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Development of a Sankey Diagram of Material Flows in the EU Economy based on Eurostat Data

Monitoring of non-energy & non-food material flows in the EU-28 for the EC Raw Materials Information System (RMIS)

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Abstract

Europe relies on reliable and robust knowledge on materials stocks and flows to promote innovation along the entire value chain of raw materials. The concept of the circular economy, recently adopted by the European Commission, aims at maintaining the value of products, materials, and resources in the economy for as long as possible, and minimize waste generation. One of the prerequisites for better monitoring materials use across the whole life-cycle is a good understanding of material stocks and flows. The goal of this report is thus to show how readily available statistical information can be used to generate a Sankey diagram of material flows and their circularity in the 28 member states of the European Union (EU-28).

Despite several data challenges, it is possible to develop a visual representation of material flows and their level of circularity in the EU-28 as well as for individual member states for the period 2004 to 2014 (with future updates possible as new statistical data sets become available). The focus is on non-energy and non-food materials in line with the European Innovation Partnership on Raw Materials (EIP-RM). This includes material flows used for their material quality including, e.g., metals, construction minerals, industrial minerals, and biomass like timber for constructions or fibres for paper or textiles. Materials used for their energy content like fossil fuels, fuel wood, feed or food are excluded. A combination of regularly available data sources including economy-wide material flow accounts (EW-MFA) and EU waste statistics are used to generate a Sankey diagram showing the flows and net additions to stocks of four major material categories (metals, construction minerals, industrial minerals, and biomass (timber and products from biomass)).

In 2014, the turnover of non-energy and non-food materials in the EU economy is found at 4.8 Gt[1] (direct material input + recycling and backfilling). Recycled materials make up around 0.7 Gt (15%) of all materials used in the EU-28 in 2014. Socioeconomic stocks are growing in the EU-28 at about 2.2 to 3.4 Gt each year (net additions to stocks during the period from 2004 to 2014). For example, in 2014 around 51% (2.3/4.5 Gt) of all non-energy and non-food materials used domestically within the EU were added to stocks. Stock accumulation limits the potential for current recovery because material stocks are not immediately available for recycling (but will become available in the future when products providing useful services to the EU economy reach their end-of-life). In 2014, total waste generated from non-energy and non-food materials use in the EU-28 amounted to 2.2 Gt. Some 1.9 Gt of this waste was treated in the EU-28. The largest share of this waste (about 41%) was subject to landfilling operations. About 33% of the waste treated in the EU-28 in 2014 was sent to recycling operations (recovery other than energy recovery and backfilling) and 10% was used in backfilling. The EU is largely self-sufficient for construction minerals and industrial minerals, somewhat import dependent for biomass (for materials purposes), but highly import-dependent for metals.

Sankey diagrams for eight individual member states including Austria, Belgium, Czech Republic, Finland, Spain, France, Germany, and Italy are generated and compared with each other. Overall material throughput is highest for Germany, France, and Italy. Belgium's economy depends on imports of a large number of raw materials, while several other EU countries domestically produce construction minerals and industrial minerals. Metals are imported by all member states although some EU countries (e.g., Finland) also have limited metal mining activities. In the eight EU member states examined, recycling and backfilling ranges between 11% and 68% at end-of-life (output side) and 6% and 27% when compared to overall material inputs (input side). Germany is used as a case study to show how the proposed visualization framework can be used to generate member state Sankey diagrams for multiple years.

[1] One gigaton (Gt) is equal to 1,000,000,000 metric tons.

Further research is needed to confirm these findings, fill in data gaps (e.g., trade in waste products), and better estimate selected flow parameters. However, the proposed assessment and visualization do provide a reasonable first picture of raw material uses and their flow magnitudes (by major material categories) in Europe, and how these evolve over time. The resulting Sankey diagrams will feed into the EC's Raw Material Information System's (RMIS) MFA module[2] (currently in development) to better visualize related material flows for the EU and at individual country level. The level of circularity can be measured considering different groups of raw materials. Because for materials used for energy purposes materials recovery is mostly not possible, we recommend including resource categories including fossil energy materials and biomass for food and energy purposes in future studies to obtain a more holistic picture of raw materials use in the EU.

[2] http://rmis.jrc.ec.europa.eu/?page=mfa-inventory-fc6a02#/countries_regions/default

1 Introduction

1.1 Material Flow Analysis

Europe relies on reliable and robust knowledge on material stocks and flows to promote innovation along the entire value chain of raw materials (EC, 2012). Using the analogy of biological systems, (Frosch and Gallopoulos, 1989) envisioned an economy in which flows of energy and materials are optimized, waste generation is reduced, and by-products are beneficially used in co-located processes. Recently, the European Commission launched a Circular Economy Package to stimulate Europe's transition toward a more circular economy (EC, 2015). Circular economy is defined as a state in which "the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste is minimized" (EC, 2015). In 2017, the Commission plans to present a report on Critical Raw Materials (CRMs) in the circular economy, a strategy for plastics, an assessment of options for the improved interface between chemicals, products and waste legislation, a legislative proposal on water reuse, and a monitoring framework on circular economy (EC, 2017).

Against this background, it is essential to better understand Europe's societal metabolism, i.e., to regularly monitor the material flows and stocks within the EU economy, their level of circularity, and highlight data gaps and possible research areas for the future. The Raw Materials Information System (RMIS) [3] acts as the central component of the EU's Knowledge Base on Raw Materials [4] and aims to help in monitoring the raw materials situation in Europe across the whole life-cycle of materials, i.e., from resource extraction to material processing to manufacturing and fabrication to use and then to collection, processing, and disposal (Manfredi et al., 2017).

Material flow analysis (MFA) approaches (Brunner and Rechberger, 2016) have been used widely over the past decade to characterize the life cycles of materials and substances (Chen and Graedel, 2012). Material flows and stocks can be illustrated using Sankey diagrams (Schmidt, 2008) if the number of transformation processes is small, or network visualizations (Nuss et al., 2016) for datasets involving a larger number of transformations steps and material flows between them. Understanding the whole system of material flows can help to quantify potential primary and secondary source strengths, manage metal use more wisely, and protect the environment.

[3] http://rmis.jrc.ec.europa.eu/
[4] https://ec.europa.eu/jrc/en/scientific-tool/raw-materials-information-system

Text box: Material Flow Analysis Studies in the EU-28.

In the European context, a number of static (describes material stocks and flows as a "snapshot" in time) and dynamic (describes how materials stocks and flows evolve over time) MFAs have been carried out for some member states or Europe as a whole (Figure 1).

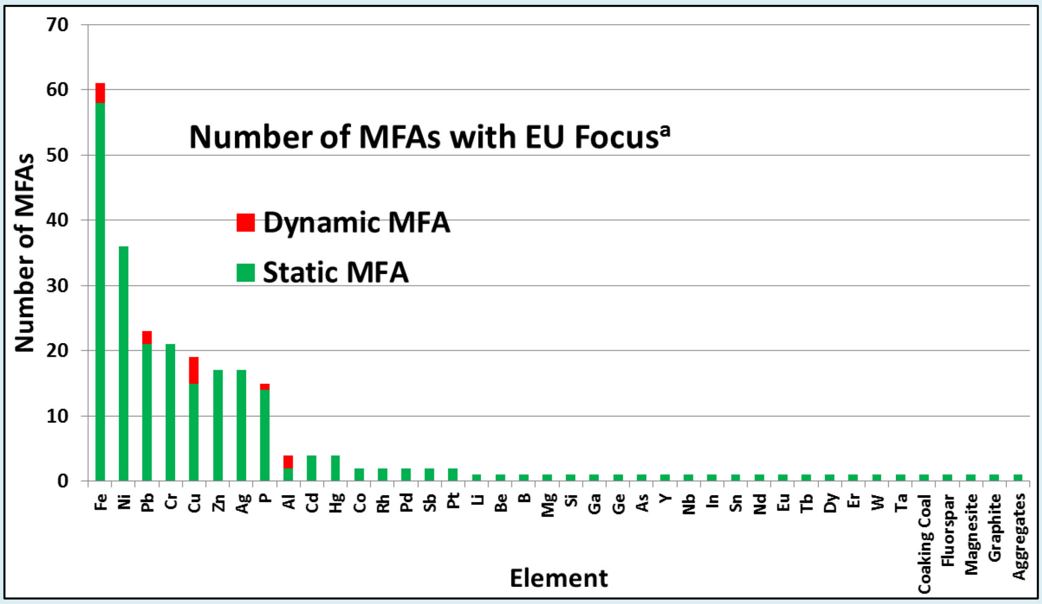


Figure 1 Number of material flow analysis (MFAs) of individual materials.

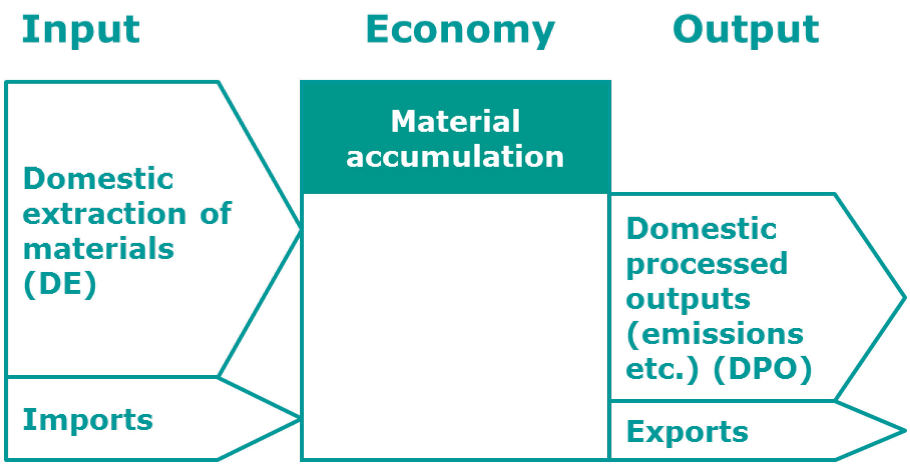
[a]Data sources: (BIO by Deloitte, 2015; Chen and Graedel, 2012). Note that the literature review by (Chen and Graedel, 2012) ends in 2012 and with the exception of tantalum (Ta) (Deetman et al., 2017) and copper (Cu) (Ciacci et al., 2017) more recent studies are not considered except for the EU MSA study (BIO by Deloitte, 2015).

Recently, the *Material System Analysis (MSA) study* (BIO by Deloitte, 2015) provides MFA results for 28 materials including a number of elements for which no MFA studies exist from other public studies. This study is currently being reviewed in the context of future maintenance and update and further expanded by adding new materials by the EC's DG Joint Research Centre (JRC) Directorate for Sustainable Resources. It is also foreseen to integrate the MSA studies into a MFA module within the RMIS.

1.2 Economy-Wide Material Flow Accounts (EW-MFA)

In contrast to material-specific assessments, economy-wide material flow accounts (EW-MFA) (Fischer-Kowalski et al., 2011) capture the domestic extraction, imports, and exports of material flows into and out of socioeconomic systems (e.g., Europe) (EUROSTAT, 2013). Eurostat compiles EW-MFA data on an annual basis and a variety of material flow-based indicators are derived from EW-MFA, for example domestic material consumption (DMC) which is an indicator in the context of, e.g., resource efficiency (Figure 2).

Figure 2 Economy-wide material flow accounts (EW-MFA) framework according to Eurostat[5]



Recently, the UNEP International Resource Panel has published a global material flow database with EW-MFA indicators for most countries over the past 40 years (UNEP, 2016). This also relates to monitoring of the United Nations Sustainable Development Goals (SDGs) 8.4[6] and 12.2[7] (United Nations, 2016). In contrast to MFA studies of individual materials (Chen and Graedel, 2012), EW-MFA provides an aggregate overview, in thousand tonnes per year, of major material categories including biomass, metal ores, non-metallic minerals, and fossil energy materials/carriers.

1.3 Circular Economy Material Flow Visualizations and Related Indicators

Based on material flow accounts and waste statistics, research entities and governments have begun to monitor the economy-wide flow of major material categories in countries and regions, and show their level of circularity. For example, basic material flow analysis for the *Japanese economy* is published by the Ministry of the Environment in the context of the Fundamental Plan for Establishing a Sound Material-Cycle Society (MOEJ, 2013, 2010, 2008). This includes a Sankey diagram showing the level of materials circularity in Japan which is used in combination with three core indicators looking at resource productivity, cyclical use rate, and the final disposal amount[8].

For the EU-27 as well as the United Kingdom, WRAP UK produced a simplified Sankey diagram showing anticipated resource flows in 2020, but without elaborating about potential indicators as a result of this (WRAP, 2016). Recently, a study by the Alpen-Adria University has used EW-MFA data in combination with their own data bases to provide additional insights into the flow and circularity of material flows in the EU economy (Haas et al., 2015). The authors of this study propose a number of possible circular economy indicators including, e.g., the share of raw materials used for materials

[5]Source: http://ec.europa.eu/eurostat/web/environment/material-flows-and-resource-productivity
[6] SDG Goal 8: Promote inclusive and sustainable economic growth, employment and decent work for all. Section 8.4: Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programmes on sustainable consumption and production, with developed countries taking the lead.
[7]SDG Goal 12: Ensure sustainable consumption and production patterns. Section 12.2: By 2030, achieve the sustainable management and efficient use of natural resources.
[8] Additional information about Japan's Fundamental Plan for Establishing a Sound Material-Cycles Society can also be found at https://www.env.go.jp/en/recycle/smcs/

purpose compared to total processed material or the share of short-lived products in comparison to processed material.

The cyclical use rate introduced by Japan has also recently been applied to the Czech Republic for 2002 – 2011 using EW-MFA data (Kovanda, 2014). The study suggested that the cyclical use rate of the Czech Republic lags behind Japan both in terms of absolute value and trend development, although the indicator is higher for biomass in the Czech Republic.

The scientific discussion on circular economy indicators has gained momentum in recent years (EASAC, 2016; Ellen McArthur Foundation, 2015; Haas et al., 2015; Hashimoto et al., 2004; Haupt et al., 2016; Huysman et al., 2017; Kovanda, 2014; Linder et al., 2017; MOEJ, 2013, 2010, 2008). More recently, discussions related to the importance of social and institutional aspects in the circular economy concept (Moreau et al., 2017) and possible limitations including on "circular economy rebound" (Zink and Geyer, 2017) and materials losses and energy requirements of closed loops (Cullen, 2017) are increasing among the scientific community. Circular economy indicators cover a wide range of topics and a recent summary is provided, e.g., in (EASAC, 2016; Ellen McArthur Foundation, 2015; Haupt et al., 2016).

1.4 Goal of this Report

EU policies, such as the Raw Materials Initiative (RMI) and Circular Economy Action Plan, rely on information and data on material flows and stocks within the EU economy and their level of circularity (EC, 2012). Against this background, the **goal of this report** is to show how readily available statistical information (based on Eurostat data) can be used to generate a Sankey diagram of material flows and their circularity in the EU-28 as well as for individual EU member states. The focus is on non-energy and non-food raw materials (i.e., raw materials used for their material qualities and not their energy content) following the focus of the European Innovation Partnership on Raw Materials (EIP-RM).

As such, we are developing an operational approach which provides a first overview of the flows of major materials categories in the EU-28 economy. It is therefore seen as complementary to more elaborate studies (e.g., (Haas et al., 2015)) that provide more details but rely on a number of assumptions and might therefore not be updated without significant research efforts.

The Sankey diagram developed in this report could then be included in the EC's RMIS (Manfredi et al., 2017) in the MFA module to show country-level features[9], as well as in other European Commission (EC) raw material dossiers that help illustrating the EU raw materials situation and the level of circularity at an aggregate level. This report also includes a critical review of available data sources and recommendations for future research needs and highlights missing data.

While the focus is on non-energy and non-food materials, the possibilities to include additional material categories including fossil fuels and biomass for food and energy purposes are discussed. Including these additional material categories would provide a more holistic assessment of material flows in the EU. They are also important to be considered in the discussion of a circular economy, because energetic uses, e.g., for heat and power generation, prohibit recycling for of the raw materials for subsequent materials purposes. A recent study of biomass flows in the EU is provided, e.g., by (Gurría et al., 2017).

[9] http://rmis.jrc.ec.europa.eu/?page=mfa-inventory-fc6a02#/countries_regions/default

2 Methodology

2.1 Modelling Framework

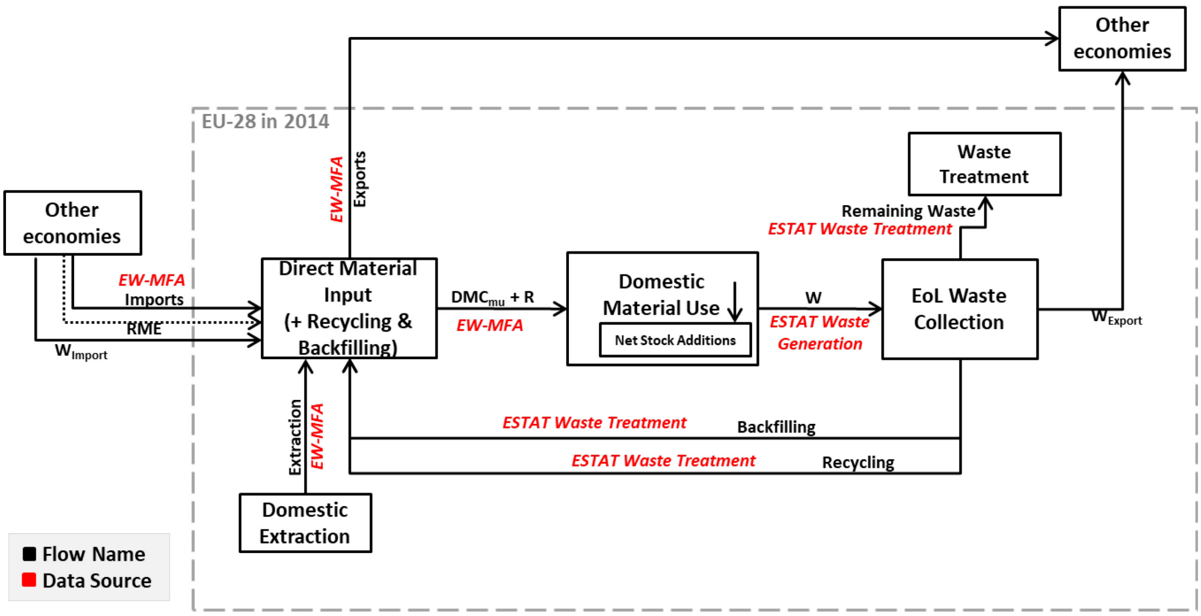
The focus of this report is on the development of a Sankey diagram showing the flow of major material categories in the EU-28. Key criteria for data selection include:

- The data availability for multiple years (i.e., time series),
- Coverage of all 28 EU member states, and
- Reliability of data sources.

For this, the most recent Eurostat data from EW-MFA (EUROSTAT, 2013) and waste statistics (EUROSTAT, 2016a) are used. The advantage of this approach is that the resulting Sankey visualization could be easily updated and might be linked to existing raw material dossiers of the Commission such as the RMIS and others. Using Eurostat data, it is also possible to track material and waste flows at individual EU member state level. A possible disadvantage is that the Sankey diagram has to follow strictly the reporting in official statistics (i.e., Eurostat) and might not provide the level of detail required by decision makers to properly monitor the material patterns of the circular economy in Europe.

Based on the Eurostat data available, a schematic illustration of the proposed Sankey diagram is shown in Figure 3. In this diagram, processes are represented as rectangles and represent the transformation or storage of materials. Processes are linked by flows (mass per time) of materials and represented by arrows in the diagram.

Figure 3 Modelling framework for material flows (only non-energy and non-food) in the EU-28[10]. Rectangles represent processes while arrows represent flows of materials between processes. Data sources, if known, are shown in red font.



[10] Note that the EU-28 system boundary shown in the figure represents a geographical boundary. As such, the process entitled 'Domestic Extraction' is located inside the system boundary, even though in EW-MFA it would be placed outside the system boundary of the EU economy. Similarly, the waste treatment process shows the flows of materials into, e.g., landfills, waste incinerators, and would be connected to a process entitled 'Domestic Processed Output (DPO)' in EW-MFA.

Flow	Explanation and Data Source
Extraction	Domestic extraction (DE) of materials (EW-MFA)
Imports	Extra EU imports of materials (EW-MFA)
Exports	Extra EU exports of materials (EW-MFA)
DMC_{mu} + R	DMC_{mu} = Domestic Material consumption for material uses (mu). R = Recovery (other than energy recovery) including recycling (Item 3a) and backfilling (Item 3b) (EW-MFA and ESTAT waste treatment)
(Net) stock additions*	In-use stock additions (i.e., the difference between domestic material consumption (incl. recovered materials) and waste generation (calculation)
W	Waste generation (ESTAT waste generation)
$W_{Import,\ Export}$	Waste imports and exports (ESTAT transboundary waste shipments)[11] (not included in this study)
Recycling	Item 3a Material Recovery (ESTAT waste treatment)
Backfilling	Item 3b Backfilling (ESTAT waste treatment)
Discards	Landfill, incineration, waste to energy, and others (ESTAT waste treatment)
RME	Raw Material Equivalents (Upstream material requirements of used extractions) (EW-MFA)

*The net stock change (net accumulation) is equal to the difference between inputs and outputs. Ideally, the Sankey diagram would show the flow into and out of stocks (with stocks as a separate process). However, because this requires additional information, e.g., on the life-time of products in use or a stocking rate estimate, we only show the net stock additions in a single year calculated simply as the difference between domestic material consumption (incl. recovered material) and waste generated.

2.2 Data Sources

2.2.1 Economy-Wide Material Flow Accounts (EW-MFA)

As indicated in Figure 3, the extraction of raw materials and their imports and exports can be captured using **Economy-Wide Material Flow Accounts (EW-MFA)**[12] (EUROSTAT, 2013) which are currently available for the following material categories: biomass (MF1), metal ores (MF2), non-metallic minerals (MF3), and fossil energy materials/carriers (MF4)[13].

While domestic extraction includes only raw materials[14], traded goods constitute primary and processed material. For simplicity, material flows as reported by Eurostat are used. This means that for domestic extraction, we do not convert metal flows from gross weight into metal content using the available conversion factors (see section 2 of the EW-MFA manual (EUROSTAT, 2013) for the conversion factors available). Similarly, no additional adjustments of water contents (into dry weight) are made in any of the data.

The external trade statistics ('extra EU imports' and 'extra EU exports') are grouped by Eurostat into material groups which are similar to the classification of material flows for

[11] http://ec.europa.eu/eurostat/web/waste/transboundary-waste-shipments
[12] http://ec.europa.eu/eurostat/web/products-datasets/-/env_ac_mfa
[13] http://ec.europa.eu/eurostat/web/environment/material-flows-and-resource-productivity/database
[14] Domestic extraction, abbreviated as DE, is the input from the natural environment to be used in the economy. DE is the annual amount of raw material (except for water and air) extracted from the natural environment (http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Domestic_extraction_(DE)).

domestic extraction (EUROSTAT, 2013). The import and export flows in EW-MFA encompass products and waste, are measured in mass weight, and refer to the traded weight of the goods. The extra EU import and extra EU exports data are used for the visualization of trade flows in the EU-28. For individual member states, the total import and total export statistics are instead used which include both intra and extra EU trade flows.

While the focus is non-energy and non-food materials following the EIP-RM, the Sankey diagrams presented in this report also include material products from animals (e.g., animal fibres, skins, furs, leather, etc.) because these represent material uses. However, the material category is only relevant for imports and exports and is found to be around 2% of all biomass imports and 2% of all biomass exports, i.e., is negligible in terms of overall flow magnitude.

Table 6 in the annex provides an overview of all material categories covered by the EW-MFA statistics and specifies those included in this assessment. Only a subset of the EW-MFA material categories is included in this Sankey visualization, namely flows relating to metals, construction minerals, industrial minerals, and non-energy & non-food biomass (Table 1).

Table 1: Resource categories taken from the Eurostat Economy-wide MFA (EW-MFA) statistics and their corresponding Eurostat identifier codes[1].

Category	Material	Code
Metals	Iron	MF21
	Copper	MF221
	Nickel	MF222
	Lead	MF223
	Zinc	MF224
	Tin	MF225
	Gold, silver, platinum and other precious metals	MF226
	Bauxite and other aluminium	MF227
	Uranium and thorium[15]	MF228
	Other metals n.e.c.	MF229
	Products mainly from metals	MF23
Construction Minerals	Marble, granite, sandstone, porphyry, basalt, other ornamental or building stone (excluding slate)	MF31
	Chalk and dolomite	MF32
	Slate	MF33
	Limestone and gypsum	MF36
	Clays and kaolin	MF37
	Sand and gravel	MF38
Industrial Minerals	Chemical and fertiliser minerals	MF34
	Salt	MF35
	Other non-metallic minerals n.e.c.	MF39
Biomass	Timber (industrial roundwood)	MF131
	Other products from animals (animal fibres, skins, furs, leather, etc.)	MF154
	Products mainly from biomass	MF16

[1]The full list of EW-MFA material categories is provided in the annex.

[15] While uranium is mostly used for energy purposes (nuclear fuel in power station reactors), thorium finds mostly use in material uses (e.g., welding electrodes, lighting, and refractories) (Harper et al., 2015). For simplification (and because the overall magnitude of uranium and thorium flows at EU-level equals only 0.07% of all metals domestic extraction, 0.03% of all metal imports, and 0.008% of all metal exports) the flows for "uranium and thorium (MF 228)" were included even though the energetic fraction is out of scope of the EIP-RM.

In the material flows visualizations, we only show the total flows for each material category, i.e., metals, construction minerals, industrial minerals, and biomass. Visualization of individual materials (e.g., iron or timber) is also possible using the EW-MFA data. However, while the EW-MFA statistics are available at material-level, the waste statistics (see following sections) are provided at the level of waste categories and waste activities. Therefore, in order to show the flow of an individual material through the whole Sankey diagram additional assumptions would be required, e.g., on the quantities of individual materials in the various waste streams, and this is outside the scope of work presented in this report.

We note that some material categories that include other non-food and non-energy type material uses (e.g., fossil fuels used for polymer production, or biomass such as straw used for building purposes) might not be included, because this would require additional research and assumptions (e.g., on the amount of fossil fuels used for polymers production globally and in the EU). Because the goal of this study is to provide a Sankey visualization based largely on official statistics, it was decided to only include those material categories that can be directly related to material uses. However, we include a discussion of this in section 4, including recommendations for future work and expansions of the Sankey diagram.

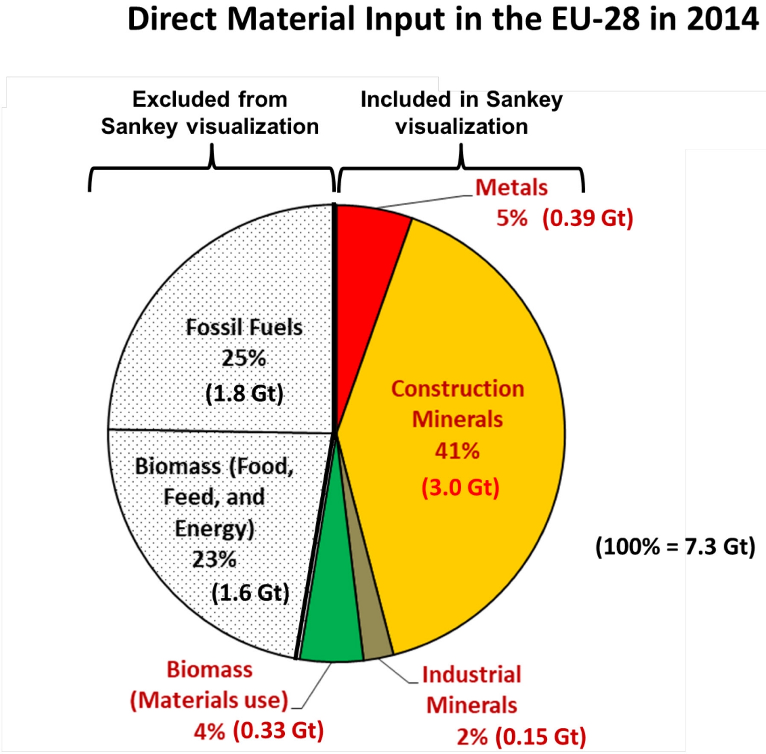
Furthermore, we note that for some material categories the gross total for the EU-28 is not reported for certain years. Hence, the sum of all individually reported values at EU member state level is used in this Sankey diagram and numbers cross-checked with the totals if reported by Eurostat.

Material Flow Coverage of the Sankey diagrams:

The material categories included in this study (i.e., under the EIP-RM scope) cover about 53% (3.8 Gt[16]) of direct material input (DMI) in year 2014 (Figure 4). The remaining 47% (3.5 Gt) consist of fossil fuels and biomass for energetic uses (food, feed, and energy). Note that the totals in Figure 4 (7.3 Gt in 2014) might not exactly match with values reported as totals for the EU-28 in Eurostat MFA statistics due to disaggregation into individual material categories, reallocation to the new overarching "materials-specific" categories, and summing up to totals (where missing EU total numbers are approximated as the sum of all individual EU-28 member states estimates as explained in the previous paragraph).

[16] One gigaton (Gt) is equal to 1,000,000,000 metric tons.

Figure 4 Direct material input (DMI) in the EU-28 in 2014. The fraction of biomass for material uses, metals, construction minerals, and industrial minerals (total = 52%) are included in this study (highlighted in red font), while the remaining 48% consist of fossil fuels and biomass for food, feed, and energy purposes are excluded.



2.2.2 EU Waste Statistics

The material flows from domestic material use (Figure 3) to the end-of-life (EoL) waste management process are quantified using the **ESTAT waste generation statistics (env_wasgen)**[17]. These represent the total quantity of waste generated in a year within the EU-28. The waste categories do not directly match with the EW-MFA material categories. Examining the waste details and compositions (ESTAT, 2010) reveals that it is often difficult, without involving additional data and assumptions, to know exactly which materials are included in the waste stream (input side) and whether the waste originates only from material- or also from energetic-uses. Because of this, a simplified approach is chosen in which all ESTAT waste generation categories are included except for the following:

- W09 Animal and vegetal wastes (waste originating from the use of biomass for food and feed purposes);
- W11 Common Sludges (waste water treatment sludges from municipal sewerage water and organic sludges from food preparation and processing);
- W124 Combustion waste (waste materials originating from energetic uses not included in this assessment).

As presented in Table 2, in several other cases it is problematic to find material inputs which correspond exactly with the wastes generated. Further research would be required to generate better correspondence tables including better harmonization between both statistics (i.e., Eurostat EW-MFA and waste generation data) by the statistical offices.

[17] http://ec.europa.eu/eurostat/web/environment/waste/database

Table 2: Waste categories captured by the ESTAT waste statistics and corresponding EW-MFA codes. Only waste categories highlighted with "Yes" are included in the Sankey diagram. In several cases, no perfect "correspondence" between the Eurostat waste statistics and EW-MFA could be found.

Code	Waste Category	Unit	Waste Details[1]	Corresponding EW-MFA Code[2]	Included in Analysis	Quantity (kg) 2014 (EU-28)	%
TOTAL	**Total Waste**	**tonne**				**2,598,140,000**	**100.00%**
W01-05	**Chemical and medical wastes (subtotal)**	**tonne**				**55,950,000**	**2.15%**
W011	Spent solvents	tonne	Basic organic chemicals, Sludges and solid wastes containing organic solvents, etc.	Fossil fuels (MF4), Biomass (MF1), Metals (MF2)	**Yes**	2,400,000	0.09%
W012	Acid, alkaline or saline wastes	tonne	Chlorofluorocarbons, Sludges and solid wastes containing organic solvents, etc.	Various	**Yes**	5,890,000	0.23%
W013	Used oils	tonne	Oils, fat and wax from meachinal engineering, metal sludge	Fossil fuels (MF4)	**Yes**	5,090,000	0.20%
W02A	Chemical wastes	tonne	Solid and liquid catalysts, gases in pressure containers, mixed photo chemicals, packaging materials, etc.	Various	**Yes**	16,430,000	0.63%
W032	Industrial effluent sludges	tonne	Wastes from waste water treatments and water preparations (grease de-inking sludge, etc.)	Various	**Yes**	13,080,000	0.50%
W033	Sludges and liquid wastes from waste treatment	tonne	Sludges/liquids from waste treatment, landfills	Various	**Yes**	10,900,000	0.42%
W05	Health care and biological wastes	tonne	Sharps from health care, plaster casts, clothing, diapers from hospitals	Various	**Yes**	2,160,000	0.08%
W06_07A	**Recyclable wastes (subtotal, W06+W07 except W077)**	**tonne**				**237,210,000**	**9.13%**
W061	Metal wastes, ferrous	tonne	Ferrous metals (like iron, steel) and alloys	Metals (MF2)	**Yes**	75,330,000	2.90%
W062	Metal wastes, non-ferrous	tonne	Non-ferrous metals (like aluminium, copper, zinc, lead, tin, and alloys)	Metals (MF2)	**Yes**	8,820,000	0.34%
W063	Metal wastes, mixed ferrous and non-ferrous	tonne	Mixtures of ferrous and non-ferrous metals (e.g., from construction and demolition)	Metals (MF2)	**Yes**	15,270,000	0.59%
W071	Glass wastes	tonne	Waste glass packaging, glass waste from glass production, waste glass from sorting and recycling processes	Construction Minerals	**Yes**	18,750,000	0.72%
W072	Paper and cardboard wastes	tonne	Paper and cardboard	Products mainly from biomass (MF16)	**Yes**	46,170,000	1.78%
W073	Rubber wastes	tonne	End-of-life tyres	Products mainly from biomass (MF16)	**Yes**	3,220,000	0.12%
W074	Plastic wastes	tonne	Plastic packaging, plastic waste from production and machining of plastics, etc.	Fossil fuels (MF4)[18]	**Yes**	17,530,000	0.67%
W075	Wood wastes	tonne	Wooden packaging, sawdust, shavings,	Timber (industrial	**Yes**	49,880,000	1.92%

[18] Plastic waste stems from material uses of fossil fuels. However, fossil fuels are not included at the input side (because additional data would be required to know the share of oil and natural gas used for plastics production vs. energetic uses in the EU and for individual EU member states).

Code	Waste Category	Unit	Waste Details[1]	Corresponding EW-MFA Code[2]	Included in Analysis	Quantity (kg) 2014 (EU-28)	%
			cuttings, waste bark, wood from construction and demolitions, etc.	roundwood) (MF131)			
W076	Textile wastes	tonne	Textile and leather waste, textile packaging, waste from fibre preparation and processing, waste tanned leather	Other products from animals (MF154), Products mainly from biomass (MF16)	**Yes**	2,240,000	0.09%
W077_08	**Equipment (subtotal, W077+W08A+W081+W0841)**	**tonne**				**16,150,000**	**0.62%**
W077	Waste containing PCB	tonne	Oil-containing PCB, PCB in capacitors, construction and demolition wastes containing PCB (e.g., sealants resin-based floorings)	Various	**Yes**	40,000	0.00%
W08A	Discarded equipment (except discarded vehicles and batteries and accumulators waste) (W08 except W081, W0841)	tonne	Discarded electrical and electronic equipment, fluorescent tubes	Metals (MF2)	**Yes**	5,360,000	0.21%
W081	Discarded vehicles	tonne	All kinds of end-of-life vehicles	Metals (MF2) and others	**Yes**	9,080,000	0.35%
W0841	Batteries and accumulators wastes	tonne	All kinds of batteries and accumulators	Metals (MF2) and others	**Yes**	1,670,000	0.06%
W09	**Animal and vegetal wastes (subtotal, W091+W092+W093)**	**tonne**				**108,190,000**	**4.16%**
W091	Animal and mixed food waste	tonne	Animal waste of food preparation, mixed wastes of food preparation	Biomass (MF1)	No	35,960,000	1.38%
W092	Vegetal wastes	tonne	Vegetal waste from food preparation and products	Biomass (MF1)	No	55,610,000	2.14%
W093	Animal faeces, urine and manure	tonne	Slurry and manure, including spoiled straw	Biomass (MF1)	No	16,620,000	0.64%
W10	**Mixed ordinary wastes (subtotal, W101+W102+W103)**	**tonne**				**286,280,000**	**11.02%**
W101	Household and similar wastes	tonne	Mixed municipal solid waste, bulky waste, street cleaning waste, etc.	Various	**Yes (Partially)**[3]	157,840,000	6.08%
W102	Mixed and undifferentiated materials	tonne	Unspecific wastes and mixed waste	Various	**Yes (Partially**[3]	44,510,000	1.71%
W103	Sorting residues	tonne	Combustible waste (refuse derived fuel), non-composted fractions of biodegradable waste	Various	**Yes**	83,930,000	3.23%
W11	**Common sludges**	**tonne**	**Waste water treatment sludges from municipal sewerage water and organic sludges from food preparation and processing**		**No**	**18,350,000**	**0.71%**
W12-13	**Mineral and solidified wastes (subtotal)**	**tonne**		Construction Minerals		**1,876,010,000**	**72.21%**
W121	Mineral waste from construction and demolition	tonne	Concrete, bricks, and gypsum waste from construction and demolition, Insulation materials, etc.	Construction Minerals	**Yes**	301,540,000	11.61%
W12B	Other mineral wastes (W122+W123+W125)	tonne	Asbestos materials, Mineral wastes from mining and quarrying, etc.	Construction Minerals	**Yes**	841,230,000	32.38%
W124	Combustion wastes	tonne	Wastes from flue gas cleaning	Energetic use not	No	129,700,000	4.99%

Code	Waste Category	Unit	Waste Details[1]	Corresponding EW-MFA Code[2]	Included in Analysis	Quantity (kg) 2014 (EU-28)	%
			(desulphurization sludges, filter dust and cakes, fly ashes, solid waste), Slags, drosses, skimmings, boiler dusts and ashes from thermal processes	considered.			
W126	Soils	tonne	Soil and stones incl. excavated soil from contaminated sites	Construction Minerals, Industrial Minerals	**Yes**	457,760,000	17.62%
W127	Dredging spoils	tonne	Dredging spoils from construction and demolition	Construction Minerals	**Yes**	80,820,000	3.11%
W128_13	Mineral wastes from waste treatment and stabilised wastes	tonne	Bottom ash and slag from waste incineration and pyrolysis, Fly ashes and other wastes from flue gas treatment in waste incineration plants, Solidified, stabilised and, vitrified wastes from, waste treatment	Construction Minerals, Industrial Minerals, Metals	**Yes**	64,960,000	2.50%

[1]Based on details provided in (ESTAT, 2010).
[2] (EUROSTAT, 2013)
[3]Multiplied by 0.69 assuming an average composition of 31% vegetable matter (putrescibles) in EU municipal solid waste (MSW) (Fraunhofer, 2014) which are excluded in this assessment. The remaining waste consists of 29% paper and cardboard, 11% glass, 8 % plastics, 5% metals, 2% textiles, and 13% others. Note that the EU waste composition can vary by year and numbers should only be seen as a proxy. However, ‘household and similar wastes (W101)’ in 2014 make up only 6% and ‘mixed and undifferentiated materials (W102)’ 1.7% of total waste generated and slight variations in the waste composition would therefore not significantly affect the overall results of the Sankey visualization.

Waste generation is broken down into waste flows originating from (1) Mining and Quarrying, (2) Manufacturing, (3) Construction, (4) Households, and (5) Other (see Table 3 for a full list of waste generating activities reported by ESTAT that could be included in the Sankey diagram). These are visualized to provide additional details.

Table 3: Waste generating activities in Europe captured by the ESTAT waste generation statistics.

Code	Waste Generating Activity
A	Agriculture, forestry and fishing
B	**Mining and quarrying**
C	**Manufacturing**
C10-C12	Manufacture of food products; beverages and tobacco products
C13-C15	Manufacture of textiles, wearing apparel, leather and related products
C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
C17_C18	Manufacture of paper and paper products; printing and reproduction of recorded media
C19	Manufacture of coke and refined petroleum products
C20-C22	Manufacture of chemical, pharmaceutical, rubber and plastic products
C23	Manufacture of other non-metallic mineral products
C24_C25	Manufacture of basic metals and fabricated metal products, except machinery and equipment
C26-C30	Manufacture of computer, electronic and optical products, electrical equipment, motor vehicles and other transport equipment
C31-C33	Manufacture of furniture; jewellery, musical instruments, toys; repair and installation of machinery and equipment
D	Electricity, gas, steam and air conditioning supply
E36_E37_E39	Water collection, treatment and supply; sewerage; remediation activities and other waste management services
E38	Waste collection, treatment and disposal activities; materials recovery
F	**Construction**
G-U_X_G4677	Services (except wholesale of waste and scrap)
G4677	Wholesale of waste and scrap
EP_HH	**Households**
TOTAL_HH	All NACE activities plus households

Only waste generating activities shown in purple colour in the table are shown explicitly in the Sankey diagram. All other waste categories are combined into an "other" category.

ESTAT waste generation statistics are available for the EU-28 as a whole, as well as for the majority of member states. Note that data may not be reported for all member states or material categories for a country. Data are published bi-annually and are currently available for 2004, 2006, 2008, 2010, 2012, and 2014. Due to data availability it is not possible to capture the flow of the material categories (metals, construction minerals, industrial minerals, and biomass) provided by EW-MFA and shown in the first processes of the Sankey diagram.

The difference between the total material quantities of DMC and waste generation is considered as **net additions to stocks**[19] in a single year. This provides an indication of the physical growth rate of the EU economy in which new materials are added to the economy's stock in a single year, e.g., in buildings and infrastructure, household appliances, vehicles, and other durable goods (with a life-time longer than 1 year).

The split from waste management into different waste treatment options is captured using the **ESTAT waste treatment statistics (env_wastrt)**[20]. These provide a split of

[19] The net stock change (net accumulation) is equal to the difference between inputs and outputs.
[20] http://ec.europa.eu/eurostat/web/environment/waste/database

waste materials into the fractions going to landfills, incineration without energy recovery, incineration with energy recovery, materials backfilled[21], and recovery[22].

We note that waste treatment includes wastes imported into the EU and the reported amounts are therefore not directly comparable with the waste generation statistics (EUROSTAT, 2016a). Due to the difficulty of determining waste imports and exports, we close the balance by introducing a phantom flow in the Sankey diagram termed "other waste treatment". As can be seen in the results section this "phantom flow" varies in magnitude and is generally found between 0 – 12% of the material flows into waste treatment. Further research is required to determine what this difference is due to.

Table 4 presents the waste treatment processes captured by Eurostat and how they correspond to processes in the Sankey diagram.

Table 4: Waste treatment processes captured by the ESTAT waste treatment statistics.

Label	**Name used in the Sankey diagram**
Total waste treatment	-
Landfill / disposal (D1-D7, D12)	Landfill
Deposit onto or into land	
Land treatment and release into water bodies	
Incineration / disposal (D10)	Incineration
Incineration / energy recovery (R1)	Energy Recovery
Recovery other than energy recovery	-
Recovery other than energy recovery - backfilling	Backfilling
Recovery other than energy recovery - except backfilling	Recycling

Eurostat waste treatment statistics are available for the whole EU-28, as well as for most individual member states and for years 2004, 2006, 2008, 2010, 2012, and 2014. However, the data collections were revised by Eurostat in 2010, taking into account changes in legislation and some simplifications in reporting obligations (Eurostat, 2013), and therefore statistics before 2010 might not be directly comparable with later data reported[23]. In particular, no individual data are reported for "Recovery other than energy recovery – backfilling" and "Recovery other than energy recovery – except backfilling" prior to 2010, but only totals for "Recovery other than energy recovery" (i.e. recycling and backfilling flows) are provided. As a result, Sankey diagram prior to 2010 (2004 – 2008) show only a single "recovery" flow in the Sankey diagrams generated, while Sankey diagrams starting from 2010 show both recycling and backfilling flows. Furthermore, for some waste categories (e.g., common sludges and combustion wastes) which are not reported in all years prior to 2010, we use 2010 estimates and assume that these stayed constant during the time period from 2004 to 2008.

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[21] Backfilling is the use of waste in excavated areas for the purpose of slope reclamation or safety or for engineering purposes in landscaping.

[22] Recovery is defined by ESTAT as: "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations." The common idea behind recycling is that a waste material is processed in order to alter its physicochemical properties allowing it to be used again for the original or for other purposes and thus of closing the economic material circle.

[23] Differences are due to a re-categorization and further disaggregation of waste flows since 2010 which makes the allocation of highly aggregated waste categories before 2010 difficult and can be subject to uncertainties

2.2.3 Additional Possible Data Sources (Not Used)

Additional data sources are available that could be incorporated into the Sankey diagrams to provide supplementary information for specific material categories and cross-check results. For example, the MSA study provides information on in-use stocks and the flow of aggregates (construction minerals) in Europe (BIO by Deloitte, 2015). Additional data sources and approaches of capturing material flows in the EU-28 are provided elsewhere (Haas et al., 2015).

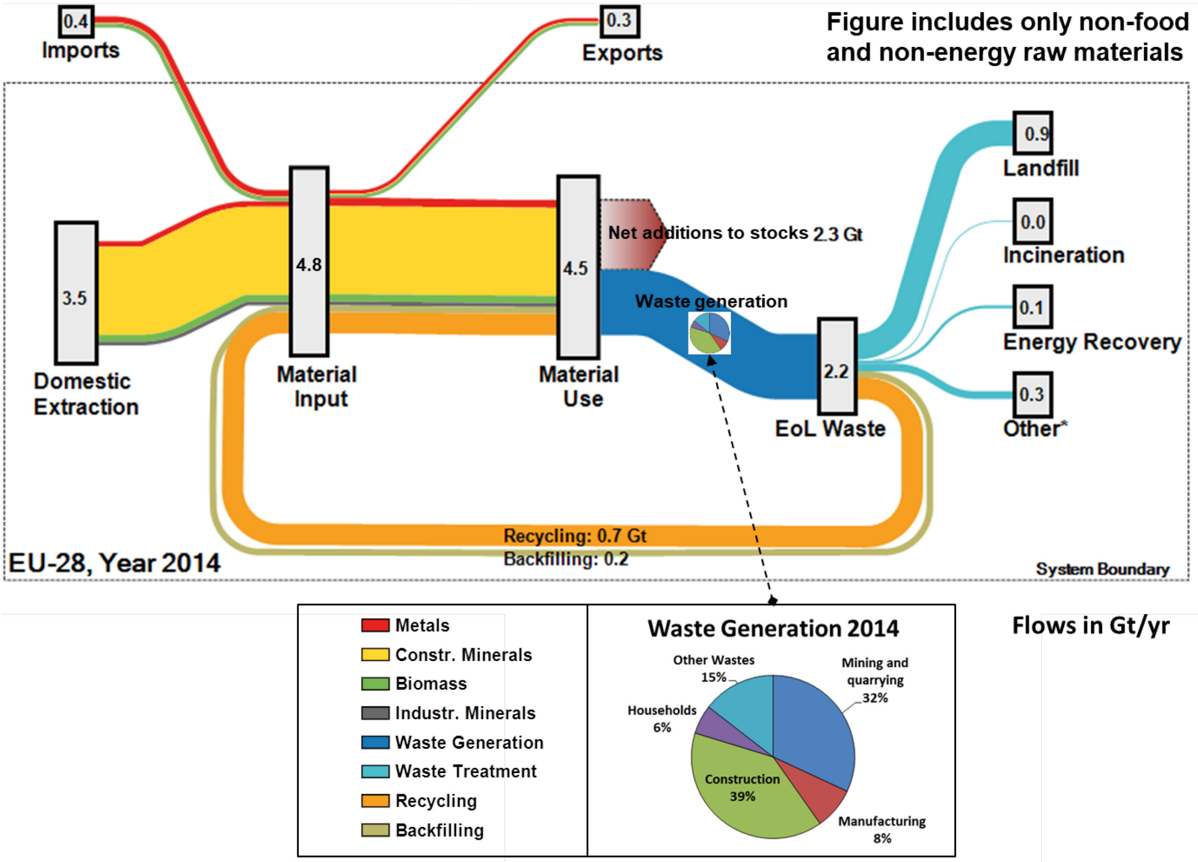
However, in this study, we rely mostly on Eurostat data and these additional data sources are therefore not further considered.

3 Results

3.1 EU-28 Sankey Diagrams

Using the combination of Eurostat statistics for EW-MFA, waste generation, and waste treatment statistics, the resulting Sankey diagram for the EU-28 in 2014 is shown in Figure 5.

Figure 5 Sankey diagram of bulk material flows (non-energy and non-food) in the EU-28 in 2014. Numbers show the size of flows in Gt/yr.



Notes: The pie chart showing waste generation refers to the composition of the flow from material use to EoL waste treatment. The process "Materials Use" consists of the sum of domestic extraction (DE), recycling, backfilling, and imports (but excluding exports). EoL: End-of-Life. *Flow used to balance the Sankey diagram because waste generation and treatment statistics do not always match, e.g., due to non-quantified waste imports and exports.

Domestic extraction (DE) of non-energy and non-food raw materials in the EU-28 account for 3.5 Gt in 2014. The largest share of domestically extracted materials includes construction minerals (84%) followed by biomass (7%), metals (5%), and industrial minerals (3%). Material inputs into the European economy (including recycling and backfilling) equal 4.8 Gt and consist of domestic extraction, imports, recycling, and backfilling. Metals make up the bulk share of all imports equal to 0.21 Gt (52% of all metals inputs[24]) in 2014. This highlights European dependency on metal imports. On the

[24] Note that because the quantities from domestic extraction in the EU are in gross ore weight, and metal contents (especially for precious metals) in the ores are generally lower than in products which may be imported, this can result in underestimations of the import dependency of the EU for metals.

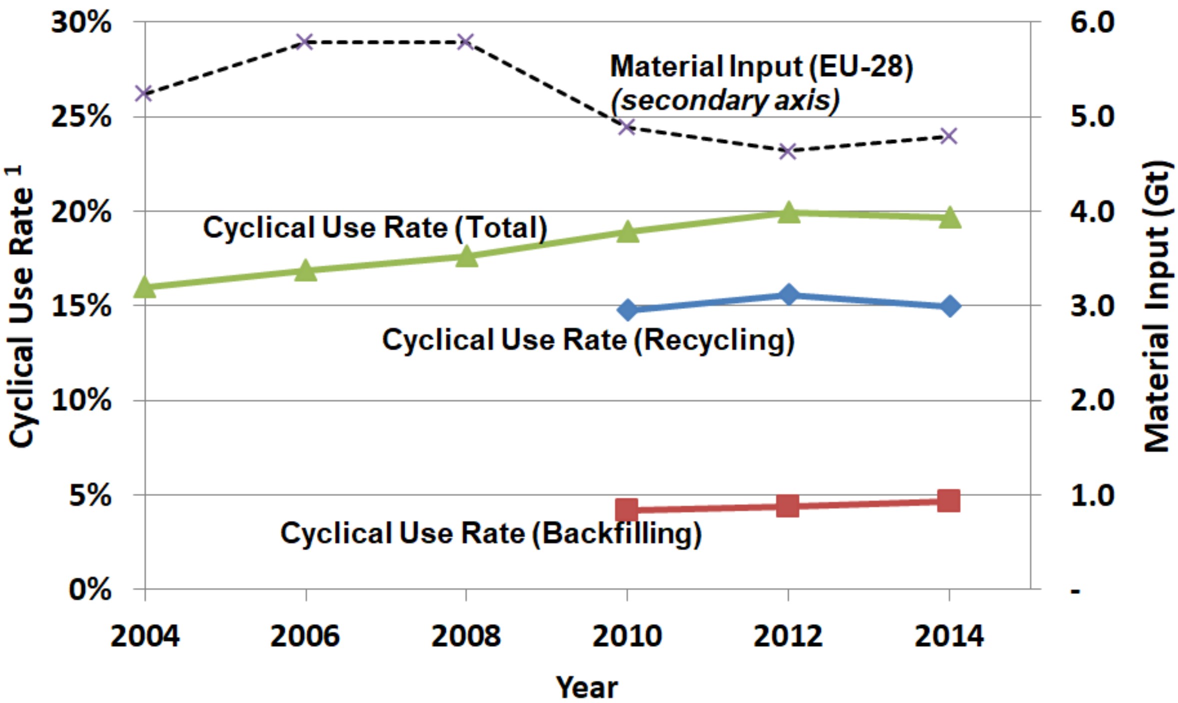
other hand, construction minerals and industrial minerals are to a large extent produced domestically.

Recycled materials[25] represent about 15% (0.7 Gt) of all materials input into the EU-28 in 2014. This flow stream provides circular use of materials within EU borders. In addition, about 0.2 Gt of all materials are backfilled[26], e.g., in using materials as roadbed aggregates. The overall cyclical use of non-energy and non-food materials in the EU-28 can be approximated using the cyclical use rate (Kovanda, 2014; MOEJ, 2013) calculated as:

$$Cyclical\ Use\ Rate = \frac{Recycling + Backfilling}{(Direct\ Material\ Input + Recycling + Backfilling)}$$

The cyclical use rate from 2004 to 2014 is presented in Figure 6. Note that the individual contributions of recycling and backfilling are only provided starting in 2010 based on Eurostat reporting.

Figure 6 Cyclical use rate in the EU-28 from 2004 to 2014 considering non-food and non-energy materials (i.e., excluding, e.g., fossil fuels used predominantly for energy purposes with no or little recycling). [1]The cyclical use rate is calculated as Recycling + Backfilling / Total Material Input (i.e., DMI (Domestic Extraction + Imports) + Recycling + Backfilling).



For the EU-28 the cyclical use rate of materials has been slowly but constantly increasing from 16% in 2004 to 20% in 2014 (Figure 5). Recycling is the largest contributor to this with around 15%, while backfilling contributes about 5%. This is mostly due to reductions in overall material inputs to the EU economy (denominator in the cyclical use rate equation) in particular for construction purposes (see also discussions in later sections). Recovery (i.e., recycling and backfilling in the denominator of the equation) remained at a level of 0.8 to 1 Gt/year throughout the 10 year period from 2004 to 2014. Furthermore, we note that our assessment only captures non-food and non-

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[25] Recovery operations other than energy recovery and backfilling (Item 3a) according to the Eurostat waste statistics.
[26] Item 3b: Backfilling (according to Eurostat waste statistics).

energy materials and, therefore, excludes fossil fuels which are mostly used as combustive fuels with limited downstream circular uses. Adding fossil fuels to the analysis would further reduce the share of recycled materials compared to overall resource inputs to the European economy.

In 2014, about 2.3 Gt of materials flow into in-use stocks (net additions to stocks), for example, in the form of new infrastructure, vehicles, equipment, and other products which remain in the economy at the end of the year. This also includes backfilled material. However, we note that the net stock additions are based on the difference in input flows (from EW-MFA and the recycling and backfilling flows from waste statistics) and output flows (from waste generation statistics). Furthermore, we only show net additions to stocks in a single year and not the existing in-use stock that has previously accumulated. Such estimates at EU-level could be increasingly provided, e.g., by the EU MSA study (BIO by Deloitte, 2015) and other recent research projects (Krausmann et al., 2017). The flow into stocks highlights that socioeconomic stocks in the EU economy are still growing. This limits the potential for current recycling (but not of circular use of raw materials) because raw materials are not sent for recycling until they stop providing their useful service to society.

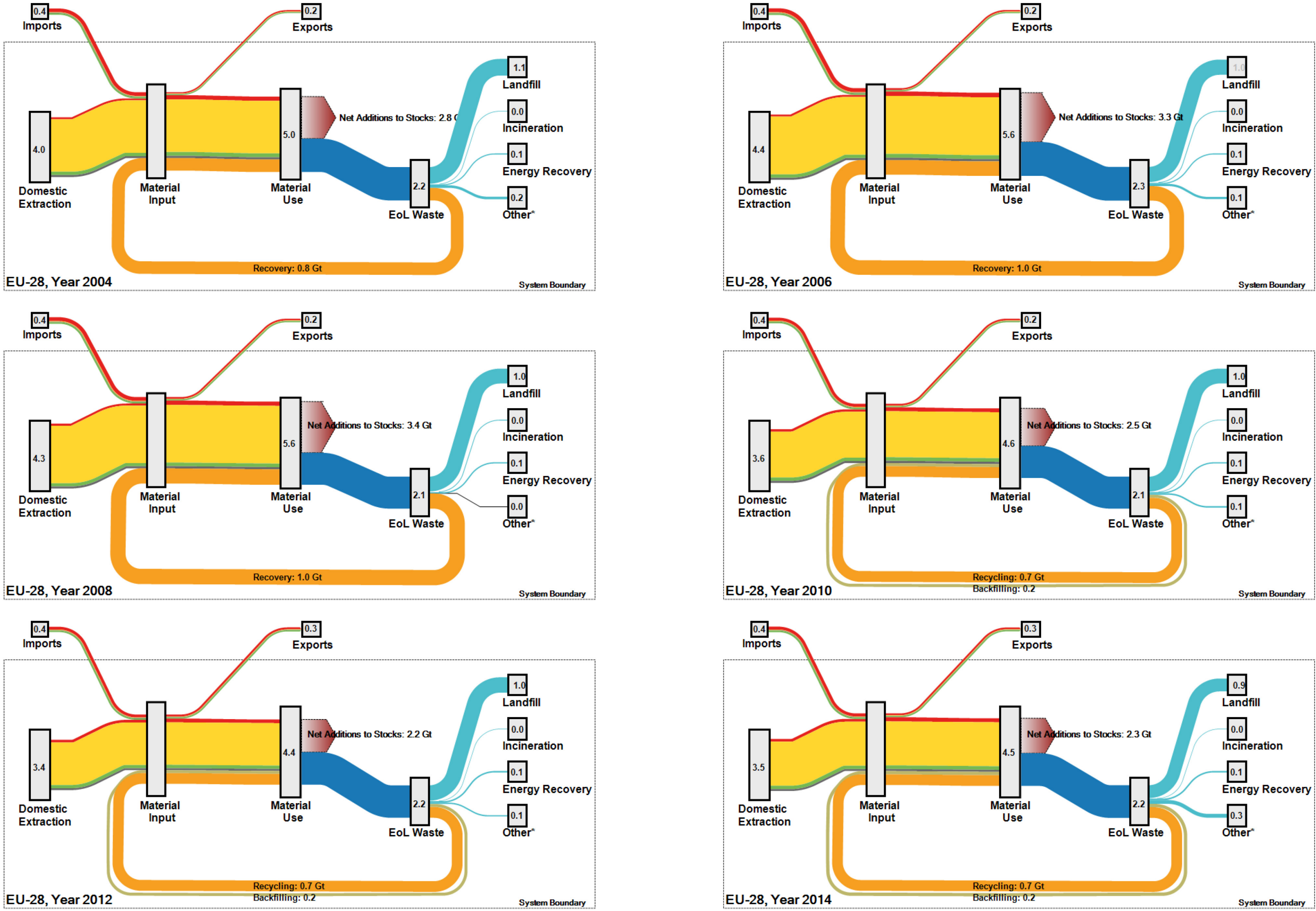
In 2014, total waste generated from non-energy and non-food material uses in the EU-28 by all economic activities and households amounted to 2.2 Gt. As shown in the pie chart in Figure 5, the construction sector (encompassing construction & demolition wastes) contributed 39% of the total (with 0.86 Gt) and was followed by mining and quarrying (32% or 0.7 Gt), manufacturing (8% or 0.18 Gt), households (6% or 0.13 Gt), and other economic activities (15% or 0.32 Gt). In 2014, some 1.9 Gt of waste were treated in the EU-28 (from non-energy and non-food material uses only). The largest share of this waste (about 39%) was subject to landfilling operations[27]. A further 33% of the waste treated in the EU-28 in 2014 was sent to recycling operations[28].

In 2014, 10% of the waste treated was backfilled. Backfilling is the use of waste in excavated areas for the purpose of slope reclamation or safety for engineering purposes in landscaping (EUROSTAT, 2016b). The remaining 6% were incinerated with 4% going to waste-to-energy plants and the remaining 2% to incineration plants without energy recovery. Note that because the waste treatment statistics include treatment of waste imports, they are not directly comparable with the waste generation statistics (Eurostat, 2009). In order to balance flows an "other" waste category is included which equals 0.3 Gt (12% of overall waste treatment) in 2014.

Figure 7 presents how the flow of materials in the EU-28 has evolved over the period 2004 – 2014. Note that the distinction into recycling vs backfilling is only provided from 2010 onwards. Therefore, total recovery (consisting of both recycling (Item 3a in the Eurostat waste statistics) and backfilling (Item 3b in the Eurostat waste statistics) is reported from 2004 – 2008.

[27] Recorded in Eurostat statistics as the sum of: (1) Deposit onto or into land and (2) Land treatment and release into water bodies.
[28] Recovery operations other than energy recovery and backfilling.

Figure 7 Sankey diagram of bulk material flows (non-food and non-energy materials) in the EU-28 for the period 2004 – 2014.[1] See Figure 5 for a legend of material flows. Numbers show the size of flows in Gt/yr.

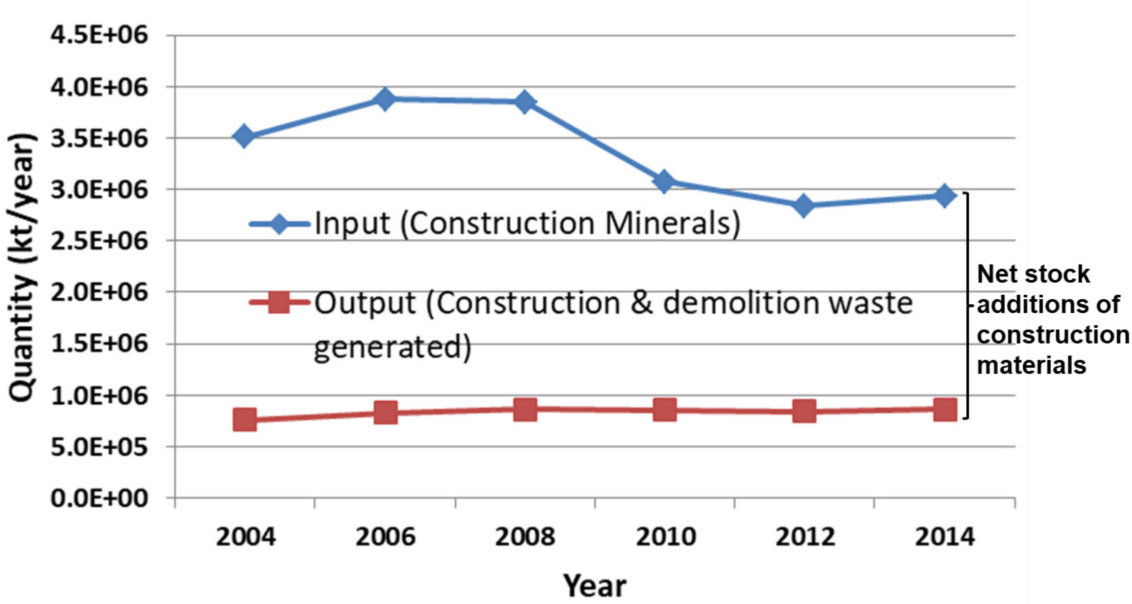


[1]Note that all 28 EU member states are taken into account in all years (i.e., we also include Bulgaria and Romania (entered in 2007) and Croatia (entered in 2013) over the whole period from 2004 to 2014). *Phantom flow used to balance the Sankey diagram because waste generation and treatment statistics do not always match, e.g., due to non-quantified waste imports and exports.

The comparison of different years shows that from 2004 to 2008 domestic extraction ranged between 3.4 and 4.4 Gt, but decreased significantly in 2010 to 3.6 Gt and remained more or less at this level until to date. Similarly, EU material use ranged between 5.0 and 5.6 Gt from 2004 to 2008 and fell to 4.6 Gt in 2010. This seems mainly due to a breakdown in the EU's domestic construction sector during the economic crisis around 2008 when domestic extraction of construction mineral decreased substantially. This trend is also reflected in the net additions to stocks which reached their peak in 2008 (3.4 Gt), but range 'only' around 2.2 to 2.5 Gt in subsequent years (2010 to 2014).

Recovery (i.e., recycling and backfilling) remained at a level of 0.8 to 1 Gt/year throughout the 10 year period from 2006 – 2014. The reason that recovery flows were not impacted by the decrease in construction-related materials turnover is likely due to the fact that buildings and infrastructure have long life-times, i.e., a decrease in construction activities does not immediately impact the flow of construction materials coming out of use as waste materials (time delay). This is further illustrated in Figure 8 which shows the inputs of construction minerals to the EU-28 economy between 2004 and 2014 (blue line) and corresponding waste generation from the construction sector (red line). The difference between the inputs (blue line) and outputs (red line) gives an indication of net stock additions of construction-related materials, e.g., in buildings and infrastructures. As the figure illustrates, outputs of construction wastes remained relatively constant over time even though inputs of construction minerals decreased substantially after 2008.

Figure 8 Inputs of construction minerals to the EU-28 economy between 2004 and 2014 (blue line) and corresponding waste generation from the construction sector (red line).



In other words, longer time series data will be required to recognize trends related to long-lived products[29] and their implications on the magnitude of recycling. We also note, that the correspondence between an input flow (here: construction minerals) and an output flow (here: wastes from the construction sector) cannot be determined for most material categories. Similarly, the composition of the recycling flow is somewhat unclear. Therefore, it is generally not possible to break down the stock additions into different

[29] In this assessment the (net) stock additions are simply the difference between inflows (EW-MFA) and waste generation.

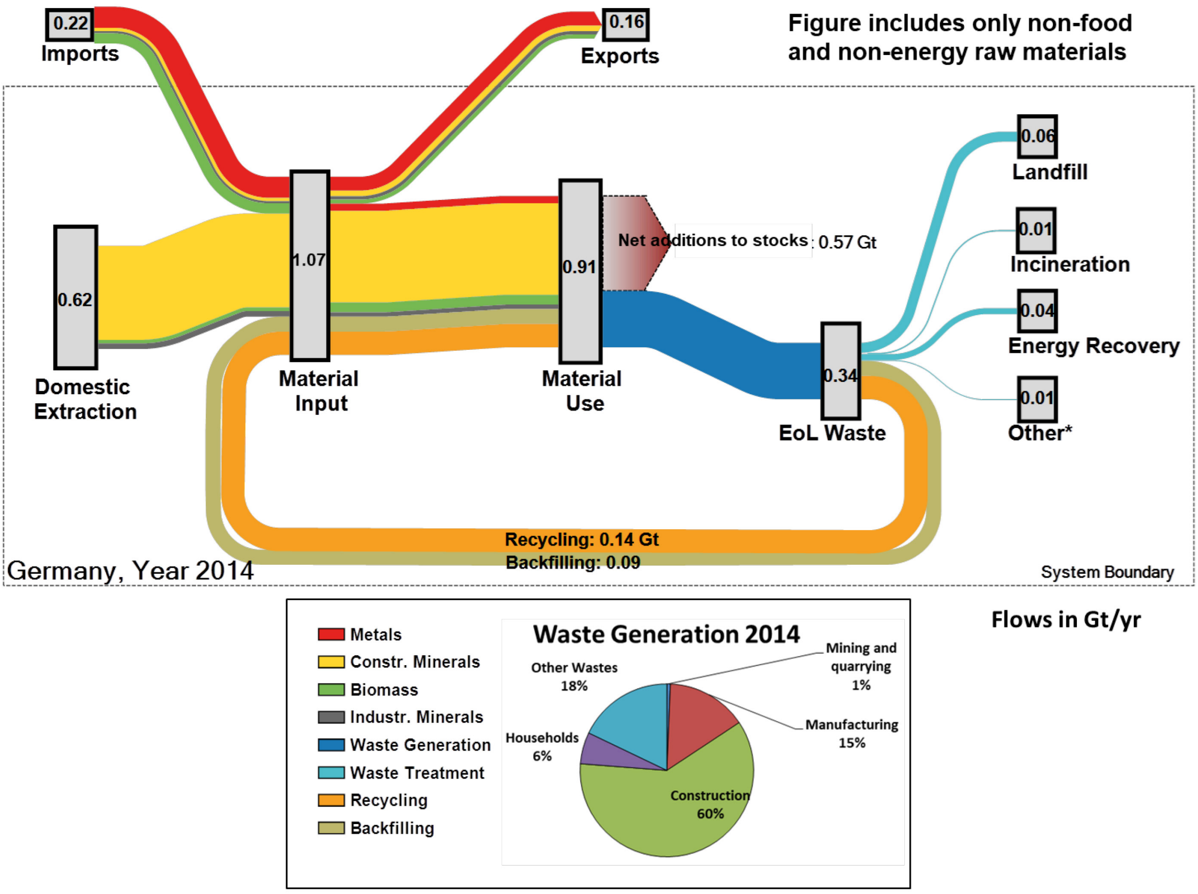
material categories. For this, further information on the material categories present in the waste stream and recycled and backfilled flows would be required.

3.2 Individual EU Member States

3.2.1 Case Study: Germany's Material Flows from 2004 to 2014

Eurostat data visualizations can also be provided at individual member state level (given that in most cases statistics are also available for individual countries in the EU). For the Sankey diagrams at member state level the import and export flows are based on the total import/export EW-MFA statistics provided by ESTAT[30]. However, it should be noted that data reporting might slightly differ between countries and, as with the Sankey visualization at EU level, the resulting figures for individual countries should only be seen as a first overview of the raw materials situation and the level of circularity. An example is provided for Germany in Figure 9 for year 2014 and Figure 10 for the period 2004 to 2014.

Figure 9 Sankey diagram of bulk material flows (non-food and non-energy materials) in Germany (as an example of an individual EU member state) in 2014. Numbers show the size of flows in Gt/yr.

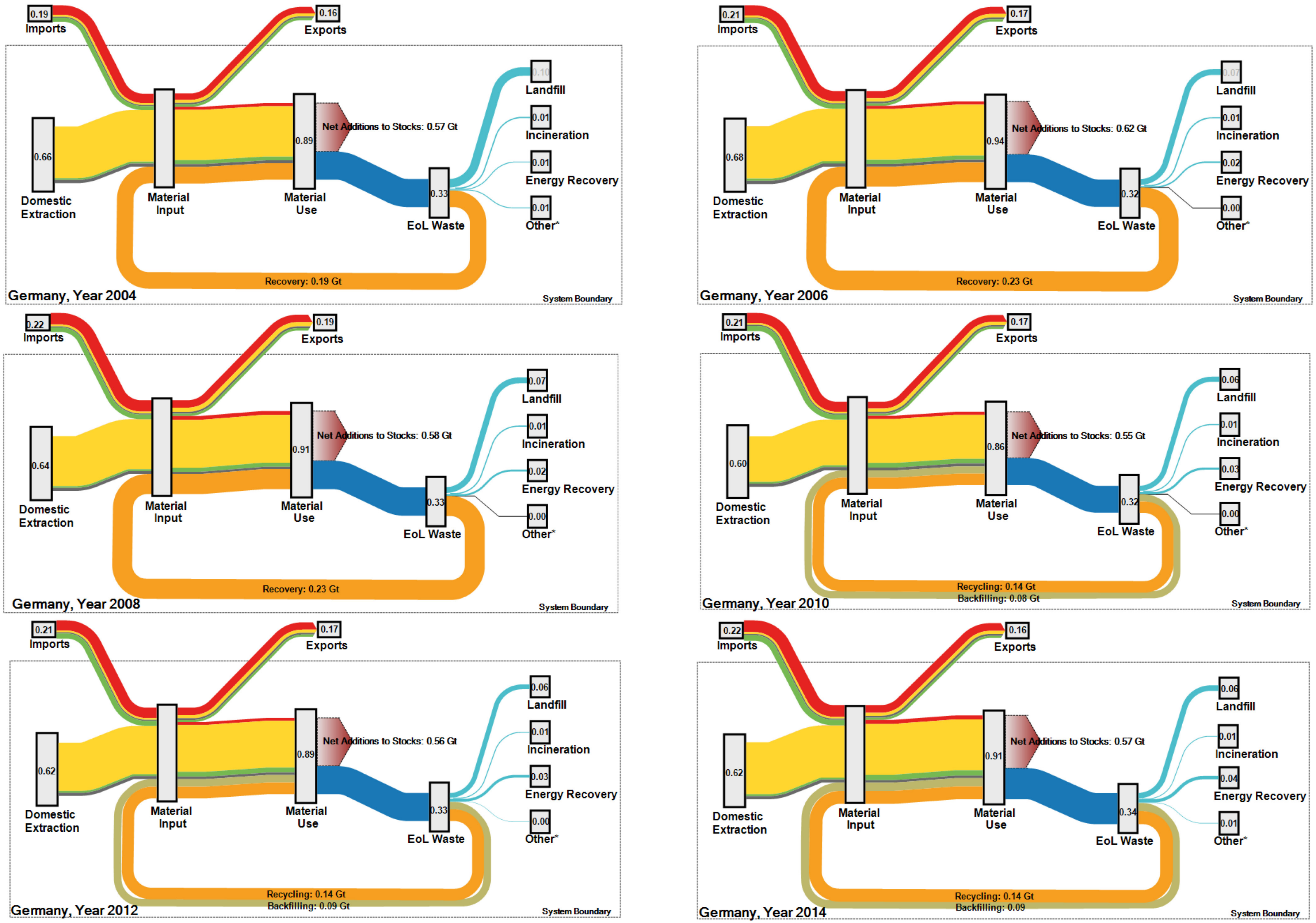


30 The data on total trade flows of EU Member States equals the sum of intra and extra EU trade flows.

Notes: The same municipal solid waste (MSW) composition as for the EU-28 is assumed for waste generation statistics to correct for vegetable matter in typical MSW. *Flow used to balance the Sankey diagram because waste generation and treatment statistics do not always match, e.g., due to non-quantified waste imports and exports.

In 2014, Germany's domestic material inputs including domestic extraction, imports, recycled materials, and backfilling equalled 1.07 Gt. Recycling is with 0.14 Gt about twice the backfilling flow (0.09 Gt). Stock additions equalled 0.57 Gt and range between 0.56 and 0.62 Gt over the 10-year period from 2004 to 2014. Of all waste treated, 41% were recycled, 26% backfilled, 18% landfilled, and 13% incinerated (of this 11% with energy recovery) in 2014. Because the waste treatment statistics include treatment of waste imports, they are not directly comparable with the waste generation statistics (Eurostat, 2009). In order to balance flows an "other" waste category is included which equals 2% of overall waste treatment in 2014.

Figure 10 Sankey diagram of bulk material flows (non-food and non-energy materials) in Germany for the period 2004 – 2014. *Flow used to balance the Sankey diagram because waste generation and treatment statistics do not always match, e.g., due to non-quantified waste imports and exports. Legend: See Figure 9. Numbers show the size of flows in Gt/yr.



3.2.2 Country-Level Analysis for Other EU Member States

Data can also be visualized for other countries in order to allow country-level analyses and visualize country-specific features. As an example, Sankey diagrams for eight member states are provided for year 2014 including Austria, Belgium, Czech Republic, Finland, France, Germany, Italy, and Spain.

Due to differences in country size and subsequent overall flow magnitude, the seven EU member states are divided into two groups which are shown at the same scale to allow better visual inspections between countries within one group.

Group 1 includes Austria, Belgium, Czech Republic, Finland, and Spain for which material use ranges between 0.11 Gt and 0.24 Gt in 2014. Group 2 includes France, Germany, and Italy for which the material use is significantly higher ranging between 0.35 and 0.91 Gt in 2014.

The following four figures present the Sankey diagrams of group 1 (can be visually compared with each other).

Figure 11 Material flows (non-food and non-energy in Gt/yr) in Austria in 2014.

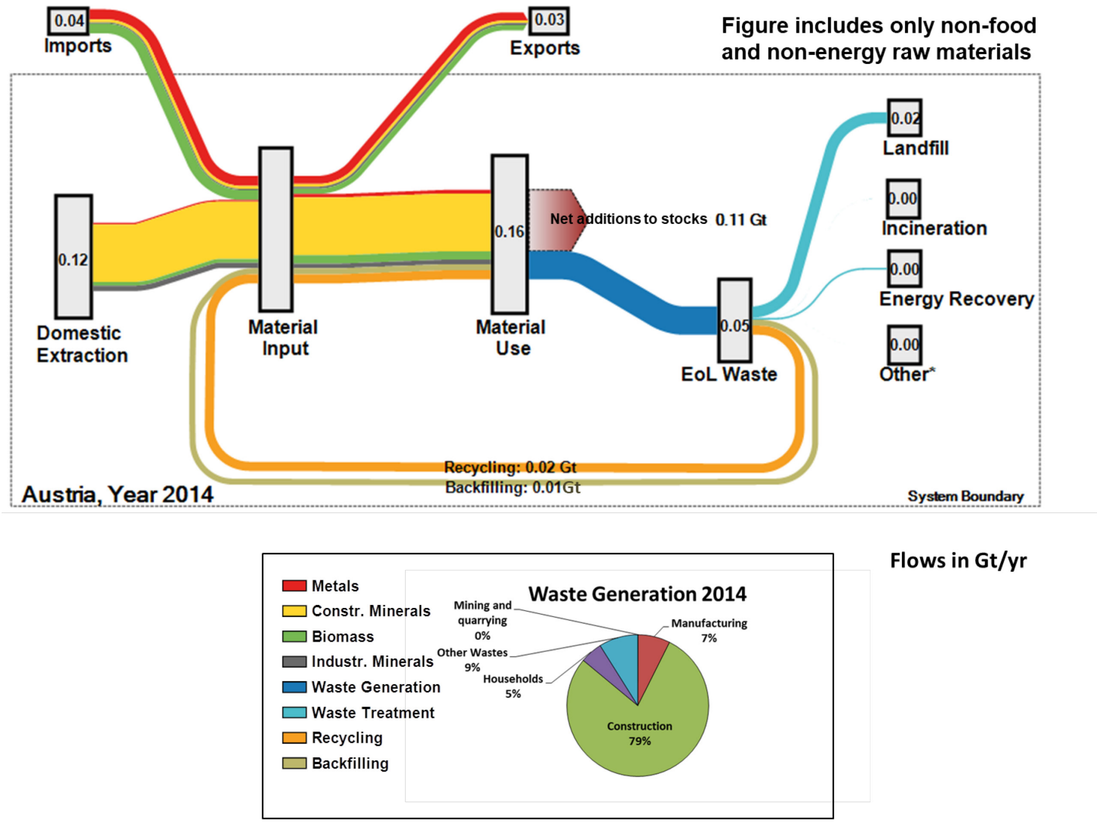


Figure 12 Material flows (non-food and non-energy in Gt/yr) in Belgium in 2014.

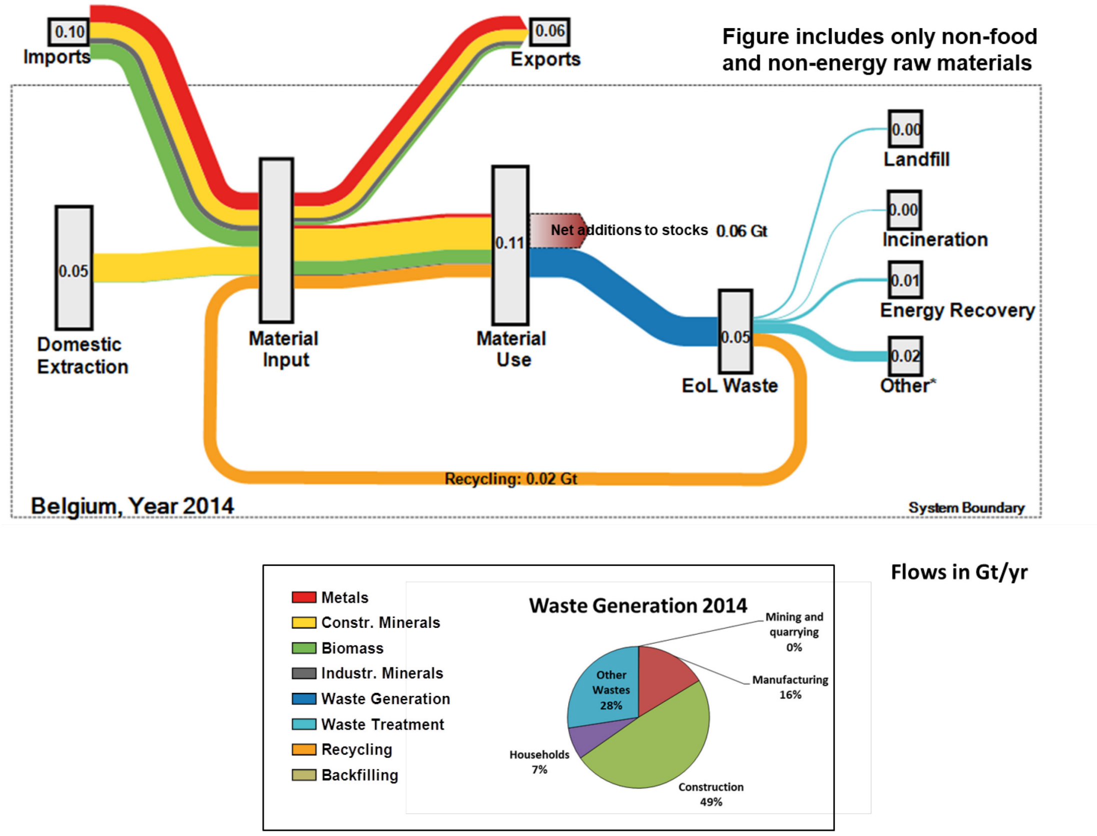


Figure 13 Material flows (non-food and non-energy in Gt/yr) in the Czech Republic in 2014.

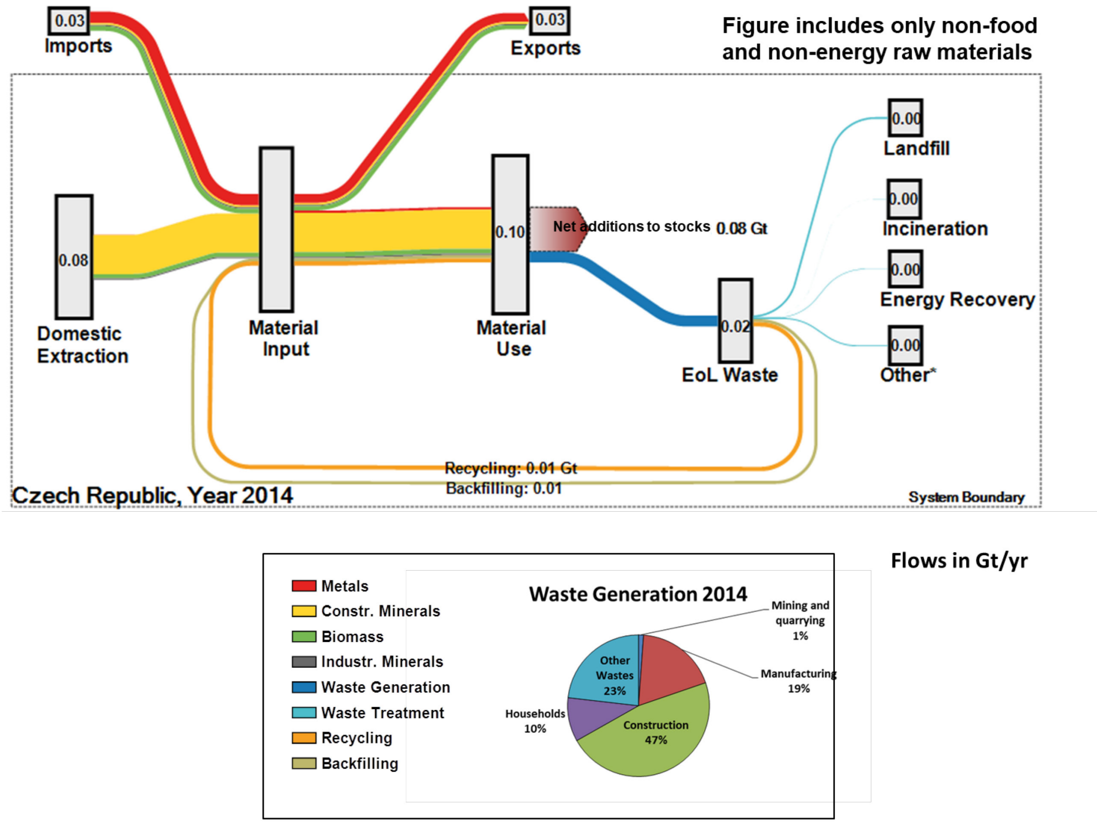


Figure 14 Material flows (non-food and non-energy in Gt/yr) in Finland in 2014.

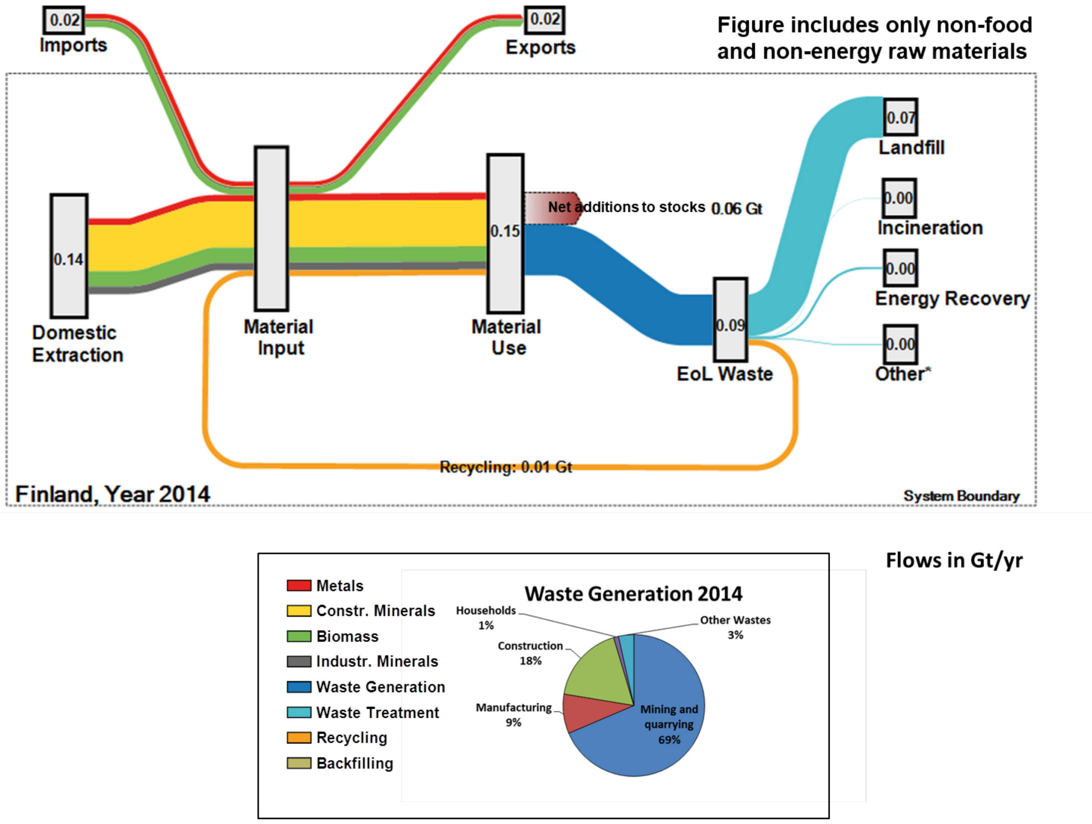
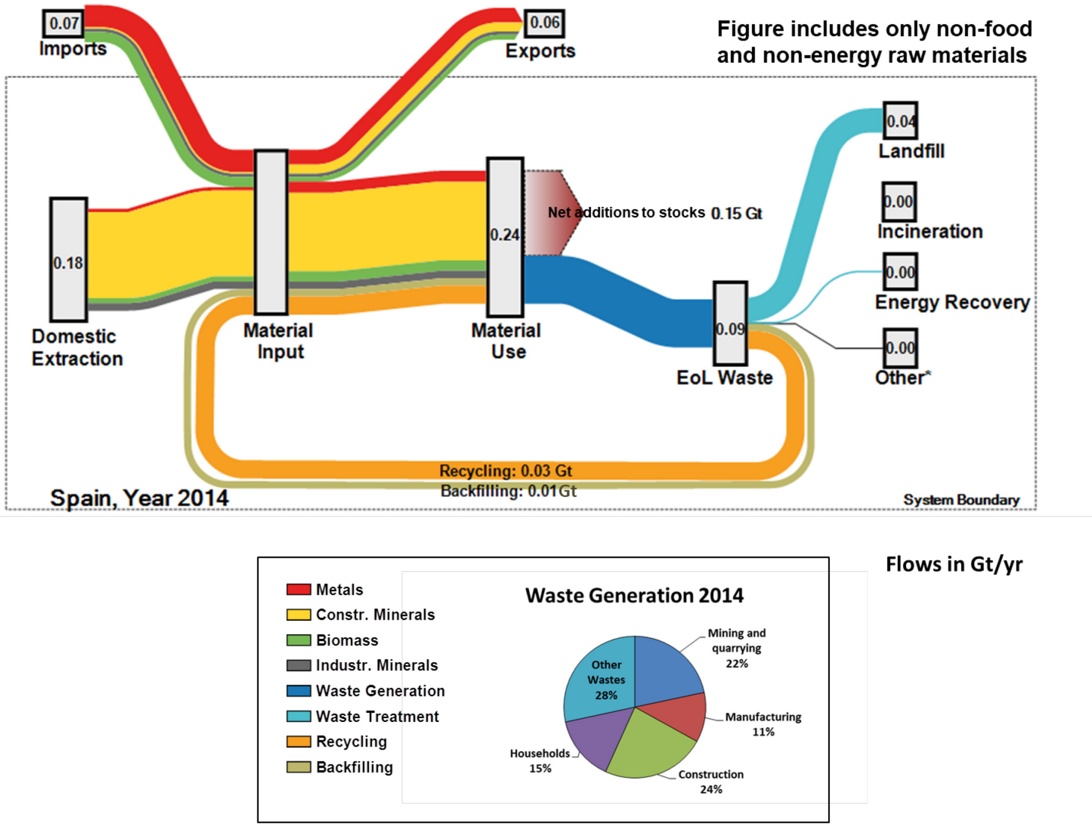


Figure 15 Material flows (non-food and non-energy in Gt/yr) in Spain in 2014.



The following three Sankey visualizations belong to group 2 (can be visually compared with each other).

Figure 16 Material flows (non-food and non-energy in Gt/yr) in France in 2014.

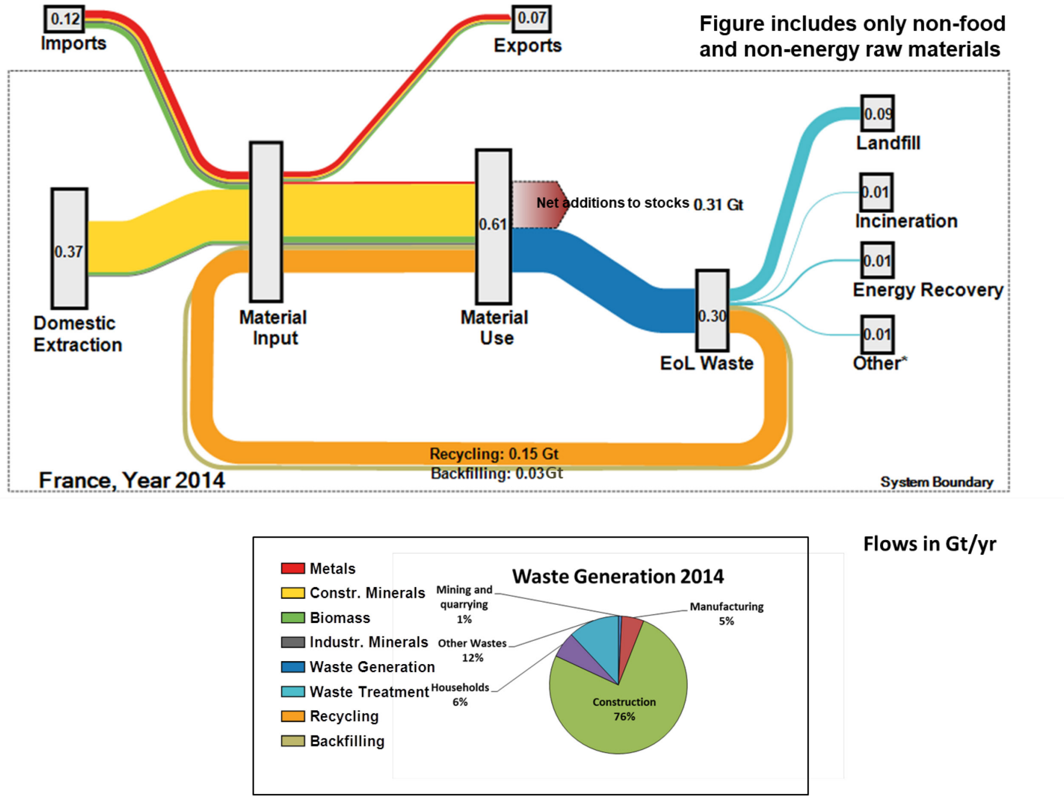


Figure 17 Material flows (non-food and non-energy in Gt/yr) in Germany (2014).

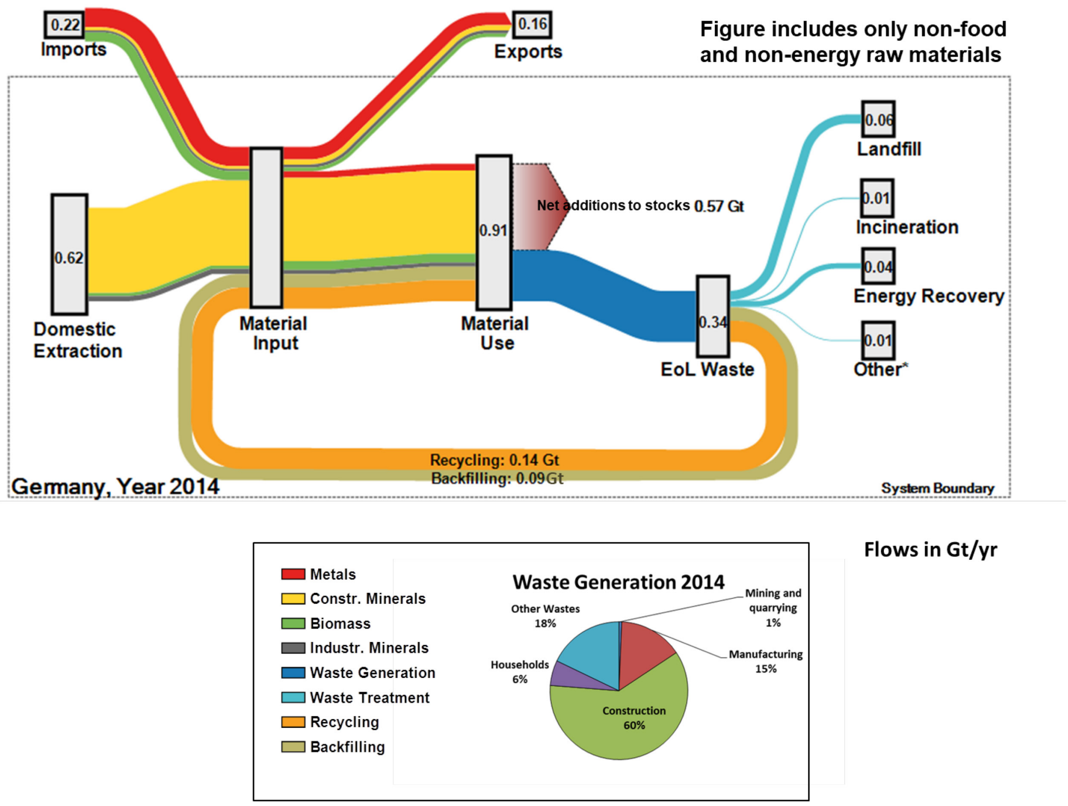
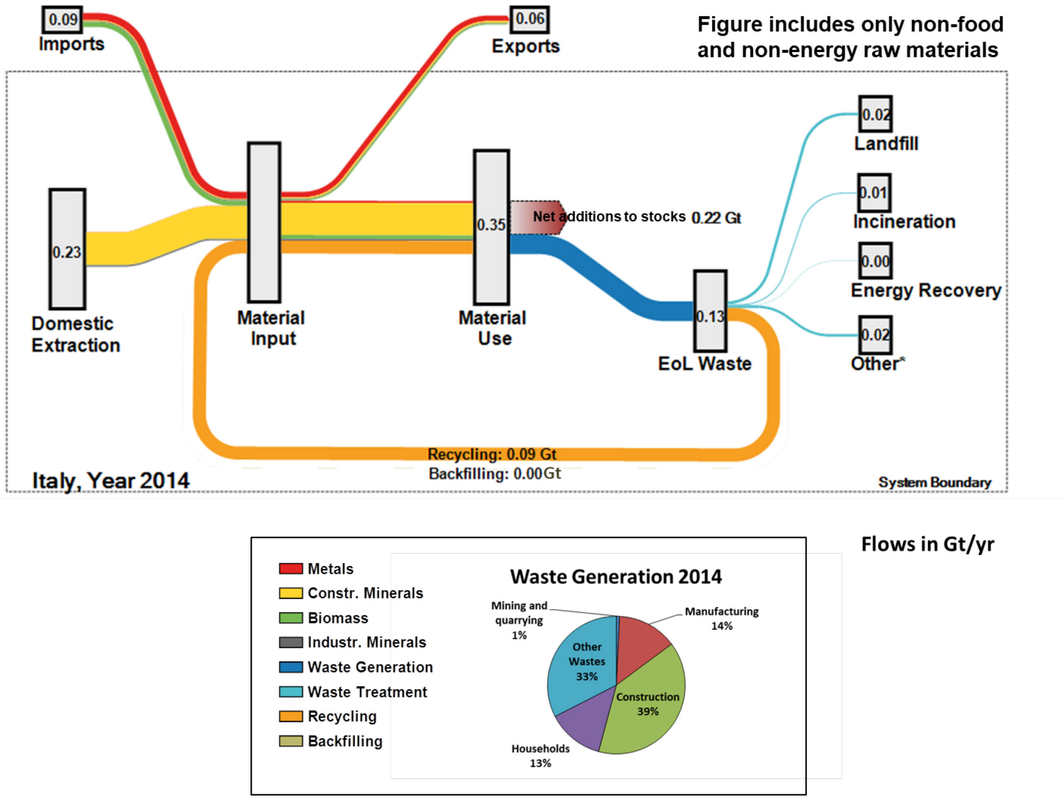


Figure 18 Material flows (non-food and non-energy in Gt/yr) in Italy in 2014.



Comparing the ESTAT data visualizations at member state level shows, firstly, the large differences in overall material flow magnitudes between EU countries (therefore divided into two separate groups with different scaling of the Sankey arrows). Secondly, the magnitude of imports and exports varies by member state. For example, Belgium is dependent on one third of its material inputs (a large part of which is sourced from other EU countries), while Finland is largely self-sufficient (in terms of overall mass inputs) and is one of the few metal producing countries within the EU. For Finland, the share of domestic biomass production is more distinct that for other EU countries which could be a result of wood products (e.g., panels) being historically used for building purposes. The majority of EU member states assessed produce the bulk share of construction materials domestically (with the exception of Belgium), while they all are highly dependent on the imports (often from outside the EU) of metals into their national economies.

Net additions to stocks in 2014 are lowest for Finland (38% of overall material use) and highest for the Czech Republic (80% of overall material use), while for the other countries the estimate ranges between 51% to 68% of overall material use. It should be noted that the estimates of stock additions can be influenced by differences in reporting of EW-MFA and waste generation statistics between EU member states.

Table 5 suggests that the magnitude of recovery (recycling and backfilling) flows varies by country and ranges between 11% and 68% at end-of-life (output side). At the input side, the share of recycled and backfilled material range between 6% and 27%.

Table 5 Country-level analysis of end-of-life recycling rate and cyclical use rate in selected EU member states.

Country	End-of-life recycling rate[a]	Cyclical use rate[b]
Austria	54% (32% recycling, 21% backfilling)	14% (9% recycling, 5% backfilling)
Belgium	44% (44% recycling, 0% backfilling)	13% (13% recycling, 0% backfilling)
Czech Republic	67% (39% recycling, 28% backfilling)	10% (6% recycling, 4% backfilling)
Finland	11% (11% recycling, 0% backfilling)	6% (6% recycling, 0% backfilling)
France	62% (51% recycling, 11% backfilling)	27% (22% recycling, 5% backfilling)
Germany	68% (41% recycling, 26% backfilling)	21% (13% recycling, 8% backfilling)
Italy	67% (67% recycling, 0% backfilling)	21% (21% recycling, 0% backfilling)
Spain	53% (38% recycling, 15% backfilling)	15% (11% recycling, 4% backfilling)
EU-28	43% (33% recycling, 10% backfilling)	20% (15% recycling, 5% backfilling)

[a]Percentage recovered (recycling and backfilling) at end-of-life.

[b]Share of recycled and backfilled material compared to total inputs.

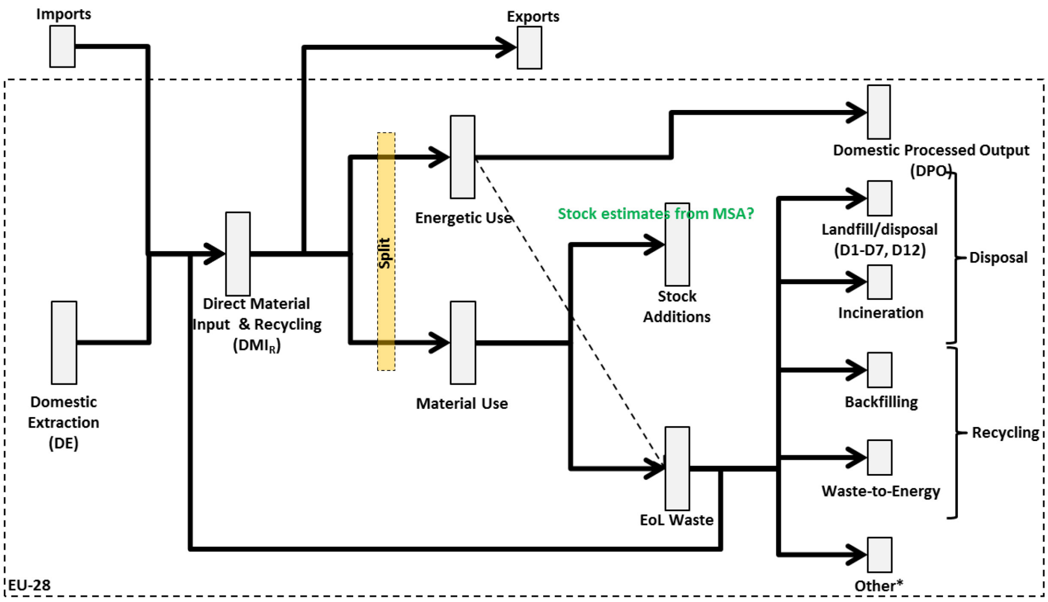
4 Discussion of Data Gaps and Needs

Readily available Eurostat data can provide an initial analysis of bulk material flows in the EU economy as well as for individual member states. However, a number of data gaps currently exist that are briefly described below together with recommendations for future research.

4.1 Expansion to include energy and food-type materials uses

The focus of the Sankey diagram in its current format is on non-energy and non-food materials. However, in order to better monitor circular material uses, it would be beneficial to also account for energy uses and biomass for non-material purposes. For this, material categories as well as wastes would need to be split into material uses and energetic uses (Figure 19), similar to what has been done in recent work by (Haas et al., 2015). However, for this additional information on the fraction of materials used for material vs. energy purposes would need to be collected.

Figure 19 Schematic diagram showing how the existing Sankey diagram framework might be expanded to include energetic uses (energy and food/feed) in the future.



*Flow used to balance the Sankey diagram.

4.2 Different classifications between EW-MFA and waste statistics are used

The Sankey diagrams in this report combine the Eurostat material flow data (input side) with the waste generation statistics (output side). However, currently no correspondence table exists to properly match the material categories from EW-MFA with the waste categories from the waste generation statistics. In order to overcome this, Table 2 lists the waste categories included in this study and the possible EW-MFA material category that is assumed to be the origin of the waste. We recommend that statistics available on the input and output side be increasingly harmonized in the future. Furthermore, waste statistics from individual countries could be further harmonized making them more transparent (what is included in the individual categories) and also providing information on main material types included in the individual waste categories.

4.3 Waste generation and waste treatment statistics are not always aligned

At the output side, the waste treatment statistics include treatment of waste imports, they are not directly comparable with the waste generation statistics (Eurostat, 2009). In order to balance flows an "other" waste category is included in this assessment (which can be up to about 25% of overall waste treatment flows). Future research should focus on closing this gap, e.g., by clearly reporting the waste imports and exports that lead to this discrepancy. It would be beneficial to increasingly incorporate trade in waste materials into the Sankey visualizations in a next step (see also Figure 3).

4.4 In-Use Stocks

The Sankey diagrams in this report combine EW-MFA flows with waste flows to derive a full systems metabolic perspective of the EU28 (excluding non-energy and non-food materials). While this flow perspective covers inputs into the EU-28 socioeconomic system and outputs to nature, flows within the socioeconomic system remain under-explored. Not all inflows are transferred to outputs within one year, but are added to societal in-use stocks. In-use stocks require a considerable fraction of all materials (and energy) input for building up and maintenance and consist a major determinant of material flows (Krausmann et al., 2017). As long as additions to stocks grow at such high rates, even high EOL recycling rates will make a limited contribution to overall circularity. In order to be able to provide useful information for policy makers on how circularity can be increased, and where constraints to such aims are rooted, the inclusion of material stocks is required. Complementary information could also increasingly be provided by the EU MSA study, e.g., for the in-use stocks and the flow of aggregates (construction minerals) in Europe (BIO by Deloitte, 2015).

4.5 Raw Material Equivalents and recycling rates

Eurostat work on raw material equivalents (RME)[31] could be increasingly incorporated into the Sankey visualizations showing the global material footprints associated with (raw) material imports. This could help to highlight were burden shifting is taking place, e.g., when increasing imports and reducing domestic extraction. Similarly, information on recycling rates outside the EU could be used as a weighting factor when determining whether exports of materials to other countries would lead to higher or lower levels of material circularity when compared to keeping them in the EU economy (i.e., the EU circularity rate could be compared to the circularity rate of the country importing the goods from the EU).

[31] http://ec.europa.eu/eurostat/statistics-explained/index.php/Material_flow_accounts_-_flows_in_raw_material_equivalents

5 Conclusion

Europe increasingly relies on reliable and robust knowledge on materials stocks and flows to better understand its resource base, monitor its performance of circular material use, and promote innovation along the entire value chain of raw materials. Data collected by the EU statistical services provides a valid basis for discussing available knowledge and starting to monitor raw materials in the EU. Assessments such as the Sankey visualizations provided in this report provide a first foundation for pointing out important data gaps and needs for future research to better monitor the physical raw materials basis of the EU.

Using existing data and information, it is possible to generate Sankey diagrams providing a "bird-eyes" view on the flows and net additions to stocks of major non-energy and non-food material categories in the EU (as well as at member state level) for different years and show their level of circularity. As these diagrams can be generated using statistics already available today, they can be readily implemented and used to provide future updates, e.g., when new waste statistics (next update will be for year 2016) become available within the near future and new EW-MFA data are published.

However, further research is needed to fill in data gaps, especially in better relating the EW-MFA data with waste generation and treatment statistics, and better estimate selected flow parameters. This will require an increased dialogue between the various stakeholders involved in providing, collecting, and disseminating the data at EU level. For example, it is often difficult to know which materials are present in different waste streams. Similarly, some data are reported at the level of materials while other data are reported at the level of activities or sectors (e.g., construction) and this makes it difficult to fully break down the Sankey diagram by material categories.

The material categories covered in this study represent about 53% of all direct material inputs (DMI) to the EU economy in 2014 (excluding inputs of recycling and backfilling). The remaining 47% consist of fossil fuels and biomass for food, feed, and energy purposes for which materials recovery is mostly not possible. In order to highlight this fact even more we recommend to include these two material categories in future studies to obtain a more holistic picture of raw materials use in the EU.

In the future, the material flow visualizations should be extended to other EU member states. Future work should also focus on generating Sankey diagrams for individual material categories and selected materials. However, in order to show material-specific Sankey diagrams additional assumptions would be required, e.g., on the quantities/shares of individual materials in the various waste streams, which could be collected from data sources going beyond the officially provided EU statistics.

In conclusion, the proposed assessment and visualization provide a reasonable first picture of non-food and non-energy raw material uses and their flow magnitudes (by major material categories) in the EU-28 as well as at EU member state level, and how these evolve over time (from 2004 to 2014 given currently published EU statistics). The resulting Sankey diagrams will feed into the EC RMIS's MFA module (currently in development) to better visualize related material flows for the EU-28 and at individual country level.

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7 Annex

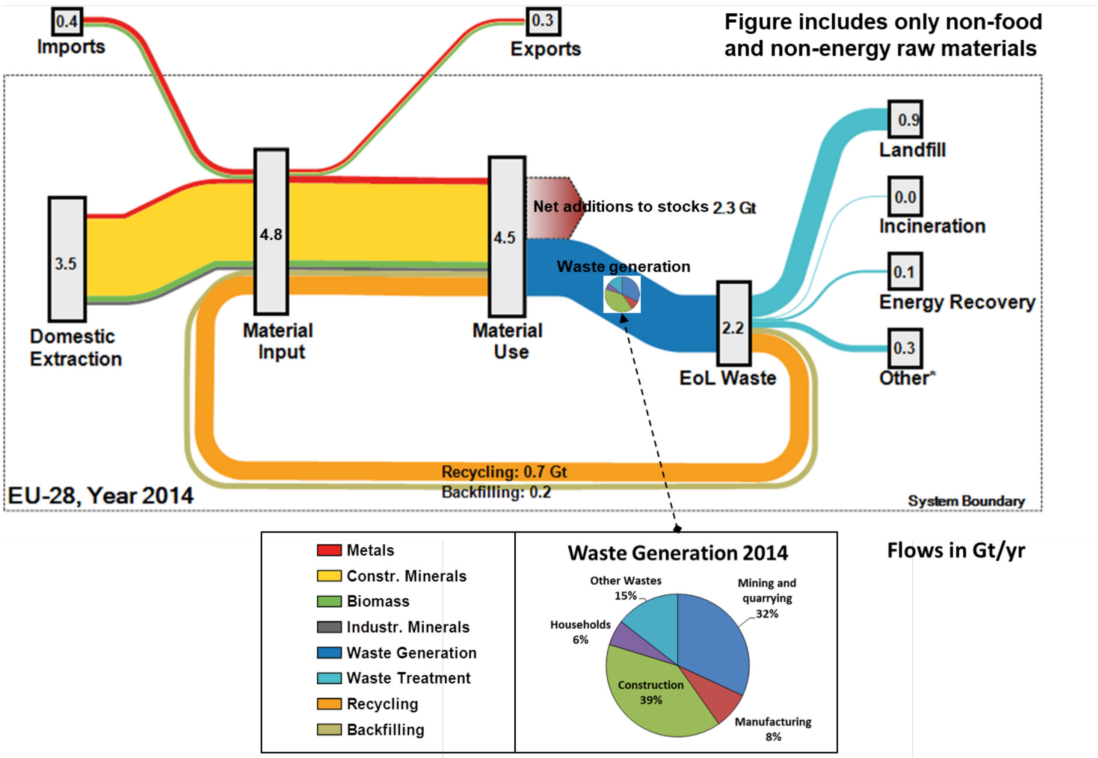
7.1 EW-MFA Categories

Table 6 Material categories included in the EW-MFA statistics. Only the material categories highlighted in the third column are included in the Sankey diagram. Other material categories might also include material uses (e.g., fossil fuels used for polymers), but have been excluded in this exercise because additional assumptions/data sources would be required and the focus is on developing a "streamlined" Sankey visualizations with as few as possible assumptions required.

Code	EW-MFA Material Categories	Material Category in Sankey Diagram	Notes
MF1	**Biomass**		
MF11	Crops (excluding fodder crops)	-	Food biomass
MF111	Cereals	-	Food biomass
MF112	Roots, tubers	-	Food biomass
MF113	Sugar crops	-	Food biomass
MF114	Pulses	-	Food biomass
MF115	Nuts	-	Food biomass
MF116	Oil-bearing crops	-	Food biomass
MF117	Vegetables	-	Food biomass
MF118	Fruits	-	Food biomass
MF119	Fibres	-	Food biomass
MF1110	Other crops n.e.c.	-	Food biomass
MF12	**Crop residues (used), fodder crops and grazed biomass**		
MF121	Crop residues (used)	-	Energy use. Left on fields.
MF1211	Straw	-	Energy use. Materials use, e.g., as insulation material in buildings.
MF1212	Other crop residues (sugar and fodder beet leaves, other)	-	Energy use, Left on fields
MF122	Fodder crops and grazed biomass	-	Fodder
MF1221	Fodder crops (including biomass harvest from grassland)	-	Fodder
MF1222	Grazed biomass	-	Fodder
MF13	**Wood**		
MF131	Timber (industrial roundwood)	Biomass	Material use, e.g., in buildings
MF132	Wood fuel and other extraction	-	Energy use
MF14	Wild fish catch, aquatic plants/animals, hunting and gathering	-	Food biomass
MF141	Wild fish catch	-	Food biomass
MF142	All other aquatic animals and plants	-	Food biomass
MF143	Hunting and gathering	-	Food biomass.
MF15	Live animals other than in 1.4, and animal products	-	Live animals. Also material products from animals
MF151	Live animals other than in 1.4	-	Live animals. Also material products from animals
MF152	Meat and meat preparations	-	Food products
MF153	Dairy products, birds' eggs, and honey	-	Food products
MF154	Other products from animals (animal fibres, skins, furs, leather, etc.)	Biomass	Material uses
MF16	Products mainly from biomass	Biomass	Material uses
MF2	**Metal ores (gross ores)**		
MF21	Iron	Metals	Metals
MF22	Non-ferrous metal	Metals	Metals
MF221	Copper	Metals	Metals
MF222	Nickel	Metals	Metals
MF223	Lead	Metals	Metals
MF224	Zinc	Metals	Metals
MF225	Tin	Metals	Metals
MF226	Gold, silver, platinum and other precious metals	Metals	Metals
MF227	Bauxite and other aluminium	Metals	Metals
MF228	Uranium and thorium	Metals	Metals (energy uses)
MF229	Other metals n.e.c.	Metals	Metals
MF23	Products mainly from metals	Metals	Metals
MF3	**Non-metallic minerals**		
MF31	Marble, granite, sandstone, porphyry, basalt, other ornamental or building stone (excluding slate)	Construction Minerals	
MF32	Chalk and dolomite	Construction Minerals	
MF33	Slate	Construction Minerals	
MF34	Chemical and fertiliser minerals	Industrial Minerals	

MF35	Salt	Industrial Minerals	
MF36	Limestone and gypsum	Construction Minerals	
MF37	Clays and kaolin	Construction Minerals	
MF38	Sand and gravel	Construction Minerals	
MF39	Other non-metallic minerals n.e.c.	Industrial Minerals	
MF311	Products mainly from non metallic minerals	Industrial Minerals	
MF4	**Fossil energy materials/carriers**		
MF41	**Coal and other solid energy materials/carriers**		
MF411	Lignite (brown coal)	-	Fossil fuels
MF412	Hard coal	-	Fossil fuels
MF413	Oil shale and tar sands	-	Fossil fuels
MF414	Peat	-	Fossil fuels
MF42	**Liquid and gaseous energy materials/carriers**		
MF421	Crude oil, condensate and natural gas liquids (NGL)	-	Fossil fuels. Partly also for polymers (materials purposes)
MF422	Natural gas	-	Fossil fuels. Partly also for polymers (materials purposes)
MF423	**Fuels bunkered (Imports: by resident units abroad); (Exports: by non-resident units domestically)**		
MF4231	Fuel for land transport	-	Fossil fuels
MF4232	Fuel for water transport	-	Fossil fuels
MF4233	Fuel for air transport	-	Fossil fuels
MF43	Products mainly from fossil energy products	-	Fossil fuels

7.2 EU-28 Sankey Diagrams



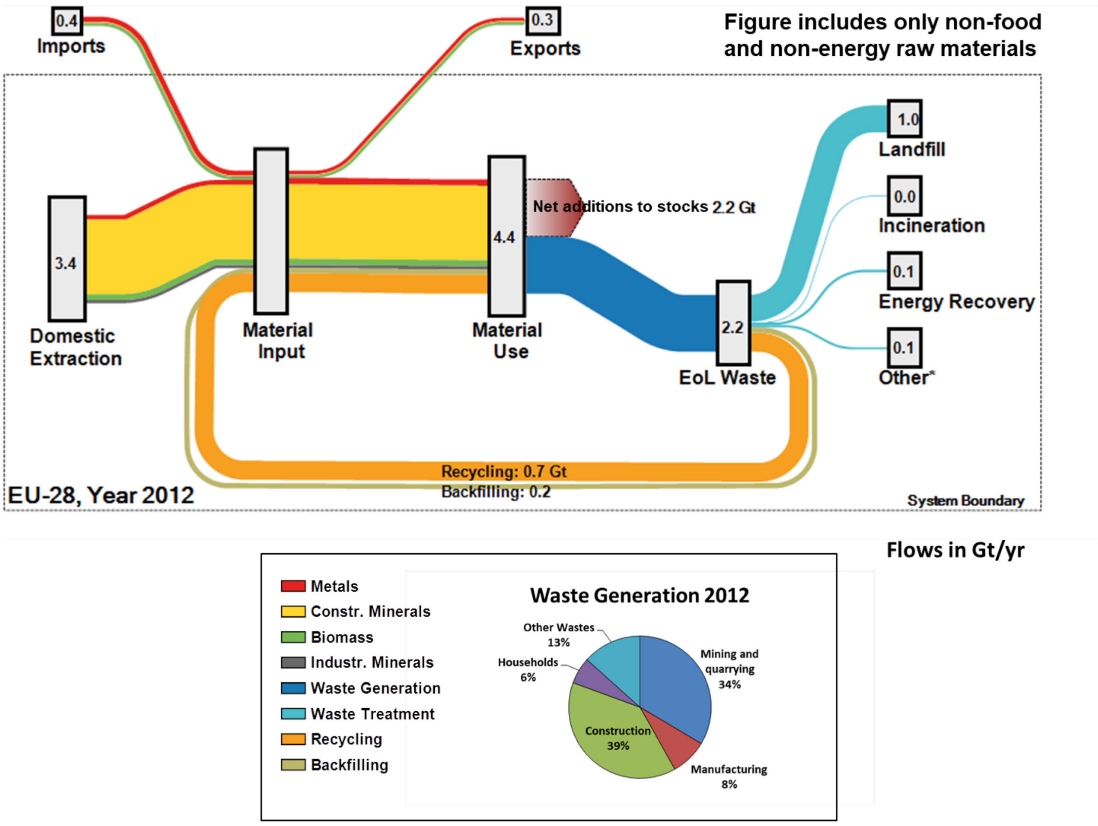


Figure includes only non-food and non-energy raw materials
0.4
Imports
0.3
Exports
3.4
Domestic Extraction
Material Input
4.4
Material Use
Net additions to stocks 2.2 Gt
2.2
EoL Waste
1.0
Landfill
0.0
Incineration
0.1
Energy Recovery
0.1
Other*
Recycling: 0.7 Gt
Backfilling: 0.2
EU-28, Year 2012
System Boundary
Flows in Gt/yr
Metals
Constr. Minerals
Biomass
Industr. Minerals
Waste Generation
Waste Treatment
Recycling
Backfilling
Waste Generation 2012
Other Wastes 13%
Households 6%
Mining and quarrying 34%
Construction 39%
Manufacturing 8%

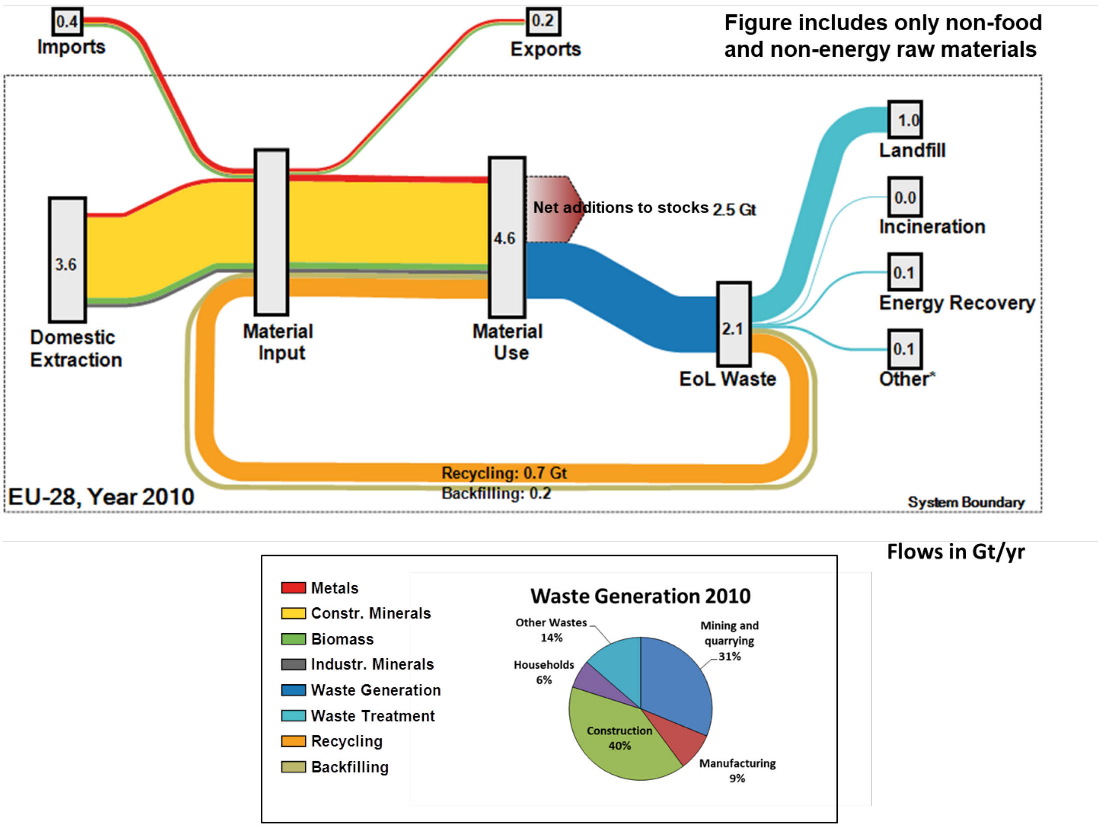
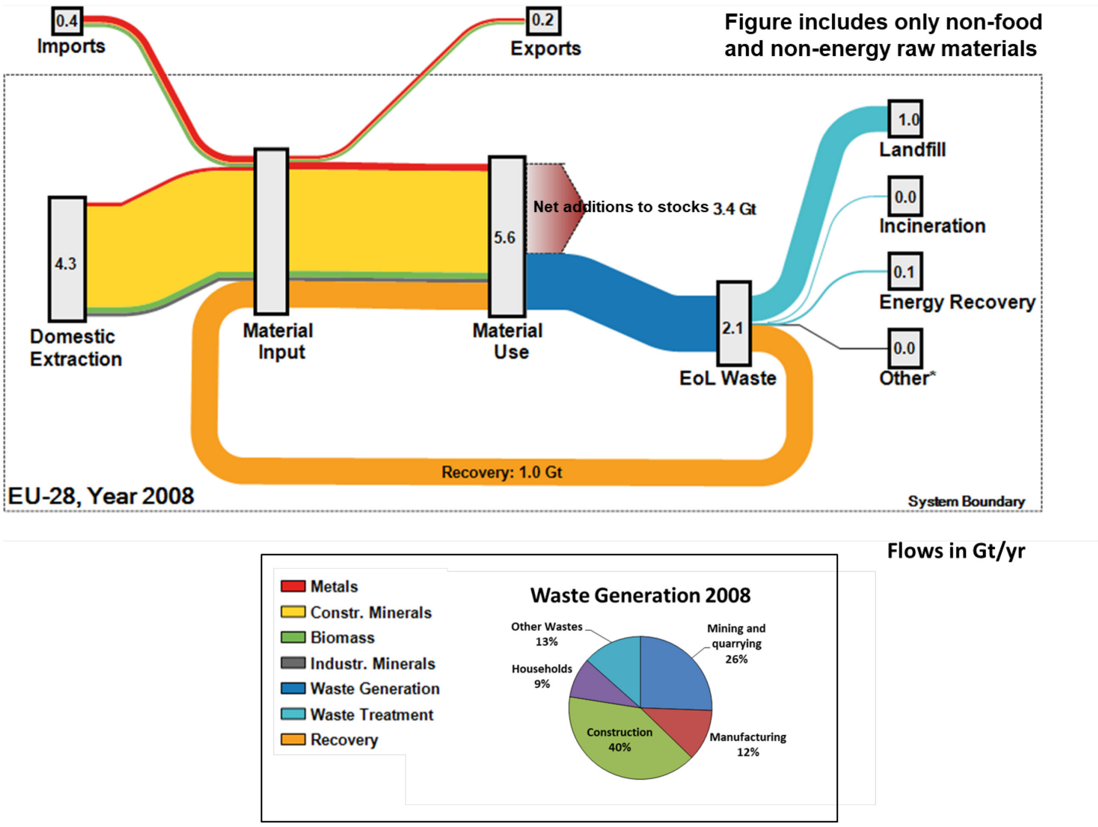
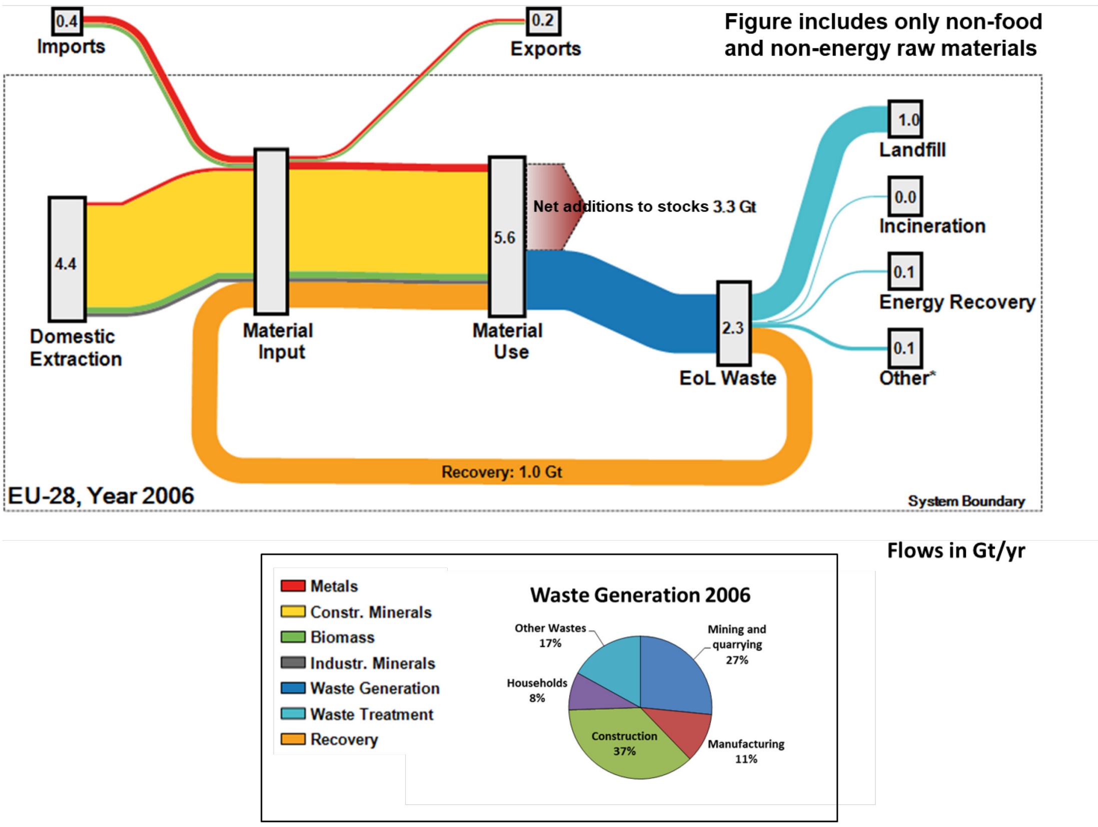


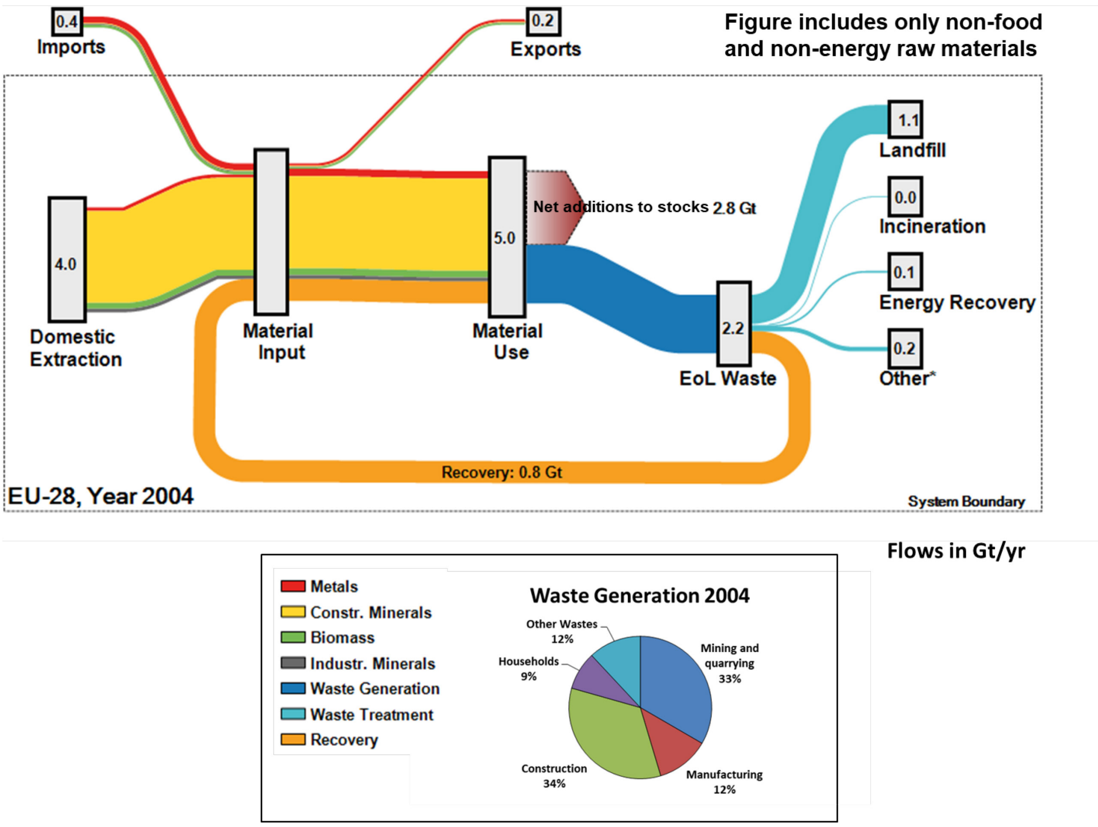
Figure includes only non-food and non-energy raw materials
0.4
Imports
0.2
Exports
3.6
Domestic Extraction
Material Input
4.6
Material Use
Net additions to stocks 2.5 Gt
2.1
EoL Waste
1.0
Landfill
0.0
Incineration
0.1
Energy Recovery
0.1
Other*
Recycling: 0.7 Gt
Backfilling: 0.2
EU-28, Year 2010
System Boundary
Flows in Gt/yr
Metals
Constr. Minerals
Biomass
Industr. Minerals
Waste Generation
Waste Treatment
Recycling
Backfilling
Waste Generation 2010
Other Wastes 14%
Households 6%
Mining and quarrying 31%
Construction 40%
Manufacturing 9%



0.4
Imports
0.2
Exports
Figure includes only non-food and non-energy raw materials
1.0
Landfill
0.0
Incineration
0.1
Energy Recovery
0.0
Other*
Net additions to stocks 3.4 Gt
4.3
5.6
2.1
Domestic Extraction
Material Input
Material Use
EoL Waste
Recovery: 1.0 Gt
EU-28, Year 2008
System Boundary
Flows in Gt/yr
Metals
Constr. Minerals
Biomass
Industr. Minerals
Waste Generation
Waste Treatment
Recovery
Waste Generation 2008
Other Wastes 13%
Mining and quarrying 26%
Households 9%
Construction 40%
Manufacturing 12%



0.4
Imports
0.2
Exports
Figure includes only non-food and non-energy raw materials
1.0
Landfill
0.0
Incineration
0.1
Energy Recovery
0.1
Other*
Net additions to stocks 3.3 Gt
4.4
5.6
2.3
Domestic Extraction
Material Input
Material Use
EoL Waste
Recovery: 1.0 Gt
EU-28, Year 2006
System Boundary
Flows in Gt/yr
Metals
Constr. Minerals
Biomass
Industr. Minerals
Waste Generation
Waste Treatment
Recovery
Waste Generation 2006
Other Wastes 17%
Mining and quarrying 27%
Households 8%
Construction 37%
Manufacturing 11%


0.4
Imports
0.2
Exports
Figure includes only non-food and non-energy raw materials
1.1
Landfill
0.0
Incineration
0.1
Energy Recovery
0.2
Other*
4.0
Domestic Extraction
Material Input
5.0
Material Use
Net additions to stocks 2.8 Gt
2.2
EoL Waste
Recovery: 0.8 Gt
EU-28, Year 2004
System Boundary
Flows in Gt/yr
Metals
Constr. Minerals
Biomass
Industr. Minerals
Waste Generation
Waste Treatment
Recovery
Waste Generation 2004
Other Wastes 12%
Households 9%
Mining and quarrying 33%
Construction 34%
Manufacturing 12%

List of abbreviations and definitions

CE:	Circular economy
DMC:	Domestic material consumption
DMI:	Direct material input
EC:	European Commission
EIP-RM:	European Innovation Partnership on Raw Materials
ESTAT:	Eurostat
EU:	European Union
EW-MFA:	Economy-wide material flow accounts
Gt:	Gigaton
MFA:	Material flow analysis
MSW:	Municipal Solid Waste
NSA:	Net additions to stocks
RMIS:	EU Raw Materials Information System

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