QUANTIFYING THE PETROLEUMSCAPE:

USING A STOCK DRIVEN MATERIAL FLOW ANALYSIS MODEL TO ASSESS THE POSSIBILITIES FOR MATERIAL CIRCULARITY IN THE OIL INDUSTRY

MASTER THESIS INDUSTRIAL ECOLOGY

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PREFACE

Lying before you is a master thesis, a final outcome of a project which concludes my time as a student. A time which has not always been easy for me or those around me, and which certainly has not always gone to plan. Unfortunately, but not unexpected, this thesis was no exception to that trend. For me, overcoming the difficulties that studying in general and the thesis project in particular threw at me makes the completion of it all the sweeter. However, this is not something that I could have done alone, and there are many people that I owe my thanks to, many more than fit in this preface.

First of all, I need to wholeheartedly thank both my supervisors, Sebastiaan and Carola, for their guidance, their understanding, their constructive criticism, and their patience. When things did not go according to plan or I had any other difficulty, they were there to help me along. It is safe to say that I could not have done it without them.

Then, I need to thank prof. dr. Ester van der Voet, for kick-starting this project, and helping with the first steps. I also need to thank Yanan Liang, who is writing her PhD on a similar subject, for her information and explanation. Acknowledgement is also reserved for drs. ing. Harmen-Sytze de Boer, researcher at PBL, for a thorough deepdive on the IMAGE modelling.

My gratitude goes out to Paula, my study advisor at CML, who has supported me however and wherever she could throughout my entire master.

The support I got from my friends during this project has been heartwarming. Providing mental support as well as fun and sporty intermezzos during my toughest times, while simultaneously giving me the space to socially isolate myself to focus on my thesis is a combination that is hard to believe. In particular I need to thank my roommates for giving both support and distractions when needed, and I also cannot go without thanking my study friends, the BK Shiners, who helped me and each other through the thesis struggles. Keep shining, my friends.

And although many friends helped in this endeavour, there are some who I want to mention personally. I need to thank Bart “Billy” Helder for being a Python wizard with incredible patience and explanatory skills, Sarah for her writing help and advice, Ewoud for his keen eye when it comes to visuals, and Mitchel Mitchel Knipscheer for his support and mean (but just) commenting on my draft.

The one person that is closest to me was also the one that had to deal with most of the hardship, problems, and uncertainties, while already having more than enough on her own plate. Dear Nilgün, I cannot thank you enough for your support. Her şey artık çok güzel.

Lastly, I want to mention my family. I consider myself privileged to have a supportive family around me that I can always rely on, whatever the situation. Most importantly, I want to thank Papa en Mama, who have been there for me during my entire study time. They supported me during the lowest lows and the highest highs, and always kept believing in me. I will never be able to express the full gratitude and love that I feel towards them. From the bottom of my heart: thank you.

SUMMARY

Petroleum plays a major role in the current energy system, and based on different scenarios it will to some extent keep doing so for the foreseeable future, despite its known negative impacts on society and both the local and global environment. This study sets out to assess the material-based consequences of potential changes in this so-called industrial petroleumscape.

To do so, this study models the evolution of the world's petroleum infrastructures based on two SSP2 scenarios: a baseline scenario and a 1.5-degree scenario. Based on the current situation, it estimates embedded materials from 1971 towards 2050, as well as the associated in- and outflow, by performing a stock driven dynamic material flow analysis. Based on the end-of-life characteristics of the sector, this study assesses the potential for material circularity within the sector.

The Main Research Question of this study is formulated as:

"How do future changes in petroleum demand influence the industry's material circularity?"

Current situation

It is found that pipelines and storage are the main drivers for current material use in the petroleum industry, accounting for 45% and 42% respectively. This leads to material use, with the materials most used within the oil sector's infrastructure being steel and concrete, with a mass-based share of 54% for steel and 42% for concrete.

Future developments

When looking at future developments in the sector and their influence on the material flows, It is concluded that when the baseline scenario is followed, the material stock, inflow, and outflow, are only going to increase over time. Conversely, the 1.5-degree scenario shows that a decrease in petroleum demand will lead to a comparable decrease in stock, subsequently leading to a reduction in the necessary material inflow in the system. It is also clear from both scenarios that any changes in the oil demand will only have influence on the material outflow of the system after 2040.

Circularity potential

When comparing the different materials in- and outflow of the system over time, it becomes clear that based on the baseline energy scenario and current projections of end-of-life practices, circularity is still beyond reach for the system towards 2050. Circularity can only be reached when the material outflow surpasses its inflow. For this to happen in 2050 in the baseline scenario, the material inflow would need to decrease 21.5% for steel, and 12.0% for concrete. These results indicate that the demand for petroleum as an energy source needs to be reduced sharply to allow for circularity.

In the 1.5-degree scenario, the inflow and outflow do allow for circularity: the outflow surpasses the inflow. However, the results show that end-of-life practices need to be improved to enable material circularity. For the system to become circular, the total end-of-life recycling rate needs to improve from 47% to 87% for steel, and from 11% to 75% for concrete.

Practical and policy implications

First of all, it can be concluded that compared to the global material market, the material consumption of the oil industry only plays a marginal role. The total material inflow necessary in 2019 accounted for less than 1% of the total global consumption.

The results of this study point to three major implications if the oil industry ever were to reach material circularity. Firstly, the global oil demand needs to be reduced. Secondly, regardless of the developments in the demand for petroleum, ambitious global decommissioning policies need to be employed to increase the collection of the petroleum infrastructure. The collection of both onshore and offshore pipelines, as well as

other off-shore infrastructure, such as extraction platforms, offer room for improvement. Lastly, for the material sector to be circular, the recycling of concrete needs to be improved.

Further research

The results of this study can be used to improve energy scenarios, by including the embedded energy costs of used materials in different energy technologies. Additionally, end-of-life practices can be included in scenario design, leading to more accurate projections. The modelling approach used within this research can also be applied to assess other impacts of the petroleum industry, such as land use or health related issues.

One of the main problems this study encounters is the lack of reliable, publicly available data. This is true for data on the global oil sector, as well as for the data on embedded materials in specific installations. Further research could help address these data gaps.

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LIST OF ABBREVIATIONS

API	American Petroleum Institute
BB	Billion barrels
bbl	Barrel of crude oil
Boe	Barrel of oil equivalent
CBA	Consumption Based Accounting
CDW	Construction and Demolition Waste
dMFA	Dynamic Material Flow Analysis
EIA	U.S. Energy Information Administration
EU	European Union
GHG	GreenHouse Gas
IEA	International Energy Agency
IMAGE	Integrated Model to Assess the Global Environment
Koe	Kilogram of oil equivalent
LCA	Life Cycle Assessment
MB	Million Barrels
MFA	Material Flow Analysis
MJ	MegaJoule
Mt	Megatonne
MRQ	Main Research Question
ODYM	Open Dynamic Material Systems Model
RQ	Research Question
SI	Supplementary Information
SSP	Shared Socioeconomic Pathways
Toe	Tonne of oil equivalent

1. INTRODUCTION

Over the last 150 years, activities related to petroleum consumption have massively impacted our surroundings (Hein, 2018). The infrastructure required for extraction, transport, storage and refinement of petroleum has influenced the landscape and buildings around us (Shamasunder & Johnston, 2021). This physical influence of the oil industry is part of the petroleumscape, which is defined as the physical, represented, and everyday practices of the oil industry (Hein, 2018).

Examples of this petroleumscape are abundant and can be found all around the world, as is illustrated by Figure 1.1. These infrastructural installations take up valuable land (Matemilola et al., 2018), they are leading to health and environmental concerns (Kim et al., 2022; Saviotti Orozco, 2021), and are linked to violating indigenous peoples rights (Lau, 2022; Yakovleva, 2011; Zentner et al., 2019).

The negative influences of the petroleumscape are the result of a global dependency on petroleum for energy (Hein, 2018; Martins et al., 2018). On a national level, this oil dependency causes economical, strategical, and political concerns (Benedictow et al., 2013; Deutch et al., 2006; McGoven et al., 2020). On a global level, the knowledge that oil consumption leads to global climate change has been known for decades (Franta, 2018). Consequently, the need for global transition to an energy system based on renewables has been expressed for decades as well (Solomon & Krishna, 2011). The detrimental effects of global climate change are looming large over humanity (IPCC, 2022), but the current energy system still relies mainly on oil and other fossil fuels (IEA, 2021b; Martins et al., 2018). Challenges for the energy transition are abundant (Adewuyi et al., 2020; Mata Pérez et al., 2019), leading to fossil fuels still being used in many different sectors (Martins et al., 2018).

a

b

c

d

e

Figure 1.1 - Imagery of the global petroleumscape: an overview of all the oil industry near Rotterdam (a), satellite imagery revealing the extent of oil extraction on and around the Arabian peninsula (b), flaring pollution in the port of Antwerp (c), a disguised oil derrick in Beverly Hills (d), and the Trans-Alaska pipeline (e).

This signifies that the energy transition still needs accelerating, even though investments in clean energy production have been slowly but steadily increasing in the last decade (IEA, 2022a). This is widely understood, and many scenarios enabling this energy transition have been created (Deason, 2018; Harrisson, 2018; IEA, 2020a; Riahi et al., 2017; Volkart et al., 2018). However, other scenarios for the energy supply are also modelled, in which the fossil fuel sector, and more specifically the petroleum sector, remains the same or even expands (Harrisson, 2018; IEA, 2021a). All in all, it is safe to say that it is hard to imagine a world without the petroleum industry.

But what if we did? What would be the effects of scaling the oil industry down, instead of up? This research focuses on that question, and specifically looks into what this shift away from the oil industry would mean for material use.

Focusing on the effects on material use in the petroleum industry can be highly relevant, since the material demands for the total energy sector are expected to grow significantly (Buchholz & Brandenburg, 2018; Månberger & Stenqvist, 2018; Valero et al., 2018). These studies however, focus mostly on the material needs of emerging technologies. Moreover, the main focus in research is often on specific minerals or critical raw materials (Bazilian, 2018; Calvo & Valero, 2022; Pommeret et al., 2022; Vakulchuk & Overland, 2021). Either way, material reclamation from an obsolete energy technology could help mitigate the material needs of the energy sector as a whole.

To analyse the effects on material use, this research will assess the possibilities for material circulation within the oil industry. After all, before providing materials for the rest of the energy system, the oil industry would have to be able to support its own material needs. Furthermore, reaching material circularity is an important contributing factor to the Sustainable Development Goals (RMIS - EU Science hub, 2023; Schroeder et al., 2019)
Other research on predictive bulk material requirement with climate implications in mind has been done on electricity (Deetman et al., 2021), the built environment (Deetman et al., 2020; Soonsawad et al., 2022), and transport (Watari et al., 2019). The study by Le Boulzec et al. (2022) assesses the material use within the fossil fuel industry as a whole, with no particular focus on the petroleum sector.

This study aims to address the lack of specific research into the future bulk material developments of the petroleum sector, by quantifying the demands and possible yields in different future scenarios, and assessing its possibility for circularity. With its negative impact on the environment, controversial image, political importance, and high reliance from society, the oil sector faces many challenges over the coming decades (Bathrinath et al., 2021). The high variety in projections on oil demand make fully understanding the consequences of choices in the energy sector all the more important.

1.1 RESEARCH QUESTIONS

This research aims to shed light on the material circularity possibilities of the industrial petroleumscape. The main research question (MRQ) is therefore is defined as:

“HOW DO FUTURE CHANGES IN PETROLEUM DEMAND INFLUENCE THE INDUSTRY’S MATERIAL CIRCULARITY?”

To answer the MRQ adequately, three sub questions have been created. These sub questions will be answered by using a modelling approach. The following research questions have been drafted:

RQ1:
What are the current global stocks of material in use in the oil industry infrastructure?

RQ2:
Based on different scenarios, what would be the anticipated material in- and outflows in the oil industry infrastructure towards 2050?

RQ3:
To what extent do these material flows allow for circularity within the oil industry?

Answering these research questions will yield specific insights into the petroleum industry. The results from this study can inform how future changes in oil demand influence the petroleum industries material circularity. First, by studying current global stocks of material, this analysis identifies the types and volumes of material in the oil industry infrastructure, as well as the contribution of each of the stages of the petroleum sector. Subsequently, with a dynamic Material Flow Analysis (dMFA), this analysis reveals the anticipated material in- and outflows in the oil industry infrastructure towards 2050, based on two future scenarios. This helps in identifying the extent and the timeframe in which changes will happen based on current and future developments. Third, the circular assessment reveals how the reusable outflows compare to the necessary inflows in the petroleum sector, identifying the attributing factors for enabling material circularity. All in all, these results will help to quantify the petroleumscape, which in this research refers solely to the physical representation of the petroleum sector.

1.2 OUTLINE

This report starts with a description of the methods employed and the modelling framework capturing the fossil fuel system with the different stages and the system boundaries (Chapter 2). This chapter is followed by a description and overview of the data used (Chapter 3). A model is developed to calculate the current global stocks of material, the material in- and outflows of the oil industry towards 2050 and a circular assessment of these material flows. The insights from this analysis are gathered to provide insight into the effects that changes in oil demand have on the material use in the petroleumscape (Chapter 4). The study continues by discussing the limitations of this study and practical and policy recommendations that are drawn from the outcomes of this model (Chapter 5), before concluding with answering the research questions (Chapter 6)

2. METHODS

For this research, a modelling approach is used. More specifically, a dynamic Material Flow Analysis will be performed. The reasons for choosing this analysis type will be presented in this chapter. Furthermore, the model setup, the system boundaries, and other modelling choices are discussed, giving a clear overview of the methods used within this research.

For this research, a dynamic Material Flow Analysis will be performed. The analysis will be performed in Python, using the Scientific PYthon Development EnviRonment (Spyder), version 5.1.5. Within this research, the Open Dynamic Material Systems Model (ODYM) as presented by Pauliuk & Heeren (2020) is used to perform the dynamic stock modelling over time. (Pauliuk & Heeren, 2020). The code can be found in Supplementary Information (SI) 2.

2.1 MATERIAL FLOW ANALYSIS

Many studies analysing the material cycles of metals in the anthroposphere are based on Material Flow Analysis (MFA) (Muller et al., 2014). To analyse the energy system, a simple material flow model is used, consisting of material inflow in the form of infrastructure into the system, stock buildup within the system, and outflow after the infrastructure has reached its end-of-life. The model is based on the following equation:

inflow = outflow + stock buildup

This can be seen in Figure 2.1. It is notable that in this specific research, material refers to the materials needed in the infrastructure for the production of oil products, not the material that is being produced.

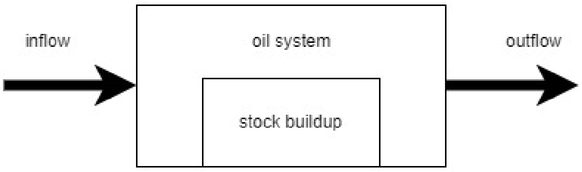


Figure 2.1 - A basic overview of the material flow.

To assess the material impact of the global petroleumscape a dynamic material flow analysis is used (dMFA). A dMFA keeps track of the flows and stocks for different materials, and models the changes over time (Graedel, 2019). The results can give insight into the past, current, and future material flows, quantities, location, and availability (Müller et al., 2014). MFA's are a widely used methodology within the field of Industrial Ecology (Pauliuk et al., 2015, 2017).

A dFMA is not without drawbacks. It requires a large amount of data, and the availability of relevant data is often limited. Gathering the data from multiple sources also means that the quality often varies widely (Laner et al., 2014). Using different sources inevitably leads to uncertainties, possibly adding up to a large uncertainty in dMFA results (Cencic, 2016; Müller et al., 2014). Moreover, the data found can create conflict with the model constraints (Cencic, 2016; Klinglmair et al., 2016). Multiple mathematical options to solve these issues have been developed (Cencic, 2016), but with different model layouts based mainly on the studies' goal and scope, even research on a similar topic with similar data sources can have very different uncertainty assessments (Klinglmair et al., 2016). The data needs within this research and the choices made regarding their uncertainty are described in detail in Chapter 3.

2.1.1 STOCK DRIVEN MODEL

In this dMFA, a stock driven approach is used. This means the material inflow and outflow will be calculated based on the stock that is needed for the system to operate. This approach is opposite to the flow driven approach, which assumes that the in- and outflow of materials are the driving forces, leading to a certain stock buildup in the system. In that case (some of) the in- and outflows need to be known to properly execute the analysis. In this study the stock driven approach is used since calculating the expected in- and outflow of materials based on their current stocks is insightful when it comes to dealing with the recycling streams (Brattebø et al., 2009).

Another reason for opting for the stock driven approach is that, since the oil industry totally relies on its stocks (the infrastructure) to produce the desired product, data on the current numbers of installations in the petroleum system are available.

2.1.2 SYSTEM BOUNDARIES AND DIVISION

To understand the material requirements of the oil sector, it is important to break it up into its different components and draw clear system boundaries. The following schematic (Figure 2.2) gives an overview of the sector and what is included within this research. This research includes the infrastructure related to the upstream, midstream, and partially the downstream supply chain. This means that both the infrastructure needed for production of petroleum (or crude oil) and that of its products (e.g. kerosine, petrol, diesel) are included. The cutoff point is the infrastructure needed for local distribution and final use.

Stages and types

Figure 2.2 shows that the petroleum sector is divided into five stages: extraction, pipelines, transport, storage, and processing. Each of these stages is further separated into different types. These types are listed in Table 2.1

Table 2.1 - Stages and their types within the petroleum industry.

stage	type
extraction	onshore offshore
pipelines	crude product
transport	rail cargo ocean ships inland ships road
storage	crude product
processing	refinery

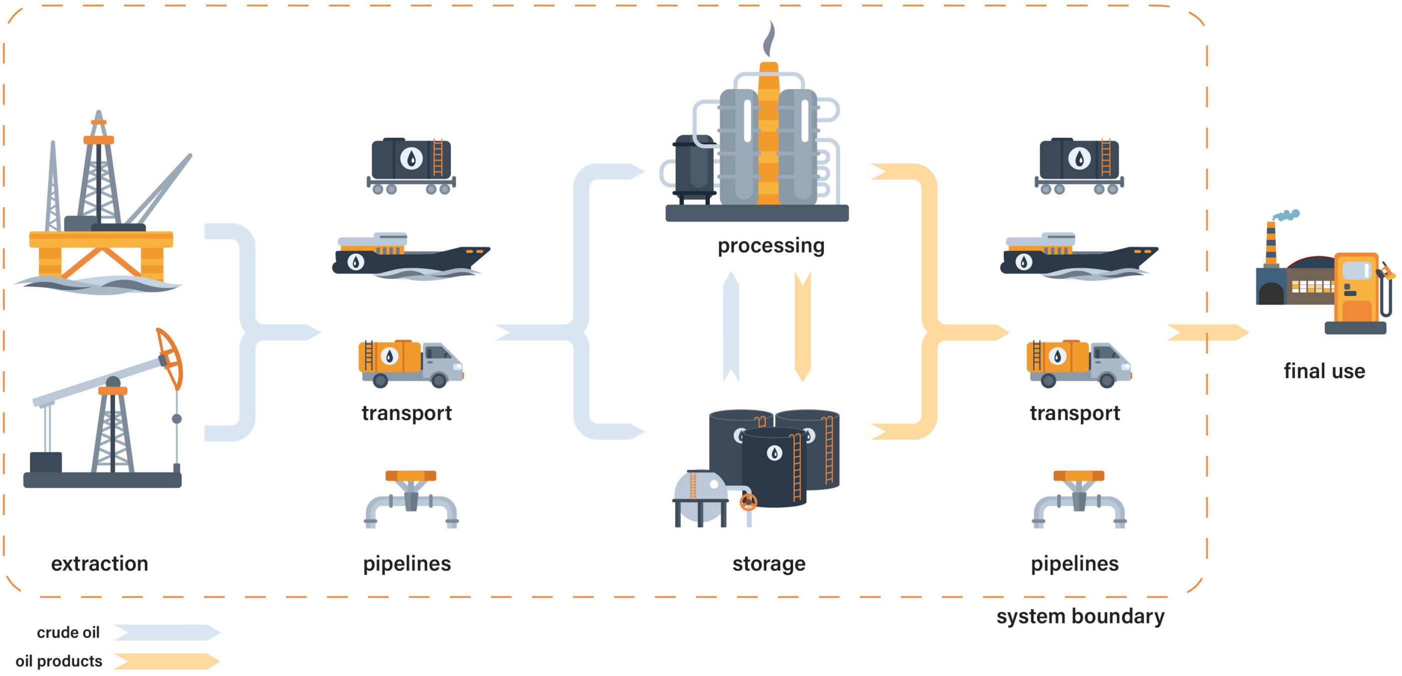


Figure 2.2 - Overview of the oil industry with the system boundary for this research.

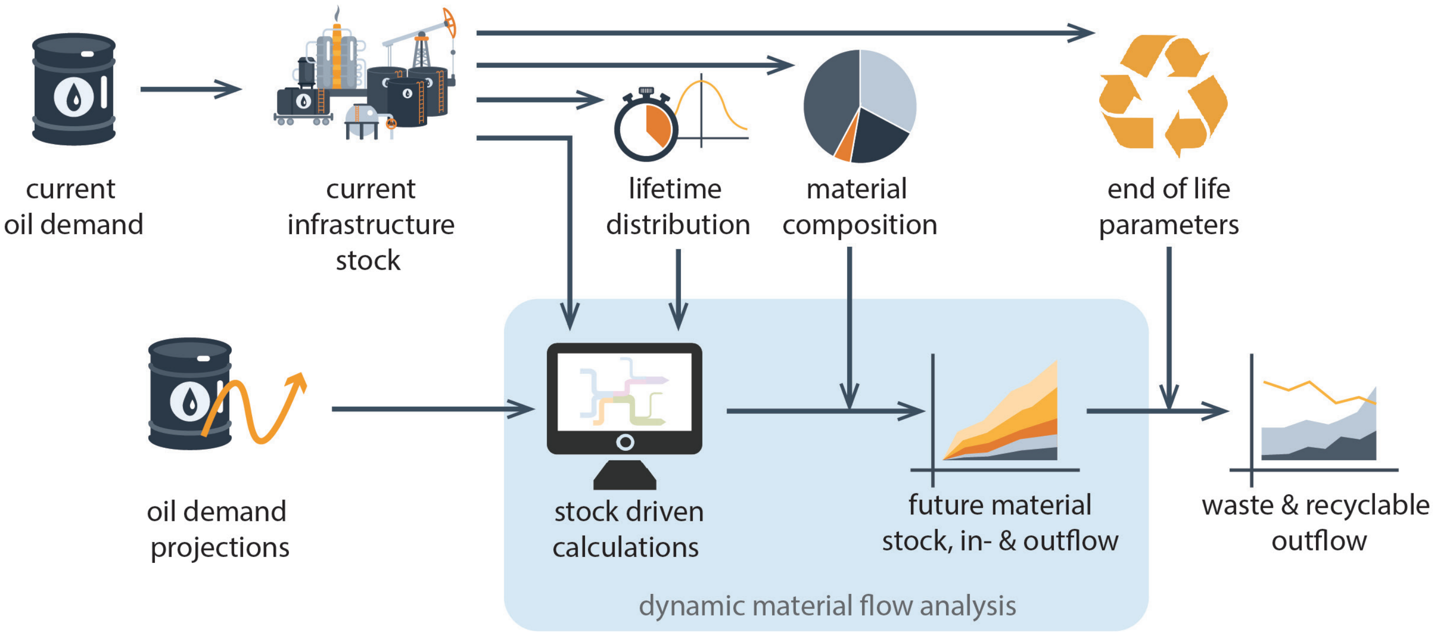


Figure 2.3 - Schematic overview of the modelling approach.

2.2 MODEL SETUP

In Figure 2.3 the model setup is shown schematically. Firstly, the current stocks have to be quantified to get an adequate overview of the scale and current material usage within the sector. This, combined with the current oil output of the system, leads to the stocks needed to produce a certain amount of service. Combining this with projections of oil demands over time gives an overview of the stocks needed to accommodate that demand. With the infrastructure's lifetime distribution the outflow is determined, enabling the necessary inflow of infrastructure to be calculated. Then, the material composition allows for the calculation of the material based inflow, outflow, and stocks. Lastly, to determine possibilities for circularity, end-of-life parameters are integrated into the model to calculate the recyclable outflow and waste.

2.2.1 SURPLUS MODELLING AND STOCK CALCULATIONS

In a conventional stock driven dMFA the stock in the system is either known or directly linked to a driving value in the system. In the case of this research, this driver is the annual oil demand. This demand can fluctuate greatly over the years, leading this model to implicate similarly abrupt changes in the infrastructure stock, and by extension the in and outflow. However, this is of course not what is to be expected in real life, as the infrastructure will not be demolished or decommissioned completely, but rather stay dormant.

To account for this, the direct relationship between the flows and the driving factors needs to be discarded, allowing for surplus stock in the model. This is done by letting the material outflow be determined only by the time the infrastructure enters the system, and its respective lifetime value and distribution. This means that the outflow is no longer influenced by the demand for oil, and that new inflow in infrastructure stock actually lives out its entire lifetime. The total system is shown in schematic form in Figure 2.4, and explained below.

To calculate the stock at time t, the calculation starts with the stock output of the time period prior (t-1). The infrastructure stock of that year is reduced by the outflow based on the infrastructure's lifetime distribution, leading to the surviving stock at time t. For the stock demand at t, the oil demand is still the driving factor. The necessary and surviving stock at time t are then compared and when needed, new inflow is added, leading to the new total stock at time t.

From the overview it becomes clear that the outflow is no longer depending on the oil demand, and that the inflow compensates for any difference between the surviving stock and the stock demands. Lastly, when the surviving stock is larger than the stock demand, the inflow gets to 0, and the stock surplus remains in the system.

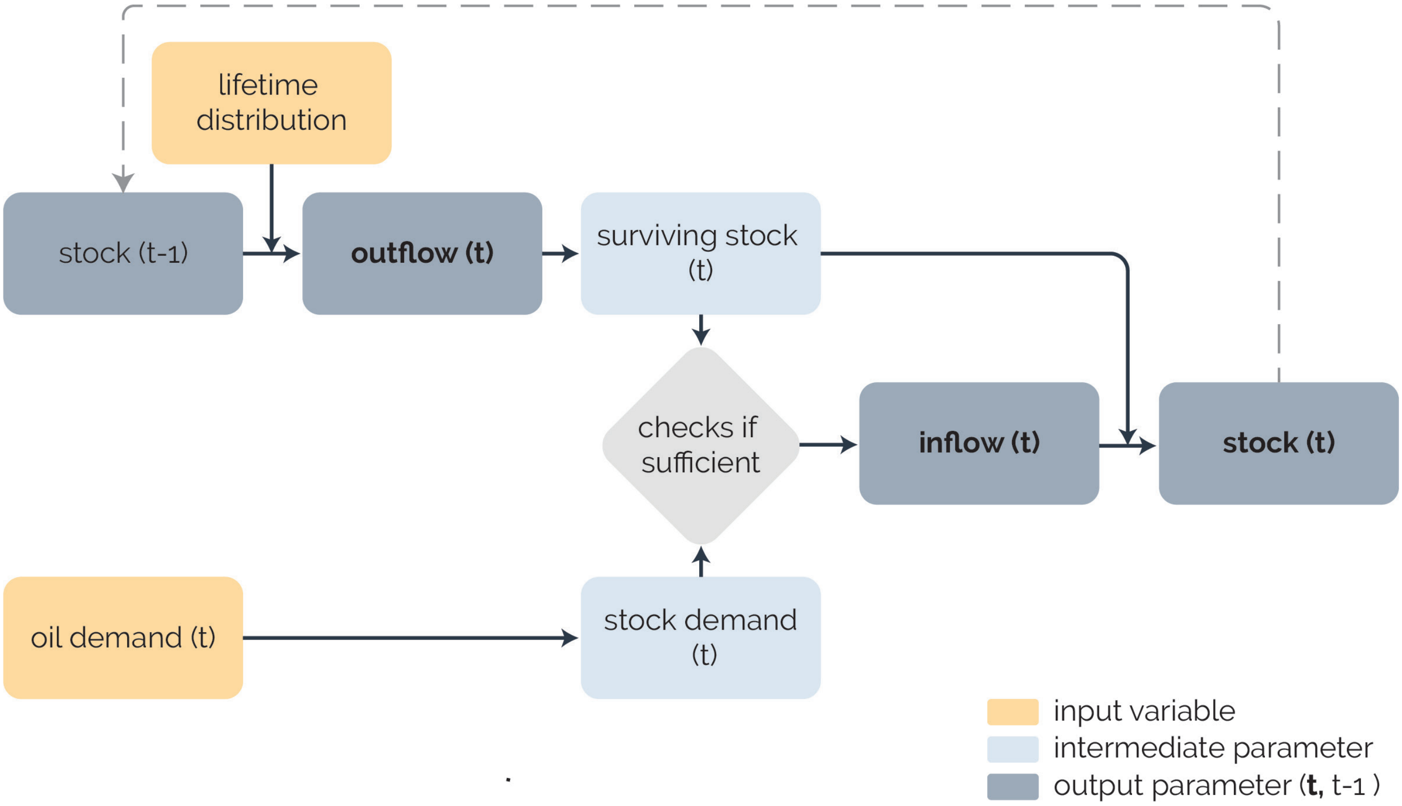


Figure 2.4 - Overview of the stock calculations, allowing for surplus stock and unlinking the outflow from the driving factor.

Rolling averages

Another way of dealing with large fluctuations in the calculated flows is taking a rolling average over a certain number of years. In this research, the rolling average is used when calculating the final results, smoothing out abrupt changes in any of the material flows. This helps to provide a more accurate image of long-term trends.

2.2.2 REGION SPECIFIC PARAMETERS

Although the aim of this research is to get a global overview of the material implications of the petroleum sector, for some parameters the setup of the model is on a regional basis. Most importantly, the energy demands which drive the material flows are region specific. This means that the oil demand is known per geographical region.

Consequently, stages which are depending on the local demand of oil products could be modelled to be region specific too. Oil storage is a prime example of this, since more oil demand in a certain area directly influences the demand for oil storage in that area. However, storage is not only needed in the region of final consumption. Large oil storage terminals are located strategically based on international transport routes and production locations (Menon, 2021) meaning that changes in local demand can have influence on storage needs elsewhere. Furthermore, linking the other stages' infrastructure to a specific region is also not straightforward, since the region's oil consumption and production are not the same. For example, the kerosene that is needed to fulfil demands in Brazil, could be derived from a refinery in Mexico, with the crude oil from that refinery originating from an offshore platform off the coast of Canada. Linking any region's oil demand to another region's oil production is a complicated step that falls outside of this study's scope.

Consumption based accounting

To mitigate the problem mentioned above, consumption based accounting (CBA) is used. This type of accounting can be used for associating emissions or other influences associated with the consumption of goods instead of the production (S. J. Davis & Caldeira, 2010; Franzen & Mader, 2018).

For this research this means that the in-use infrastructure is not tied to the region of its geographical location, but rather to the region where the demand is coming from. Therefore, the material allocated per region is the material driven by the oil consumption within that region. This approach considers the sum of all the global infrastructure and then divides it based on the consumption pattern between regions. Within this research, all stages of petroleum production are modelled using this approach. To acquire this global infrastructure data, sometimes local data has to be used. Specifically, data on local installed oil related infrastructure is needed to accumulate to a global total. It is important to distinguish these two types of regional infrastructure data.

2.2.3 DYNAMIC PARAMETER MODELLING

To create a truly dynamic Material Flow Analysis, the model should describe not just the current situation, but rather the development of the system over time (Chen & Graedel, 2012; in Müller et al., 2014). As discussed above, this research will implement changing oil demands to model changes in the petroleum system. However, the model allows for other parameters to behave dynamically. For example, the share between different types of infrastructure can change over time, which can be accounted for with the dynamic parameters. Within this research however, the use of dynamic parameters is limited to the end-of-life parameters.

The approach taken to model dynamic parameters is a linear interpolation between two known (or projected) values, which differ over time. Before the first and after the last known value, those respective values will be used as a constant. Between the two values, the progression is modelled to be linear. This is one of the mostly used methods to solve data gaps between two values (Blu et al., 2004).

2.2.4 BASE YEAR

The COVID-19 outbreak has had a massive impact on society as a whole, but on the energy sector in particular (Tahir & Batool, 2020; A. K. Verma & Prakash, 2020; Zhang et al., 2021). The petroleum sector had to deal with plummeting demand due to lockdowns, which lead to relatively low oil prices, consequently leading to higher stocking of oil in storage facilities (Narayan, 2020; C. Verma et al., 2021). Since the goal of this research is to link the oil demand to its material demands, these irregular years are not very representative. Therefore, the year 2019 will be used as the base year for the analyses, meaning data from 2019 will be used wherever possible.

2.2.5 HISTORIC STOCK BUILDUP

A general issue that arises when using a stock-driven approach is that the stock values need to be known for the total time in which the stock builds up. If the buildup-period is not known, or when the model is set up in the middle of a time period with pre-existing stock, the first year of the model would require an inflow equal to the first year stock. This can be derived from Figure 2.4: the stock (t-1) would be 0, so the outflow (t) and surviving stock (t) would also be 0. This means that to fulfil the stock demand (t), the inflow (t) would have to be equal to the stock (t). This would not only be highly unrealistic, but also influence the inflow and outflow for the rest of the modelled years.

In this research, the modelling of the stock follows the oil demand data used as an input, which starts in 1971. The oil industry and its infrastructure were of course well developed by then. To not have all the 1971 stocks entering the system at that year, the model assumes a linear buildup of stock from 1900 until 1970.

3. DATA NEEDS

To assess the current stock of material in use in the oil industry, a lot of data about this industry and the infrastructure within is necessary. With this large amount of data needed for an accurate dMFA, a lack of scientific studies in this specific field, and limited public access to the sectors database, the use of both academic and non-academic sources is needed to make proper assumptions and to come to a reliable and complete overview.

This chapter describes the data, used sources, and assumptions for each of the components of the model. It starts with the driving energy demand, before the data needs for every stage and type of the oil production supply chain are discussed. This includes the material intensity, lifetime, and end-of-life parameters. Next, the data required per material is described. The chapter concludes with discussing the material intensities A complete overview of all the input data can be found in Appendix D.

3.1 ENERGY DEMAND & SCENARIO SELECTION

For the energy demand data this research will make use of the outcomes of the IMAGE modelling framework. This framework is designed to examine long-term impacts of human impact on a global level, based around their energy use (PBL, 2021a). One of the outputs of this model is a set of energy demands in Joule for different energy sources per year, from 1970 towards 2100. The scenario results from 2021 (PBL, 2021b; van Vuuren et al., 2021) will be used in the dMFA to serve as the driving forces for the material flows.

3.1.1 SCENARIO SELECTION

The IMAGE model models energy use based on Shared Socioeconomic Pathways, which are intended to cover all plausible future scenarios (Harrisson, 2018). The scenarios range from SSP1 to SSP5, corresponding to a range from sustainable (SSP1) to fossil fuel driven (SSP5). The scenarios are based on socioeconomic trends that might shape global society as it progresses (Harrisson, 2018).

In this research, using projections from the SSP2 scenario will be used, which is the "middle of the road scenario". This means that although progress is made in a lot of technological and societal fields, the shifts are not radical or evenly spread around the globe. Development towards sustainability is generally slow. Within the SSP2 scenarios different paths are mapped, based on the temperature increase compared to pre-industrial times (IPCC, 2022). More specifically, these pathways are based on the comparable solar radiation in w/m2. Within this research the SSP2 baseline scenario and the SSP2 1.9 w/m2 scenario will be compared. These are the farthest apart within the SSP2 scenario, which will show the influence of the path that we as humanity choose the best. The SSP2 1.9 w/m2 scenario translates to limiting global temperature increase to 1.5˚C above pre-industrial levels (IPCC, 2022). From now on, these scenarios will be referred to as *the baseline scenario* and the 1.5*-degree scenario* respectively. The outcomes of the IMAGE model that are used within the model are shown in Figure 3.1. This figure shows the energy demand for the petroleum industry in EJ over a time period from 1971 - 2050.

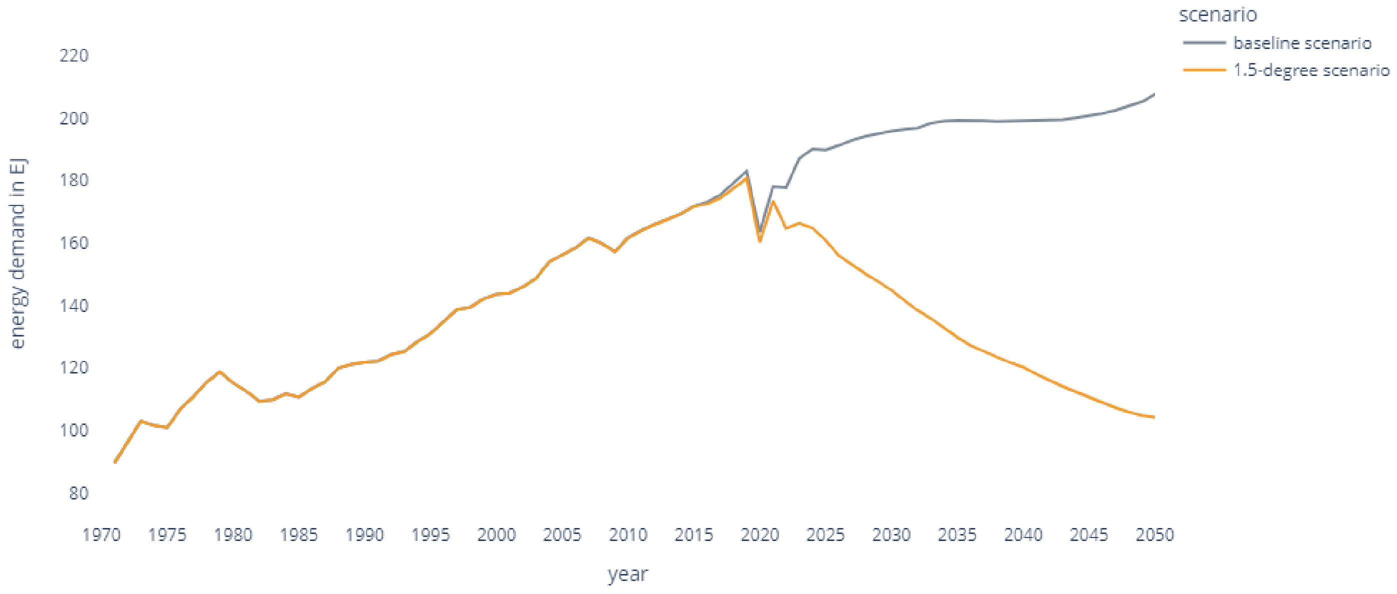


Figure 3.1 - The energy demand for the oil sector for the 2 scenarios. Data via IMAGE

3.2 DATA NEEDS PER STAGE AND TYPE

For each of the five stages specified in section 2.1.2, and their underlying types, certain data has to be retrieved. The first factor to include is the share of this underlying type for every stage (e.g. what percentage of the world's pipelines are offshore). Then, it is necessary to find the currently installed infrastructure, since this will be linked to the current oil demand.

To calculate the specific material needs, the material composition of every type of infrastructure is needed. Since the size of any installation is often related to its capacity (e.g. a large refinery can process more oil than a smaller one), the material composition should be relative to this stage specific capacity. This data will be described in section 3.2.2.

This will lead to what is known as a *material intensity*. The material intensity coefficient (MI) refers to the amount of material needed for a specific service unit (Heeren & Fishman, 2019). In the case of this research, this service unit is the production of oil, and the material intensity will be looked into for every stage and type separately. For example, finding how much steel is needed to extract one kg of crude oil using offshore infrastructure, or how much concrete is used in the refining of 1 tonne of oil. In the end, the different intensities can be accumulated, leading to an overall material intensity: how much of each material is needed to extract, transport, store, and process a certain amount of oil. This overall accumulation will be performed in section 3.4.

For modelling the expected outflow over time, the lifetimes per type are needed. The lifetimes, as well as their distribution, are described and listed in section 3.2.3.

To calculate the recycling possibilities the end-of-life parameters are necessary: a collection rate per type of infrastructure. Lastly, there is a time gap between the decommissioning of the infrastructure and the recycled materials being ready for use. This timeshift differs per type of infrastructure, and is modelled accordingly. The collection rate and timeshift are presented in section 3.2.4.

All of the used parameters will be described below. An overview of their values can be found in each section, with a total overview in Appendix D, Table A.6. A total overview of the assessment methods and sources can also be found in Appendix D, in Table A.7.

`The data known per stage and type are listed below, with oil storage as an example:

The global amount of infrastructure	How much storage capacity is currently in operation?
The share of each type for its stage	How much storage is dedicated to crude oil, and how much for oil products?
The material composition of the infrastructure, relative to its capacity	How much material is needed to construct a tank storing one tonne of oil?
The lifetime of the infrastructure?	How long can an oil storage facility be used?
A collection rate	What percentage of the oil storage facilities will be demolished and collected for recycling, and how many will just be left in place?
A timeshift	How long does it take to demolish a storage facility and retrieve the useful materials?

A total overview of these values can be found in Appendix D, Table A.6, and the assessment methods and sources can be found in Appendix D, Table A.7

3.2.1 LCA DATABASES

A lot of different sources can be used to fulfil the data needs described in the previous paragraph. This includes previous MFA and Life Cycle Assessment (LCA) studies, official statistics, legislative documents and standards, and industry reports. Of the aforementioned options for data retrieval, LCA studies are the most promising. Life Cycle Assessment is "a cradle-to-grave or cradle-to-cradle analysis technique to assess environmental impacts associated with all the stages of a product's life, which is from raw material extraction through materials processing, manufacturing, distribution, and use" (Muralikrishna & Manickam, 2017). This means that all the processes needed to produce a product that are taken into account are documented, including their capacity, raw material use, and often lifetime. This can be a valuable data source for this MFA research.
When using LCA databases it is important to keep in mind this type of analysis uses allocation to attribute material use to an end product. A stock driven dMFA changes the order: what is the current stock, and how much product does it produce? It is therefore critical that conversions are executed carefully and that assumptions and simplifications are well documented (Müller et al., 2014).

Life Cycle Analyses on petroleum

In their comprehensive overview, Vineyard and Ingwersen (2017) list and analyse five different LCA models that are used to assess the impacts of petroleum products. (Vineyard & Ingwersen, 2017). One of these models is the EcoInvent database (EcoInvent, 2022). An advantage of using this database is that it consists not only of numeric values for material use within processes, but also contains background reports which hold valuable assumptions like assumed product composition and lifespan. Ecoinvent is therefore used within this research as the standard for gathering data about material composition, capacity, lifetime, and share per type. Since this research is about the global petroleum system and EcoInvent data is not designed to cover global material demands, the EcoInvent numbers are cross checked with other sources.

3.2.2 AMOUNT OF INFRASTRUCTURE AND MATERIAL COMPOSITION

To perform this dMFA analysis, the most important factors are the amount of infrastructure needed to fulfil the petroleum demand, and its corresponding material composition. Below, every stage is shortly discussed, presenting the data needs, the sources used to find this data, and the calculation method. Wherever necessary, the results are discussed based on alternative findings. A schematic overview of the most important findings is presented in section 3.4.1, and the material intensities per stage are shown in section 3.4.2, with additional details provided in Appendix A - D.

Extraction

The defining features of the extraction infrastructure needs are the total amount of extracted oil and the division between the two types of extraction. This data can be found in Table 3.1. For each of these extraction types, the yield of a single extraction facility and its material composition are needed. The material composition based on these numbers can be found in Figure 3.3.

For this study the total oil demand as provided by the IMAGE model (PBL, 2022) is used as the extracted oil figure, meaning that no losses are accounted for. The share of the onshore oil is set to be 70%, in accordance with the US Energy Information Administration (EIA, 2016), with offshore extraction being responsible for the remaining 30%. The EcoInvent database is used to find the data on a standard onshore oil field, as well as a standard offshore oil platform. The output and lifetime of these extraction methods are then used to determine the number of necessary installations.

For offshore extraction, the number of needed platforms turns out to be just over 1000 offshore oil platforms, according to data from two Ecoinvent reports (Faist Emmenegger et al., 2007; Jungbluth, 2007a). Comparing this to existing literature, this number seems to be low.

In their 2019 overview of environmental opportunities and challenges regarding offshore oil and gas structures, Sommer et al. illustrate the number of oil and gas platforms with a global map, showing 7,885 major installations. These numbers are derived from a 2006 paper by Parente et al. See Figure 3.2 below. Hamzah notes that there are "over 7,000 oil and gas installations/platforms" worldwide, where Ars and Rios more recently stated the number to be 12,000 (Ars & Rios, 2017; Hamzah, 2003). More than 2,600 installations are projected to stop being operational by 2040 according to Hem et al. (Hem et al., 2016). Some grey literature sources report much lower numbers, around 1,000 operational installations (StatInvestor, 2018) which is more in line with the findings in this research. Other sources report as little as 200 offshore oil rigs (Sönnichsen, 2022). On the other end of the scale, OpenStreetMap data lists over 50,000 offshore oil rigs (OpenStreetMap, 2022).

The difference between the number of platforms found based on the Ecoinvent database and the numbers from literature can be explained by the difference in platform size. Comparing the standard Ecoinvent platform to some of the largest platforms in the world, it is clear that this production value is on the high end of the spectrum, meaning that less platforms are needed to produce the same amount of petroleum. This is confirmed when considering the mass of the other platforms (see Appendix A for the full comparison). Since the low number of platforms is compensated for by high production numbers and high masses, the Ecoinvent platform is used within this study. However, it needs to be noted that smaller oil platforms might have different material intensities, meaning that they need different quantities of material for producing the same amount of oil.

For the onshore extraction, the number of oil fields based on the Ecoinvent reports is almost 12,000 (Jungbluth, 2007b, 2007c). LCA's on oil extraction consider only carbon and other GHG emissions and do not take material use or production capacity into account (Masnadi et al., 2018; Rahman et al., 2015; Sulistyawati et al., 2020). Grey literature sources report relatively low numbers for onshore as well as for offshore (Sönnichsen, 2022). However, the ratio between offshore and onshore rigs is similar to that found via Ecoinvent. Therefore, the Ecoinvent model has been used.

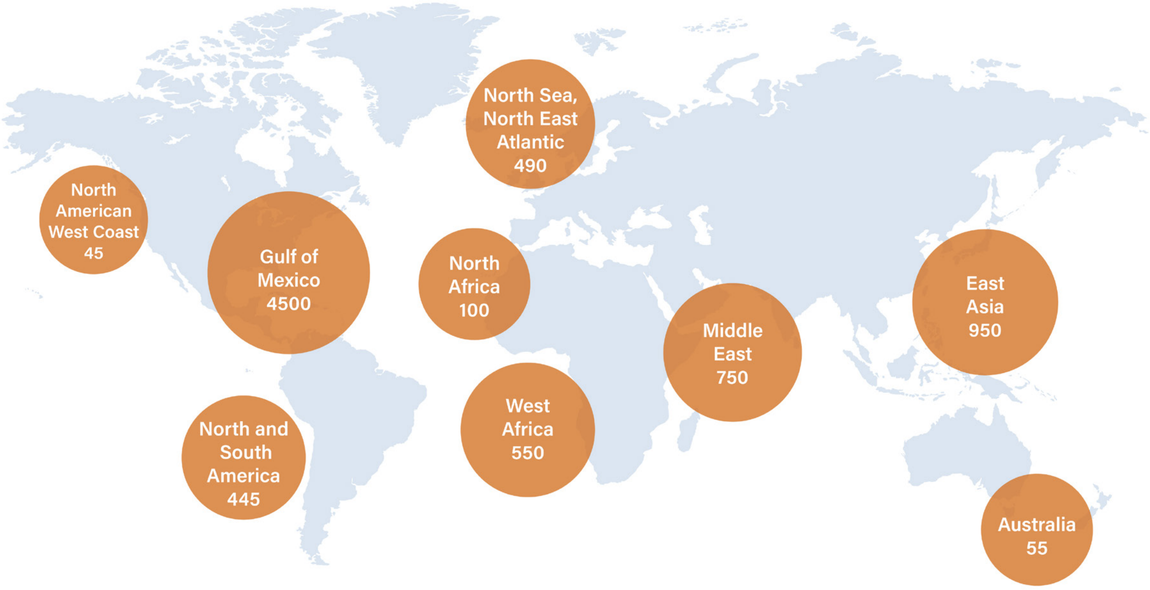


Figure 3.2 - Global overview of major oil and gas installations, numbers based on (Parente et al., 2006). Since then, numbers might have doubled (Ars & Rios, 2017)

The specific material composition for both onshore and offshore extraction, based on the annual production value per platform and oil field, can be found in SI1, sheet 3.1. These material compositions are based on work by Jungbluth (2007b, 2007e) Combined with the share of onshore and offshore platforms, this leads to the material composition as shown in figure 3.3.

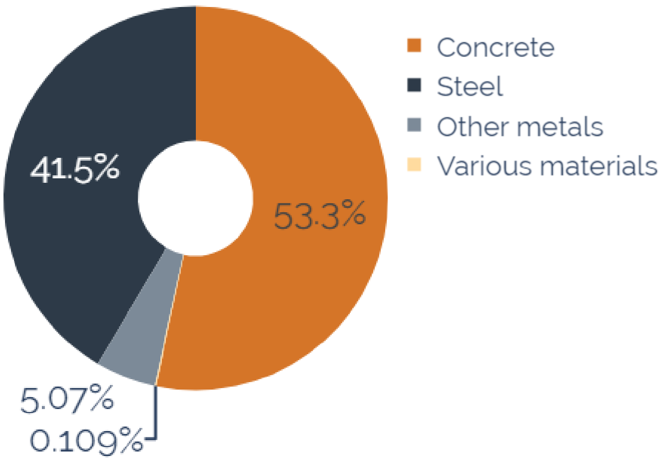


Figure 3.3 - The material composition of the oil extraction infrastructure, based on EIA (2016) shares and EcoInvent material compositions (Jungbluth, 2007b, 2007e)

Table 3.1 - Extraction figures and ratio between extraction types

stage	type	share	genenral information	
			parameter	value (2019)
extraction	onshore	70%[1]	total annual extraction	3.06e12 kg/year [2]
	offshore	30%[1]		1.31e12 kg/year [2]

[1] Data from EIA (2016)

[2] Share of type multiplied with the total oil use in 2019, total oil aggregated from IMAGE Model, unit conversion via IEA data (IEA, 2016; PBL, 2022)

Pipelines

For pipelines there are four defining characteristics. The first three are the total pipeline length, the share between the types of pipelines for onshore and offshore use, and the material composition of those types. However, the data on pipeline length is often divided differently. The division used mostly is that between pipelines used for crude oil and pipelines used for oil products. Therefore, the share between onshore and offshore is needed per type (crude and product) of pipeline.

To start with the latter, it is necessary to understand what offshore pipelines are used for. Offshore pipelines are categorised into infield pipelines for transporting fluids within an extraction field, export pipelines for bringing crude oil from the extraction field to the shore, and transmission pipelines for transporting crude oil and products between countries (National Ocean Industries Association, n.d.). Within this research, the material demand of infield pipelines is covered by the material needs of the extraction infrastructure. Furthermore, the transport of crude oil and its products between countries is assumed to be done only by onshore pipelines. That leaves only the export pipelines for transportation from oil fields to the shore.

To assume their share in the total pipeline length, first the share of offshore crude oil pipelines is assumed to be the same as the extraction share (EIA, 2016). This means that of the total crude pipelines 30% should be allocated to an offshore extraction facility. However, not all platforms are connected directly to shore with a pipeline. Oil fields further from the coast make use of a Floating (Production) Storage and Offloading vessel for their transportation needs (Muspratt, 2018). Therefore, it is assumed that 50% of the extraction sites are connected to the shore with a pipeline. Combining these assumptions leads to an overall estimation of 15% of the crude pipelines being offshore, and 85% onshore.

For the pipeline length, data from the CIA World Factbook (Central Intelligence Agency, 2021) is combined with other sources to compute the total pipeline length per country. This is then aggregated to match with the regions as they are specified in the IMAGE model outcomes. The numbers per region can be found in SI1, sheet 1.2. For the material composition for both onshore and offshore pipelines the Ecoinvent database was used (Jungbluth, 2007e). These material compositions are listed in SI1, sheet 3.2.

The overall pipeline length and the share between the different types can be found in Table 3.2. The corresponding material composition of the pipeline stage as a whole is presented in Figure 3.4.

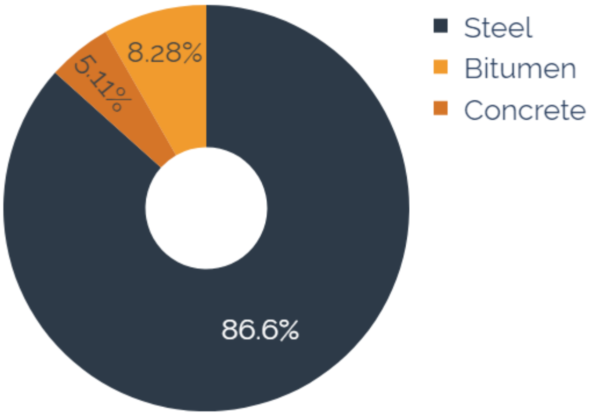


Figure 3.4 - The material composition of the oil pipeline infrastructure, based on regional data shares and EcoInvent material composition

Table 3.2 - Pipeline lengths and ratio between pipeline types

stage	type	share	geneneral information	
			parameter	value (2019)
pipelines	crude	59%[1, 2]	total pipe length	601 925 km[1, 3] 15% offshore, 85% onshore
	product	41%[1, 2]		411 212 km[1, 3, 4]

[1] Global aggregates, region specific in the model input

[2] Non-driving values, but derived from their respective general information values

[3] Aggregation of regional data. (Central Intelligence Agency, 2021; Natural Resources Canada, 2020; OECD, n.d.; United States. Department of Transportation. Bureau of Transportation Statistics, 2019)

[4] Aggregation or regional data. When not available, the share based on other regions is used for determining the product pipeline length.

Transport

Transporting oil products is done by different means. In this study, the transport focuses on four types of transport: ocean shipping, inland shipping, rail, and trucks. To quantify the material needs associated with transporting petroleum and its products, the following data is needed: the transport demand, and the share and the material composition for each type of transport.

To find the transport demand associated with the petroleum sector, the share for every type of transport is determined per product in Ecoinvent (2022). The included products are diesel (both low-sulphur and regular), heavy fuel oil, light fuel oil, kerosene, liquefied petroleum gas, lubricating oil, naphtha, and petroleum. Including all of these fuels ensures the whole petroleum sector is covered. The average share is derived from analysing different regions, namely Brazil, Switzerland, Colombia, India, Peru, South Africa, and Europe. The resulting values are reported in SI1, sheet 1.4, and the overall numbers can be found in Table 3.3.

The market share per transport type is then assumed to be a global average, and multiplied with the total amount of km of transport necessary for every kg of petroleum produced. To transform the transport data into material demands, two more steps are conducted. First, the transport data in tonne km (tkm) is multiplied by the vehicle intensity. This is necessary to compensate for the differences in vehicle size and load, and results in the total global mass of the specific transport type. Lastly, this total weight of the transport type is multiplied by its respective share per material. The values for the material intensity and material fraction are derived from EcoInvent and can be found in SI1, sheet 3.3 and 3.4 respectively. The overall material composition of the transport stage, based on the different stages and shares, can be found in figure 3.5.

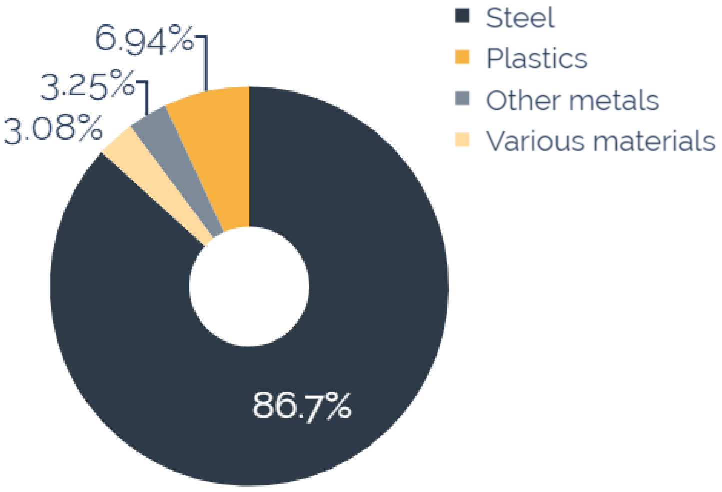


Figure 3.5 - The material composition of the oil transport stage, based on EcoInvent transport needs and material compositions

Table 3.3 - Annual transport figures and ratio between transport types

stage	type	share	geneneral information	
			parameter	value (2019)
transport	rail cargo	0.5% [1]	total annual transport	2.4e11 tkm/year [2]
	ocean ships	98.6% [1]		4.6e13 tkm/year [2]
	inland ships	0.3% [1]		1.6e11 tkm/year [2]
	trucks	0.6% [1]		2.7e11 tkm/year [2]

[1] Non-driving values, but derived from their respective general information values

[2] Transport needs per type multiplied with the total oil production. Transport needs are an aggregation of numbers from EcoInvent 3.8 Dataset Documentation on light fuel oil, heavy fuel oil, lubricating oil, diesel, petroleum, kerosene, and naphtha. Total oil use aggregated from IMAGE Model, unit conversion via IEA data. (EcoInvent, 2022; IEA, 2016; PBL, 2022; Wernet et al., 2016)

Storage

Storage infrastructure is characterised by three features: the total installed storage capacity, the share between crude and product storage, and the material composition of the storage facility. The total installed capacity is computed by checking official sources per country. For the countries where this was not available, the global average has been used to calculate the expected storage capacity, based on the countries respective oil consumption. The same method is used for the share between crude and product storage. The only reliable data found was that of South Korea (Vahn & Lee, 2021) and the USA (EIA, 2022).

Combining this with an assumed filling rate of 76% (Rystad Energy, 2020), this results in a global storage capacity of 5.805 billion barrels (BB) in 2019, see Table 3.4. Numbers per region can be found in SI1, sheet 1.3.

Comparing this to other data shows that this number could be an underestimation. According to Rystad Energy 7.2 billion barrels of oil storage was in use worldwide, of which 5.9 onshore, as of March 2020 (Rystad Energy, 2020). The same source reports a filling rate of around 76%. This results in a total estimation of 7.76 BB of onshore oil storage capacity.

Furthermore, a total global storage capacity of 5.8 BB and a filling rate of 76% would mean that on average, every region has a petroleum reserve for 56 days of their respective consumption. Importing member countries of the EIA have to fulfil the requirement of having at least 90 days of their consumption in storage. Applying this requirement globally would result in a storage capacity of over 9.1 BB. However, the current approach uses verified data, is region specific, and with more data on countries' storage capacity, the accuracy of the used estimation could be improved.

Table 3.4 - Total storage capacity and share between storage types

stage	type	share	geneneral information	
			parameter	value (2019)
storage	crude	61%[1, 2]	total storage capacity	3566 mb [1, 3]
	product	39%[1, 2]		2239 mb [1, 3]

[1] Global aggregates, region specific in the model input
[2] Non-driving values, but derived from their respective general information values
[3] Storage capacity based on regional data. When not available, the global oil use to storage ratio is used. Total oil use aggregated from IMAGE Model, unit conversion via IEA data (EIA, 2022; IEA, 2016; PBL, 2022; Vahn & Lee, 2021)

Storage is the only stage for which no EcoInvent documentation was found for the material composition. The LCA studies that include oil storage in their system do not account for its material usage (Shrivastava & Unnikrishnan, 2021). To overcome this, a standard oil tank has been modelled. The diameters of the tank are based on an analysis of existing oil storage facilities (Cooper, 1997; Kameshwar & Padgett, 2015). The material and construction method are derived from the corresponding standards from the American Petroleum Institute (API, 2011) See Appendix B for the dimensions and assumptions on this tank, and figure 3.6 for the material composition (or SI1, sheet 3.5). It is assumed that there is no specific difference between crude oil and petroleum products storage.

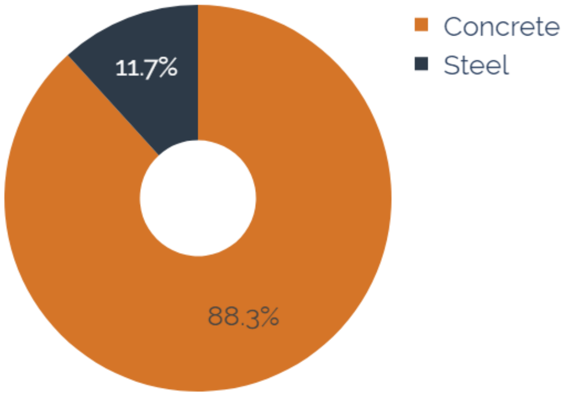


Figure 3.6 - The material composition of the oil storage infrastructure, based on existing oil infrastructure reports and API standards

Processing

To calculate the processing material demands the following numbers are needed: The total installed refinery capacity, and the material intensity of petroleum refining. The material intensity will be based on a standard refinery in terms of total refining capacity over its lifetime, and the materials needed for construction.

When analysing the global refinery system it is important to acknowledge the difference between the amount of processed oil, and the installed capacity. The latter is the most relevant for this research, since it most accurately reflects the material demand of the industry. According to data from the statistical report by BP (2020), the daily throughput is using just above 80% of the installed capacity, a number that has been constant for the last 30 years. See appendix B for an overview. Therefore, a capacity use of 80% is assumed in this research. It is assumed that all produced oil is refined, so for the data on refined oil the IMAGE number is used. See table 3.5.

For the material numbers, a definition on a general refinery is needed in terms of capacity and material use. Defining such a standard refinery is not an easy task for multiple reasons. First of all, many different types of petroleum refinery exist, optimised for different qualities of crude input as well as for a wide array of fuel products as output (Han et al., 2015). These differences make it notoriously difficult to analyse from a life cycle perspective, since every output needs to be allocated for (Bredeson et al., 2010; Han et al., 2015; Vineyard & Ingwersen, 2017). Even so, many life cycle analyses of fuel have been performed (An et al., 2011; Liu et al., 2020; Morales et al., 2015; Rahman et al., 2015; Restianti & Gheewala, 2012), and there are some examples of analysis on the refinery sector as well (Abella & Bergerson, 2012; Bredeson et al., 2010; Young et al., 2019)

What all of these studies have in common, is a focus on either GreenHouse Gas (GHG) emissions, or energy usage. This is justifiable since refining is accountable for the largest share of GHG emissions in the fuel production process, when disregarding the use phase, i.e. the combustion, of the fuel (Han et al., 2015).
However, the Ecoinvent database was the only database that currently has an overview of the material demands for a typical refinery (Jungbluth, 2007d). Therefore, the material composition and annual capacity per refinery are taken from the EcoInvent database (Jungbluth,

2007d). The final material composition of a standard refinery can be seen in figure 3.7.

To check whether the EcoInvent based refinery can be used as a generalisation, the resulting global number of refineries is calculated. Based on the assumptions mentioned above this number turns out to be 5410 refineries. Estimates from the fractracker alliance are around 536 in 2017, and based on information by the IEA and the EIA the number should be around 725 (IEA, 2020b; U.S. Energy Information Administration (EIA), 2022a). The large number of refineries needed according to the EcoInvent database is due to the relatively small throughput, when compared to other refinery installations (Jungbluth, 2007d; U.S. Energy Information Administration (EIA), 2022b). The trend of increased refinery size has been going on for decades (Chan, 2019). However, in terms of energy use and GHG emissions, more complex refineries are not necessarily more efficient than less complex ones (Han et al., 2015). For this study, it is assumed that this is also the case for material efficiency.

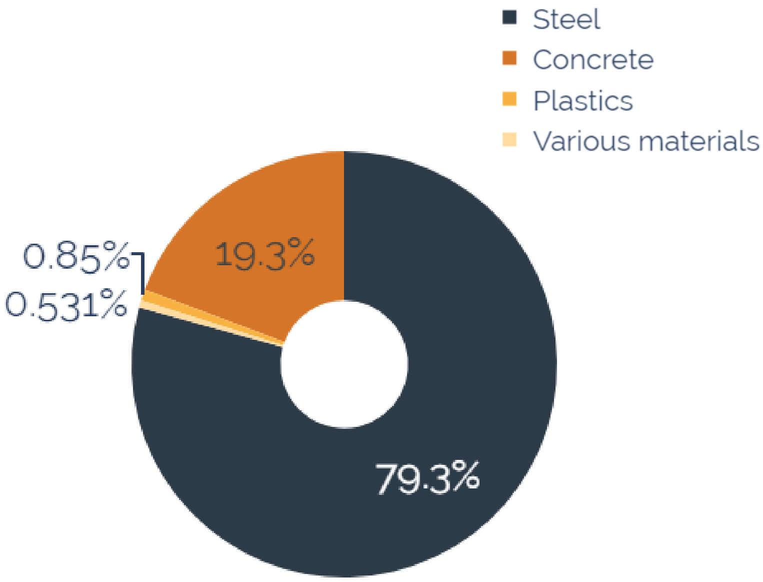


Figure 3.7 - The material composition of the oil refinery infrastructure, based on EcoInvent

Table 3.5 - Installed refinery capacity

stage	type	geneneral information	
		parameter	value (2019)
processing	refinery	used capacity	80% [1]
		total installed annual refining capacity	5.4621e12 kg/year [2]

[1] BP (2020)

[2] Total oil use divided by the utilised installed refining capacity. Refining capacity usage from BP, total oil use aggregated from IMAGE model, unit conversion via IEA data. (BP, 2020; IEA, 2016; PBL, 2022)

3.2.3 LIFETIMES AND DISTRIBUTION

For each of the stages and types, a mean lifetime is specified. These lifetimes can be found in Table 3.6, Appendix D (Table A.6), and SI1, sheet 4.

Extraction

For onshore extraction, the average is taken from the maximum and minimum lifetime, resulting in a lifetime of 30 years (Canadian Association of Petroleum Producers, 2022). For offshore extraction, the data from the EcoInvent background report and other reports has been used, averaging out to 22.5 years (Faist Emmenegger et al., 2007; Louise Davis, 2018; Zeldovich, 2019).

Pipelines

The lifetime from the Ecoinvent background report on pipeline construction (Jungbluth, 2007e) has been used for both types of pipelines, meaning both are assumed to have lifetimes of 50 years.

Transport

For transportation, lifetimes from the thesis of Deetman have been assumed in this model (Deetman, 2021). The lifetimes differ per type, ranging from 12 to 26.7 years for truck and ocean ships respectively. Both inland ships and rail cargo are assumed to have lifetimes of 26 years.

Storage

The report on safety guidelines for oil terminals from the United Nations Economic Commission for Europe lists lifetimes of 25 years for storage facilities (UNECE, 2015). This number has been used for both crude and product storage infrastructure.

Processing

For the processing stage, data from the same UNECE report have been averaged with an EcoInvent background report, as well as a report on the life cycle of different refinery components, resulting in a refinery lifetime of 25 years (Jungbluth, 2007d; Kozhemyatov & Bulauka, 2019; UNECE, 2015). All this data can be found in Table 3.6 and a total schematic overview of the calculation methods and sources can be found in Appenix D.

Table 3.6 - The lifetimes per stage and type

stage	type	lifetime (years)	source
extraction	onshore	30	Average from the minimum and maximum listed lifetimes (Canadian Association of Petroleum Producers, 2022)
	offshore	22.5	Average from EcoInvent background report and secondary sources (Faist Emmenegger et al., 2007; Louise Davis, 2018; Zeldovich, 2019)
pipelines	crude	50	Data from EcoInvent background report (Jungbluth, 2007e)
	product	50	
transport	rail cargo	26	Data from PhD Thesis on lifetime (Deetman, 2021)
	ocean ships	26.7	
	inland ships	26	
	road	12	
storage	crude	25	Data from UNECE report on safety guidelines for oil terminals (UNECE, 2015)
	product	25	
processing	refinery	25	Average from EcoInvent background report a nd secondary sources (Jungbluth, 2007d; Kozhemyatov & Bulauka, 2019; UNECE, 2015)

Lifetimes distribution

The lifetimes are modelled to have a folded normal distribution around the mean. In this research, this entails that the function shows the probability of the lifetime being a certain number, with the mean being the lifetime found above. Since lifetimes cannot be below 0, all values below zero are 'folded' over the y axis by taking their absolute value.

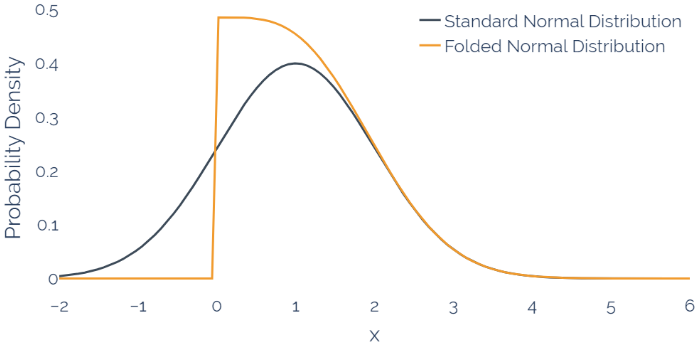


Figure 3.3 - A comparison between a folded normal distribution (in orange) and a normal distribution (in grey) , both with a mean (μ) of 1 and a standard distribution (σ) of 1

The distribution around the mean is based on a percentage of the lifetime itself, based on current literature. Smith et al. (2019) make use of 3 different lifetimes (30, 40 and 50 years) with a standard deviation of 6 years for each of these lifetimes in their analysis of the current fossil fuel industry. This means a standard deviation of 12 - 20% of the lifetime (Smith et al., 2019). When using a log-normal distribution, Davis et al. (2007), make use of a standard deviation of 20% of the lifetime in their dynamic material flow analysis for iron and steel (J. Davis et al., 2007). Accordingly, the standard deviation for the lifetime distribution in this study is modelled to be 20% of the mean lifetime.

3.2.4 END-OF-LIFE PARAMETERS: COLLECTION RATE & DECOMMISSIONING TIME

The outputs of a dMFA are the stocks, inflow, and outflow of any given material over time. In this research, the outflow is of special interest, since it quantifies the expected material available for recycling. However, not all the expected outflow can be easily recycled. To accommodate this fact, 3 parameters are introduced to the model, influencing the assessment of circularity. These are a collection rate, a recycling rate and finally a decommissioning time. The recycling rate is determined by the specific material, but the collection rate and time shift are depending on the stage of the petroleum production process. Therefore, these will be discussed below per stage and type. The collection rate quantifies how much of the original construction will be retrieved for recycling, in accordance with (Haupt et al., 2018; Wen et al., 2009) and the decommissioning time is the time between the infrastructure no longer being in operation and the materials being ready to be recycled.

To make the collection rate a dynamic variable, a linear interpolation method is used. This method requires 2 data points. Therefore, the collection rate in both 2019 (the baseyear) and 2050 (the last year of this research's analysis) are investigated. The collection rate and decommissioning time can be found in Table 3.7 and 3.8 respectively. They are also found in SI1, sheet 5 and 7. An overview of all the values, the assessment method and sources are presented in Appedix D.

The **collection rate** refers to the percentage of infrastructure that is recovered to be recycled after decommissioning

The **decommissioning time** refers to the time it takes for the infrastructure to be recovered, recycled, and the materials being ready for use again

Onshore infrastructure

To reuse, refurbish, or recycle infrastructural installations, first the installations have to be demolished and the materials retrieved. This demolition waste is often recovered, especially in developed countries. For example, the greater EU region had a Construction and Demolition Waste (CDW) recovery rate of around 90% in 2018 and 2020 (Eurostat, 2022).

This does not tell the whole story though, since this number ranged from 51% to 100% between member states. In the US the collection rate was around 76% for 2018 (US EPA, 2022). However, in China this number was less than 10% in 2017 (Hao et al., 2020), and in India in 2015 the number varied between 25% and 75% depending on the building (Ponnada & P, 2015). These numbers are dealing with the general CDW. Retrieving petroleum infrastructure comes with a whole set of additional difficulties, which differ per stage and type (Frontier Industrial Corporation, 2018). Data on the collection rate for any specific stage is hard to come by.

Therefore, the following assumptions are made for all onshore infrastructure excluding pipelines, meaning storage, processing, and onshore extraction. The collection rate in 2018 is assumed to be 56.25%, the average of the recovery rates found for the EU, US, India and China. For these stages, the collection rate for 2050 will be assumed to be 90%, the recovery rate of the greater EU region in 2018 as listed by Eurostat (2022).

A time period of 2 years was found to be necessary for storage terminal decommissioning (Duff, 2022), whereas refinery decommissioning ranged from 5 to 8 years (Geipel-Kern & Noé, 2017; Reuters, 2019). Therefore, 2 years is assumed for the storage decommissioning time, and 6 years for processing.
The decommissioning process of onshore extraction infrastructure was found to be 'multiple years', with the physical activity lasting 'several months' (Nexstep, 2017). For this study, 2 years is therefore assumed.

Offshore extraction

When offshore oil rigs are decommissioned, there are multiple ways of dealing with the remaining infrastructure, including demolition and recycling, CO2 capturing facilities, hotels, reef building projects, and simply leaving them in place (Sommer et al., 2019). Issues regarding the retrieval of these platforms are not only financial, but also environmental (Rowe, 2022; Sommer et al., 2019). The plugging of wells can lead to oil spills (Rowe, 2022), and the newly established ecosystem around the rigs can be heavily impacted by recycling operations (Lusseau et al., 2016). This is contested though, since leaving these rigs in place is not necessarily good for the biosphere, even if they increase local biodiversity (Bliss, 2022). There are technical considerations too, especially considering older rigs which are not designed to be dismantled or recycled (Bliss, 2022; Rowe, 2022). However, when rigs are taken to shore, a high recycling rate can be achieved (Getech Group plc, 2021; Veolia Planet, 2017).

To get a potential collection rate, the North Sea and specifically the UK is looked into, since the industry monetary spending on decommissioning practices is expected to increase there (Journal of Petroleum Technology, 2020). In the UK, 125 topside platforms and over 200 subsea structures are projected to be removed over the coming decade (Journal of Petroleum Technology, 2020; OGUK, 2021). In total, about 600 platforms need to be decommissioned in the North Sea over that time period (Zeldovich, 2019). The UK is responsible for 69% of all North Sea oil platforms (OGUK, 2021), meaning that its total number of decommissioned platforms will be 414. With 125 planned to be removed, the collection rate is around 30%. This will be the collection rate used for both 2019 and 2050, since no proper projections later than 2030 could be found on this matter.

The total time for decommissioning a single offshore oil platform can be up to 9 years (Sommer et al., 2019), where the physical offshore activity can last up to 3 years (Boon, 2021). Other sources report 8 months for the removal of a platform from sea after production was stopped (Kulovic, 2022) and up to 7 years for the total decommissioning process (Bliss, 2022). The total time from the decommissioning process being awarded to the platform reaching land was more than 18 months (Kulovic, 2022). Over 2 years is needed for the total dismantling of a platform (Getech Group plc, 2021). Based on these numbers, a decommissioning time of 5 years for offshore platforms from stopping production to recycled materials is assumed.

Pipelines

Decommissioned, dormant, and abandoned pipelines are either left in place (in situ) or are excavated and recycled (Di Lullo et al., 2020). For LCA's this results in the choice between a high value, modelling all pipelines to be removed (Di Lullo et al., 2020), a medium value, using a general recycling rate (Xu et al., 2022), and not including the end-of-life at all (Strogen & Horvath, 2013).

In reality oil pipelines are most often left in place, sometimes with detrimental consequences (Calma, 2020; Douglass, 2014). This is especially true for underground and offshore pipelines (Wheeling, 2021), as pipeline retrieval is almost exclusively performed on above-ground pipelines, since these pipelines can be refurbished and/or reused (NiGen, 2021). Therefore, in this study the approach for 2019 will be the 0% following Strogen & Horvaths approach, and for 2050 Xu et al. (2022) will be followed, using a 40% collection rate.

Offshore pipelines are mostly left in situ, meaning that they are plugged to prohibit contamination and then left on or below the seafloor. Although UK guidelines now state that operators should actively remove decommissioned pipelines, other countries often leave the pipelines in place (Rouse et al., 2018). Moreover, burial of the pipelines and the lack of existing technology to remove larger pipelines are reasons to leave the pipelines in place. (Rouse et al., 2018). Therefore, the assumption is made that no offshore pipelines are recovered, meaning a collection rate of 0% in 2019. The UK Oil and Gas Association expects that over the coming decade the decommissioning and removal of subsea structures will steadily increase. Still, the expectation is that only 349 km of pipeline will be removed towards 2030, whereas 18 458 km will be decommissioned (OGUK, 2021). That is a collection rate of just over 2%, which will be used as the 2050 value for this research.

Since the types of pipeline are divided into product and crude, the data found above needs to be combined with their respective share of onshore and offshore pipelines. For product pipelines, the onshore numbers can be used, meaning a 0% collection rate in 2019 and a 40% in 2050. The share for crude oil is 15% offshore pipeline and 85% onshore, leading to a collection rate of 0% in 2019 and 34% in 2050.

The decommissioning time of offshore pipelines is assumed to be 5 years, based on the numbers of the Brent Pipeline Decommissioning Report (Shell U.K., 2020). Those for onshore pipelines are assumed to be 3 years, based on a 2014 report of the removal of an oil pipeline (Fisher, 2014). This process started with a 2010 plan, and operations finished in November 2013. With these numbers, the time it takes for crude and product pipelines to be recycled are 4 and 3 years respectively.

Transport

Within the transport stage, the collection rates differ per type. All the types are briefly discussed below.

Rail rolling stock is generally well suited for recycling (Belov et al., 2022). In their comprehensive overview, Silva and Kaewunruen (2017) list the recycling rates of independent components per train type. Petroleum transport per rail is done by freight trains, of which the recycling rate is listed to be 90-98% (Silva & Kaewunruen, 2017). The average (94%) is used for the collection rate for rail cargo in 2019. For 2050, the high end value (98%) is used, since the recycling and recyclability of trains is of increasing importance for the industry (Andriès, 2016; Belov et al., 2022). The time it takes for rail is assumed to be similar to decommission other heavy vehicles, which is documented to be less than a year in a paper on dismantling, remanufacturing and recovering of these vehicles (Saidani et al., 2020). This is confirmed by reports on actual train recycling (Barker, 2021; van der Bogaard, 2019).

For trucks, the well documented vehicle recycling rate is used for the calculations. In Europe, this rate was 95% in 2019 (Eurostat, 2021) whereas in China and Japan this was 90% and 98% respectively (Wang et al., 2021).

Table 3.7 - The collection rate in 2019 and 2050, per stage and type

stage	type	collection rate		source	
		2019	2050	2019	2050
extraction	onshore	56.25%	90%	average CDW recovery for Europe, China, India, and USA (Eurostat, 2022; Hao et al., 2020; Ponnada & P, 2015; US EPA, 2022)	average CDW recovery for the greater EU region in 2018 (Eurostat, 2022)
	offshore	30%	30%	UK projected recovery for 2020-2030 (OGUK, 2021; Zeldovich, 2019)	assumed not to change
pipelines	crude	0%	34%	based on low-end LCA end-of-life option. (Strogen & Horvath, 2013)	offshore pipeline recycling from OGUK 2030 forecasts, onshore based on LCA end-of-life option. (OGUK, 2021; Xu et al., 2022)
	product	0%	40%		Based on LCA end-of-life option. (Xu et al., 2022)
transport	rail cargo	95%	98%	average recycling rate for freight train components (Silva & Kaewunruen, 2017)	high end recycling rate for freight train components (Silva & Kaewunruen, 2017)
	ocean ships	93%	93%	scrapped ships compared to lost ships in 2019 (Allianz, 2020; NGO Shipbreaking Platform, 2020; Norwegian Maritime Authority, 2021; Vessels Value, 2022)	assumed not to change
	inland ships	93%	93%		
	trucks	90%	95%	average vehicle recycling rate for Europe, US, and China (Adams, 2020; Eurostat, 2021; Wang et al., 2021)	average vehicle recycling rate of the greater EU region in 2019 (Eurostat, 2021)
storage	crude	56.25%	90%	Average CDW recovery for Europe, China, India, and USA (Eurostat, 2022; Hao et al., 2020; Ponnada & P, 2015; US EPA, 2022)	average CDW recovery for the greater EU region in 2018 (Eurostat, 2022)
	product				
processing	refinery	56.25%	90%	Average CDW recovery for Europe, China, India, and USA (Eurostat, 2022; Hao et al., 2020; Ponnada & P, 2015; US EPA, 2022)	average CDW recovery for the greater EU region in 2018 (Eurostat, 2022)

In the US, this number is around 85%, based on numbers from the Automobile Recycling Association (Adams, 2020). For the global 2019 number, the average of the rates of the EU, US, and China has been used. For the 2050 number, the 2019 EU rate is assumed to be the global average. The decommissioning time of trucks is assumed to be similar to that of other heavy vehicles, which is documented to be less than a year (Saidani et al., 2020).

The collection rate for ships is generally regarded as high (Norwegian Maritime Authority, 2021). Since shipbreaking, the dismantling and scrapping of end-of-life vessels, often occurs under conditions causing harm to both worker safety and environmental harm, it is getting more attention (Directorate-General for Environment, 2020). Still, there is no number for the exact percentage of ships that are scrapped rather than abandoned. To accommodate for this, the amount of scrapped ships is compared to the number of lost ships, assuming that all end-of-life vessels that are not lost, are scrapped. The first number is assumed to be 600, averaging numbers from different sources (NGO Shipbreaking Platform, 2020; Norwegian Maritime Authority, 2021; Vessels Value, 2022). The number of lost ships is 41, retrieved from the 2020 Allianz Safety and Shipping Review (Allianz, 2020). This gives a total collection rate in 2019 of 93%. It is assumed that this does not change towards 2050. It is also assumed that the collection rate for inland shipping is the same as for ocean shipping.
Multiple sources quote a dismantling time from a few months up to a year Gwin Wrinkler (Gomersall, 2019; Gwin, 2014; Wrinkler, 2008). Based on this, the model assumes that the materials coming from shipbreaking enter the market the same year, meaning that there is no delay, or a decommissioning time of 0 years.

Table 3.8 - The decommissioning time per stage and type

stage	type	decommissioning time (years)	source
extraction	onshore	2	based on information from Nexstep (Nexstep, 2017)
	offshore	5	aggregation of time from decommissioning to scrapyard and dismantling the platform, averaged with a total decommissioning time (Boon, 2021; Getech Group plc, 2021; Kulovic, 2022,S ommer et al., 2019)
pipelines	crude	3	offshore timeshift based on Shell report, onshore based on decommissioning report (Fisher, 2014; Shell U.K., 2020)
	product	4	based on decommissioning report (Fisher, 2014)
transport	rail cargo	0	based on study on heavy vehicle recycling and industry news reports (Barker, 2021; Saidani et al., 2020; van der Bogaard, 2019)
	ocean ships inland ships	0	based on data from multiple sources (Gomersall, 2019; Gwin, 2014; Wrinkler, 2008)
	trucks	0	based on study on heavy vehicle recycling (Saidani et al., 2020)
storage	crude & product	2	based on news report on oil storage terminal decommissioning. (Duff, 2022)
processing	refinery	5	Rounded down average of news reports on refinery decommissioning and demolition (Geipel-Kern & Noé, 2017; Reuters, 2019)

3.3 DATA NEEDS PER MATERIAL

Some of the parameters within the model are not depending on the stage, but are linked to a material. Since some materials are grouped together, some generalisations have been made.

3.3.1 RECYCLING RATE & DENSITY

Unlike the data needs per stage, the data needs for every material are almost the same for every material. Since for some materials the demands are listed as a volume rather than a mass, a conversion is necessary. Therefore, for those materials (notably concrete) a density is needed.

Recycling rates

The most important data needs per material are the recycling rates. Some of the materials can be recycled once the decommissioned infrastructure has been recovered, but the difference between materials is significant. It is important to note that the recycling rates are not dynamically modelled. The value found for 2020 will be used for the entire timeframe of the model, even though this is not always the case.

Steel is the best recyclable material, with recycling rates of 85-90% being achieved (Bratkovich et al., 2015). For other metals, the United Nations Environment Programme estimates that only 18 metals have recycling rates of over 50% (United Nations Environment Programme, 2011). These include non-construction metals such as platinum and gold. According to the IEA, more commonly used metals such as copper, aluminium, and zinc have recycling rates of 46, 42, and 33% respectively (IEA, 2022b).

Even fully recyclable materials can not always simply be recycled into new materials. For example, concrete can achieve high recycling rates, up to over 90% (Jin & Chen, 2019; Tam, 2009). However, this recycled concrete can only be used as aggregate, making up around 80% of new concrete at most (Seegebrecht, n.d.) Although replacing this fully with recycled material is possible, and using recycled content has financial benefits (Wijayasundara et al., 2018), the share of recycled content is often low, ranging from 5% in the U.S. to 20% in the Netherlands (Jin & Chen, 2019).

For assessing circularity, both the recycling rate and the possible share of recycled content need to be combined. Therefore, this research assumes a combined concrete recycling rate of 12.6%, based on 90% end-of-life recycling, an aggregate use of 70%, 20% of which consists of recycled content. This 20% content can be considered high (Jin & Chen, 2019), this assumption is made to show the circularity potential based on the currently highest achievable level. It is important to know that

Table 3.9 - Recycling rates per material

material	recycling rate	source
steel	85%	Bratkovich et al., 2015
concrete	12.6%	Jin & Chen, 2019; Seegebrecht, n.d.
bitumen	80%	Chomicz-Kowalska & Maciejewski, 2020
aluminium	42%	IEA, 2022b
zinc	32.8%	IEA, 2022b
copper	45.5%	IEA, 2022b
plastics	8.7%	US EPA, 2017

this is a best case scenario based on current practices (GCCA, 2023), and that the global practices generally do not come close to that number. Moreover, the majority of recycled concrete is not used as an aggregate for new concrete, but rather in roadway, pavement, or other bulk applications (Grand View Research, 2020).

For bitumen, the recycling rate was found to be 80% (Chomicz-Kowalska & Maciejewski, 2020), For plastics, the number found by the US EPA was used, being 8.7%.

The recycling rates and their sources can be found in Table 3.9, and SI1 sheet 6. The materials for which a recycling rate is known are the bulk of the materials used in the petroleum industry. Since no information was found the model assumes a recycling rate of 0% for any other material.

Densities

Within this research, the density of steel and concrete are used. The concrete density is expecially important since Ecoinvent usually lists the concrete figures in m^3. The densities of these materials can be found in Table 3.10 and SI1, sheet 0.

Table 3.10 - Densities of steel and concrete.

material	density	source
steel	7900 kg/m^3	BuildingClub, n.d.; Civil's Guide, 2021a
concrete	2400 kg/m^3	Civil's Guide, 2021b; Engineering Toolbox, 2004

3.3.2 MATERIAL SPECIFICITY

Data from the EcoInvent database is often very specific in its material use. This is a necessity for performing proper Life Cycle Analyses.However, for the purposes of this research, this specificity is unnecessary, since this study focuses on more general material streams. Therefore, when different types of the same material are listed, these are all added together. For example, steel alloys or steel produced with a specific production method are all grouped together under 'Steel'. This combining of different materials from EcoInvent takes place before the data is used within the model.

Material groups

Not only is the material data For this reason, some materials are grouped together, whereas others are not included in the analysis.

Since this research aims to compile an image of the future infrastructural demands and possible yields of the petroleum industry, only materials used in the construction of the infrastructure and fit for recycling are taken into account. These materials are steel, concrete, and bitumen.

Other metals, such as aluminium, zinc, and copper, are grouped into the "other metals" category. Similarly, all plastics are categorised under "plastics". Lastly, any other construction material is listed under "various materials". This includes, among others, glass, wood, and rubber.

The aim of this grouping is to get a clearer overview of the largest material groups. However, these materials are only grouped within the model after the dynamic material stock calculations have been performed. This ensures that the results for any specific material still are available. Hereafter, when 'materials' are mentioned, this refers to these grouped materials.

Sand

One notable construction material that has been excluded from the material flows is sand. Sand is especially used a lot in the construction of pipelines, where it is used as levelling, stabilising bedding material, as well as backfill after the underground pipes are laid (Kouretzis et al., 2013). Although important for the construction, it is excluded from this research since it is not suitable for material reclamation when the infrastructure becomes obsolete.

3.4 MATERIAL INTENSITY

As explained in Section 3.1, the found data on material composition per stage can be combined with their respective production value to find the material intensity per stage. These material intensities can be calculated per stage, as well as for the petroleum industry as a whole.

This parameter shows the amount of material needed for a certain amount of output. In the case of this research, it shows the amount of construction material (in Mt) needed to fulfil an energy demand (in EJ). The material intensities for the baseyear 2019 can be found in Table 3.11. These values are grouped according to the groups described in Section 3.3.2.

Table 3.11 - Material intensities per stage

stage	steel	concrete	bitumen	other metals	plastics	various materials
extraction	0.02	0.02	0	0.002	0	0
pipelines	0.92	0.05	0.09	0	0	0
transport	0.07	0	0	0.003	0.006	0.002
storage	0.12	0.87	0	0	0	0
processing	0.13	0.33	0	0	0.001	0.001
total[1]	1.25	0.98	0.09	0.005	0.007	0.003

[1] Total aggregates might not add up to the sum of the column due to rounding

4. RESULTS

In this chapter, the results of the dMFA will be elaborated on. Firstly, the current stocks on which the model depends will be discussed, before the developments of the stock, inflow, and outflow over time will be looked into. Lastly, taking the recyclability for steel into account, the resulting possibilities for recycling will be shown and discussed.

4.1 CURRENT STOCKS

As discussed in Chapter 2, the first step in the analysis is to calculate the stocks currently in place to facilitate every stage in the petroleum production process. These stocks rely on the amount of necessary infrastructure, as well as on the material demands of this infrastructure. The total amount of stock in mass for 2019 is 423 megaton. This is comparable to the total annual construction material consumption of Africa (Huang et al., 2020)

With the total stock and its composition known, it is possible to gain some insights into the driving forces of material use within the oil industry, and into the materials that are currently embedded in the petroleum industry.

4.1.1 STAGES

To start with the driving forces, Figure 4.1 shows the stages and their respective contribution to the petroleum industries total stock. The results clearly indicate that pipelines and storage facilities are the main driving forces for infrastructural material use, followed by processing, other modes of transport, and extraction. This means that improvements in those stages can have the largest influence for the system as a whole.

When looking specifically into the material demands regarding the transportation of petroleum and its products, it is interesting to see that pipelines are responsible for more than 10 times as much material use compared to all the other forms of transport combined. Considering the length of the global pipeline this is to be expected. However, given the fact that pipelines are generally considered to be the best option for transporting oil, the high impact in material use is striking, especially since their collection rate is comparatively low.

Another remarkable result is the relatively small material impact of the extraction stage, which contributes around 2% of the total material stock. This might be due to the small number of oil platforms in the current model, as discussed in section 3.2.2. A more in-depth discussion on the used data will be reserved for section 5.3.

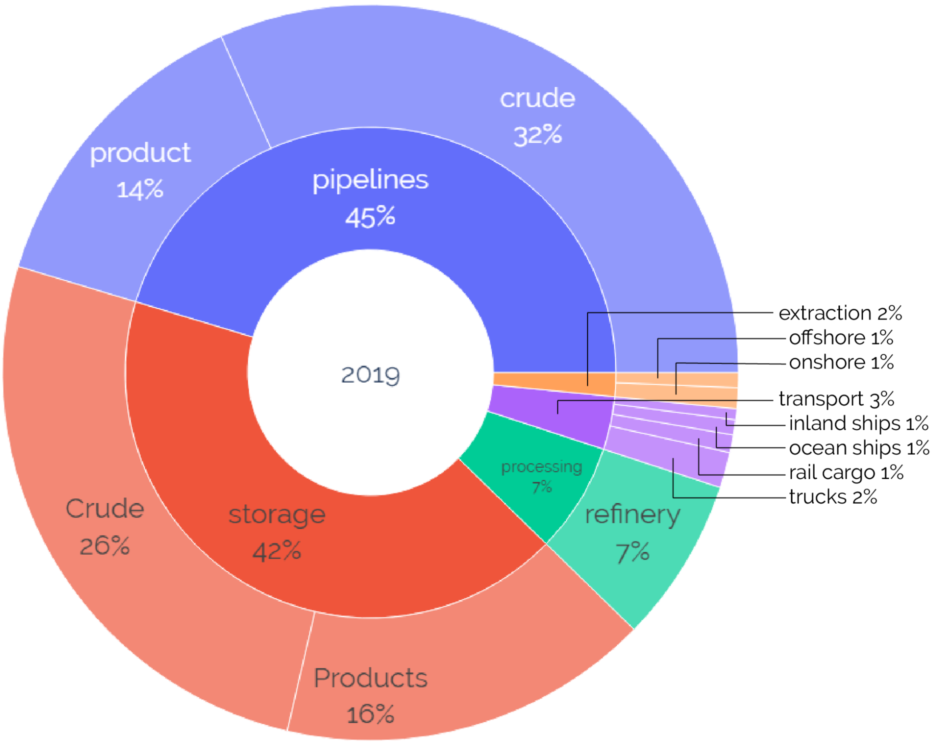


Figure 4.1 - The total 2019 stock in the petroleum industry, divided by stage and type.
Note: percentages might not add up to 100% due to rounding.

4.1.1 MATERIAL

Another important metric to analyse is the material composition of the current stock. In Figure 4.2, this composition is shown.

Steel is the most used material by mass with almost 54%, closely followed by concrete (42%). Bitumen is the third largest material group (4%), with the other materials having only a marginally small share of under 0.5%.

The material composition of the two stages contributing the most, pipelines and storage, has a large influence on the outcomes of the material composition of the whole sector. This explains the relatively large amount of concrete in the total material composition, which is due to the high share of concrete in the storage material intensity, seen in Figure 3.3d.

Another remarkable result is that bitumen is the third largest material, even though it is only used by one stage. This can be explained by pipelines having the largest share of material use, but the fact that all the plastics, all the non steel metals, and all the various materials combined do not even come close is notable.

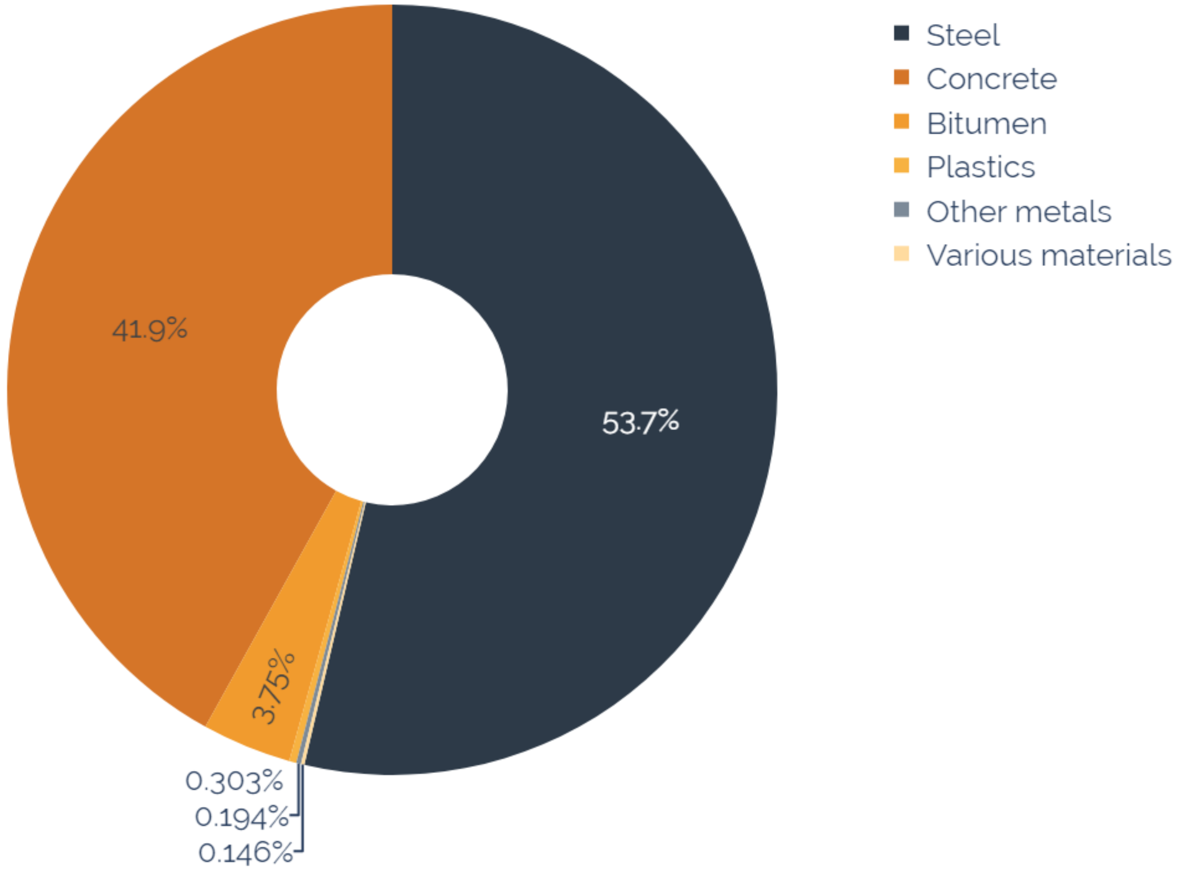


Figure 4.2 - The total 2019 stock in the petroleum industry, divided per material. Note: percentages might not add up to 100% due to rounding.

4.2 DEVELOPMENTS OVER TIME

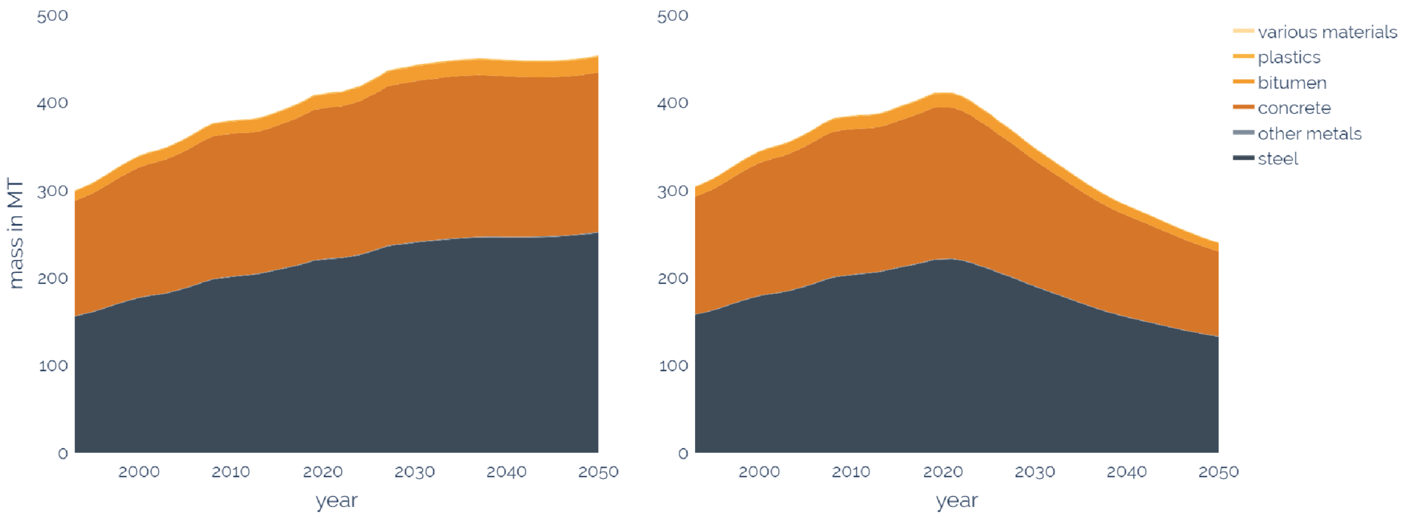
With the material use modelled for a given year with a given oil demand, it is now possible to model the necessary stocks over time. The resulting material stock over time then allows for the calculation of the expected outflow, based on the expected lifetime distribution of the different infrastructure. The development over time for stock, inflow, and outflow can be seen are discussed below.

4.2.1 STOCKS

Since the model uses a stock-driven approach, the first analysis will be done on the stock development over time (see Figure 4.1). When comparing the 1.5-degree scenario to the baseline scenario, it immediately becomes clear that the decrease in oil demand in the 1.5-degree scenario has the expected consequence: a steady drop in the embedded material stocks, where the baseline scenario shows the stocks steadily increasing before flattening off.

To assess the differences between the scenarios, the total embedded stock of 2050 is compared to 2019, the baseyear of the analysis. In both scenarios, the 2019 stock is 421 Mt. For 2050, the total embedded stock in the baseline scenario adds up to 458 Mt, an increase of 9% over 2019. In the 1.5-degree scenario, the total material stock is 234 Mt, a decrease of 44%.

Additionally, the difference between the total embedded stock in 2050 is looked into for both scenarios, which is useful to compare the stock developments with those of the material inflow and outflow. This will be done by calculating the reduction that the 1.5-degree scenario shows over the baseline scenario by 2050. In the case of embedded stock, this is a reduction of 49%.



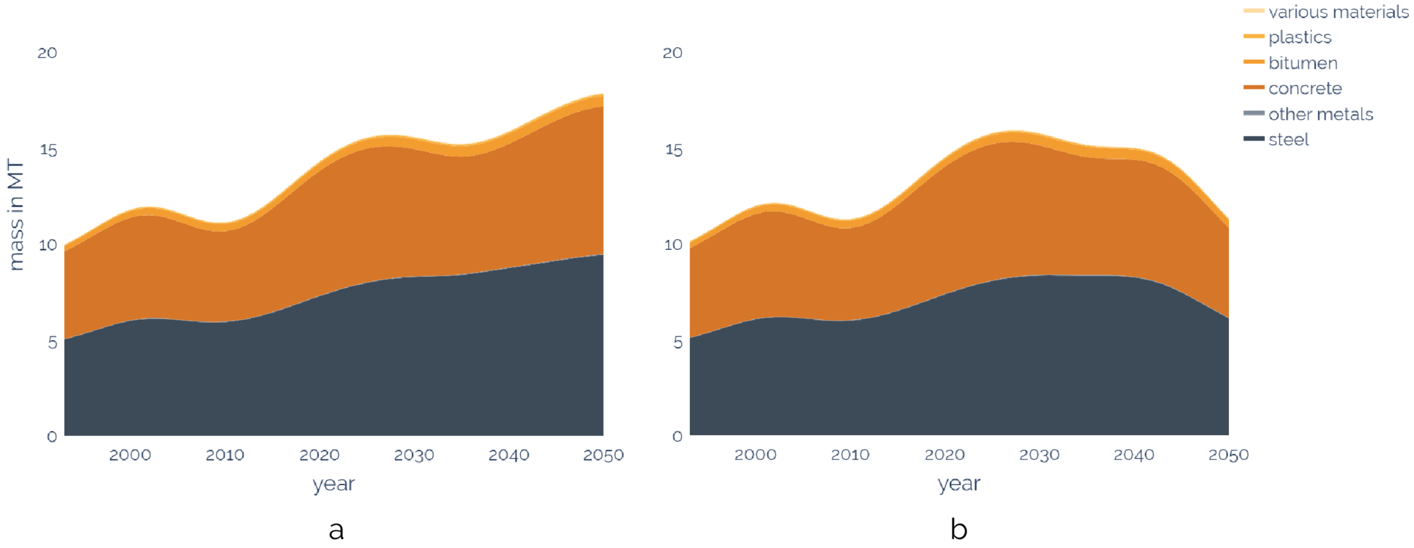
a b

Figure 4.3 - The development of embedded material stock in the petroleum sector in the baseline (a) and the 1.5-degree scenario (b). Values are computed over a 5-year rolling average.

4.2.2 OUTFLOW

The developments in material outflow reflect those of the stock, with the material outflow steadily increasing in the baseline scenario, and a decrease showing in the 1.5-degree scenario. Contrary to the stock, this decrease in the 1.5-degree scenario only occurs after 2040. This time delay occurs because the outflow of materials is depending on the in place stock and the lifetime of the infrastructure. Since the model allows for surplus stock to stay in place, all installed infrastructure will stay in the system for its total distributed lifetime, and will not enter the outflow before. This effect can be best seen when comparing the 1.5-degree scenarios outflow (Figure 4.4b) with its stock developments (Figure 4.3b). The drop in the outflow follows approximately 15 to 20 years after the peak in in-place-stock.

The relatively small influence the decline in oil demand has on the material outflow, can be observed when comparing the total aggregated outflow from 2019 towards 2050 in both scenarios. Contrary to stock, which shows an embedded amount of material, the inflow and outflow can be aggregated per year, better illustrating the differences between the scenarios over periods of time. In the baseline scenario, the total outflow adds up to 497 Mt, whereas in the 1.5-degree scenario, the outflow over the same time period is 454 Mt. This means that over time, the outflow reduction of the 1.5-degree scenario over the baseline scenario is 9%. Comparing this to the reduction in stock of 49%, shows the limited influence of the stock developments on the outflow.



a

b

Figure 4.4 - The development of material outflow from the petroleum sector in the baseline (a) and the 1.5-degree scenario (b). Values are computed over a 5-year rolling average.

4.2.3 INFLOW

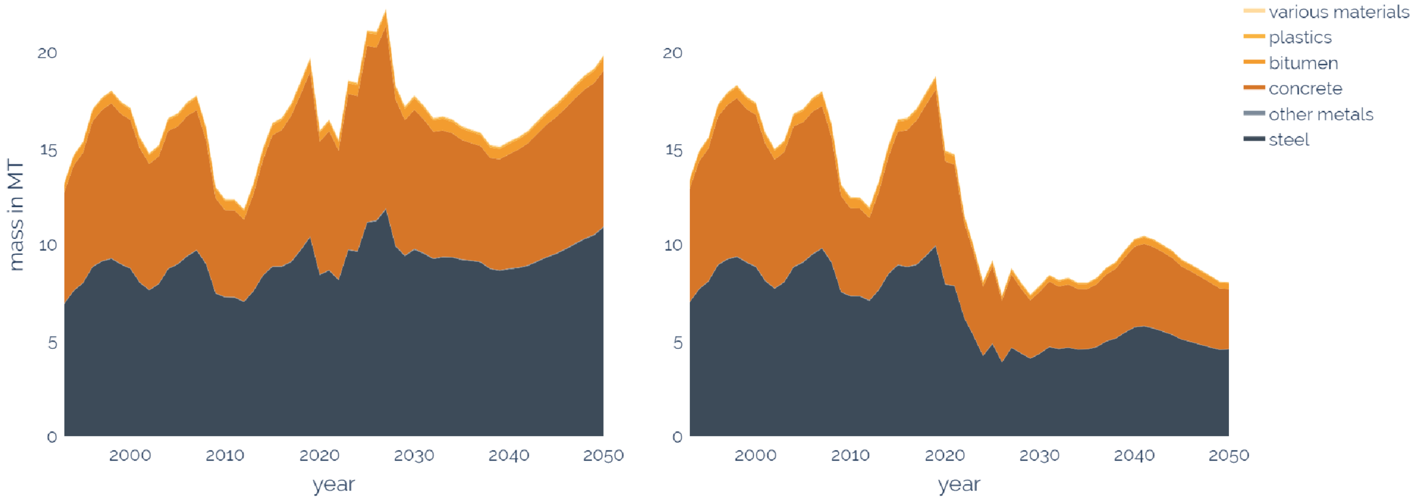
The difference between the two scenarios becomes apparent when looking into the inflow necessary for the petroleum infrastructure to fulfil demands (see Figure 4.5). The inflow graphs are highly oscillating, which can be explained by the stock driven approach and surplus stock being allowed. See section 2.2.1 for an in depth explanation, but in short: the material stock is mainly depending on the oil demand, and the outflow is depending on the stock and lifetime. Given this approach, the material inflow value compensates for the differences that exist between the old stock and the new. These differences can differ greatly per year, resulting in oscillating inflow graphs, compared to the material outflow and stock. However, when looking at the general development of the inflow in both scenarios, differences and behaviours can be identified.

Contrary to the outflow, the inflow has no delay in its reaction to material stock and petroleum demand developments, as whenever the stock is sufficient to fulfil petroleum demands, no new material inflow is necessary. Allowing for surplus stock enhances this behaviour, since dormant stock can compensate for some of the material outflow.

For the baseline scenario, this results in an overall increasing level of inflow to enable the increasing stock needs. On the other hand, the 1.5-degree scenario shows a steep decrease in the necessary inflow, immediately when the stock starts to drop. When the necessary stock (see Figure 4.3b) decreases, no inflow is necessary to grow the system, and surplus stock will be available to provide the necessary renewal of older infrastructure. This causes the inflow to steeply decrease in the years 2020 - 2025, and remain low for the decade afterwards.

Then, between 2035 and 2040, even though the stock is still in constant decline, the inflow is increasing again with a peak around 2040. This can be explained by the end-of-life renewal. The material outflow at that point is very high, due to the bulk of the 2020 stock peak reaching the end of its lifetime. This means that the total stock declines very rapidly. However, the necessary stock does not decline as fast, meaning that new inflow still is necessary, even though the total demand is decreasing.

The difference between the material inflow in the two scenarios is illustrated by the fact that the total aggregated inflow from 2019 to 2050 is 539 Mt for the baseline scenario, whereas it is 276 Mt for the 1.5-degree scenario. Therefore, the material demand reduction the 1.5-degree scenario offers is 48%. This is in line with the difference between the two scenarios in embedded stock over the same time period, which was calculated to be 49%.



a b

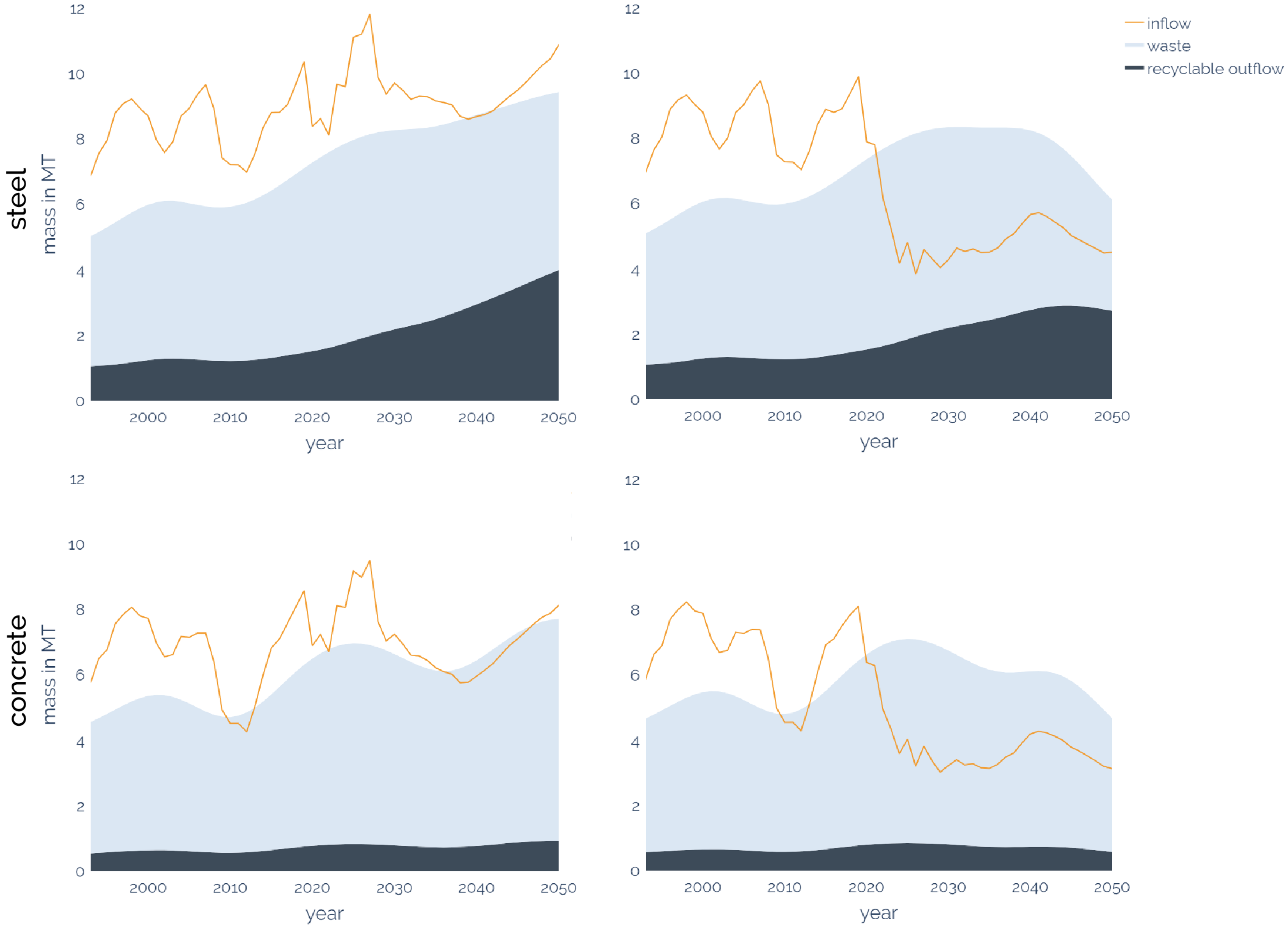
Figure 4.5 - The development of material inflow into the petroleum sector in the baseline (a) and the 1.5-degree scenario (b). Values are computed over a 5-year rolling average.

4.3 POSSIBILITIES FOR CIRCULARITY

When comparing the inflow and outflow, it is tempting to simply check where the outflow is greater than the inflow, and mark those areas as possibilities for full circularity. And although this ratio is a usable metric for circularity, it does not take into consideration the collection rate of the infrastructure, the recycling rate of the materials, nor the time delay between the decommissioning of the infrastructure and the materials entering the market again. These parameters and their modelling are discussed in more detail in Chapter 3. A full list can be found in Table 3.1 and SI1.

This analysis shows that steel is the most used material in the oil industry by mass, followed by concrete, together making up more than 95% of the total mass. Therefore, these are the two selected materials to analyse the possibilities for circularity in the petroleum industry. The other material groups' circularity assessment can be found in Appendix E.

In figure 4.6 the inflow (orange line) is depicted over the outflow, with the outflow being separated into *recyclable outflow* (in dark blue) and *wasted outflow*, (in light blue). For circularity to be possible, the recyclable outflow needs to be greater than the needed inflow.



baseline scenario

1.5-degree scenario

Figure 4.6 - The recycling potential of steel and concrete in the baseline and the 1.5-degree scenario. Values are computed over a 5 year rolling average.

Something that should be noted here is that the recyclable outflow has a delay in its reaction to the total outflow. This is due to the time that is necessary between the decommissioning and the actual demolition and recycling (the timeshift). This timeshift also enables the spreading of the recyclable outflow over a longer time period, dampening the direct link between the outflow and the recyclable outflow. For example: in the 1.5-degree scenario the sharp decrease in concrete outflow after 2040 is not reflected as steeply in the recyclable outflow (see figure 4.6).

4.3.1 BASELINE SCENARIO AND THE IMPORTANCE OF REDUCING OIL DEMAND

When assessing the graphs of the baseline scenario, it becomes clear that reaching full circularity within the petroleum industry is still a long way ahead of us. The necessary material inflow is higher than the outflow for the majority of the time. When the inflow is actually smaller than the outflow, this is not the case for long, nor is it lower by a large margin. This means that in the baseline scenario, material circularity is not possible. Since the outflow is not expected to change up until 2040, this shows the importance of lowering the necessary inflow.

The main driver for this inflow is the oil demand, showing the need for a decrease in oil demand, if material circularity is to be reached. Another factor that can contribute to creating less need inflow is a longer lifetime of installations, although increasing these is shown to have only limited effect (Le Boulzec et al., 2022), and elongating lifetimes might have consequences on other results as well, impacting the circularity (Deetman, 2021). Therefore, reducing oil demand remains the main solution for decreasing the necessary material inflow. For the material inflow to be lower than the outflow in 2050 the baseline scenario, it needs to decrease with 21.5% for steel, and with 12.0% for concrete.

4.3.2 1.5-DEGREE SCENARIO AND THE IMPORTANCE OF END-OF-LIFE PRACTICES

Even in the 1.5-degree scenario, full circularity is not possible by 2050, with the inflow being higher than the recyclable outflow for both materials. A more optimistic view on these results show that in the 1.5-degree scenarios, the amount of total outflow out of the system surpasses the inflow towards 2050. This shows the importance of end-of-life practices. When considering 2050 in the 1.5-degree scenario, the recyclable outflow makes up only 47% of the total outflow for steel, and 18% for concrete.

Looking at Figure 4.6 and Table 4.1, it becomes clear that this is not enough to fulfil the necessary inflow demands. When comparing the necessary inflow to the total outflow, the necessary recyclable outflow can be calculated. These figures show that the recyclable outflow rate should increase from 47% to 87% for steel and from 11% to 75% for concrete (see Table 4.1).

Table 4.1 - Comparing the current and necessary end-of-life characteristics for steel and concrete in the 1.5-degree scenario.

material	inflow 2050 (Mt)	total outflow 2050 (Mt)	recyclable outflow 2050 (Mt)	recyclable outflow rate 2050	necessary recyclable outflow rate
steel	4.87	5.62	2.62	47%	87%
concrete	3.14	4.19	0.48	11%	75%

Collection and Recycling Rate

As explained in section 3.2.4 and 3.3.1, the recyclable outflow rate is determined by two variables: the collection rate and the recycling rate. The collection rate is dependent on the stage and type of infrastructure, and shows what percentage of the infrastructure is actually demolished and collected for recycling. To give an example, only 30% of offshore extraction infrastructure is collected to be recycled. The recycling rate is specified per material, and indicates what percentage of the recovered material can be recycled. For example, steel is one the best and most recycled materials, having a recycling rate of 85% (Bratkovich et al., 2015).

When comparing the two most used materials again (see Table 4.2)., we can see that not only the recycling rate, but also the collection rate is different for each material. This is because steel is used more in infrastructure which is often not recovered, such as extraction platforms or pipelines, whereas concrete is mainly used in infrastructure types with higher collection rates, such as storage facilities.

These results show that for the 2 most used materials in the oil industry, different aspects need to be improved. For steel, a material with a well-established recycling industry, the main focus should be on increasing the collection of the infrastructure.

For concrete on the other hand, there is a lot of progress to be made in the recycling of the material itself. The recycling rate of 12.6% is mainly responsible for the low recyclable outflow, and can already be considered high (Jin & Chen, 2019). Therefore, for reaching material circularity in concrete the recycling rate needs to be improved.

Table 4.2 - The collection rate, recycling rate, and recyclable outflow rate in 2050 in the 1.5-degree scenario.

material	collection rate (2050) [1]	recycling rate (2050)	recyclable outflow rate (2050)
steel	55%	85%	47%
concrete	88%	12.6%	11%

[1] It is important to note that the collection rate is not taken from the model directly. Instead, it is calculated using the recycling rate and the recyclable outflow rate. This means that the delay and dampening effect of the timeshift described above are in full effect. Due to the fact that in 2050, the outflow is already decreasing but the recyclable outflow is not yet following, this yields a relatively high recyclable outflow rate. With a fixed recycling rate, only the collection rate can compensate for this discrepancy, resulting in a relatively high collection rate.

5. DISCUSSION

This chapter will firstly discuss the implications of the outcomes of the model. Then, considerations on data sources are presented, followed by a discussion on the model parameters and their influence on the outcome. Furthermore, the practical and policy recommendations and recommendations for further research will be given.

5.1 COMPARISON WITH PREVIOUS STUDIES

To understand whether or not the results of chapter 4 are viable, the material intensity is compared to the projection of Le Boulzec et al. (2022). In their study, the fossil fuel industry is aggregated as one system, only being divided into upstream, midstream, and downstream respectively. Specific data for oil is therefore limited to material intensity (Le Boulzec et al., 2022, Table 2). Still, the material intensity gives a good indication of the material use within the system. The compared material intensities can be found in Table 5.1.

The comparison shows that this study has lower outcomes for all analysed material intensities, which in term would lead to lower value for stock, inflow, and outflow.

The consumption of materials by the oil industry can also be considered low when compared to the annual production values of said materials. In Table 5.2, the necessary inflow is listed, next to the annual production values in 2019 for steel (Worldsteel Association, 2020), concrete (U.S. Geological Survey, 2020), copper (Flanagan, 2021) and plastics (OECD, 2022).

This shows that the petroleum industry plays a marginal role when it comes to global material consumption, consuming not even 1% of global steel supply, and even less of the other materials.

Table 5.1 - Comparison of material intensity between studies.
Material intensity in Mt of material stock per EJ of annual energy..

	year	steel	concrete	copper	aluminium
(Le Boulzec et al., 2022)	2015	3.8	2.5	0.023	0.006
this study	2019	1.3	1.0	0.0004	0.003

Table 5.2 - Comparison of consumption by the oil industry and the global production value.

material	inflow in the oil infrastructure 2019 (Mt)	total global production 2019 (Mt)	percentage consumed by oil infrastructure
steel	11.4	1870	0.6%
concrete [1]	9.06	10660 [1]	0.08%
copper	0.005	24.5	0.02%
plastics	0.08	460	0.01%

[1] For the concrete production value the sourced cement value is multiplied by 2.6 in accordance with M25 concrete (Bureau of Indian Standards, 2009; Dream Civil, 2022).

5.2 SENSITIVITY ANALYSIS

The parameters within this research all have different impacts on the final outcome. To assess the influence of a few of these parameters, a sensitivity analysis is performed on the model outputs. In their comprehensive evaluation of sensitivity analyses, Dzubur et al. (2017) conclude with a flowchart for choosing the right type of sensitivity analysis for different cases (Džubur et al., 2017). In accordance with that overview, four types of variables from different parts of the model will be individually analysed. This will be divided into 3 stage-based parameters and 1 material-based parameter.

5.2.1 PARAMETER SELECTION

One parameter is an input variable changing the material composition (the share of offshore pipelines), one is a modelling choice within the dMFA (the standard deviation for the lifetimes), and the last is one of the end-of-life parameters (the collection rate of crude pipelines). Changing the share of offshore pipelines would normally also have an influence on the collection rate of crude pipelines, but for this analysis, the goal is to see the influence of the material composition. Therefore, the collection rate is not changed in the first sensitivity analysis. This is possible since the calculations for the collection rate are done in the data gathering phase rather than the modelling phase, and are therefore not depending on each other in the model itself. The three selected variables will be assigned a low and a high value, next to their standard value. The 1.5-degree scenario is selected for this analysis. The two outcome parameters which are analysed are the stock mass and the circularity percentage in 2050, both for steel. The reasons for this material choice are the well documented recycling rate and the fact that it is the most used material in the fossil fuel industry.

Selecting one specific stage ensures the model's dependency on the parameters is actually being analysed, not the overall share of any stage within the model. To ensure this, the outcome parameters will also be specific for the pipeline stage. The pipeline stage is selected because the material composition as well as the overall pipeline length is very well documented.

However, to assess the overall dependency the model might have on a material based parameter, another sensitivity analysis has been performed. In line with the modelling choices in section 3.3.1 and the findings in section 4.3.2, the recycling rate of concrete is taken into consideration. To properly assess its influence, the outcome parameter checked is the concrete circularity potential in 2050. In line with the sensitivity analysis on the stage dependent parameters, this analysis will also take the 1.5-degree scenario into consideration.

5.2.2 OUTCOMES

The outcomes of the sensitivity analyses based on the stage dependent model parameter can be seen in Table 5.3, and those of the analysis on the concrete recycling rate can be found in Table 5.4.

Before diving into the results of the analysis it is important to emphasise that the results are only applicable to the specific pipeline stage, which accounts for less than half of material demand. This means that for the overall results, the analysed parameters have a lot smaller influence.

The first sensitivity analysis, the effect of changing the share between different types, is limited to the material composition. This means that the amount of pipelines remains the same, but the share and by extension the material composition is changed. The resulting change in outcome signifies that the share of different types, and by that the material composition of a stage, have significant influence on the material stock development, but almost no effect on the circularity potential.

This can be explained by exploring what actually changes in this analysis. The material composition indicates which materials are used within a certain type or stage. If one type of infrastructure (in this case the offshore pipelines)

Table 5.3 - Outcomes of the sensitivity analysis performed on 3 stage dependent model parameters.

parameter	value			steel stock (2050) [1]		steel circularity potential (2050) [1]	
	type	value	change	value (Mt)	change	value (%)	change
share of offshore pipelines [2]	standard	15%	0%	95.64	0%	35.6%	0%
	low	7.5%	-50%	88.86	-7.2%	35.7%	+0.3%
	high	22.5%	+50%	102.4	+7.2%	35.5%	-0.3%
lifetime standard deviation factor	standard	0.2	0%	95.64	0%	35.6%	0%
	low	0.1	-50%	97.28	+1.7%	36.2%	+1.7%
	high	0.3	+50%	95.53	-0.1%	35.0%	-1.8%
collection rate of crude pipelines in 2050	standard	34%	0%	95.64	0%	35.6%	0%
	low	17%	-50%	95.64	0%	24.8%	-30.2%
	high	51%	+50%	95.64	0%	46.4%	+30.4%

[1] For this analysis, the stock and circularity potential are specific for the pipeline stage

[2] For this analysis, the influence of the share of offshore pipelines is limited to the material composition

Table 5.4 - Outcomes of the sensitivity analysis performed on the concrete recycling rate,

parameter	value			concrete circularity potential (2050)	
	type	value	change	value (%)	change
concrete recycling rate	standard	12.6%	0%	16.1%	0%
	low	6.3%	-50%	8.1%	-50%
	high	18.9%	+50%	24.2%	+50%

have relatively more steel per km of pipeline than the onshore type, it can be expected that this is shown in the stock developments: a higher share of offshore pipelines would mean a higher share of steel in the total pipelines material stock.

On the other hand, since the material inflow and outflow are related to the necessary and obsolete stock, the circularity potential of the stage is not expected to change. This is due to the fact that if more steel is embedded in the stock, more steel inflow is needed, but more steel will also be in the outflow of the system. Therefore, the influence on the circularity potential is limited. This is in line with what is observed in the sensitivity analysis.

Secondly, the lifetime distribution only has limited influence on the end results. This is due to the fact that the lifetime itself does not change. The pipelines will, on average, stay in service for the same amount of time. The change made is that the timeframe over which they possibly can be decommissioned is either smaller or larger. This timeframe being smaller would lead to a more spiky and oscillating outflow of material, whereas it being larger would lead to a more gradual outflow. This development over time is not shown within the final 2050 stock or circularity value.

Additionally, the collection rate influences the circularity potential, while having no influence at all on the stock. The high influence the collection rate has on the circularity outcomes (50% change leading to 30% change in the outcomes) indicates its importance for a proper circularity assessment. This is explained by the fact that if more crude pipelines would actually be collected, the recyclable outflow would of course significantly increase. Again, the large change found in this analysis is due to the choice of analysing the effect on this specific stage.

Lastly, the outcomes of the sensitivity analysis on the concrete recycling rate (Table 5.4) show a direct link between the recycling rate and the circularity potential. This is no surprise given the setup of the model, but it still signifies the importance of the material-based end-of-life practices for all materials.

The two sensitivity analyses underline the importance of well-defined and validated assumptions on the division between different types of infrastructure within the same stage, as well as on material composition. Furthermore, it emphasises the importance of validating both the collection and recycling rates before assessing the circularity, given their direct influence on the circularity results.

5.3 LIMITATIONS

This research encounters some limitations due to the availability of data and modelling choices. Both will be discussed below.

5.3.1 DATA-BASED LIMITATIONS

Since it relies on online available data describing the oil supply chain over time, the data points used within this research pose some limitations. For many parameters (Table 3.1), data from different academic and grey literature have been retrieved. This study also uses figures from several governmental bodies and institutes such as Eurostat, IEA and US EPA. Ecoinvent is used the most in this research since it has the most data on the material composition of the different stages of the petroleum industry, but various papers mention the methodological issues related to allocation and recycling (Frischknecht et al., 2005; Wernet et al., 2016).

When using the Ecoinvent database, assumptions made can yield problems too when it is used to calculate global infrastructure. This is showcased by the calculated number of global offshore oil platforms. Here, the standard Ecoinvent platform is among the largest in the world, resulting in a high production per unit, and consequently a total number of units far smaller than other sources report. Conversely, the Ecoinvent based number of oil refineries is higher than those found in existing literature, due to a relatively low capacity in the EcoInvent assumptions. Wherever possible, Ecoinvents report covering global industries were used, but the background reports show that they are often based on regional findings (e.g. Faist Emmenegger et al., 2007).

Another notable limitation is the lack of data on material intensity petroleum storage facilities, which could not be found in the EcoInvent or any other LCA database. To mitigate this, this research modelled a standard oil storage tank, based on historical data and industry standards. This basic model might not be representative for the global storage facilities.

The use of grey literature such as news articles and company reports impose some limitations as they are often not peer-reviewed or cross-checked. Most of the figures used are based on findings from higher income regions such as Europe and North America. The used data does not make sufficient distinctions between the different oil industry infrastructures and is therefore not specific to regional differences.

The model presented in this research bases its material demands solely on projections of petroleum demand, taking the SSP2 scenario as its scenario. However, developments in petroleum demand differ widely between sources and scenarios (Harrisson, 2018; IEA, 2020a). Taking two pathways from the same source as scenarios ensures that the comparison between scenarios is viable, but the uncertainty in oil demand projections is still considerable.

5.3.2 MODEL-BASED LIMITATIONS

Some modelling approaches also pose limits on the realism of the data. First of all, the materials used for decommissioning activities are not taken into account in the model. These include for example the plugging of wells (Vrålstad et al., 2019), but also the specific equipment needed to deal with decommissioning petroleum infrastructure, especially offshore (Tan et al., 2021). Including these in the model could affect the effectiveness of collecting and recycling.

Furthermore, the consumption based accounting used in this research limits the geographical scalability of the results. This demand driven approach does not allow for countries to develop a decommissioning strategy, since the infrastructure they are accountable for often is not installed within their own borders. Moreover, the complexity of the global petroleum supply chain creates large diversity between countries, since they can have totally different roles within the system (consumer, producer, transporting and storage hubs, etc). This approach is therefore mainly useful to create an image of the global system

In short, the data used are describing their respective technological, geographical, and temporal scope, but since the petroleum system is composed of incredibly complex, varied, and dynamic systems, the data might not always be representable of the system or the time period as a whole.
The complexity of the system combined with the consumption based accounting approach taken by this research make the results mainly useful for the creation of a global system overview.

5.4 PRACTICAL AND POLICY IMPLICATIONS

This research set out to assess the possibility for material circularity for the petroleum industry. The findings of this study might indicate that, when the 1.5-degree scenario is followed, the petroleum industry is on its way to positive development. However, this must not be seen without the broader context. The petroleum industry has been widely criticised for their high emissions and the issues caused by the disposal of oil residues. Besides contributing to climate change, the petroleum industry is responsible for negatively impacting the environment, ecosystems, species and populations (Bathrinath et al., 2021).

Taking the environmental and social impact of the petroleum industry into consideration there is a need for a substantial reduction of fossil fuels and a shift to renewable energy. Even though the material use within the sector is less than 1% of the total global use (see Table 5.2), reaching material circularity is still an important goal for reaching the Sustainable Development Goals (RMIS - EU Science hub, 2023; Schroeder et al., 2019). Based on the findings of this study and the need for material circulation, decreasing oil demand is not only needed for environmental reasons, but also for material reasons.

In the baseline scenario, the circularity assessment indicates that sectoral material circularity is not possible, as the material demand remains higher than the material outflow for almost the entire time frame. Reducing the global demand of oil would significantly decrease the necessary material inflow. The findings of the 1.5-degree scenario are more promising for the circularity of the industry, as the material inflow is lower than the material outflow. However, in this scenario the recycling and collection rate are still not sufficient to reach full circularity. So in both scenarios, a global approach to discourage and further decrease the use of oil is required to reach material circularity.

According to this study's results, decommissioning policies of companies and countries increasing material collection and recycling could be pivotal for reaching circularity. Decommissioning policies fostering material recovery could lead to a reduction of extraction of primary material. However, decommissioning also can impact the environment and removing the existing infrastructures could consume a large amount of energy (Tan et al., 2021;). Decommissioning policies are needed regardless of whether society partially reduces the use of fossil fuel or completely phases out oil use (Le Boulzec et al., 2022). It is also important to note that despite ambitious decommissioning strategies, some 'removal processes' might require material such as material to cover the oil wells and it is inevitable that some material might be left in its place (Vrålstad et al., 2019).

So far, only a few countries have set ambitious decommissioning policies (Kaiser & Liu, 2018), other countries are still developing ambitious decommissioning strategies (Le Boulzec et al., 2022; Melbourne-Thomas et al., 2021). However, most countries lack decommissioning strategies that include the reuse of materials. Considering the global nature of the fossil fuel industry, a global approach is required. Currently, there are several international conventions covering the removal of installations (e.g. UN Geneva Convention on the Continental Shelf 1958; London Convention and Protocol 1996) (Ounanian et al., 2020). International conventions and national legally binding legislations emphasising circularity and promoting viable and ambitious decommissioning policies could greatly increase the recovery and recycling efforts of the oil industry.

Lastly, the low recycling rate of concrete makes reaching full circularity of that material currently impossible. Ways in which recycled concrete can be used in a way similar to its original purpose need to be investigated (Li et al., 2022, Le & Bui, 2020). Policies encouraging these practices should be implemented. This is not only useful for the material use in the oil industry, but would contribute to the circularity goals of the construction sector as a whole (Le & Bui, 2020).

A global effort to discourage and **decrease the use of oil** is necessary.

Decommissioning policies need to be implemented and improved upon, especially regarding the recovery of **pipelines and offshore extraction** infrastructure.

Policies aimed at improving the **recycling of concrete** need to be implemented.

5.5 RECOMMENDATIONS FURTHER RESEARCH

Based on the findings, limitations, and uncertainties of this paper the following recommendations are made. To accurately assess the circularity of materials in the oil industry infrastructure, a higher quality of data is needed. In particular, data of material intensity has to be improved. A better overview of existing infrastructure, such as the number of oil refineries, production platforms, and storage units is needed, as well as more specific data on the material use for such infrastructure

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Regional data on oil infrastructure has to be improved. To provide insights on a regional, national or even local level, the link between production and consumption needs to be investigated. With such local data, more accurate estimations for material recycling opportunities could be made.

Another way in which this model in particular, and research on this topic in general can progress is by the incorporation of changing material efficiencies. Increasing the material efficiency can lead to sharp decreases in virgin material use and energy demand (Allwood et al., 2011; Ruuska & Häkkinen, 2014) and could be part of the solution to energy problems (Hernandez et al., 2018). Modelling these changes in material intensity over time could enhance the accuracy of dMFA's, and by extension provide better circularity projections.

Furthermore, within the model used in this research there is no distinction between the in-use stock and the surplus stock. Clarifying when and how much dormant stock will be in place can help better understand how much of existing infrastructure might be obsolete.

The framework presented in this research could be used for the analysing of other fossil fuels as well, with limited needs for adjustments. With data on all obsolete fossil fuel technology, and the possible material yields, it would then be interesting to see how this compares to the increasing material needs posed by the renewable energy sector.

In the introduction, the influence and impacts of petroleum infrastructure are discussed. These influences on the spaces around us are known as the physical petroleumscape (Hein, 2018). Since the petroleumscape has many negative impacts (Kim et al., 2022; Matemilola et al., 2018; Zentner et al., 2019), another way in which this research approach could be continued, is using it to model some of these other impacts. For example, the land use of industrial systems could be modelled in a similar fashion, showing the associated spatial impact of the industry. Given the consumer based accounting principle of this framework, social impacts such as health related issues could also be considered, since those often do not occur in the country where the final consumption takes place.

Additionally, this research could help improve research into energy scenario development in two ways. With a well-established material intensity, the material demand could be taken into account when comparing energy scenarios. Material production has a large energy cost. Therefore, including the material demands and their respective energy impacts in energy scenarios would more accurately show the consequences of changes in the sector.
Lastly, this research highlights the large impact of the collection and recycling rate on possible material circularity. Accurate projections of these rates need to be further researched, especially considering differences in policy. Adding these parameters to future material and/or energy scenarios would greatly enhance their accuracy.

Energy scenarios can be improved by including the energy costs of embedde materials

End-of-life practices should be included in scenario design,

The approach used within this research can be applied to model other impacts

The lack of reliable, publicly available data. on material use and oil infrastructure should be addressed

6. CONCLUSION

This study set out to assess the material based consequences of changes in future oil demand and their influence on potential material circularity. This conclusion chapter aims to include all aspects of the material developments in the petroleumscape, by discussing the three research questions, before ending with answering the Main Research Question

This study set out to assess the material based consequences of changes in future oil demand and their influence on potential material circularity. In doing so, the research aims to quantify the current physical petroleumscape, and model possible future developments based on different scenarios. To do so, this study dynamically models the evolution of the world's petroleum infrastructures based on two SSP2 scenarios; a baseline scenario and a 1.5-degree scenario. It estimates embedded materials from 1971 towards 2050, as well as the associated in- and outflow. Based on the end-of-life characteristics of the sector, the model assesses the potential for material circularity within the sector. To include all aspects of the material developments in the petroleumscape, three research questions have been created. The answers to all three will be discussed below, before ending with a conclusion of the research as a whole.

RQ1.

WHAT ARE THE CURRENT GLOBAL STOCKS OF MATERIAL IN USE IN THE OIL INDUSTRY INFRASTRUCTURE?

To answer this research question, the infrastructure and material needs of 5 stages of the petroleum production process have been modelled for 2019, being the extraction, pipelines, transport, storage, and processing. Adding the material used in these stages allows for the first conclusion to be drawn, which is that the current material embedded within the petroleum industry is considerable, with a total current stock of 423 megatonne. The stages with the highest material use are pipelines and storage, each contributing over 40% to the total material use, with 45% and 42% respectively. Processing is responsible for 7% of the material usage, transport 3%, and extraction 2%.

Since all of these stages have different material intensities, i.e. they use different types and quantities of materials, these material intensities are included in the model, leading to an overall material composition of the petroleum sector. From this material composition, it can be concluded that steel and concrete are the most used materials within the oil industry by weight, with steel having a share of over 50% of all materials used. The share of concrete is over 40%, with bitumen, the next material, having a share of just over 3%. Any other material has a share of under 0.5%.

The current global material stock embedded in the petroleum industry is 423 megatonne,

The production stages with the highest material use are pipelines (45%) and storage (42%)

The materials mostly used are steel (54%) and concrete (42%).

RQ2.

BASED ON DIFFERENT IMAGE MODEL SCENARIOS, WHAT COULD BE THE ANTICIPATED MATERIAL IN- AND OUTFLOWS IN THE OIL INDUSTRY INFRASTRUCTURE TOWARDS 2050?

To model the anticipated in- and outflow of material over time, the energy scenarios from the IMAGE model have been used. For this study, the SSP2 baseline and SSP2 1.5-degree scenario have been considered. The energy demand for the oil industry in these scenarios has been linked to the infrastructural demands, and by extension to material demands. Therefore, the developments in necessary stock closely resemble the differences in oil demand. Combined with assumptions on lifetime the stock projections allow for calculating the material in- and outflow towards 2050.

The outcomes show that in the baseline scenario, the inflow and outflow are both steadily increasing over time. Meanwhile, the 1.5-degree scenario shows a steep decrease in the inflow, before levelling out at a significantly lower level than before. However, the outflow follows largely the same path as the outflow in the baseline scenario, only starting to decrease after 2040. This is due to the currently installed infrastructure serving out its entire lifetime.

Based on these outcomes, it can be concluded that up until 2050, any changes in oil demand would mostly impact the inflow of materials, while not having a big effect on the outflow. Large differences in the outflow of the system can only be expected after 2040.

In the baseline scenario, the inflow and outflow are steadily increasing over time.

The declining oil demand in the 1.5-degree scenario has an immediate influence on the inflow of materials, causing a steep decrease after 2020.

The effect on the outflow of material is delayed by the lifetime of infrastructure and starts to show after 2040.

RQ3.
TO WHAT EXTENT DO THESE MATERIAL FLOWS ALLOW FOR CIRCULARITY WITHIN THE OIL INDUSTRY?

To assess the potential material circularity, the end-of-life characteristics recovery rate, recycling rate, and timeshift are included in the model. This allows for projecting the reusable outflow over time. Comparing this to the necessary inflow gives insight into the potential circularity. This research assesses the circularity for steel and concrete since these are the most used materials within the petroleumscape, together making up more than 95% of all materials.

In the baseline scenario, material circularity within the industry is not possible. The necessary inflow is almost consistently larger than the outflow.This means that even when all the obsolete infrastructure would be fully recovered and recycled, circularity would still not be reached. This shows the importance of decreasing the necessary inflow, which can be achieved by reducing the global oil demand.

When assessing the potential for material circularity in the 1.5-degree scenario, the importance of end-of-life practices becomes apparent. Even though the future outflows are greater than the necessary inflows in this scenario, material circularity can not be reached due to low material reclamation. The amount of outflow that is recycled needs to improve from 47% to 87% for steel and 11% to 75% for concrete to realise circularity. This indicates the need for improving the recycling possibilities for concrete in particular, given it has an recycling rate of only 12.6% at best. When looking at the different stages of the production process, improvements in the collection of infrastructure for recycling are especially needed in the pipeline sector, given that it is the largest contributor to material use, and it has a collection rate of only 34-40% in 2050. One other stage with a low collection rate is the offshore extraction, but that specific type of stage only contributes 1% to the total material stock.

Circularity is not possible in the baseline scenario, due to high necessary inflow

In the 1.5-degree scenario circularity can only be achieved when end-of-life practices are improved upon.

Improvements are mostly needed in the collection of pipelines for steel and the material recycling of concrete

The answers to these research questions allow for a final conclusion, based on the Main Research Question. This question is formulated as:

MRQ:
"HOW DO FUTURE CHANGES IN PETROLEUM DEMAND INFLUENCE THE INDUSTRY'S MATERIAL CIRCULARITY?"

All in all, this research shows that the material quantities currently embedded in the petroleumscape are substantial. Furthermore, the results suggest that any changes made to the petroleum demand in the short term will have almost no influence on the outflow of the system up until 2040. However, this immediate reduction in oil demand is still necessary, since it will decrease necessary material inflow. This is needed to reach full circularity before 2050, but will not be enough on its own. The end-of-life practices need to be increased to actually achieve material circularity within the sector.

Lastly, it needs to be noted that even when material circularity within the petroleum industry is being reached, this does not mitigate the large number of negative impacts that the sector has made in any way. Nor would it enable the progression towards a renewable energy system, since this material circularity assessment just considers the petroleum supply chain. The material output of the petroleum sector would have to surpass its own demands, for it to actually be able to contribute to the energy transition.

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IMAGE ATTRIBUTIONS

Cover image:

Industry Overview The refinery is an industrial area with sunrise and cloudy skies, oil and natural gas storage tanks, the refinery industry. By jutawat. Via https://stock.adobe.com/

Figure 1.1, Societal impacts of the oil industry;

a) Port of Rotterdam, Overzichtkaart Raffinaderijen Olieterminals, via https://www.portofrotterdam.com/en/setting/industry-port/refining-and-chemicals/oil-refineries
b) Geology.com, Persian Gulf, This satellite image was compiled by NASA; the annotations, caption, and inset map were produced by Geology.com, via https://geology.com/articles/oil-fields-from-space/
c) Zone Luithagen Haven, via https://www.zone-luithagen.be/2019/01/steekvlam-in-antwerpse-haven-tot-30.html
d) Sarah Craig, Faces of Fracking, via http://www.stand.la/history-of-oil-in-los-angeles.htm
e) Rashah McChesney/Alaska's Energy Desk, via https://www.alaskapublic.org/2018/09/07/the-company-that-runs-the-trans-alaska-pipeline-is-cutting-workforce-by-10-percent/

2. Methods Page:

Programming code abstract technology background of software developer and Computer script. By monsitj. Via https://stock.adobe.com/

Figure 2.2 , Schematic overview of the oil industry with the system boundary for this research.

Created with vectors from Macrovector: Fuel Icon Vector and Computer Icon Vector. Retrieved via Freepik

Figure 2.3

Created with vectors from Macrovector: Fuel Icon Vector and Computer Icon Vector. Retrieved via Freepik

3. Data needs page

Left: Steel factory stacked steel. By gui yong nian. Via https://stock.adobe.com/
Right: oil pipeline nature, via https://www.freepik.com/author/photo

4. Results page

Panorama of Oil and Gas central processing platform in twilight, offshore hard work occupation twenty four working hours. By pichitstocker. Via https://stock.adobe.com/

5. Discussion page

Top right: refinery. By photollurg. Via https://stock.adobe.com/
Bottom Left: Aerial view oil terminal is industrial facility for storage tank of oil and petrochemical industry products ready for transport to further storage facilities. By Kalyakan. Via https://stock.adobe.com/

6. Conclusion page

Left: Zone Luithagen Haven. via https://www.zone-luithagen.be/2019/01/steekvlam-in-antwerpse-haven-tot-30.html
Bottom right: Pipeline in the Mojave Desert, California. By James. Via https://stock.adobe.com/

Appendix page

Petrochemical Photo. By Tawatchai07. Retrieved via Freepik

APPENDIX

B. GLOBAL PETROLEUM REFINING CAPACITY

When analysing the total refinery system, it is important to acknowledge the difference between the amount of processed oil, and the installed capacity. The latter is the most relevant for this research, since it most accurately reflects the material demand of the industry. According to data from the statistical report by BP, the daily throughput is using just above 80% of the installed capacity, a number that has been constant for the last 30 years, see table A2 (BP, 2020).

Table A2 - Global refinery capacity and throughput.

year	capacity[1] (thousand barrels daily)	throughput[1] (thousand barrels daily)	used share (%)
2019	101340	82989	81.9%
2010	93225	75222	80.7%
2000	82406	67903	82.4%
1990	74170	60365	81.4%

[1] data via BP (2020)

C. STANDARD OIL STORAGE TANK

Types of storage facilities

There are multiple ways in which oil and oil products can be stored on land. It is important that there is a difference between the storage of crude oil and refined oil products, being that the former can be stored in empty underground caverns, whereas the latter legally cannot (Ma et al., 2016).

For the purposes of material intensity, only above ground storage is considered. Within the above ground storage, different types of tanks can be identified:

- Open top tanks, tanks with no coverage, which are only used for rainwater storage (PetroWiki, 2021)
- Floating roof tanks, tanks with a thin film of coverage on the top of the content. This floating roof rises and drops with the level of the fluid in the tank. This helps against evoparting of the fuel. Used for both petroleum and products storage. (PetroWiki, 2021; Schmitt, 2021)
- Fixed roof tanks, tanks with a fixed roof, shielding the contents from the elements. Sometimes floating roofs are installed inside fixed roof tanks to combat evaporation. Used for both petroleum and products storage. (ANSON, n.d.; PetroWiki, 2021)

Within this research, only fixed roof tanks and floating top tanks are considered.

Standard tank definition

To still define a standard tank, two main sources of information have been used. First of all, the American Petroleum Institute (API) standards for steel tanks for petroleum storage have been looked into. Secondly, reports on storage tanks have been analysed to find numbers on average tank sizes and types. These data sources have been combined to define certain material needs, specifically wall, floor, and roof thickness, and underlying structures.

From the API 650 standard, the requirements for minimal wall thickness related to tank diameter have been retrieved (see table A3). Furthermore, the API Standard lists a minimal roof plate thickness of 5mm, and a general value of the roof slope of 10 degrees. (API, 2011). For the foundation, it describes a reinforced concrete slab of 1 metre in width, and 0.20 metre deep, along the circumference of the tank. Assumed is that the wall of the tank sits in the middle of this foundation.

From the comprehensive analysis of earthquake damage to petroleum tanks (Cooper, 1997), plus the assumptions done in a fragility report in oil tanks (Kameshwar & Padgett, 2015), the average characteristics of petroleum tanks were collected. These include diameter, height, capacity, and the ratio between fixed and floating roof designs. These dimensions allow the minimal nominal wall thickness to be calculated as well. All these numbers can be found in table A4.

Table A3 - Minimal plate thickness in welded petroleum storage tanks based on diameter.

diameter[1]		minimal plate thickness[1]	
ft	m	inch	mm
<50	<15	3/16	5
50 - <120	15 - <36	1/4	6
120 = 200	36-60	5/16	8
>200	>60	3/8	10

[1] Data retrieved from API Standard 650, 11th edition, p55

With these values, and a few more assumptions, the material demands can be calculated. The following assumptions have been made:

- The tank is completely made out of steel plating. Any constructional elements other than the concrete foundation ring are ignored.
- The thickness of the floor is the same as the thickness of the walls
- The thickness of a floating roof is equal to half the thickness of the walls
- The steel density in the reinforced concrete is 110 kg/m3

This leads to the following material needs for the general storage tank: 9.69e4 kg of steel, and 7.28e5 kg of concrete (see Table A5)

Table A4 - Average dimensions of petroleum storage tanks.

parameter	value
diameter	20.50 m
height	10.59 m
capacity	4270.4 m3
fixed roof share	55.3%
floating roof share	44.7%
wall thickness	5.71 mm

Table A5 - The material needs for the construction of a 4270.4 m3 standard oil tank.

material	amount
steel (shell)	6.35e4 kg
concrete	7.28e5 kg
steel (reinforced concrete)	3.34e4 kg

D. INPUT DATA OVERVIEW

The main information about the stage and type input parameters can be found in Table A.6. In Table A.7, the documentation on the sources and calculation methods is presented for the driving factors in the model.
In Table A.8, the recycling rates per material are listed.

Table A.6 - Overview of the input parameters per stage and type.

stage	type	share	general information		lifetime	collection rate		decom. time
			parameter	value (2019)		2019	2050	
extraction	onshore	70%	total annual extraction	3.06 e12 kg/year	30 year	56.25%	90%	2 year
	offshore	30%		1.31 e12 kg/year	22.5 year	30%	30%	5 year
pipelines	crude	59%[1, 2]	total pipe length	601925 km[1] 15% offshore, 85% onshore	50 year	0%	34 %	3 year
	product	41%[1, 2]		411212 km[1]	50 year	0%	40%	4 year
transport	rail cargo	0.5% [2]	total annual transport	2.4e11 tkm/year	26 year	95%	98%	0 year
	ocean ships	98.6% [2]		4.6e13 tkm/year	26.7 year	93%	93%	0 year
	inland ships	0.3% [2]		1.6e11 tkm/year	26 year	93%	93%	0 year
	trucks	0.6% [2]		2.7e11 tkm/year	12 year	90%	95%	0 year
storage	crude	61%[1, 2]	total storage capacity	3566 mb[1]	25 year	56.25%	90%	2 year
	product	39%[1, 2]		2238.7 mb[1]	25 year	56.25%	90%	2 year
processing	refinery	100%	total installed annual refining capacity	5.46 e12 kg/year	25 year	56.25%	90%	5 year

Table A.7 - Documentation on sources and assessment methods of the input parameters.

datapoint	stage	type	assessment	sources
Share	Extraction	All	Data from EIA	EIA, 2016
Total extraction	Extraction	All	Share of type multiplied with the total oil use in 2019, total oil aggregated from IMAGE Model, unit conversion via IEA data	IEA, 2016; PBL, 2022
Total pipe length	Pipelines	Crude	Aggregation of regional data.	Central Intelligence Agency, 2021; Natural Resources Canada, 2020; OECD, n.d.; United States. Department of Transportation. Bureau of Transportation Statistics, 2019
		Product	Aggregation or regional data. when not available, the share based on other regions is used for determining the product pipeline length.	
Total annual transport	Transport	All	Transport needs per type multiplied with the total oil production. Transport needs are an aggregation of numbers from EcoInvent 3.8 Dataset Documentation on light fuel oil, heavy fuel oil, lubricating oil, diesel, petroleum, kerosene, and naphtha. Total oil use aggregated from IMAGE Model, unit conversion via IEA data	EcoInvent, 2022; IEA, 2016; PBL, 2022; Wernet et al., 2016
Total storage capacity	Storage	All	Storage capacity based on regional data. When not available, the global oil use to storage ratio. Total oil use aggregated from IMAGE Model, unit conversion via IEA data	EIA, 2022; IEA, 2016; PBL, 2022; Vahn & Lee, 2021
Installed capacity	Processing	Refinery	Total oil use divided by the utilised installed refining capacity. Refining capacity usage from BP, total oil use aggregated from IMAGE Model, unit conversion via IEA data.	BP, 2020; IEA, 2016; PBL, 2022
Lifetime	Extraction	Onshore	Average from the minimum and maximum listed lifetimes	Canadian Association of Petroleum Producers, 2022
		Offshore	Average from EcoInvent background report and secondary sources	Faist Emmenegger et al., 2007; Louise Davis, 2018; Zeldovich, 2019
	Pipelines	All	Data from EcoInvent background report	Jungbluth, 2007e
	Transport	All	Data from PhD Thesis on lifetime	Deetman, 2021
	Storage	All	Data from UNECE report on safety guidelines for oil terminals	UNECE, 2015
	Processing	Refinery	Average from EcoInvent background report and secondary sources	Jungbluth, 2007d; Kozhemyatov & Bulauka, 2019; UNECE, 2015

Table A.7 (continuation) - Documentation on sources and assessment methods of the input parameters.

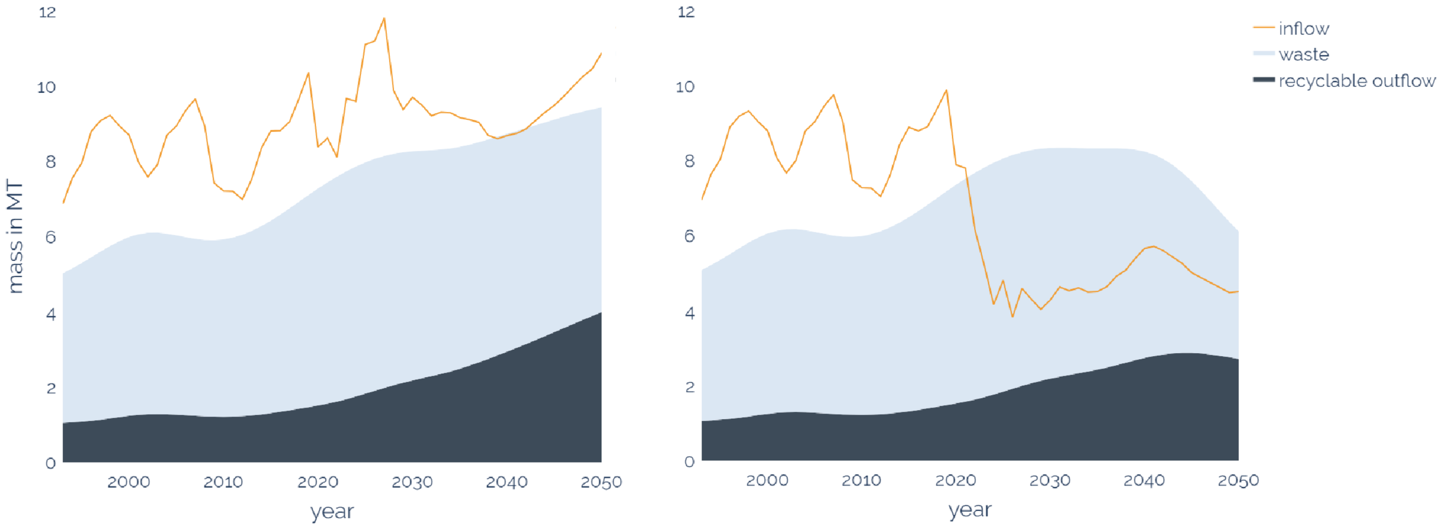
datapoint	stage	type	assessment	sources
Collection rate 2019	Extraction	Onshore	Average CDW recovery for Europe, China, India, and USA	Eurostat, 2022; Hao et al., 2020; Ponnada & P, 2015; US EPA, 2022
		Offshore	UK projected recovery for 2020-2030	OGUK, 2021; Zeldovich, 2019
	Pipelines	All	Based on low-end LCA end-of-life option	Strogen & Horvath, 2013
	Transport	Rail Cargo	Average recycling rate for freight train components	Silva & Kaewunruen, 2017
		Ships	Scrapped ships compared to lost ships in 2019	Allianz, 2020; NGO Shipbreaking Platform, 2020; Norwegian Maritime Authority, 2021; Vessels Value, 2022
		Trucks	Average vehicle recycling rate for Europe, US, and China	Adams, 2020; Eurostat, 2021; Wang et al., 2021
	Storage		Average CDW recovery for Europe, China, India, and USA	Eurostat, 2022; Hao et al., 2020; Ponnada & P, 2015; US EPA, 2022
	Processing		Average CDW recovery for Europe, China, India, and USA	Eurostat, 2022; Hao et al., 2020; Ponnada & P, 2015; US EPA, 2022
Collection rate 2050	Extraction	Onshore	Average CDW recovery for the greater EU region in 2018	Eurostat, 2022
		Offshore	UK projected recovery for 2020-2030	OGUK, 2021; Zeldovich, 2019
	Pipelines	Crude	Offshore pipeline recycling from OGUK 2030 forecasts, onshore based on LCA end-of-life option.	OGUK, 2021; Xu et al., 2022
		Product	Based on LCA end-of-life option.	Xu et al., 2022
	Transport	Rail Cargo	High end recycling rate for freight train components	Silva & Kaewunruen, 2017
		Ships	The 2019 rate is assumed not to change towards 2050	Allianz, 2020; NGO Shipbreaking Platform, 2020; Norwegian Maritime Authority, 2021; Vessels Value, 2022
		Trucks	Average vehicle recycling rate of the greater EU region in 2019	Eurostat, 2021
	Storage	All	Average CDW recovery for the greater EU region in 2018	Eurostat, 2022
	Processing	Refinery	Average CDW recovery for the greater EU region in 2018	Eurostat, 2022

Table A.7 (continuation) - Documentation on sources and assessment methods of the input parameter.s

datapoint	stage	type	assessment	sources
Decom. Time	Extraction	Onshore	Assumption based on information from Nexstep	Nexstep, 2017
		Offshore	Aggregation of time from decommissioning to scrapyard and the time to dismantle the platform averaged with a total decommissioning time.	Boon, 2021; Getech Group plc, 2021; Kulovic, 2022, Sommer et al., 2019
	Pipelines	Crude	Offshore timeshift based on Shell report, onshore based on decommissioning report	Fisher, 2014; Shell U.K., 2020
		Product	Based on decommissioning report	Fisher, 2014
	Transport	Rail Cargo	Based on study on heavy vehicle recycling and industry news reports	Barker, 2021; Saidani et al., 2020; van der Bogaard, 2019
		Ships	Based on data from multiple sources	Gomersall, 2019; Gwin, 2014; Wrinkler, 2008
		Trucks	Based on study on heavy vehicle recycling	Saidani et al., 2020
	Storage		Based on news report on oil storage terminal decommissioning.	Duff, 2022
	Processing		Rounded down average of news reports on refinery decommissioning and demolition	Geipel-Kern & Noé, 2017; Reuters, 2019

E. CIRCULARITY POTENTIAL PER MATERIAL GROUP

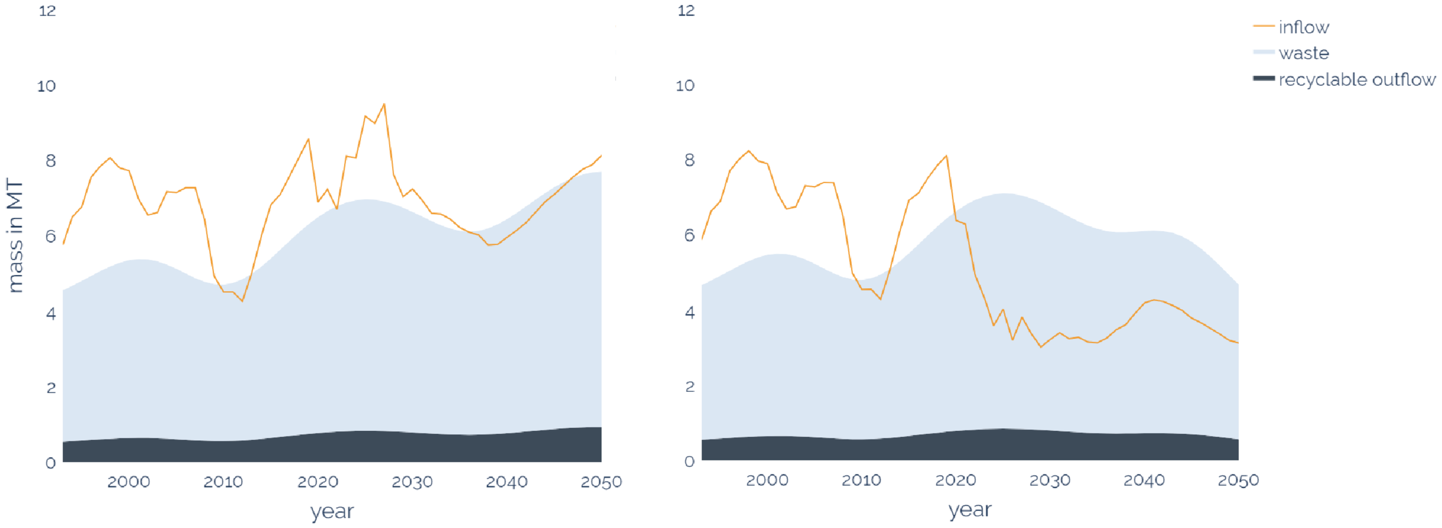
To assess the potential circularity, the necessary material inflow (orange line) is mapped over the total material outflow, divided in wasted outflow (light blue) and the recyclable outflow (dark blue). This is done for the material groups Steel, Concrete, Bitumen, Plastics, Other Metals. The last group, Various Materials, is so diverse that showing its circularity potential does not add any value or insights.



a

b

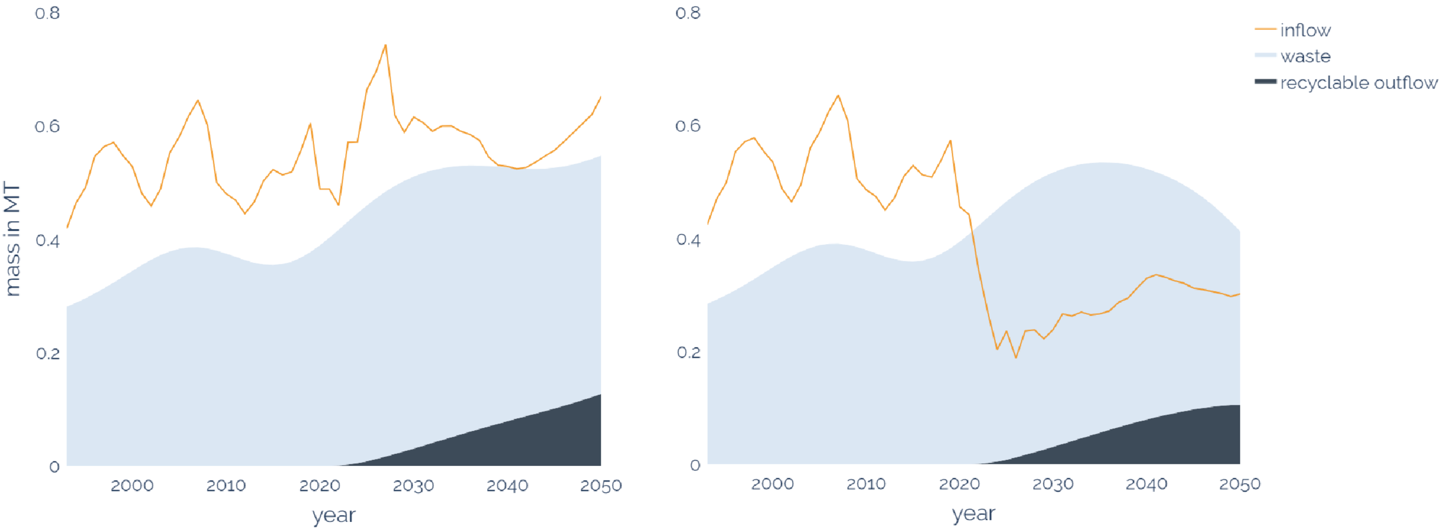
Figure A.1 - The recycling potential of steel in the baseline (a) and the 1.5-degree scenario. Values are computed over a 5 year rolling average.



a

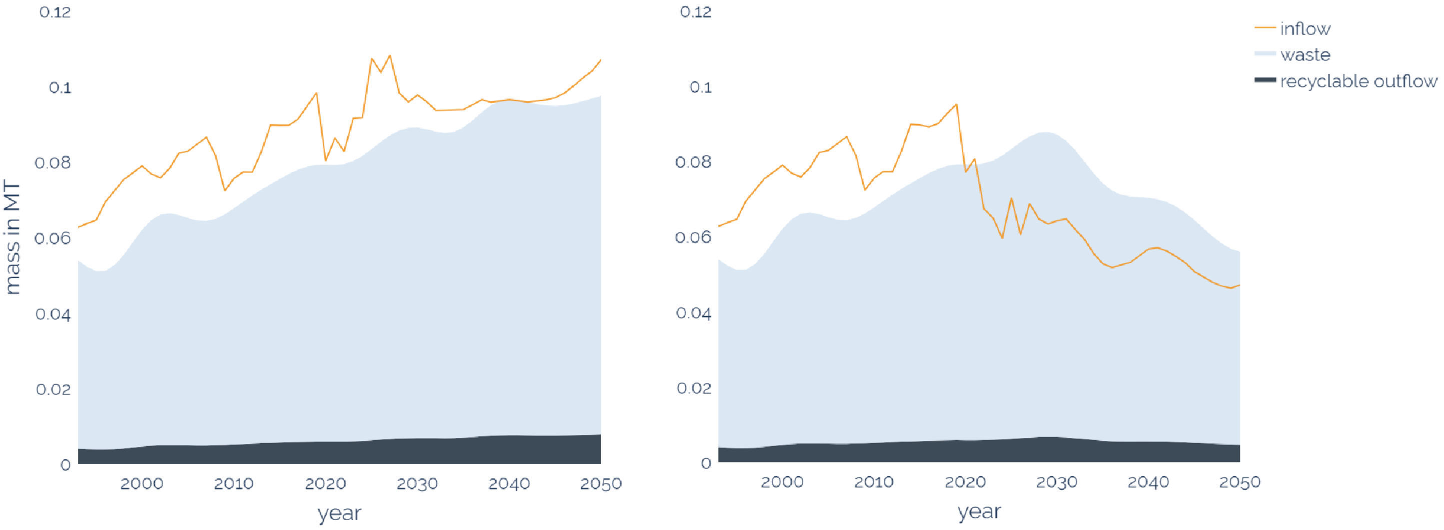
b

Figure A.2 - The recycling potential of concrete in the baseline (a) and the 1.5-degree scenario. Values are computed over a 5 year rolling average.



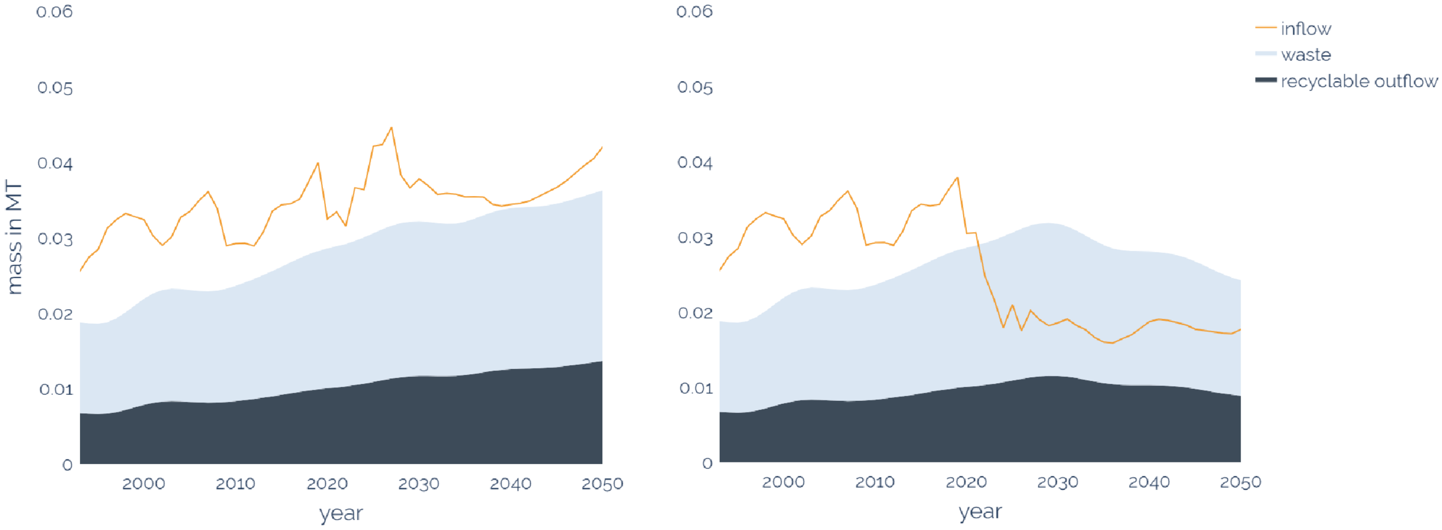
a b

Figure A.3 - The recycling potential of bitumen in the baseline (a) and the 1.5-degree scenario. Values are computed over a 5 year rolling average.



a b

Figure A.4 - The recycling potential of plastics in the baseline (a) and the 1.5-degree scenario. Values are computed over a 5 year rolling average.



a b

Figure A.5 - The recycling potential of metals in the baseline (a) and the 1.5-degree scenario. Values are computed over a 5 year rolling average.

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