RENEWABLE CARBON INITIATIVE
REPORT

RCI Carbon Flows Report:

Compilation of supply and demand of fossil and renewable carbon on a global and European level

Prepared by Ferdinand Kähler, Olaf Porc, Michael Carus
nova-Institut, www.nova-institute.eu
Funded by: Renewable Carbon Initiative

First edition, March 2023

Imprint

How to cite:

Kähler, F., Porc, O. and Carus, M. 2023. RCI Carbon Flows Report: Compilation of supply and demand of fossil and renewable carbon on a global and European level. Editor: Renewable Carbon Initiative, February 2023. Available at: www.renewable-carbon-initiative.com

Authors:

Ferdinand Kähler, nova-Institute, Expert LCA and Material Flow Analysis, ferdinand.kaehler@nova-institute.de

Olaf Porc, nova-Institute, Expert TEE and Renewable Feedstocks

Michael Carus, Executive Manager of RCI and Founder and CEO of nova-Institute

V.i.S.d.P. (responsible):

Michael Carus, nova-Institut GmbH, Hürth (Germany)

Acknowledgements

nova experts thank the Renewable Carbon Initiative (RCI) for the funding of this report.

Special thanks to all scientists providing feedback to the draft version of this report
(in the alphabetic order of companies/institutions):

- Manuela Koehler (Beiersdorf)
- Eric de Deckere, Bernard de Galembert (Cefic)
- Anastasios Perimenis (CO2Value Europe)
- Ilkka Hannula (IEA)
- Robert M'Barek, Patricia Gurria (JRC)
- Charlotte Delvaux de Fenffe (PlasticsEurope)
- Joel A Tickner, Aude M Bechu (UMASS Lowell)
- Harriëtte Bos (Wageningen University and Research)
- Jukka Kantola (WCBEF)

About this report

This report builds on the nova-Institute's long-standing work on biomass and carbon flows over the past 10 years and takes it to the next level. **The result is a comprehensive, detailed and updated carbon flow data basis that significantly surpasses previous publications**. All data have been corroborated as best as currently possible by scientific publications, feedback from experts and additional research. Remaining gaps and differences are transparently depicted and explained as well as possible.

If you have read previous reports on carbon flows and shares, you will find a number of **data in this new report that differ from previous publications** – ours or those of other authors. For example, the share of biomass in chemical feedstocks is lower than in previous publications.

The figures have changed mainly because nova experts were able to gain particularly **deep insights into the data** and because we consulted many experts and associations for their input and feedback – thankfully possible due to the financial budget of the Renewable Carbon Initiative (RCI).

One central aim was to generate **a data basis as uniform and transparent** as possible, so that it can then be used and shared by industry, associations and politicians alike.

This report is designed to be a **living document** that we would like to update every one to two years if possible. This also means that we look forward to your feedback, additional input, new data and suggestions from any interested party. Please directly contact the main author of the study for this: ferdinand.kaehler@nova-institut.de

RENEWABLE CARBON INITIATIVE

renewable-carbon-initiative.com

THE VISION OF RCI

The Renewable Carbon Initiative (RCI) addresses the main cause of anthropogenic climate change by facilitating the transition from fossil carbon to renewable carbon for all organic chemicals and materials.

Members of the RCI are pioneers who support the urgently needed acceleration and increase of volume of this transformation.

MEMBERS OF THE INITIATIVE

LARGE ENTERPRISES

ADM, Alfa Laval, ALPLA, BASF, Beiersdorf, Borealis, Braskem, Clariant, Cosun Beet Company, Covation Bio, Covestro, Dow, Evonik, Firmenich, Givaudan, Peter Greven, Henkel, H&R, iff, Kemira, Kuraray, Lenzing, Lubrizol, Mane, Neste, PCC SE, Reckitt, SCGC, SHV Energy, Stahl, Südzucker Group, Sulzer, Symrise, TÜV Austria, Uniper, UPM Biofore, Vaude, Verbio, Wacker

RENEWABLE CARBON INITIATIVE

Bio-based
CO_2-based
Recycling

... and more than
200 personal supporters

MEMBERS OF THE INITIATIVE

SME

START-UPS

RESEARCH INSTITUTES

PARTNERS OF THE INITIATIVE

Executive summary

RCI report: Carbon Flows – supply and demand of fossil and renewable carbon in the global and European economy

The new report provides a comprehensive understanding of today’s carbon flows and what it means to replace fossil carbon with renewable carbon in the materials and chemicals sectors

In the last five years, the mindset around carbon has changed fundamentally. Of course, there is no way around the fact that the rising concentration of carbon dioxide in the atmosphere pose an existential threat to life on Earth. But at the same time, carbon is the main component of our food, the basis of all organic chemicals and plastics, and the backbone of life on Earth.

When it comes to carbon, the focus has long been on achieving a zero-carbon, decarbonised energy system wherever possible to avoid CO_2 emissions. This is crucial and more urgent than ever to achieve net zero emissions by 2050. However, it is now becoming clear that other large volume sectors such as food and feed, but also all organic chemistry, plastics and significant parts of the materials sector are fundamentally and increasingly dependent on carbon. In the chemicals and plastics sectors in particular, almost 90% of the carbon used as feedstock is fossil carbon. This fossil carbon must be replaced by renewable carbon from recycling, biomass and CO_2 by 2050 to avoid a further influx of fossil carbon into our technosphere and atmosphere.

Policymakers today are talking about “sustainable carbon cycles”, “defossilisation” and above all “carbon management”: which sectors should be supplied by which carbon sources in the future? To answer such complex questions and develop realistic targets and strategies, a resilient and comprehensive data basis on the carbon flows of all sectors, both globally and in Europe, has been missing until now.

The Renewable Carbon Initiative (RCI) has commissioned a study from the nova-Institute to fill this gap as best as possible. It builds on the nova-Institute's long-standing work on biomass and carbon flows over the past 10 years and takes it to the next level. The result is a comprehensive, detailed and updated carbon flow data basis that significantly surpasses previous publications. All data have been corroborated as best as currently possible by scientific publications, feedback from experts and additional research. Remaining gaps and differences are transparently depicted and explained as well as possible.

The nova experts assessed data from a multitude of sources. A wide range of data on material flow are used to compile a comprehensive inventory of carbon stocks and flows. The sectors covered include all applications of organic carbon from fossil resources and biomass production, from raw materials through utilisation to final end-of-life. This includes use of carbon for feed and food, for materials, for energy and for fuels. A special focus is put on the carbon demand in the chemical and plastic industry

Executive summary

today and tomorrow, with several figures specifically zooming into this sector and including scenarios for a full defossilisation by 2050.

If you have read previous reports on carbon flows and shares, you will find a number of data in this new report that differ from previous publications – ours or those of other authors. For example, the share of biomass in chemical feedstocks is lower than in previous publications. The figures have changed mainly because nova experts were able to gain particularly deep insights into the data and because we consulted many experts and associations for their input and feedback – thankfully possible due to the financial budget of the Renewable Carbon Initiative (RCI). One central aim was to generate a data basis as uniform and transparent as possible, so that it can then be used and shared by industry, associations and politicians alike.

The Carbon Flows report is designed to be a living document that we would like to update every one to two years if possible. This also means that we look forward to your feedback, additional input, new data and suggestions from any interested party. Please directly contact the main author of the study for this: ferdinand.kaehler@nova-institut.de

The report contains in total 80 pages with more than 35 graphics and tables plus corresponding descriptions of methodology, source material and data as well as five pages of literature sources. The format of the report allows to easily present the graphics to any audience.

The RCI commissioned a study from nova-Institute to compile a comprehensive inventory of carbon stocks and flows. All sources of organic carbon used in economic activities and all sectors where resources containing organic carbon are used are covered. The sources of carbon include the fossil resources, oil, gas and coal, as well as renewable carbon sources, namely biomass, recycling and CO_2, where already in use. The report determines the share of fossil carbon at 63%, while biomass contributes 35% and recycling 2% to the entire global supply of organic carbon. In Europe, the fossil share is even higher with 67%. Sectors that rely on organic carbon include food and feed, the material and chemical sector and energy and transport. The report presents material flow data for all these manifold sectors and determines the corresponding flows of carbon.

Carbon can be used in fundamentally different ways. On the one hand, it is used as energy carrier where the energy stored in the molecules of hydrocarbons is released in combustion processes for power generation or for transport. On the other hand, there are applications where carbon is embedded in the final product as a fundamental part. These include food and feed as well as the material and chemical sectors, where hydrocarbons are used or converted to form often complex chemical molecules. The material sector includes wood for construction and furniture, paper, cotton for textiles, and fossil and renewable carbon for a wide range of chemicals and plastics.

While the energy and transport sector can and should be decarbonised using renewable energy, electrification and hydrogen, carbon cannot be replaced in food and material applications. The material sector can only be defossilised, meaning a shift from fossil to renewable carbon sources. In the report, the renewable carbon share of

Executive summary

carbon embedded in materials and chemicals is calculated to a remarkably high figure of 48% (37% from primary biomass, 11% from recycling) at world level and 44% at the European level (see figure 1 & 2). The material use of renewable carbon is dominated by wood for construction and furniture as well as pulp and paper.

These two sectors are large and consume significant amounts of carbon in form of primary biomass but also non-negligible shares of recycled bio-based products.

On the other hand, the chemical industry uses only small shares of biogenic carbon and carbon from recycling (6 and 3% globally and 4 and 3% in the EU).

Zooming in on the chemical industry, it still strongly depends on fossil carbon as raw material feedstock with more than 90% fossil carbon share, both globally and in the EU. When compared to other statistics, this figure is surprisingly high, but in the RCI's report the heavy oil fraction (mainly bitumen) is included for the first time – an application sector exclusively consuming fossil carbon so far.

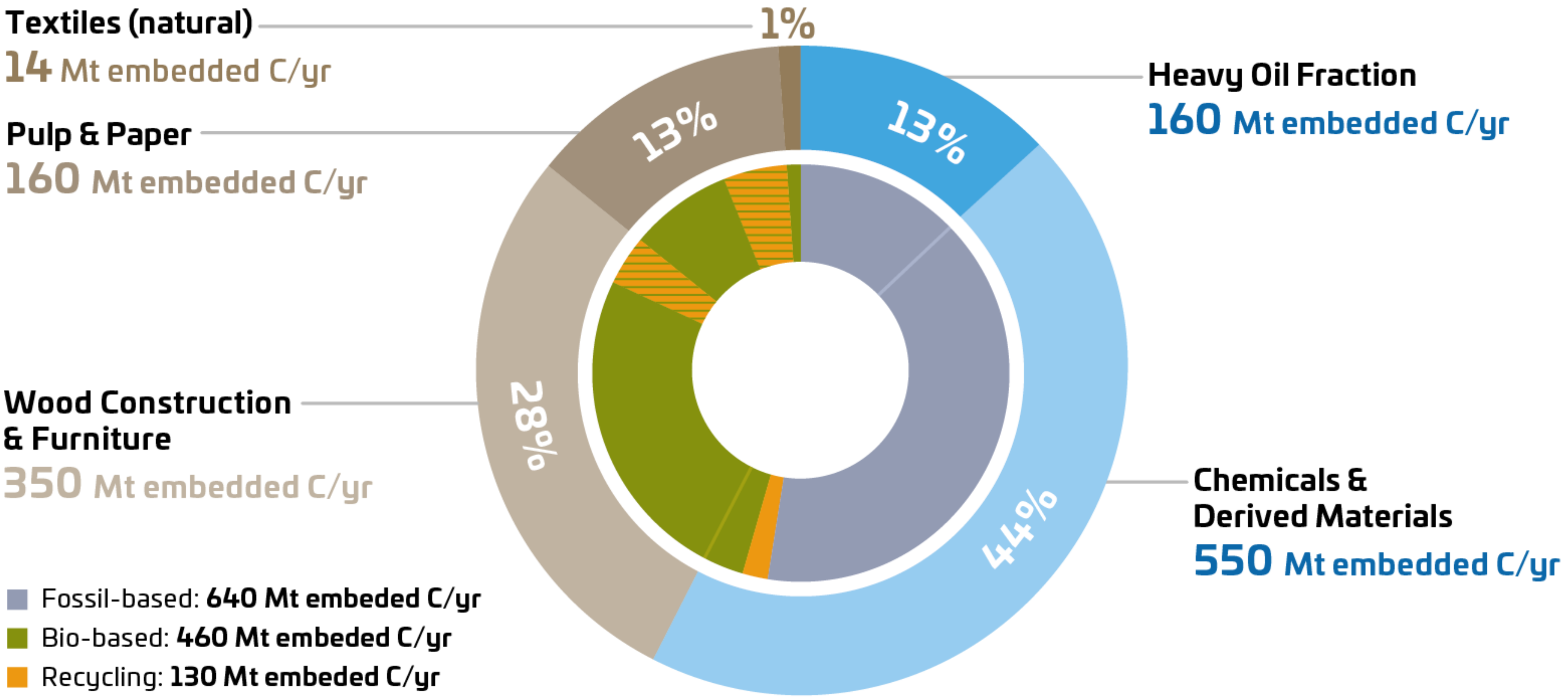
In the report, comprehensive depictions of current supply of carbon are drawn. An in-depth analysis is carried out for the chemical sector. Next to the carbon contained in energy carriers that is used in the chemical industry, an additional annual demand of 710 megatons of carbon (Mt C) is embedded in feedstock used for material purposes. The sub-sector of chemicals and derived materials currently uses 88% fossil feedstock.

From this point, the authors outline an explorative scenario for 2050 that considers a growing demand due to rising consumption of chemicals and plastics and rising demand for road infrastructure on the one hand. On the other hand, the scenario is based on a complete phase-out of fossil feedstock and a shift to renewable sources of carbon. For chemicals and derived materials, a share of 55% is assumed based on ambitious exploitation of both mechanical and advanced recycling. But recycling alone cannot completely close the carbon cycle, additional carbon must be fed into the circular carbon flow. In the explorative scenario, biomass is required to meet the demand for chemicals and derived materials but the share is limited to 20% due to constrained limited availability of agricultural and forestry areas as well as biodiversity loss. The remaining share of 25% is provided by Carbon Capture and Utilisation (CCU) technologies, using CO_2 emissions from fossil and biogenic point sources and direct air capture.

The collected data emphasise the dependence of the energy and transport sector on fossil sources of carbon. Furthermore, the data can be used as a basis for the material sector to phase out fossil carbon, a process referred to as defossilisation. The information can set the basis to shape the future distribution of renewable carbon sources for the feed and food, material and chemical and energy and transport sectors: a comprehensive carbon management across all sectors.

Global Demand for Carbon Embedded in Materials and Chemicals

Total: **1200 Mt embedded C/yr** Reference Years: **2015–2022**

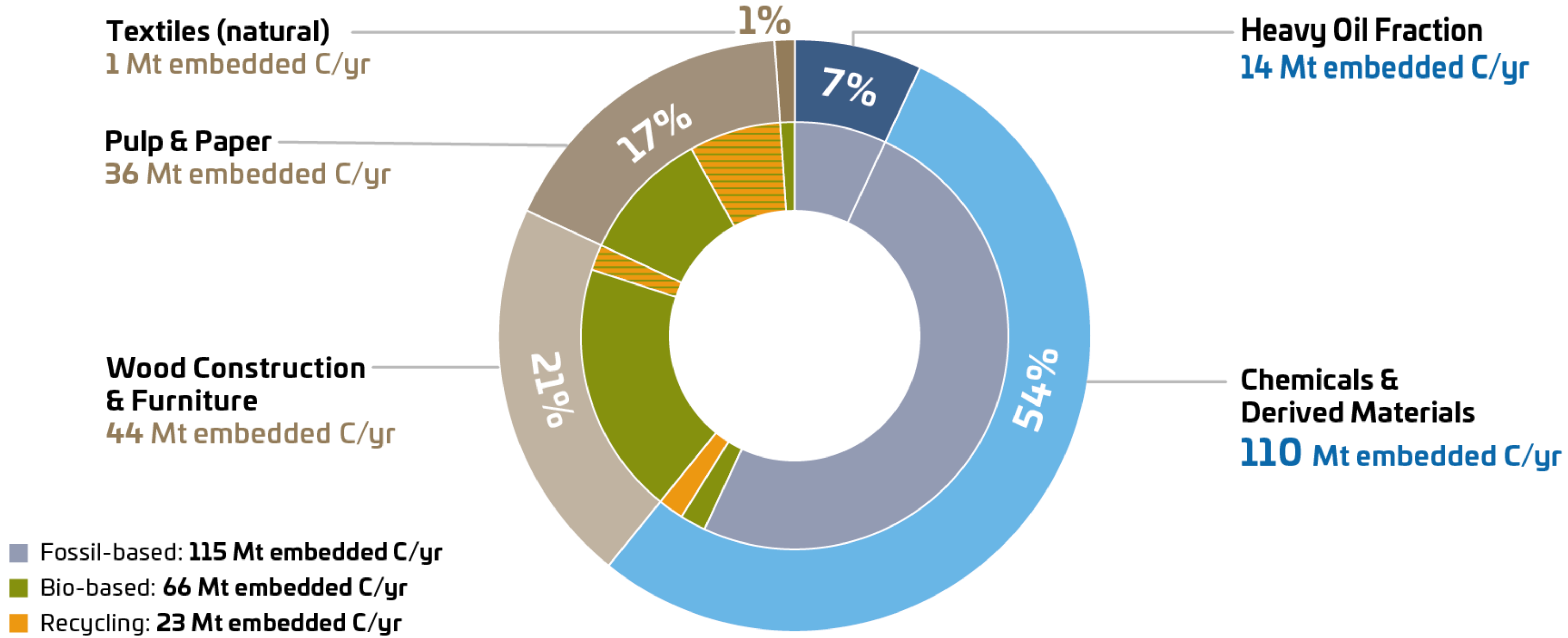


available at www.renewable-carbon.eu/graphics

Main Sources: updated data using methodology based on Piotrowski et al. 2015, Levi and Cullen 2018, Plastics Europe 2022b, Skoczinski et al. 2022, FAO Global Forest Resource Assessment 2020

EU-27 Demand for Embedded Carbon in Materials and Chemicals

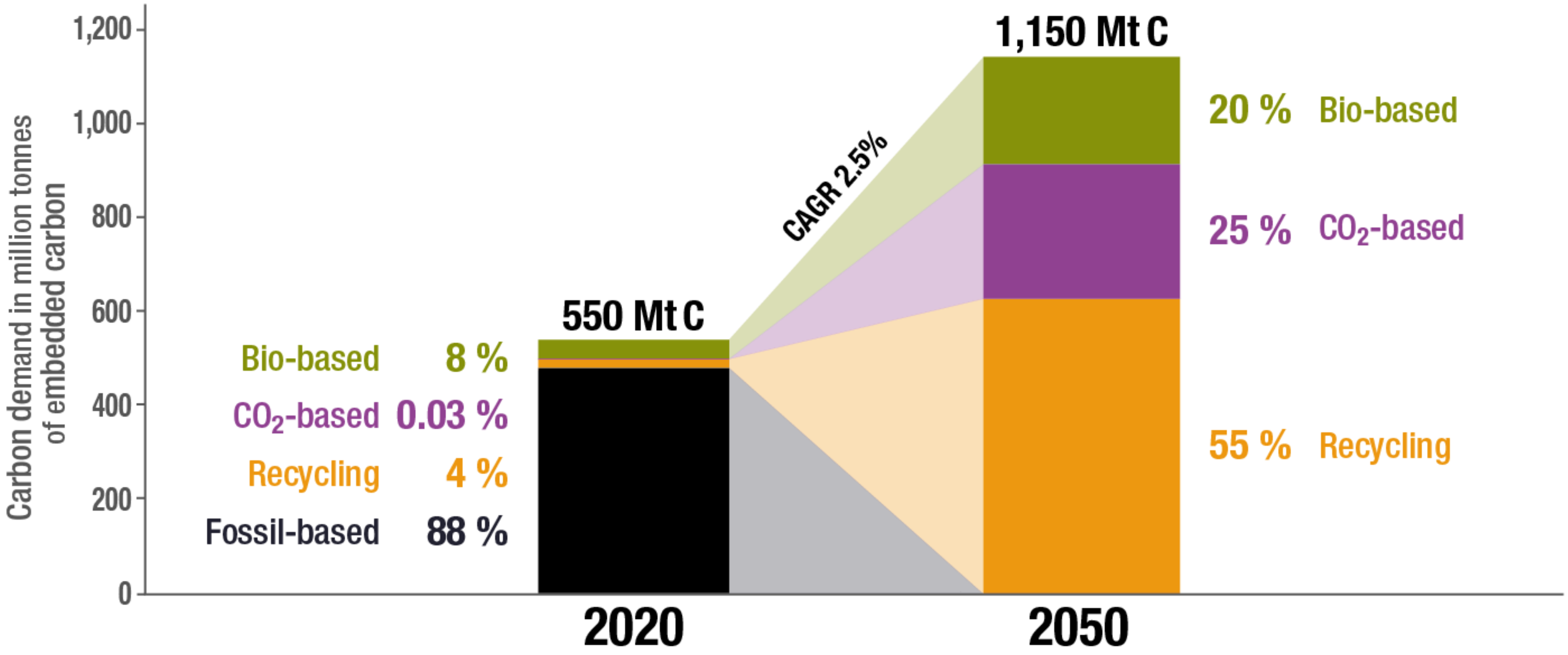
by Sectors; Total: **200 Mt embedded C/yr** Reference Years: **2018–2021**



Main sources: Own data based on Eurostat prodcom 2022, NACE class C20.1, Eurostat energy balance 2018, JRC biomass flows 2020, Mantau 2012, CEPI 2020, Plastics Europe 2022

available at www.renewable-carbon.eu/graphics

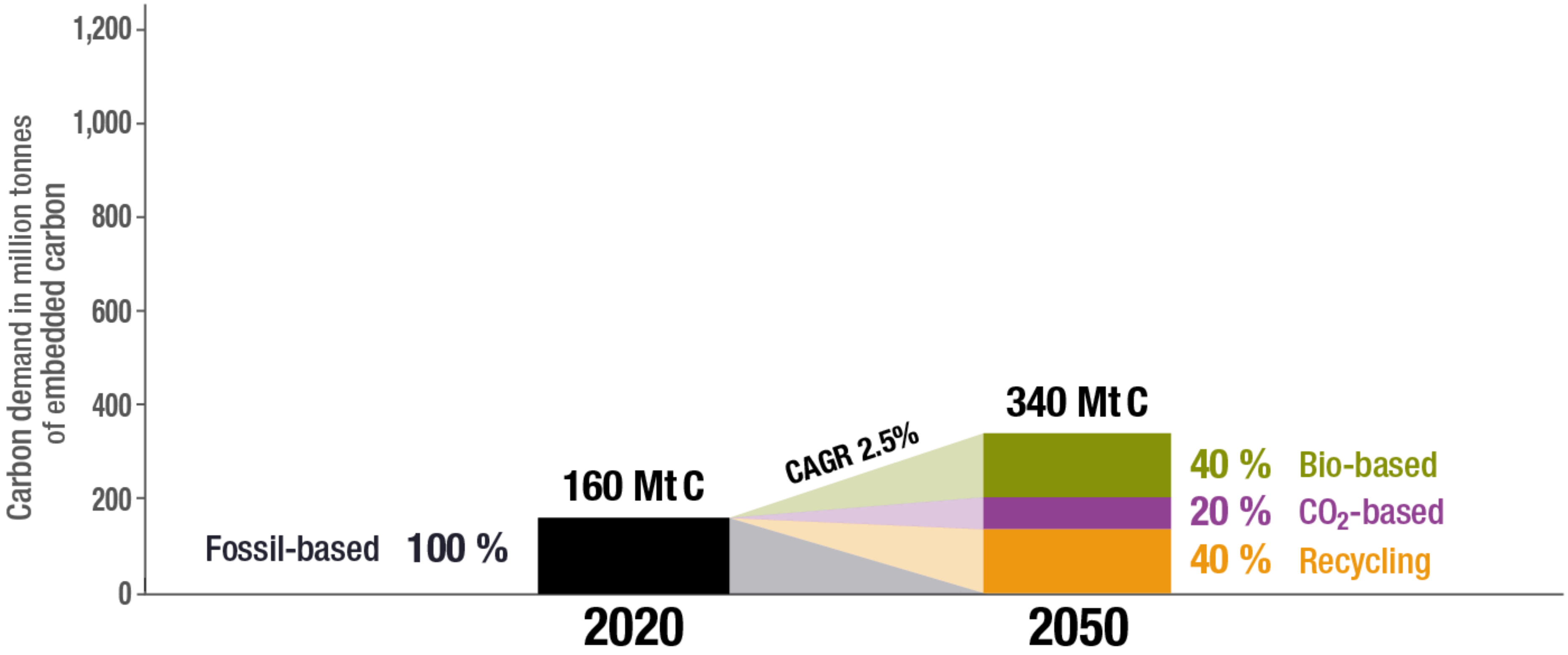
Carbon Embedded in Chemicals and Derived Materials



available at www.renewable-carbon.eu/graphics

Carbon Embedded in the Heavy Oil Fraction

(Bitumen, Lubricants, Paraffin Waxes)



available at www.renewable-carbon.eu/graphics

Content of this presentation

1. Aim and method

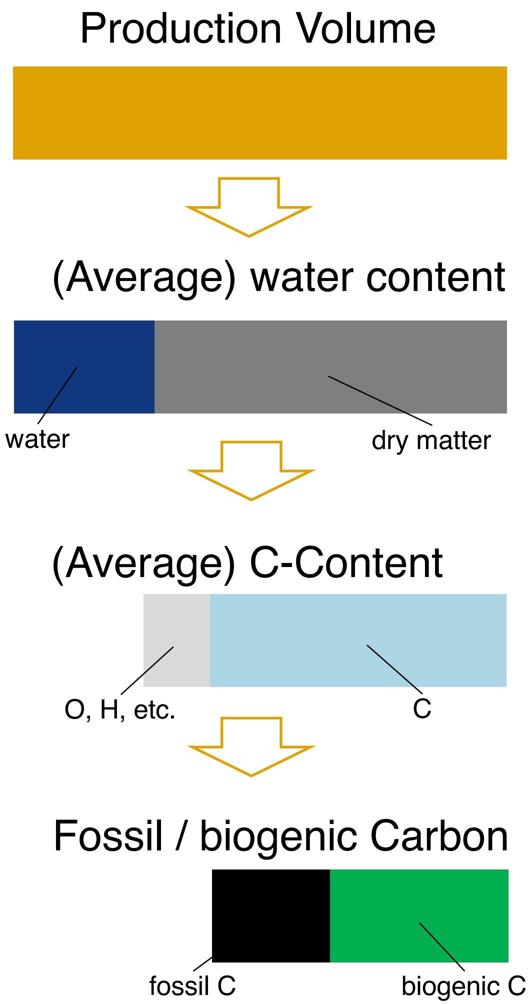
Aim and outlook

- The aim of this report is to compile a comprehensive picture of current use of carbon in the global and EU economy – as a result, this report provides **a solid, reliable data basis in regards to the resource carbon**.
- In order to achieve this, the carbon flows were **shared and discussed with several other organisations and research institutes**, including CEFIC, IEA, JRC, CVE, Plastics Europe, WCBEF, Wageningen University and UMASS Lowell.
- This data basis can now be used as a **foundation for well-rounded conclusions and the establishment of a proper future carbon management**.
- Additionally, **the data basis can be used to develop and state recommendations**, e.g. on defossilisation of the energy sector and renewable carbon supply for the chemical and material sector.

Method

- The focus of this report is the consumption of carbon, not the related emissions.
- The method is based on existing **material flow analyses and energy balances**.
- Using these existing analyses and balances, we apply **conversion factors to derive carbon flows**.
- **Smaller data gaps** are filled with own estimations and assumptions, where necessary.
- **Larger data gaps** are highlighted and open for discussion.

General method to determine carbon flows



- Production volume / Energy balances
  - Energy statistics, Biomass supply and demand (Piotrowski et al. 2015), Waste statistics
- Average water content
- Average C-Content
  - Chemicals: Molecular structure, composition
  - Biomass: Constituents (Starch, Cellulose, etc.)
- Separate collection of fossil, recycled, biogenic carbon if available
  - Estimation where feasible

Collection of carbon shares (selection)

Conversion of non-mass units

From	to	factor
Mtoe	TJ	41868 (IEA 2016)
Mtoe coal	Mt C	1.21 (own calculation based on production volume-weighted average)
Million barrel crude oil	Mt C	0.1166 (own calculation)
m^3 wood products	t wood products	1.674 (Mantau 2012)
m^3 paper products	t paper products	3.615 (Mantau 2012)

Materials, products, waste

Substance	C content	Comment
Polypropylene	85.7 %	Molecular structure
MTBE	68.2 %	Molecular structure
Plastics (unspecified)	71.2 %	Production volume-weighted average
Wood products	44 %	Phyllis2 database
Paper products	47 %	Phyllis2 database
Food waste (wet)	20 %	Phyllis2 database

Fossils

Substance	C content	Comment
Natural Gas	73.0 %	Composition-weighted average
Petroleum	85.5 %	Krist 2013
Coal	74.7 %	Production volume-weighted average

Biomass, Biofuels

Substance	C content	Comment
Cellulose in biomass	44.4 %	Phyllis2 database
Sugar in biomass	42.1 %	Molecular structure
Protein in biomass	55.7 %	Phyllis2 database
Fat in biomass	76 %	Phyllis2 database
Biomass unspecified (dm)	47.5 %	FAO 2020
Fish (dm)	45 %	Czamanski et al. 2011
Fish (wet)	11.9 %	Czamanski et al. 2011
Biodiesel	76.2 %	Kent et al. 2012
Renewable Diesel	84.9 %	Kent et al. 2012
Ethanol	52.2 %	Molecular structure

Definitions of demand along the value chain

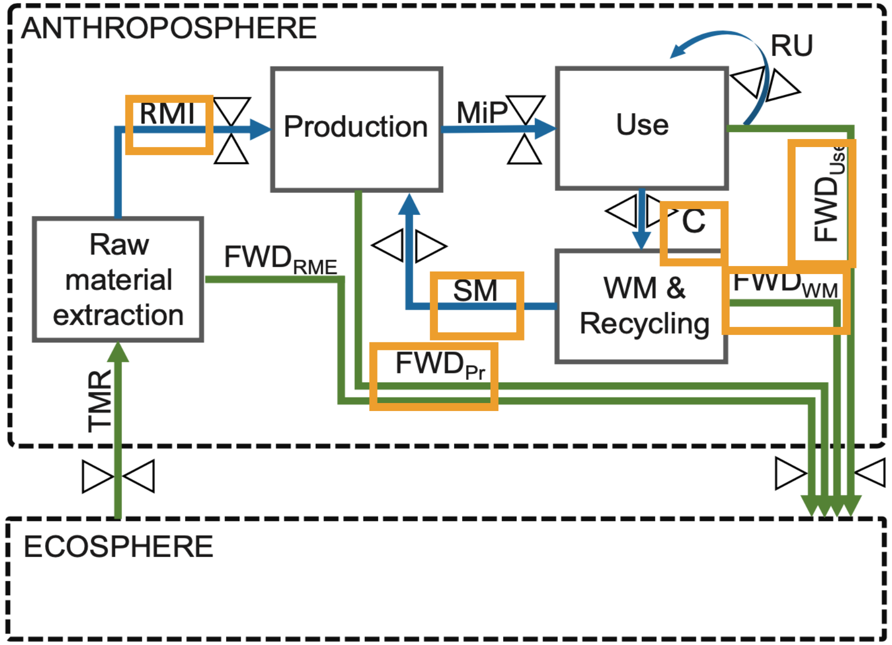
- Across the value chain, material flows are transformed (chemical / physical / mechanical / energetic transformation, change in water content, transformation of intermediates, occurring of losses or wastes).

- The focus of this report is the demand of industrial sectors. Where not stated differently, this includes losses occurring in the sector.

Denotation of flows, according to Helander et al. 2019

→ Preferred scope of this study, when data availability allows:

- Supply and demand per sector: Raw material input and secondary materials, NOT materials in product
- End of Life: Materials collected for Recycling and Final waste disposal from processing

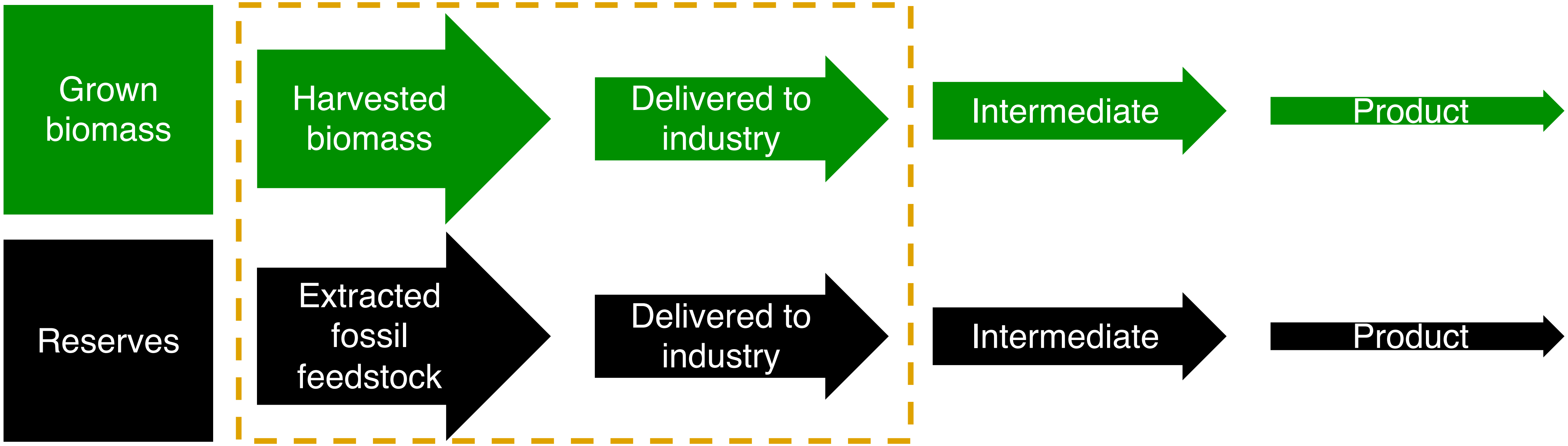


- **C, materials collected for recycling;**
- FWD_{Pr}, FWD from production;
- FWD_{RME}, final waste disposal from raw material extraction;
- FWD_{Use}, FWD from the use phase;
- FWD_{WM}, FWD from waste management and recycling;
- MiP, materials in product;
- **RMI, raw material input;**
- RU, reuse (redistribution for reuse or refurbishment);
- **SM, secondary materials;**
- TMR, total material requirement
- **Final waste disposal from processing ($FWD_{Pr} + FWD_{Use} + FWD_{WM}$)**
- Final waste disposal ($FWD_{Pr} + FWD_{Use}\ FWD_{WM} + FWD_{RME}$)

Definitions of demand along the value chain

Levels of demand along the value chain (based on Helander et al. 2019)

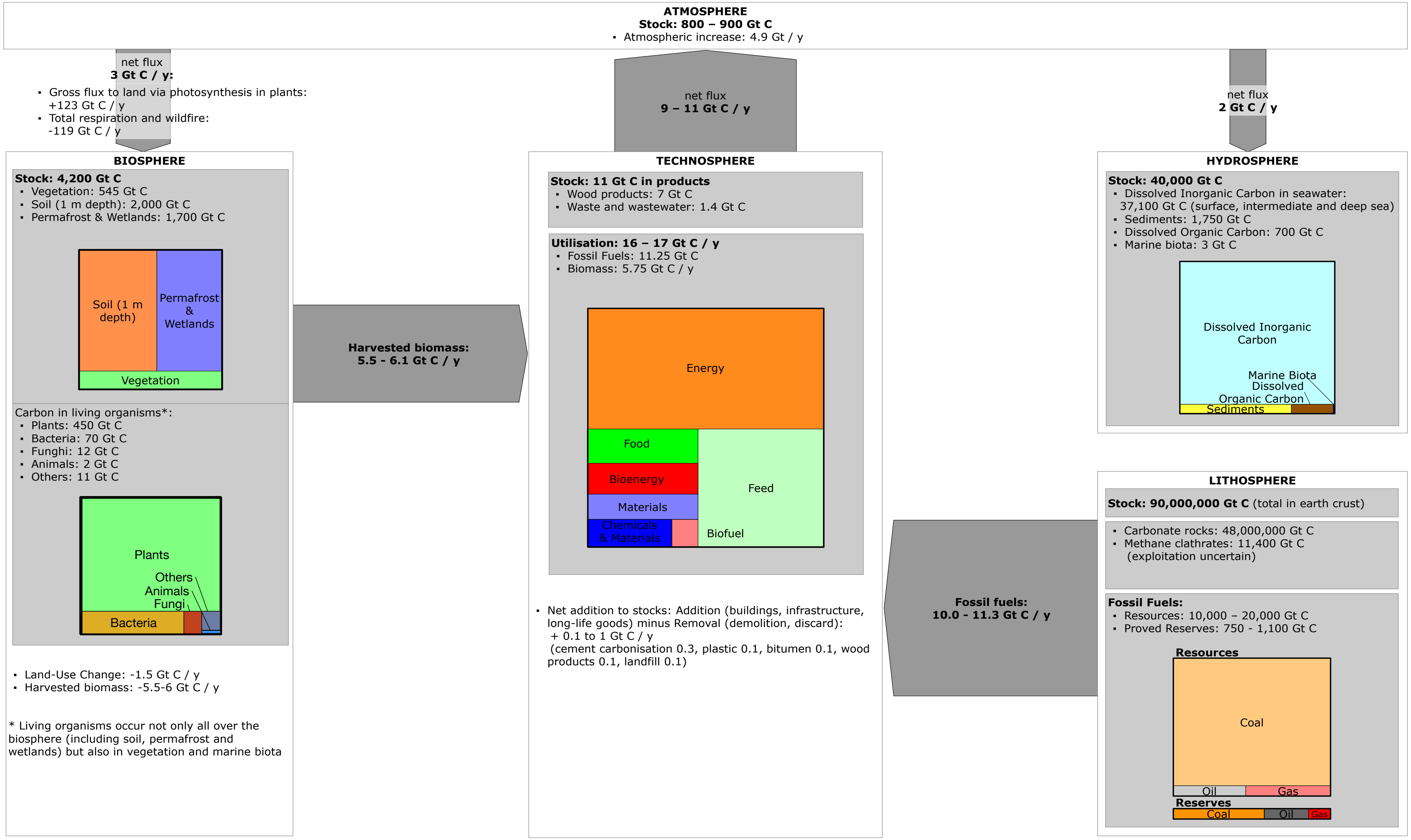
n.a.	Total material requirement	Raw material input + Secondary materials	n.a.	Materials in Product



Main focus of this study

2. Global natural and anthropogenic carbon flows

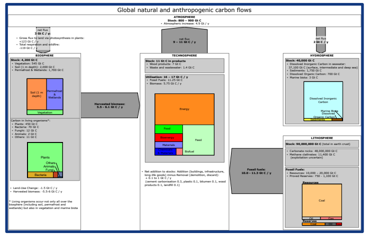
Global natural and anthropogenic carbon flows



Natural Flows: Natural Flows: Ciais et al. 2014, Hepburn et al. 2019, Bar-On et al. 2018, Janowiak et al. 2017, Ajani et al. 2013
Technosphere: BP Statistical Review 2019, BGR 2019, IEA 2020, Piotrowski et al. 2015, Haas et al. 2015, Friedlingstein et al. 2019

Global natural and anthropogenic carbon flows

- The subject of has been assessed by Ciais et al. 2014, Hepburn et al. 2019 and others. This figure provides a summary of flows between the major spheres (atmosphere, biosphere, hydrosphere, lithosphere, and technosphere) together with important insights into the stocks within the spheres.
- The anthropogenic carbon cycle is tiny compared to the natural carbon cycle. Yet, anthropogenic changes are enough to disrupt the natural carbon cycle.



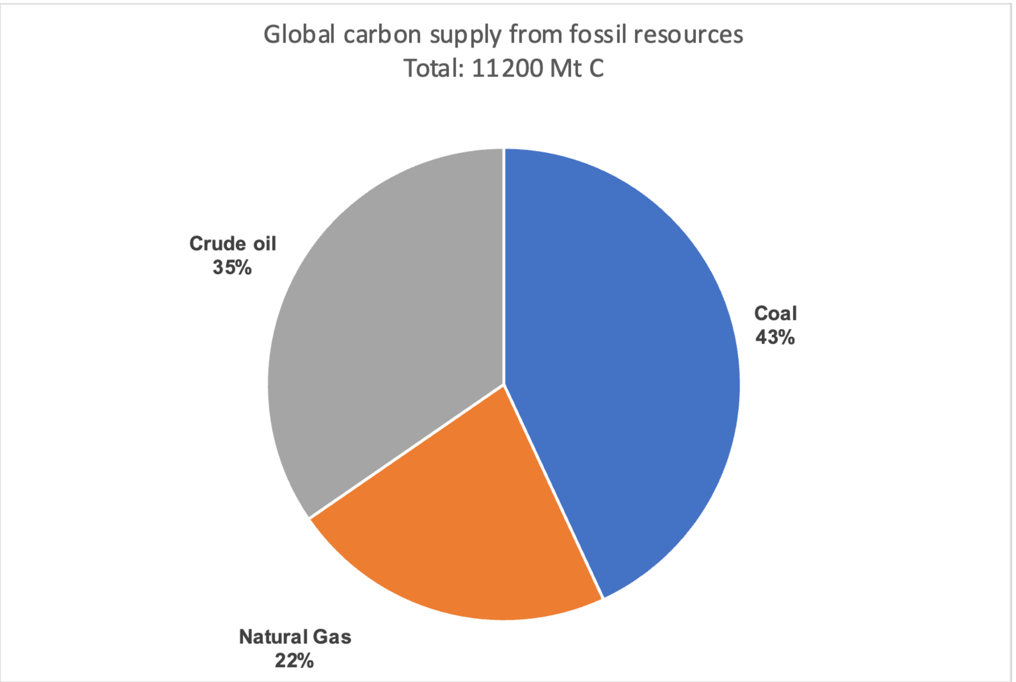
- The relevance of the information chosen to be summarised here is subjective. Some flows, that could be evaluated important are shown, some are left out:
  - E.g., flows from technosphere to biosphere (e.g., organic fertilisers) are not shown
  - E.g., new research results on dead plankton sequestering 12 Gt C / y, see Dominguez-Huerta et al. 2022
- The boundaries between the spheres is blurry. Some streams could be accounted to several spheres
  - E.g., marine biota shown in the hydrosphere also belong to plants and animals of the biosphere
- The in- and outflows of a sphere do not always add up. Since several sources where used, this must not mean that the stock increases or decreases accordingly. If information on stock was available, it is stated explicitly.

3. Carbon flows in the global economy

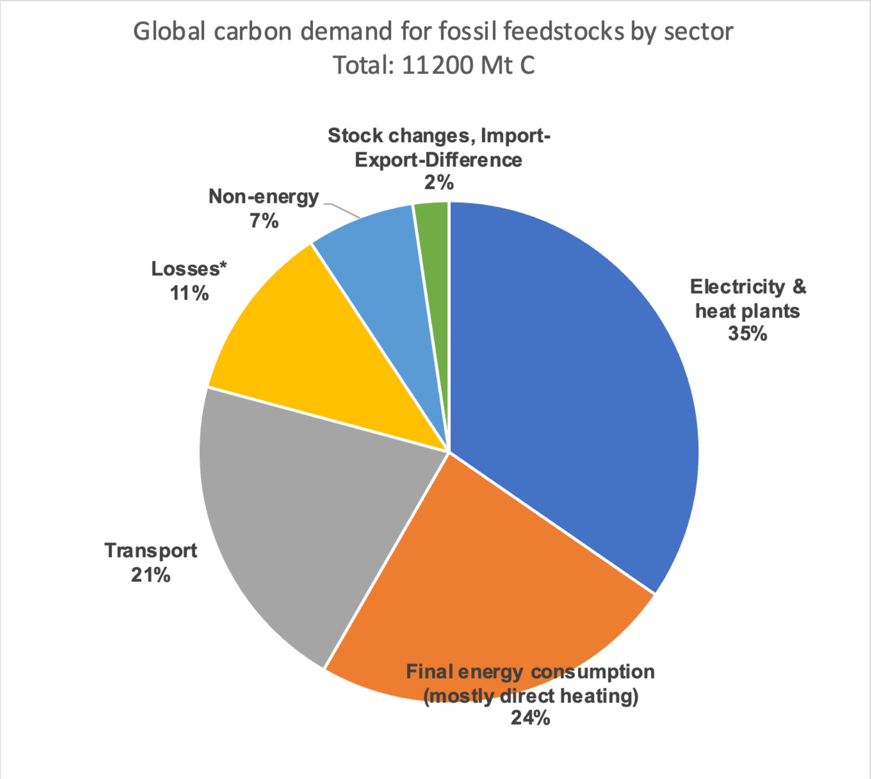
Carbon flows in the global economy

- Fossil and biogenic carbon flows are determined separately.
- Fossil flows:
  - Based on IEA Energy Balances 2019
  - Converted to C
  - Losses are used from IEA Energy Balances 2019 and estimated where not available (based on average efficiencies of combustion, etc.)
- Biogenic flows:
  - IEA Energy Balances cover the category “Biofuels and waste”, however, not further disaggregated.
  - Hence, a new methodology based on Piotrowski et al. 2015 is introduced with updated data.
- Waste statistics and information on recycled material is added.
- A comprehensive Sankey diagram with C flows is compiled.

Global fossil carbon supply and demand

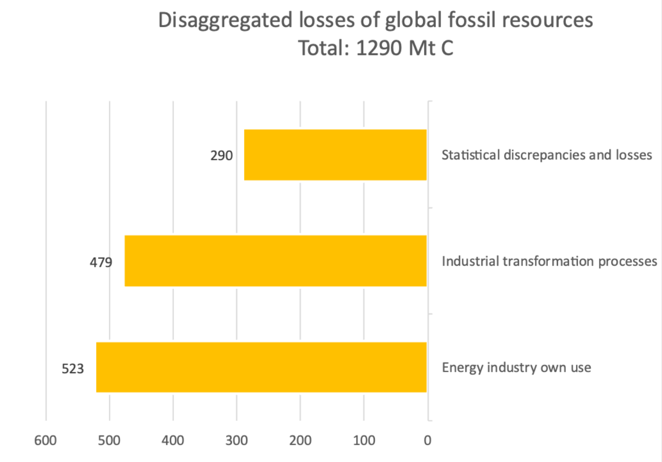


IEA Energy Balances 2019

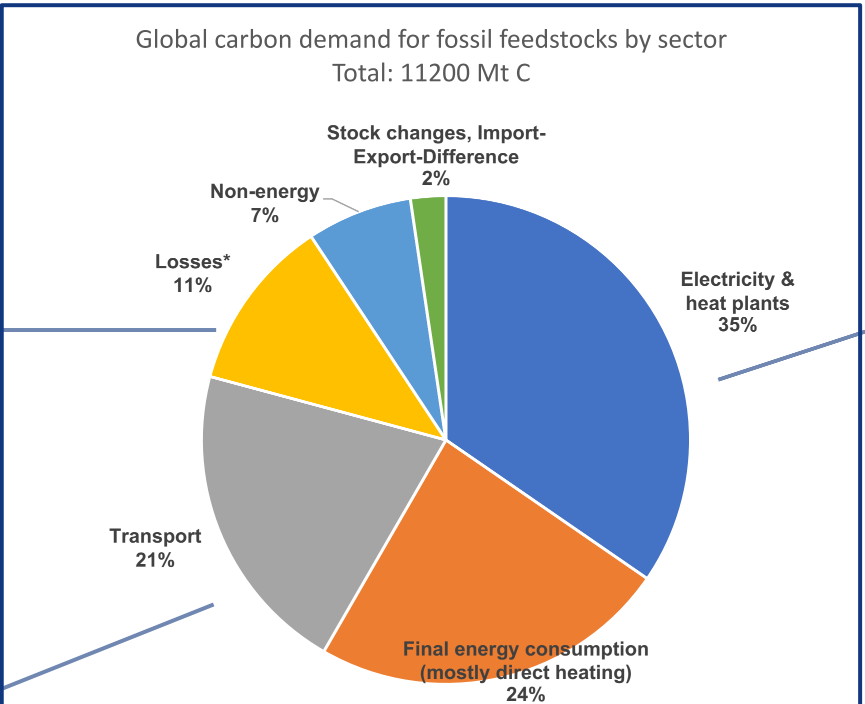


IEA Energy Balances 2019

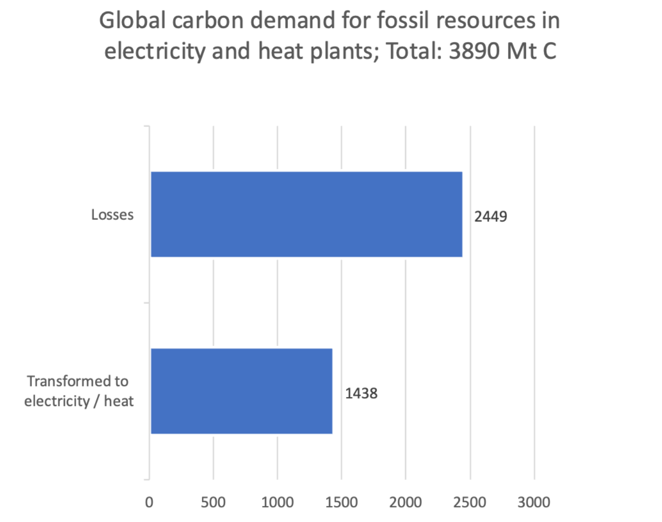
RENEWABLE CARBON INITIATIVE

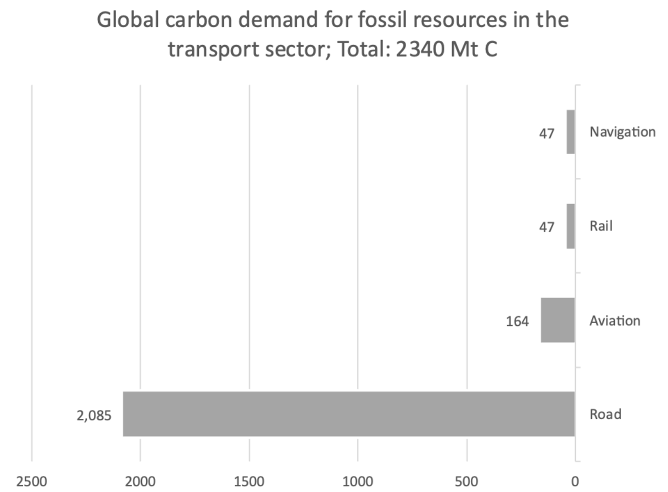


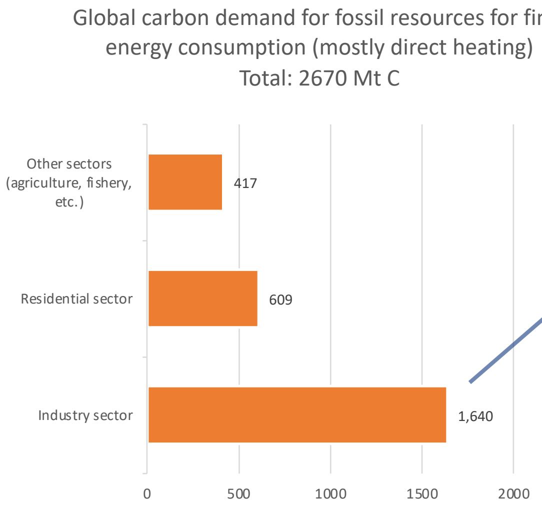
In addition, losses occur in end-use applications: in transport (e.g., vehicle engines) and electricity and heat plants (e.g., turbines)

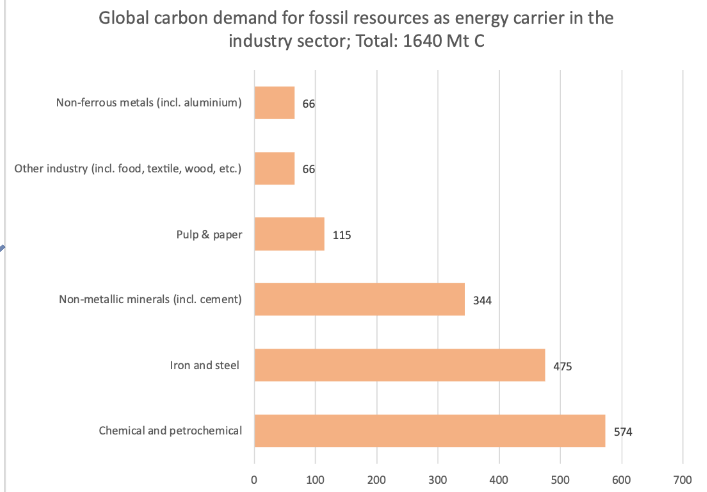


* includes statistical differences, energy industry own use and losses in industrial transformation processes. Additional losses occur in end-use, e.g., fossil power plants or vehicle engines

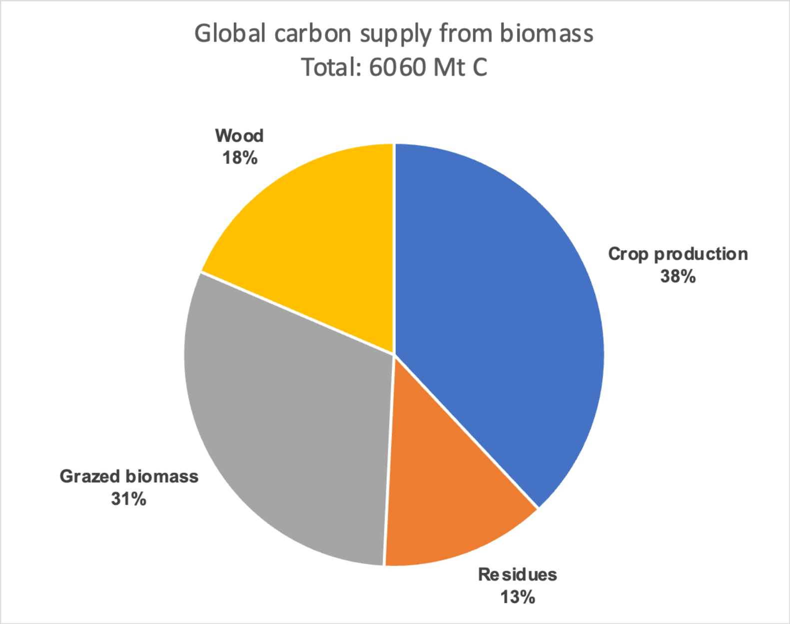


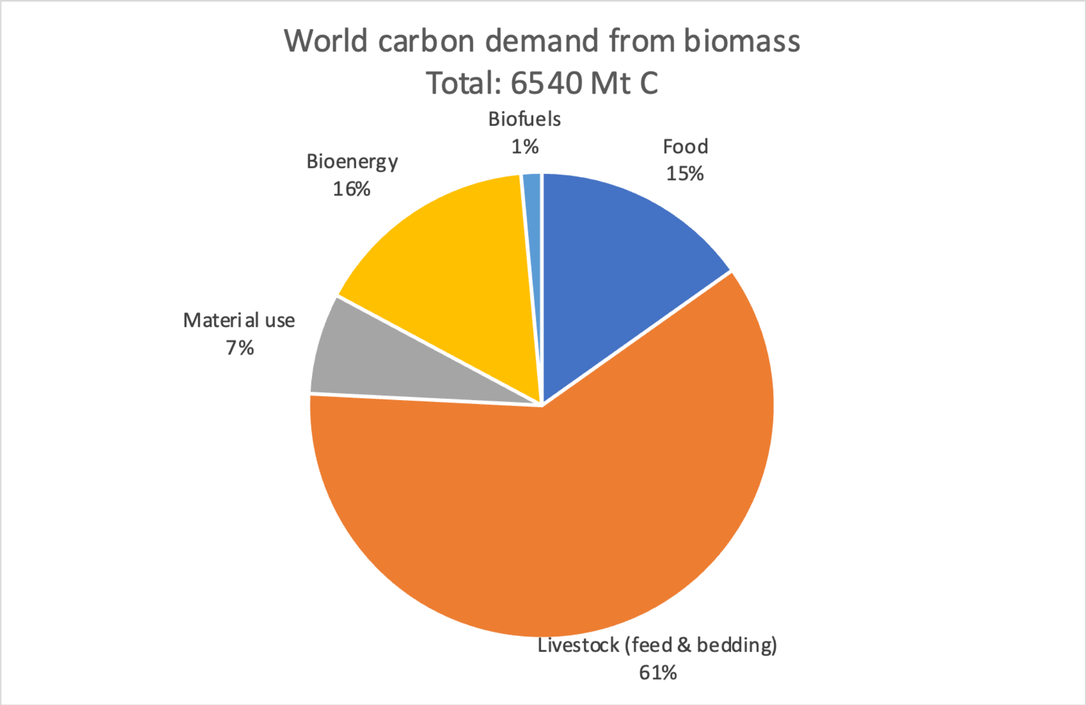






Global bio-based carbon supply and demand





nova-Institute 2023, based on Piotrowski et al. 2015, updated data. Reference years: 2018–2020

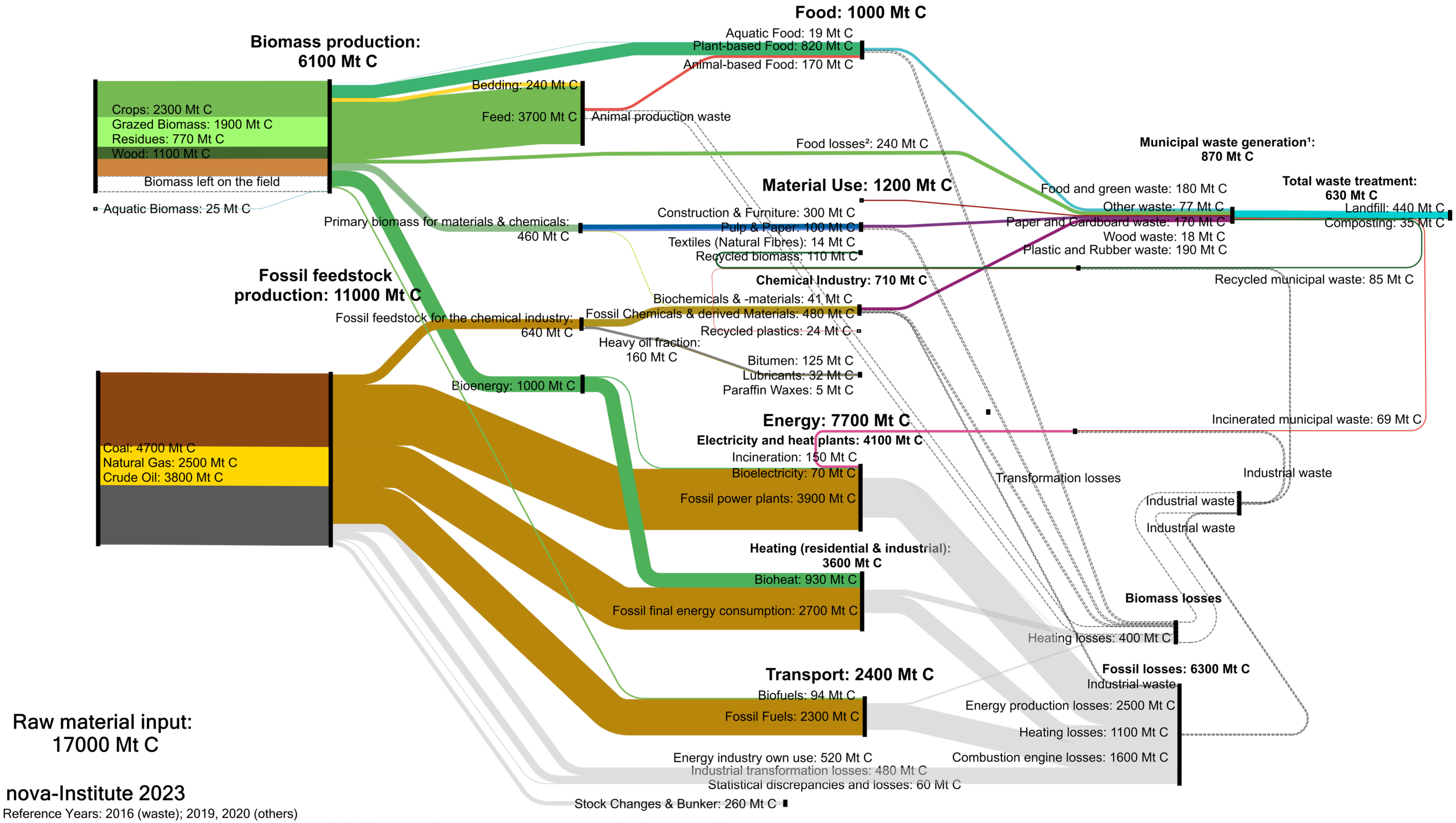
nova-Institute 2023, based on Piotrowski et al. 2015, updated data Reference years: 2018–2020

Difference in supply and demand figures due to statistical discrepancies

Biomass losses

- For fossil feedstock, IEA Energy Balances include several types of losses (e.g., energy industry own uses). Other losses have been estimated by nova-Institute (e.g., losses in fossil combustion car engines).
- For biomass, no comparable source of losses is available. Therefore, these figures are not yet included in the graphs presented here.
- Bos & Broeze 2020 report the following losses:
  - Grazed Biomass: Losses of biomass from meadows and pastures exceed their usage by more than double
  - Crops: Biomass losses from crops (burned, aboveground and belowground) exceed their utilization by 20%
  - Forestry: Felling losses are around 30 % the amount of used wood
  - Livestock production: Manure output is 18 times higher than animal-based food output (C in manure is widely used as fertiliser)

Flows of organic carbon in the global economy



nova-Institute 2023

Reference Years: 2016 (waste); 2019, 2020 (others)

Main sources: Own data based on IEA Energy Balances, FAO 2022, Levi & Cullen 2018, Kähler et al. 2021, The Fiber Year 2022, World Bank 2018; Updated data using methodology based on Piotrowski et al. 2015

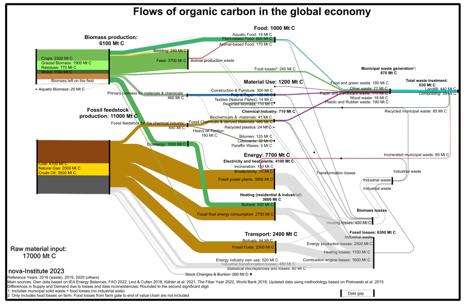
Differences in Supply and Demand due to losses and data inconsistencies. Rounded to the second significant digit.

1: Includes municipal solid waste + food losses (no industrial wate)

2: Only includes food losses on farm. Food losses from farm gate to end of value chain are not included

Flows of organic carbon in the global economy

- Fossil C flows are predominantly derived from IEA Energy Balances, biogenic C flows from nova-Institute's own data using methodology based on Piotrowski et al. 2015, with updated data. Several other sector-specific sources where used.
- Use of carbon-based feedstock can be separated between food, material use, energy, and transport.
- The material use presented in the graph only includes the carbon embedded in the materials. For example, the 710 Mt C stated for the chemical industry is only the carbon in fossil and biogenic feedstock. Additionally, the chemical industry uses energy, which is accounted for in the section of Electricity and heat plants. The same applies for other sectors, e.g., material and energetic use of carbon in the paper industry.
- Data gaps remain in the following sectors:
  - Biomass left on the field
  - Losses and waste (see next slide)



Challenges in data for global waste

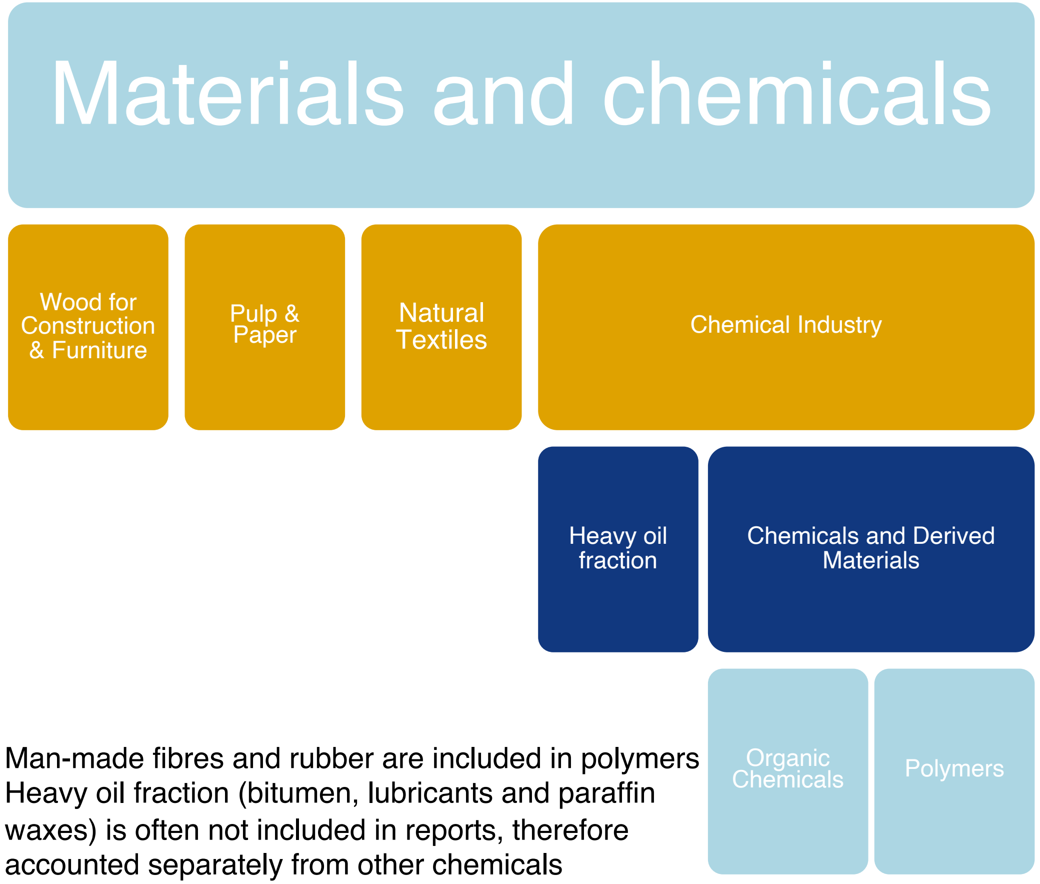
- For the determination of carbon in global waste streams, comprehensive data are necessary that specify the types of streams (e.g., plastics, wood waste, biowaste, etc.).
- Such comprehensive data is provided by World Bank 2018, however, this only includes municipal solid waste (MSW).
- Comprehensive data for all waste types and sources – including process / industrial waste – is missing.
  - For example, wood waste is only 2 % of MSW or 40 Mt (18 Mt C). In contrast, all end-of-life options for wood products combined result in 300 Mt C*
    Food losses and waste: Data for food waste are covered by World Bank 2018. In addition, data for food losses at farm level were retrieved from UNEP 2021.
  - A data gap remains for food losses between farm and retail
- Another data gap remains for carbon flows into wastewater (e.g., manure, municipal wastewater, excrements. detergents, etc.).

(* see separate slide for Flows of organic carbon in the global material and chemical sector below)

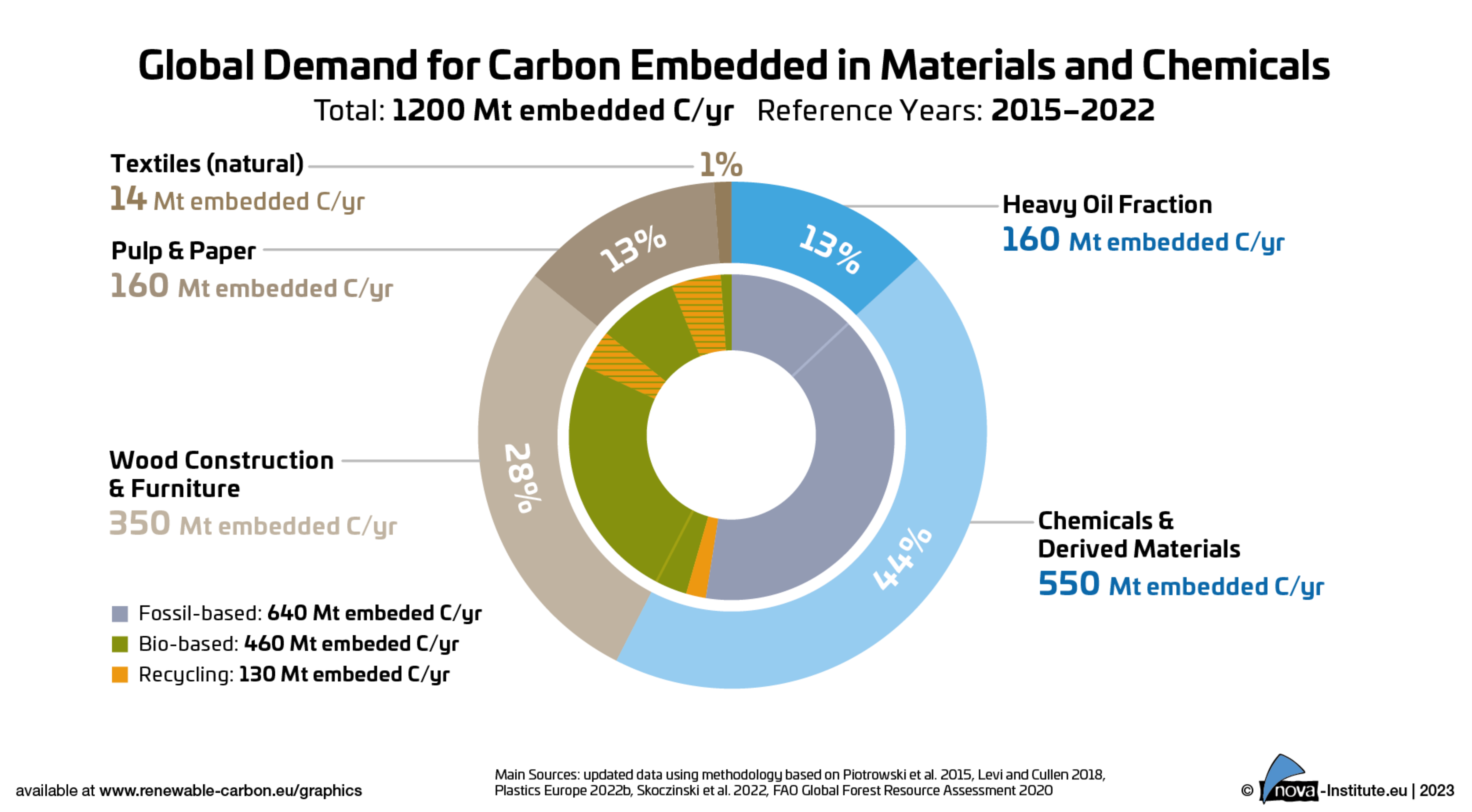
4. Carbon embedded in materials produced globally

Carbon embedded in materials produced globally

- For the material sector, no agreed definition exists
- The scope of this report are materials based on organic carbon
- We use the following structure to aggregate the flows of embedded carbon:

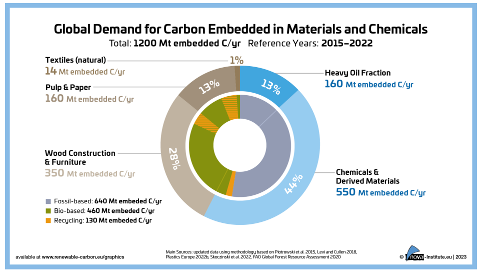


Man-made fibres and rubber are included in polymers
Heavy oil fraction (bitumen, lubricants and paraffin waxes) is often not included in reports, therefore accounted separately from other chemicals



Global Demand for Carbon Embedded in Materials and Chemicals
Total: 1200 Mt embedded C/yr Reference Years: 2015–2022
Textiles (natural)
14 Mt embedded C/yr
1%
Pulp & Paper
160 Mt embedded C/yr
13%
Heavy Oil Fraction
160 Mt embedded C/yr
13%
Wood Construction & Furniture
350 Mt embedded C/yr
28%
Chemicals & Derived Materials
550 Mt embedded C/yr
44%
Fossil-based: 640 Mt embeded C/yr
Bio-based: 460 Mt embeded C/yr
Recycling: 130 Mt embeded C/yr
available at www.renewable-carbon.eu/graphics
Main Sources: updated data using methodology based on Piotrowski et al. 2015, Levi and Cullen 2018, Plastics Europe 2022b, Skoczinski et al. 2022, FAO Global Forest Resource Assessment 2020
© nova-Institute.eu | 2023

Global demand for embedded carbon in materials and chemicals



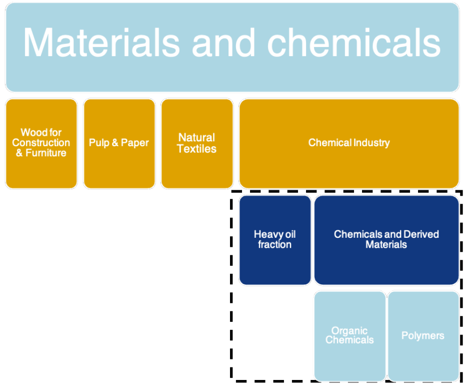
- The graph above summarises demand for carbon-based feedstock for natural textiles, pulp & paper, wood for construction & furniture, and for the chemical industry, which includes the heavy oil fraction (bitumen, lubricants and paraffin waxes) and the class of chemicals and derived materials (incl. plastics).
- The total demand for carbon embedded in feedstock for materials and chemicals is **1,200 Mt C / year**.
- The demand only includes the carbon embedded in the feedstock for production of materials and chemicals. Additional carbon is used in these sectors as energy carrier.
- Biomass is the origin for feedstock of the sectors wood for construction and furniture, pulp & paper, and natural fibres for textiles. This includes both, primary biomass and recycled biomass streams.
- Fossil feedstock is used for bitumen, lubricants and paraffin waxes and for chemicals and derived materials. The latter also uses biomass and recycled feedstock, while the former only uses fossil feedstock so far.

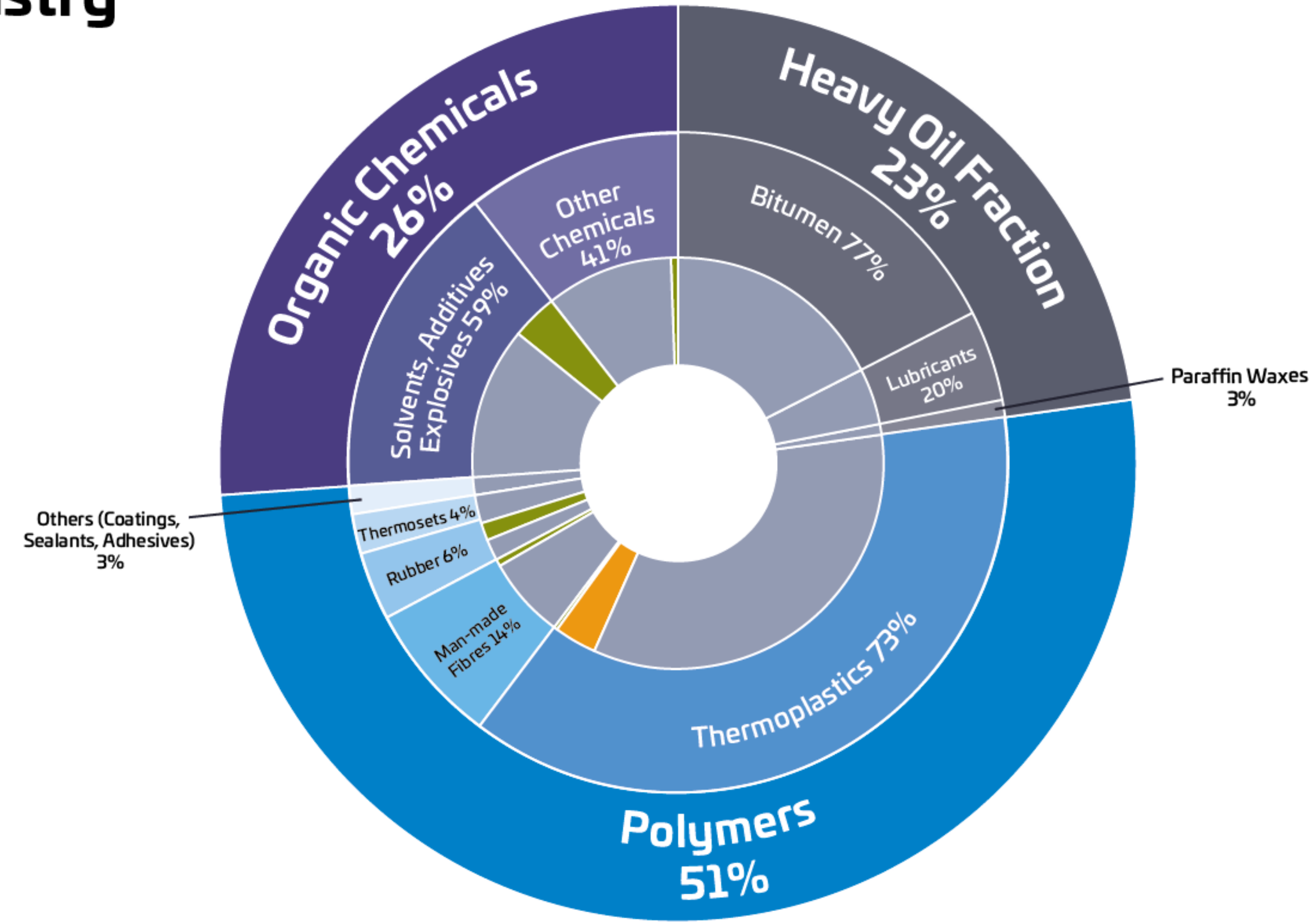
Consumption of Embedded Carbon in the Global Chemical Industry

Total: **710 Mt embedded C/yr**

Reference Years: **2015–2022**

- Fossil-based: **640 Mt embedded C/yr**
- Bio-based: **41 Mt embedded C/yr**
- Recycling: **24 Mt embedded C/yr**
- CO_2-based: **0.2 Mt embedded C/yr**

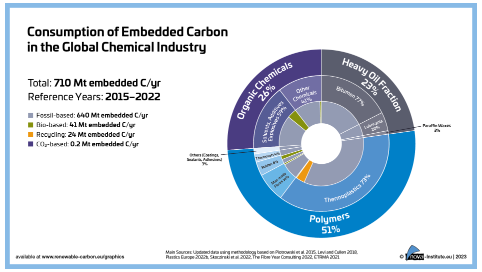




available at **www.renewable-carbon.eu/graphics**

Main Sources: Updated data using methodology based on Piotrowski et al. 2015, Levi and Cullen 2018, Plastics Europe 2022b, Skoczinski et al. 2022, The Fibre Year Consulting 2022, ETRMA 2021

Global demand for embedded carbon in the chemical industry

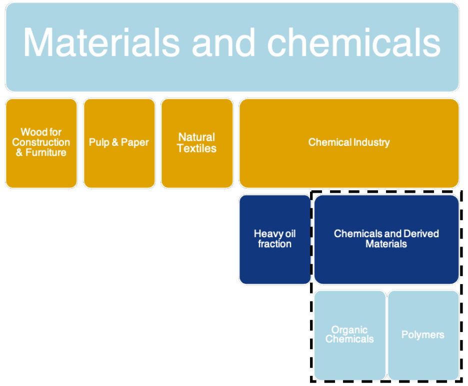


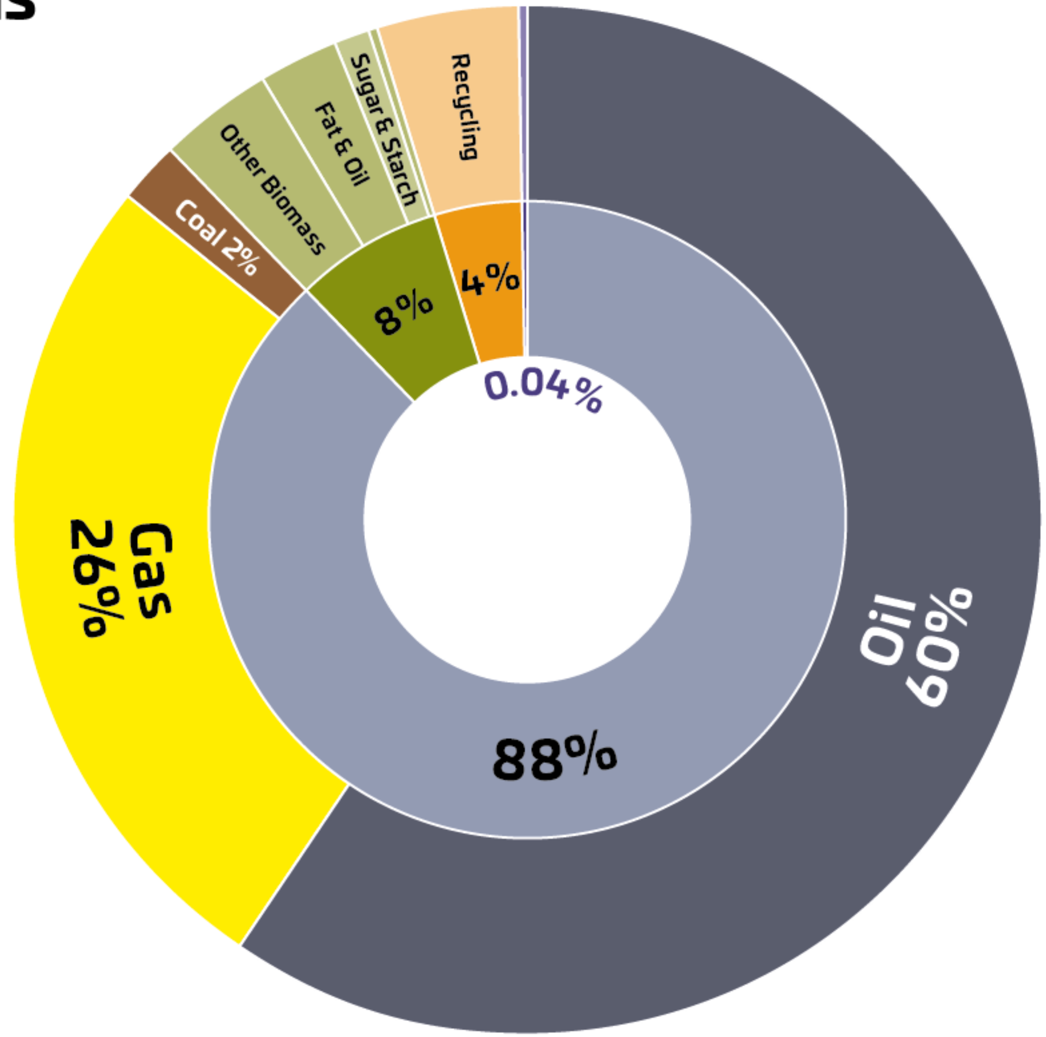
- The graph above summarises the demand for carbon-based feedstock for the chemical industry, which includes the heavy oil fraction (bitumen, lubricants and paraffin waxes), polymers & rubber (incl. thermoplastics, man-made fibres, thermosets & adhesives, and natural and synthetic rubber) and organic chemicals. The heavy oil fraction is not considered in many other studies.
- The total demand for carbon embedded in feedstock for the chemical industry is **710 Mt C / year**.
- The demand only includes the carbon embedded in the feedstock for production of chemicals and polymers. Additional carbon is used as energy carrier.
- The composition of feedstocks used in the chemical industry is dominated by fossil feedstock. The share of bio-based feedstock is only relevant for certain organic chemicals, where plant oils are used, for natural rubber and for cellulose fibres. A relevant recycling share is currently only achieved for thermoplastics.

Global Supply for Embedded Carbon in Chemicals and Derived Materials
by Type of Feedstock

Total: **550 Mt embedded C/yr**
Reference Years: **2015–2022**

- Fossil-based: **480 Mt embedded C/yr**
- Bio-based: **41 Mt embedded C/yr**
- Recycling: **24 Mt embedded C/yr**
- CO_2-based: **0.2 Mt embedded C/yr**





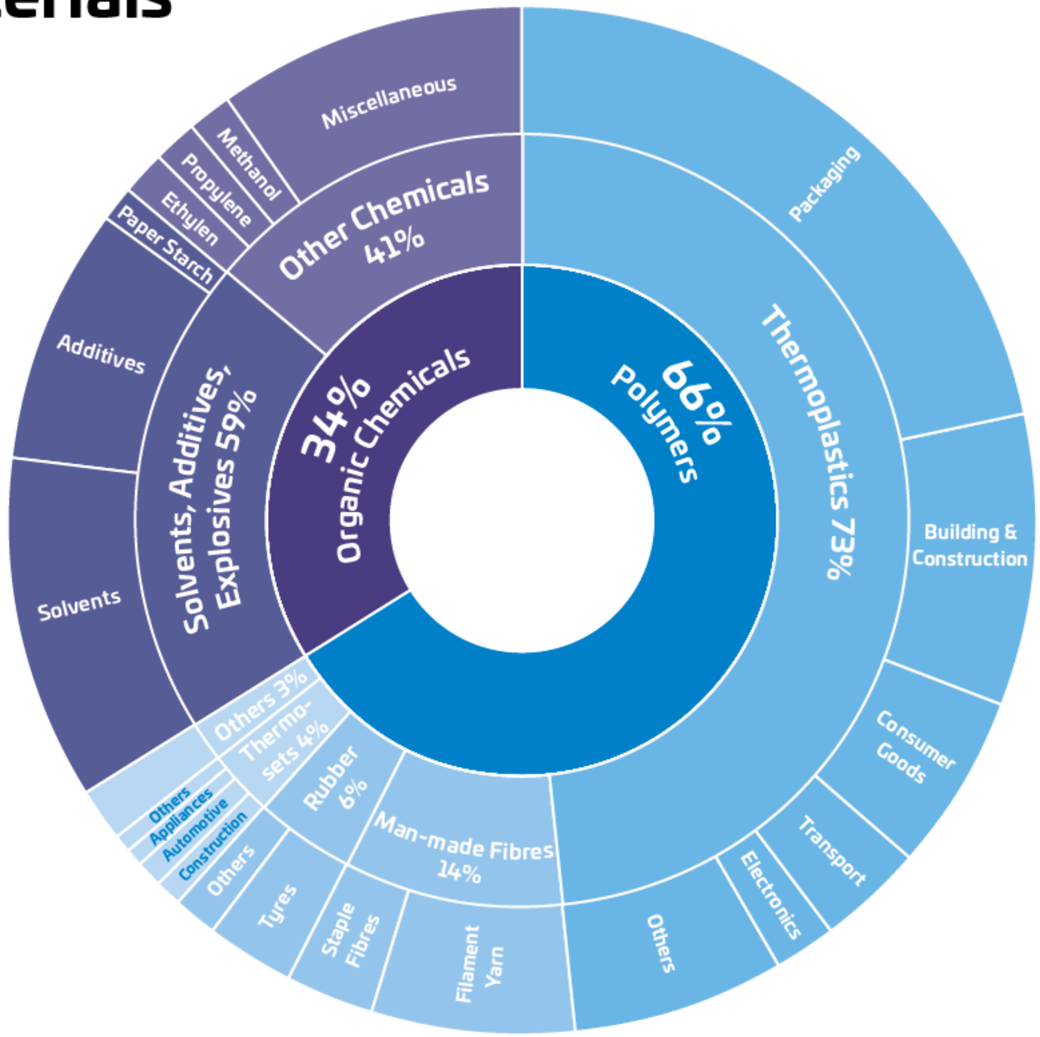
available at **www.renewable-carbon.eu/graphics**

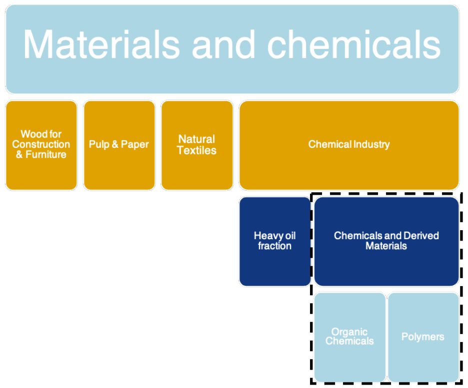
Main Sources: Updated data using methodology based on Piotrowski et al. 2015, Levi and Cullen 2018, Plastics Europe 2022b, Skoczinski et al. 2022

Consumption of Embedded Carbon for Global Chemicals and Derived Materials
by End-user Application

Total: **550 Mt embedded C/yr**

Reference Years: **2015–2022**





Main Sources: Geyer et al. 2017, Levi and Cullen 2018, Mordor Intelligence 2019, The Fibre Year Consulting 2022, Plastics Europe 2022b, Skoczinski et al. 2022, ETRMA 2021

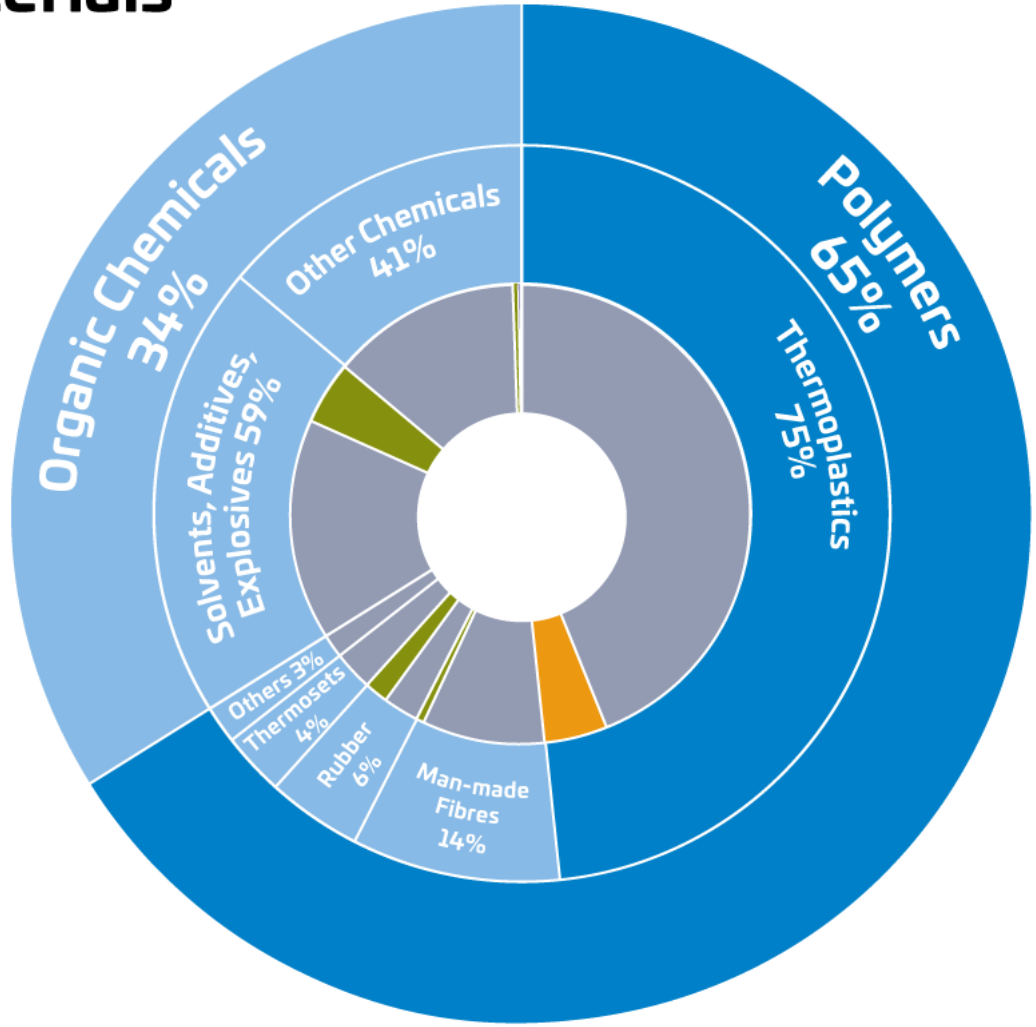
Consumption of Embedded Carbon for Global Chemicals and Derived Materials

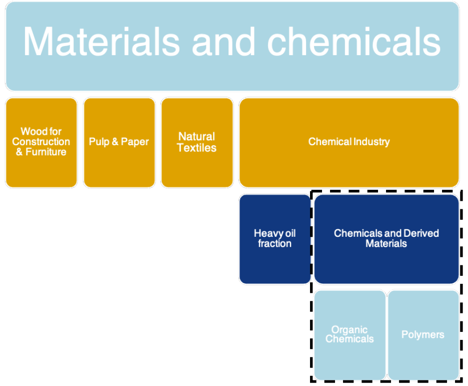
by Carbon Feedstock

Total: **550 Mt embedded C/yr**

Reference Years: **2015–2022**

- Fossil-based: **480 Mt embedded C/yr**
- Bio-based: **41 Mt embedded C/yr**
- Recycling: **24 Mt embedded C/yr**
- CO_2-based: **0.2 Mt embedded C/yr**



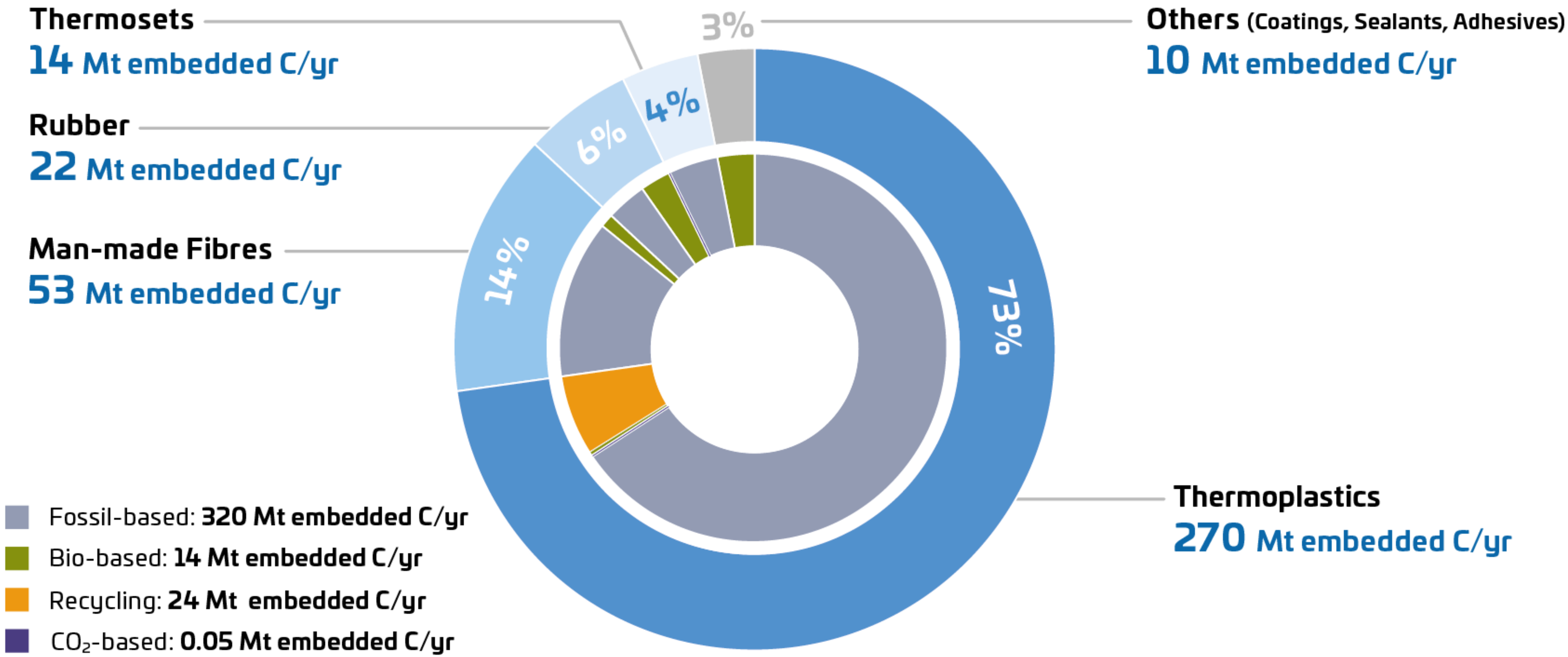


available at www.renewable-carbon.eu/graphics

Main Sources: Updated data using methodology based on Piotrowski et al. 2015, Levi and Cullen 2018, Plastics Europe 2022b, Skoczinski et al. 2022, The Fibre Year Consulting 2022, ETRMA 2021

Consumption of Embedded Carbon for Global Polymers

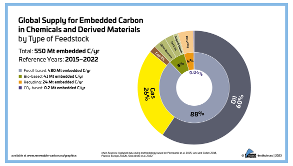
Total: **360 Mt embedded C/yr** Reference Years: **2020–2022**

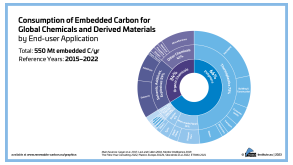


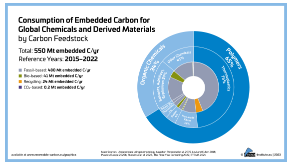
Main Sources: Updated data using methodology based on Plastics Europe 2022, Conversio 2022, nova-Institute 2023, The Fiber Year 2022, ETRMA 2021

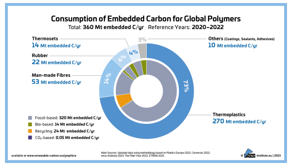
Embedded carbon in chemicals and derived materials on a global level

- Chemicals and derived materials include organic chemicals based on carbon and polymers (incl. man-made fibres, synthetic, and natural rubber)
- The total demand for carbon embedded in chemicals and derived materials is **550 Mt C / year**.
- The demand only includes the carbon embedded in the feedstock for production of chemicals derived materials. Additional carbon is used as energy carrier
- Depending on the scope of the study and the underlying statistics, either carbon in product is in focus or carbon in feedstock. The latter includes losses.
  - Carbon embedded in products is 450 Mt C, see Kähler et al. 2021,
  - Carbon in feedstocks for chemicals and derived materials is 550 Mt C
- Synthetic fertilisers are an important group of chemicals by production volume. These are not included here.
  - Inorganic chemicals don't contain relevant amounts of carbon. Natural gas is used as an energy carrier in ammonia production but ammonia (NH_3) does not contain carbon
  - Organic fertilisers like manure contain organic carbon but are not part of the chemical industry
- CO_2 as a feedstock is still neglectable for all sectors in scope of this study
  - 0.2 Mt C from CO_2 is used for chemicals (mostly Salicylic acid, cyclic carbonate esters and methanol).
  - Urea production generally also uses C from CO_2 in large amounts (44 Mt C) but fertiliser production is out of scope of this study.
  - 0.07 Mt C from CO_2 is used for plastics (mostly aromatic polycarbonate).









Global polymer / plastic production

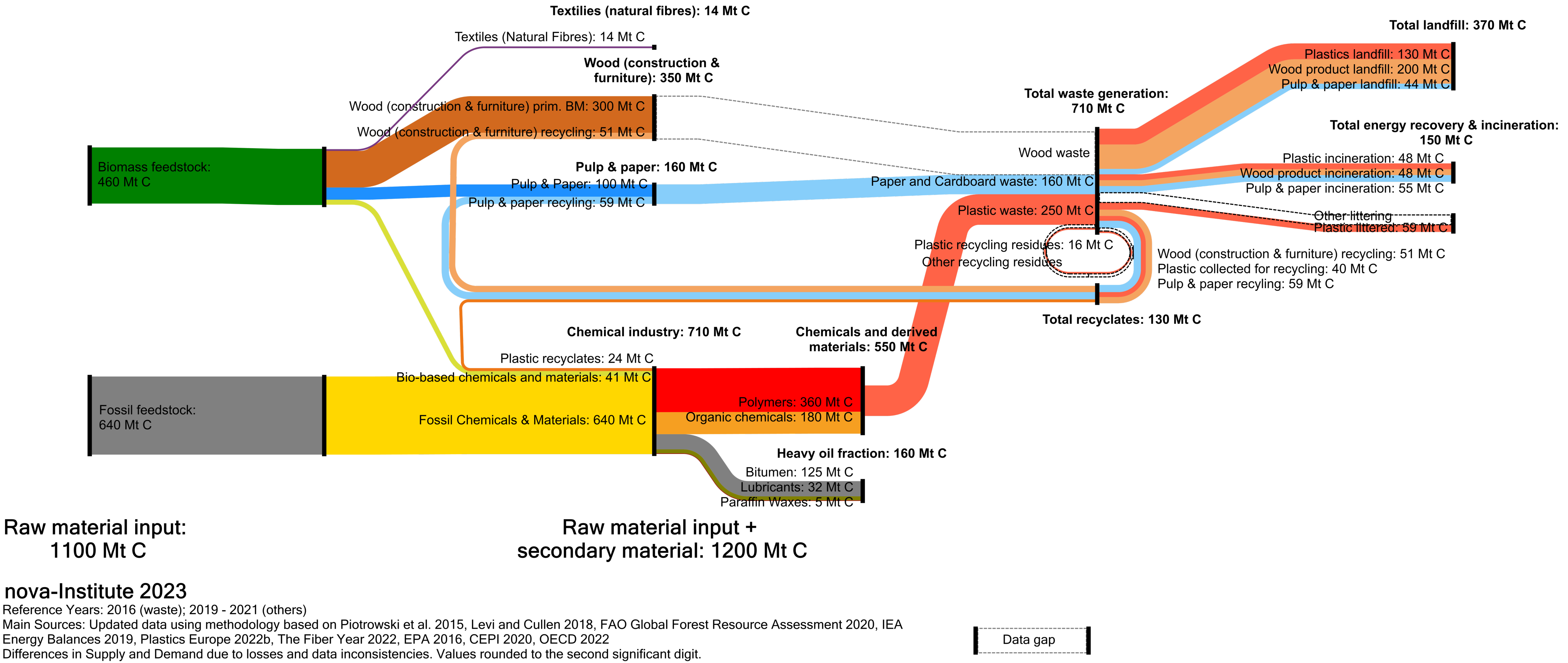
Plastic type	Production volume [Mt]	C Amount [Mt C]	Reference year	Source
Plastic type	74.3	63.7	2021	PlasticsEurope (2022b)
Polypropylene (PP)	55.4	47.5	2021	PlasticsEurope (2022b)
Low density polyethylene, Linear low density polyethylene (LDPE, LLDPE)	49.6	19.1	2021	PlasticsEurope (2022b)
Polyvinylchloride (PVC)	48.1	41.2	2021	PlasticsEurope (2022b)
High density polyethylene (HDPE)	23.9	14.9	2021	PlasticsEurope (2022b)
Polyethylene terephthalate (PET)	20.4	18.8	2021	PlasticsEurope (2022b)
Polystyrene, Expanded polystyrene (PS, EPS)	21.2	13.8	2021	PlasticsEurope (2022b)
Polyurethane (PUR)	27.3	20.8	2021	PlasticsEurope (2022b)
Thermosets	27.3	14.2	2021	PlasticsEurope (2022b)
Adhesives	9.4	6.1	2015	Grand View Research (2015a)
Sealants	1.8	1.2	2015	Grand View Research (2015a)
Coatings	2.8	1.8	2017	Sinograce chemical (2017)
Marine coatings	0.5	0.4	2019	OECD Stat (2022)
Road marking coatings	0.7	0.4	2019	OECD Stat (2022)
PP fibres	3.2	2.7	2021	The Fiber Year (2022)
PES fibres	62.9	39.3	2021	The Fiber Year (2022)
PA fibres	5.4	3.4	2021	The Fiber Year (2022)
Other fibres	2.5	1.6	2021	The Fiber Year (2022)
Synthetic rubber (tyres and non-tyres; mainly Styrene-Butadiene Rubber)	14.2	12.4	2020	ETRMA (2021)
Cellulosic fibres	7.4	3.3	2021	The Fiber Year (2022)
Natural rubber	11.0	9.7	2022	nova-Institute (2023)
Bio-based thermoplastics	3.1	1.6	2022	nova-Institute (2023)
Bio-based Epoxy	1.4	0.9	2022	nova-Institute (2023)
Recycled plastics	31.9	24.3	2021	Plastics Europe (2022b)
CO_2-based thermoplastics	1.0	0.7	2022	nova-Institute (2023)
CO_2-based thermosets	0.05	0.04	2022	nova-Institute (2023)
Total	**506**	**363**		

Table based on UNEP 2018: Bio-based and CO_2-based polymers are often only partly bio- / CO_2-based. T46he figures shown here indicate the bio- / CO_2-based and the fossil-based production combined.

Challenges in data for global plastics

- In the plastic value chain, various intermediates exist (raw materials, monomers, polymers, plastics with additives, etc.).
- It is questionable, if all the data stated refer to the same level in the value chain.
- Furthermore, some material streams may be double counted (e.g., once as polymers, once as plastics).
- This are the best data available.

Flows of organic carbon in the global material & chemical sector

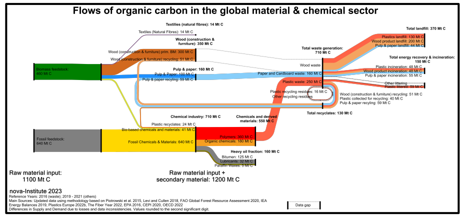


nova-Institute 2023

Reference Years: 2016 (waste); 2019 - 2021 (others)
Main Sources: Updated data using methodology based on Piotrowski et al. 2015, Levi and Cullen 2018, FAO Global Forest Resource Assessment 2020, IEA Energy Balances 2019, Plastics Europe 2022b, The Fiber Year 2022, EPA 2016, CEPI 2020, OECD 2022
Differences in Supply and Demand due to losses and data inconsistencies. Values rounded to the second significant digit.

Flows of organic carbon in the global material and chemical sector

- Material use of primary biomass was derived from updated data using methodology based on Piotrowski et al. 2015. Data for secondary biomass was retrieved from various sources sector specific.
- Data for chemicals and derived materials are based on the data collection illustrated on the previous slides (mainly own data and Plastics Europe 2022b).



- Data for the heavy oil fraction is based on IEA 2022.
- Data for total waste generation and composition were derived from World Bank 2018. This reports covers only municipal solid waste. The amounts of individual waste fractions were then multiplied by shares in disposal options for each waste fraction.
    - For wood no data for global disposal options could be found. The shares for each disposal option in the US was used as a global proxy, based on EPA 2016. The overall amount of wood waste remains a data gap.
    - Shares in disposal options for pulp & paper was taken from CEPI 2020.
    - Absolute figures for each disposal option for plastics were derived from Plastics Europe 2022b.

Summary of global carbon flows today (Mt C / yr)

	World[1]		Global Materials & Chemicals[2,3]		Global Chemical Industry[2,4]		Global Chemicals & Derived Materials[2,5]	
Total	17000	100 %	1200	100 %	710	1004%	550	100 %
Fossil total	11000	63 %	640	52 %	640	91 %	480	88 %
Coal	4700		12		12		12	
Gas	2500		140		140		140	
Oil	3800		490		490		330	
Primary Biomass	6100	35 %	460	37 %	41	6 %	41	8 %
Cellulose	2700		370		3		3	
Sugar & Starch	1300		10		6		6	
Fat/Oil	500		14		13		13	
Protein	800		0		0		0	
Others[6]	800		63		20		20	
Recyclates, Secondary biomass	280[7]	2 %	130	11 %	24	3 %	24	4 %

1 - includes carbon input of fossil and biogenic raw materials plus recyclates in the world economy (food and feed, energy sector, transport, materials and chemicals)
2 - only embedded carbon; energetic use excluded
3 - includes chemicals and derived materials (plastics, rubber), including the heavy oil fraction (bitumen, paraffin waxes, lubricants) and bio-based industries wood for construction, pulp & paper, textiles)
4 - includes chemicals and derived materials (plastics, rubber), including the heavy oil fraction (bitumen, paraffin waxes, lubricants)
5 - includes chemicals and derived materials (plastics, rubber)
6 - includes lignin, natural rubber, etc
7 - includes material recycling and incineration Various sources; Various reference years, mainly 2018–2020

Share of renewable carbon

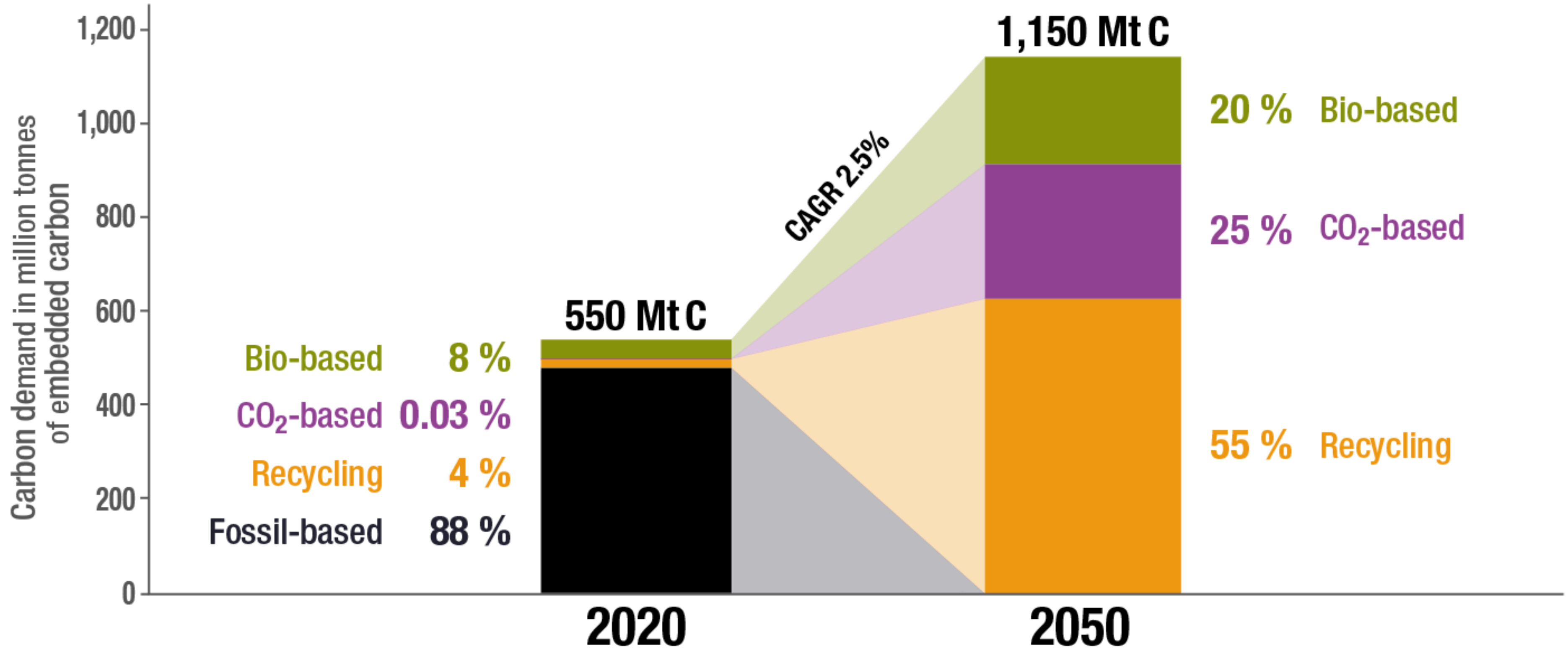
- According to these data, the share of renewable feedstock is
  - Total: 37 % (35 % bio-based, 2 % recycling)
  - Materials & Chemicals: 48 % (37 % bio-based, 11 % recycling)
  - Chemical Industry: 9 % (6 % bio-based, 3 % recycling)
  - Chemicals & Derived Materials: 12 % (8 % bio-based, 4 % recycling)

- The share of renewable feedstock in materials & chemicals is high due to traditional industries like pulp & paper, construction industry that use large shares of biomass feedstock
- The share of fossil feedstock in the whole chemical industry is larger compared to only chemicals & derived materials because the chemical industry also includes the heavy oil fraction (bitumen, lubricants and paraffin waxes), which are 100 % fossil.
- While data for fossil value chains include fossil losses, most of the losses in bio-based value chains are not included due to the lack of comprehensive data. Hence, the share of renewable feedstock in chemical sectors are likely higher.

The bio-based share refers to primary biomass.
The recycling share refers to plastic recycling and recycled biomass.

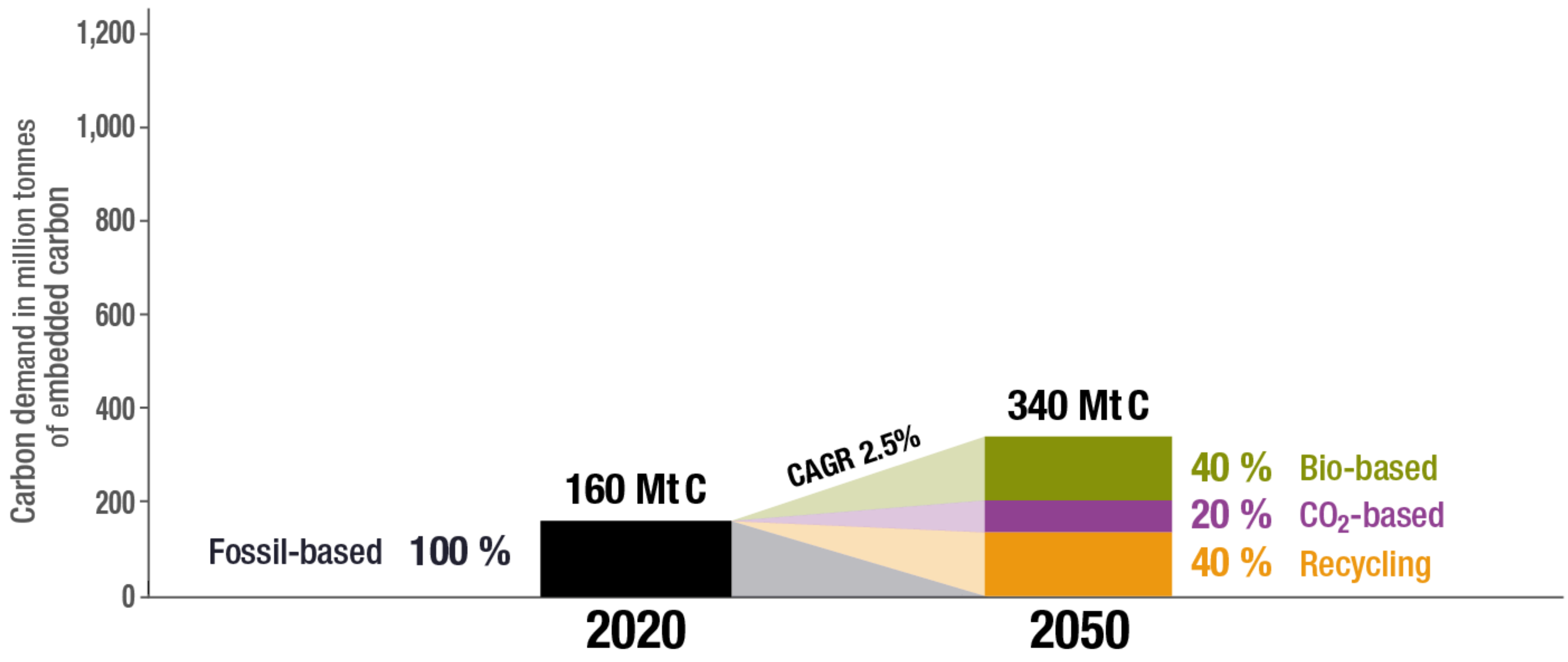
5. Explorative scenarios for the chemical industry in 2050

Carbon Embedded in Chemicals and Derived Materials



Carbon Embedded in the Heavy Oil Fraction

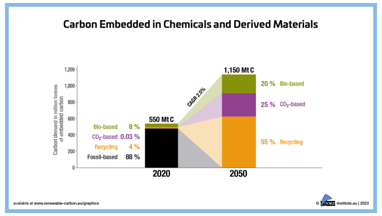
(Bitumen, Lubricants, Paraffin Waxes)



available at www.renewable-carbon.eu/graphics

Explorative scenarios for the chemical industry in 2050

- The figure shows a so-called explorative scenario that is based on plausible assumptions on the basis of which the future is to be explored. What are the consequences of such a scenario? This is deliberately not a prediction, as the occurrence of the scenario depends above all on political framework conditions and corresponding investments.
  It will not become reality by itself.

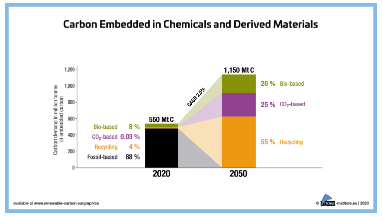


- **What are the assumptions behind the scenario?**
  - CAGR = 2.5% is in line with other studies and about 1% lower than in previous decades. This lower growth is mainly based on efficiency improvements as well as reservations towards plastics, which are replaced in some areas e.g. by cellulose/paper.

RENEWABLE CARBON INITIATIVE

Explorative scenarios for the chemical industry in 2050

- Shares of the different renewable carbon references for **chemicals and derived materials**:
  - Current policy focuses clearly on recycling, primarily mechanical recycling. For the fractions that cannot be recycled mechanically, chemical recycling becomes a key option. Various studies see a maximum overall recycling rate of 50 to 60%. When it comes to plastics only, even 70% can probably be achieved. However, since the total quota also includes detergents and solvents, we have set 55% in the scenario, which is ambitious in any case.
  - The limitation of the biomass share to 20% results mainly from limited areas available for cultivated biomass and planted forest. The limitation is mainly based on the need to preserve biodiversity, which is increasingly becoming a focus of sustainability, also in policy. About a quarter of the area (that supplies the 20% of biomass) comes from land that was previously used for biofuels but is now being freed up by ongoing electrification.
  - The remaining 25% is covered by direct utilisation of CO_2 (from point sources and direct air capture), which represents only a small share of the possible potential of CO_2 utilisation.

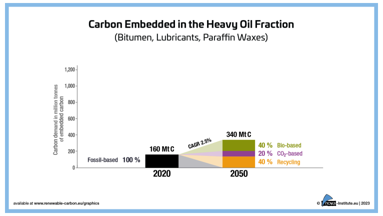


  - A first study to evaluate the consequences of the exploratory scenario has already been conducted. It shows that in principle even the entire carbon demand of the chemical industry worldwide could be covered by direct utilisation of CO_2 – and with an energy demand that would require “only” 1.3% of the Sahara desert used for photovoltaic (Kähler et al. 2022)
  - In the here presented scenario, mainly the commodities of the chemical industry are produced from utilisation of CO_2 and chemical recycling, while special molecules with particularly favourable pathways are produced from biomass, e.g. fine chemicals or polyamides from castor oil and PLA from lactide acid.

RENEWABLE CARBON INITIATIVE

Explorative scenarios for the chemical industry in 2050

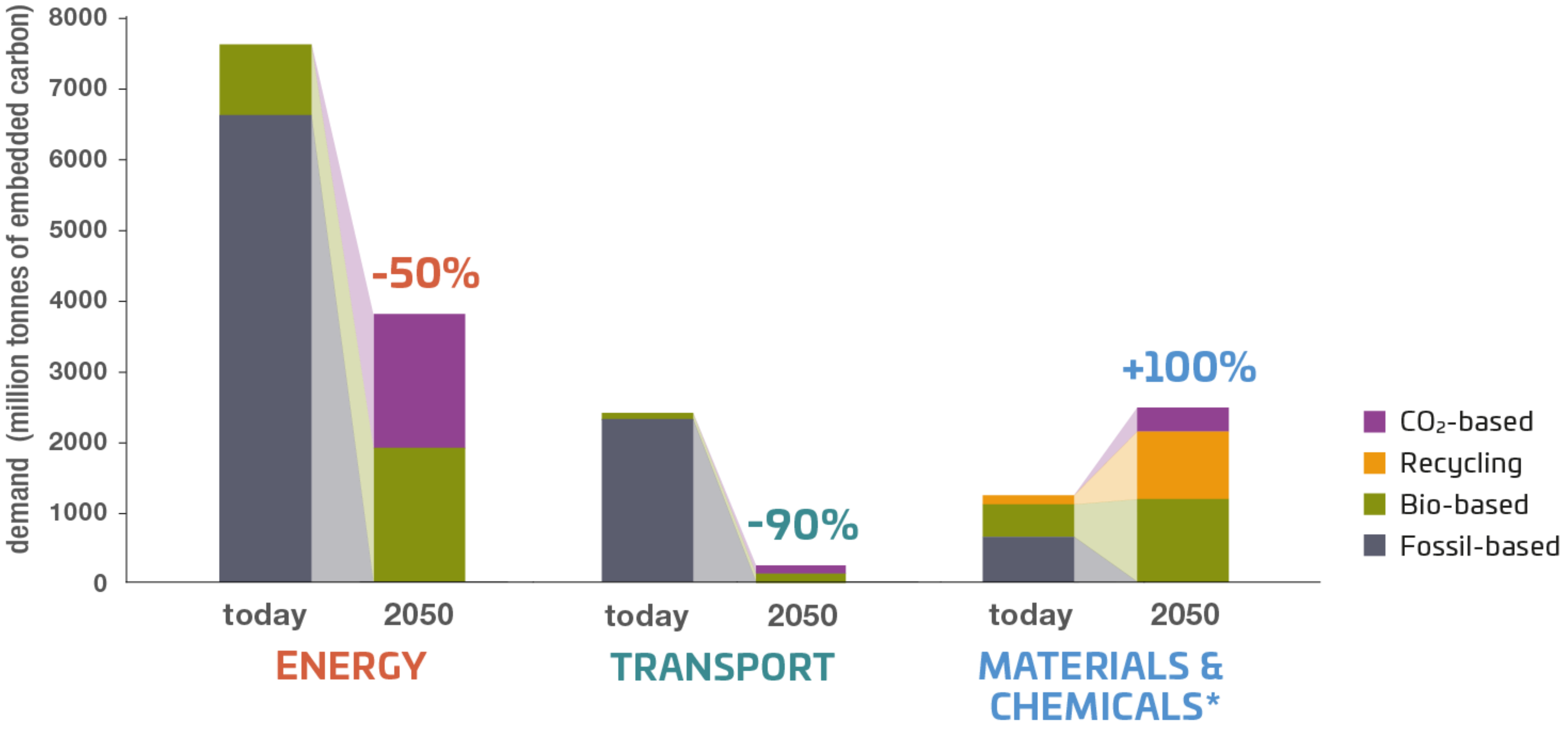
- Shares of the different renewable carbon references for the **heavy oil fraction:**
  - In the heavy crude fraction, which is mainly bitumen, but also lubricants and paraffin waxes, the shares of the different renewable carbon sources differ compared to the shares of chemicals and derived products:
    - Biomass: 40%, mainly based on the utilisation of lignin, UCO/plant oil hydrogenation for lubricants and waxes, and pyrolysis oil from biogenic waste streams for bitumen and waxes.



    - CO_2: 20%, mainly waxes from Fischer Tropsch.
    - Chemical recycling/pyrolysis: 40%, pyrolysis oil from plastic waste streams for bitumen and waxes

Embedded Carbon Demand for Main Sectors

Today (2015–2020) and Scenario for 2050 (in Million Tonnes of Embedded Carbon)

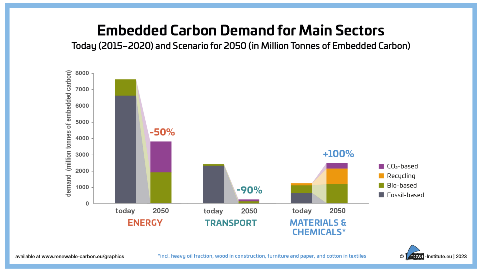


available at www.renewable-carbon.eu/graphics

*incl. heavy oil fraction, wood in construction, furniture and paper, and cotton in textiles

Explorative scenarios for the chemical industry in 2050

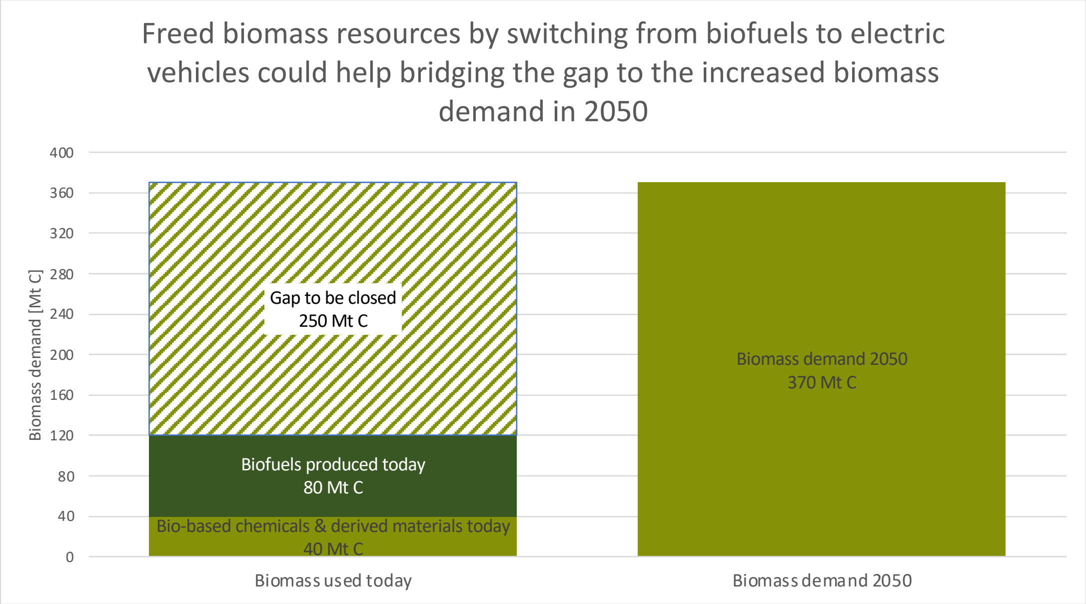
- The next figure for “Embedded Carbon for Main Sectors” also includes scenarios for the energy and transport sectors worldwide.
- The data for “materials and chemicals” are consistent with the data described above. The scenarios for energy and transport were roughly developed on the basis of various reports and simple assumptions that depend heavily on future policy.
- The carbon demand for the energy sector is estimated to decrease to 50% by 2050 due to electrification, the use of hydrogen and the direct utilisation of solar heat in the energy sector. About half of the remaining demand will be met by bioenergy and by e-fuels (CO_2).



- The demand for carbon-based fuels in the mobility sector will decrease to 10 % due to strong electrification and the utilisation of hydrogen. About half of the remaining demand will be met by bioenergy and by e-fuels (CO_2).
- The carbon demand for materials and chemicals will double if the same assumptions as above are used and, in addition, the use of wood in construction and furniture and of natural fibres in textiles is further increased. This means that the carbon demand for materials and chemicals will increase from a share of about 10 % today to about 40 % in 2050.

Electrification in the transport sector could free biomass from biofuels

- The exploratory scenarios shows an increase in demand for biomass by 2050 (230 Mt C for chemicals & derived materials and 140 Mt C for the heavy oil fraction)
- When electrification of transport continues, biomass today used for biofuels will become available (80 Mt C today)
- This biomass can help reducing the gap to be filled. The increase in biomass demand of 330 Mt C could be lowered to 250 Mt C by using the 80 Mt C from today's biofuel sector.



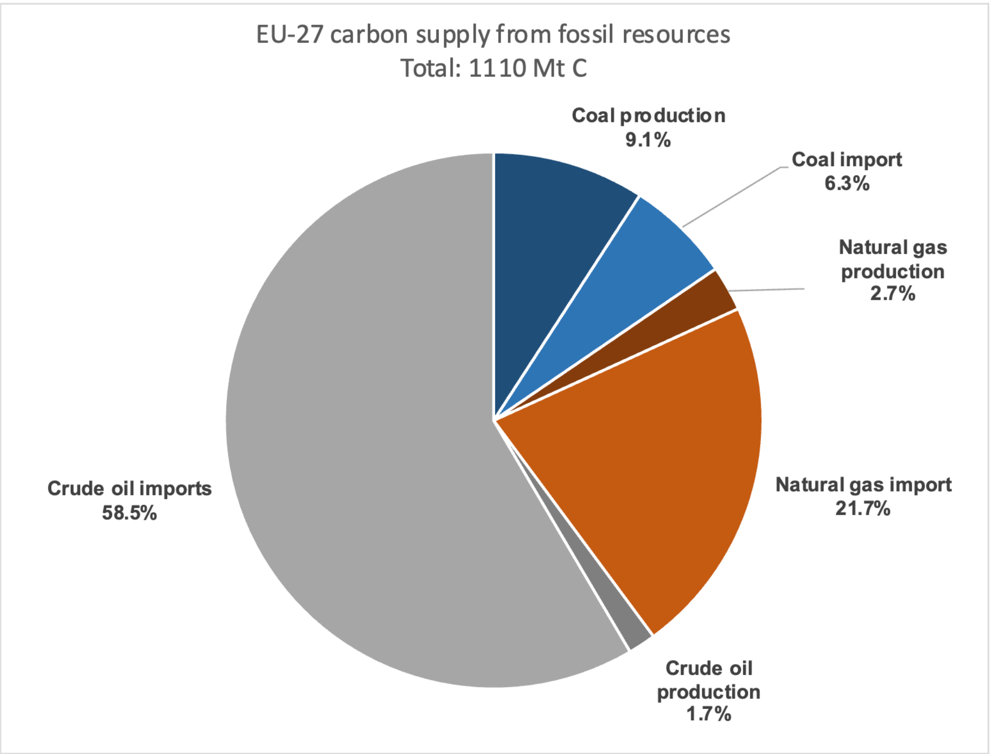
Own calculation for biofuel data based production volumes of ethanol, biodiesel and HVO (IEA 2020b)

6. Carbon flows in the EU-27 economy

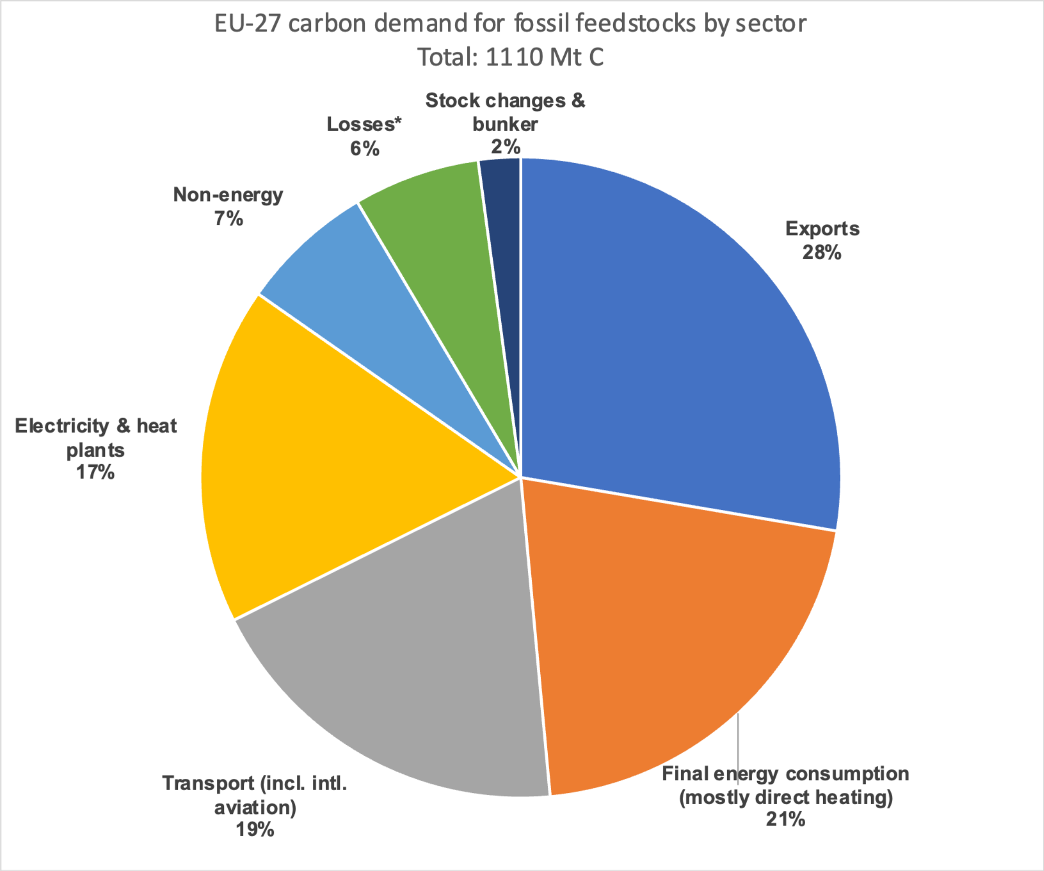
Carbon flows in the EU-27 economy

- For determination of European carbon flows, similar method is applied, based on Eurostat Energy statistics, JRC biomass flow, own data and others
- EU-27 carbon supply is dominated by fossil imports
- Around 2/3rd of EU's C supply is covered by fossil resources, 1/3rd by biogenic C
- The largest share of fossil C is consumed by energy uses: Final energy consumption (dominated by heating) and power plants

EU-27 fossil carbon supply and demand

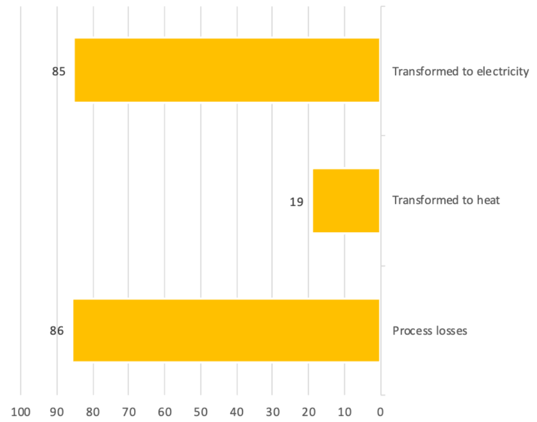


Eurostat EU-27 energy balance 2020

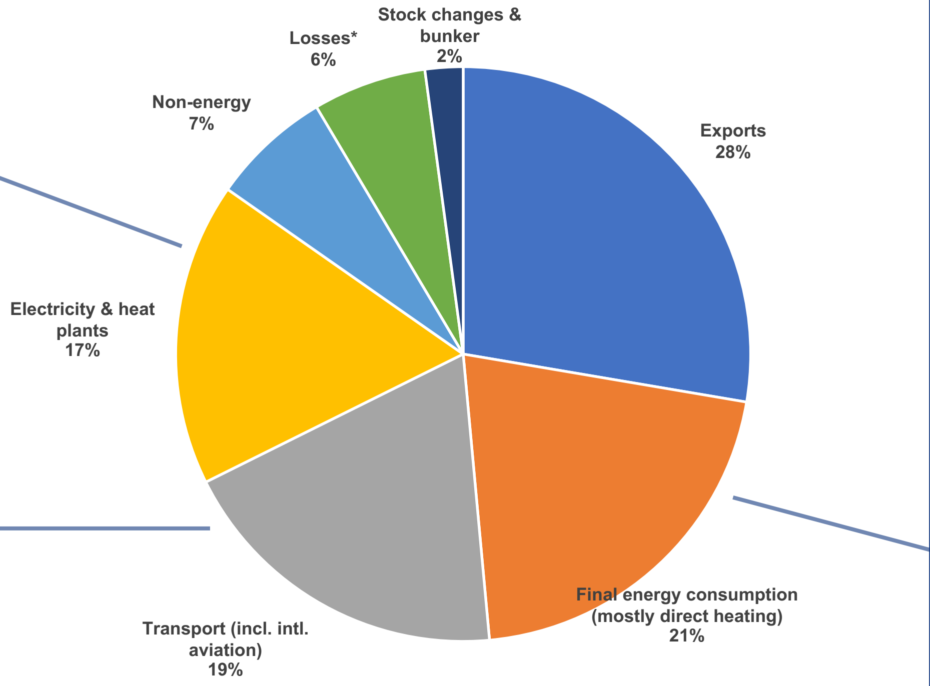


* includes statistical differences, energy industry own use and losses in industrial transformation processes
Eurostat EU-27 energy balance 2020

EU-27 carbon demand for fossil resources in electricity and heat plants ; Total: 190 Mt C

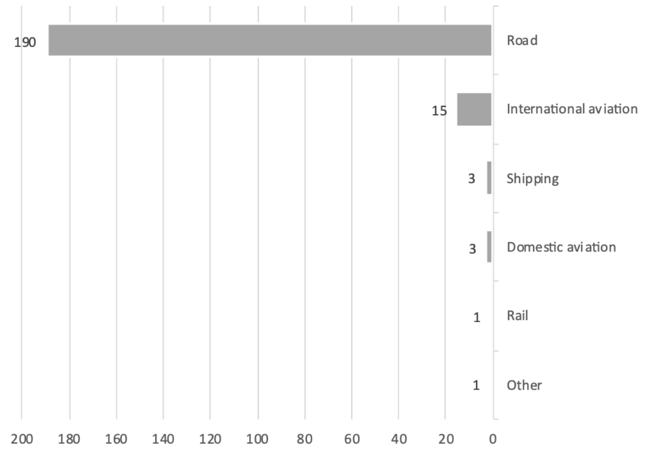


EU-27 carbon demand for fossil feedstocks by sector
Total: 1110 Mt C

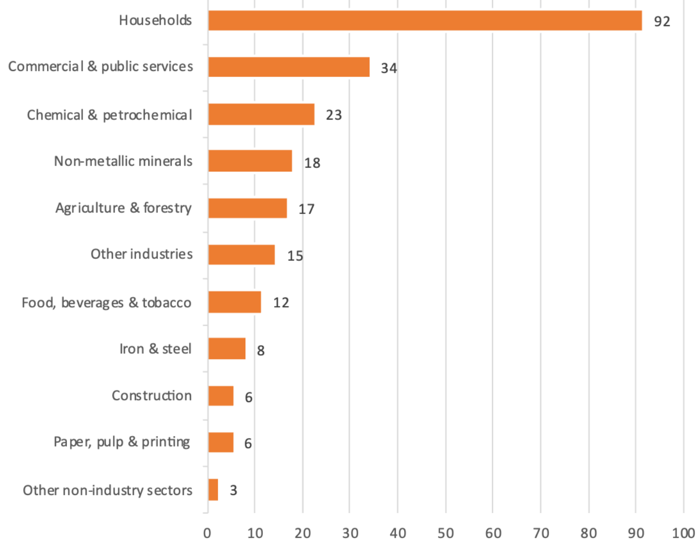


* includes statistical differences, energy industry own use and losses in industrial transformation processes. Additional losses occur in fossil power plants

EU-27 carbon demand for fossil resources in the transport sector; Total: 210 Mt C

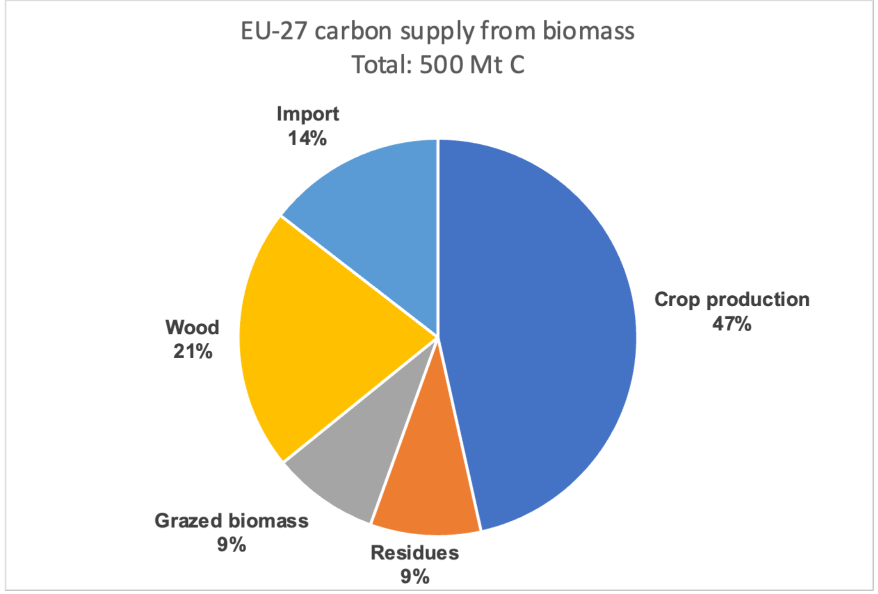


EU-27 carbon demand for fossil resources for final energy consumption (mostly direct heating); Total: 230 Mt C

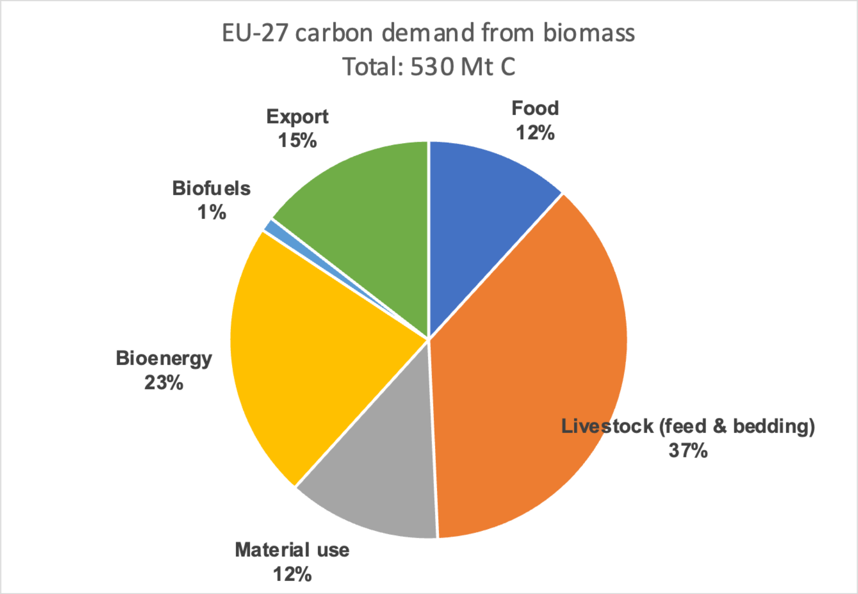


Eurostat EU-27 energy balance 2020

EU-27 bio-based carbon supply and demand

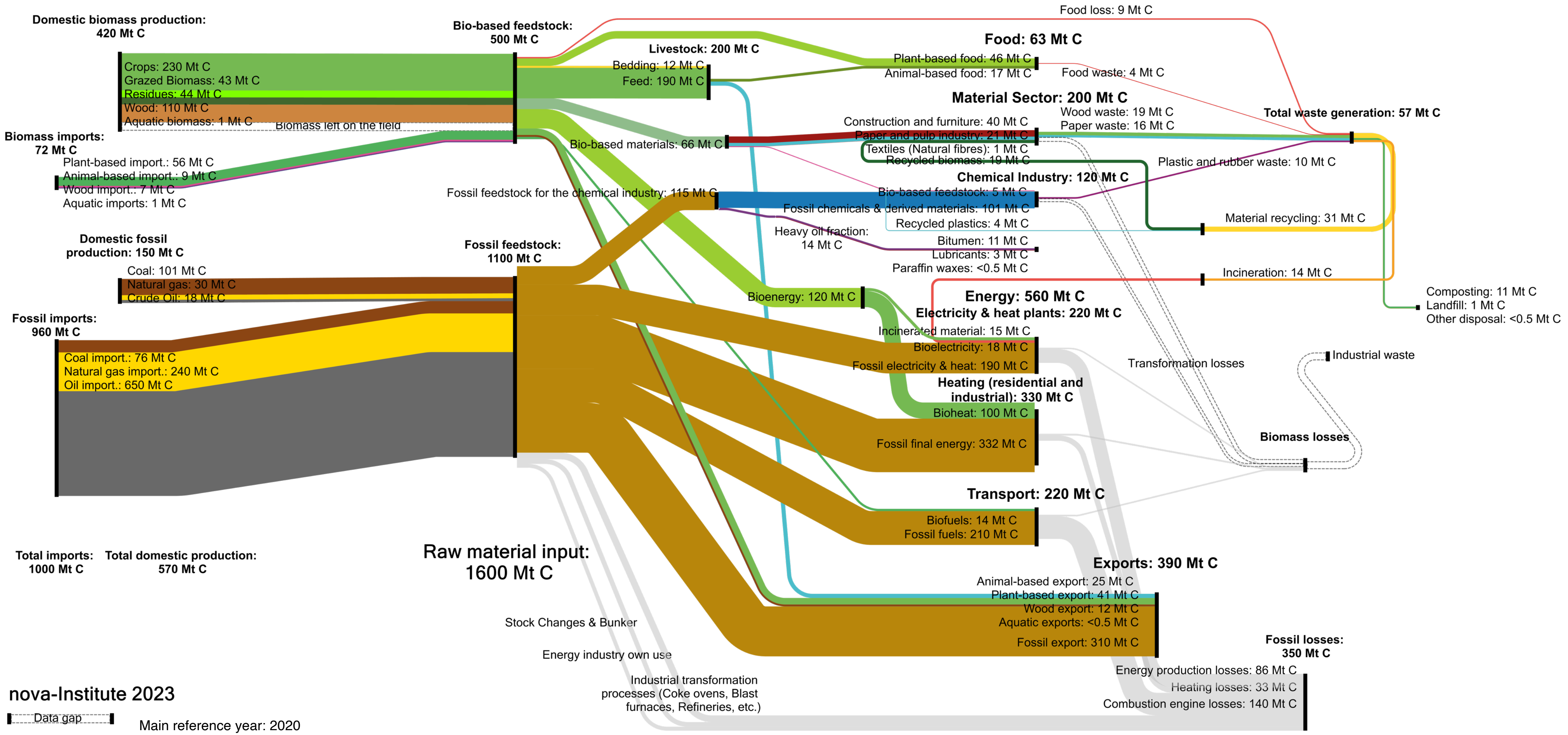


nova-Institute 2023, based on JRC biomass flows 2020, updated data using methodology based on Piotrowski et al. 2015
Reference years: 2018–2020



nova-Institute 2023, based on JRC biomass flows 2020, updated data using methodology based on Piotrowski et al. 2015
Reference years: 2018–2020

Flows of organic carbon in the EU-27 economy



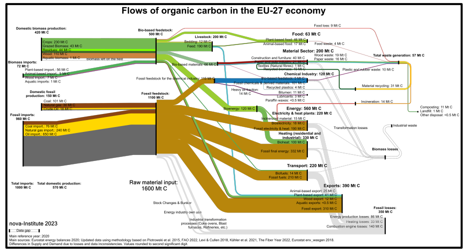
Main reference year: 2020

Main sources: Eurostat energy balances 2020; Updated data using methodology based on Piotrowski et al. 2015, FAO 2022, Levi & Cullen 2018, Kähler et al.2021, The Fiber Year 2022, Eurostat env_wasgen 2018. Differences in Supply and Demand due to losses and data inconsistencies. Values rounded to second significand digit.

RENEWABLE CARBON INITIATIVE

Flows of organic carbon in the EU-27 economy

- Fossil C flows are predominantly derived from Eurostat energy balances, biogenic C flows from nova-Institute's own data using methodology based on Piotrowski et al. 2015. Several other sector-specific sources where used.
- Use of carbon-based feedstock can be separated between food, material use, energy, and transport.
- The material use presented in the graph only includes the carbon **embedded** in the materials. For example, the 120 Mt stated for the chemical industry is only the carbon in fossil and biogenic feedstock. Additionally, the chemical industry uses energy, which is accounted for in the section of Electricity and heat plants. The same applies for other sectors, e.g., material and energetic use of carbon in the paper industry.



- Data gaps remain in the following sectors:
  - Biomass left on the field
  - Process losses in the material sector
  - Import of products (e.g., intermediates for the chemical industry), that may not be covered by Eurostat energy balances
  - Waste data are derived from Eurostat (env_wasgen). The statistic covers all economic activities and households. However, closed loop recycling may not be included in this data. Furthermore, some streams are not displayed in the Sankey, such as use of biowaste for biogas.

7. Carbon embedded in materials produced in the EU-27

EU-27 plastic production

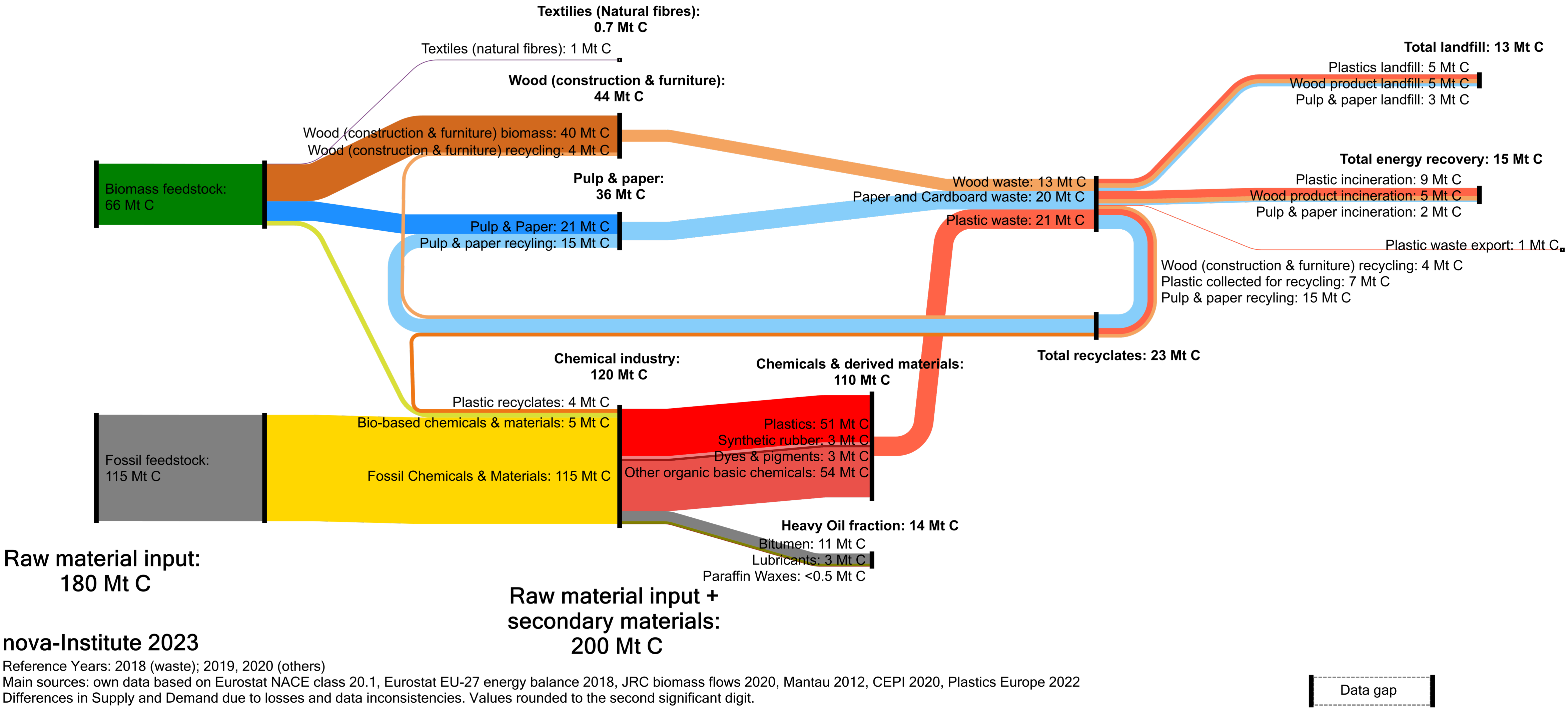
Plastic type	Production volume [Mt C]	C Amount [Mt C]	Reference year	Source
Polypropylene (PP)	9.5	8.1	2021	Plastics Europe (2022b)
Low density polyethylene, Linear low density polyethylene (LDPE, LLDPE)	8.4	7.2	2021	Plastics Europe (2022b)
Polyvinylchloride (PVC)	6.5	2.5	2021	Plastics Europe (2022b)
High density polyethylene (HDPE)	5.3	4.6	2021	Plastics Europe (2022b)
Polyethylene terephthalate (PET)	3.0	1.9	2021	Plastics Europe (2022b)
Polystyrene, Expanded polystyrene (PS, EPS)	3.5	3.2	2021	Plastics Europe (2022b)
Polyurethane (PUR)	3.1	2.1	2021	Plastics Europe (2022b)
Other Thermoplastics	6.9	5.3	2021	Plastics Europe (2022b)
Thermosets	3.8	2.0	2021	Plastics Europe (2022b)
Adhesives	1.8	1.2	2015	Due to lack of data, Global production volume is multiplied with Europe's share in global plastic production, see next slide
Sealants	0.3	0.2	2015	
Coatings	0.5	0.3	2017	
Marine coatings	0.1	0.1	2015	
Road marking coatings	0.1	0.1	2015	
PP fibers	0.6	0.5	2021	
PES fibres	12.0	7.5	2021	
PA fibers	1.0	0.7	2021	
Other fibres	0.5	0.3	2021	
Cellulosic fibres	0.04	0.02	2021	The Fiber Year Book (2022)
Synthetic rubber (tyres and non-tyres; mainly Styrene-Butadiene Rubber)	2.0	1.7	2020	ETRMA (2021)
Natural rubber	0	0		Assumption
Bio-based epoxy resins	0.6	0.4	2022	nova-Institute (2022)
Bio-based thermoplastics	0.05	0.02	2022	nova-Institute (2022)
Recycled plastics	5.8	4.4	2022	Plastics Europe (2022b)
Total	**75.5** (58.5+16.9)	**54.2** (43.3 +10.8)		

Table based on UNEP (2018)

Challenges in data for EU plastics

- As for global plastics, it is questionable, if all the data stated refer to the same level in the value chain (raw materials, monomers, polymers, plastics with additives, etc.).
- The data compiled in the table on the previous slide result in a production volume of around 75 Mt / yr or 54 Mt C / yr. In contrast, evaluating the prodcom class C20.16 “Plastics in primary forms” from Eurostat results in 70 Mt or 51 Mt C / yr. The small difference in these figures obtained from different methodologies emphasises their robustness.
- For some plastic types, no data for EU production is available: Thermosets, Adhesives, Sealants, Coatings, Marine coatings, Road marking coatings, PP fibres, PES fibres, PA fibres, Other fibres. To estimate these production volumes, global production volumes are multiplied with the EU's share in global plastic production of 19 % (see OECD 2018).

Flows of organic carbon in the EU-27 material & chemical sector

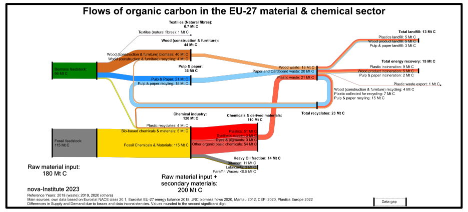


nova-Institute 2023

Reference Years: 2018 (waste); 2019, 2020 (others)
Main sources: own data based on Eurostat NACE class 20.1, Eurostat EU-27 energy balance 2018, JRC biomass flows 2020, Mantau 2012, CEPI 2020, Plastics Europe 2022
Differences in Supply and Demand due to losses and data inconsistencies. Values rounded to the second significant digit.

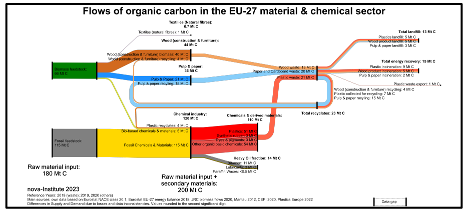
Flows of organic carbon in the EU-27 material and chemical sector

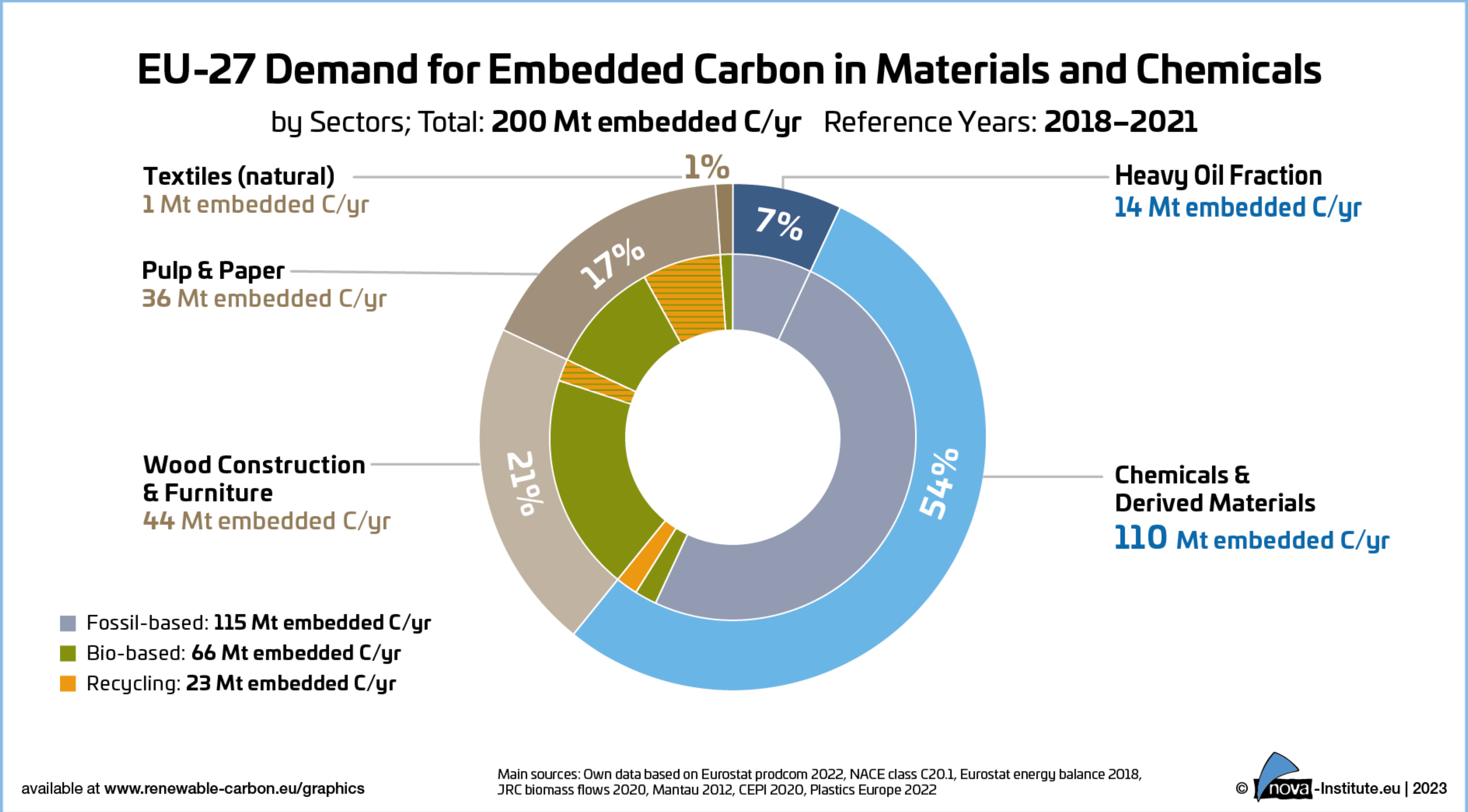
- Data for biomass demand in the material sector is derived from JRC 2022. Data gaps for bio-based chemicals & derived materials were filled with own methodology.
- Data for fossil demand is based on own methodology with derived data from Eurostat prodcom 2022. Data for plastic production and waste is used from Plastics Europe 2022.
- Data for C flows for EU-27 plastic production show similar results when using different data sources, as shown above. Therefore, data for plastics shown in the Sankey diagram are derived from Eurostat C20 class.
  - Import and export of plastics or plastic intermediates are not included. How the complex situation of intermediate import and export can be reflected in carbon flow charts is an open research question.



Flows of organic carbon in the EU-27 material and chemical sector

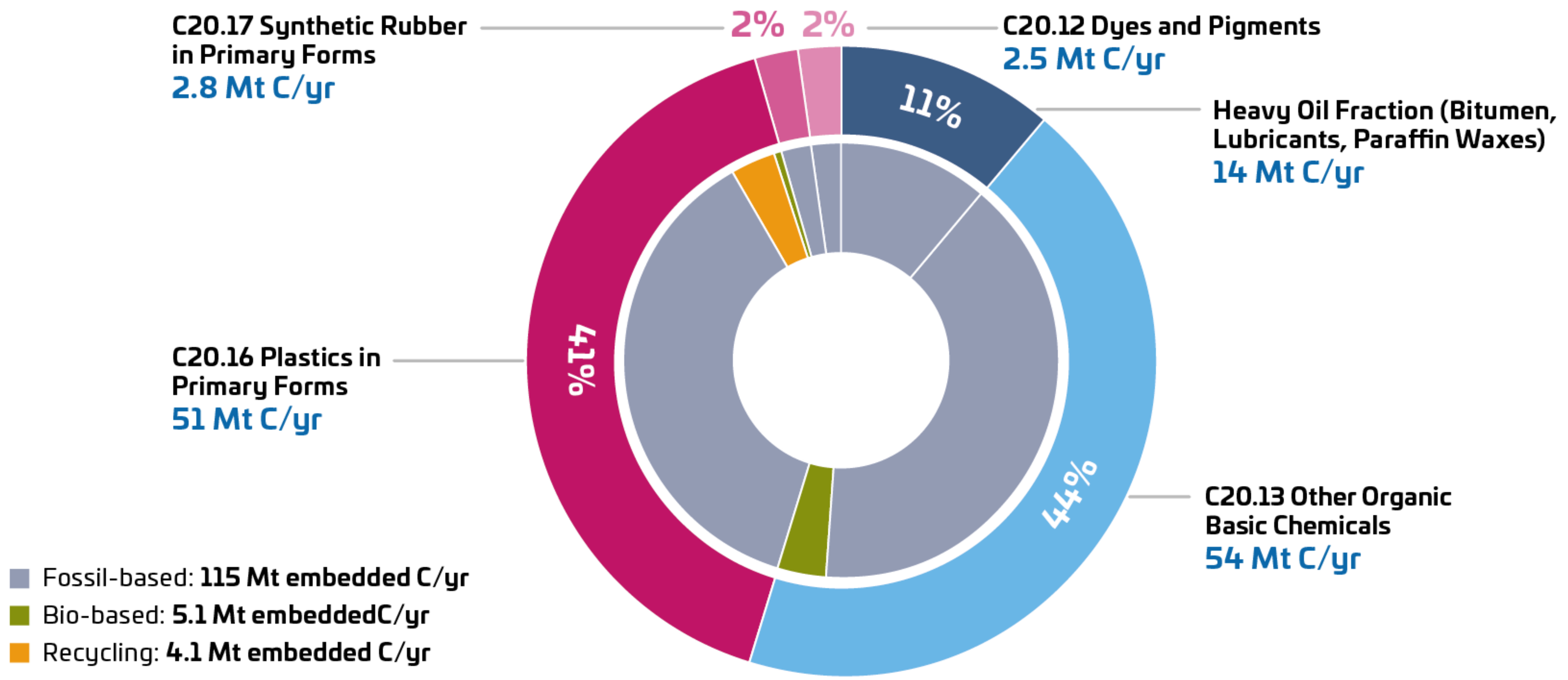
- Statistics for waste treatment types derived from Eurostat differ from data found in other sources.
  - For plastic waste, Eurostat states only around 0.6 Mt or 0.4 Mt C for landfill, while Plastics Europe 2020 state 6.9 Mt or 5.0 Mt C. Similar discrepancies occur for other waste treatment types.
  - For wood waste, Eurostat states 23.5 Mt or 10.3 Mt C for incineration and energy recovery of wood. In contrast, Mantau 2012 states, that 12.1 % of all wood products are incinerated, which corresponds to 4.8 Mt C.
  - For paper waste, Eurostat states 9.9 Mt or 7.1 Mt C. In contrast, CEPI 2020 report a recycling share of 74 %, which corresponds to 15.2 Mt C, when multiplied with the primary biomass input of 20.5 Mt C.
  - Reasons for the difference in data from Eurostat and from respective industry associations or cited studies may be different levels in the value chain (industrial waste / end-user waste / total waste), different definitions of sectors, different definitions of waste treatment shares (e.g., inclusion of waste exports).




EU-27 Demand for Embedded Carbon in Materials and Chemicals
by Sectors; Total: 200 Mt embedded C/yr Reference Years: 2018–2021
Textiles (natural)
1 Mt embedded C/yr
1%
Heavy Oil Fraction
14 Mt embedded C/yr
7%
Pulp & Paper
36 Mt embedded C/yr
17%
Wood Construction & Furniture
44 Mt embedded C/yr
21%
54%
Chemicals & Derived Materials
110 Mt embedded C/yr
Fossil-based: 115 Mt embedded C/yr
Bio-based: 66 Mt embedded C/yr
Recycling: 23 Mt embedded C/yr
available at www.renewable-carbon.eu/graphics
Main sources: Own data based on Eurostat prodcom 2022, NACE class C20.1, Eurostat energy balance 2018, JRC biomass flows 2020, Mantau 2012, CEPI 2020, Plastics Europe 2022
© nova-Institute.eu | 2023

Carbon Demand for Embedded Carbon in the EU-27 Chemical Industry

Total: **124 Mt embedded C/yr** Reference Years: **2018–2021**



Main sources: Own Data Based on Eurostat prodcom 2022, NACE class C20.1, Eurostat energy balance 2018, Plastics Europe 2022b, Plastic recyclates

How we define "chemicals and derived materials"

- There is no established definition of the sector of chemicals and materials derived from it ("derived materials" include plastic and rubber)
- The following sectors are included for chemicals and derived materials:

Product group	included / excluded	explanation
C19 coke and refined petroleum products	excluded	Mostly energy / transport sector
C20.1 Basic chemicals, fertilisers and nitrogen compounds, plastics and synthetic rubber in primary forms	included (with exceptions, see below)	Basic chemicals needed for other (sub-) classes
C20.11 Industrial gases	excluded	Non-carbon gases
C20.13 Other inorganic basic chemicals	excluded	Inorganic chemicals are out of scope
C20.2 to C20.6 (e.g., agrochemicals, paints, fibres, etc.)	excluded	Derived from basic chemicals contained in class 20.1
C21 Pharmaceuticals	excluded	Derived from basic chemicals
C22 Rubber and plastic products	excluded	Derived from basic chemicals
Heavy oil fraction (Bitumen, Lubricants, Paraffin waxes)	included	This class is presumably not covered in C20

NACE classes C19 to C22 according to EU prodcom statistics, "Others" according to Eurostat energy balances

Challenges in data for EU chemical and derived material sector

- It is questionable if it is necessary to exclude all the classes stated on the previous slide to avoid double counting.
- Furthermore, import of intermediates (like monomers) consumed by plastic converters among others is not included. It remains unclear, if import of intermediates is accounted for in Eurostat energy imports or if other data sources can be evaluated to fill that gap.
- When using data for production volume from Eurostat, carbon in products is account for, instead of carbon embedded in feedstock demand for these products. A loss factor could be considered, that reflects losses between feedstock to product. Due to high uncertainty, this is not carried out here. So, the actual feedstock demand may be even higher.
- The result achieved with this method (124 Mt C, of which 115 Mt C_{fossil}) differ drastically from data from Eurostat energy balances (75 Mt C_{fossil} Final non-energy consumption (see Flows of organic carbon in the EU-27 economy)
- The reason for these discrepancies remain unclear.
  - It is not clear, if and where the heavy oil fraction is accounted for in EU prodcom statistics. For this study, figures for the heavy oil fraction were ADDED to the prodcom C20.1 class.
  - De Smedt 2022 estimates the fossil feedstock supply in the chemical industry lower at around 66 Mt C, based on data on European crackers

Summary of EU-27 carbon flows today (Mt C / yr)

	EU-27[1]		EU-27 Materials & chemicals[2,3]		EU-27 Chemical industry[2,4]		EU-27 Chemicals & derived materials[2,5]	
Total	**1700**	**100 %**	**200**	**100 %**	**124**	**100 %**	**110**	**100 %**
Fossil total	1100	67 %	115	56 %	115	93 %	100	92 %
Coal	180		2.7		2.7			
Gas	270		16		16			
Oil	670		96		96			
Primary Biomass	500	30 %	66	32 %	5.1	4 %	5.1	5 %
Cellulose	185		55		0.5		0.5	
Sugar & Starch	145		2		1.5		1.5	
Fat/Oil	54		2		1.8		1.8	
Protein	58		0		0.0		0.0	
Others[6]	53		8		1.3		1.3	
Recyclates, Secondary biomass	38[7]	3 %	23	11 %	4.1	3 %	4.1	4 %

1 - includes carbon input of fossil and biogenic raw materials plus recyclates in the world economy (food and feed, energy sector, transport, materials and chemicals)
2 - only embedded carbon; energetic use excluded
3 - includes chemicals and derived materials (plastics, rubber), including the heavy oil fraction (bitumen, paraffin waxes, lubricants) and bio-based industries (wood for construction, pulp & paper, textiles)
4 - includes chemicals and derived materials (plastics, rubber), including the heavy oil fraction (bitumen, paraffin waxes, lubricants)
5 - includes chemicals and derived materials (plastics, rubber)
6 - includes lignin, natural rubber, etc
7 - includes material recycling and incineration
Various sources; Various reference years, mainly 2018-2020

Share of renewable carbon

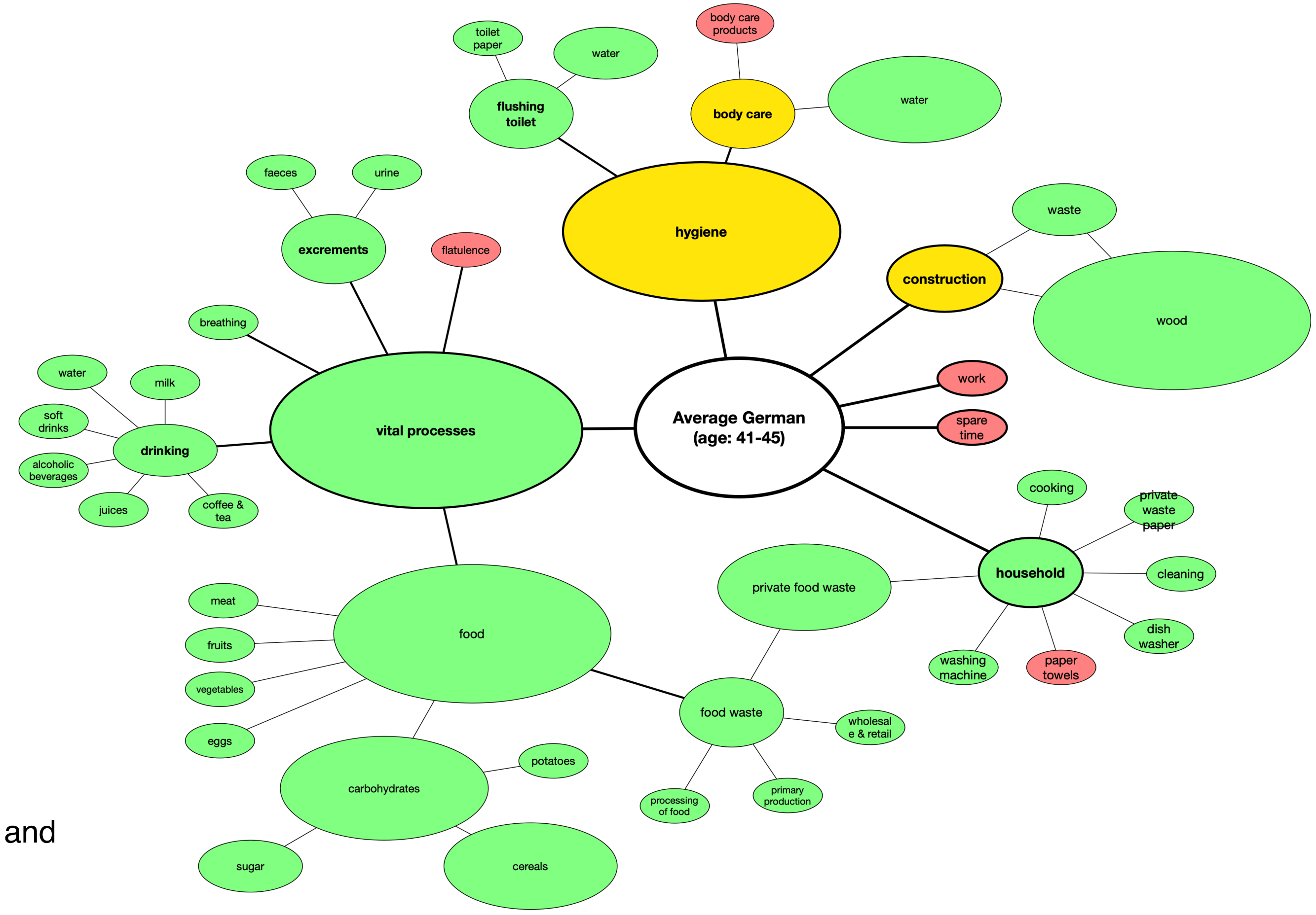
- According to these data, the EU-27 share of renewable feedstock is
  - Total: 33 % (30 % bio-based, 3 % recycling)
  - Chemicals & materials: 44 % (33 % bio-based, 11 % recycling)
  - Chemical industry: 7 % (4 % bio-based, 3 % recycling)
  - Chemicals & derived materials: 8 % (5 % bio-based, 4 % recycling)
- For the bio-based economy, nova-Institute calculates a bio-based share of 9 % (in the 2022 update to the BIC report, see Porc et al. 2022). The difference lays in different definitions of the bio-based economy and the chemical industry:
  - The bio-based economy (classes of prodcom C20, that contain bio-based products) includes some subclasses that are out of scope of this report (see How we define "chemicals and derived materials")
  - Fertilisers (C20.15), an important class by production volume and a relatively high bio-based share
    - Inorganic fertilisers are excluded due to the focus on organic carbon only
    - Organic fertilisers (manure) are not included in the scope of chemicals & materials
  - Despite chemicals & derived materials, the class "Chemical industry" also includes the heavy oil fraction (bitumen, lubricants and paraffin waxes), which are 100 % fossil
- While this study focuses on carbon demand, the BIC study focuses on production volume

8. Carbon Flows caused by a single human

Carbon flows caused by a single human

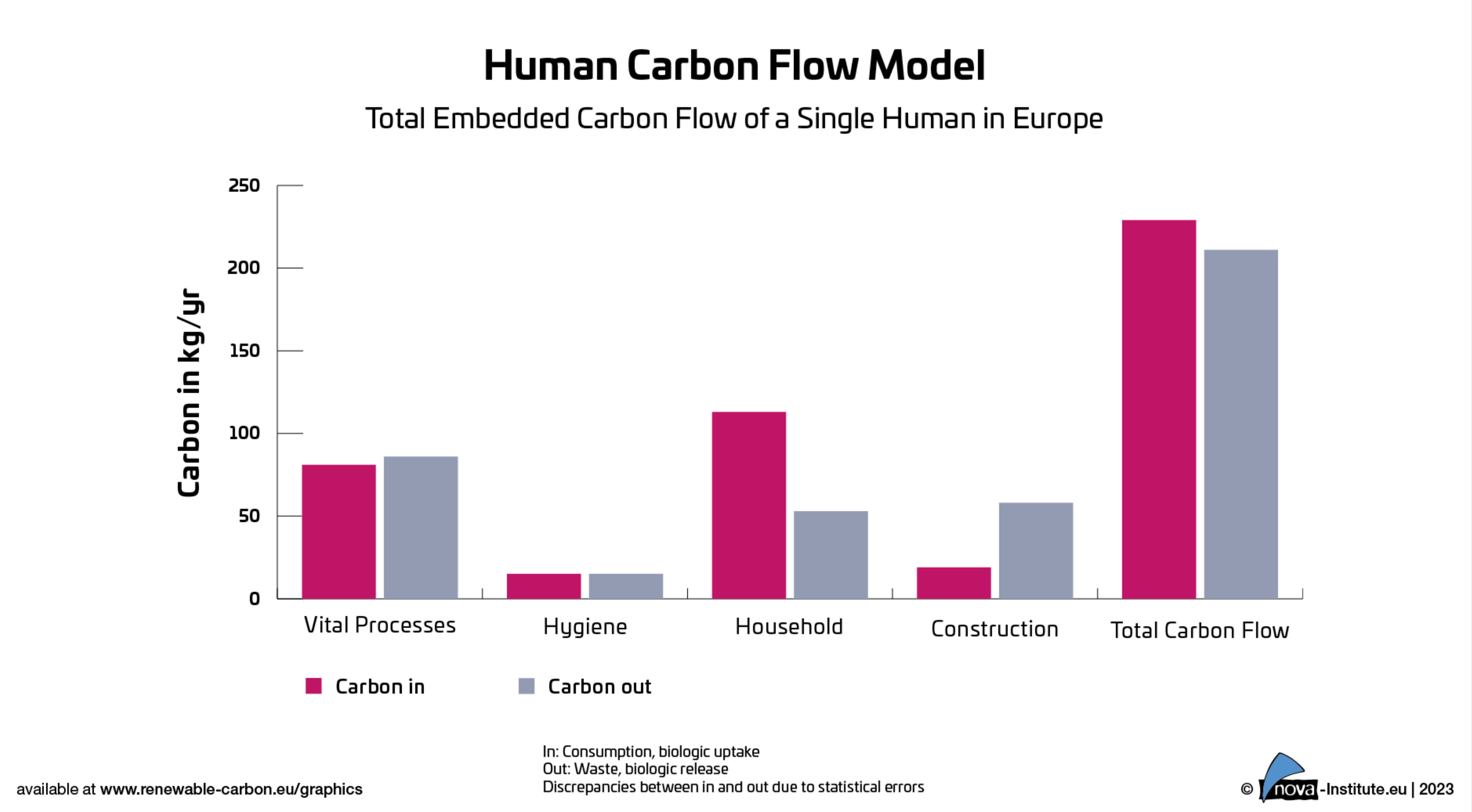
- All data assessed in this study follow a top down approach: Supply and demand are accounted on the level of whole-economies
- In contrast, a bottom-up approach is tested in the following chapter. It is examined, whether meaningful data can be collected, when the consumption of carbon flows by a single person are gathered.
- A test subject was chosen: nova employee, 25 years old, German, male
- All every-day activities associated with consumption of substances based on organic carbon were tracked for a time period and extrapolated for yearly consumption and partly corrected to represent an average person. Where tracking was not feasible, estimations are applied. Remaining data gaps were filled with bottom-up data.
- Detailed documentation can be found in the Carbon Economy study, where we initially published the approach, see European Commission 2021

Aspects considered for embedded carbon flows caused by a single human

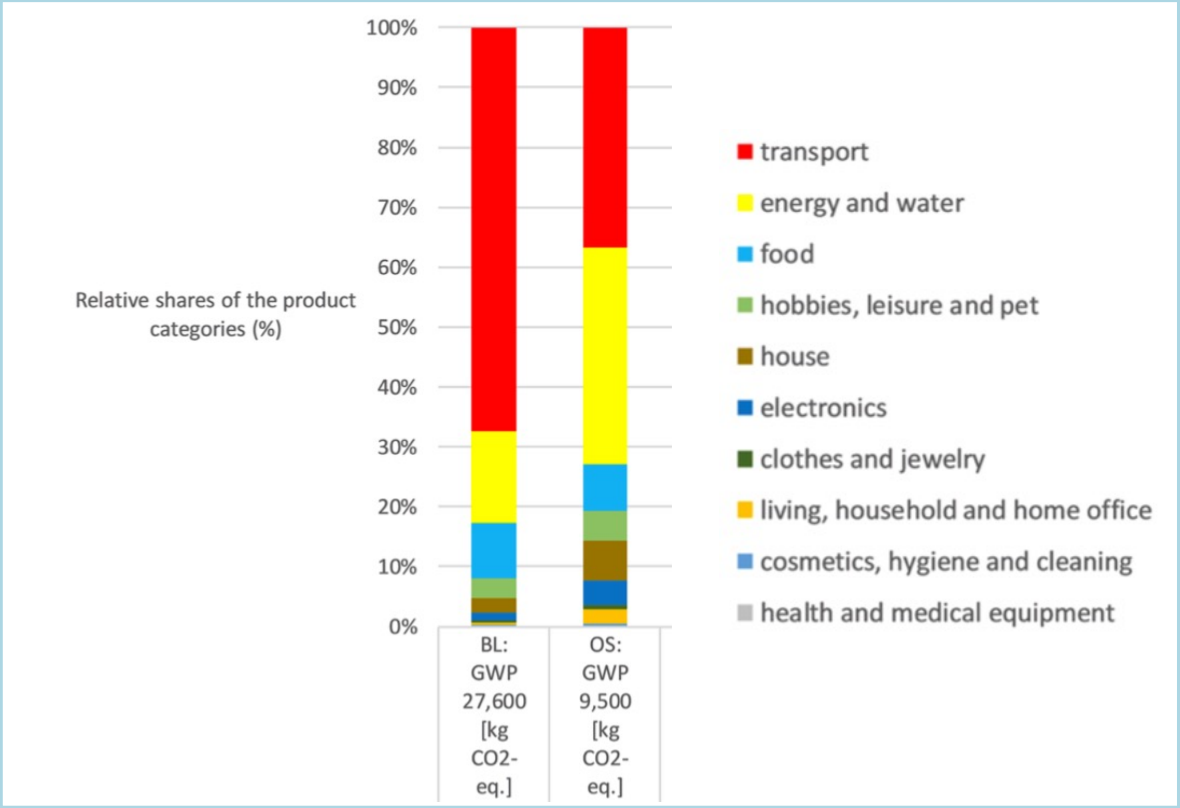


Colour indicates data quality:
green – good data quality;
yellow – fair data quality;
red – poor data quality
No data were measured for heating and transport, among others

nova-Institute 2021


Human Carbon Flow Model
Total Embedded Carbon Flow of a Single Human in Europe
Carbon in kg/yr
250
200
150
100
50
0
Vital Processes
Hygiene
Household
Construction
Total Carbon Flow
Carbon in
Carbon out
In: Consumption, biologic uptake
Out: Waste, biologic release
Discrepancies between in and out due to statistical errors
available at www.renewable-carbon.eu/graphics
© nova-Institute.eu | 2023

Similar approach from another study to calculate GHG emissions caused by a single human



BL – Baseline scenario; OS – optimised scenario
Source: Bossek et al. 2021.
https://doi.org/10.1007/s11367-021-01924-y

RENEWABLE CARBON INITIATIVE

Sources

- Ajani, J. I., Keith, H., Blakers, M., Mackey, B. G. and King, H. P. 2013. Comprehensive carbon stock and flow accounting: a national framework to support climate change mitigation policy. Ecological Economics, Vol. 89 61-72
- Bar-On, Y. M., Phillips, R. and Milo, R. 2018. The biomass distribution on Earth. Proceedings of the National. Academy of Sciences, Vol. 115 (25), 6506-6511.
- BGR 2019. BGR Energy Study 2018 – Data and Developments Concerning German and Global Energy Supplies (22). Federal institute for Geosciences and natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe – BGR) (Ed.), Hannover, Germany.
- Bos, H. L. and Broeze, J. 2020. Circular bio-based production systems in the context of current biomass and fossil demand. Biofuels, Bioproducts and Biorefining, Vol. 14 (2), 187-197. doi: 10.1002/bbb.2080
- Bossek, D., Goermer, M., Bach, V., Lehmann, A., Finkbeiner, M. Life-LCA: the first case study of the life cycle impacts of a human being. Int J Life Cycle Assess 26, 1847–1866 (2021). https://doi.org/10.1007/s11367-021-01924-y
- Boucher, J., Friot, D., 2017. Primary Microplastics in the Oceans : a Global Evaluation of Sources. International Union for Conservation of Nature and Natural Resources, Gland, Switzerland. https://holdnorgerent.no/wp-content/uploads/2020/03/IUCN-report-Primary-microplastics-in-the-oceans.pdf
- BP Report. Dudley, B. 2019. BP statistical review of world energy 2019. BP (Ed.), London, UK, Download at https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical- review/bp-stats-review-2019-full-report.pdf

Sources

- CEPI (2020). Global Life Cycle Paper Flows, Recycling Metrics, and Material Efficiency, https://doi.org/10.1111/jiec.12613
- Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J. and Heimann, M. 2014. Carbon and other biogeochemical cycles. Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press (Ed.).
- Czamanski, Marie & Nugraha, Adi & Pondaven, Philippe & Lasbleiz, Marine & Masson, Annick & Caroff, Nicolas & Bellail, Robert & Tréguer, Paul. 2011. Carbon, nitrogen and phosphorus elemental stoichiometry in aquacultured and wild-caught fish and consequences for pelagic nutrient dynamics. Marine Biology. 158. 2847-2862. 10.1007/s00227-011-1783-7.
- de Smedt (Cefic), Philip. 2022: Personal communication. 22-11-22.
- Dominguez-Huerta, G., Zayed, A. A., Wainaina, J. M., Guo, J., Tian, F., Pratama, A. A., Bolduc, B., Mohssen, M., Zablocki, O., Pelletier, E., Delage, E., Alberti, A., Aury, J.-M., Carradec, Q., da Silva, C., Labadie, K., Poulain, J., Bowler, C., Eveillard, D., Guidi, L., Karsenti, E., Kuhn, J. H., Ogata, H., Wincker, P., Culley, A., Chaffron, S. and Sullivan, M. B. 2022: Diversity and ecological footprint of Global Ocean RNA viruses. Science, Vol. 376 (6598), 1202-1208. doi: doi:10.1126/science.abn6358
- EPA (2016). Wood: Material-Specific Data. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/wood-material-specific-data
- European Commission 2021: Carbon economy : studies on support to research and innovation policy in the area of bio-based products and services.

Sources

- European Tyre & Rubber Industry - Statistics Edition 2021. https://www.etrma.org/wp-content/uploads/2021/12/20211030-Statistics-booklet-2021VF.pdf
- Eurostat 2022: Complete energy balances [nrg_bal_c]. (Ed.), Download at https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_c/default/table
- Eurostat 2022b: Prodcom - Statistics by products. (Ed.), Download at https://ec.europa.eu/eurostat/web/prodcom/
- FAO. *Knowledge Reference For National Forest Assessments - Modeling For Estimation And Monitoring*. 2020 [cited 2020 11-05-2020]; Available from: http://www.fao.org/forestry/17111/en/>
- Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Hauck, J., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Le Quéré, C., Bakker, D. C. E., Canadell, J. G., Ciais, P., Jackson, R. B., Anthoni, P., Barbero, L., Bastos, A., Bastrikov, V., Becker, M., Bopp, L., Buitenhuis, E., Chandra, N., Chevallier, F., Chini, L. P., Currie, K. I., Feely, R. A., Gehlen, M., Gilfillan, D., Gkritzalis, T., Goll, D. S., Gruber, N., Gutekunst, S., Harris, I., Haverd, V., Houghton, R. A., Hurtt, G., Ilyina, T., Jain, A. K., Joetzjer, E., Kaplan, J. O., Kato, E., Klein Goldewijk, K., Korsbakken, J. I., Landschützer, P., Lauvset, S. K., Lefèvre, N., Lenton, A., Lienert, S., Lombardozzi, D., Marland, G., McGuire, P. C., Melton, J. R., Metzl, N., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S.-I., Neill, C., Omar, A. M., Ono, T., Peregon, A., Pierrot, D., Poulter, B., Rehder, G., Resplandy, L., Robertson, E., Rödenbeck, C., Séférian, R., Schwinger, J., Smith, N., Tans, P. P., Tian, H., Tilbrook, B., Tubiello, F. N., van der Werf, G. R., Wiltshire, A. J. and Zaehle, S. 2019. Global Carbon Budget 2019. Earth System Science Data, Vol. 11 (4), 1783-1838. doi: 10.5194/essd-11-1783-2019

Sources

- Grand View Research, 2015a. Adhesives and Sealants Market Analysis By Technology (Water-based, Solvent-based, Hot Melt, Reactive), By Product (Acrylic, Polyurethane, Polyvinyl Acetate (PVA), Epoxy, EVA), By Application (Pressure Sensitive, Construction, Automotive, Packaging, Furnit [WWW Document]. URL https://www.grandviewresearch.com/industry-analysis/adhesives-and-sealants-market (accessed 1.4.18).
- Haas, W., Krausmann, F., Wiedenhofer, D. and Heinz, M. 2015. How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005. Journal of Industrial Ecology, Vol. 19 (5), 765-777. doi: 10.1111/jiec.12244
- Helander, H., Petit-Boix, A., Leipold, S. and Bringezu, S. 2019. How to monitor environmental pressures of a circular economy: An assessment of indicators. Journal of Industrial Ecology, Vol. 23 (5), 1278-1291. doi: 10.1111/jiec.12924
- Hepburn, C., Adlen, E., Beddington, J., Carter, E. A., Fuss, S., Mac Dowell, N., Minx, J. C., Smith, P. and Williams, C. K. 2019. The technological and economic prospects for CO2 utilisation and removal. Nature, Vol. 575 (7781), 87-97. doi: 10.1038/s41586-019-1681-6
- Krtková, E., Danielik, V., Szemesová, J., Tarczay, K., Kis-Kovács, G. and Neuzil, V. 2019. Non-Energy Use of Fuels in the Greenhouse Gas Emission Reporting. Atmosphere, Vol. 10 (7), 406. doi: 10.3390/atmos10070406
- IEA 2020. World Energy Balances Overview 2020. IEA (Ed.)
- IEA Energy Balances (2019). https://www.iea.org/data-and-statistics/data-tables
- IEA Technology Roadmap – The global iron and steel sector. International Energy Agency, 29th March 2019, Paris. https://iea.blob.core.windows.net/assets/imports/events/169/0.PeterLevi.pdf

Sources

- IEA (2020b). IEA Renewables 2020 - Analysis and forecast to 2025. https://iea.blob.core.windows.net/assets/1a24f1fe-c971-4c25-964a-57d0f31eb97b/Renewables_2020-PDF.pdf
- Janowiak, M. C., William J.; Dante-Wood, Karen; Domke, Grant M.; Giardina, Christian; Kayler, Zachary; Marcinkowski, Kailey; Ontl, Todd; Rodriguez-Franco, Carlos; Swanston, Chris; Woodall, Chris W.; Buford, Marilyn. 2017. Considering Forest and Grassland Carbon in Land Management_USDA. United States Department of Agriculture, Forest Service (Ed.), Considering Forest and Grassland Carbon in Land Management. Gen. Tech. Rep. WO-95. Washington, D.C., Download at https://www.fs.usda.gov/treesearch/pubs/54316
- JRC – Joint Research Centre (2022) - Biomass flows. https://datam.jrc.ec.europa.eu/datam/mashup/BIOMASS_FLOWS/index.html
- Kähler, F., Carus, M., Porc, O. and vom Berg, C. 2021. Turning off the Tap for Fossil Carbon – Future Prospects for a Global Chemical and Derived Material Sector Based on Renewable Carbon. nova-Institute (Ed.), Hürth, Germany, Download at https://renewable-carbon.eu/publications/product/turning-off-the-tap-for-fossil-carbon-future-prospects-for-a-global-chemical-and-derived-material-sector-based-on-renewable-carbon/
- Kähler, F., Carus, M., vom Berg, C. and Stratmann, M. 2022. CO_2 Reduction Potential of the Chemical Industry Through CCU. nova-Institute (Ed.), Hürth, Germany, Download at https://renewable-carbon.eu/publications/product/co2-reduction-potential-of-the-chemical-industry-through-ccu-pdf/

RENEWABLE CARBON INITIATIVE

Sources

- Krist, T., Formeln und Tabellen Grundwissen Technik: Daten und Begriffe für Techniker und Ingenieure. 2013: Vieweg+Teubner Verlag.
- Levi, Peter G., and Jonathan M. Cullen. "Mapping global flows of chemicals: from fossil fuel feedstocks to chemical products." Environmental science & technology 52.4 (2018): 1725-1734.
- Mantau, U. (2012): Wood flows in Europe (EU27). Project report. Celle 2012, 24 pp
- nova-Institute 2021. Bio-based Building Blocks and Polymers – Global Capacities, Production and Trends 2020–2025
- OECD (2008), Measuring material flows and resource productivity. - The OECD guide 1
- OECD (2022), Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options, OECD Publishing, Paris, https://doi.org/10.1787/de747aef-en.
- *Phyllis2, database for (treated) biomass, algae, feedstocks for biogas production and biochar*. 2020; Available from: https://phyllis.nl/ECN.TNO.
- Piotrowski, S., Essel, R., Carus, M., Dammer, L. and Engel, L. 2015. Nachhaltig nutzbare Potenziale für Biokraftstoffe in Nutzungskonkurrenz zur Lebens- und Futtermittelproduktion, Bioenergie sowie zur stofflichen Nutzung in Deutschland, Europa und der Welt. nova-Institut (Ed.), Hürth, Germany, 2015-08. Download at http://bio-based.eu/markets/#Biomassepotenziale
- Porc, O., Hark, N., Carus, M., Dr. Carrez, D. and BIC 2022. European Bioeconomy in Figures 2008–2019. nova-Institute (Ed.), October 2022. Download at https://renewable-carbon.eu/publications/product/european-bioeconomy-in-figures-2008-2019-pdf/

Sources

- PlasticsEurope (2020). Plastics – the Facts 2020 - PLASTICS DEMAND BY RESIN TYPE 2019
- PlasticsEurope, 2016b. Plastics Europe. PlasticsEuropeMarket Research Group (PEMRG) / ConsulticMarketing & Industrieberatung GmbH
- PlasticsEurope 2022 - THE CIRCULAR ECONOMY FOR PLASTICS - A European Overview
- PlasticsEurope 2022b - Plastics – the Facts 2022
- S. Kent Hoekman, Amber Broch, Curtis Robbins, Eric Ceniceros, Mani Natarajan. Review of biodiesel composition, properties, and specifications. Renewable and Sustainable Energy Reviews, Volume 16, Issue 1, 2012, Pages 143-169, https://doi.org/10.1016/j.rser.2011.07.143
- Sinograce chemical, 2017. Global coating emulsion polymer in 2020 will reach 5 million tons [WWW Document]. URL http://www.sinogracechem.com/ blog/global-coating-emulsion-polymer-in-2020- will-reach-5-million-tons_b14 (accessed 1.4.18).
- TFY 2022. The Fiber Year. https://thefiberyear.com
- UNEP (2018). UN environment programme (2018). Mapping of global plastics value chain and plastics losses to the environment - With a particular focus on marine environment. https://www.unep.org/resources/report/mapping-global-plastics-value-chain-and-plastics-losses-environment-particular

Sources

- UNEP (2021). Zhongming, Z., Linong, L., Xiaona, Y., Wangqiang, Z. and Wei, L. 2021. UNEP Food Waste Index Report 2021. UNEP (Ed.), Download at https://www.unep.org/resources/report/unep-food-waste-index-report-2021
- World Bank, Kaza, S., Yao, L., Bhada-Tata, P. and Van Woerden, F. 2018. What a waste 2.0: a global snapshot of solid waste management to 2050. World Bank (Ed.), Download at https://datatopics.worldbank.org/what-a-waste/