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On the intrinsic recycling potential of carbon-based materials and products; an assessment method and outlook

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ABSTRACT

In this paper we investigate the market size of all materials and products presently produced from (organic) carbon and we present a method to estimate the intrinsic recycling potential of these materials/chemicals as a function of their respective applications. The method is based on the expert assessment of a number of variables that are important within the different application categories and markets of the carbon-based materials/chemicals. Applying the method, the paper presents the recycling potential of all carbon-based products. Following, an estimation of the amount of new products that can be produced each year through recycling of discarded products is presented and the amount of carbon that needs to come from other sustainable sources to fulfil our demand for new products is calculated.

We distinguish nine different categories of (organic) carbon-based materials/chemicals: plastics, textile fibres, thermoset resins, rubbers, surfactants, solvents, fine chemicals, paper/board and wood products. Within these nine categories the most important materials/chemicals types were taken into account. Fossil-based and bio-based materials/chemicals were assessed separately. For each of the materials/chemicals types, the market size in terms of mass (Mt) was calculated for the main applications in which they are applied. Next, for all materials/chemicals types in these applications, the maximum recycling potential, in case mechanical or physical recycling methods are applied, was assessed, using an expert panel. Also, inevitable leakage of materials/chemicals in the different applications was assessed. Finally, the amount of feedstock coming from recycling streams that may be made available for chemical recycling or carbon capture and utilisation technologies was derived. From this, the magnitude of carbon-based materials/chemicals that need to be replaced each year by other renewable feedstock than recycled content in terms of Mton carbon was calculated.

The analysis is relevant in view of implementation of a circular economy and reuse and recycling of materials, to combat depletion of raw materials. Next, it is relevant in view of phasing out fossil-feedstock to combat climate change. Our analysis indicates that the recycling potential of carbon-based materials and products through mechanical or physical methods lies around 50%, even in a system that is fully optimised for recycling. Chemical recycling and carbon capture and utilisation may provide another 25% of the renewable-carbon feedstock needed, but they generally require far more energy and other inputs to produce new materials and chemicals than the mechanical and physical recycling methods. The remaining demand for renewable-carbon feedstock thus needs to come from either biomass or CO_2 through carbon capture and utilisation technologies. Based on our findings, we argue that the composition of our present carbon-based products pool needs to be redesigned on a fundamental molecular level, towards material types that contain more oxygen. Carbon-based materials that contain more oxygen generally can be recycled more efficiently, and are also easier to produce from the alternative feedstocks biomass and CO_2 through CCU.

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1. Introduction

1.1. The circular economy and recycling

Many governments have taken action in recent years to promote the development of a circular economy; the EU (European Commission, 2020; European Parliament, 2021), the US (EPA, 2023; EllenMacArthurfoundation, 2022b), Canada (Government of Canada, 2023) and China (Bleischwitz et al., 2022) to name just a few. The ambitions of most of these plans are high, mostly aiming for a 100% circular economy in 2050, by following the R-ladder (Rood and Kishna, 2019; Rijksoverheid Nederland, 2022) in which reuse and recycling of materials after use play an important role. However, the plans also face criticism on numerous aspects, such as that the circular economy has diffused limits and unclear theoretical grounds (Corvellec et al., 2022), that they fail to address the necessary phasing out of the linear economy (Johansson, 2021) or that they fail to address the societal changes that are needed for such a transition (Jaeger-Erben et al., 2021). There is, however, another more fundamental matter that is often overlooked when the circular use of materials is advocated, and that is the second law of thermodynamics; the fact that materials degrade and dilute and are generally not easily brought back into their original state, without the investment of a considerable amount of energy. Next to that, materials are often contaminated during use and may then be in a state or form that hampers reuse or recycling. Furthermore, they may get uncontrollably dispersed in the environment during their use phase. Based on these considerations we state that the maximum reachable recycling potential of materials and chemicals lies well below 100%. Even though a circular economy is a concept that is much broader than just recycling of materials, recycling is still an important aspect of it, and a maximum recycling potential of well below 100% means that a significant input of virgin (new) feedstock will be needed yearly to produce the materials and chemicals which are used worldwide, even when we leave the expected increase in material use out of the analysis.

But what is the recycling potential, and how can we estimate it? This is a relevant question because there are many different recycling technologies applied and developed at this moment (d'Ambrières, 2019), all with their specific requirements regarding the input-materials and with widely differing efficiencies. In addition, the products we use in our daily life are made of a wide range of materials such as glass, metals, minerals and carbon-based materials like wood, plastics and textiles. In this paper we focus entirely on all materials/chemicals that are based on organic carbon. These materials are broadly applied in product categories such as packaging, textiles, automotive and many others.

1.2. Renewable carbon for carbon based materials

Some of the carbon-based materials are produced from biomass, while others are presently based on fossil feedstock, generally fossil oil. For the fossil oil based materials and chemicals yet another issue is at stake. The energy transition, needed to fight climate change, focuses on decarbonisation of the energy system by applying non-carbon-based energy sources (sun, water and wind). New energy solutions are introduced at increasing speed (Jones, 2023). Some even argue that a fast transition to a decarbonized energy system is economically more profitable than a slow transition. (Way et al., 2022). However, a potential complete phasing out of fossil oil feedstocks means that, for the carbon-based materials and chemicals that are presently produced from fossil sources, a new renewable feedstock needs to be found. For these materials and chemicals, a transition towards renewable carbon as the new feedstock, thus, is urgently needed.

There are basically only three sources of renewable carbon we can use for materials and chemicals (Nova Institut, 2021). These three sources of renewable carbon are:

- Recycled materials, which can be converted back into new materials by a variety of technologies.
- Biomass, which, apart from being the source of our food, can be converted into all kinds of materials, either by mechanical, physical or (bio)chemical technologies
- CO_2, which can be converted into an array of small molecules by CCU (Carbon Capture and Utilisation) technologies, and that can subsequently be converted into carbon-based materials.

Each of these three sources has different constraints:

- The volume of materials that can be produced from recycled materials is limited by the total amount of materials already present, and, on top of that, by the efficiency of collection systems and conversion technologies, as we will show in this paper.
- The amount of biomass that can be made available for the production of biobased materials is limited by the availability of agricultural land and forests, the input of (non-renewable) fertilizers, the yield per hectare of the various crops and by the potential competition with food and feed production.
- CCU technologies are partly still in an early stage of technological readiness and generally require relatively large amounts of energy and the availability of renewable hydrogen as one of the important reagents. Furthermore, CCU technologies require concentrated CO_2 (or CO). Even if the concentration of CO_2 in the atmosphere has risen by more than 50% since pre-industrial times (NOAA Climate.gov, 2020), the absolute amount of CO_2 in the atmosphere is still very low, presently about 410 parts per million, therefore preferably point sources of CO_2 are used.

In order to implement effective policies to support the availability of sufficient feedstock, it is important to get a better grasp of the relative future contributions of these three sources of renewable carbon and the related technological pathways and innovation tasks.

In this paper we make an estimate of the present world-wide use of carbon-based materials. Furthermore, we present a method to address the recycling potential for these materials and chemicals in a wide range of applications, as a function of their application. And, finally, by applying this approach, we make an estimate of the maximum recycling potential of all carbon-based materials under optimal conditions.

The overall research questions addressed in this paper are:

1. What is the present magnitude of application of carbon-based materials/chemicals world-wide in all markets together, expressed in mass?
2. How can we estimate the recycling potential of all (organic) carbon-based materials and chemicals as a function of their application, and what is its magnitude, expressed in percentage and mass?
3. What is the maximum contribution of the recycling routes to the production of renewable feedstock for all (organic) carbon-based materials and chemicals we presently use, and, consequently, how much of our carbon-based materials will we need to source from virgin feedstock each year?

1.3. The present magnitude of application of carbon-based materials/chemicals world-wide

Concerning the first question, a total overview of all carbon-based materials has to our knowledge not been presented up till now, but information on the different categories of carbon-based materials is presented by various authors. (IEA, 2018; IEA, 2021) presents a magnitude of the application areas of (fossil) oil, not only for energy production, but also as feedstock for the chemical industry. (Plastics Europe, 2020) presents regular updates of the application of the main types of polymers in a wide variety of markets within the European Union. (López et al., 2017) present an overview of the total use of biomass within the EU, for food and feed but also including non-food application in the form of Sankey diagrams. Furthermore, several commercial parties (see Section 3) report on the market size of numerous products. By combining data from a wide range of sources we were able to construct a total overview of the global market for carbon-based materials and chemicals. The Renewable Carbon Initiative (Kähler et al., 2023) present a compilation of supply and demand of fossil and renewable carbon on a global and European level. However, they do not start from as detailed a level as we do, but from material flow analyses and energy balances, and using these existing analyses and balances, they apply conversion factors to derive carbon flows.

1.4. The recycling potential of organic carbon-based materials

Regarding research question 2, recycling and recycling efficiency of carbon-based materials, a significant number of authors have addressed part of these issues for different types of materials, products or applications. (Brouwer et al., 2020) investigated technical limits in the circularity for plastic packages in the Dutch context. Their work focuses on the three main polymers used in packaging (PE, PP and PET), and they investigate the technical recycling limit that can be reached with an optimal organisation of the recycling chain and its stakeholders. An improved framework to address recycling percentages, for instance in case of recycling technologies that provide multiple outputs is proposed by (Caro et al., 2023). Their focus lies strongly on improving the mass balance rules for the processes used in the recycling chain. (Klotz et al., 2023) present a broad study on 11 plastic types in 69 product groups consumed and arising as waste in Switzerland. They investigated to which extent plastics' circularity can be increased by mechanical recycling under a number of future scenarios involving increased waste collection, improved product design, and improved waste sorting. They were able to quantify the amounts of consumption, waste, and secondary material utilizable in product manufacturing for the year 2040 b y means of a material flow analysis. (Lase et al., 2023) investigate the potential contribution of chemical recycling processes to plastic waste recycling using a materials flow analysis method. (Fazli and Rodrigue, 2020) present a review on the recycling options of rubber. Because rubber cannot be meaningfully recycled into similar materials, they focus on the use of recycled rubber waste into new (thermoplastic elastomer) materials, but conclude that also recycling into blended materials with acceptable properties is not yet a viable option. These authors focus mainly on the potential of the recycling processes, but the effect of the service-life in various applications of the products to be recycled is mostly not included.

In the field of metals, however, taking into account aspects of the service-life of a product when assessing recycling potential is more common. (Henckens, 2021) for instance presents a number of use aspects that infuence recycling potential of metals: Concentration, material composition, product composition, dispersed use and contamination. As far as we know an assessment that takes into account such aspects has not yet been presented for polymers and other carbon-based materials and we think this is a serious omission These aspects are expected to drastically influence recyclability in a negative way for many products with a longer lifetime, or in more dispersed applications. Not to assess them leads to too optimistic estimations of recycling potential.

Therefore, in this paper, we present a method to assess the recycling potential of carbon-based materials which is rooted in the material characteristics which are relevant in the most important applications of these materials. In line with (Henckens, 2021) we have taken into account aspects which are relevant for carbon-based materials in the various applications we studied: composition, ageing, ease of collection, ease of recovery, contamination and the presence of additives. Furthermore, we have applied our method not only to plastics. In this paper we focus on all (organic) carbon-based materials and chemicals: plastics, textile fibres, thermoset resins, rubbers, surfactants, solvents, fine chemicals, paper and board and wood products. We have not found a study of this breadth in literature up till now.

1.5. The maximum contribution of the recycling routes to the production of renewable carbon

Concerning research question 3, we assessed the potential contribution of recycled carbon-based materials to the total renewable carbon demand. We thus present an estimate of the contribution of recycling as may be reached in the future under ideal circumstances, assuming that the composition of the present materials/chemicals pool is not changed. The recycling methods considered in this assessment are either mechanical recycling methods (MR) that involve only mechanical processes (sorting, washing and drying, chopping, grinding) and subsequent reprocessing of material into a product, or physical recycling methods (PR) (via dissolution and recovery) and subsequent reprocessing of material into a product. This choice was made because these methods leave the polymeric structure of the materials intact, do not require large chemical infrastructures and have the potential to produce new products with limited energy input compared to chemical recycling methods (Hann and Connock, 2020). Furthermore, the assessment method involved an estimate of the amount of material that cannot be recovered and thus is expected to be lost.

Based on the numbers that followed from the assessment, a potential magnitude of carbon sources for other technologies, either Chemical Recycling (CR) or CCU technologies, can be derived. In CR the material is chemically broken down in a controlled way to retrieve feedstock that can be subsequently converted into new materials or products. CCU technologies can be based on a potential CO_2 or CO_2/CH_4 point source resulting from incineration or anaerobic digestion of the materials/chemicals.

Based on an estimated efficiency of CR and CCU technologies, we present an indication of the contribution of these methods to the production of renewable carbon feedstock.

Combined, these data give an estimate of the amount of renewable carbon that can potentially be made available each year by all different recycling options together, in a fully optimised situation. From this, the total amount of virgin feedstock needed each year can be derived.

2. Methods

2.1. General approach

The approach and the subsequent steps we have taken to answer the three research questions is presented in Fig. 1.

Fossil feedstock is used predominantly in seven different categories: plastics, textile fibres, thermoset resins, rubbers, surfactants, solvents, and fine chemicals (FC) (e.g. plasticisers, dyes). Biomass is used predominantly in six different, partly overlapping, categories: textile fibres, rubbers, surfactants, solvents, paper and board and wood products. All these categories were assessed separately. Furthermore, the specific applications/markets in all these categories (i.e. packaging, automotive, etc.) were assessed separately as much as possible (Fig. 1, step 1–4).

As starting point an extensive overview was made of the amounts in mega tonnes (Mt) of the (most applied) carbon-based materials in their most important applications/markets, based on market data available from various public sources, such as freely available (parts of) market studies, etc. For all entries also the amount of carbon present in the materials/chemicals was calculated in Mt (Fig. 1 step 5–6).

In the next step, a scoring method was developed to assess the recycling potential for all these materials, taking into account the effects their service life in the specific applications has on recycling potential. The scoring method is based on the separate scoring of a number of parameters and calculating from this an overall relative value for recycling potential. The relevant parameters were determined in an in-depth discussion with an expert panel. The members of the expert panel each

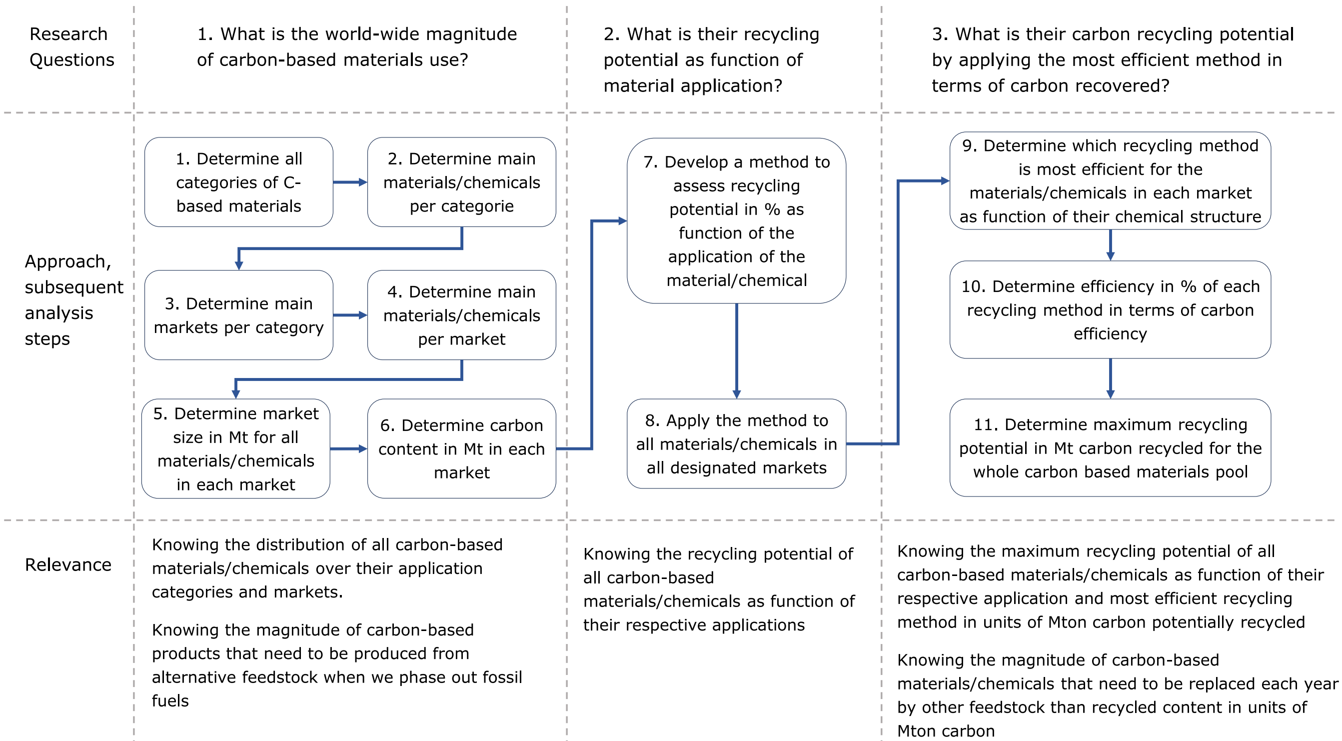

Fig. 1. Representation of the analysis steps and work-flow presented in the paper.

have numerous years of experience in (polymer) materials science and development, and are all presently employed at Wageningen University & Research in applied research (Fig. 1 step 7).

Subsequently, the assessment of the recycling potential was performed by the expert panel (Fig. 1 step 8). As the first step for each of the applications/markets the expert panel made an assessment of the percentage of materials that is expected to be uncontrollably released into the ecosphere, i.e. not collected in any way, which we refer to as leakage in line with the Ellen MacArthur Foundation (EllenMacArthurfoundation, 2022a). The difference between the total market and the assessed leakage gives the amount of materials that can be collected, see Equation (1):

$$\text{market size [Mt]} - \text{leakage [Mt]} = \text{collectable material [Mt]} \qquad (1)$$

Next, for all the materials/chemicals in their most relevant applications/markets the expert panel assessed the feasible percentage of the materials that can be recycled into a similar product (closed loop recycling), following the scoring method. The focus of the expert assessment was on the application of mechanical recycling (MR) or physical recycling (PR), i.e. recycling methods which keep the materials intact on a polymeric level. Direct re-use of a product was not taken into account by the assessment.

The difference between the amount of collectable materials and the amount of material that is deemed by the experts to be feasibly recycled (i.e. fraction$_{MR+PR}$) is the amount of material that cannot be recycled through MR or PR methods, and may thus be available for CR or CCU methods (i.e. fraction$_{CR+CCU}$), see Equation (2), even though presently, this non-MR, non-PR fraction is often used for energy recovery (i.e. incineration without CCU), or is even landfilled:

$$\text{collectable material [Mt]} - \text{fraction}_{MR+PR}\ \text{[Mt]} = \text{fraction}_{CR+CCU}\ \text{[Mt]} \qquad (2)$$

After this assessment step, in order to complete the picture of the possible contribution of both CR and CCU technologies to the production of feedstock for new materials, a rough estimate was made for each of the material types, which CR or CCU process is most suitable. Finally, based on an estimate of the efficiency of the CR and CCU processes, the amount of carbon that can be recovered through these processes was calculated (Fig. 1 step 9–11).

All numbers were converted to the amount of carbon (C) present in the materials (in Mt). In this way, the comparison of the contribution of recycling as a source of renewable carbon to the other sources of renewable carbon (biomass and CCU technologies) can be based on the carbon content only.

The steps are explained in more depth in the next paragraphs.

2.2. Determination of market size

For the categories plastics, textile fibres, thermoset resins, rubbers, surfactants, paper/board and wood products, an estimate was made of the present global market demand in Mt, based on various market research reports. The amount of carbon in each of the materials was calculated based on their (average) molecular composition.

For the remaining two categories (solvents and fine chemicals) it turned out to be impossible to find market data on the required level of aggregation. Therefore, for these two categories, the market size was determined as the total amount of carbon that is fed into the petrochemical industry, minus the use of fossil feedstock for the markets of plastics, textile fibres, thermoset resins, rubbers and surfactants (see Equation (3)). The wood products and paper/board markets are not taken into account in this calculation because they are not based on fossil carbon.

$$C_{f(\text{solvents and FC})} = C_{f(\text{petrochemical industry})} - C_{f(\text{plastics, textiles, thermosets, rubbers, surfactants})} \qquad (3)$$

The total amount of fossil feedstock fed into the petrochemical industry was determined using the approach presented by Bos and Sanders (2013), which is based on the fact that the petrochemical industry is sourced by only a limited number of hydrocarbons: methane (C_1), ethene (C_2), propene (C_3), butene and butadiene (C_4), and the aromatics

BTX, benzene (B), toluene (T) and xylene (X). From these base chemicals, the (petro)chemical industry produces its entire range of chemicals and materials. The world-wide market size in 2020 for each of these hydrocarbons was derived from various sources and based on these numbers and the atomic composition of each of the hydrocarbons the total amount of carbon fed into the petrochemical industry was determined. The market size of the solvent/fine chemicals market was subsequently derived from this number.

2.3. Designing the scoring method

For the set-up of the scoring method a set of criteria (6 in total), that are deemed to be most important for recycling potential through mechanical or physical methods, (analogous to criteria for metals (Henckens, 2021)) was determined and defined more specifically together with the expert panel:

- Composition; i.e. is the material in this application usually applied as a mono-material or as a blend?
- Ageing; is the expected lifespan in this application short or long, and is the material expected to be exposed to factors that affect its quality i.e. extreme temperature fluctuation, oxidation, UV light, acidity, micro-organisms?
- Collection; is the material in this application collected easily?
- Recovery; is the material in this application easy to recover from a mixed stream?
- Contamination; is the material in this application expected to be contaminated by external substances such as fats and greases, solvents, inks, etc?
- Additives; does the material in this application require the addition of a large number of additives?

In order to determine the recycling potential, leakage, and CR/CCU potential for each material for the different applications/markets, the following steps in the procedure were used:

- First, inevitable leakage of carbon (%) in each specific application/market was estimated by expert judgement.
- Next, for each of the markets/applications the scoring method was followed to determine the recycling potential (RP). For each of the criteria a score was given by the experts ($score_{experts}$), ranging from 0 to 4. A maximum score for the recyclability ($score_{max}$) was 24 (6 criteria times 4).
- Next, the RP for mechanical and physical recycling processes, $RP_{MR + PR}$, expressed in %, was calculated following Equation (4):

$$RP_{MR + PR}\,[\%] = (score_{experts}/score_{max})*(100\text{-leakage}\,[\%]) \quad (4)$$

- For the criteria “collection” (for recycling) and “recovery” (of the target material) the following rule was applied: if one of these categories scores a 0 then recycling potential is set to 0.
- When the market size was 0, the score was not determined.
- RP for CR and CCU processes ($RP_{CR + CCU}$) expressed in % was calculated following Equation (5):

$$RP_{CR + CCU}\,[\%] = 100\text{-leakage}\,[\%] - RP_{MR + PR}\,[\%] \quad (5)$$

2.4. Determination of mechanical/physical recycling potential and leakage

The expert panel made an estimate for a theoretically feasible percentage of recycling (potentially reachable by 2050). The assessment was done for each of the material/market combinations studied, assuming mechanical or physical recycling methods which keep the molecular structure of the materials intact. To base the estimate solely on the intrinsic properties of the materials, the assessment was done under the assumption that an optimal functioning recycling system is in place, thus assuming that:

- Products are designed for recycling.
- A proper collection system is in place.
- Consumers are willing and able to dispose of waste in a proper way.
- Separation and recycling technology is well developed and on commercial scale.
- There is an established market for recycled products.
- Recycling leads to a new, similar product of the same material.

For each application/market group, a separate overview was created with a compilation of the final results *(See all tabs ‘overview’ of the respective categories of the* supporting *material)*. Once the $RP_{MR + PR}$, leakage [%] and the $RP_{CR + CCU}$ were determined, the absolute weight in Mt for each of the materials and market categories was calculated based on the total market size. Next, based on the molecular composition of the categories, the weights in Mt carbon were calculated. These values are incorporated in the overall tab ‘Carbon for recycling 2050’ of the supporting material. In a few cases the method was less applicable, and another approach was taken, which is explained in Chapter 3.

2.5. Determination of the relative contribution of CR and CCU technologies to renewable carbon feedstock

The possible contribution of either CR or CCU to retrieval of renewable carbon was calculated for each category separately.

Chemical recycling back to building blocks aims at depolymerising the polymer down to the level of the original building blocks. This route can only be applied for polycondensation polymers such as polyesters, polyamides and polyurethanes. (Payne and Jones, 2021) investigated different catalysts for depolymerisation of both PLA and PET and they report high yields for these processes, some around 99%, starting from a mono-stream. As with the other recycling technologies, mixtures of materials are expected to make the processes less efficient, therefore in our calculation we set the recycling efficiency at 80%.

For the addition polymers (like PE, PP, PS and PVC), and other materials that contain little or no oxygen, such as most rubbers, chemical recycling may resemble a pyrolysis or cracking process. In these processes a mixture of small hydrocarbons is produced which is not necessarily directly suited to produce the materials that served as input for the process. Presently, many of these processes mostly produce fuels. (Hann and Connock, 2020). (Dogu et al., 2021) find that the processes yield a wide range of different hydrocarbons, generally over 20 different types. They report for pure PE an optimal yield of ethene, the building block of PE, of only 20–25%. For pure PS they find a yield of styrene of 76.8%. Mixed plastic waste yields a mixture of over 20 different molecules, all fractions significantly lower than 10 wt%.

For materials where CR technologies are not an option, either incineration or anaerobic digestion (in case the material/product is biodegradable) can be performed. Both these processes produce heat and CO_2-rich gas, which via Carbon Capture (CC) may serve as point source for CCU technologies. CC from point sources is at this moment generally performed at an efficiency of 90% (Brandl et al., 2021). The process of anaerobic digestion produces next to CO_2 also 50%–70% methane (CH_4) (Wahid et al., 2019), which may also be used as feedstock for (already existing) chemicals production routes. Generally, incineration may be more suited for larger products, including wood products. Anaerobic digestion may be more suitable for solvents and small materials fragments such as sewage sludge and the rejects from recycled paper.

Efficiencies for recycling and recovery used in our calculations were based on recent data reported in the literature (see Table 1 for the overview).

Table 1
Estimated processing (carbon) efficiencies for the chemical recycling and carbon capture processes.

Process efficiency carbon recovered (%)	Process	Based on reference
80	Recovery of building blocks through depolymerisation	Payne and Jones (2021)
25	Recovery of building blocks through pyrolysis of polyolefins (excl PS)	(Dogu et al., 2021)
75	Recovery of building blocks through pyrolysis of styrene	(Dogu et al., 2021)
20	Recovery of building blocks through pyrolysis of mixed fractions	(Dogu et al., 2021)
70	Recovery of CO_2 from incineration for CCU	(Brandl et al., 2021)
80	Recovery of CO_2 and CH_4 from anaerobic digestion for CCU	(Brandl et al., 2021)

3. Results

3.1. Market size of all relevant material categories

The **Plastics** category was split up into the main plastics categories, polyethylene (PE), polypropylene (PP) polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyurethane (PU), and polystyrene (PS) including expanded polystyrene (EPS). All other material categories (polycarbonate (PC), poly (methyl methacrylate) (PMMA), acrylonitrile butadiene styrene (ABS) and others), were taken together under the category "other", because their volume is relatively small and the variety of applications is very large. For the calculation of the carbon content of this category, the molecular structure of polycarbonate (PC) was assumed as a proxy.

The global market share (in weight %) of each of the plastics categories was derived from data of Plastics Europe (Plastics Europe, 2020). This European market share was assumed to be also applicable for the total global plastics market. From the European data the contribution of the various types of plastics to 6 main markets (packaging, building & construction, automotive, electrical & electronics, agriculture and household, leisure & sports) was determined. All other markets were combined under the category other. The total global plastics market size was assumed to be 368 Mt in 2019 (Plastics Europe, 2020).

The estimated world-wide market share (%) and absolute market size (Mt) in each of these categories is given in Table 2.

The contribution of the new bio-based polymers to the total polymer market is still small, 2.11 Mt in 2019 (European Bioplastics, 2021), less than 0.6% of the present polymer market. Therefore we did not include them in this paper.

The world **textile fibre** market was derived from the market Report 2021 by Textile Exchange (Textile Exchange, 2021). The main textile application areas are apparel, home and other (including technical), and their market share was derived from the report. Subsequently, textiles were categorized in the three main fibre types, i.e. synthetic, natural and regenerated fibres, and their respective market size was also derived from the report. For each type of fibre, the market size for each application area was calculated based on the overall market share. For this the assumption was made that the relative market share in each application area is the same for each type of fibre. The results are presented in Table 3.

The world **thermoset resin** data were derived from a variety of sources. The global unsaturated polyester (UP) market was approximately 5 Mt in 2017 (SNNTV, 2021), and the global polyurethane (PU) resins market was estimated to be 24 Mt in 2020 according to (Statista, 2021b). However, in the European Plastics data polyurethane (including foams) is already included, so to avoid double counting these number were left out under the category of thermoset resins. Global epoxy resin was estimated to be 3.5 Mt in 2020 (MordorIntelligence, 2021a). The main formaldehyde based resin categories, phenol formaldehyde (PF), urea formaldehyde (UF) and melamine formaldehyde (MF), were taken together and the estimated global market size in 2020 was 45 Mt (Report Linker, 2021). The thermoset resins were not split into different market application categories, due to lack of data and their limited recycling potential in any application (because they are strongly chemically cross-linked and cannot be melted or dissolved).

Table 3
Market share and size of the various types of textile fibres in their main applications.

Textiles	Apparel	Home	Other	Total
Market share (%)	**44**	**23**	**33**	**100**
Market size	**Mt**	**Mt**	**Mt**	**Mt**
Synthetic				
PET	23.3	14.1	19.6	57.1
PA	0.4	1.0	4.0	5.4
PP	0.3	0.6	2.1	2.9
Acryl	1.3	0.3	0.1	1.7
Elastane	1.0	0.0	0.1	1.1
Subtotal	***26.3***	***16.0***	***25.9***	***68.2***
Natural				
Cotton	15.5	6.8	3.9	26.2
Jute	0.0	0.3	2.9	3.2
Coir	0.0	0.1	1.2	1.3
Flax	0.6	0.3	0.1	1.0
Hemp	0.0	0.0	0.2	0.2
Wool	0.6	0.4	0.0	1.0
Subtotal	***16.8***	***7.8***	***8.3***	***32.9***
Regenerated				
Viscose	3.6	0.8	0.8	5.2
Lyocell	0.1	0.1	0.1	0.3
Acetate	0.0	0.0	0.9	0.9
Cupro	0.0	0.0	0.0	0.0
Modal	0.2	0.0	0.0	0.2
Subtotal	***4.0***	***0.9***	***1.7***	***6.6***
Total	**47.1**	**24.7**	**35.9**	**107.7**

Table 2
Market share and size of the various types of plastics in their main applications.

Plastics	Packaging	Building & Construction	Automotive	Electrical & Electronic	Agriculture	Household, Leisure & Sports	Other	Total
Market share (%)	**39.6**	**20.4**	**9.6**	**6.2**	**3.4**	**4.1**	**16.7**	**100**
Market size	**Mt**	**Mt**	**Mt**	**Mt**	**Mt**	**Mt**	**Mt**	**Mt**
PE LL,L,M,H	74.1	12.9	3.5	2.9	3.5	1.8	13.1	**111.8**
PP	34.0	5.8	9.7	3.4	4.5	5.1	10.2	**72.6**
PVC	3.4	28.0	1.0	0.5	0.9	1.4	1.8	**37.0**
PET	28.0	0.0	0.0	0.0	0.0	0.0	0.0	**28.1**
PU	0.3	6.8	5.4	2.0	0.0	0.2	12.8	**27.5**
PS EPS	8.8	9.6	0.5	1.3	0.2	1.4	2.1	**23.9**
other	3.6	9.6	15.5	11.5	2.5	4.3	20.1	**67.2**
Total	**152.1**	**72.7**	**35.5**	**21.7**	**11.6**	**14.2**	**60.2**	**368.0**

The estimated market size in each of these categories is presented in Table 4.

The world-wide **rubber** market was estimated from various sources. The global synthetic rubber market was estimated at 14.4 Mt in 2020 (Statista, 2021a). The total market share of natural rubber versus synthetic rubber was approximately 47% in 2017 (Market Publishers, 2018), from which a market size for natural rubber of 12.8 Mt can be derived. Based on the total market size of the synthetic rubbers and the percentage of market share of the various types of synthetic rubbers (RubberNews, 2017), the market size in Mt of each type of synthetic rubbers was determined. The estimated market share and market size of the main types of rubber is presented in Table 5.

The **surfactants** market is for approximately 85 % made up of anionic and non-ionic surfactants in equal proportions (MordorIntelligence, 2021c). We therefore estimated the global size of surfactants from the market size of the main molecules in these two categories (IHS Markit, 2019), Alkylpolyglycoside (APG) for the non-ionic surfactants and (fossil-based) linear alkylbenzene sulphonate (LABS) and (bio-based) Sodium lauryl sulphate (SLS) for the anionic surfactants. LABS is assumed to be 75% of the anionic market (Smithers, 2017). The two main applications for surfactants are in Home and Personal Care (HPC), which we assumed to form two thirds of the total market and Industrial Applications which are assumed to cover the remaining third of the market (PRNewswire, 2016).

The estimated market share and market size in each of these categories is presented in Table 6.

To derive the size of the **solvent** and **fine chemicals** market, the overall carbon demand of the petrochemical industry was determined (Bos and Sanders, 2013). The market size in 2020 for each of the hydrocarbons C_1 to C_4 and BTX was deduced from a variety of sources. For C_1 the market size for methanol was used. Sources were for C_1 (MordorIntelligence, 2021b), for C_2 (Statista, 2022a), for C_3 (Statista, 2022d), for C_4 (Mordor Intelligence, 2022), for B (Statista, 2022b), for T (Statista, 2022c) and for X (Statista, 2022e). Based on these numbers and the atomic composition of each of the hydrocarbons the total carbon demand of the petrochemical industry was calculated. The numbers are presented in Table 7.

The **solvent** market is a very diverse and large market which comprises methanol, ethanol, butanol, propylene glycols, glycol ethers, butyl glycol ethers, acetone, esters, aromatics and hydrocarbons to name just a few (Fortune Business Insights, 2020). The assumption we made for the solvents from fossil sources, is that 50% of the difference between the total amount of carbon that is processed by the petrochemical industry, minus the amount of (fossil-based) carbon in the markets of polymers, textiles, composite resins, rubbers and surfactants is the carbon content of fossil-based solvents. To convert the Mt carbon in solvents to a total market share of the solvents in Mt, the atomic composition of ethanol was taken as a proxy.

Furthermore, presently 95% of ethanol is produced from biomass (DMI, 2023), and this share is increasing. For ease of calculation, we assumed presently all ethanol is based on biomass. The ethanol market for solvents was assumed to be 20% of the total ethanol production (Grandview Research, 2019). The estimated market size in Mt of solvents market is given in Table 8.

The **fine chemicals** market is the most diverse of all and very difficult to estimate (EFCG, 2019; Research and markets, 2020). One important group of fine chemicals are the plasticisers, of which the market size was estimated at 7.5 Mt in 2018 (Wikipedia, 2019). Another significant category are the textile chemical auxiliaries, which are estimated to be roughly 10 % of the textile fibre volume, and thus amount to approximately 10 Mt (Schindler and Hauser, 2004). The assumption we made is that 50% of the difference between the total amount of carbon that is processed by the petrochemical industry minus the amount of (fossil-based) carbon in the markets of polymers, textiles, thermoset resins, rubbers and surfactants is the carbon content of fossil-based fine chemicals. To convert the Mt carbon in fine chemicals to a total market share of the fine chemicals in Mt, the atomic composition of alkyl polyglycoside (APG) was taken as a proxy.

Market size of the fine chemicals is presented in Table 8.

Total size of the **paper and board** market was taken from McKinsey as 420 Mt (Mckinsey, 2019). Paper and board are assumed to comprise 95% cellulose fibres (Bodewes Collectiebeheer, 2021) therefore the market size of wood-based content in paper and board was set to 399 Mt. Wood lignocellulose, which is the feedstock for these cellulose (paper) fibres, is estimated to contain 75% cellulose and hemicellulose and 25% lignin (van Dam et al., 2017) (which is removed during paper production). Lignin is a large carbon containing stream, thus estimated to sum up to 133 Mt. The size of the total **wood products (including construction)** market was then deduced from the total demand for wood for material use (wood products), estimated by Bos and Broeze as 1000 Mt (Bos and Broeze, 2020). From this number the market size for paper and board and for lignin was subtracted. The market size of wood products and construction was thus estimated to be 468 Mt.

Table 4
Market size of the main types of thermoset resins. The value for PU is in italics because it is already included in the table on plastics.

Thermoset resins	All markets
Market share (%)	**100**
Market size	**Mt**
UP	5
PU	*24*
Epoxy	3.5
PF/MF/UF	45
Total	**53.5**

3.2. Carbon content of all relevant materials

For all materials and chemicals, the molecular composition was determined from the overall atomic structure in terms of weight percentage of carbon, hydrogen, oxygen, nitrogen, chlorine and sulphur atoms. Mostly this was derived from general textbooks and (our) expert knowledge. In some cases a proxy was taken: for the category of 'other polymers' the proxy was polycarbonate, for acryl it was PAN (polyacrylonitrile), for elastane it was polyurethane, for wool it was cysteine (amino acid) and for flax it was cellulose (natural polymer). For coir a composition of 42% lignin and 58% cellulose was assumed (Muensri et al., 2011). For the unsaturated polyester a styrene bridge length of 3 was assumed ($n = 3$), the epoxy structure was based on DGEBA (Diglycidyl Ether of Bisphenol-A) based epoxies. For formaldehyde resins the proxy was a novolac PF (Phenol Formaldhyde) resin, nitrile rubber was supposed to contain 33% acrylonitrile. Alkylpolyglycoside (APG) was assumed to contain one sugar ring ($m = 1$) and a fatty acid component with chain length of 18 ($n = 17$). For all solvents the proxy was ethanol and for the fine chemicals it was APG.

The total overview can be found in the supporting material under tab 'overview atomic composition'.

3.3. Recycling potential and leakage of all carbon-based material categories

The most relevant findings of the expert panel are presented below. The scoring for all materials in all considered applications can be found in the supporting material.

3.3.1. Plastics

An example of the constructed overview table, containing the expert assessment, in this case for plastics in packaging applications is given in Table 9.

Table 5
Market size of the various types of rubbers in the most important applications.

Rubbers		Tires & Automotive	Footwear	Tubes & Industrial	Construction	Other	Total
Market share (%)	**Natural Rubber**	**49**	**17**	**15**	**0**	**19**	**100**
	Synthetic Rubbers	**65**	**10**	**5**	**15**	**5**	**100**
Market Size		**Mt**	**Mt**	**Mt**	**Mt**	**Mt**	**Mt**
Natural rubber	Natural Rubber (NR)	6.3	2.2	1.9	0.0	2.4	**12.8**
Synthetic rubbers	SBR	3.2	0.5	0.2	0.7	0.2	**4.9**
	EPDM	0.8	0.1	0.1	0.2	0.1	**1.3**
	Butylrubber (IIR)	0.7	0.1	0.1	0.2	0.1	**1.2**
	Nitrilrubber (33% ACN) (NBR)	0.4	0.1	0.0	0.1	0.0	**0.6**
	Butadienerubber (BR)	2.2	0.3	0.2	0.5	0.2	**3.5**
	Other (Proxy NR)	2.0	0.3	0.2	0.5	0.2	**3.0**
Subtotal		***9.4***	***1.4***	***0.7***	***2.2***	***0.7***	***14.4***
Total		**15.6**	**3.6**	**2.6**	**2.2**	**3.1**	**27.2**

Table 6
Estimated market size of fossil-based and biomass based surfactants in their two main markets.

Surfactants	Home & Personal Care	Industrial	Total
Market share (%)	**66.7**	**33.3**	**100**
Market size	**Mt**	**Mt**	**Mt**
Fossil based			
Linear alkylbenzene sulphonate (LABS)	4.2	2.1	**6.3**
Biomass based			
Sodium laurylsulphate (SLS)	1.4	0.7	**2.1**
Alkyl polyglycoside	5.6	2.8	**8.4**
Total	**11.2**	**5.6**	**16.8**

Table 7
Overall carbon use in the petrochemical industry, derived from the market size of the main base chemicals.

Base Chemicals		Market size	Carbon use Chemical industry	
		Mt	Weight % Carbon	Mt C
C1	Methanol	84	0.375	31
C2	Ethene	168	0.857	144
C3	Propene	116	0.857	99
C4	Mixture	12	0.889	11
B	Benzene	58	0.923	54
T	Toluene	29	0.913	26
X	Xylene	48	0.906	43
Total		**515**		**409**

Table 8
Overview of the estimated market size of solvents and fine chemicals.

Solvents & FC	All markets
Market share (%)	**100**
Market size	**Mt**
Solvents (excl ethanol)	25.1
Ethanol	12.0
Fine Chemicals	19.6
Total	**56.7**

The expert panel estimated for plastics, overall, a low leakage percentage (smaller or equal to 5%), only in agriculture applications the leakage was assumed to be relatively high at 10%.

In packaging the lifespan of a plastic packaging product is generally very short, varying from only a few days up to several months, so ageing generally is not an important parameter. The recycling potential, $RP_{MR + PR}$, of PET in packaging was estimated by our expert assessment to be rather high, 75%. The polyolefins PE and PP were estimated to have a lower $RP_{MR + PR}$ of 51%. The number for PET is well in line with the estimation presented by (Brouwer et al., 2020) of 72% for all plastic packaging in an optimally designed recycling system. Our estimate for PE and PP recycling however is lower, which is especially caused by assumed difficulties in recovery, high contamination, and a high additives content, as scored by the experts. PVC ranges around 63% especially influenced by high additive content (e.g. plasticisers).

For building & construction $RP_{MR + PR}$ of PVC and PE came out very high (79%), because these materials are mostly used in piping and tubing, therefore suffer little from ageing due to external influences and can be collected relatively easily and reprocessed. $RP_{MR + PR}$ of PUR in building was estimated to be zero, because in these applications PUR is generally used as a (cross-linked) foam and can therefore not be melted and reprocessed.

In automotive $RP_{MR + PR}$ for most of the materials lies around 50%. Cars are by (EU) law recycled after end-of-life, but especially ageing, contamination and a high additives content make mechanical recycling into a high value product difficult.

The other markets are small compared to the three just described. Also the category ‘other polymers’ is small compared to the polymers described in detail. Within this category there are materials such a Polycarbonate (PC) and Acrylonitrile-Styrene-Butadiene copolymer (ABS) for which recycling processes through a dissolution route (physical recycling) are under development. (Cefic, 2023; Trinseo, 2023). Other examples in the category “other polymers” are more difficult to recycle by mechanical recycling technologies or more difficult to recover. The expert panel found it too difficult to judge both the category other markets as well as the category other polymers, because their composition is less well defined. We therefore decided to allocate an $RP_{MR + PR}$ of 25% after subtraction of leakage to these categories in all cases.

Detailed data on the scoring can be found under the tab ‘overview plastics’ in the supporting information.

For the overall plastics markets an $RP_{MR + PR}$ of 44 % was determined through the applied methodology. This is well in line with the range of 41–46% of recycling by mechanical recycling as estimated in the most optimistic scenario by (Lase et al., 2023) through a mass flow analysis. Our finding is, however, more optimistic than the 31% of mechanical recycling potential presented by (Klotz et al., 2023), from a material flow analysis focusing on Switzerland.

Table 9
Example of the assessment sheet filled in by the expert panel, for plastics in packaging applications. The last column gives the total score of the expert assessment. (Assessment sheets for all other materials/chemicals categories can be found in the supporting material). The numbers for recycling potential in the left side table follow from the experts assessment.

Market type	Packaging	Recycling potential	Leakage	CR/CCU potential	Recycling potential	Leakage	CR/CCU potential		Compo-sition	Ageing	Collection	Recovery	Conta-mination	additives	Total score
% of EU market	40%		5%						blend=0 pure =4	excessive=0 limited=4	hard=0 easy=4	complex=0 easy=4	high=0 low=4	high=0 low=4	
	market size [Mt]				Mt	Mt	Mt	max	4	4	4	4	4	4	24
PE LL,L,M,H	74.1	51%	5%	44%	38.1	3.7	32.3		2	4	4	1	1	1	13
PP	34.0	51%	5%	44%	17.5	1.7	14.8		2	4	4	1	1	1	13
PVC	3.4	63%	5%	32%	2.2	0.2	1.1		3	4	3	3	3	0	16
PET	28.0	75%	5%	20%	21.0	1.4	5.5		3	4	4	3	3	2	19
PU	0.3	0%	5%	95%	0.0	0.0	0.3					0			
PS EPS	8.8	87%	5%	8%	7.6	0.4	0.7		4	4	3	3	4	4	22
Other	3.6	24%	5%	71%	0.9	0.2	2.6		1	1	1	1	1	1	6
Total	**152.1**				**87.3**	**7.6**	**57.2**								

3.3.2. *Textiles*

Scoring of textiles was not done by the expert panel, (because they are less knowledgeable on textiles), but by two of the authors (Bos and Harmsen), following the same methodology, based on profound knowledge of textiles, their composition, applications and recycling potential (Harmsen et al., 2021).

For apparel (clothing) it was assumed that 15% of materials may not be collected or may get lost due to the loss of microfibres through washing and wear and tear. Reported values of microfibre loss differ but range between 0.02% and 0.37% of the original garment weight per washing cycle, with increased microfibre release as clothes age (Hartline et al., 2016; Napper and Thompson, 2016). The EllenMacArthurfoundation, 2022b estimates that each year 0,5 Mt microfibres enter the marine environment through washing (EllenMacArthurfoundation, 2017), but this number does not account for the microfibres that get dispersed in the environment by everyday wearing.

For the other two textiles categories, home and other, the estimated leakage was lower: 10%.

Textiles at this moment consist mostly of blended fibres, and recycling of textile fibres into textiles of similar functionality is extremely low. The EllenMcArthur foundation reported in 2017 a value of less than 1 % (EllenMacArthurfoundation, 2017). Recyclability of textile fibres is, furthermore, negatively influenced by the presence of a large amount of different additives such as finishes and dyes (Harmsen et al., 2021).

The $RP_{MR + PR}$ of mono-materials of PET, nylon, viscose, cotton and other cellulose fibres, is expected to be significant, although for most of the fibres it does not exceed 50%, following the method. However, for this recycling potential to be reached, the composition of textile fibres and the use of additives will need to change drastically (Harmsen et al., 2021). For wool, due to its high value and delicate handling during usage, an $RP_{MR + PR}$ of 64% was estimated. Detailed numbers can be found in the tab 'overview textiles' in the supporting information.

3.3.3. *Thermosets and rubbers*

Leakage of thermosets was estimated to be rather low (4%), because thermosets are often found in larger structures that can easily be collected. Most leakage is expected to happen with coatings and adhesives. However, thermoset resins are crosslinked systems and therefore inherently non-recyclable into similar products by mechanical or physical methods. Some developments are underway to make thermosets with reversible crosslinks (Post et al., 2020) but according to the experts this will have only a limited effect in most thermoset applications. The recycling potential was therefore set at 0. The detailed numbers can be found in the tab 'overview thermosets' in the supporting information.

Leakage for both rubber application in tyres & automotive and in footwear was estimated by the experts to be high, due to tear and wear (20 and 30% respectively).

Most rubbers are crosslinked systems and therefore not recyclable by mechanical or physical methods into a similar product. EPDM, especially in automotive bumpers, is estimated to have some potential for recycling. The detailed numbers can be found in the tab 'overview rubbers' in the supporting information.

3.3.4. *Surfactants, solvents and fine chemicals*

The category of surfactants was not judged by the expert panel, because they felt they lacked expertise, but by the authors. For the home and personal care market it is assumed that recovery is not possible, as most products will end up in sewage water after use and are collected in sewage treatment plants, where they could be anaerobically digested and/or subsequently burned to provide feedstock for CCU technologies. Only 1 % was assumed to be leaked, but this is fully dependent on the presence of an optimal wastewater treatment infrastructure.

For industrial surfactant applications the same 1% was expected to be lost, but on top of that, recovery and subsequent recycling of circa 5% of the materials could be feasible in a controlled industrial setting. The detailed numbers can be found in the tab 'overview surfactants' in the supporting information.

Also, the category of solvents was not judged by the expert panel but by the authors. For solvents most of the criteria relevant for the other materials categories are not applicable, so part of the scoring approach was not applied. Solvents may get lost during application (e.g. in paint), for which a leakage of 5% is estimated. Within industrial setting most solvents are expected to be recovered and recycled (95%). The detailed numbers can be found in the tab 'overview solvents FC' in the supporting information.

Similarly, the category of fine chemicals was not judged by the expert panel but by the authors, and part of the scoring approach was not applied. Fine chemicals are expected to be leaked in large amounts (60%), because their application is diffused over millions of products. Therefore, also recyclability is set to 0. The detailed numbers can be found in the tab 'overview solvents FC' in the supporting information.

3.3.5. Wood based products and paper and board

Collection of wood from construction is increasingly done, collection of other wood products is often not done separately, but rather through the mixed waste stream (Borzecka, 2018). At this moment wood waste is mostly used either for energy production or for production of panel board. (Circular, 2022). Recycling of wood into a similar product is estimated to be approximately 54 % due to contamination, ageing and the difficulty to recover a pure stream, since many wood products are laminated, painted or otherwise treated. This number seems to be in line with the finding that from the wood that is recovered in EU approximately 50% is reused in products (Borzecka, 2018). However, it can also be argued that most of these applications can be considered as downcycling, since panel board is the main target product (Circular, 2022).

Paper and board can be well recycled, estimated by the expert panel at approximately 71%, which is well in line with the 73% recycling reported by CEPI for the European countries that have a very good paper recycling system in place (European Paper Recycling Council, 2021).

The detailed numbers can be found in the tab 'overview wood' in the supporting information.

3.4. CR and CCU technologies

The possible contribution of CR and CCU was assessed for each materials/chemicals category separately. The following assumptions were applied:

- Polycondensation polymers, both in plastics and in textiles, are assumed to be chemically recycled (CR) through depolymerisation to building blocks.
- Polyaddition polymers, both in plastics and in textiles, are assumed to be chemically recycled (CR) through pyrolysis.
- Natural textile fibres and regenerated textile fibres are assumed to be processed through anaerobic digestion with subsequent Carbon Capture (CC), to serve as point source for CCU.
- Rubbers are assumed to be chemically recycled (CR) through pyrolysis.
- Thermosets are assumed to be incinerated with subsequent CC to serve as point source for CCU, because their relatively high oxygen content makes them less suitable for pyrolysis.
- Surfactants are assumed to be processed through anaerobic digestion (in sewage water sludge) with subsequent CC, to serve as point source for CCU.
- Solvents are assumed to be processed through anaerobic digestion with subsequent CC, to serve as point source for CCU.
- Fine chemicals are assumed to be incinerated with subsequent CC to serve as point source for CCU.
- Wood products are assumed to be incinerated with subsequent CC to serve as point source for CCU.
- Paper and board is assumed to be processed through anaerobic digestion with subsequent CC, to serve as point source for CCU.

3.5. Compilation of the results

The results for all markets considered, including the calculation of the amount of carbon that may become available for CR or CCU technologies is presented in Table 10. The green inputs in the table are presently biomass based and the grey inputs are fossil-based.

The results for all carbon-based chemicals and materials together are presented in Table 11, where again the green inputs in the table are presently biomass based and the grey inputs are fossil-based.

Based on our calculations and expert input, we thus estimate that 39 % of all fossil carbon-based products can be recycled and 59 % of all biomass based products.

We have not been able to find data in the literature that cover all product categories that are made of (organic) carbon, as we have investigated in this paper. However, for a number of large categories, such as plastics in packaging and paper and board our numbers are in range with the findings of other authors as discussed above.

The potential contribution of chemical recycling and carbon capture,

Table 10
Overview of all markets, the total carbon content in these markets and the estimated recycling potential (both RP_{MR+PR} and PR_{CR+CCU}) and leakage. The grey rows are the products that are presently based on fossil feedstock, the green rows are the products presently based on biomass. Wood products include construction wood.

	Total market size [Mt]	Total carbon content in market [Mt C]	RP_{MR+PR} [Mt C]	RP_{CR+CCU} [Mt C]	Carbon leakage [Mt C]
Plastics	368.0	280.7	122.2	144.4	14.2
Textiles	68.2	43.5	20.3	18.0	5.2
Textiles	39.5	17.7	8.6	6.8	2.2
Thermosets	53.5	42.1	0.0	40.4	1.7
Rubbers	14.4	12.7	0.0	10.2	2.5
Rubbers	12.8	11.3	0.5	9.0	1.8
Surfactants	6.3	4.2	0.0	4.1	0.0
Surfactants	10.5	10.9	0.0	10.8	0.1
Solvents	25.1	13.1	12.4	0.0	0.7
Solvents	12.0	6.3	0.1	2.4	3.8
Fine chemicals	19.6	13.1	0.0	12.4	0.7
Wood products	468.0	232.0	124.4	105.3	2.3
Paper and board	399.0	168.5	120.0	40.0	8.4
Total	**1496.8**	**856.0**	**408.6**	**403.9**	**43.5**

Table 11
RP_{MR+PR}, PR_{CR+CCU} and leakage in percentages, both in Mt and in Mt C content.

	Total size and potentials of all markets in Mt				Total size and potentials of all markets in Mt Carbon			
		RP_{MR+PR}	PR_{CR+CCU}	Leakage		RP_{MR+PR}	PR_{CR+CCU}	Leakage
	[Mt]	[Mt]	[Mt]	[Mt]	[Mt C]	[Mt C]	[Mt C]	[Mt C]
Fossil	555.1	219.0	302.1	33.9	409.4	154.9	229.6	24.9
% of total		39%	54%	6%		38%	56%	6%
Biomass	941.8	555.2	347.7	39.0	446.6	253.6	174.3	18.6
% of total		59%	37%	4%		57%	39%	4%
Totals	1496.8	774.2	649.8	72.9	856.0	408.6	403.9	43.5
% of total		52%	43%	5%		48%	47%	5%

RP_{CR+CCU}, to the production of renewable carbon is presented in Table 12.

4. Discussion

In this paper we present a method to estimate the maximum recycling potential of all (organic) carbon-based materials and chemicals, by assessing the material properties and aspects that are important for each of the materials/chemicals within the different categories of applications, assuming an optimal collection and recycling system is in place. Therefore, the number presented in this paper gives the maximum reachable recycling percentage for materials from a materials scientists' standpoint. This analysis is relevant for assessing the ambitions of the circular economy and reuse of materials. Our analysis points out that

Table 12
Overview of all markets and the estimated contribution of CR and CCU to new feedstock production. The two chemical recycling technologies, depolymerisation and pyrolysis are considered separately. Also incineration and anaerobic digestion technologies, providing point sources for CCU to the production of renewable carbon feedstock are presented separately. Numbers were calculated assuming the efficiencies presented in Table 1. The column carbon not recovered shows the carbon that is lost during the conversion processes assumed due to process inefficiencies. The grey rows are the products that are presently based on fossil feedstock, the green rows are the products presently based on biomass.

	RP_{CR+CCU}	CR depolymerisation	CR pyrolysis	CCU anaerobic digestion	CCU incineration	Carbon not recovered
	Mt C	**Mt C**	**Mt C**	**Mt C**	**Mt C**	**Mt C**
Plastics	144.4	22.4	30.5	0.0	0.0	91.4
Textiles	18.0	13.0	0.4	0.0	0.0	4.6
Textiles	6.8	0.0	0.0	5.5	0.0	1.4
Thermosets	40.4	0.0	0.0	0.0	28.3	12.1
Rubbers	10.2	0.0	2.0	0.0	0.0	8.2
Rubbers	9.0	0.0	1.8	0.0	0.0	7.2
Surfactants	4.1	0.0	0.0	3.3	0.0	0.8
Surfactants	10.8	0.0	0.0	8.7	0.0	2.2
Solvents	0.0	0.0	0.0	0.0	0.0	0.0
Solvents	2.4	0.0	0.0	1.7	0.0	0.7
Fine chemicals	12.4	0.0	0.0	0.0	8.7	3.7
Wood products	105.3	0.0	0.0	0.0	73.7	31.6
Paper and board	40.0	0.0	0.0	32.0	0.0	8.0
Total	**403.9**	**35.4**	**34.8**	**51.2**	**110.7**	**171.9**

(mechanical or physical) recycling is by no means able to solve the demand for feedstock for the yearly production of new materials/chemicals.

Furthermore, our analysis also highlights a number of other points.

Much attention, both by the governments and by the research cited in this paper, goes to the largest material categories, notably plastics in packaging applications, textiles, wood products and paper and board. However, as we show, even though these categories are the largest, there are many other product categories in which significant amounts of materials and thus carbon are used. For many of these categories, it can be said that a relatively diverse set of materials is used. For instance, plastics for packaging comprise for the larger part PE, PP and PET (see Table 2), but in some of the other application categories a much more diverse palette of materials is used (Table 2), which makes collection and recycling inherently more difficult.

Next to this come the categories of rubbers and thermosets, comprising a smaller, but still significant market share, which are impossible to recycle by mechanical/physical methods because they are mostly crosslinked materials.

And the last point stressed by our assessment is the large amount of (organic) carbon-based products that are not materials, but rather functional chemicals such as surfactants, solvents and fine chemicals, and which are for the most part very difficult to collect, let alone recycle. These categories are often overlooked in the plans for more circularity, but still comprise a significant market for (mostly) fossil-based feedstock. Finding an alternative feedstock for these applications is just as urgent in view of the phasing out of fossil feedstock as discussed in the introduction.

So, how does this translate to the options we have for our future materials/chemicals supply? Fig. 2 is a visual compilation of part of the results of Table 10, with fossil-based and bio-based materials/chemicals taken together. In this graph all numbers are expressed in Mt carbon atoms present in the respective material types. This graph gives an overview of the ultimate possibilities to produce renewable carbon feedstock from all (organic) carbon-based materials and products we produce and use every year.

As can be seen, mechanical/physical recycling methods can only supply part of the renewable carbon needed each year, and the amount differs strongly per material/product category. Several critical issues that relate directly to the way the materials are applied have been identified:

(1) Issues related to the composition of the material, i.e. is the material a mono-material or a blend of different materials and does it contain many additives? The fact that materials may consist of a blend of different materials or may contain additives is often (but not always) related to the functionality that is needed in the targeted application. An example are additives that provide fire retardancy.
(2) Issues related to the product life of the application, i.e. ageing. Is the expected lifespan in this application short or long; is the material expected to be exposed to factors that affect its quality (i.e. extreme temperature fluctuation, UV light) and contamination; is the material in this application expected to be contaminated by external substances (i.e. fats and greases, solvents, inks, etc.)?
(3) Issues related to the end-of-life phase of the product, i.e. collection. Is the material in this application collected easily; is it likely to be contaminated or mixed with other materials during collection; is the material in this application easy to recover from a mixed stream?
(4) The issue of so-called legacy SVHC (substances of very high concern), such as lead in PVC that was used as a stabiliser during processing. Recycling may keep these substances in the system and thus in the recycled products and may cause exposure to these harmful substances. Or these substances could limit

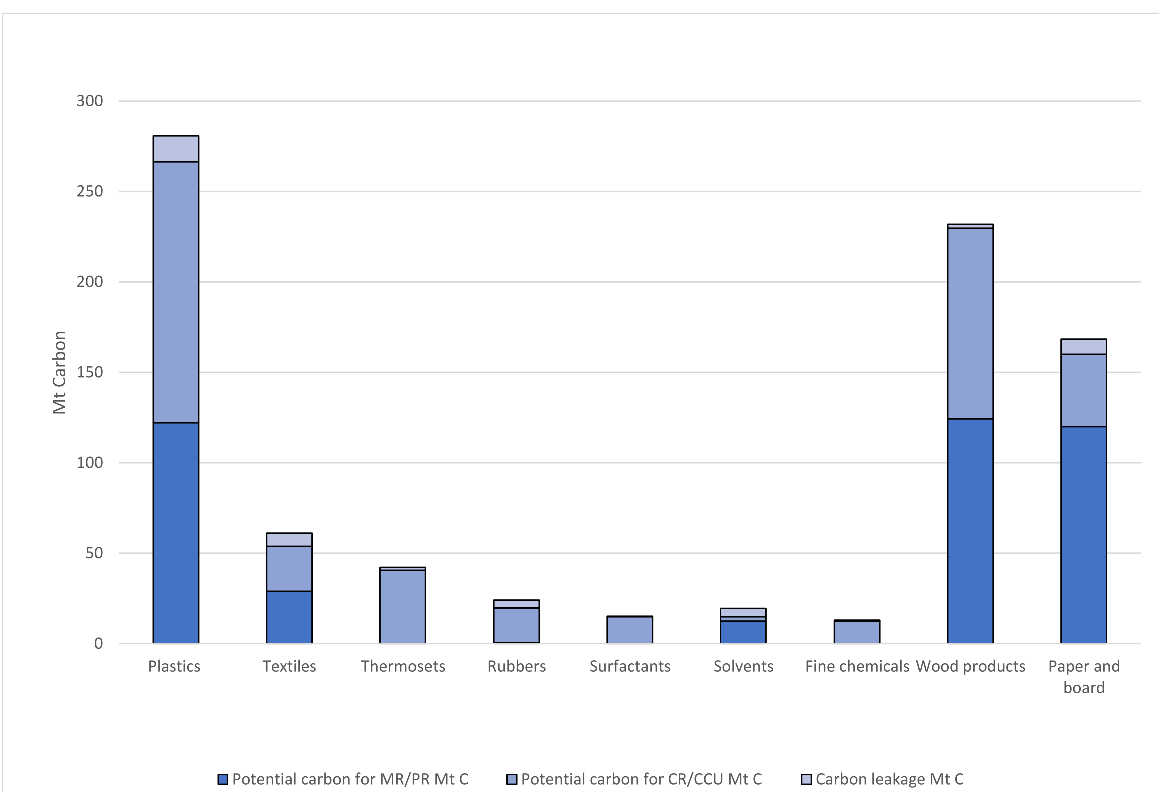

Fig. 2. The intrinsic recycling potential expressed in Mt C, through mechanical/physical methods, potentially collectable fraction for CR/CCU and inevitable carbon leakage of the 9 different categories of carbon-based materials and chemicals.

recyclability as large quantities of materials would have to be incinerated.

These issues relate directly to the products that the materials are used in and are not always easy and sometimes impossible to avoid. For reaching optimal recycling percentages, these issues need to be considered and tackled as much as possible. For instance, when making a choice for a certain material for a certain application (i.e. is a specific additive really necessary for the proper functioning of the material, or can it be left out), but also in case of designing and implementing collection and recovery systems.

Even if we assume that in the optimised system as assessed by our method no additional losses of mechanically/physically recycled materials take place, and that demand is unchanged every year, each year approximately 48 % of the carbon in all newly produced materials/chemicals may come from mechanical/physical recycling. When considering only the products that are presently fossil-based, this potential percentage is only 38%. For biomass based products it is 57%, a number positively influenced by the high recycling potential of paper and board (Table 10). It is interesting to find that (Kähler et al., 2023) using a different method also conclude that for the carbon embedded in chemicals and materials, only 55% may be sourced from recycled content. They expect that 25% of future chemicals and materials will be based on CCU and 20% on biomass.

CR or CCU technologies can be applied to 47 % of all carbon-based materials and chemicals. Most of these technologies have a conversion efficiency considerably lower than 100%. Furthermore, they do not produce the original materials or chemicals, as the mechanical/physical recycling methods do, but rather chemical building blocks or a mixture of chemical building blocks or just CO_2 that can be used to produce new materials or chemicals. Even though the data in Table 12 are a relatively rough estimate, a number of general points follow from this calculation.

One point to be addressed here is the difference in carbon recycling efficiency between the polycondensation polymers and the polyaddition polymers (Table 1). If more of our plastic products would be produced from polycondensation polymers rather than addition polymers (see also Table 2), the potential production of new building blocks via CR would increase considerably. This would be a plea to re-evaluate the specific types of polymer materials we use today. As we will argue below, also a switch from fossil feedstock to biomass feedstock would benefit from a change in the direction of using more polycondensation polymers.

The second point that needs to be addressed is that even though the pyrolysis (CR) process has a low efficiency in terms of recovery of the original building blocks, it still has the advantage over carbon capture for CCU technologies that the produced molecules are building blocks. If these same building blocks would need to be produced through CCU technology, they would require a significant amount of input in terms of energy and hydrogen. Therefore, at the present state of technology, if one has a choice, chemical recycling technologies would be the technologies of choice.

The final point is the carbon that gets lost; the last column in Table 12 presents the carbon that cannot be recovered through CR and CCU processes due to the expected process inefficiencies. This number is high, over 40% of the carbon that is deemed available for CR and CCU technologies is lost. Note that almost half of this carbon loss comes from plastics (the amount of carbon lost for plastics is even larger than the total carbon content in the market for textiles, thermosets, rubbers, surfactants, solvents and fine chemicals together). This loss adds up to the carbon that inevitably leaks from the system as estimated by the expert panel, presented in the last column of Table 10 (6% of the total carbon). This implies that even in an optimised system with collection and processing for mechanical, physical and chemical recycling, and carbon capture for CCU processes, approximately 25% of all the carbon embedded in the materials/chemical produced yearly cannot be made available from the materials/chemical pool but needs to come from virgin sources.

The only two virgin sources not based on fossil input are either biomass or CCU, in this case CCU processes based on direct air capture or other point sources than the ones addressed in our assessment. These technologies have different trade-offs: biomass production needs land and inputs such as fertilisers and water, CCU technologies have a high energy demand, high CAPEX, need hydrogen as important input and are preferably linked to CO_2 point sources. But not only on the production side, also on the application side there are large differences:

- Biomass contains, besides carbon, also oxygen and sometimes nitrogen atoms. Chemical building blocks with acid- and alcohol functionalities (for condensation polymers) can be efficiently produced from biomass. Biomass is also the only source of natural polymers like cellulose, starch, and natural materials like fibres (wool, cotton, linen), paper, board, leather and wood.
- Carbon Capture (CC) is regarded a robust carbon source, as requirements for input streams (wastes and residues) are limited. Once the CO2 is concentrated, it can be used as feedstock for CCU processes to make small molecules. These small molecules can then be converted into monomers (chemical building blocks) to produce both condensation and addition polymers and other chemicals. However, as with biomass, because CO2 is oxygen rich, the production of oxygen containing chemicals and building blocks is likely to be more energy efficient than the production of oxygen poor chemicals, for which CH_4 may be a better starting molecule.

When we exclude wood products and paper and board, 88% of the feedstock of our present carbon-based materials and chemicals comes from fossil oil. Polyolefins (e.g. PE, PP, PVC and PS) and also rubbers are mostly built up from carbon and hydrogen. It is these materials that are applied most, PE, PP, PVC and PS together make up 65% of all plastics presently in use, but also are relatively difficult to recycle and most difficult to produce from alternative sources. This may imply that we need to change our preferred materials in the future towards materials that contain more oxygen, such as using more polyesters and less polyolefins.

Finally, the use of materials is still expected to grow significantly in the future (nova Institut, 2023), and because the recycling percentages we present in this paper are the maximum reachable recycling percentages, this implies that also the pressure on the alternative sources for materials and chemicals, thus biomass and CCU, with their related trade-offs, will grow, which pleads for an awareness that we definitely will need to reduce our materials consumption by applying the other, higher, R-strategies, including refuse, rethink, reduce, reuse and repair, starting today (Rood and Kishna, 2019; Rijksoverheid Nederland, 2022).

5. Conclusions

It is clear from our investigation that the total pool of carbon-based materials and products is much bigger than the materials that are often discussed in light of the circular economy. Furthermore, our results show that only a limited amount of renewable carbon feedstock for new materials and chemicals can come from mechanical/physical recycling of the present materials, i.e. less than 50%, even if we assume a system fully optimised for recycling. Chemical Recycling (CR) and Carbon Capture and Utilisation (CCU) technologies may provide roughly another 25% of the renewable carbon feedstock needed, but require far more energy and other inputs to produce new materials and chemicals. The remaining demand needs to come from either biomass or CCU technologies based on other than recycled streams. However, the use of biomass and CCU technologies, both come with different trade-offs, and may not be able to efficiently produce the same materials that we use now, let alone be sufficient for the expected growth in demand.

A number of recommendations follow from our work. First comes the awareness that we cannot simply recycle ourselves out of the problems we created and that a re-evaluation of the way we use materials and chemicals is urgently needed. This means that we need to drastically reduce our material use, starting today. Further, that we need to redesign many of our materials on a fundamental molecular level towards material types that contain more oxygen, which are easier to produce from the alternative feedstocks biomass and CCU, and generally also more easy to recycle. We also need to work on further improving conditions and technologies for mechanical recycling, to reach the percentages presented as the maximum achievable in this paper. Furthermore, large scale and optimised CR technologies need to be developed and implemented, preferably focusing on the CR technologies for polycondensation polymers. Next, we need to optimise and implement technologies to funnel contaminated, degraded, complex or diluted end-of-life streams to C_1 building blocks for CCU technologies. And finally, we will need to (re)design all materials and products taking their end-of-service life into account in order to be able to also fulfil our materials demand in the future.

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CRediT authorship contribution statement

Harriëtte L. Bos: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Daan S. van Es:** Writing – review & editing, Methodology. **Paulien F.H. Harmsen:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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