Discussion paper

Analyzing and Visualizing Material Flows within the Circular Economy

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Index

1. Introduction

The circular economy (CE) is becoming more and more important as a means to reduce the economic need for natural resources and the associated environmental impacts. In order to support policy makers Statistical agencies throughout Europe are working to produce statistical data on the physical stocks and flows of materials as well as to derive key policy indicators, such as Domestic Material Consumption (DMC), Circular Material Use Rate (CMUR), and Resource Productivity. There is a growing need for more detailed information, for more advanced analyses, and for visual aids in order to unlock and disseminate the wealth of statistical information.

The objective of this project is to provide more detailed statistical information on the circular economy, in particular the Circular Material Use Rate (CMUR), as well as on compositional changes over time, and to develop a visualisation tool that provides policy makers and other users with better access to information on the structure and development of the circular economy.

In chapter 2 we will present a methodology for EU countries to develop a supply-use framework of material flows within the economy. The framework applies SEEA concepts and definitions and is based on statistics that are mandatory for reporting to Eurostat. From data in this framework CMURs that address a broad spectrum of policy issues are estimated. The results will be incorporated in Sankey diagrams derived from a visualization tool developed in chapter 4. The visualization tool consist of an open source R package which allows users (e.g. statistical agencies) to insert their own data in order to compile Sankey diagrams for the circular economy. In chapter 3 we investigate the drivers behind the use of primary abiotic resources, a key CE policy target in the Netherlands. For this an index decomposition analysis (IDA) is presented in R. Data is drawn from official statistical sources, making it possible for statistical agencies in other EU countries to use the same methodology. This report sums up with a discussion and recommendations.

2. CMUR with material breakdown

The Circular Material Use Rate (CMUR) is an important indicator for measuring progress towards a circular economy. The CMUR is one of the key CE indicators compiled by Eurostat for the EU. Currently, the CMUR is compiled for four main material categories, namely biomass, fossil energy carriers, metals and non-metal minerals. One of the objectives of this report is to develop a more detailed specification of types of material flows. This will enable us to estimate a CMUR that addresses a broader spectrum of policy issues, for example related to renewables like biomass.

This chapter is broken down into two parts. The first part describes the methodology for integrating different modules of the environmental accounts, such as the Economy Wide Material Flow Accounts (EW-MFA) and energy accounts, and national accounts into physical supply and use tables (PSUTs). This methodology has been applied already by the Netherlands (Berkel and Delahaye, 2019) to compile the Material Flow Monitor (MFM). In this chapter guidelines are presented for other countries to use the more advanced techniques to compile the MFM. In order to provide comprehensible guidelines, the Dutch methodology is tailored to other EU countries as much as possible. The information on physical material flows within the economy in the MFM is used in the second part of this chapter to compile Sankey diagrams for policy-relevant material flows. We look into the construction and textile sector. Indicators, like the CMUR, that can be derived from the Sankey diagrams are described. The Sankey diagrams are compiled by using the visualisation tool presented in chapter 4.

2.1 Compilation of physical supply and use tables

2.1.1 Introduction

In the Netherlands, physical (million kilos) supply and use tables (PSUTs) and its derived indicators are referred to as the Material Flow Monitor (MFM). The MFM is a macro-economic database of all material flows within the economy, imports and exports and flows between the economy and the environment. The MFM is compiled by Statistics Netherlands every two years, in order to support Dutch policy on the circular economy (Potting *et al*, 2018).

Physical supply and use tables are compiled according to the same concepts and definitions as the monetary supply and use tables of the national accounts, (UN *et al.*, 2009) and the System of Environmental Accounts (SEEA((UN *et al*, 2012). This creates the possibility to compare these statistics with their economic counterparts like GDP, employment, consumption and other economic figures per economic industry (NACE) like production values. Figure 2.1.1 is taken from the SEEA Central Framework and illustrates the physical supply and use tables. The MFM follows the same structure and also contains additional information on non-monetary physical flows like residuals and natural inputs. These flows show the relationship between the environment and the economy. On the other hand, the National Accounts contain additional non-physical information like the production of services or trade margins. For more detail on the compilation of the MFM see a technical report by Berkel and Delahaye (2019).

	Industries	Households	Accumulation	Rest of the world	Environment	Total
Supply table						
Natural inputs					Flows from the environment	Total supply of natural inputs
Products	Output			Imports		Total supply of products
Residuals	Residuals generated by industry	Residuals generated by final household consumption	Residuals from scrapping and demolition of produced assets			Total supply of residuals
Use table						
Natural inputs	Extraction of natural inputs					Total use of natural inputs
Products	Intermediate consumption	Household final consumption	Gross capital formation	Exports		Total use of products
Residuals	Collection & treatment of waste and other residuals		Accumulation of waste in controlled landfill sites		Residual flows direct to environment	Total use of residuals

Figure 2.1.1 Physical supply and use tables

The next section elaborates on the data requirements and methodology used for compiling MFM (or PSUTs) with regard to implementation by EU member states. In short the following steps will be discussed: monetary supply and use tables are converted to kilos by applying unit values (euro per kilo). Subsequently these tables are improved and enhanced with additional information. Finally, supply and use are balanced for both commodities and sectors.

2.1.2 Data sources and methodology

Step 1: MSUT conversion to kilo's

The first step in compiling the MFM is to convert the monetary supply and use tables (MSUTs) into physical (kilo) values. The monetary supply and use tables (MSUTs) are compiled by the National Accounts department of statistical offices. Statistical offices report MSUTs to Eurostat at a relatively low level of detail of around 60 commodities by 60 sectors[1]. However, for conversion to kilo's it is important to have commodities and sectors that are as detailed, and therefore as homogenous, as possible. Therefore, it is much preferred to use MSUTs at a higher of detail than is reported to Eurostat. In the Netherlands, MSUTs of round 300 commodities and 130 sectors are used as a starting point. The use table should be converted into basic prices: leaving margins, subsidies and taxes out provides a better match with the unit values (see next paragraph) that are used to convert the monetary values to kilos. In the Netherlands, an additional adjustment is made to the MSUTs before conversion related to the recording of goods sent for processing and production abroad in the System of National Accounts (SNA). According to the SNA (UN *et al*, 2009), goods sent for processing and production abroad should be recorded as a service and not as product flows related to these services. Because we would like to include these product flows for our analysis, we adjust the MSUT data in order to record the actual product flows. The recording we want is similar to definitions and concepts used in the international trade statistics and the Economy wide Material Flow Accounts (EW-MFA). However, in the MSUTs not only imports and exports need to be adjusted, but also domestic supply and use. The good news for other member states is that goods sent for processing and production abroad may not play a substantial role in their countries and corrections may not be necessary. For the Netherlands it is important because it is a small country with an open economy.

The monetary values are divided by unit values in order get a first estimate of a supply and use tables in physical units (kilo's). Unit values are the price per kilo for a specific good and sector. As pointed out before, the more homogeneous products and sectors are, the easier it becomes to

[1] All Eurostat data can be found at https://ec.europa.eu/eurostat/data/database

estimate a reliable unit value and, therefore, kilo estimates. However, it should be kept in mind that this first step is only a first estimate of the PSUTs. Therefore, using less accurate unit values does not need to be a problem because in later steps, adding additional physical data and balancing, will improve the data. Unit values can be derived from different sources. Two sources that are available for all EU countries are discussed below.

First, monetary and physical data from international trade statistics can be used to estimate unit values. International trade statistics cover almost all commodities present in MSUTs. A link between international trade (CN codes) and national accounts (CPA) classifications can be found at the RAMON classification server[2]. Some of the physical trade values are not in kilo's but in other physical units (e.g. pieces or m³). Conversion factors, to convert these units into kilo's, can be obtained from Eurostat[3]. Unit values of imported goods are applied to the monetary use table and unit values of exported goods are applied to the monetary supply table to calculate the physical figures. The reason for this is that goods used by industries are partly imported. Supplied goods are partly exported. Statistics on international trade are mandatory for EU countries to report to Eurostat. However, due to confidentiality not all figures can be published by Eurostat. Therefore, it is better to use the complete dataset that is present at the national statistical office.

Second, Prodcom provides statistics on the production of manufactured goods in terms of volumes and euros. The advantage of this source is that it provides unit values of goods for the different sectors. This means that different unit values can be found depending on the sector that is supplying this product. Therefore, with regard to domestic production, united values estimated by Prodcom overrule estimations made by trade statistics. Prodcom statistics are also compiled in each EU country and collected by Eurostat. Similar to the trade data: a more complete set of data is probably available at the statistical office. In order to convert non-kilo units to kilo's the conversion factors of the international trade statistics can be used. There is a link between the international trade statistics classification and the Prodcom classification.

Other data sources can, of course also be used. Maybe a country has more specific data on energy prizes or on prizes paid by housholds.

The first step results in a first estimate of physical supply and use tables related to products flows. Below, in step two, these figures are 1) enhanced with better quality data and 2) elaborated with extraction and data on residues.

Step 2: PSUTs improved and enhanced with additional information

In step two, the result from step one is partly replaced with better quality data from additional data sources. First, physical import and export data from the international trade statistics are inserted. This data is regarded of better quality than estimations made in step one because most of this data is collected in physical terms (so no conversion is needed) and "production abroad"/"goods sent for processing" does not play a role here. International trade data should already be available because it was already collected when estimating the unit values in step one. Second, data on energy carriers can be replaced with data from the physical energy flow accounts (PEFA). This requires an unit conversion to be made from joules to kilo's for each energy carrier. Conversion factors are available from Eurostat MFA manual[4]. At Statistics Netherlands we use conversion factors from our energy department because these are more accurate for the

[2] https://ec.europa.eu/eurostat/ramon/index.cfm?TargetUrl=DSP_PUB_WELC

[3] http://epp.eurostat.ec.europa.eu/newxtweb/downloadobject.do?keepsessionkey=true&filenameOut=INTRASTAT_NET_MASS_SINCE_2006.zip&mimeType=application/zip&objectID=610438034&objectType=LOB&disposition=attachment

[4] https://ec.europa.eu/eurostat/web/products-manuals-and-guidelines/-/KS-GQ-18-006

Netherlands. Data from the energy accounts also meet the residence principle criteria. Third, Prodcom data can be used to enhance outut data by industry. Notice that Prodcom contains only data of companies with 20 or more employees. This is one of the reasons why Prodcom was not used by the Netherlands. Again, Prodcom data might already be available because it was also used in establishing unit values in step one. Fourth, physical production by agriculture might be used here using data from agriculture statistics. This data is reported to Eurostat and often in country-specific statistics. Finally, other data sources that are available for specific countries can be used. For example, until recently, we had data available on the amount of consumption per product by households.

The product classification of the extra data sources used in step two should somehow be linked to the classification used in PSUTs. For some data sources correspondence tables provided by Eurostat can be used[5]. For others new correspondence tables have to compiled. For example, in the Netherlands, the link between classifications of energy carriers from the energy accounts and the national accounts was made in accordance with experts in the field.

Beside enhancing the physical data of our initial estimate in step one, we now have to add physical data that is not covered by products with a monetary value. These are the natural inputs and residuals of figure 2.1.1. These entries are also needed to balance the columns of our supply and use tables (step three). Extraction of resources, including harvest, can be obtained from the Economy wide Material Flow Accounts (EW-MFA). These figures only need to be allocated to the appropriate sector that is doing the extraction. Notice that, as a rule of thumb, the amount of extraction cannot exceed the amount of production of a similar good. Data on the production of waste can be taken from the waste statistics, mandatory to report to Eurostat. Import and export of waste can be derived from the trade statistics. A list of CN codes that can be regarded waste are provided by Eurostat[6]. Make sure there is no double counting with any of your product groups derived from the national accounts. With regard to the use of waste only information is available on the amount processed by the waste collection and treatment facilities (NACE 38) in order to prepare waste for recycling. Hardly any information is available on the use of waste or by other sectors or the further use of secondary products produced by NACE 38. Here we recommend to use expert guesses. Balancing items that relate to the combustion of fossil fuels also need to be added. Data on CO_2 emissions can be taken from the annual mandatory air emissions accounts. Other balancing items like H_2O, O_2 and N can be derived with the help of conversion factors provided by the Eurostat MFA handbook. Balancing items are part of table G of the MFA questionnaire. Bulk water is not part of the MFM. Therefore, addition (e.g. production of beverages) or loss (e.g. drying of wood) of water needs to be part of the balancing items (another option is to compile supply and use tables in dry matter weight). The water balancing item is determined by estimating the water content of all products on the supply and use side per industry. The difference is the water balancing item. Information of the water content of products was taken from several sources amongst which JRC (Joint Research Centre). Finally, for some sectors a balancing item needs to be introduced that deals with the fact that these sectors use products that are no part of their physical output. Examples are restaurants, that buy food but produce a service, and agriculture, that use fertilizer and pesticides of which most do not end up in a product. The result of step two are supply and use tables that can be balanced for both rows and columns. This is explained in step 3.

Step 3: balancing PSUTs

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5 https://ec.europa.eu/eurostat/ramon/relations/index.cfm?TargetUrl=LST_REL&StrLanguageCode=EN&IntCurrentPage=3

6 https://ec.europa.eu/eurostat/documents/8105938/8465062/cei_srm030_esmsip_CN-codes.pdf

Due to the integration of different data sources with differences in data quality, it is very likely that supply does not equal use. This applies for both the rows (commodities) and columns (sectors). The final step to complete the MFM is to balance both supply and use of goods and input and output of sectors. Large differences between supply and use are investigated and solved by manually adjusting the values in the PSUTs. The decision to correct a certain value is dependent on the confrontation of different data sources where one data source could be of better quality than the other. Also, additional data sources can be consulted to verify the right amount of kilos. When the differences are analysed and reduced to sufficient amounts (less than 10 percent), balancing software (which is also used for balancing to MSUTs) solves the remaining differences completely.

2.1.3 Result: physical supply and use tables

The application of methodology described above results in a complete and balanced physical supply and use table. Figures 2.1.3a and 2.1.3b show, respectively, the supply and use tables on an aggregated level of detail. The first 22 rows represent products equal to the products in the national accounts. Two additional rows show waste and extraction. These two entries are similar to the residuals and natural inputs present in table 2.1.1. Finally a balancing entry is added. The balancing row contains, for example, emissions to or from air, water loss or gain during the production process (e.g. beverage industry) or production of services (e.g. restaurants). Balancing items, depending on their nature, can appear both in the supply and use tables. The columns show economic sectors, households, accumulation (like investments but also cultivated landfills) and trade similar to the classification of the national accounts. A column representing the environment is also part of the physical table.

	Agriculture, forestry and fishing	Mining industry	Manufacture of food products, beverages and tobacco products	Manufacture of textiles, wearing apparel and leather products	Manufacture of wood and paper products	Manufacture of coke and refined petroleum products	Manufacture of chemicals and pharmaceutical products	Manufacture of rubber and plastics products	Manufacture of other non-metallic mineral products	Manufacture of basic metals	Manufacture of metal products, except machinery and equipment	Manufacture of computer, electronic and optical products	Manufacture of electrical equipment	Manufacture of machinery and equipment n.e.c.	Manufacture of transport equipment	Manufacture of furniture and other manufacturing a	Electricity, gas and steam supply	Water treatment and supply; sewerage; waste treatment	Construction	Services	**Total collum 1–20**	Consumption households	Accumulation	Import	Flows from the environment	**Total**
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Products of agriculture, forestry and fishing	26 119															11					**26 130**			30 732		**56 862**
Products of cattle breeding	19 190																				**19 190**			1 315		**20 505**
Energy carriers	1 860	42 913	368		503	348	1 582										258	1 394		118	**49 344**			133 396		**182 740**
Other mining products		27 008					4 347	632											683	96	**32 766**			42 538		**75 304**
Fish and meat products	98		4 897																	16	**5 011**			2 884		**7 895**
Potato, vegetable and fruit products			4 173																	225	**4 398**			3 619		**8 017**
Diary products	42		6 043																	72	**6 157**			2 538		**8 695**
Grain mill and starch products			4 018																	28	**4 046**			3 228		**7 274**
Other food products			29 966		4		174													137	**30 281**			9 788		**40 069**
Beverages and tobacco products			5 745																	32	**5 777**			3 204		**8 981**
Textiles, wearing apparel and leather products				670	19		10	2			9			11		12				53	**786**			1 650		**2 436**
Wood products, except furniture				8	2 635		3	3	6							78			2	77	**2 812**			5 867		**8 679**
Printing and paper products				10	5 363			18		3	7					19				63	**5 483**			6 310		**11 793**
Coke and refined petroleum products						80 741	4 245			3 220											**88 206**			82 012		**170 218**
Chemical and pharmaceutical products	9	311	285		2	1 190	44 563	220	25	26	12		25	5				2 785		413	**49 871**			35 417		**85 288**
Rubber and plastic products				1	29		60	2 645		2	33		3	32	3	32				17	**2 857**			2 455		**5 312**
Other non-metallic mineral products		16		4			22	37	23 531	44	4	6	35			1			72	255	**24 027**			8 514		**32 541**
Basic metals			20				5	12	4	8 727	636		3	15						24	**9 446**			13 603		**23 049**
Metal products, except machinery			6	1	2			23	6	108	4 616	5	4	116	5	38			19	87	**5 036**			1 735		**6 771**
Machinery and equipment					5			7	7	51	81	243	945	3 310	24	109				173	**4 955**			6 884		**11 839**
Transport equipment										22	33			88	2 527	43			10	159	**2 882**			3 605		**6 487**
Furniture and other manufactured goods				5	1 133		26				1		1			941				848	**2 955**			1 643		**4 598**
Total row 1-22	**47 318**	**70 248**	**55 521**	**699**	**9 695**	**82 279**	**55 037**	**3 599**	**23 579**	**12 203**	**5 432**	**254**	**1 016**	**3 577**	**2 559**	**1 284**	**258**	**4 179**	**786**	**2 893**	**382 416**			**402 937**		**785 353**
Waste and recycled products	4 977	54	7 903	48	701	722	855	143	572	1 876	384	19	49	151	130	245	2 022	16 531	18 760	5 818	**61 960**	8 165	11 418	27 494		**109 037**
Extraction																									116 331	**116 331**
Balancing item	65 300	3 423	23 302	295	2 424	18 566	30 701	504	4 007	10 031	776	556	199	379	363	1 181	80 798	15 349	64 939	73 102	**396 195**	60 401			267 300	**723 896**
Total	**117 595**	**73 725**	**86 726**	**1 042**	**12 820**	**101 567**	**86 593**	**4 246**	**28 158**	**24 110**	**6 592**	**829**	**1 264**	**4 107**	**3 052**	**2 710**	**83 078**	**36 059**	**84 485**	**81 813**	**840 571**	**68 566**	**11 418**	**430 431**	**383 631**	**1734 617**

Figure 2.1.3a: Physical (million kilo's) supply table the Netherlands, 2016

	Agriculture, forestry and fishing	Mining industry	Manufacture of food products, beverages and tobacco products	Manufacture of textiles, wearing apparel and leather products	Manufacture of wood and paper products	Manufacture of coke and refined petroleum products	Manufacture of chemicals and pharmaceutical products	Manufacture of rubber and plastics products	Manufacture of other non-metallic mineral products	Manufacture of basic metals	Manufacture of metal products, except machinery and equipment	Manufacture of computer, electronic and optical products	Manufacture of electrical equipment	Manufacture of machinery and equipment n.e.c.	Manufacture of transport equipment	Manufacture of furniture and other manufacturing a	Electricity, gas and steam supply	Water treatment and supply; sewerage; waste treatment	Construction	Services	**Total collum 1–20**	Consumption households	Accumulation & other final demand	Export	Flows to the environment	**Total**
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	23	24	22	26	27
Products of agriculture, forestry and fishing	3 876		30 076	27	543		11	37											11	1 219	**35 800**	3 842	- 725	17 945		**56 862**
Products of cattle breeding	485		17 945	4																84	**18 518**	147	156	1 684		**20 505**
Energy carriers	3 970	696	1 838	66	869	60 067	11 006	98	521	5 222	140	13	266	63	49	20	20 530	536	155	3 589	**109 714**	8 823	-1 290	65 493		**182 740**
Other mining products	748	4 734	112	75	130		1 841	155	13 331	10 081	134	4		5		107			25 712	2 264	**59 433**	159	835	14 877		**75 304**
Fish and meat products			1 447	42																504	**1 993**	1 346	2	4 554		**7 895**
Potato, vegetable and fruit products	5		640				2													715	**1 362**	2 042	6	4 607		**8 017**
Diary products	5		2 524				239													697	**3 465**	2 052	69	3 109		**8 695**
Grain mill and starch products	87		3 490		49		44	1										2	22	221	**3 916**	873	69	2 416		**7 274**
Other food products	12 521		8 168		13	297	412	22									15	2		1 062	**22 512**	4 099	194	13 264		**40 069**
Beverages and tobacco products	4		428				4				4	3			6				6	2 628	**3 083**	2 327		3 571		**8 981**
Textiles, wearing apparel and leather products	5		4	255	32		1	19	2		3	6	13	11	3	28		1	8	126	**517**	475	92	1 352		**2 436**
Wood products, except furniture	92	3	300	41	1 342	2	147	117	66	64	128	22	8	106	78	462	6	1	1 387	1 367	**5 739**	308	166	2 466		**8 679**
Printing and paper products	20	2	1 143	8	3 634		189	94	38	8	43	31	10	131	39	79	2		12	1 214	**6 697**	348	63	4 685		**11 793**
Coke and refined petroleum products	634	7	51	3	36	25 344	13 631	8	47	2 484	24		3	11	19	67	823	58	1 049	10 740	**55 039**	6 153	- 486	109 512		**170 218**
Chemical and pharmaceutical products	1 856	97	722	214	388	833	25 977	2 152	134	88	115	481	65	45	40	349	10	390	462	1 871	**36 289**	505	429	48 065		**85 288**
Rubber and plastic products	69	3	372	7	131	3	123	233	96	11	75	8	86	97	115	62	4	5	561	569	**2 630**	263	114	2 305		**5 312**
Other non-metallic mineral products	67		825		72		71	9	4 497	299	96	13	67	19	29	72	83	27	18 004	2 067	**26 317**	522	202	5 500		**32 541**
Basic metals	5			4	24		83	130	154	1 280	4 490	50	121	1 405	784	332		4	734	257	**9 857**		288	12 904		**23 049**
Metal products, except machinery	4	1	260		37	2	66	9	5	2	571	23	2	454	270	335	28	1	1 505	366	**3 941**	97	435	2 298		**6 771**
Machinery and equipment		24	18								76	114	190	895	324	160	1	5	558	472	**2 837**	309	2 903	5 790		**11 839**
Transport equipment											2			5	1 007				8	299	**1 321**	363	718	4 085		**6 487**
Furniture and other manufactured goods	2	1	38	3	4		15	4	1	4	6	12	7	10	18	74	6		89	1 260	**1 554**	1 270	571	1 203		**4 598**
Total row 1-22	**24 455**	**5 568**	**70 401**	**749**	**7 304**	**86 548**	**53 862**	**3 088**	**18 892**	**19 543**	**5 907**	**780**	**838**	**3 257**	**2 781**	**2 147**	**21 508**	**1 032**	**50 283**	**33 591**	**412 534**	**36 323**	**4 811**	**331 685**		**785 353**
Waste and recycled products	8 910	62	5 933	39	2 950		1 367	748	2 966	2 732	32			500			1 740	26 830	30 719		**85 528**		1 142	22 367		**109 037**
Extraction	41 131	65 377					5 680		4 143												**116 331**					**116 331**
Balancing item	43 099	2 718	10 392	254	2 566	15 019	25 684	410	2 157	1 835	653	49	426	350	271	563	59 830	8 197	3 483	48 247	**226 203**	32 590	101 551		363 552	**723 896**
Total	**117 595**	**73 725**	**86 726**	**1 042**	**12 820**	**101 567**	**86 593**	**4 246**	**28 158**	**24 110**	**6 592**	**829**	**1 264**	**4 107**	**3 052**	**2 710**	**83 078**	**36 059**	**84 485**	**81 838**	**840 596**	**68 913**	**107 504**	**354 052**	**363 552**	**1734 617**

Figure 2.1.3b: Physical use (million kilo's) table the Netherlands, 2016.

Behind these aggregated tables are more detailed PSUTs that distinguish around 130 sectors and 300 commodities. These detailed tables are only used for analytical purposes and are not published as official Statistics Netherlands data. The reason for this is that it is difficult to judge the plausibility of all the variables present; added to this, plausibility may differ between variables in the detailed dataset. However, the detailed dataset is judged plausible enough to derive indicators that support Dutch policy on circular economy. For example, in relation to monetary SUTs, resource efficiency (value added per kilo input) indicators can be derived per sector. Another way to estimate resource efficiency is to derive the amount of waste produced per kilo output (or input). Another example of an important indicator that is derived from this data set is the input of secondary materials relative to the input of primary materials, also referred to as the Circular Material Use Rate (CMUR), per sector. The CMUR is explored in more detail in the next chapter.

The MFM dataset can also be used to compile material Sankey diagrams. We already compile a Sankey diagram for the Netherlands similar to the one that Eurostat publishes[7]. This Sankey diagram shows material flows to and from the economy, divided in the four main material categories: biomass, minerals, metals and fossil. However, it is also possible to use the MFM to compile Sankey diagrams that focus on more specific sectors and product groups that are relevant with regard to the circular economy and especially the CMUR indicator.

2.2 Sankey diagrams for relevant material flows

The main challenge of developing Sankey diagrams based on data from the MFM is to combine all available data in one clear and easy to interpret Sankey diagram. This is essential to exploit the rich data sources and to make policy relevant information easily accessible and understandable for users. Two examples are the Sankey diagrams for the textile and construction industry shown in paragraph 2.2.2 and 2.2.3. Breakdowns have been presented for the most relevant material flows and material categories. However, there are some limitations with developing Sankey diagrams based on MFM data, which will be explained first.

2.2.1 Limitations in compiling Sankey diagrams

The MFM provides detailed information on the material flows supplied and used by industry. However, it does not provide information on who delivers to whom. Lack of this information causes a limitation for compiling Sankey diagrams. For instance, the MFM shows how much wood is used by the construction sector, but it does not show whether this wood is imported from abroad or supplied by domestic production, and in the latter case, by which industries. A physical input-output table is required to know who delivers to whom. Because there is no such physical input-output table available, the monetary input-output table was used to obtain information on who delivers certain products to whom.

However, using the monetary input-output table is not sufficient to completely solve the problem. Only products with monetary values are included in the monetary input-output table. Waste residuals, with no monetary value, are not part of the monetary input-output table. This is a limitation because the Sankey diagrams in this chapter are aimed at providing insight into the circularity of certain industries, in which the reuse of waste flows is an important aspect. Therefore, the origin of some secondary flows could not be shown or could only be shown by making some assumptions.

2.2.2 Textile sector

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7 https://ec.europa.eu/eurostat/cache/sankey/circular_economy/sankey.html?geos=NL&year=2017&unit=THS_T&materials=TOTAL&highlight=0&nodeDisagg=0101000000&flowDisagg=false&translateX=200&translateY=70&scale=0.7&language=EN&xyz=89&material=TOTAL

In this paragraph we explore a Sankey diagram of the textile industry. Textile was chosen as an example because it gets more and more attention by both European (e.g. EEA, 2019)and Dutch policy makers[8]. The reason for this is that the environmental and social impact related to textile production and consumption is rather large. A more sustainable production of textile can be achieved by means of more circular textile flows and a more sustainable biobased production. The data provided in the Sankey diagram could be used to derive several useful indicators like the share of secondary input (CMUR), resource dependency, material efficiency and the share of biotic resources used.

With regard to the textile Sankey diagram data on the amount of waste generated, energy carriers used and carbon emissions emitted by the textile industry are obtained directly from the MFM. Regarding the waste flows presented in the Sankey diagram, only waste that has been reported as textile waste is included. Mixed waste for instance, which may also contain parts of textile waste is not included. The textile waste generated by domestic consumption is mainly generated by households, this information is obtained from the MFM. However, the Sankey diagram focuses only on materials flowing through the domestic textile industry and not on imports of textile products directly sold to households. In the Netherlands less than a third of all consumed textile products are produced domestically, the remainder is imported from abroad. The monetary input-output table was used to determine this share, which is applied to determine the amount of textile waste generated by households related to the domestic textile industry. In this way, waste generated by households from imported products is excluded.

Explanation of the Sankey diagram

In figure 2.2.2 a Sankey diagram is presented that has been developed for the Dutch textile industry. In this Sankey diagram the textile industry includes NACE codes C13 - Manufacture of textiles, C14 - Manufacture of wearing apparel and C15 - Manufacture of leather and related products. To provide better insight in the circularity of the industry several material breakdowns have been made. The following materials were distinguished: 1) secondary materials because they provide information on the amount of materials being reused; 2) fossil energy carriers for energetic purposes because they are lost in the production process and cannot be reused; and 3) biotic and abiotic materials because a more circular economy requires a shift to biotic materials[9].

The total material input in the textile industry (left hand side) is broken down by primary and secondary materials. The input of primary materials is further broken down by imports and domestic supply, while the input of secondary materials is presented as one group in which imports and domestic produced secondary materials are merged. This was done because it is not exactly known how much of the textile waste used by the textile industry comes from imported or domestic produced waste.
Total material input in the textile industry must equal total material output (right hand side). Most of the used materials end up in textile products, of which a large share is exported and a part is consumed domestically. But not all materials used end up in textile products. Part of the materials, i.e. fossil energy carriers, are used for energetic purposes and are lost in the production process. Also textile waste generated during the production process is part of the output of the textile industry. All materials lost for energetic purposes, waste generated and materials ending up in products taken together should equal total material input.
Waste is not only generated in the production process, but also disposed of textile products at the end of life leads to waste. Notice that textile waste as part of mixed waste and secondary textile is not taken into account here due to data limitations.

[8] Dutch policy on textile (in Dutch only):
https://www.rijksoverheid.nl/documenten/kamerstukken/2020/04/14/beleidsprogramma-circulair-textiel-2020-2025
[9] Fossil energy carriers for non-energetic use are allocated to abiotic materials.

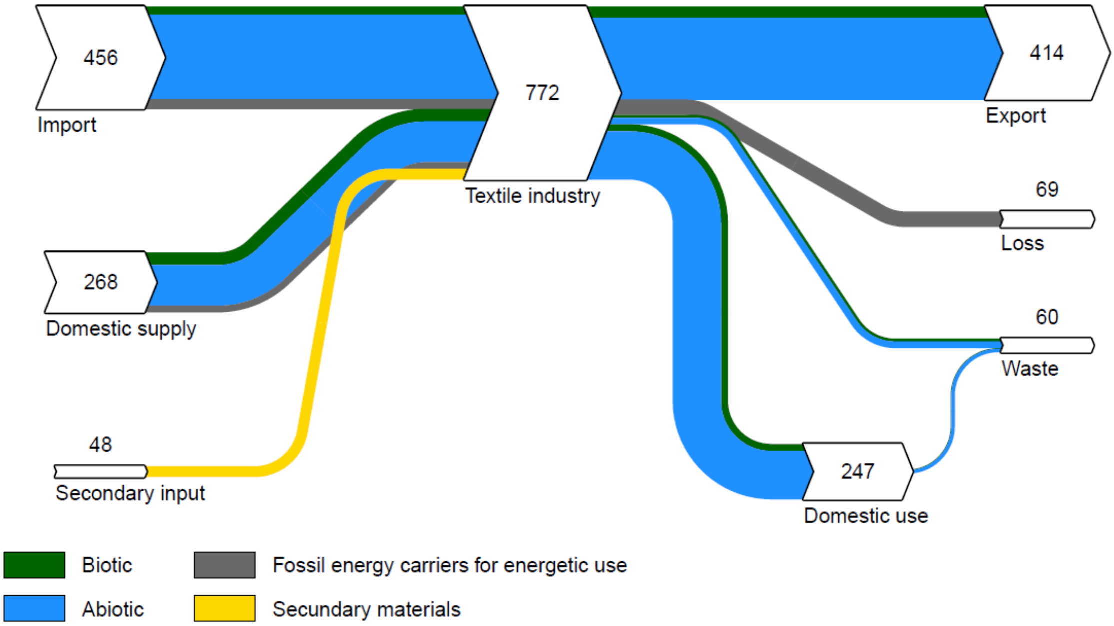


Figure 2.2.2., Biotic and abiotic in and out of the Dutch textile sector, 2016.

CE relevant information that can be derived from the Sankey

The Sankey diagram and its derived indicators provide useful insights in the textile industry, its level of circularity and possible opportunities to become more circular. This paragraph will briefly discuss the kind of information that can be derived.

From the Sankey diagram the Circular Material Use Rate (CMUR) can be derived. The CMUR is an important EU indicator that indicates the share of secondary input in the total input[10]. In case of the textile industry the share of secondary inputs (48 mln kilogram) in total material input (772 mln kilogram) results in a relatively small CMUR of 6 percent. The use of more secondary materials could improve the textile industry's level of circularity.

The textile industry is dependent on inputs from abroad. Disregarding secondary inputs, total material imports (456 mln kilogram) exceed domestic supply (268 mln kilogram). The share of abiotic materials flowing through the textile industry greatly exceeds biotic materials. So, for the textile industry there is an opportunity, or challenge, to become more circular by increasing the use of biotic resources. Notice that it is very important to make sure biotic resources are sustainably produced. Another way, to decrease the amount of used abiotic natural resources is to reduce the use of fossil energy carriers (i.e. natural gas) in the production process. Maybe it is possible to make production processes more energy efficient or, otherwise, substitute fossil energy use by renewable energy sources.

On the output side, the Sankey diagram shows that the largest amount of used materials end up in textile products (661 mln kilogram), of which the largest part is exported (414 mln kilograms) and a smaller part is consumed domestically (247 mln kilograms). Simultaneously the Sankey diagram shows how much materials are being lost for the purpose of energy recovery, or turned into waste either during the production process or discarded after domestic use. The "loss" node in the Sankey due to energy use amounts to 161 million kilo of carbon dioxide emissions. The amount of textile waste produced by the textile industry relative to the amount of textile products produced says something about the efficiency of the production process. The less materials are lost the more efficient the production process is. Part of the waste generated is being reused domestically and becomes a

[10] https://ec.europa.eu/eurostat/web/products-datasets/-/cei_srm030

secondary input in the textile industry. However, currently it is not possible to tell which share of the domestically produced waste is being exported abroad and which share is being reused domestically. The data in the Sankey diagram could also be presented in combination with additional data sources, like national and environmental accounts data, or different economic sectors. This could be useful to place the textile industry in perspective, both in economic (e.g. employment and value added) and environmental terms (e.g. emissions and material use). Also, efficiency measured as euro value added per kilo resource used can be estimated by combining figures from different accounts. Monitoring the described indicators over time would provide useful insights in the transition to a more circular textile sector over time.

2.2.3 Construction sector

In this paragraph we explore a Sankey of the construction sector. Construction was chosen as an example because it plays an important role with regard to circular economy indicators. The reason for this is the use of large quantities of primary and secondary materials in production processes. Also, construction activities have the potential for a transition towards more biotic resources. From the Sankey diagram several useful indicators can be derived.

Explanation of the Sankey diagram

The construction sector, for which the Sankey diagram has been developed, consists of NACE 41-43. A relatively simple but clear and interpretable Sankey diagram was compiled. As a consequence some corners were cut[11] and some small material flows were omitted. Examples of the latter are the import of secondary material and loss of material due to combustion and landfilling. Therefore, the Sankey diagram is only a simplified representation of reality and does not fully balance.
A material breakdown was chosen that provides information that is of interest regarding the circular economy. Therefore, the following material inputs were distinguished: 1) secondary materials, because they provide information on how much they are used relative to primary materials (CMUR); 2) biotic, like wood, and abiotic, like glass and metal, materials because a more biobased economy reduces the demand of non-renewable resources; and 3) sand and gravel because they are the main bulk of materials used and play an important role in achieving CE targets.

[11] There are several issues that complicate the construction of a realistic Sankey. For instance, in reality there are many different feedback loops within 'domestic supply' and within the construction sectors itself. Also NACE 41, 42 and part of NACE 43 consist of construction activities that add materials to the stock (e.g. infrastructure and buildings). However, NACE 43 also includes demolition of infrastructure and buildings, i.e. demolition of stocks, which means this activity should be located somewhere between the nodes "stocks" and "waste".

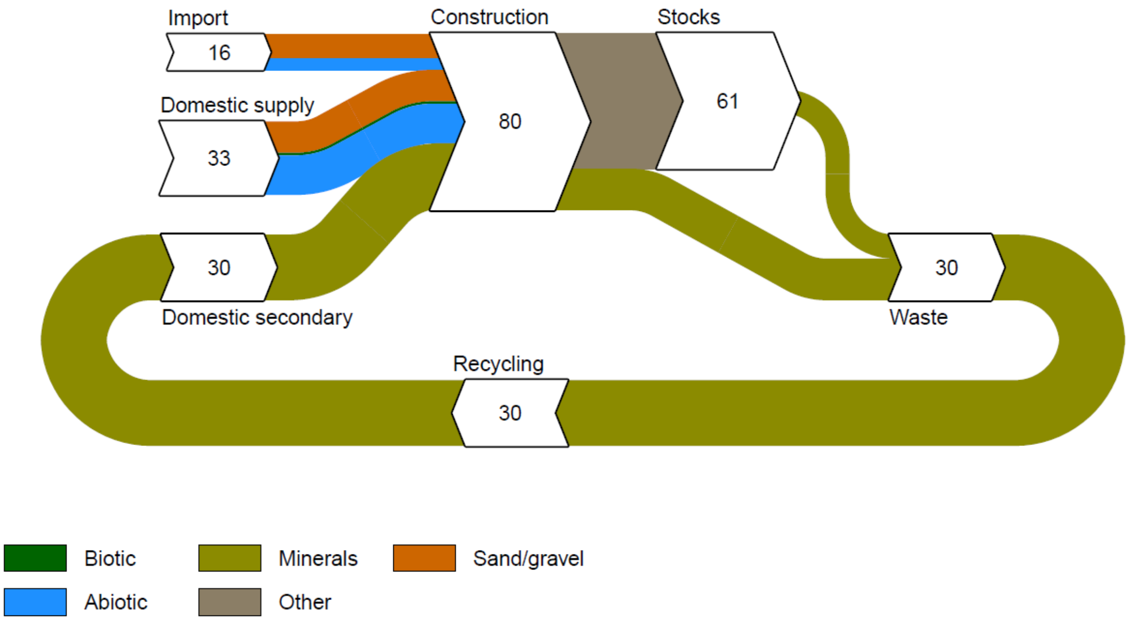


Figure 2.2.3., Material flows in and out of the construction industry , 2016

CE relevant information that can be derived from the Sankey

The Sankey diagram, as presented in figure 2.2.3, and the indicators that can be derived from it provide useful insights in the construction sector. This paragraph will briefly discuss what kind of information can be derived from the Sankey and what it tells about the circularity of the construction sector.
On the input side the Sankey shows the total amount of materials used by the construction sector broken down by secondary input, import and domestic input. This already provides useful information. It shows the total amount of materials used by the construction sector and it dependency on imports which is relative small compared to, for example, the textile industry. The Netherlands are a small and densely populated country in which the extraction of minerals for construction competes with other uses of the land. For example, lime is no longer extracted from 2019 onwards because the extraction site is converted into a nature reserve. For lime we are now completely depend on other countries. The Sankey diagram also shows a CMUR that is very high (37 percent) relative to other sectors like the textile industry (6 percent). Therefore, it appears that the construction sector is highly circular. However, most of the mineral waste is used underneath houses or roads. Currently it is debated if more high end use of mineral waste (e.g. for the construction of new houses) would lead to less demand of building materials.
On the output side the Sankey diagram shows on the one hand how much materials end up in the economic stocks (buildings and infrastructural works) and on the other hand the amount of produced waste. Waste is produced as a result of building activities or demolition activities. In the latter case the waste is produced from the stocks. The imbalance between the input and output of the stocks indicates the amount of extra buildings and infrastructure that is needed as a result of, for example, increasing population and economic growth. A more high-end reuse of stocks, for example due to refurbishment of buildings, decrease both primary material inputs and outputs of the stock. The amount of materials lost, e.g. dioxide emitted and the waste flows that cannot be reused, is not included in the Sankey diagram because these flows are relatively small. The same goes for the relative small international trade flows of construction waste. In the Sankey diagram it is assumed that all domestic waste is being reused domestically.

The Sankey diagram does not only show total material flows, but also breakdowns by different material categories. This adds another dimension to the information and indicators described above. For

instance, the breakdown in the use of biotic and abiotic materials shows the biobased potential in the use of construction materials.
The Sankey diagram could also be presented in combination with additional data from the economy as a whole. This places the construction sector, the amount of materials used, carbon dioxide emitted or waste produced, into perspective. Also economic indicators like value added and employment could be used to place the construction sector, and its physical aspects, into perspective. The efficiency of the production process can be estimated from the amount of used materials relative to the value added or the square meters of houses build. Finally, all information and indicators mentioned above become even more interesting if they could be measured over time and thus provide insights in the transition towards a more circular economy.

3. Drivers behind changes in material use

The aim of a transition to a more circular economy is to reduce the input of non-renewable natural resources and to reduce the amount of waste leaving the economy. Changes over time in the amount of non-renewable resource use is driven by: a) substitution of renewables by non-renewables, b) increased use of secondary materials (recycling), c) resource efficiency and d) economic growth. In this chapter an index decomposition analysis (IDA) is presented that quantifies drivers behind the CE target set in the Netherlands: a 50 percent reduction of primary abiotic resources by 2030. Paragraph 3.1 presents the used methodology. In paragraph 3.2 the results are presented and discussed.

Data are drawn from the official statistical sources on physical material flows (Material flow accounts, Waste statistics and Air Emission accounts) and the national accounts, making it possible for statistical agencies in other countries to use this methodology. In annex A an user-friendly R-script for performing the IDA compilation is given.

3.1 Methodology used for Index Decomposition Analyses

3.1.1 Index Decomposition Analyses: mathematics

In an Index Decomposition Analyses (IDA) the variable (primary abiotic resource consumption) of which changes are analysed is written as the product of factors underlying these changes in time:

$$\boldsymbol{Prim_{abiotic}} = \frac{\boldsymbol{Prim\_abiotic}}{\boldsymbol{Prim}} \times \frac{\boldsymbol{Prim}}{\boldsymbol{Total}} \times \frac{\boldsymbol{Total}}{\boldsymbol{GDP}} \times \boldsymbol{GDP}$$

Of which:

Prim_abiotic: Primary abiotic resource consumption, including abiotic but excluding biotic and secondary materials. A Dutch policy target is to reduce the use of primary abiotic resources with 50 percent in 2030.

Prim: Primary resource consumption, including both biotic and abiotic materials.

Total: Total consumption including secondary, biotic and abiotic materials

GDP: Gross Domestic Product of the Dutch economy. For the sector analysis value added (VA) per sector is taken.

Underlying drivers are:

Prim_abiotic / Prim: Substitution of abiotic resources by biotic materials.

Prim / Total: Recycling of secondary materials

Total/ GDP : Resource efficiency

GDP: Economic growth

For an IDA with 4 factors, as presented here, we can derive 24 non-unique equations. We take the average of those 24 equations but as some factors appear in multiple equations each factor has a different weight. We use the equations partially derived in Erik Dietzenbacher & Bart Los (1998) to get to the correct answer. The full R code that has been used for the IDA is presented in Annex A.

These sets of equations are applied to two sets of data: data on the national-level of the Netherlands and to a more detailed (A66) level for different economic sectors. On the national-level the data is available annually from 1996-2016 and on the industry-level biannually between 2010-2016. For the analysis on the national level we take annual changes into accounts. For the analysis on industry level we only consider changes between 2010 and 2016 as the effects on the long term are more important than the short term trends.

3.1.2 Data requirements national analysis

Two different datasets are used. The first data set for the national analysis is taken from regular statistics that can be found in the Eurostat database. Thus, this data is available for all EU member countries. The second set for the sector analysis contains detailed data from the Dutch Material Flow Monitor (MFM) and is discussed in paragraph 3.1.4. First the dataset for national analysis is discussed.

Data on material flows

Data on material flows is taken from the Economy Wide Material Flow Accounts (EW MFA). Material consumption (DMC) is estimated by: extraction plus import minus export. Notice that DMC estimates apparent consumption in which production of waste and use of energy carriers are also part of consumption. Total DMC equals total consumption of biotic and abiotic materials (factor **Prim**). Biomass can also be excluded from the DMC leaving only the abiotic materials (factor **Prim_abiotic**). The substitution, biotic versus abiotic materials, driver is estimated by dividing **Prim** by **Prim_abiotic**. Notice that most biomass is used for food and not for substitution of abiotic materials. However, a distinction of the latter cannot be made in the MFA.

Data on recycling

Data on recycling is available from waste statistics. However, data on recycling in the Eurostat database comprises treatment of domestically generated waste. This means domestic generated waste that is treated abroad is also taken into account and, on the other hand, imported waste recycled domestically is excluded. In case a country compiles waste accounts it is recommended to use these figures instead of the waste statistics reported to Eurostat because waste accounts represent waste recycled within a country. Also, biomass waste that is recycled for purposes of feed for animals (and not substitution of abiotic materials) should not be included. Recycled animal and vegetable waste can be omitted by assuming that most of it is used for animal feed. Due to a revision of the Dutch waste accounts we could not leave this waste category out and, therefore, included it in our analysis. The factor **Total** is **Prim** plus the amount of recycled materials.

Data on economic growth

Data on economic growth can also be derived from the Eurostat website. We took **GDP** in market prizes estimated as chain linked volumes. Chain-linked level series are obtained by successively applying previous year's price's growth rates to the current price figure of a specific reference year, in this case 2015.

3.1.3 Results national analysis

Figure 3.1.3 shows the relative change of abiotic resource consumption between 1996 and 2016 (black solid line). A decline of 15 percent can be observed. The other lines represent the drivers behind this change: 1) substitution of biotic for abiotic materials, 2) recycling of secondary materials, 3) resource efficiency and 4) economic growth. Economic growth increased by 37 percent and is the main driver behind an increase in resource consumption. Substitution effect do not have a significant impact and can have both a positive or negative effect depending on the year. In order for abiotic resource consumption to decline, the economic growth driver is counteracted by two drivers. Recycling, one of these drivers, contributes only a small amount to the decline of resource consumption. The recycling rate is already around 80 percent in the Netherlands[12]. Therefore, for the future we cannot expect recycling to have much additional impact on resource use reduction. Substitution of abiotic by biotic materials is probably overrated in the figure because food and feed are also included. However, in the future this driver can have more impact, because currently the biobased economy is still small but might take flight in the future. The driver that counteracts the effect of economic growth most is resource efficiency. If resource efficiency had not taken place, consumption of resources had grown significantly instead of showing a decrease. Resource efficiency is defined as total material consumption divided by GDP. The reasons behind efficiency increase can be manifold and need further investigation. For example, resource efficiency is improved when resource intensive industry moves abroad and is replaced by more service driven industry. This structural change of the economy affects the use of primary abiotic resources as the production of goods is more material intensive than the production of services. Such a structural change took place in the Netherlands as the total output of services rose from 59 percent in 1995 to 65 percent in 2016, at the expense of manufacturing. Although the latter is probable the most important cause for the change in resource efficiency another possible cause is a change in importance of certain economic activities like repair, refurbishment or re-use. With regard to policy that aims for a transition towards a circular economy it would be very relevant to know what exactly is behind resource efficiency improvement. Further investigation is needed to divide the resource efficiency driver into relevant components, including the shift of producing goods to producing services.

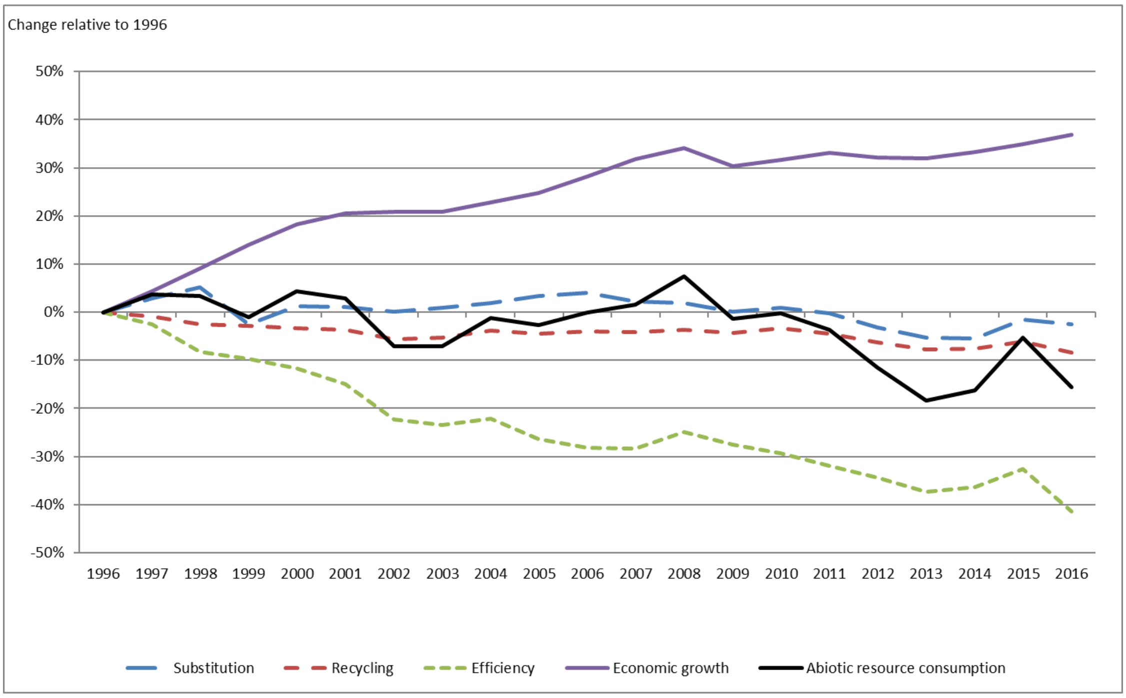


Figure 3.1.3: The relative contribution of four drivers behind the change in abiotic resource consumption.

3.1.4 Data requirements sector analysis

Data used for the IDA on sector level is taken from the detailed tables of the Material Flow Monitor (MFM) as discussed in chapter 2. All 300+ commodities in the MFM are labelled either biotic, like food and biofuels, or abiotic, like ore and oil. Also secondary materials, mainly waste, are identified. For each sector similar variables as used in 3.1.3 can be derived: primary abiotic resource consumption, primary resource

[12] https://www.cbs.nl/en-gb/society/nature-and-environment/green-growth/resource-efficiency/indicatoren/waste-recycling

consumption and total consumption. The difference is that now the input, instead of national consumption, per sector is considered. Notice that adding up all inputs does not equal total input in the Netherlands because of double counting between sectors (sectors delivering goods to each other for intermediate consumption). This is not a problem if your aim is to see how specific sectors have developed over time. Also notice that, by using the MFM, a selection of biobased commodities can be made that can potentially substitute abiotic materials. Thus food and feed commodities can be omitted. For example, wool as input in the textile industry is taken into account as it replaces synthetic materials. Sometimes, the sector that uses the commodity is also considered: vegetable oil used by the chemical sector is taken into account but vegetable oil used by the food industry not. Instead of total GDP for the Netherlands, value added, an estimate of a firm's economic profit, per sector is obtained from the national accounts. The set of equations of 3.1.1 are applied to a A66 NACE sector classification of industry. The drivers behind the developments between 2010 and 2016 are considered.

3.1.5 Results sector analysis

For each of the 66 industries we analysed the drivers behind the change in abiotic resource input between 2010 and 2016. Figure 3.1.5 show the sectors that make a large contribution to the total change in inputs. These are the "mining and quarrying" and the "manufacturing of coke and petroleum" sectors. The petroleum sector became more efficient but had much larger value added in 2016 than in 2010. Please notice that the value added of this sector can be very volatile. For this sector production and use values are very large but at the same time the value added is small. Therefore, a relative small change in production or use values can have a large impact on the value added. The mining and quarrying industry shrunk in size due to a reduction in extraction of natural gas in the Netherlands. This is why they use less materials even though they have become less efficient. The rest of the sectors made only small contributions of 1 percent or less for the different drivers. For the energy sector substitution is relative large, compared to substitution in other sectors, negative driver for the abiotic material consumption. This is due to abolition of subsidies for co-firing biomass in power plants.

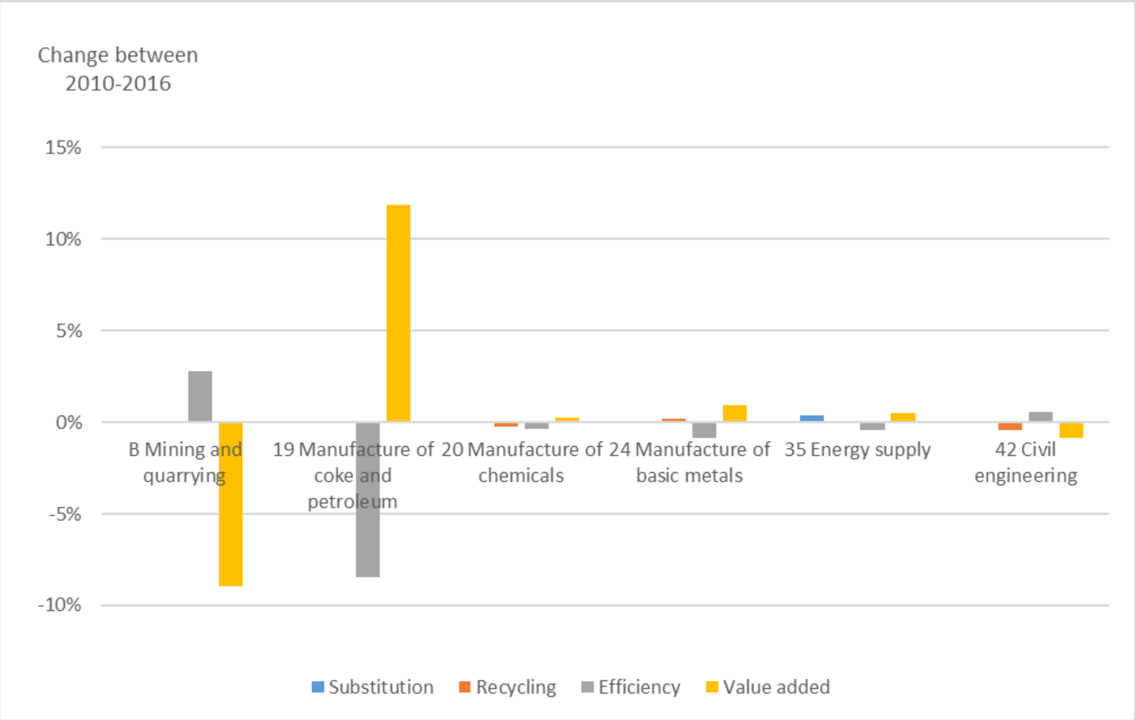


Figure 3.1.5: Sectors (NACE) that have a large change in the drivers behind abiotic resource input, differences between 2010 and 2016

4. Construction of Sankey diagrams

4.1 Introduction

Sankey diagrams are highly recognisable as well as an informative and attractive way of presenting statistical information in a concise fashion. An open source R-package has been developed which allows users (e.g. statistical agencies) to insert their own data in order to compile Sankey diagrams for the circular economy (or any other application. The R package is available from CRAN (the R software repository) with accompanying documentation and tutorials, using a permanent URL[13]. A brief summary of the package is given here, and a more expanded overview is given in annex B of this report.

The R-package supports the main environmental accounts that are collected and standardised by Eurostat (material flows, energy, water, waste) with a policy-relevant breakdown into main material categories (see Sankey diagrams of chapter 2). More detailed material categories can be accounted for by either including additional 'substances' (see below), either within a main Sankey diagram, or within a separate Sankey diagram that zooms in into a particular main category.

The R package allows for enrichment of the diagrams with appropriate labels and indicators of flow quantities. Changes over time could be visualized by merging multiple diagrams into an animation (not shown here).

In order to promote the adoption by, and involvement of, stakeholders, the package will be actively distributed among the network of Statistics Netherlands. Involvement in the quality of the software package is ensured by using a github repository[14], which allows for comments on the software and sharing of the code.

4.2 Sankey diagrams

Sankey diagrams are a special type of diagram, consisting mainly of arrows of varying width, which represent the flow of energy, material or any other conservative substance through a system. Usually the diagram depict the various (cyclic) routes that these substances can take, including convergence and divergence of flow paths and the various transformations along the way.

Sankey diagrams were originally developed for the visualization for the flow of energy, and it's transformations, through a heat engine a.k.a. a steam engine (Kennedy *et al*., 1898).

As with energy, matter is created nor destructed, only transformed. The flow of materials through the economy is thus very similar to the flow of energy through a heat engine, and well visualized by a Sankey diagram.

[13] https://cran.r-project.org/package=PantaRhei
[14] https://github.com/pwbogaart/PantaRhei

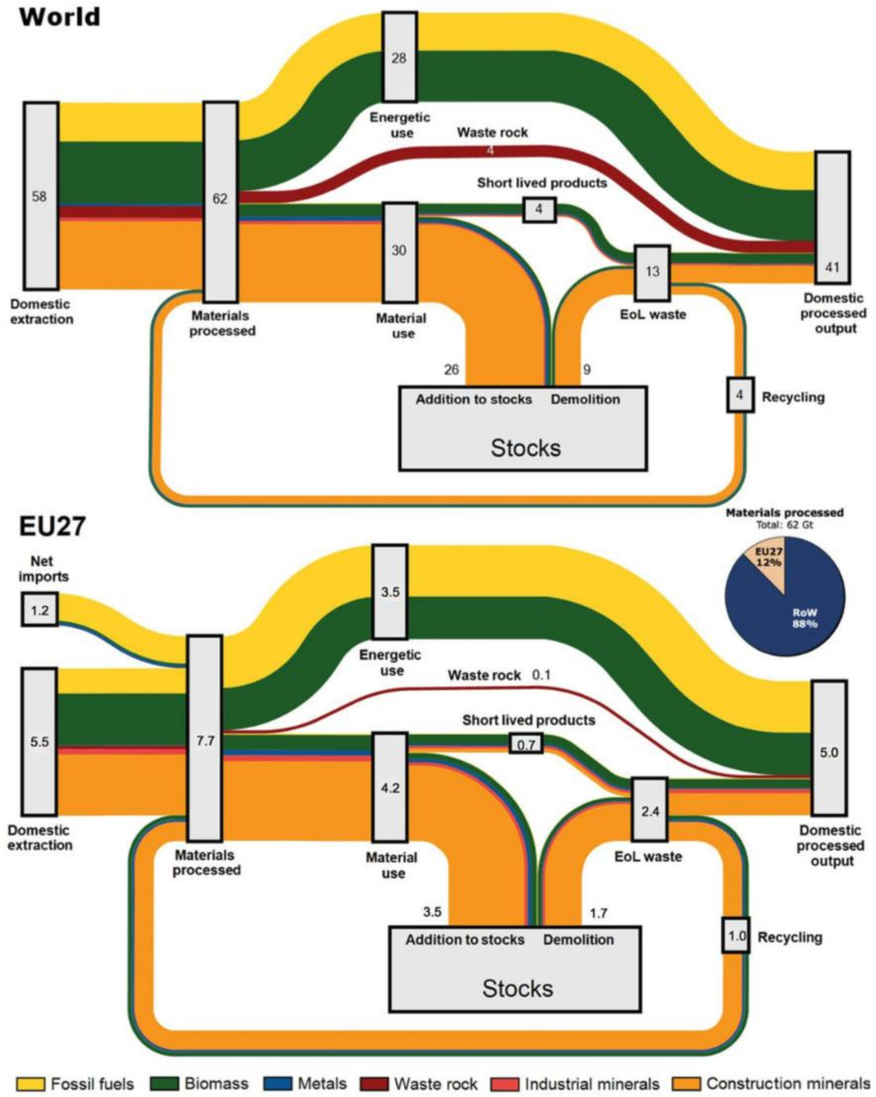


Figure 2 Sankey diagram of material flows through the global economy (world) and the EU-27 in 2005. Numbers show the size of flows in Gt/yr. For a definition of flows, see the article text. EU = European Union; EoL waste = end-of-life waste; Gt/yr = gigatonnes per year; RoW = rest of the world.

Figure 4.2. Example Sankey diagram of the material flow; Source: Figure 2 of Haas et al. (2015)

Figure 4.2 shows a Sankey diagram published by Haas *et al* (2015) to illustrate the material flow on global and EU levels. This diagram was used as inspiration by Statistics Netherlands in their reports on the circular economy (Berkel and Delahaye, 2016; Potting *et al*, 2018).

Due to the complex nature of Sankey diagrams, involving many different flows, the construction of these diagrams by hand (i.e. by graphical drawing software such as Adobe Illustrator) is very tedious and time consuming. While there are some software tools available, they are either commercial (e.g. e!Sankey) or limited in their scope (i.e. R's `alluvial` package).

In order to assist National Statistical Institutes (NSIs) and other interested parties in the development of Sankey diagrams, an R package has been developed to construct Sankey diagrams based on tabulated data on flow magnitudes. The package is named `PantaRhei` after the famous aphorism *Panta Rhei* (Everything flows), often attributed to the Greek philosopher Heraclitus.

The package is available through the CRAN (Comprehensive R Archive Network) network, using an permanent URL[15]. The package is easily installed within each modern R distribution

```
install.packages("PantaRhei")
library(PantaRhei)
```

The R package comes with full documentation, including help screens for all functions, and an user manual, which can be shown from within R as

```
vignette("panta-rhei")
```

This section summarizes the most important elements of the package. A more extensive description is given Annex B.

4.3 A Simple material flow example.

A Sankey diagram in its simplest form consists of 1 or more *flows* connecting 2 or more *nodes*. Information on nodes and flows and colors are stored into R `data.frame` objects. In these sample examples, they are constructed `by hand', but in real world applications they will typically be read from spreadsheet files or database systems.

4.3.1 Nodes

The **nodes** data frame provides information on the nodes: at least an unique identifier and their position.

- **ID** (character) : to identify the node
- **x** (numeric) : the x-coordinate of the node (in arbitrary units)
- **y** (numeric) : the y-coordinate of the node.

And additional fields to control labels and layout, such as

- **label_pos** (character) : to control label placement relative to the node

```
nodes <- tribble16(
  ~ID,    ~label,          ~x,        ~y,       ~label_pos,
  "imp",  "Import",        "0",       "0",      "left",
  "exp",  "Export",        "proc+2", "imp",    "right",
  "dom",  "Domestic use", "exp",     "proc",   "above",
  "proc", "Processing",    "imp+2",   "imp-1",  "below"
)
sankey(nodes, flows, colors, legend=TRUE)
```

Note that node coordinates can be given either explicitly (as a number), or relative to other nodes.

4.3.2 Flows

The **flows** data frame provides information on the flow between the nodes. It requires at least

- **from** and **to** (character) : the IDs of the starting and ending nodes,
- **quantity** (numeric) : the magnitude of the flow.

[15] https://cran.r-project.org/package=PantaRhei

[16] The R function **tribble()** is part of the tibble package (in turn part of the tidyverse). It allows the construction of data frames row-by-row

And optional a column for

- **substance** (character) : the type of material, energy carrier etc.

```
flows <- tribble(
  ~from,  ~to,   ~substance, ~quantity,
  "imp",  "exp", "Cocoa",      10,
  "imp",  "proc", "",           5,
  "proc", "dom",  "",           2,
  "proc", "exp",  "",           3,
  "imp",  "exp",  "Sugar",      2,
  "imp",  "proc", "",           6,
  "proc", "dom",  "",           5,
  "proc", "exp",  "",           1
)
```

Note there that it is not required to repeat the `substance` labels for every row in the table. For rows where it is left blank, the last specified value is re-used.

Flows for each substance can be visually distinguished by specifying a color, using again a data.frame

```
colors <- tribble(
  ~substance, ~color,
  "Cocoa",    "chocolate",
  "Sugar",    "#FFE4C4"
)
```

Note that all color specifications that R understands are allowed. For example, red can be specified by **`"red"`**, **`"#FF00000"`** and **`rgb(1,0,0)`**. (use **`colors()`** or search the internet for “R colors” to learn more about R color names)

4.3.3 Layout

Node layout can be controlled by using an option **`node_style`** (which must be a list). The following example

- uses a different node type (**`type="arrow"`**, to plot chevron-type arrows)
- specifies the colors of this node (**`gp=gpar(fill="lightblue", col="white", lwd=4)`**) using the syntax of **`gpar()`**, which is part of the **`grid`** package on which PantaRhei is built.

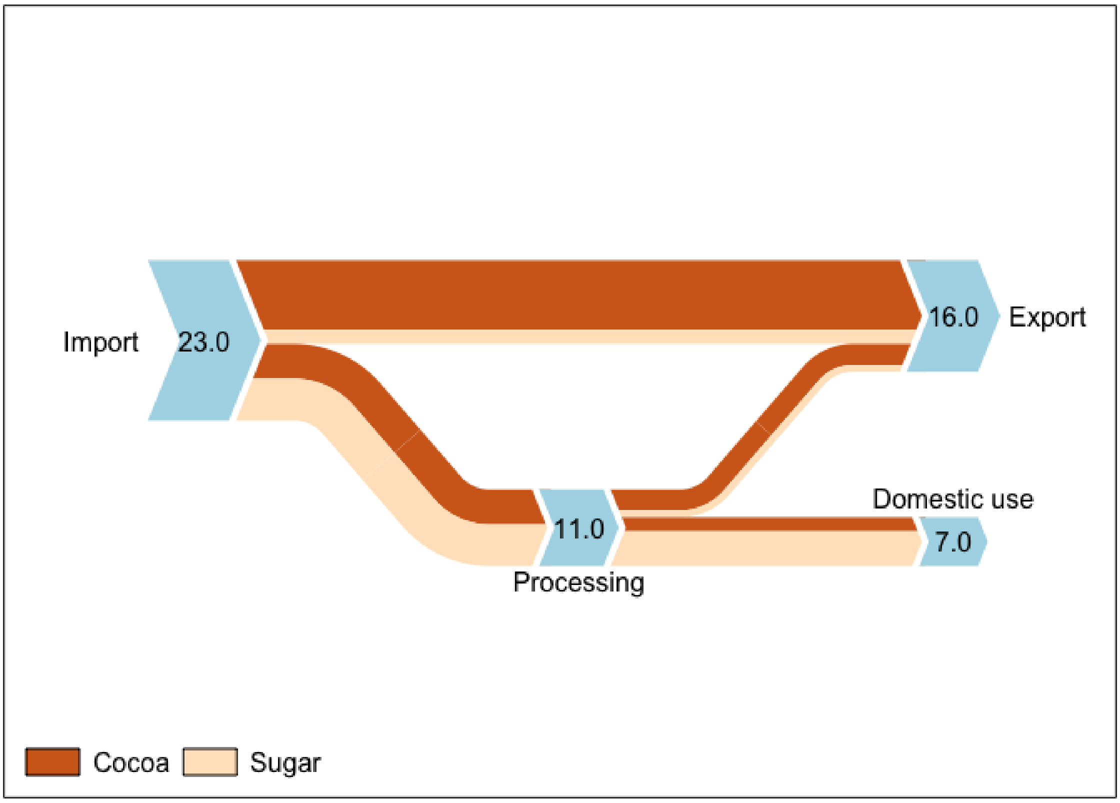
```
library(grid) # Loads: gpar()
ns <- list(type="arrow", gp=gpar(fill="lightblue", col="white", lwd=4))
```

4.3.4 Constructing the Sankey

Finally the Sankey diagram can be constructed by calling the **`sankey()`** function:

```
sankey(nodes, flows, colors, node_style=ns, legend=TRUE)
```

resulting in:



4.4 Complex example

For completeness, here is a full example to plot a Material Flow Account (MFA) for The Netherlands. The data set is included with the package

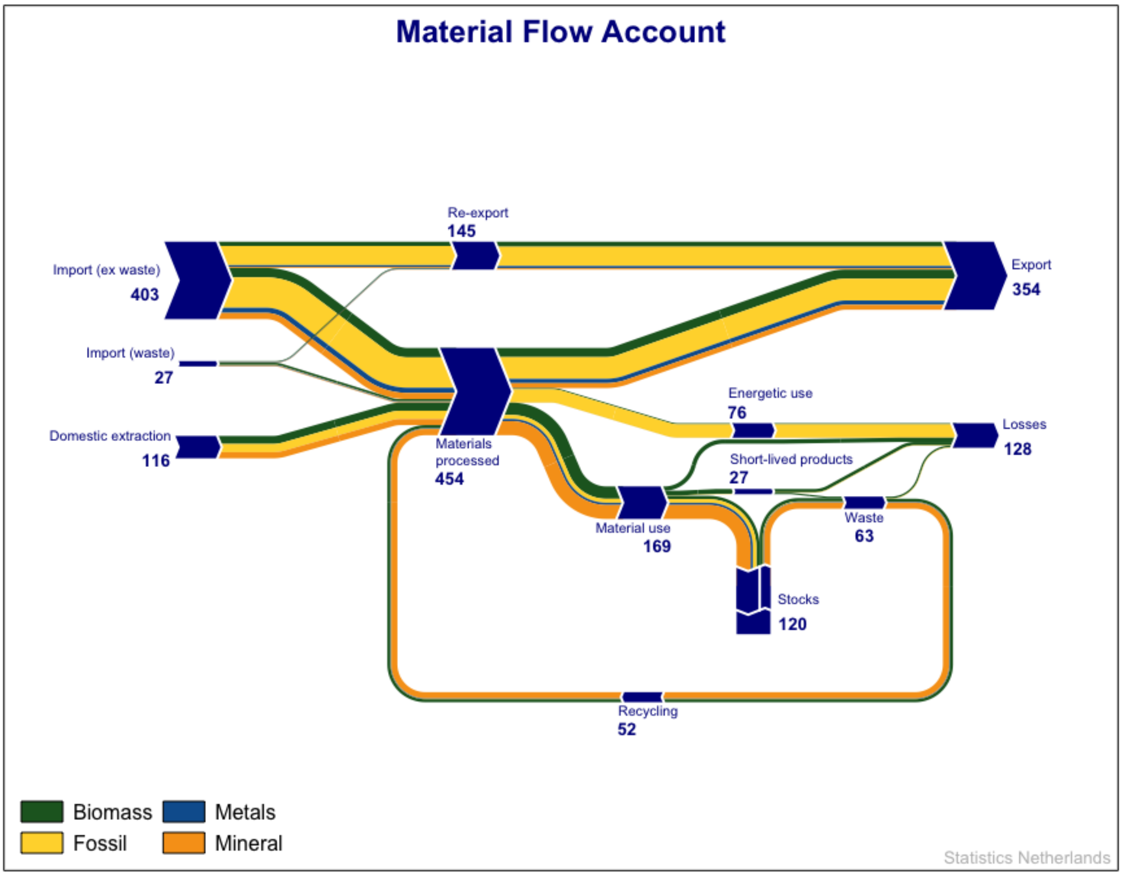
```
data(MFA) # Load Material Flow Account data (list of data.frames)

dblue <- "#00008B" # Dark blue

my_title <- "Material Flow Account"
attr(my_title, "gp") <- grid::gpar(fontsize=18, fontface="bold", col=dblue)

# node style
ns <- list(type="arrow",gp=gpar(fill=dblue, col="white", lwd=2),
           length=0.7,
           label_gp=gpar(col=dblue, fontsize=8),
           mag_pos="label", mag_fmt="%.0f", mag_gp=gpar(fontsize=10,fontface=
"bold",col=dblue))

sankey(MFA$nodes, MFA$flows, MFA$palette,
       max_width=0.1, rmin=0.5,
       node_style=ns,
       page_margin=c(0.15, 0.05, 0.1, 0.1),
       legend=TRUE, title=my_title,
       copyright="Statistics Netherlands")
```



More detailed explanation and guidance is given in Annex B and the package documentation.

5. Discussion and recommendations

This report provides a methodology for other EU members to set up physical supply and use tables (Material Flow Monitor, MFM) that contains data on material flows to, from and within the economy. Although the input for the MFM are some of the regular environmental accounts, detailed monetary supply and use tables from the national accounts are essential input. Therefore we recommend EU countries to undertake the task only if detailed monetary supply and use tables are available from there NSI.

The application of the MFM for deriving relevant CE indicators, like the CMUR, is shown for the textile and construction industry. For textile it is shown that the Netherlands are dependent on imports, that there is a potential to a more biobased textile industry and potential to increase the input of secondary materials. For construction industry it is shown that a considerable part of their input consists of secondary material and that inflow in stock is much larger than the outflow. In order to disseminate the results in a visual attractive manner Sankey diagrams are compiled with an especially designed visualization tool. During the compilation of the Sankey diagrams we noticed that an input-output table was required next to the supply and use data from the MFM. The reason for this is that supply and use tables do not provide information on whom is suppling to whom. Currently we only have monetary input-output tables at our disposal. In order to improve the data, as a next step, we recommend to develop physical input-output tables.

One of the Dutch circular economy targets is to reduce the input of non-renewable natural resources by 50 percent in 2030. By performing an Index Decomposition Analysis (IDA) we investigated the drivers behind changes in time in the amount of non-renewable resources used. Economic growth is the main driver behind an increase in resource use. This is compensated almost completely by an increase in resource efficiency. An increase in resource efficiency can have different causes like e.g. more efficient production processes, more service based industry or more re-use or repair. Dutch policymakers are very much interested to know the details behind the efficiency increase. Therefore, it is recommended to investigate this further in more advanced IDAs. The use of secondary materials has only a limited effect as a driver but can be important for specific economic activities like the production of plastics or building materials. However, because the Netherlands has a recycling percentage of around 80 percent there is not much potential for improvement in the future. The biotic-abiotic substitution driver has a relative small effect but here there is a potential for future improvement in for example the production of chemical products and textile products. Data for the IDA is drawn from official statistical sources making it possible for other EU countries to use the provided R package to compile a IDA for themselves.

The Sankey diagrams in this report are based on a tailor made visualization tool. The visualization tool, an open source R package with accompanying documentation and tutorials, is made available to EU member states[17,18] in order to support policy makers with recognizable as well as an informative and attractive ways of presenting material flow related statistical information. We recommend to use the package in order to strengthen the salience of environmental accounts in a uniform way. Users and stakeholders can enhance the usability of the CE visualization tool by providing comments for improvement using the *issues* functionality of the github software repository[19].

[17] And in fact the general public
[18] https://cran.r-project.org/package=PantaRhei
[19] https://github.com/pwbogaart/PantaRhei

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UN (United Nations), EC (European Commission), IMF (International Monetary Fund), OECD (Organization for Economic Co-operation and Development) and World Bank (2009), *System of National Accounts 2008*, New York, United States of America

UN (United Nations), (EC) European Commission, (IMF) International Monetary Fund, OECD (Organization for Economic Co-operation and Development) and World Bank (2012), *System of Environmental-Economic Accounting, Central framework*, New York, United States of America.

Explanation of figures

Empty cell	Figure not applicable
.	Figure is unknown, insufficiently reliable or confidential
*	Provisional figure
**	Revised provisional figure
–	(between two numbers) inclusive
0 (0.0)	Less than half of unit concerned
2022–2023	2022 to 2023 inclusive
2022/2023	Average for 2022 up to and including 2023
2022/’23	Crop year, financial year, school year, etc., beginning in 2022 and ending in 2023
2020/’21–2022/’23	Crop year, etc., 2020/’21 to 2022/’23 inclusive

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