Mapping carbon of the Dutch industry today and how this can evolve towards circularity.

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Master thesis

Written in the context of the Industry 2050 project initiated by Prof. dr. Gert Jan Kramer

Abstract

The pressure of climate change resulted in national climate policy towards 2050. The Dutch climate agreement mentions that in this period a complex system change for base industries regarding energy and material use is needed to lower emissions, and that the industries must evolve towards circularity. To understand the relationship between industrial activities and how carbon ends up in the environment, an inventory of carbon flows is required.

This thesis presents carbon flow models based on material flow analysis methodology for thirteen individual fossil carbon-intensive industries. The models explain the energetic and non-energetic conversion of carbon within industrial processes, and show how carbon ends up in the atmosphere or become fixed in products. Furthermore, the results show import, export, and intermediate flows of carbon for the petrochemical industry.

The mapping of carbon provides a reference point that can be applied for assessments on the feasibility and consequences of decarbonization directions. The thesis includes one assessment of the chemical recycling of plastic waste. This assessment unveils that friction can be expected when realizing ambitions for circularity, as the availability of sufficient and suitable chemically recyclable waste is not guaranteed. The current state of carbon flow models opens up opportunities for further research on the decarbonization of the industry. Additionally, the models can be expanded and improved by including direct and indirect energy use, and by developing frozen technology and business as usual carbon flow models for 2050.

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The thesis before you is the last requirement to finish the master Sustainable Development: Energy and Materials at the Utrecht University. The thesis discusses a large industrial system. Studying this has resulted in a sincere appreciation of its complexity, and how this can change towards the future. Knowing that there is much more to discover has led to an ambition to study this system to a greater extend.

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Mapping carbon of the Dutch industry today and how this can evolve towards circularity.

1. Introduction

With the pressure of anthropogenic climate change in mind, agreements on an international level direct national governments to take action to reduce their climate impact (UNFCCC, 2015). This has resulted in national climate policy towards 2050. The Dutch climate agreement mentions that this transition embeds a complex system change for its industries regarding energy and material use, and that the industries must evolve towards circularity. More specifically, the government has set goals for the industry to reach climate neutrality in 2050, and as an intermediate goal to reduce at least 49% of its CO_2-eq emissions in 2030 compared to 1990. An additional target for 2030 is to reduce 55% of its emissions. In physical terms, this means that the Dutch industrial emissions must be lower than 44,2 Mton CO_{2}-eq to reach its target in 2030, or 38,74 Mton assuming the optimistic goal. (Rijksoverheid, 2019). Individual industrial sectors have studied multiple pathways toward decarbonization. (Ben Römgens & Mieke Dams, 2018; Pöyry & VNP, 2018; Samadi et al., 2016). These pathways mainly point out financial and technology barriers, but do not cover cross-industry conformity, which is considered a necessity according to the climate agreement (Rijksoverheid, 2019).

The motive of this research is the observation that there is a lack of understanding of the consequences of the decarbonization of industries towards 2050. To create understanding, a model of carbon flows is needed for today. This model must answer the question of what the starting point is for decarbonization. This can be designed by quantifying current carbon flows within all carbon-intensive industries of the Netherlands. With the current carbon flows available, it is possible to start thinking about the future and to translate the carbon flow model into plausible scenarios for decarbonization in 2050.

Given the problem definition the following research questions are proposed*:* What are carbon flows within the Dutch industry today and how can these evolve towards circularity?

- What, and how big are the carbon flows within the industry in 2017?
- How and at what aggregation level can carbon flows of the Dutch industry be represented to best inform the main research question?
- Use the above to explore how the linear carbon flows of the petrochemical industry can evolve towards greater circularity by 2050 and beyond.

2. Methodology

2.1 Designing a carbon flow model

As a foothold for the research, the Substance flow analysis (SFA) methodology provided by Brunner and Rechberger (Brunner & Rechberger, 2016) is applied. Designing a CFM is done through multiple steps. These steps are shown as a process in the methodological framework of figure 1. The methodological framework implies that some steps are not consecutive and are done iteratively. The rest of the chapter describes these steps in detail.

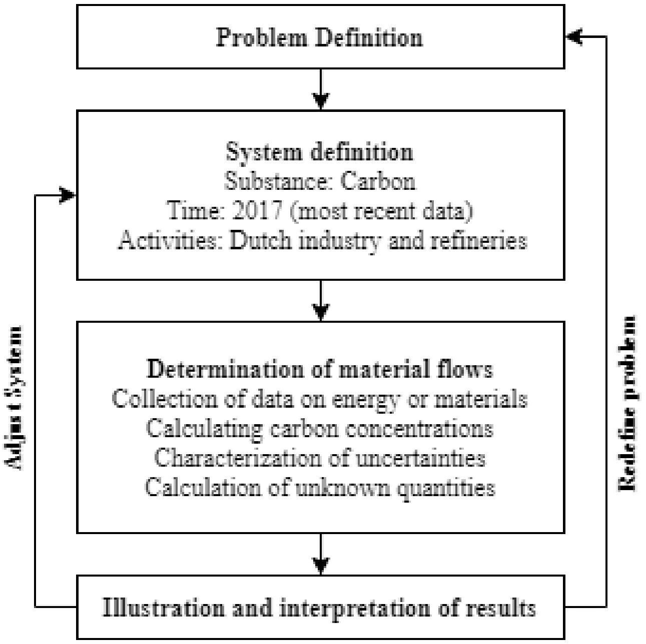

Figure 1: Methodology framework (Adapted from (Brunner & Rechberger, 2016)

2.2 System definition

The investigated system is the Dutch industry in 2017. This system identifies as an open system, as carbon flows enter and leave through import, export, consumption, disposal, or emissions to the environment.

Within the Dutch industry, the objective is to map the flows of carbon and how they derive from fossil sources into products or the environment. The primary focus is to visualize this for the industries with heavy net fossil fuel input. Industries are considered heavy when their net fossil carbon use is higher than 1 percent of the total net fossil carbon use of all industrial activities (excluding the energy sector) [1]. Next to these industries, crude oil refineries are considered as well since they play a big role in supporting raw materials for other industries. Simultaneously the plastic product industry is included to estimate how carbon ends up in final products. The chemical industry will be researched in more detail as this is the most carbon-intensive industry. The industries that meet the criterion are shown in table 1.

The column *SBI* refers to the Dutch industry classification number (Kruiskamp, 2019)[2]. *Industry* states the core activity of that industry and *[C%]* shows the share of net carbon used by the specific industry compared to the overall industrial activities.

Table 1 - Scope of industries

SBI	Industry	[C%]
10	Manufacturing of food products	5,24
17	Manufacturing of paper and paper products	1,35
19.2	Manufacture of refined petroleum products	n.a.
20	Manufacture of chemical products	76,35
	20.11 Manufacturing of industrial gasses	
	20.12 Manufacturing of painting materials	
	20.13 Manufacturing of other inorganic bulk chemicals	
	20.14 Manufacturing of organic bulk chemicals	
	20.15 Manufacturing of nitrogen compounding materials and fertilizers	
	20.16 Manufacturing of plastic products.	
	20.2 / 20.6 Other chemical industries	
22	Manufacture of plastic and rubber products	n.a.
23	The manufacture of non-metal mineral materials	1,81
24	Manufacture of metals primary form	8,35

These seven industries account for roughly 93% of the net fossil carbon use of all industries. These industries are responsible for 90% of all emissions within the Dutch industry (excl. refineries). The choice of focus on fossil fuels excludes other carbon resources, such as biomass, from the scope of the CFM. Secondly, only the direct use of carbon flows is investigated. This excludes indirect carbon flows for the heat and power industry, and other indirect carbon flows such as emissions through transportation and distribution.

The year 2017 is chosen as the temporal scope of the CFM. This is due to the availability of data. There is information available for 2018, but these are sensitive to changes. On the other hand, data used for 2017 is certain and additionally provides insight into company-specific carbon emissions. The applied databases are discussed in paragraphs 2.3. to 2.5.

2.3 Determination of material flows: Energy statistics

Energy statistics provide energy data [PJ] on the total supply, conversion, and use of energy within the Dutch economy. The total supply of energy consists out of the delving of energy, the net supply rate, the net difference of the national stock, and statistical differences. The sum of this number minus the discharge of energy flows is available for conversion and energy use. Conversion data provide insight into the conversion of energy for either secondary products, such as the generation of electricity using coal, or non-energetic appliances, such as the use of crude oil to refine into naphtha. The final energy use is the sum of energy that is combusted for a desired process after which the energy carrier has no use, such as the burning of gasoline to move a vehicle, or to meet the heat demand of an energy-intensive process (CBS, 1990). For the final energy use, it is assumed that carbon leaves this industry fully as emissions. On top of that, there is a different way for carbon to be emitted through non-energetic conversion. If hydrocarbons enter processes with non-energetic purposes, then the energy statistics provide no information on how much carbon is emitted. Energy statistics are used as they provide information on how much energy carriers are entering an industry and how they are applied. Before this can be estimated, first the energy flows need to be converted to an amount of carbon that is embedded within a petajoule of energy. For that, the Carbon Conversion Factors (CCF) of table 2 are used.

Table 2 - Carbon Conversion Factors [kton C · PJ $^{-1}$] for energy flows applied by energy statistics.

Energy flow	**CCF**	**Sources**
Coal and lignite	25,94	a
Coke-oven gas	27,46	a
Blast furnace gas	61,94	a
Other coal products	25,93	a
Crude oil	19,99	b,c
Residual gases from oil	17,02	b,c
Liquefied petroleum gas (LPG)	18,19	b,c
Naphtha	19,99	b,c
Gasoline	20,77	b,c
Kerosene	19,28	b,c
Gas, diesel oil, and light fuel oil	20,10	b,c
Heavy fuel oil	21,11	b,c
Other oil product	20,35	b,c
Natural gas	16,31	b,c
Renewable household waste	29,89	c
Solid and liquid biomass	29,89	c
Biogas	17,06	b,c
Waste and other sources of energy	28,69	c

[a](IEA, OECD, & Eurostat, 2004), [b](CBS, 1990) [c](Zijlema., 2007)

The CCFs are calculated using equation 1, where n is the energy flow, E is the size of energy flow n [PJ]. LHV is the lower heating value of one kilogram of energy flow n [MJ · kg^{-1}], and α is the carbon embedded in one kilogram of the energy flow n [kg C · kg^{-1}]. Some assumptions are made when the energy flow classifications are a group of multiple physical entities, such as coal and lignite. In such a case, the LHV and embedded carbon of these entities were averaged out equally. For example, coal and lignite is a combination of anthracite, coking coals, and other bituminous coals.

$$CCF_n = \frac{E_n}{LHV_n} \cdot \alpha_n \qquad \text{Eq.1}$$

Data regarding the flow of energy into industries is available, however, the relation between different industries is unspecified. For instance, refineries produce chemicals useful for the industry that manufactures organic chemical products (SBI 20.14). However, it is unclear how much of these chemicals are delivered by Dutch refineries, or instead by import.

2.4 Determination of material flows: Dutch emission registration

The emission database collects information about different environmental pollutants, including carbon embedding chemicals. The database shows how much chemicals are being emitted by companies in all industrial sectors. This database is used to collect the quantity of carbon that industries are emitting into the atmosphere. It should be clearly emphasized that the focus is on physical carbon that is emitted, and not the effect on climate change, as is the case with CO_2-equivalents. In contrast with the energy statistics, this database does provide insight into exact emissions. It is assumed that the difference between the carbon embedded in the registered emissions, and the carbon directly emitted through energetic conversions in the energy statistics is carbon lost in process emissions. Carbon embedding pollutants that are considered are CO and CO_2. The chemical composition of pollutants is converted to exact carbon. Other substances are not considered as they contribute negligible amounts (<0,005 wt%) to carbon emissions.

Big enterprises within the industry are obliged to present a environmental annual report, which includes emission registration. These registered emissions are then reviewed by the authorized supervision. Emissions for other (smaller) enterprises are being estimated with the use of statistical information and are assessed by taskgroups[3] and statistical and governmental institutes. Overall a 3% error is estimated for the emissions of carbon dioxide. No concrete benchmark is given for the distinction between small and big enterprises.

2.4 Determination of material flows: ProdCom

ProdCom, provided by Eurostat, contains data on the total mass and monetary value of the production and the sales of products. These statistics are applied to get an estimation of the quantity of produced goods and hence the embedded carbon in these goods. For product categories in ProdCom CCFs are calculated to assess the embedded carbon in manufactured goods, in a similar approach as with the energy carriers. (Eurostat, 1985). These CCFs for products can be reviewed in Appendix A.

Using ProdCom comes with two limitations in the research. First of all, many products do not contain any manufacturing information. To illustrate this: 3707 products are being registered in the ProdCom statistics. Of these products, 1748 products' data are confidential, and 1232 products' data are estimated on zero kilograms of products and 534 products contain no data. Out of 3707 products, only 193 remain with existing quantities of sold goods. Only 63 products' data remains accessible for manufactured goods. Second of all, there is no clear percentual coverage of all products that are registered in the statistics, as companies with less than 20 employees are exempt from responding to the survey of the national statistics institute. This limitation is not an issue when an industry consists of a small group of large sellers, which is the case for the base industry. However, this uncertainty becomes larger down the value chain.

Using the above data, it is possible to assess the in- and outflow of carbon for each industry. It will be presented using Sankey Diagrams (see figure 1-14).

2.5 Connecting the flows of carbon between industries.

Changes brought to the environment result from material flows caused by human activities. Physical Supply and Use Tables (PSUT) provide information on physical flows within the economy and between the economy and environment. This part of the methodology use data from 2016 due to the unavailability of data for 2017. At the end of the paragraph, the consequences of this choice are argued. First, it is explained which data is represented in the PSUTs, and this is followed by how it is applied for this research.

PSUT consists out of 2 tables that have a similar structure. The supply table shows physical flow types as rows and supplying origins as columns. The use table shows physical flow types as rows and receiving destinations as columns. Origins and destinations include industries, governments, households, accumulation, and the environment. Physical flow types include raw a wide range of products such as iron ore, iron and steel products, and iron scrap. Origins and destinations are classified using the SBI classification system and physical flow types are classified using the Classification of Products by Activity (CPA) system. CPA is designed to show the economic origin of products. This is why the first four digits are equal to the SBI classification ((CBS, 2019a). The PSUTs only include non-durable goods with an expected lifetime of less than one year. This excludes products that are purchased for transfer without value that is added to the product (UN DESA, 2018). This means that retail and wholesale are excluded from the carbon flow model.

For the application of this database one assumption is made. The assumption is required to be able to design a carbon flow model at a similar aggregation level as the individual CFMs. The arose difficulty when not applying the assumption is that the PSUT table combines the basic chemical industry (20.1) where previously the carbon in- and outputs were provided for subindustries SBI 20.11 – 20.16. It is assumed that when a CPA product is used by an industry, the product comes from the assumed economical origin according to the first four digits of the CPA. As an example, The chemical industry uses 10 ton naphtha with CPA 1920231, then refineries with SBI 19.2 provide these 10 tonnes of naphtha to the chemical industry.

The following section discusses the calculations that have been made to translate the PSUT data towards the carbon flows. Equation 1 and equation 2 calculate the mass share of a delivery from import (*iu*) and domestically produced products (*pu*) towards the receiving industry. Equation 4 and 5 calculate the weighted average for delivery from imported and domestically manufactured products towards the receiving destination.

$$iu_{x,y} = \frac{U_{x,y}}{TS_x - E_x - R_x} \qquad \text{Eq.2}$$

Where $iu_{x.y}$ is the share of the total net supply by the import of product x, to be delivered to industry y. $U_{x.y}$ is the use of product x by industry y in tonnes. TS_x is the total supply of product x in tonnes. E_x is the export of product x, in tonnes and R_x is the re-export of product x in tonnes.

$$pu_{x,y} = \frac{U_{x,y}}{TS_x - R_x} \qquad \text{Eq.3}$$

In equation 3 $pu_{x.y.}$ is the share of the total supply by domestically produced material x, to be delivered to industry y.Net imported goods are delivered toward all end-users except for export and re-export. Nationally produced goods are delivered towards all end-users with exception of re-export. The end-users are the crude oil refineries (19.2). The base chemical industry(20.1), the plastic industry (22), combined other industries (000), export (exp), households (320), and others residuals (999), which includes the accumulation of products in the market, stocks and environmental deposition Re-exports are neglected in the calculations as these are viewed as unimportant in the context of circular carbon. Other chemical industries (SBI 20.2 to 20.6) are excluded as a purchaser of goods, as no data is available on these industries.

The purpose of equations 3 and 4 is to calculate how imported and domestically produced flows move towards the user. It is used to be able to translate the PRODCOM outputs into flows.

Equation 3 shows the calculation of the weighted average of how imported products are distributed to all industries. The weighted average is the sum of the arrays of use shares of materials x (*iu*), multiplied with the Net Import Ratio (*NIR*). The *NIR* is the ratio of which the product x is net imported compared to other products that are originating from the respective industry.

Equation 4 shows the calculation of the weighted average of products that are supplied by their respective industry. As mentioned before, it is assumed that products are produced by the industries represented in the first four digits of the CPA label. The weighted average is then the sum of the array of *pu*-shares of materials x, multiplied with the ratio (PRx) of which this product is domestically supplied compared to all the materials that are originating from this industry.

$$\boldsymbol{S_x import} = \sum_{i=1}^{n=x} (iu_{17}\ \ iu_{19}\ \ iu_{20.1} \dots iu_{999}) \times NIR_x \qquad \text{Eq.4}$$

$$\boldsymbol{S_x domestic} = \sum_{i=1}^{n=x} (pu_{17}\ \ pu_{19}\ \ pu_{20.1} \dots pu_{exp} \dots pu_{999}) \times PR_x \qquad \text{Eq.5}$$

The weighted array of shares of industry x are then multiplied with the known PRODCOM outcome of that industry. The size of the imported flows of carbon is determined using a ratio of the locally produced goods compared to the imported goods.

Using these calculations the delivery of carbon embedding products of industries is generalized under one weighted average. For two reasons this choice has been made. First of all, the CPA classifications are more broadly categorized compared to ProdCom product classifications. For example, in ProdCom the statistics speak of ethylene and propylene whilst in the PSU tables, these are categorized by other acyclic hydrocarbons. In this case the similarity is evident, but the similarity is less evident for other products. (e.g. benzene or naphthalene in ProdCom versus aromatics or other cyclic hydrocarbons in the PSUT) Second of all, because the data used in the PSUT is based on the year 2016, whilst the rest of the carbon flow model uses data from 2017, generalization by shares would lower the impact of systemic changes that could have happened between 2016 and 2017, such as the shutdown of a refinery.

However, by generalizing an industry output the carbon flow model will imply that deliver a diverse group of products from the industry a to industry b, compared to the reality where only 1 product type is delivered to the receiving industry while all other products from that industry are delivered in larger quantities towards remaining industries. As an example, the primary plastics industry (20.16) has a large number of carbon exports. The model suggests that carbon products are equally exported, compared to reality where the exported flow consists of a majority out of polyurethane where almost no polyurethane is used domestically. To summarize, the choice to calculate the dispersion of carbon through a weighted average comes with one advantage and one disadvantage. It is now possible to measure the dispersion of products on the sub-industry level (20.11 – 20.12 etc). However, the results should be interpreted as indicative, due to its large generalizations.

3. Results on carbon flows

3.1 Carbon flow models for individual industries

This section shows the carbon flow models per individual industry. For each industry, the input and output flows of carbon will be discussed. What is relevant is how carbon is applied. If it is used for heating, auto industrial electricity generation, CHP, or other conversions. Carbon flow models that are presented within this paragraph for individual industries can be interpreted with the aid of the legend shown in figure 1.

Legend

🟫 CAL: Coal and lignite
🟫 COG: Cokes oven gas
🟫 BFG: Blast furnace gas
🟫 OCP: Other coal products
🟫 CO: Crude oil
🟧 ROG: Residual gasses from oil
🟧 LPG: Liquified petroleum gas
🟧 NFT: Naphtha
🟧 CAR: Car gasoline
🟧 JET: Kerosine
🟧 GDL: Gas, diesel and light fuel oil
🟧 HVY: Heavy fuel oil
🟧 OOP: Other oil products
🟨 NG: Natural gas
🟩 SFB: Solid and fluid biomass
🟩 WST: Waste and other energy sources
🟦 PRODCOM: Products output by manufacturing or sales data
🟦 UNK: Unknown carbon flow
🟪 CE: Carbon emissions

Figure 1 - Legend for individual industry carbon flow models.

Each single industry model will show similar flows. 'Input' is a combination of the available energy carriers for usage within the industry, and the products that are used as input for further processing. 'Incineration' is derived from the final energy demand, which is defined as the conversion of energy flows after which there is no use for the energy carrier anymore (CBS, 1990). It is assumed that this flow is fully transformed into combustion gasses. 'CHP/P' is a similar process, but the purpose is combined thermal energy and electricity generation, or solely electricity generation. 'Other conversion' processes are more diverse but include all conversions of the energy flows that are not for energetic purposes. For sectors such as the refineries and the steam crackers, these other conversion processes are clear, but for more diverse sectors, such as the combined group of other chemical industries (SBI 20.2 – 20.6), it may remain uncertain how carbon flows are otherwise converted. Implied emissions are the sum of emissions derived from incineration, CHP, or power generation processes, as well as other conversions if the outcome is evident. ‘Registered emissions’ are emissions that are registered in the emission registration database. ‘Unexplained emissions’ are an imbalance when the registered emissions are higher than the implied emissions. ‘PRODCOM’ are known manufactured products from the eponymous database, or represent known sold goods if indicated that way. ‘Unknown carbon’ represents uncertainty where the state of carbon is unknown. ‘Unknown carbon product’ represents similar uncertainties, but it is known that it went through other conversions hence it is likely to be a carbon product.

3.1.1 The manufacture of processed food – Industry SBI 10

The industry processes food from goods, such as livestock and crops to final food products through industrial facilities. Examples of activities are the processing and preservation of meat, fish, fruit, and vegetables and the manufacture of dairy products, bakery products, and prepared meals, and many other activities. Figure 2 shows that 99 percent of the carbon input is used for energy purposes, of which the main source is natural gas. The residual is used for unknown other conversions. The implied emissions are 346 kton C higher than what is registered. It is unknown how this flow of carbon leaves the industry.

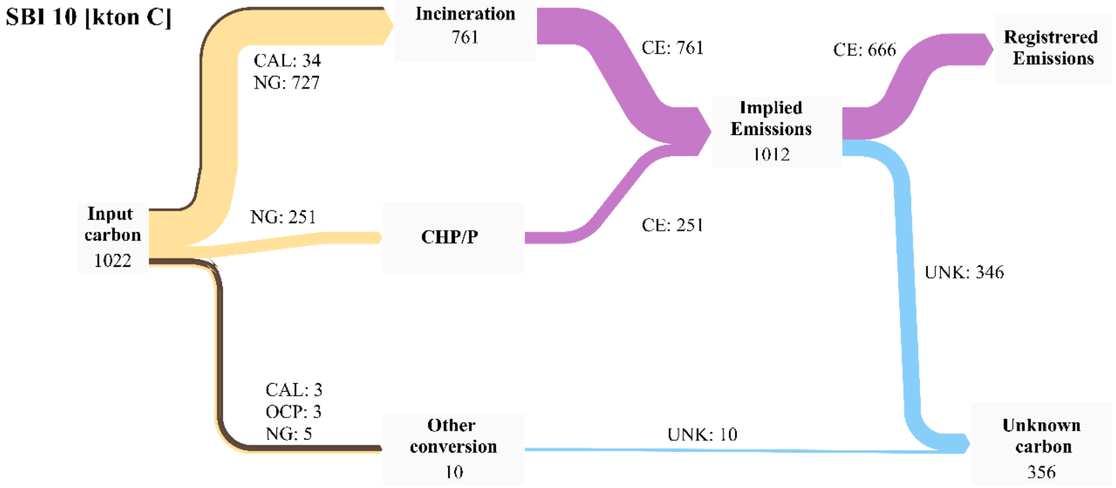

Figure 2 – Industry carbon flows for the food processing industry.

3.1.2 The manufacture of paper and cardboard, and its derived products – Industry SBI 17

The industry processes old paper and woody materials for the manufacturing of pulp, paper, paperboard, paperboard containers, and other paper-based products. Figure 3 shows that 95 percent of the known carbon input is used for energetic purposes. The remaining are oil derivatives used in other conversions with an unknown outcome. The implied emissions are lower than the registered emissions, leading to 91 kton C of unexplained emissions. After 6 recycling loops, the paper is usually separated. As paper gets recycled multiple times, fibres become unstable. Next to this residual paper flow, wood waste is combusted for energy recovery. These two carbon flows may partly explain the difference in explained and registered carbon emissions (Pöyry & VNP, 2018).

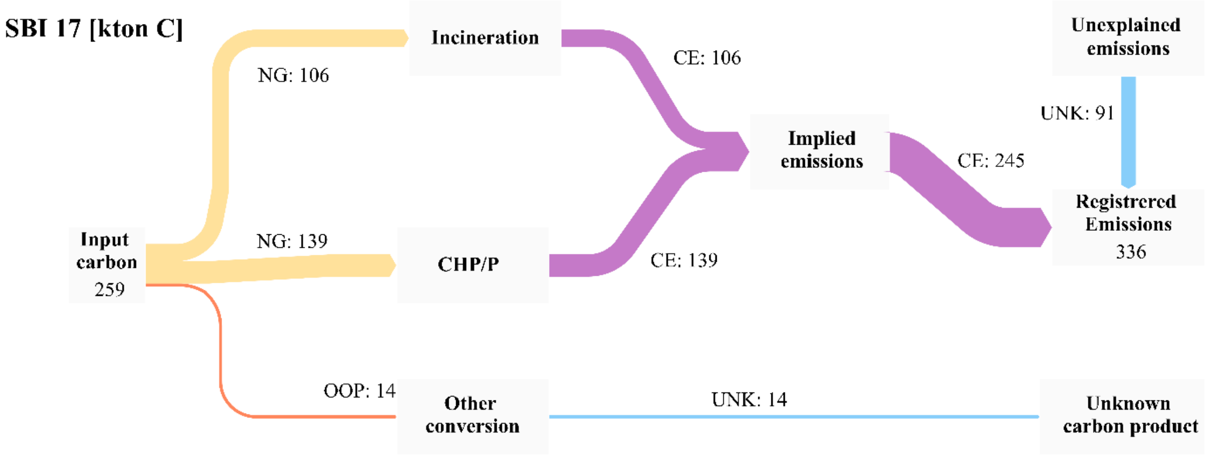

Figure 3 - Industry carbon flows for the manufacture of paper and cardboard.

3.1.3 Crude oil refining – SBI 19.2

Refineries process fossil-based crude oil for the manufacturing of refined oil products that are characterized mainly as; liquified petroleum gasses, naphtha, gasoline, kerosene, gas, diesel, and light fuel oil, heavy fuel oil, other oil products, and residual oil gasses. Crude oil is a feedstock that consists of many different hydrocarbon chemicals with varying lengths and sizes. Through separation, conversion, and treating steps the different chemicals can be used and applied in society. The flows of carbon within the refineries are non-linear compared to other industries where energy carriers are solely used for energetic purposes. In the Netherlands, there are 5 refineries. Refineries are various in sizes and complexity. Over the years they have been developed more unique to refine products in a specific desired output, with increased conversion and blending techniques that are applied (Worrell & Galitsky, 2005). Working with sectoral level statistics on refineries does not truly acknowledge the diversity of these individual facilities. However, at a sectoral level, the carbon flows are presented in figure 4. Crude oil and a range of oil products (51592 kton C) enter the refinery process, while a sum of 698 kton C of natural gas is applied for heating, CHP/P, and hydrogen gas synthesis. After the refining process, oil products are discharged with exception of residual oil gasses, LPG, and other oil products that are used for heating (1485 kton C) and CHP/P (133 kton C). Natural gas that is applied for non-energetic appliances is fully used for steam reforming and the synthesis of hydrogen gas (Taraphdar, Yadav, & Prasad, 2012). This hydrogen gas is applied in hydrotreaters, where contaminations such as sulfur are removed, and in hydrocrackers where hydrogen is used to over a hot catalyst bed to crack heavier hydrocarbon chains into mainly naphtha, diesel oil, and kerosine

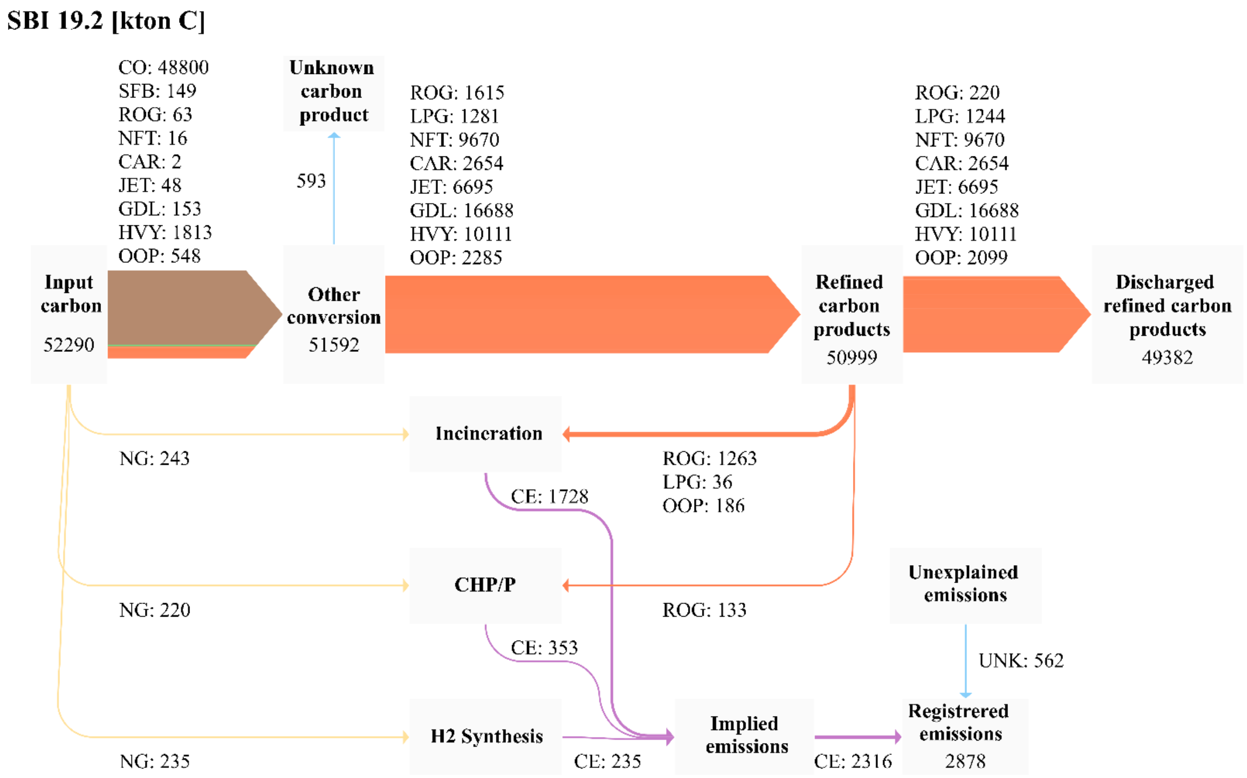

Figure 4 - Industry carbon flows for the refinery sector.

Not all hydrogen is provided by a steam reformer, because the catalytic reformer which converts oil products to car petrol, is a net producer of hydrogen. (Worrell & Galitsky, 2005) Theoretically, the manufactured output of refinery steam reformers is estimated at 78,84 kton H_2. However, this does not reflect the total use of hydrogen, because of additional hydrogen production by the catalytic reformer, and how much is purchased from the industrial gasses sector are not taken into account. Based on the molar ratio of (1/1) between CH_4 and CO_2 as can be seen in chemical reactions (1) and (2), it is assumed that carbon from hydrogen synthesis leaves as carbon dioxide. However, CO_2 provided by the hydrogen synthesis unit of Shell Pernis is partly subdued and distributed over the horticulture sector. This is not included in the carbon flow model as there is no exact certainty of the quantity of recycled CO_2 (Shell, 2019). Input and output are inequal. 593 kton of carbon leaves the refining process as uncertainty, and 562 kton C of the carbon emissions can not be explained.

(1) $CH_4 + H_2O \rightleftharpoons CO + 3\ H_2$
(2) $CO + H_2O \rightleftharpoons CO_2 + H_2$

3.1.4 The manufacture of industrial gasses – Industry SBI 20.11

The industry manufactures pure gasses that are applied in various activities, such as in the chemical, steel, food processing, and machine industry. Manufactured gasses include hydrogen, oxygen. nitrogen, argon, and carbon dioxide. 40 percent of all input energy carriers are used for energy purposes. The remaining 60 percent go through other conversions. An important substance in the industry is hydrogen gas. The manufactured output of hydrogen of which it is assumed to emanate from the industrial gasses industry is 166 kton H_2. For this manufacturing process, 243,4 kton C embedded in natural gas is required, which leaves the process as CO_2 with a high purity that can be applied elsewhere in the industry (Chauvy, Meunier, Thomas, & De Weireld, 2019; Naims, 2016). Not all CO_2 that is produced through the steam reforming process leaves the system as ProdCom output, as an additional 18 kton C surplus of carbon emissions can be added as explainable emission. It is unknown how the remaining natural gas (199 kton C) and residual oil gasses are applied in other conversions.

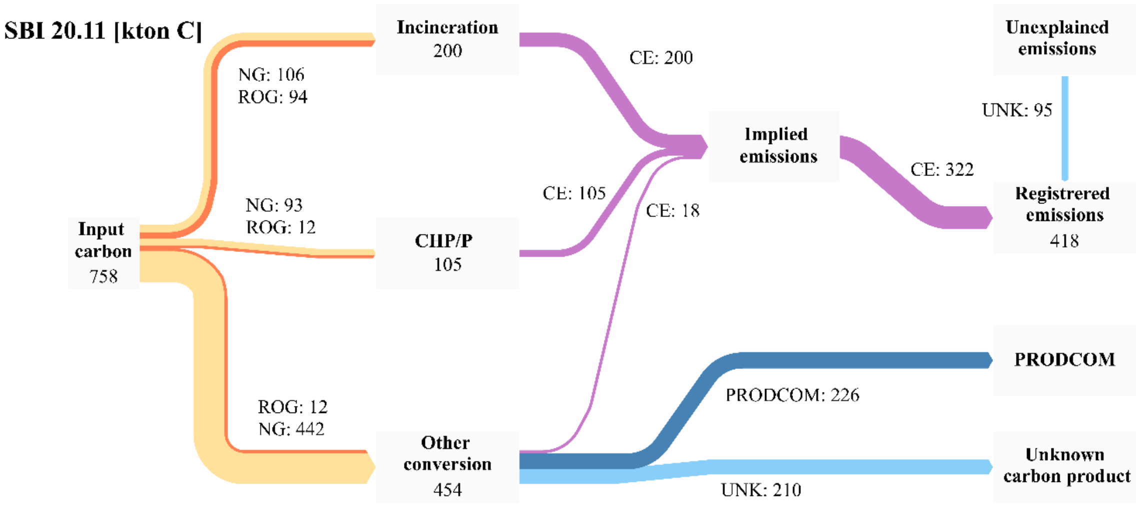

Figure 5 - Industry carbon flows for industrial gasses.

3.1.5 The manufacture of primary colours and paint – Industry SBI 20.12

The industry manufactures chemicals used for painting and colouring in primary form or as a concentrate. In carbon quantity, painting and colouring industries are the smallest within the chemical industry. As can be seen in figure 6, the industry uses natural gas for thermal energy. The industry output is 3 kton C embedded in concentrated synthetic organic and inorganic colouring matter. The industry emissions are 34,2 which leads to an unknown flow of input of 24,2 kton C that contributes to emissions.

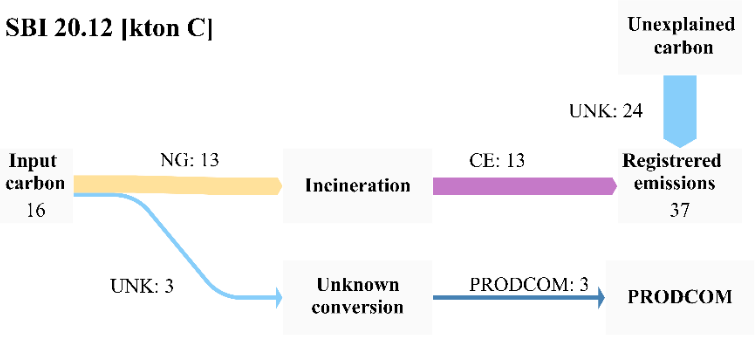

Figure 6 - Industry carbon flows for the manufacture of paint and colour.

3.1.6 The manufacture of inorganic bulk chemicals – Industry SBI 20.13

The industry is responsible for the manufacture of a broad group of inorganic chemical products, such as the enrichment of nuclear materials, distilled water, inorganic acids, alkalis, lixivium, and other compounds. 39 percent of input is used for energetic purposes, while the remaining 61 percent undergoes other conversions. The industry has no information on product output within ProdCom statistics, which leaves most of the output flows unknown.

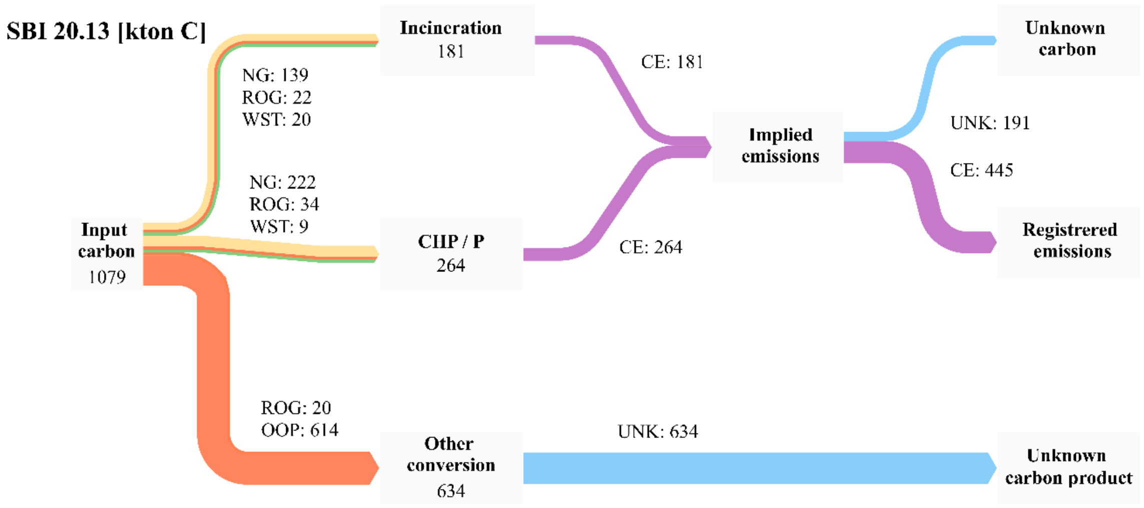

Figure 7 - Industry carbon flows for the manufacture of other inorganic bulk chemicals.

3.1.7 The manufacture of organic bulk chemicals – Industry SBI 20.14

The industry can be seen as two parts: Most importantly, the manufacturing of petrochemical products, and secondly; the manufacturing of other organic basic chemicals. The leading process for the manufacturing of petrochemical products is steam cracking, which uses mainly naphtha as a feedstock. Output includes olefins such as ethane and propane, styrene, and aromatics such as toluene, benzene, and xylene. Other organic basic chemicals include halogens, phenols, alcohols, carbon and amino acids, and ethers. Similar to refineries, steam crackers are complex and heterogenic facilities that are integrated and dependent upon demand in the value chain (Amghizar, Vandewalle, Van Geem, & Marin, 2017; Rafael Cayuela Valencia, 2013). This analysis does not truly reflect what happens within individual steam crackers, however on a sectoral level the carbon flows are shown in figure 8.

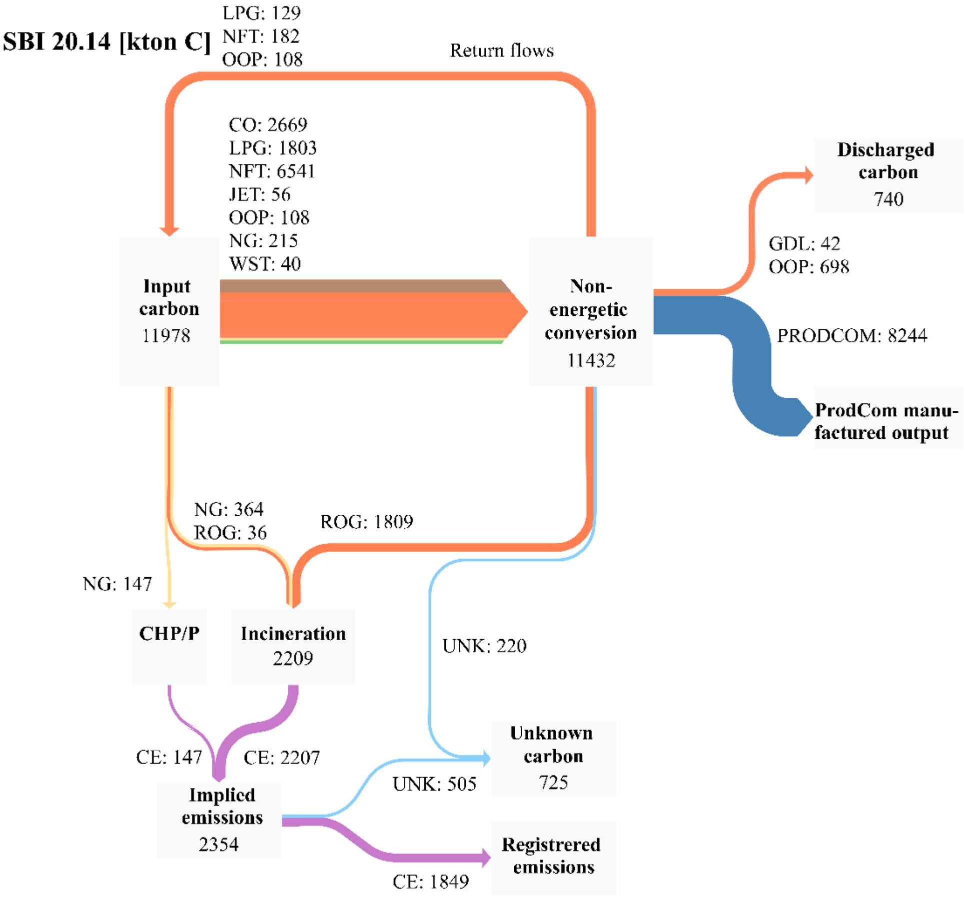

Figure 8 - Industry carbon flows for the basic organic chemical industry.

Initially, 5 percent of available carbon is used for energy conversion. After chemical processes when residual oil gasses become available, 16 percent of processed carbon flows are applied for heating purposes. Currently, the demand for feedstock within the organic basic industry consists out of mainly naphtha (6541 kton C), crude oil (2669 kton C) LPG (1803 kton C) and natural gas, waste, kerosine, and other oil products (419 kton C) In total 11432 kton C is used as input for non-energetic conversion processes. The total product output for this industry is shown in figure 9. The sum of these products is 10814 kton C. This is more than is shown in the carbon flow model. A deduction has been done to minimize double-counting by intermediate products that are required for the manufacturing of styrene and propylene oxide. Deductions of 488,8 kton C for ethylene, 615 kton C for propylene, 1170 kton C for benzene and a 296,5 kton reduction for BTX (Benzene, Toluene, and Xylene) is done. These deductions lead to a total manufacturing output of 8244 kton C. There is an uncertainty of 202 kton C remaining after this deduction. The implied emissions are higher than the registered emissions, leading to an imbalance of 505 kton C.

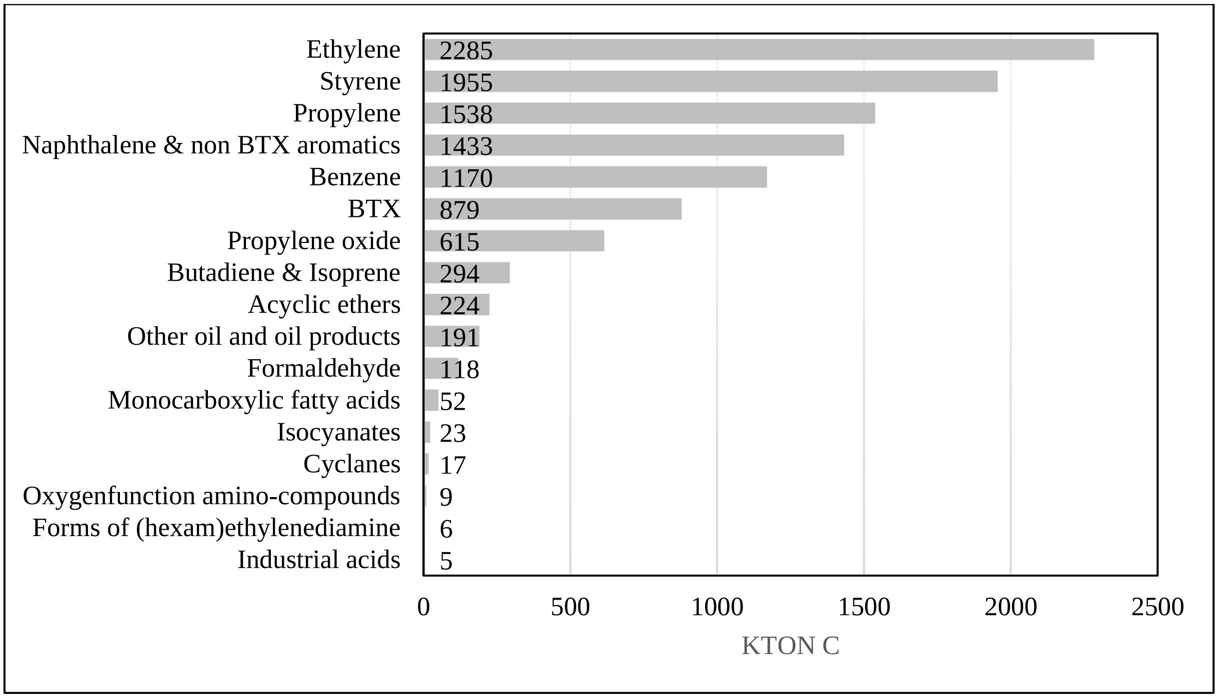

Figure 9 - Product output of the organic base industry including intermediate products

3.1.8 The manufacture of fertilizers and other nitrogenous chemicals – Industry SBI 20.15

The industry manufactures ammonia, urea, and ammonia-based products, and other simple and complex nitrogenous, phosphatic, and potassium fertilizers and chemicals. The industry uses most of its carbon input for other conversions, as 26 percent is applied for heat, power, or combined. ProdCom statistics show little information on fertilizer output. However, data provided by PBL shows that 3003 kton NH_3, 1666 kton of urea, and 2251 kton of nitric acid is produced by Yara and OCI Nitrogen, which are the two largest fertilizer producers in the Netherlands (M. Batool & W. Wetzels, 2019). The manufacturing process includes steam reforming of natural gas where CO_2 is released, followed up by the Haber-Bosch process shown in chemical reaction (3). The formation of urea (4&5) requires CO_2 as an input where the carbon atom is maintained. This leads to an estimated production output of 333 kton C embedded in urea, and a corresponding 802 kton C embedded in CO_2 that are released as emissions. However, the information provided by PBL does not fully represent the total fertilizer industry, as this excludes product output by the two other fertilizer companies Rosier and ICL Fertilizer.

(3) $1\ N_2 + 3\ H_2 \rightarrow 2\ NH_3$
(4) $2\ NH_3 + CO_2 \rightarrow H_2N\text{-}CO_2\text{-}NH_4$
(5) $H_2N\text{-}CO2\text{-}NH_4 \rightarrow H_2N\text{-}CO\text{-}NH_2 + H_2O$

Furthermore, there is an imbalance in implied emissions and registered emissions of 246 kton.

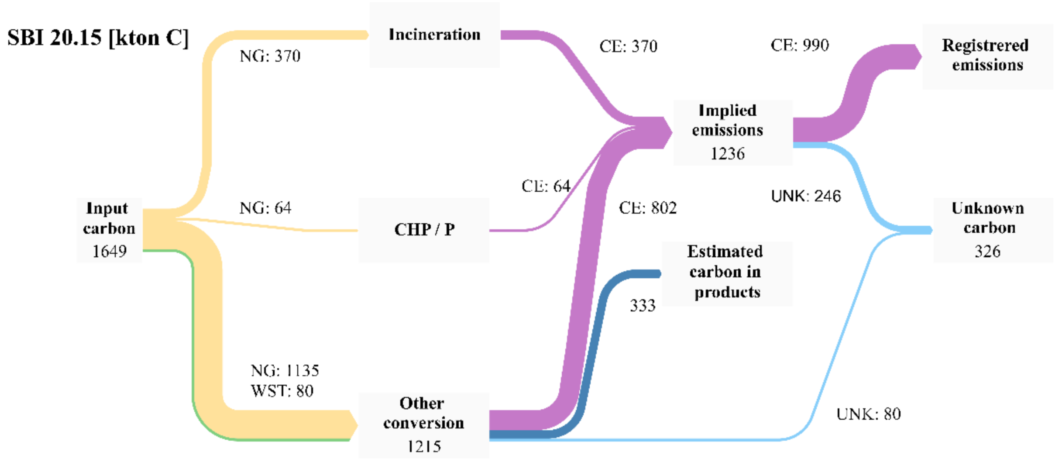

Figure 10 - Industry carbon flows for the manufacture of fertilizers.

3.1.9 The manufacture of primary plastics – Industry SBI 20.16

The industry reflects the manufacture of polymers, including polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chlorides (PVC), and other plastics and rubber chemicals in primary form. In the industry, there is uncertainty in the quantity of carbon that is used as input for the manufacture of polymers. When a 100% manufacturing efficiency is assumed roughly 9 percent of carbon input is used for energetic purposes.

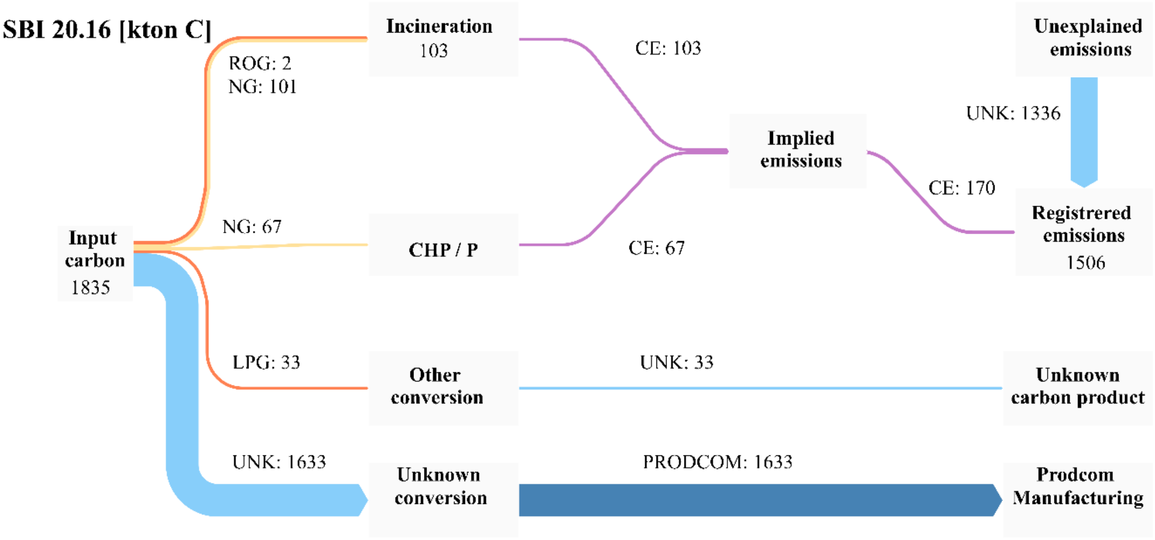

Figure 11 - Industry carbon flows for the manufacture of primary plastics.

3.1.10 Other chemical industry – 20.2 – 20.6

This is a combined group of multiple industries within the chemical industry. Industries include the manufacturing of pesticides and biocides (20.2), paint and ink (20.3), cosmetics and detergents (20.4), other chemical products industry, including gunpowder and explosives, glue, etheric oils, and other products

(20.5), and synthetic fibre production (20.6). 58% of the carbon that enters the industry is used for energetic purposes. The remaining 42% is for other conversions. However, there is no information available on the produced output of this group of industries. There is data available on the amount of sold goods within the Netherlands, which can be a combination of products imported and sold on the Dutch market and domestically produced goods which are sold there.

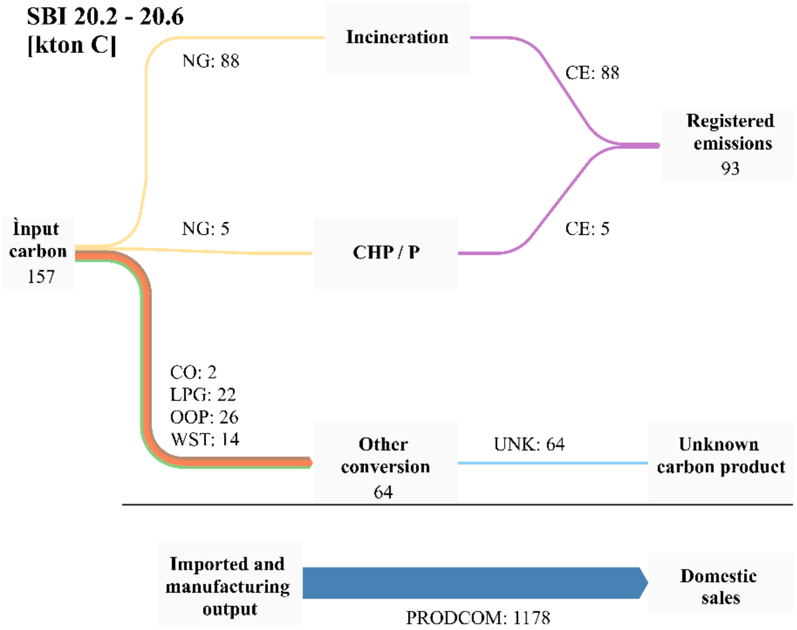

Figure 12 - Industry carbon flows for the residual chemical industry.

3.1.11 The manufacture of rubber and plastic products – Industry SBI 22

The industry processes primary plastic and rubber chemicals into plastic and rubber products such as plastic sheets, pipes, profiles, packaging, building products, tires, and hoses amongst many other applications for plastic or rubber products. The industry uses all the energy carriers as an input for the generation of heat, which is incinerated and leaves a 57 kton C imbalance compared to the registered emissions. Similar to the other chemical industry (SBI 20.2-20.6), there is no data available on the manufacturing output.

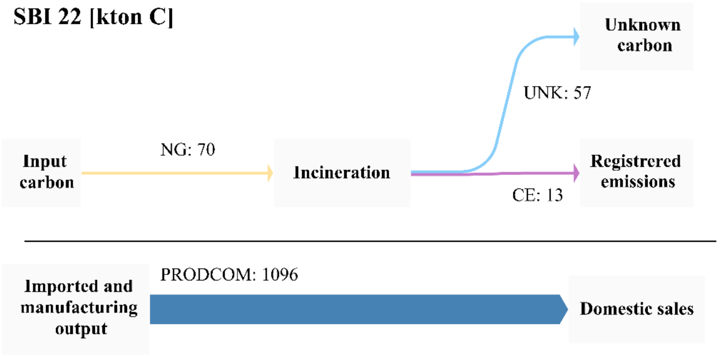

Figure 13 - Industry carbon flows for the manufacture of rubber and plastic products.

3.1.12 The manufacture of non-metal mineral materials – Industry SBI 23

The industry manufactures building materials such as glass, ceramics, concrete, limestone, lime, plaster, and natural stone products. The industry solely uses energy carriers as fuel for conversion for thermal and electrical energy. These leave the system as emissions. However, 89 kton C of the registered emissions remains unexplained.

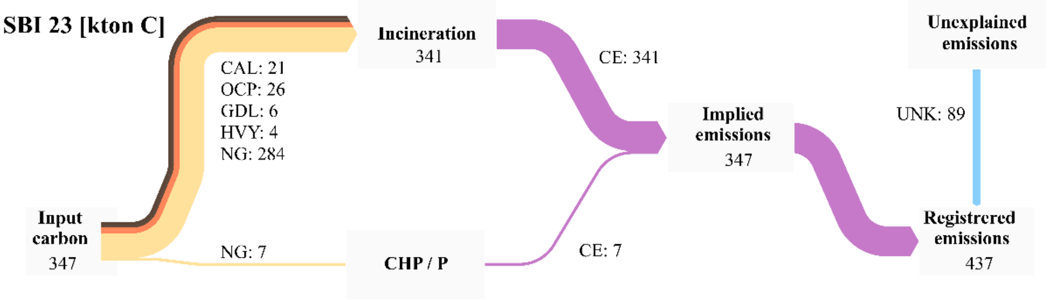

Figure 14 - Industry carbon flows for the manufacture of building materials

3.1.13 The manufacture of metals in primary form – Industry SBI 24

The industry manufactures iron and steel in primary form. Most important is the reduction of iron ore and metal scrap for the production of pig iron and steel. What is also included in the industry is the manufacture of iron and steel products, such as the production of profiles, sheets, tubes, and rails amongst many other iron or steel applications. Carbon flows in the iron and steel industry are primarily represented by the blast furnaces of Tata Steel. Of the initial carbon input, 14% percent is used for energy conversion. However, after the basic oxygen steelmaking process, 749 kton C of blast furnaces gasses become available to meet heat and electricity demand. When these gasses are allocated to heat and power demand, it would result in a 38% percent of input that is used for energetic purposes. The remaining blast furnaces gasses are transferred to a combined cycle gas turbine of Vattenfall in Velsen where the energy carrier is used for the generation of electricity (Vattenfall,). Furthermore, during the steelmaking process carbon remains in the product. Generally this is between 0,1 wt% and 1,04 wt% (Matmatch, 2018). In 2017 Tata steel produced 6,9 Mton carbon steel. (Tata Steel IJmuiden, B V, 2017). When assuming the mean embedded carbon as 0,62% 33 kton C remains in steel. 348 kton C remains uncertain after the blast furnace process.

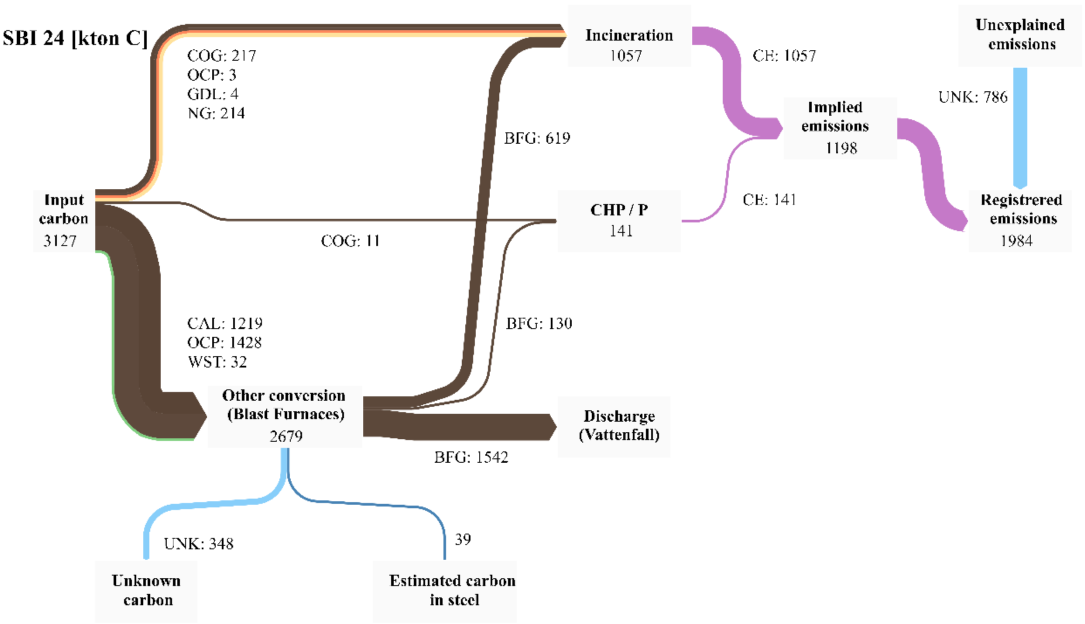

Figure 15 - Industry carbon flows for the iron and steel industry

3.1.14 Summary on energetic and other conversions within all industrial sectors

In table 3 the allocation of carbon to C_{energy} is done by calculating the final sum of carbon that is used for energetic conversions. The remainder is then allocated to C_{Other}. This choice was made as in the refinery and organic chemical industry carbon is first used for other conversions, and consequently used as an energy source. The table shows that 8621 kton C is used for energetic conversions and 62501 kton C is used for other conversions.

Table 3 - Summarized results of input energy carriers which the total kton carbon and shares of carbon that are used for energetic and other conversions.

Scope of industries	C_{input}	C_{Energy}	C_{Other}	$\%_{Energy}$	$\%_{Other}$
Food processing industry (10)	1022	1012	10	99%	1%
Paper and paper cardboard industry (SBI 17)	259	245	14	95%	5%
Refineries (19.2)	51592	2081	49511	4%	96%
Industrial gasses industry (20.11)	758	304	454	40%	60%
Primary colours and paint industry (20.12)	13	13	0	100%	0%
Inorganic chemical industry (20.13)	1076	442	634	41%	59%
Organic chemical industry (20,14)	10821	2207	8614	20%	80%
Fertilizer industry (20.15)	1651	435	1215	26%	74%
Primary plastics industry (20.16)	202	170	33	84%	16%
Other chemical industry	161	97	64	60%	40%
Rubber and plastic products industry (22)	70	70	0	100%	0%
Building material industry (23)	347	347	0	100%	0%
Iron and steel industry (24)	3149	1198	1951	38%	62%

3.2 Carbon flows within the economy

This section discusses the spread of carbon products from delivering industries towards receiving users in table 4 and 5, and the carbon embedded in products that are imported in table 6. Carbon products include naphtha and LPG from refineries and the sum of manufactured products from ProdCom from the industrial gasses industry, organic base industry, the fertilizer industry, and the primary plastics industry. Furthermore, the spread of sold plastic and rubber products is shown in figure 16. Receiving users that are discussed in this paragraph are the refineries (SBI 19.2), the basic chemical industry (SBI 20.1), the plastic industry (SBI 22), Exports, Households, Accumulation plus stock changes and environmental deposition (ASE), and other users, which is the sum of all remaining users within the Dutch economy.

Table 4 - Flows of carbon between delivering industries and receiving users in 2017 [kton C]

Receiving users	Refineries (SBI 19.2)	The basic chemical industry (SBI 20.1)	Plastic and Rubber products (SBI 22)	Other domestic users	Exports	Households	ASE
Delivering industries							
Refineries (LPG + Naphtha) (SBI 19.2)	3604	4008	228	42	2984	67	17
Manufacture of industrial gasses (SBI 20.11)		123	5	89	6		3
Manufacture of org. base chemicals (SBI 20.14)	27	3780	806	147	3456		27
Manufacture of fertilizers and nitrogen chem. (SBI 20.15)		40		46	245	1	2
Manufacture of primary plastics (SBI 20.16)		68	290		1145		18
Totals	3632	8019	1329	323	7836	68	68

Table 5 - Flows of carbon between delivering industries and receiving users [%]

Receiving users	Refineries (SBI 19.2)	The basic chemical industry (SBI 20.1)	Plastic and Rubber products (SBI 22)	Other domestic users	Exports	Households	ASE
Delivering industries							
Refineries (LPG + Naphtha) (SBI 19.2)	32,9	36,6	2,1	0,4	27,2	0,6	0,2
Manufacture of industrial gasses (SBI 20.11)		54,4	2,3	39,2	2,5		1,5
Manufacture of org. base chemicals (SBI 20.14)	0,3	45,8	9,8	1,8	41,9		0,3
Manufacture of fertilizers and nitrogen chem. (SBI 20.15)		12,0		13,9	73,5	0,2	0,5
Manufacture of primary plastics (SBI 20.16)		4,5	19,0		75,3		1,2

Table 6 - The distribution of imported products over end-users [kton C]

Importing users	Refineries (SBI 19.2)	The basic chemical industry (SBI 20.1)	Plastic and Rubber products (SBI 22)	Other domestic users	Households	ASE
Imported products						
LPG and Naphtha	988	1239	103	19	30	
Industrial gasses		4		3		
Organic basic chemicals	46	2558	714	130	3	10
Fertilizers and nitrogen compounding chemicals		7		8		
Primary plastics		40	167	79	0	11
Totals	1034	3848	984	239	33	21

Table 4 shows that in general 63% of domestically produced carbon products initially stay within the Dutch economy. The remaining 37% is directly exported. In the refinery sector, the basic chemical industry is the primary user of naphtha and LPG (36,6%), followed by deliveries of carbon within its sector (32,9%) and as export (27,2%). The use of naphtha and LPG within the refinery sector is surprising, as the information provided by the energy statistics (shown in figure 4) implies almost no intermediate use of naphtha. For the industrial gasses industry, it should be emphasized that the only carbon-containing industrial gas is carbon dioxide, while the shown flows are derived from the distribution of all industrial gasses. Surprising is the large flow that is used in the basic chemical industry, and the absence of any flow towards refineries, as this is anticipated by the distribution of H_2. Other users include human health activities (SBI 86), the manufacturing of computer, electronic and optical products (SBI 26) horticulture (SBI 1.2), recycling (SBI 38.3), and the building industry (SBI 43). There is almost no export (2,5%). Products produced by the organic chemical industry are used by the basic chemical industry (45,8%). This represents intermediate processes, such as the upgrading of short-chain alkenes towards polymers. Slightly fewer carbon products are exported (41,9%). Furthermore, 806 kton C embedded in products are used by the plastic and rubber products industry. This could suggest that some of these producers are capable of the polymerization of basic organic chemicals such as ethylene, propylene, and styrene. Carbon embedded in fertilizers and other nitrogen compounding chemicals are mostly exported (73,5%). 12% is used within the basic chemical industry. This likely represents the upgrading of urea or ammonia towards more complex NPK fertilizers. The remaining fraction is mostly dispersed over the agricultural industry. For the primary plastics industry, the largest share of carbon is exported (75,3%). Furthermore, carbon is used in the plastic and rubber products industry (SBI 22), although this quantity of carbon is 516 kton C less as what the organic basic industry (20.14) is delivering. This is unexpected, as the plastic and rubber product industry is expected to use basic plastics as a feedstock for processes such as injection moulding and extrusion. Table 6 shows the total embedded carbon in five product types that are imported. The most prominent flow is organic basic chemicals are imported and used by the basic chemical industry. Furthermore, 984 kton carbon is imported and 1329 kton is delivered by domestic industries to the plastic and rubber products industry. This suggests that the plastic product industry processes 2313 kton C for the manufacture of plastic and rubber products. However, this information cannot be validated as manufacturing data is unavailable.

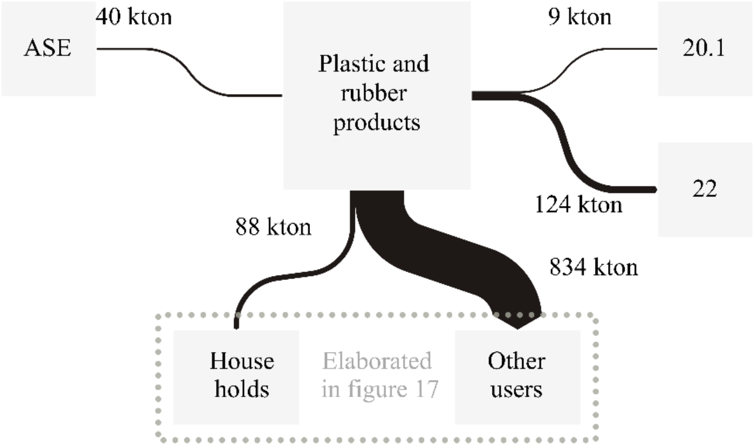

Figure 16 - Distribution of plastic and rubber products in the Dutch economy

Contrary to tables 4 and 5, figure 16 shows the data of sold plastic and rubber products within the Netherlands. This is a combination of products that are imported for domestic sales, and the locally manufactured products for domestic sales. This means the production output of the plastic product industry (SBI 22) is unknown. 124 kton C of carbon is used within the industry. Most of the carbon is used by households and other industries, services, and governmental activities. The distribution over other users and households is seen in figure 17, which shows the industries and their respective SBI on the left, and the used kton C on the right. The distribution of carbon embedded in plastic and rubber products is widespread. The most prominent users are (SBI 43) specialized construction activities, (SBI 10) food processing industry, and (SBI 320 Households). The ‘Residual users’ shown in the figure are a sum of the remaining economy-wide users that use less than 0.5% of the total embedded carbon in sold plastic and rubber products. This includes roughly 50 residual users.

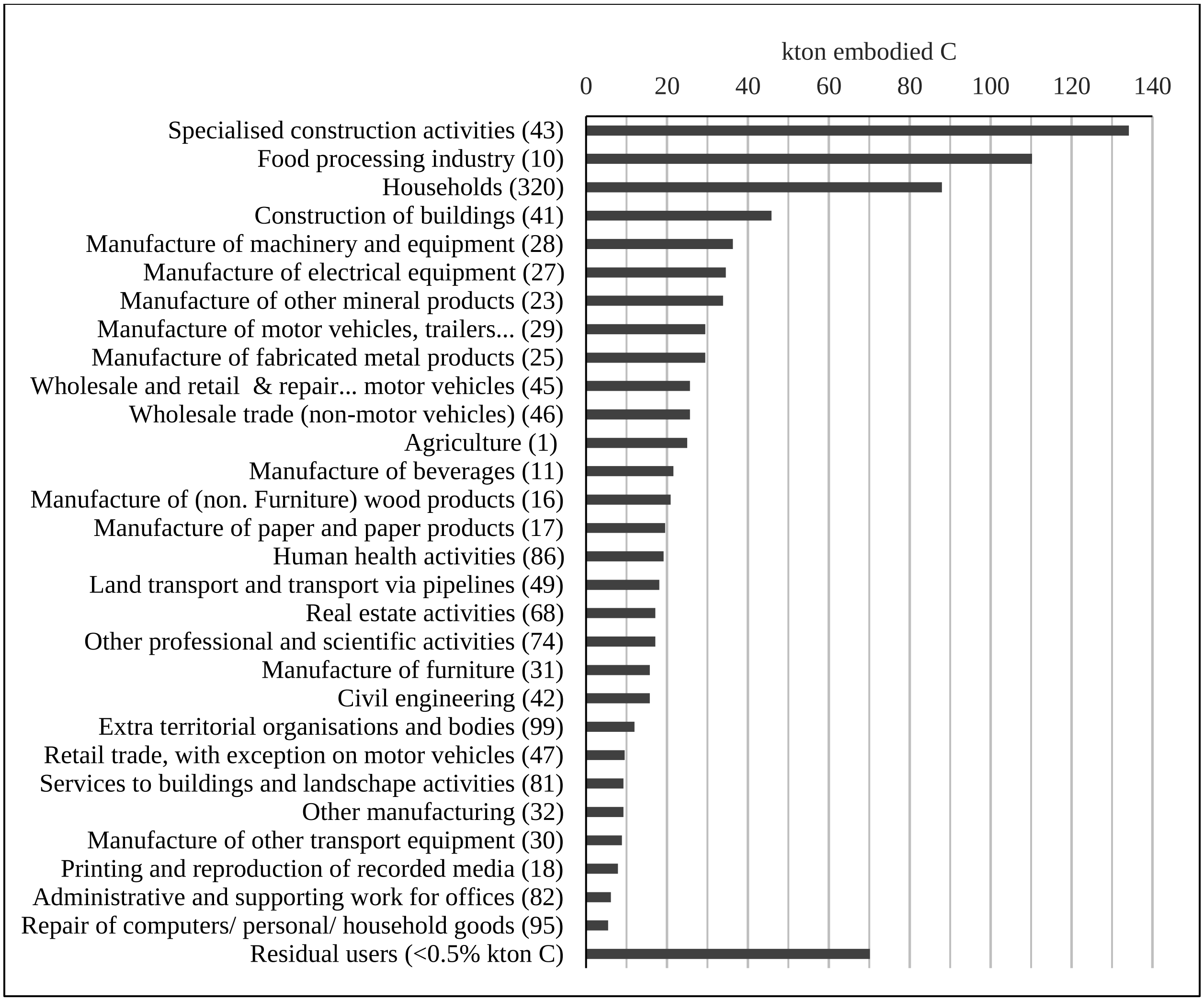

Figure 17 - Distribution of embedded carbon within sold plastic products in the Dutch economy

4. Implications of carbon circularity in the Dutch industry

The results chapter unveils carbon flows for thirteen industries. This allows researching decarbonization directions for each of these. However, this chapter aims to answer the third sub-question, namely how the linear carbon flows of the petrochemical industry (including refineries, organic chemical, and primary plastics industries) can evolve towards greater circularity by 2050 and beyond. First, a range of decarbonization directions that are currently being discussed are shown in paragraph 4.1. This is followed by an assessment in paragraph 4.2 on chemical recycling in line with the third sub-question.

4.1 Current directions of change for feedstocks and products with embodied carbon

Table 7 shows perspectives for decarbonization from the view of the national government and the umbrella organizations of the refinery and chemical industries. Commonality can be found in their points of view. These directions include options that affect energy use, such as electrification, hydrogen as fuel, and non-energy use, such as carbon capture and storage (CCS) or recycling. As the CFMs do not include energy flows it is not possible to assess directions that directly relate to energy use. Paragraph 5.5.1 discusses the application of energy use in future CFMs. Renewable feedstocks for petrochemical processes and end of life of carbon are directions of change that can be assessed using the CFMs. Paragraph 4.2. will discuss the direction of chemical recycling, which impacts both directions. However, it should be noted that decarbonization directions occur simultaneously. Multiple technological trends, next to socio-economic factors will have an impact on future carbon flows. Hence, the goal of paragraph 4.2 is not to develop a scenario or vision for the future, but to describe the direction of chemical recycling in line with the provided data and describe possible frictions towards 2050.

Table 7 – Focal areas for the decarbonization of industries from different perspectives

National government (Wiebes, 2020).	**Refineries** Ben Römgens & Mieke Dams, 2018).	**Chemical industry** (Stork, de Beer, Lintmeijer, & Den Ouden, 2018).
-	Energy efficiency until 2030	-
Green hydrogen	Blue hydrogen until 2030 Green hydrogen until 2050	Green hydrogen
CCS	CCS on non-hydrogen related emissions until 2050	CCS on internal processes & waste incineration
Electrification	Electrification until 2050	Electrification
Biorefining	-	Biobased feedstock
Chemical recycling	-	Mechanical and chemical recycling
Carbon capture and utilization	-	Syngas and CO2 as feedstock
-	-	Geothermal energy

4.2 End of life of products with embedded carbon: The ambition for circularity and the availability of waste feedstock

The industry loses sight of the lifecycle of carbon when products leave the industry gates. This can be explained by discussing two observations. Firstly, the discussed industries partly manufacture their products for international markets. As is represented by figures table 5, 42% of products derived from the organic basic industry end up exported. For the primary plastics industry this is 70%. These amounts of carbon are lost outside Dutch borders. Next to this, figure 17 shows that plastic and rubber products that do remain within the national economy are widely dispersed to intermediate and final users. How the lifespan of these flows of plastic and rubber end up is thus unknown. These two observations could challenge the continuity of circular processes when the industry will start relying on sustainable materials. This would require a continuous supply of alternative feedstocks, such as any rate of biomass, syngas/CO_2, hydrogen, and/or recyclate and waste input. This requirement could make the industry dependent on aspects that occur outside industry boundaries. For instance, an infrastructure that can return wasted carbon flows to chemical clusters, or the (year-round) availability of biomass that is suitable to be used as feedstock in chemical processes (Faaij et al., 1997; Phillips, 2007; Solar et al., 2017). Simultaneously, certain choices stimulate developments that are not sustainable. A well-known consequence is the negative impact on biodiversity elsewhere with the import of biomass (Mayer, 2005). This shows that it remains important that choices that are being made for achieving circularity of carbon contribute to a global net sustainability (Korhonen, Honkasalo, & Seppälä, 2018). To finalize, the reliance on other sources of carbon, and the necessity to reach net global sustainability arises the question to which extend carbon circularity can be achieved.

As an example, a short review about the feasibility of carbon circularity for chemical recycling is given. For the chemical industry the priority with end-of-life management is mechanical recycling, but this requires waste products of sufficient quality. All waste that does not meet the criteria is suitable for chemical recycling. Through chemical recycling, carbon can re-enter the material cycle. Three techniques of chemical recycling are being discussed within the chemical industry, namely solvolysis, pyrolysis, and gasification (Stork et al., 2018). In solvolysis, a combined group of polymers become separated through the use of a solvent and thermal energy, which can be used to produce new polymers. Through pyrolysis, waste is heated in an absence of oxygen to solid, liquid, and gas components. In gasification processes, waste is converted to a gaseous mix consisting mainly out of CO, H_2 CO_2, and CH_4. (Ragaert, Delva, & Van Geem, 2017). The industry argues that in 2050 0,75 Mton of plastic production can be made from carbon derived from chemical recycling, which is 11.3% of the estimated total production output. Hypothetically translated to the year 2017, using the same chemical recycling rate this would be 315 kton of primary plastics. However, an article provided by Broeren, et al (2018) estimated the value for available plastic waste flows within the Netherlands for 2020. This is estimated at 237 kton of waste materials. This suggests the possibility that the demand is likely to be higher than the supply.

The supply of chemically recycled carbon that is suitable as a feedstock by the industry is further lessened by an efficiency rate. The process of recycling techniques such as pyrolysis or gasification is highly dependent upon multiple parameters, such as the composition of the feedstock, the presence of a catalyst, the catalyst type if applicable, temperature, pressure, and more (Olofsson & Halvarsson, 2020; Salaudeen, Arku, & Dutta, 2019; Sharuddin, Abnisa, Daud, W. M. A. W, & Aroua, 2016; Tripathi, Sahu, & Ganesan, 2016). Carbon can be lost when CO_2 originated in output gasses, or when originated methane is incinerated to meet the heat demand of those processes (Das & Tiwari, 2018; Liu et al., 2020). To conclude, the sum of carbon that useful for further processing in the chemical industry is different per process, but never at 100% efficiency. These arguments lead to the hypothesis that towards 2050 import of chemically recyclable waste flows is required. However, the availability of this carbon is questionable, considering the presence of other large chemical clusters such as the Port of Antwerp and in Nordrhein-Westfalen which have their ambitions for circularity. The chemical sector of Germany has done a similar study as the Dutch industry. Chemical clusters in Germany, aspire the collection of waste materials for chemical recycling as well. The article assumes that all packaging, production waste, and post-consumer available plastic waste that cannot be processed by mechanical recycling, will be recycled chemically towards 2050 by the German industry (Geres et al., 2019).

To conclude, there is reason to believe that towards 2050 friction might occur in the security of the supply of carbon that is recovered from chemically recycled waste. To which extend carbon circularity can be achieved requires additional research towards the severity of this friction. New research opportunities that are derived from this observation are discussed in paragraph 5.5.3.

5. Discussion of methodology

5.1 Review on the application of methodology: substance flow analysis

This section aims to discuss to what extend the CFMs are consistent with the substance flow analysis methodology as presented by Brunner and Rechberger (2016). The SFA procedures, as shown in figure 1, are equally adapted to the process described by the authors of the methodology framework (fig. 2.15, Brunner & Rechberger). The SFA aims to establish material balances of systems. A true material balance of a system (e.g. an industry) can be achieved if all input and output flows are known. However, this is rare. An uncertainty range of the total flows over 10% is common. Uncertainties in this study refer to “UNK” flows in the CFMs of industries. Reasons for running up against uncertainties are the incompleteness of data. Another common reason for errors are inaccuracies in substance concentrations, such as CCFs for products and energy carriers. Searching for additional sources of data is a solution to increase the accuracy of carbon flows. For example the change of production output for the organic basic industry and fertilizer industry by searching for additional research papers and the application of stoichiometric calculations. On the other end, undiscussed unknown factors remain in industries that were of lesser interest due because they process minor flows of carbon (e.g. in figure 7). Nevertheless, the results of the thesis achieve the goal of a static SFA, namely generating a better understanding of a system.

Brunner and Rechberger describe multiple opportunities to further reduce uncertainties by proposing methods for acquiring new data, and how to statistically treat this data. However, this study has accepted the current state of uncertainties. To illustrate, a source for uncertainty and imbalance comes from the conversion factor from product mass to carbon mass (CCFs) for energy carriers. By minimizing these uncertainties, one should measure the carbon concentrations of a large sample size of energy carriers, and try to establish one CCF per material using statistical calculations. However, the extensive amount of work would not be beneficial for long, as the feedstocks that companies choose to use in processes are not equal over time. For example, the shift from using shale gas instead of naphtha for the production of ethylene in the United States of America (Rafael Cayuela Valencia, 2013). Or the application of crude oil from different geographical origins, as crude oil consists out of varying hydrocarbon lengths and concentrations depending on its origin (Demirbas & Bamufleh, 2017).

Other uncertainties, such as the unknown destination of carbon flows, can be minimized by studying the base industry to a greater extent as the studied system consists out of a wide range of manufacturing processes, fabricated products, and consumers of those products. For instance, flows originated from other conversion processes in the inorganic chemical industry in figure 7 are completely unknown, and other flows remain partially unknown, such as the indicative results from tables 3 and 4, and figure 17. Further steps to reduce this type of uncertainty are discussed in paragraph 5.5.1.

5.2 Review on the application of methodology: physical supply and use table

Commonly PSUTs are applied with matrix calculus to analyse physical flows at an economy-wide level. For example, PSUTs has been used to identify through which key supply-chain paths the most energy flows to provide electricity for households (Heun, Owen, & Brockway, 2018). Or they can be used to account where within the economy different types of waste are generated (Lenzen & Reynolds, 2014; Tisserant et al., 2017). The chosen method for PSUT in the current research is nontypical but has led to indicative results that include the flows of carbon originating from subsectors of the basic chemical industry. The results should be used to determine new focuses for research. Such as, assessing the feasibility of circularity when carbon is mostly exported, or to envision how plastic products are used in other industries, and to what extent this can be retrieved for recycling.

5.3 Limitations of the methodology.

The chosen method has one primary limitation. The choice was made to identify carbon flows on a sectoral level, using SBI identification. These classifications identify the primary activities of business units to improve the unification of statistical and economic analysis ((CBS, 1993)). However, it is not uncommon that companies have various activities under one classification. For using ProdCom and PSUT data the assumption was done that products were derived from their respective industries using the CPA classification. (See paragraph 2.5). On the other hand, energy statistics and emission registration data are based according to SBI classification. Through combining these databases a mismatch can occur. The consequences of this limitation can best be described with the help of a real example.

The Chemelot chemical site in Geleen is an industrial park where multiple businesses operate under one SBI, namely “20.16 The manufacturing of primary plastics” (Rijkswaterstaat, RUD Zuid-Limburg, & Waterschap Limburg, 2018). For the reader to have an idea of the relevance of this site, it should be emphasized 60 industrial plants are active there, and 8100 people are employed. At the site, there is a steam cracker for organic basic chemicals, a steam reformer for fertilizers, installations for the upgrading of ethylene into low-density polyethylene, and more. This array of installations are assumed to be manufacturing products with CPAs beginning with 2014, 2015, and 2016, and hence these are assumed to be produced from companies registered as their SBI counterpart. Here a mismatch takes place when the emissions of Chemelot are accounted on SBI 20.16 while the production output that leads to those emissions, is assumed to be coming from other industries. This mismatch can be seen in figure 11, where 1336 kton C of emissions remain unexplained within the primary plastics industry. Similarly, this can be seen in figures 9 and 10 that discuss SBI 20.14 and 20.15. There the implied emissions are higher (246 and 505 kton C respectively) than what is registered. The example of Chemelot is one that is clearly recognizable in the results, but this limitation could play a role in other industrial clusters as well.

5.4 Comparison to other substance flow analysis with similar characteristics

The determination of carbon flows in and between industries for the Dutch base industry is something that is not done before. However, this paragraph aims to discuss studies with comparable features.

A study from Germany by Uihlein, Poganietz, & Schebek (2006) proposed a carbon flow model for the German anthroposphere. Material Flow Analysis methodology was used to map carbon flows. Their techniques are comparable, as the model has a similar goal. This goal is to provide an information system as a basis for rational carbon management. Next to this, the methodology is based on (the 2004 version of) Brunner & Rechberger (2016). The main difference occurs in the scope of the project which they based on carbon flows within the anthroposphere in broadly defined components such as; industry, traffic + transport, import and export, and more. Flows are classified based on CPA and grouped in broader categories, such as ‘chemical products’, and ‘coking and petroleum products’, and then multiplied with carbon coefficients (read: CCF). This difference in scope enables the assessment of energetic and non-energetic flows of different sources of carbon through an economy. But this disables the effect on carbon flows by the implementation of certain technological trends towards 2050 which is a difference in priority between the studies. The authors claim that a carbon coefficient is the biggest source of uncertainty, especially for certain products including chemicals and oil products.

Next to the German study, a study was done by Lof et al (2017) connected to the statistics bureau of the Netherlands. The aim was to develop a carbon account in the Netherlands that allows for a consistent and quantitative comparison of carbon stocks and flows in the four reservoirs; biocarbon, geocarbon, atmospheric carbon, and carbon within the economy in 2013. The study by Lof et al (2017) lacks a direct link between individual economic activities and the atmospheric reservoir. Similarly in a study of the PBL, RIVM, and CBS (2018), a need for a more precise defined relation between material use, energy, and emissions is desired. The current study adds to this need by providing insight into the conversion of carbon for individual economic activities.

5.5 Implications for research

The knowledge that provides insight into the relationship between carbon and industrial activities is in demand (Lof et al., 2017; Potting et al., 2018). Although the CFMs presented in this study provide insight into those relations, this study is a first attempt to map carbon in industries. Hence uncertainties are still present. These uncertainties provide an opportunity for future research to map carbon in greater depth. In this paragraph, a distinction will be made between what can be done to improve the current state of the model, creating a reference for 2050, and the opportunities to assess decarbonization directions for the industrial system.

5.5.1 Improving the current carbon flow models

The main limitation of the research is the mismatch between carbon flows, which is caused by irregularity between the emission registration database and other databases (see paragraph 5.3). This mismatch originated by putting the scope of the research on a sectoral level. The caused uncertainty can be reduced by researching which individual facilities within jointly registered entities are responsible for which emissions, such as within the prominent example of Chemelot. Next to this, it should be critically reviewed if (parts of) other clusters have similar constructions where the emissions of multiple industrial plants are combined under one group. This is an important aspect, as a high grade of interconnectivity between industrial sites is common and thus more joint entities can be anticipated.

In paragraph 4.2 an assessment is given on the feasibility of chemical recycling in a circular economy. This choice is argued by stating that only observations regarding feedstocks and the end of life of carbon could be made, as the model does include energy flows. Thus, analysis of decarbonization measurements that involve energy, such as electrification of processes or geothermal energy, can not be made. However, the inclusion of energy flows is relevant as 8621 kton C (12%) is directly used for the energetic conversion within the used scope of industries. The importance of carbon flows for energetic purposes can be reviewed in table 7. The table only includes carbon for direct energetic conversions, and should therefore incorporate indirect electricity and heat that is supplied by the energy sector. When it is known how much carbon is directly and indirectly used for energy, and how much energy is used by the industry in total, this opens more opportunities to assess energy-related decarbonization directions.

Another discussed limitation of the research is that destinations of carbon flows remain uncertain. However, the available data does not provide the information to indicate the flows of carbon on a sub-industrial level (e.g. organic basic chemical industry towards the basic plastic industry). To get a better understanding of the destinations of carbon flows a qualitative approach is required. It is recommended to visualize the value chain of major products. It is interesting to further investigate by which producers these are manufactured, how big their production capacity is, and which materials are required for the production of those products. With these value chains available it is possible to better assess which carbon flows go where within the Dutch economy, and how they differentiate from the initial indicative results shown in tables 3 & 4 and figure 17. Applying this more qualitative method may be useful to increase detail, but the process might be sensitive for assumptions, as there is no possibility to map the carbon on an exact level since that level of detail is unavailable in the statistics to confirm the newly estimated flows of carbon.

A suggestion is to perform a similar substance flow analysis on a company level instead of at a sectoral level. This increase in detail can lead to a decrease in uncertainties that has its origin from the main limitation of this research. When carbon flows are researched for companies, then it would be more effective to assess the consequences of decarbonization technologies on the industry carbon flows. Partly because the unknowns are smaller, but also because of the possibility to include spatial dimensions into the model. As an example, if Tata Steel, located at Ijmuiden, would change its feedstock from coal products to biobased sources. With the help of slow pyrolysis, biochar can be produced with a yield reaching 60 wt% depending on the feedstock (Ding et al., 2016; Manyà, 2012). The residual weight leaves the system as pyrolysis gas or liquids. The gasses are rich in carbon monoxide and hydrogen (Solar et al., 2017). They are in turn useful as a feedstock for olefin production through Fischer Tropsch synthesis, such as in Rotterdam (Amghizar et al., 2017). Assessing hypothetical examples as these provide a new opening for research, such as analysing governance, economic and infrastructural challenges that may arise from realizing such a project. This cannot be done if carbon flows are assessed at a sectoral level.

An attempt has been done to map the quantities of imported carbon entering the refineries, chemical industry, and plastic and rubber product manufacturers. However, the chosen methodology for estimating carbon import (see paragraph 2.5) led to superficial results. It requires further research to establish a methodology that estimates the imported carbon flows more sophisticated.

5.5.2 Extrapolating reference models for 2050

The carbon flows that are shown in this study are based on 2017. When decarbonization directions are assessed towards 2050, it is relevant that the reference situation is first corrected to that year. Creating a future reference can be based on a frozen-technology and a business-as-usual assumption. Using frozen-technology as the reference in 2050 means that the specific carbon consumption per ton of product remains equal. In that scenario, the product demand is the only variable for estimating future carbon consumption. In a business-as-usual scenario, the extrapolation is based on more trends, such as expected changes in energy efficiency and ongoing technology shifts. Creating references for 2050 is achievable without improving CFMs (as described in paragraph 5.5.1). However, it is recommended to first implement these improvements before further investigating a future year.

5.5.3 The assessment of decarbonization directions (now and for 2050)

The information that is most valuable to stakeholders that are invested in the decarbonization transition is the feasibility of decarbonization directions (described in table 7) and the consequences of implementing these. To an extent, these studies are possible with the current state of the CFMs, such as with the assessment of chemical recycling in paragraph 4.2. This example exposes that further research is necessary for optimizing the recovery of lost carbon so that domestic chemical clusters have a secure supply of feedstock. An example of a research question is: How do international and national governments collaborate with the chemical industry to assure the circularity of carbon for chemical recycling. Another issue is that transport might increase since carbon needs to be retrieved from a widespread area. Another research question can be: What is the impact on net global sustainability when carbon flows become circular through chemical recycling?

Similar assessments can be performed for other decarbonization directions. For instance, the role of biomass in the future of the petrochemical industry. The demand for carbon for products in the petrochemical industry is known, hence the required carbon retracted from biomass as a feedstock is equal or more. Different conversion techniques can be applied for biomass to be suitable in petrochemical processes, such as the conversion of biomass through pyrolysis and hydrodeoxygenation for crude oil in refineries, biomass to produce olefins through pyrolysis in the organic chemical industry, but also the manufacture of biobased plastics such as polylactic acid in the primary plastics industry. Each of these adjustments in the value chain of plastic products can lead to a change in the demand of the fossil-based feedstock. To which extend this impacts the petrochemical industry can be investigated. Another topic of interest is the change in electricity and carbon demand if hydrogen gas is manufactured through electrolysis. Currently, H_2 is required within refineries and the synthesis of ammonia. Additional analysis can be done to assess how does the carbon and electricity demand change when H_2 is used as fuel in refineries, or as a feedstock in the chemical industry. Next to H_2 gas, biomass, and chemical recycling, other decarbonization directions can be assessed dependent on the priorities of the discussed industry.

5.6 Implications for statistics

The flows of carbon will remain to be a centre point in research that studies the approach to battle climate change in industries. Measuring these is necessary to evaluate the climate transition towards 2050. For this reason, it is recommended to develop CCFs for energy carriers [kton C $\cdot$ PJ^{-1}] and ProdCom registered products [kg C/kg product], for statisticians and researchers to measure the flows of carbon uniformly. This research has proposed CCFs which can be used as a starting point. For energy carriers, these can be reviewed in table 2, and for products in Appendix A. However, these are based on assumptions and proxy values, which led to imbalances when carbon is converted to oil products or chemicals.

The previously discussed example on Chemelot (in paragraph 5.3), leads to the observation that the energy statistics do account for individual industrial facilities within jointly registered entities, contrary to what was expected. Otherwise flows of naphtha, LPG, and natural gas would have been expected to be used by SBI 20.16 for other conversions (cracking and reforming). This observation creates the belief that there is an inconsistency between emissions registration data and the energy statistics, as metadata of both sources claim to account their data on SBI classifications (CBS, 1990; RIVM, n.d.). Emissions are reported by Statistics Netherlands, yet not on the same level of detail as the energy statistics. It is recommended to present statistics which include the sub-sectoral level for the chemical industry, and that joint emission registrations are separated.

6. Conclusions and recommendations

This research contributes to the understanding of the relationship between carbon within industrial activities and the economy and environment, which is required when assessing decarbonization directions towards 2050. The main research question that leads to this insight is: What are carbon flows within the Dutch industry today and how can these evolve towards circularity?

The study used a material flow analysis methodology to design carbon flow models (CFM) for thirteen of the most carbon-intensive industries. These flow models show how much carbon is applied in industrial processes. Processes include the generation of heat and power and other conversions of carbon to products. and how these processes lead to emissions. Indicative flows of carbon products from the petrochemical and plastic product industry are presented. These flows are derived from physical supply and use tables. These results show that a large share (37%) of domestically produced carbon products are lost through export. Additionally, carbon in plastic and rubber products that are domestically used is lost, as these products are widely distributed within the Dutch economy. This makes them untraceable. Based on these observations an assessment has been performed which studies the feasibility of chemical recycling. This assessment compares the ambition for circular carbon products in the chemical industry to the availability of carbon in suitable plastic waste. The findings indicate that friction might occur as the estimated carbon availability is roughly 33% lower than the demand. To minimise this friction, further research is necessary towards optimizing the recovery of lost carbon through (international) collaboration with the chemical industry, and environmental analysis to measure the impact on global net sustainability.

More important is if the aggregation level of the current state of the CFMs is sufficient to study the transition towards circularity of carbon within the Dutch industry. This level is sufficient at a sub-sectoral level. However, the main limitation of the research is the mismatch between carbon flows, which is caused by irregularity between the emission registration database and others. This mismatch originated by choosing the aggregation level of the research to be on a sub-sectoral level. This can be reduced through improved allocation of emissions at the sub-sectoral level by eliminating the problems that caused the imbalances. Moreover, increased possibilities concerning the study towards decarbonization can be achieved by improving the CFMs: (1) It is recommended to include direct and indirect energy use in the models. This enables assessment of energy-related decarbonization directions such as energy efficiency improvement, H_2 as fuel, geothermal energy, and electrification processes. Currently, only assessments are possible that focus on carbon, such as changing feedstocks for petrochemical processes, and end of life management. (2) It is recommended to develop frozen-technology and business-as-usual scenarios towards 2050 to serve as a reference for the assessments of decarbonization directions concerning future carbon flows.

Furthermore, the flows of carbon will remain to be a centre point in research that studies the approach to battle climate change in industries. Measuring these is necessary to evaluate the climate transition towards 2050. For this reason, it is recommended to develop CCFs for energy carriers [kton C · PJ^{-1}] and ProdCom registered products [kg C/kg product], for statisticians and researchers to measure the flows of carbon uniformly.

Footnotes

[1] - In the Dutch energy statistics, the category “Nijverheid (geen energiesector)” is used. Within energy statistics, refineries are considered as part of the energy sector.

[2] - Standaard Bedrijfsindeling 2008’ (SBI2008), which is derived from the International Standard industrial Classification of All Economic Activities (ISIC) (CBS, 2019b; UN Statistics Division, 2008).

[3] - Taskgroup ENINA consists of the national institute for public health and environment (RIVM), the Netherland Environmental Assessment Agency (PBL), Netherlands Organisation for Applied Scientific Research (TNO), Statistics Netherlands (CBS), and the Netherlands Enterprise Agency (RVO).

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Appendix A

Prodcom code	Name	Proxy	CCF *[kg C/kg product]*
20111120	Argon	Ar	0
20111150	Hydrogen	H2	0
20111160	Nitrogen	N2	0
20111170	Oxygen	O	0
20111230	Carbon dioxide	CO2	0,2728925
20122150	Other synthetic organic colouring matters	C26H21N5Na4O19S6	0,3148354
20122419	Pigments and preparations based on titanium dioxide (excluding those containing ≥ 80 % by weight of titanium dioxide)	TiO2	0
20122450	Other colouring matter; pigments and preparations based on inorganic or mineral colouring matter; inorganic products of a kind used as luminophores		0,3148354
20134280	Phosphates (excluding calcium hydrogenorthophosphate and mono- or disodium phosphate); polyphosphates (excluding sodium triphosphate)	-	0
20141130	Ethylene	C2H4	0,856328
20141250	Styrene	C8H8	0,9225156
20141140	Propene (propylene)	C3H6	0,8562262
20141223	Benzene	C6H6	0,9225451
20147320	Benzol (benzene), toluol (toluene) and xylol (xylenes)	C7H8	0,9124159
20146375	Methyloxirane (propylene oxide)	C3H6O	0,6203512
20141160	Buta-1,3-diene and isoprene	C5H8	0,8823097
20146310	Acyclic ethers and their halogenated, sulphonated, nitrated or nitrosated derivatives	(C2H5)2O	0,6481382
20146111	Methanal (formaldehyde)	CH2O	0,3999867
20143197	Industrial monocarboxylic fatty acids (excluding stearic, oleic, tall oil, distilled)	C16H32O2	0,7493955
20144450	Isocyanates	C3H4ClNO	0,3414519
20141215	Cyclanes; cyclenes and cycloterpenes (excluding cyclohexane)	C10H16	0,8815973
20144290	Oxygen-function amino-compounds (excluding amino-alcohols, their esters and ethers and salts thereof, lysine and its salts and esters, glutamic acid its salts and esters)	C8H19NO	0,6615258
20144123	Hexamethylenediamine and its salts; ethylenediamine and its salts	C6H16N2	0,6201377
20143280	Lauric acid and others; salts and esters	C12H24O2	0,7194489
20145290	Nucleic acids and other heterocyclic compounds - thiazole, benzothiazole, other cycles	C9H13N2O9P	0,3334259
20144130	Cyclanic, cyclenic or cycloterpenic mono- or polyamines, and their derivatives; salts thereof	C9H11N	0,954943
20143385	Adipic acid; its salts and esters	C6H10O4	0,4930888
20141450	Derivatives of hydrocarbons containing only sulpho groups; their salts and ethyl esters	C6H6O3S	0,455557
20142100	Industrial fatty alcohols	C18H36O3	0,719401

Prodcom code	**Name**	**Proxy**	**CCF** ***[kg C/kg product]***
20143381	Oxalic, azelaic, malonic, other, cyclanic, cylenic or cycloterpenic polycarboxylic acids, salts (excluding butanedioic acid having a bio-based carbon content of 100 % by mass)	C2H2O4	0,2668
20146379	Epoxides, epoxyalcohols, -phenols, epoxyethers, with a 3-membered ring and their halogenated, sulphonated, nitrated/nitrosated derivatives excluding oxirane, methyloxirane (propylene oxide)	C2H2O4	0,2668
20147200	Wood charcoal whether or not agglomerated (including shell or nut charcoal)	C	1
20147340	Naphthalene and other aromatic hydrocarbon mixtures (excluding benzene, toluene, xylene)	C10H8	0,9370441
20147390	Other oils and oil products, n.e.c.	Table 2	0,8036345
20157100	Mineral or chemical fertilisers containing the three fertilising elements nitrogen, phosphorus and potassium (excluding those in tablets or similar forms, or in packages with a gross weight of ≤ 10 kg)	CH_4N_2O	0,2001667
20161035	Linear polyethylene having a specific gravity < 0,94, in primary forms	C8H16	0,9633003
20162035	Expansible polystyrene, in primary forms	C8H8	0,9225688
20162090	Polymers of styrene, in primary forms (excluding polystyrene, styrene-acrylonitrile (SAN) copolymers, acrylonitrile-butadiene-styrene (ABS) copolymers)	C8H8	0,9225688
20164015	Polyethylene glycols and other polyether alcohols, in primary forms	C2H4O2	0,3748761
20164020	Polyethers, in primary forms (excluding polyacetals, polyether alcohols)	(C2H5)2O	0,6953249
20164030	Epoxide resins, in primary forms	C2H4O	0,5451409
20164050	Alkyd resins, in primary forms	C2H2(CO)2O	0,2448871
20164090	Polyesters, in primary forms (excluding polyacetals, polyethers, epoxide resins, polycarbonates, alkyd resins, polyethylene terephthalate, other unsaturated polyesters)		0,6122449
20165150	Polymers of propylene or of other olefins, in primary forms (excluding polypropylene)	C3H6	0,7271516
20165390	Acrylic polymers, in primary forms (excluding polymethyl methacrylate)	C3H4O2	0,4998474
20165450	Polyamide -6, -11, -12, -6,6, -6,9, -6,10 or -6,12, in primary forms	C12H20N2O2	0,7271516
20165490	Polyamides, in primary forms (excluding polyamide -6, -11, -12, -6,6, -6,9, -6,10 or -6,12)	C12H20N2O2	0,7271516
20165670	Polyurethanes, in primary forms	C3H8N2O	0,7271516
20165700	Silicones, in primary forms	C8H24O4Si4	0,7271516
20165920	Petroleum resins, coumarone-indene resins, polyterpenes, polysulphides, polysulphones, etc., n.e.c., in primary forms	C2H2(CO)2O	0,7271516
20301150	Paints and varnishes, based on acrylic or vinyl polymers dispersed or dissolved in an aqueous medium (including enamels and lacquers)	Assumption	0,5004167
20301170	Other paints, varnishes dispersed or dissolved in an aqueous medium	Assumption	0,5004167

Prodcom code	**Name**	**Proxy**	**CCF** ***[kg C/kg product]***
20301225	Paints and varnishes, based on polyesters dispersed/dissolved in a non-aqueous medium, weight of the solvent > 50 % of the weight of the solution including enamels and lacquers	Assumption	0,5004167
20301229	Paints and varnishes, based on polyesters dispersed/dissolved in a non-aqueous medium including enamels and lacquers excluding weight of the solvent > 50 % of the weight of the solution	Assumption	0,5004167
20301230	Paints and varnishes, based on acrylic or vinyl polymers dispersed/dissolved in non-aqueous medium, weight of the solvent > 50 % of the solution weight including enamels and lacquers	Assumption	0,5004167
20301250	Other paints and varnishes based on acrylic or vinyl polymers	Assumption	0,5004167
20301270	Paints and varnishes: solutions n.e.c.	Assumption	0,5004167
20301290	Other paints and varnishes based on synthetic polymers n.e.c.	Assumption	0,5004167
20302130	Prepared pigments, opacifiers, colours and similar preparations for ceramics, enamelling or glass	Assumption	0,5004167
20302213	Oil paints and varnishes (including enamels and lacquers)	Assumption	0,5004167
20302240	Pigments, including metallic powders and flakes, dispersed in non-aqueous media, in liquid or paste form, of a kind used in the manufacture of paints; colorants and other colouring matter, n.e.c. put up for retail sale	Assumption	0,5004167
20302253	Glaziers’ putty, grafting putty, resin cements, caulking compounds and other mastics	Assumption	0,5004167
20302255	Painters’ fillings	Assumption	0,5004167
20302260	Non-refractory surfacing preparations for façades, indoor walls, floors, ceilings or the like	Assumption	0,5004167
20302273	Organic composite solvents and thinners used in conjunction with coatings and inks; based on butyl acetate	Assumption	0,5004167
20302279	Organic composite solvents and thinners used in conjunction with coatings and inks (excluding those based on butyl acetate)	Assumption	0,5004167
20302450	Black printing inks	Assumption	0,5004167
20302470	Printing inks (excluding black)	Assumption	0,5004167
20412020	Anionic organic surface-active agents (excluding soap)	$C_3H_8O_3$	0,3912477
20412050	Non-ionic organic surface-active agents (excluding soap)	$C_3H_8O_3$	0,3912477
20412090	Organic surface-active agents (excluding soap, anionic, cationic, non-ionic)	$C_3H_8O_3$	0,3912477
20413180	Soap in forms excluding bars, cakes or moulded shapes, paper, wadding, felt and non-wovens impregnated or coated with soap/detergent, flakes, granules or powders	$C_3H_8O_3$	0,3912477
20413240	Surface-active preparations, whether or not containing soap, p.r.s. (excluding those for use as soap)	$C_3H_8O_3$	0,3912477
20413250	Washing preparations and cleaning preparations, with or without soap, p.r.s. including auxiliary washing preparations excluding those for use as soap, surface-active preparations	$C_3H_8O_3$	0,3912477

Prodcom code	**Name**	**Proxy**	**CCF** ***[kg C/kg product]***
20413260	Surface-active preparations, whether or not containing soap, n.p.r.s. (excluding those for use as soap)	C3H8O3	0,3912477
20413270	Washing preparations and cleaning preparations, with or without soap, n.p.r.s. including auxiliary washing preparations excluding those for use as soap, surface-active preparations	C3H8O3	0,3912477
20414280	Artificial and prepared waxes (including sealing waxes) (excluding of polyethylene glycol)	C3H8O3	0,3912477
20414389	Other polishes, creams and similar preparations, n.e.c.	C3H8O3	0,3912477
20421150	Perfumes	C3H8O3	0,3912477
20521060	Glues based on starches, dextrins or other modified starches	C4H8O	0,6662044
20521080	Prepared glues and other prepared adhesives, n.e.c.	C4H8O	0,6662044
20531050	Concentrates of essential oils in fats... aqueous distillates, etc.	C4H8O	0,6662044
20531075	Mixtures of odoriferous substances of a kind used in the food or drink industries	C4H8O	0,6662044
20594179	Lubricating preparations not containing petroleum oil or bituminous mineral oils, excluding the ones used for treatment of textiles, leather, hides, furskins or other materials	C4H8O	0,6662044
20595210	Composite diagnostic or laboratory reagents, including paper impregnated or coated with diagnostic or laboratory reagents	C4H8O	0,6662044
20595660	Reaction initiators, reaction accelerators and catalytic preparations	C4H8O	0,6662044
20595994	Other chemical products, n.e.c.	C4H8O	0,6662044
20596080	Gelatin and its derivatives (excluding casein glues, bone glues and isinglass)	C4H8O	0,6662044
22192019	Other compounded rubber, unvulcanised, in primary forms or in plates, sheets or strip	Assumption	0,8
22192070	Plates, sheets and strip of vulcanised rubber	Assumption	0,8
22192087	Extruded solid rubber rods and profiles	Assumption	0,8
22194050	Rubber conveyor belts	Assumption	0,8
22197349	Rubber-to-metal bonded articles for other uses than for tractors and motor vehicles	Assumption	0,8
22197365	Articles of vulcanised solid rubber other than for tractors and motor vehicles	Assumption	0,8
22211070	Monofilament with any cross-sectional dimension > 1 mm, rods, sticks, profile shapes, of polymers of vinyl chloride (including surface worked but not otherwise worked)	Assumption	0,8
22211090	Monofilament with any cross-sectional dimension > 1 mm; rods; sticks and profile shapes of plastics (excluding of polymers of ethylene, of polymers of vinyl chloride)	Assumption	0,8
22212153	Rigid tubes, pipes and hoses of polymers of ethylene	Assumption	0,8
22212157	Rigid tubes, pipes and hoses of polymers of vinyl chloride	Assumption	0,38432

Prodcom code	**Name**	**Proxy**	**CCF** ***[kg C/kg product]***
22212170	Rigid tubes, pipes and hoses of plastics (excluding of polymers of ethylene, of polymers of propylene, of polymers of vinyl chloride)	Assumption	0,8
22212950	Plastic tubes, pipes and hoses (excluding artificial guts, sausage skins, rigid, flexible tubes and pipes having a minimum burst pressure of 27,6 MPa)	Assumption	0,8
22212970	Fittings, e.g. joints, elbows, flanges, of plastics, for tubes, pipes and hoses	Assumption	0,8
22213010	Other plates..., of polymers of ethylene, not reinforced, thickness ≤ 0,125 mm	Assumption	0,8
22213021	Other plates..., of biaxially orientated polymers of propylene, thickness ≤ 0,10 mm	Assumption	0,8
22213026	Other plates..., of non-cellular polymers of propylene, thickness > 0,10 mm, n.e.c.	Assumption	0,8
22213030	Other plates..., of polymers of styrene, not reinforced, etc.	Assumption	0,8
22213035	Other plates, sheets, film, foil and strip, of polymers of vinyl chloride, containing ≥ 6 % of plasticisers, thickness ≤ 1 mm	Assumption	0,8
22213065	Plates, sheets, film, foil, strip, of polyethylene terephthalate, not reinforced, etc., of a thickness ≤ 0,35 mm	Assumption	0,8
22214150	Plates, sheets, film, foil and strip of cellular polyurethanes	Assumption	0,8
22214180	Plates, sheets, film, foil and strip of cellular plastics (excluding of polymers of styrene, of polymers of vinyl chloride, of polyurethanes, of regenerated cellulose)	Assumption	0,8
22214275	Non-cellular plates, sheets, film, foil, strip of condensation or rearrangement polymerisation products, aminoresins (high pressure laminates, decorative surface one/both sides)	Assumption	0,8
22214279	Other plates, sheets, films, foil and strip, of polymerisation products	Assumption	0,8
22214280	Other plates..., non-cellular of plastics other than made by polymerisation	Assumption	0,8
22221100	Sacks and bags of polymers of ethylene (including cones)	Assumption	0,8
22221200	Plastic sacks and bags (including cones) (excluding of polymers of ethylene)	Assumption	0,8
22221300	Plastic boxes, cases, crates and similar articles for the conveyance or packing of goods	Assumption	0,8
22221925	Plastic stoppers, lids, caps, capsules and other closures	Assumption	0,8
22221950	Articles for the conveyance or packaging of goods, of plastics (excluding boxes, cases, crates and similar articles; sacks and bags,	Assumption	0,8
22231300	Plastic reservoirs, tanks, vats, intermediate bulk and similar containers, of a capacity > 300 litres	Assumption	0,8
22231990	Builders' ware for the manufacture of flooring, walls, partition walls, ceilings, roofing, etc., guttering and accessories, banisters, fences and the like,	Assumption	0,8
22292240	Self-adhesive plates, sheets, film, foil, tape, strip and other flat shapes, of plastics, whether or not in rolls >	Assumption	0,8

Prodcom code	**Name**	**Proxy**	**CCF** ***[kg C/kg product]***
	20 cm wide (excluding floor, wall and ceiling coverings of HS 3918)		
22292320	Tableware and kitchenware of plastic	Assumption	0,8
22292340	Household articles and toilet articles, of plastics (excluding tableware, kitchenware, baths, shower-baths, washbasins, bidets, lavatory pans, seats and covers, flushing cisterns and similar sanitary ware)	Assumption	0,8
22292950	Other articles made from sheet	Assumption	0,8