respectively air pollution and biodiversity loss due to measures focussing on reducing the use of materials if these only target non-metallic minerals.

When the material reduction targets more material categories than only non-metallic minerals, the additional environmental impact reduction is much higher. When all four material categories are equally reduced, proportionally to their share in the DMC after implementation of fossil fuel phase out and enhanced recycling measures, the additional environmental impact reduction reaches -7% resp. -8% for climate change and air pollution. If focus is given to measures reducing the use of biomass (over metals and fossil fuels) the additional reduction for biodiversity loss rises from -11% to -23%.

To reduce the biodiversity impact, focussing on reducing the use of biomass as much as possible clearly offers the highest potential. However there is a limit to reducing the use of biomass (in this assessment this limit is set at 2.3 tonnes per capita). Looking at the type of CE measures and interventions that are studied in literature to assess the potential impact of reducing the use of biomass, it is clear that this type of measures mostly target the agrifood system. (Kennedy et al., 2022) distinguishes three types of CE measures referring to

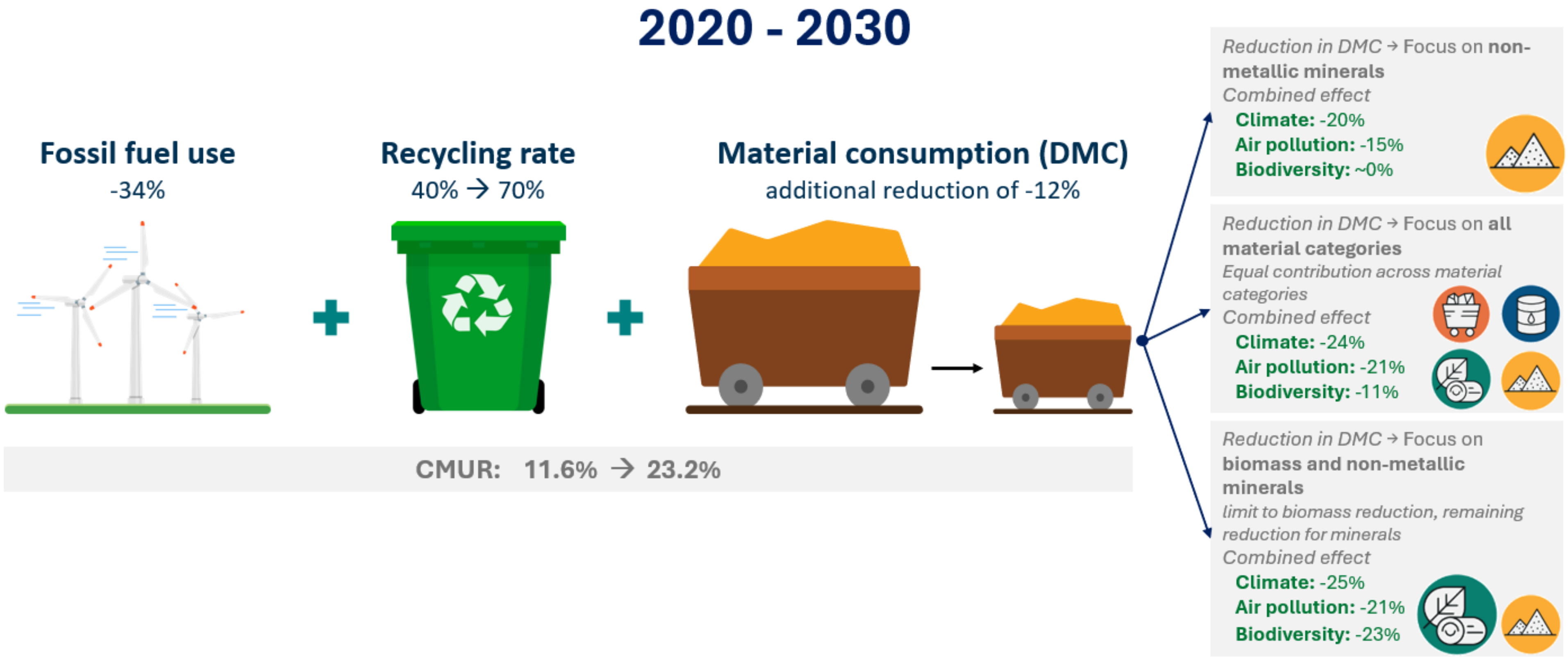
i) most narrow definition of CE focussing on closing material and product cycles, e.g. preventing food waste and use food waste as a resource;
ii) CE in a limited system focussing on reducing consumption in line with regeneration rates, e.g. dietary changes;
iii) Molecular circularity in production systems, e.g. agroforestry.

From the assessment in (Kennedy et al., 2022) with a focus on the food system (agri-foods), it is clear that the potential effect of measures from the first group (narrow CE definition) on climate change are quite limited, while the by far largest emission reduction potentials were related to regenerative agriculture and dietary changes. This is confirmed by other publications e.g. (Circle Economy, 2021) where the assessment points out that CE interventions focussing on nutrition with the highest potential for GHG emission savings are related to sustainable food production, to a lesser extent to healthy diets and measures for reducing excess food consumption have the lowest effect. However, the study also highlighted the large uncertainties in estimating the actual potential of regenerative agriculture.

Despite the limited effect of measures targeting non-metallic minerals on climate change and other environmental impacts, the effect on the volume of materials used and as such on the CMUR is significant. The reduction of the use of non-metallic minerals seems to be the most feasible and expected to require the least effort. Typical CE measures focussing on non-metallic minerals relate to housing and the building sector. (Ramboll/Fraunhofer ISI/Ecologic, 2020) shows that CE measures which are most promising target concrete, cement (and steel). These materials have a high impact in terms of greenhouse gas emissions and are used in large volumes in Europe. CE measures that are identified as offering the highest reductions in GHG emissions are measures that reduce overspecification of concrete in building plans (design phase), measures that stimulate the use of innovative and alternative cement types (production phase) and reusing structural elements (demolition and waste management phase). Measures that focus on extending the lifetime of buildings are also promising, however their full effect only plays out on a longer timescale and might therefore be underestimated in the study. The same key CE measures are identified in (Circle Economy, 2021) as being the most impacting i.e. resource efficient construction, resource efficient housing and circular construction materials.

To conclude, Figure 5-6 presents the overall cumulated environmental reduction potential of the three scenarios defined in this study.

Figure 5-6: Cumulative reduction potential of CMUR, DMC resp. climate change, air pollution and land use related biodiversity loss of EU27 in 2020 and 2030 following three scenarios: fossil fuel phase-out, enhanced recycling, and reduced material consumption



6 Conclusions

The main take-aways that follow from the application of the first version of the methodology to the CMUR case can be summarized as:

- **Fossil fuel phase out measures:**
  - only contribute to a small extent to increasing the CMUR of Europe and thus to reaching the doubling target as set out in the CEAP;
  - significantly reduce greenhouse gas emissions and air pollution;
- **Enhanced recycling measures:**
  - Have a significant effect on the CMUR, though not sufficient to reach the doubling target;
  - Have a relatively small potential effect on environmental impacts;
- **Reduced material consumption measures:**
  - are necessary to reach the CMUR target;
  - but if we in parallel want to reduce the environmental impact, it is important to focus these measures on the right type of materials;
  - Altering non-metallic minerals use is critical for increasing the CMUR, however their relatively low environmental footprint intensity limits their environmental impact reduction potential;
  - Environmental impacts differ by raw material, related to both production and use of the materials:
    - Phasing out fossil fuels is essential for tackling climate change;
    - A more sustainable use of metals can help to lower impacts on climate change, air pollution and resource depletion;
    - More circular and sustainable use of biomass helps to reduce impacts on biodiversity loss;
  - In addition to production-side changes, also demand-side changes are necessary. Policy measures focusing on final consumption are necessary to reach the doubling target of the CMUR and additionally reduce environmental pressures/impacts.

Although the environmental benefits of enhanced recycling are not contributing significantly compared to the other scenarios as defined in this study, it is commonly agreed that recycling is of high importance to ensure availability of resources and to tackle resource scarcity. The fact that higher-quality recycling can bring additional value is not captured in the assessment methodology.

The study also illustrated that reducing non-metallic minerals might not have the highest potential for reducing environmental impact, however it is critical for reducing the DMC and thus increasing the CMUR. Non-metallic minerals have the highest share in EU-27 material consumption (highest volumes)

From a methodological point of view, the case study showed the need to further develop the underlying assumptions and to dedicate more time for each of the methodological steps required to quantify the environmental benefits of CE. This will be further explored and improved by the ETC-CE during 2025.

Several studies quantifying the environmental benefits of CE have different interpretations of the scope of CE, for example whether CE measures include dietary shifts, regenerative agriculture, energy efficiency, or renewable energy. An overview of definitions that have been used when calculating the benefits of circular economy will be made, highlighting their differences, and discussing the impacts of these different definitions. These insights will inform future work on measuring the environmental benefits of CE and highlight the importance of careful considerations of the scope of CE.

Similar, different studies also have somewhat different underlying assumptions for the impact that CE measures have on changes to material flows. These underlying assumptions are crucial for the outcome of any modelling work and therefore deserve careful considerations. The future work will not only summarize what others have set as underlying assumptions but will also develop an approach for quantifying selected key CE measures' impact on material flows.

7 List of abbreviations

Abbreviation	Name	Reference
AE	Accumulated exceedance	
CE	Circular economy	
CFI	Consumption footprint indicator	
CEAP	Circular economy action plan	
CMUR	Circular Material Use Rate	
CO2 eq.	Carbon dioxide equivalent	
CTUe	Comparative toxic unit for ecosystems	
CTUh	Comparative toxic unit for humans	
DDS	Dredging spoils	
DMC	Domestic material consumption	
EEA	European Environment Agency	www.eea.europa.eu
EGD	European Green Deal	
EF	Environmental footprint	
ESR	Effort Sharing Regulation	
ESR	Excavated Soil and Rock	
ETC-CE	European Topic Centre on Circular economy and resource use	
ETS	Emission Trading System	
GDP	Gross domestic product	
GHG	Greenhouse gas	
IO	Input-Output	
IUCN	International Union for Conservation of Nature	
LCA	Life cycle assessment	
LCIA	Life cycle impact assessment	
MI	Material intensity	
MRIO	Multi Regional Input-Output	
NAS	Net additions to stock	
NDC	Nationally determined contributions	
NC	Nomenclature	
NL	The Netherlands	
NMVOC	Non-methane volatile organic compounds	
ODP	Ozone depletion potential	
PDF	Potentially Disappeared Fraction	
PM	Particulate matter	

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Annex 1: Environmental impact categories

Based on the information included in the extension tables (e.g., environmental extensions), IOA allows to assess different environmental and socio-economic impacts. The environmental extensions linked to EXIOBASE include different types of emissions to air, water and soil and resources extracted, for example, GHG emissions, particulate matter, metal ores – Tin, Zinc, … and also land use data are included.

Typically, the results of Input-Output (IO) analyses are first expressed in 'raw' extension data or pressures (e.g., kg CO_2, m² agricultural land occupation) and in a next step converted to impacts (e.g., kg CO_2 equivalents) using a life cycle impact assessment (LCIA) -method like the Environmental Footprint (EF) method which is also used in life cycle assessments (LCA). An LCIA-method connects the information collected in physical units (elementary flows in LCA or the 'raw' extension data in case of IO analysis) to one or several impact categories which they influence and assess the magnitude of their contribution to the impact. For climate change, this means that all greenhouse gases in the inventory are converted into kg carbon dioxide equivalents (CO_2 eq.) and aggregated to calculate the contribution of the system under study to climate change. Several methods have been developed to assess the contribution of elementary flows/raw extension data to specific impact categories. This contribution factor is called the characterisation factor.

Climate change and air pollution

The EF method is a method proposed by the EU which contains 16 different impact categories, including climate change and particulate matter ([52]) (see Table A1-1).

Table A1-1: Environmental impact categories of the EF 3.0 Method

Impact category	Indicator	Unit
Climate change ([53])	Radiative forcing as Global Warming Potential (GWP100)	kg CO_2 eq
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 eq ([54])
Human toxicity, cancer effects ([55])	Comparative Toxic Unit for humans (CTU_h)	CTU_h
Human toxicity, non- cancer	Comparative Toxic Unit for humans (CTU_h)	CTU_h
Particulate matter formation	Human health effects associated with exposure to PM2.5 ([56])	Disease incidences
Ionising radiation	Human exposure efficiency relative to U^{235}	kBq U^{235}
Photochemical ozone formation	Tropospheric ozone concentration increase	kg NMVOC eq ([57])
Air acidification	Accumulated Exceedance (AE)	mol H^+ eq
Terrestrial eutrophication,	Accumulated Exceedance (AE)	mol N eq
Freshwater eutrophication	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq
Marine eutrophication	Fraction of nutrients reaching marine end compartment (N)	kg N eq

52 European Commission. 2021. "Commission Recommendation of 16.12.2021 on the Use of the Environmental Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations." European Commission. https://environment.ec.europa.eu/publications/recommendation-use-environmental-footprint-methods_en.

53 The indicator "Climate Change, total" is a combination of three sub-indicators: Climate change –Change fossil; Climate change –Change biogenic; Climate change – land use and land use change. The sub-categories 'Climate change –fossil', 'Climate change – biogenic' and 'Climate change - land use and land use change' shall be reported separately, if they show a contribution of more than 5% each to the total score of climate change.

54 CFC-11 = Trichlorofluoromethane, also called freon-11 or R-11, is a chlorofluorocarbon

55 excluding long-term emissions (occurring beyond 100 years)

56 Particulate Matter with a diameter of 2,5 µm or less

57 NMVOC = Non-Methane Volatile Organic Compounds

Freshwater ecotoxicity [55]	Comparative Toxic Unit for ecosystems (CTU_e)	CTU_e
Land use ([58])	Soil quality index: - biotic production - erosion resistance - mechanical filtration - groundwater replenishment	Dimensionless ([59])
Water depletion	User deprivation potential (deprivation- weighted water consumption)	kg world eq. deprived
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq
Resource use, energy carriers	Abiotic resource depletion – fossil fuels (ADP-fossil) ([60])	MJ

The models for assessing the impact to climate change and particulate matter used in this report have been taken from the EF method:

- **Climate change**: Global impact due to changes induced to the climate, including increased average global temperatures and sudden regional climatic changes, as a consequence of the emissions to the atmosphere of the so-called greenhouse gases, such as CO_2, CH_4, and N_2O.
    - The following environmental pressures are available in the EXIOBASE extension tables for climate change: CO_2-emissions to air, CH_4- emissions to air, N_2O-emissions to air.
- **Particulate matter**: Impact on human health due to the increased ambient concentrations of particulate matter (PM) due to the emissions of primary and secondary particulates (i.e. PM2.5, NO_x, SO_2).
    - The following environmental pressures are available in the EXIOBASE extension tables for particulate matter: SO_x-emissions to air, NO_x-emissions to air, NH_3-emissions to air, PM2.5-emissions to air.

The EF method does not include any impact category named 'biodiversity', as currently there is no international consensus on an LCIA method capturing that impact. Therefore, the next paragraph documents the method used in this study to assess **biodiversity loss**.

Biodiversity loss

The EF method includes at least eight impact categories that affect biodiversity (i.e., climate change, eutrophication (aquatic freshwater), eutrophication (aquatic marine), eutrophication (terrestrial), acidification, water use, land use, ecotoxicity freshwater).

The ability to assess the effects of the circular economy on biodiversity is of great importance, as the processing and use of raw materials and products as well as the disposal of waste resulting from our production and consumption have a significant impact on the state of biodiversity in Europe and worldwide. Circular Economy can be seen as one transformation strategy addressing the way we produce and consume goods and services and offers a unique opportunity to support biodiversity protection and, depending on the sector, also to regenerate biodiversity (Günther et al., 2023). However, this requires biodiversity to be considered to a greater extent in the design and implementation of the Circular Economy which makes the evaluation of these measures in terms of their effects on biodiversity all the more important.

Therefore, here we account for land-use related biodiversity loss by applying the methodology of (Cabernard and Pfister, 2021). They propose a highly resolved MRIO database to analyse economy wide environmental footprints. With regards to biodiversity, the applied methodology quantifies the **global potential species loss (impact assessment indicator)** due to land **occupation** and for the **land use types crops, pastures, and forestry.**

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58 Refers to occupation and transformation

59 Aggregated index of indicators: kg biotic production/ (m^2*a), kg soil/ (m^2*a), m^3 water/ (m^2*a) and m^3 g.water/ (m^2*a)

60 Including uranium measured in MJ

Environmental extensions are taken from the highly resolved MRIO-model based on EXIOBASE3 and Eora26, while characterisation factors are taken from (Chaudhary et al., 2016), as recommended by (UNEP-SETAC, 2016). The characterisation factors are available at ecoregion level, country level and global level for six land use types and five taxa, expressed in potentially disappeared fraction of species per m^2. Because EXIOBASE3 and Eora26 are limited in their spatial and sectoral resolution, (Cabernard and Pfister, 2021) used more detailed and well documented data on land use. It concerns data from FAOSTAT (2019) for pasture and forestry and data from (Pfister et al., 2011) for crops.

BOX: Impact assessment method for land use related biodiversity loss (based on UNEP-SETAC, 2016)

The selected indicator is the potential species loss from land use, from Chaudhary et al. (2015, 2016). The indicator exists as a regional indicator and as a global indicator. The regional indicator represents the regional species loss taking into account the effect of land occupation displacing entirely or reducing the species that would otherwise exist on that land and the relative abundance of those species within the ecoregion. The global indicator additionally considers the threat level of the species on a global scale.

The indicator covers five taxonomic groups: birds, mammals, reptiles, amphibians, and vascular plants; and six land use types: intensive forestry, extensive forestry, annual crops, permanent crops, pasture, and urban land, in 804 terrestrial ecoregions as defined in (Olsen et al., 2001). The reference state is a current natural or close to natural habitat in the studied ecoregion.

The regional species loss is calculated using species area relationships for each land use type – referred to as the Countryside SAR model (Pereira and Daily, 2006).

To determine an estimate of the permanent global (irreversible) species loss (global characterisation factors), the regional characterisation factors for each taxon and ecoregion are multiplied by a vulnerability score of that taxon in that ecoregion. The vulnerability score is based on the proportion of endemic species in an ecoregion and the threat level assigned by the IUCN red list for different taxa and regions. If species are endemic to the ecoregion, their loss will translate into global species loss (extinction).

The aggregation over taxa in order to provide a single value for potential species loss is, for regional characterisation, done using equal weighting for each of the five taxa. For global characterisation factors, the global characterisation factors per taxon are divided by the total species diversity threat for each taxon and are then combined into a single score averaging the animal Potentially Disappeared Fraction (PDF), with equal weighting, and then again averaging animal and plant PDFs, with equal weighting.

All the above relate to the impact of land occupation. The method takes into account the impacts of land transformation by taking the regeneration time of each land use type to return to the reference state into account following (Curran et al., 2024) and multiply the occupation impact by ½ the reference time, as suggested in (Milà i Canals et al., 2006).

Limitations of the methodological approach chosen

One of the obvious limitations of the chosen method is that it does not consider effects on marine nor freshwater biodiversity. One reason for this is that the methodology used here to assess the effects on biodiversity is directly linked to the land accounts in EXIOBASE 3. Secondly, the main drivers of the loss of marine biodiversity, in addition to overfishing, are due to indirect effects of material use. These are, in particular, climate change, pollution and excessive nutrient inputs from land use (IPBES, 2019). These indirect effects are currently not covered with the applied method. One could consider looking at the LC-

IMPACT method to see if any of this can be implemented in the future ([61]). This method proposes a more complete assessment of biodiversity loss because it considers biodiversity loss due to climate change (on terrestrial and freshwater ecosystems), photochemical ozone formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, land stress and water stress.

It is important to know, that the methodological approach focuses on sectors related to land-based biomass production, namely agricultural crops, pasture as well as intensive and extensive forestry. This implies that biodiversity impacts through other land use types, for example, mining and urban land is currently not recognized. But the most relevant sectors in terms of biodiversity loss are directly related to agriculture and forestry, whereas mining contributes to less than 1% of the total land use-related biodiversity loss (Cabernard and Pfister, 2022). Further, changes on land use practices like abandonment, intensification and fragmentation and their biodiversity impact are currently not covered by the methodological approach (UNEP-SETAC, 2016). The methodological approach covers five taxa: birds, mammals, reptiles, amphibians, and vascular plants resulting in an aggregated factor established by applying equal weighting over the 5 taxa. Future work could look at the effect of different weightings in different taxa or functional position of different species in the ecosystems (UNEP-SETAC, 2016).

61 Verones et al. (2020): https://www.researchgate.net/publication/342014223_LC-IMPACT_A_regionalized_life_cycle_damage_assessment_method/link/64bcf0d68de7ed28babb6e93/download Some results of Verones et al. are pointing at climate change as a very important driver for biodiversity loss (terrestrial and aquatic), while several other sources point at land use change as the most important driver.

Annex 2: Environmental reduction potential – Results following the literature review approach for the reduced material consumption scenario

The environmental impact reduction potential as calculated in this assessment following the 3 scenarios, is graphically illustrated by the graphs below (Figure A2-1 to A2-3). Each graph starts from the impact for resp. climate change, air pollution and biodiversity loss in 2020 and shows the reduction that is reached by 2030 when implementing the 3 scenarios, starting from fossil fuel phase out, additionally implementing enhanced recycling measures and finally adding CE measures focused on improving material efficiency and reducing material consumption (based on the impacts from the ready to be used materials). The grey box represents the range of impacts when all 3 scenarios are implemented. The bars in orange indicate that these results are calculated (as is the case for the first 2 scenarios), the bars in grey indicate that this is a more uncertain result based only on literature information (see section 5.4). The corresponding CMUR that can be reached by cumulatively implementing the scenarios, is indicated below the graph.

In the figures below, these combined scenarios are seen as the upper limit and can be compared to literature:

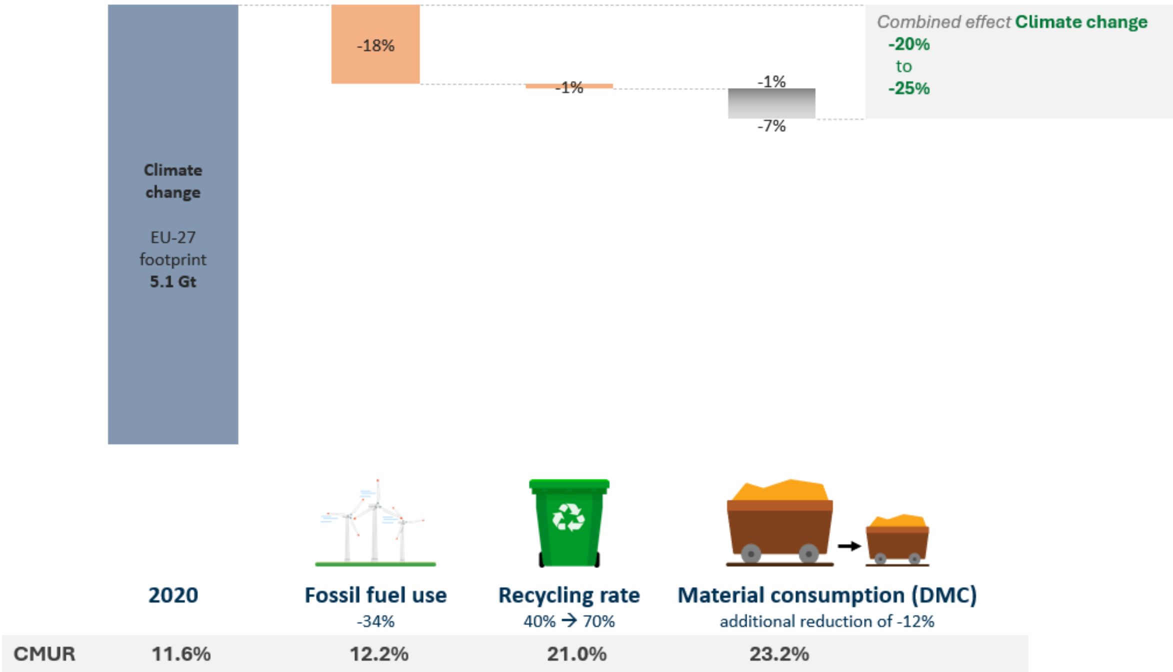
- GHG reductions: -39 to -50% compared to the current situation (Circle Economy, 2021, 2023))
- Air pollution: -33% compared to the current situation (Circle Economy, 2023))[62] (see Table 4-2 and Table 4-3).

As no information is available in the literature about the effect of this type of CE measures on biodiversity loss[63], no estimate is made for this scenario in the current assessment.

[62] In the figures below, contributions of fossil phase out and enhanced waste recycling of these total reduction potentials are based on our preliminary model runs as explained in previous sections of this report. The total reduction potential resulting from reduction in material consumption stem from the impact of ready to be used materials as explained in previous sections of this report.

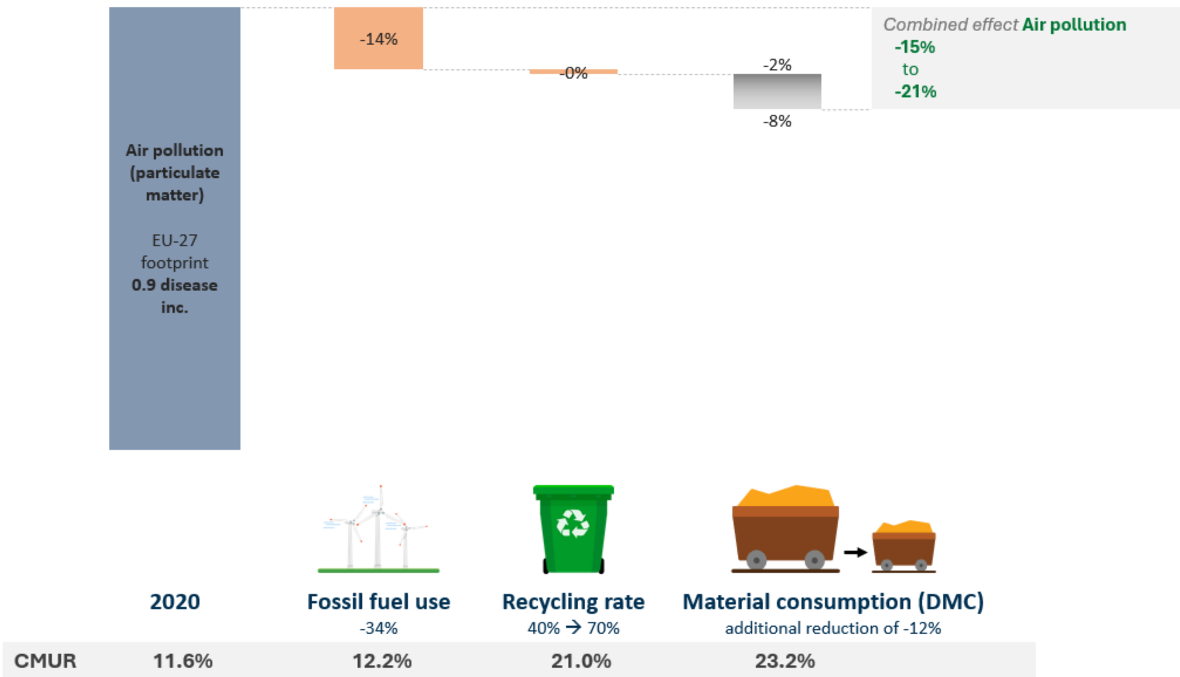
[63] (Circle Economy, 2023) provided estimates on land-system changes (see table 14 in their supplementary information). However, this could not directly be related to biodiversity loss in our study.

Figure A2-1: Climate change footprint of EU27 consumption in 2020 and 2030 following three scenarios: fossil fuel phase-out, enhanced recycling, and other economy-wide CE changes*, in Gt CO2-eq.



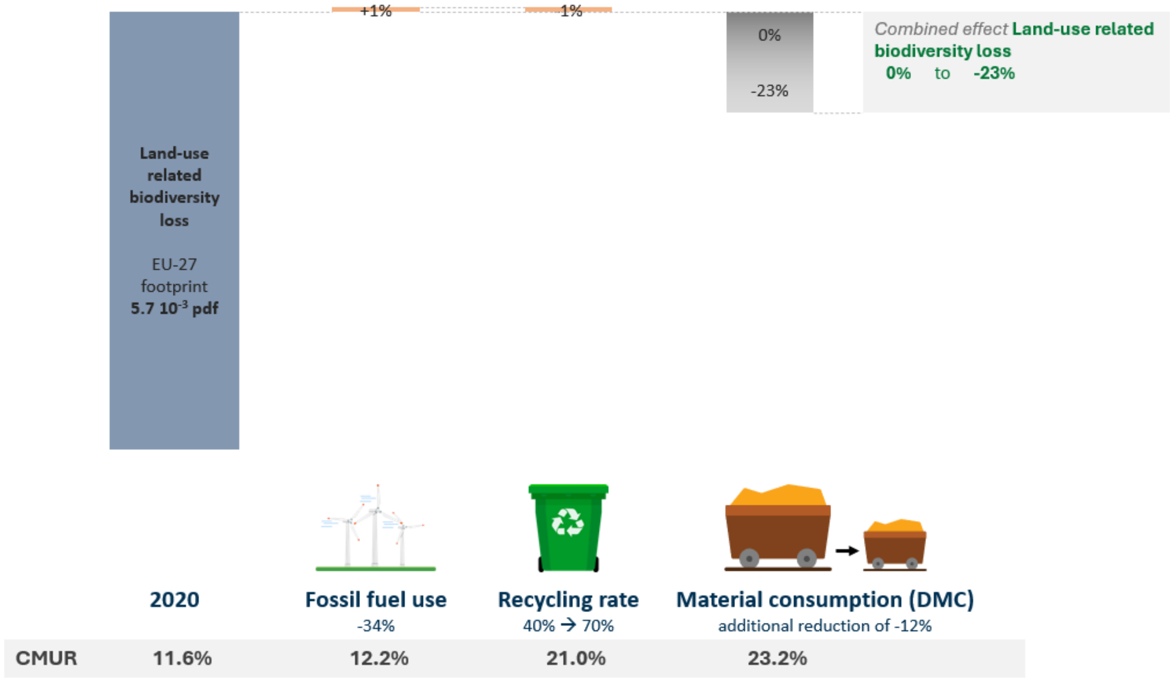
*Note: Not based on ETC-CE modelling. Possible additional environmental impacts reductions resulting from production and consumption changes (e.g., smaller per capita living space, dietary shifts, etc.). GHG-reduction estimate based on literature (Circle Economy, 2021, 2023).

Figure A2-2:Air pollution footprint of EU27 consumption in 2020 and 2030 following three scenarios: fossil fuel phase-out, enhanced recycling, and other economy-wide CE changes*, in disease inc.



*Note: Not based on ETC-CE modelling. Possible additional environmental impacts reductions resulting from production and consumption changes (e.g., smaller per capita living space, dietary shifts, etc.). Air pollution reduction estimate based on literature.

Figure A2-3: Land-use related biodiversity loss footprint of EU27 consumption in 2020 and 2030 following three scenarios: fossil fuel phase-out, enhanced recycling, and other economy-wide CE changes*, in PDF



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