UNIVERSITY OF SOUTHERN DENMARK

EXPLORING THE DYNAMICS OF BUILT ENVIRONMENT STOCKS FOR LOW CARBON CITY DEVELOPMENT

Master Thesis Report, prepared 3-06-2019 by:
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Abstract

Cities occupy just three per cent of the Earth's land, but account for 60-80 % of energy consumption and 75 % of carbon emissions. A big share is contributed by the building sector, which accounts for around 30 % of global energy consumption (UN, 2016).

Accordingly, there is the need to investigate a city's energy demand and sources of emissions to reveal climate mitigation options. Several studies did account emissions of cities or nations, though those mostly concentrated on estimating the operational emissions, which are occurring during operation respectively the use of stock. To give a holistic overview of the emissions caused by a city, the indirect or so-called embodied emissions have to be considered, too. They occur in material processing and production and are then embodied in the material. The greatest part of embodied emissions is incorporated in the built environment – the interface of a city. In research, little is done so far to analyze and quantify the amount of embodied emissions, but as studies (Heinonen, Säynäjoki, & Junnila, 2011) show they can contribute around 50 % of the greenhouse gas (GHG) emissions of a buildings life-cycle. This underlines the importance for further research about emissions in material stocks to find climate change mitigation options.

In this thesis project the total GHG emissions – embodied and operational - caused by the City of Odense were estimated for the year 2015. Furthermore, the carbon replacement value (CRV) of the built environment in Odense in year 2018 were quantified, applying CO_2-emission factors from the literature on the material stock data of the city, which was quantified in a bottom-up fashion. Additionally, the CRV of mobile stock was considered.

In 2015 the municipality emitted 1 167 kt CO_2 in total. Thereof were 840 kt CO_2 (73 %) operational emissions and the residual 327 kt CO_2 based on consumption and embodied in inflows.

The CRV of the material stock of Odense amounted to 6 039 kt CO_2 in 2018 which is equal to 24.8 tCO_2 per capita. The CRV is around sevenfold the operational emissions.

Most of the carbon is embodied in residential buildings and non-residential buildings, since the majority of the materials are erected in the built environment. Nevertheless, the mobile stock contributes with a total of 16 % to the total CRV. This finding is very interesting because the mobile stock only represents 0.4 % of the total material weight of all stock. This emphasizes the high energy requirements to provide goods like vehicles and electronics.

The CRV is an important parameter, since it can be used to estimate the future GHG emissions which will occur with rising population and economic development. This is especially of interest when thinking of developing countries, where the built environment stock and mobile stock are not advanced yet but will be build-up in the future in similar extent to the industrialized countries.

Acknowledgement

Herewith, I would like to thank my supervisor Gang Liu for guiding me through sometimes blurry periods in the process of this thesis project and inspiring me for a more meaningful study. As well I would like to thank Zhi Cao, Ruichang Mao and Morten Birkved from SDU Life-Cycle-Engineering for their time, help and good advisements.

A special thank-you goes to my co-supervisor Maud Lanau, who spent much time advising me, giving me feedback and calming me down in frustrating moments.

I hereby solemnly declare that I have personally and independently prepared this paper. All quotations in the text have been marked as such, and the paper or considerable parts of it have not previously been subject to any examination or assessment.

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1 Introduction

Half of humanity – 3.5 billion people – lives in cities and 5 billion people are projected to live in cities by 2030 (UN, 2016). Cities occupy just three per cent of the Earth's land, but account for 60-80 % of the energy consumption and 75 % of carbon emissions, hence the United Nations included *Sustainable Cities and Communities* as their 11th Sustainable Goal (UN, 2016). However, when assessing a city´s greenhouse gas (GHG) emissions the focus of researchers so far is on estimating direct emissions - here further called operational emissions - meaning emissions caused by the operation of the city, respectively its stocks. These can be the use of fuels or electricity for heating or running a vehicle, for example. The emissions to produce materials and goods, which are imported to satisfy the needs of the city and its inhabitants, are outsourced with this approach, respectively pushed out of the municipal boundary - a trade-off happens. To draw a complete picture and reveal more climate mitigation options, those indirect emissions or so-called embodied emissions driven by the production of goods and production of material for erecting and maintaining the anthropogenic stock (built environment) have to be included.

Before discussing anthropogenic stocks in further detail, it shall be pointed out that boundary issues can occur from solely evaluating operational emissions (Ramaswami, Hillman, Janson, Reiner, & Thomas, 2008). When it comes to GHG accounting for individual cities a clear cut-off is complex, since interactions with the environment impact the allocation of regional material and energy flows and blur the spatial boundary. The complexity causes great variety in the accounting methods applied by different municipalities and metropoles. However, often the accounting of operational emissions from municipalities are considered only, which brings along severe practical issues.

One issue is the assigning of commuting trips between municipalities. The counting of operational emissions only would trade-off the complete distance traveled per journey. In the case of aviation, it would trade-off the allocation of emissions from airplanes if the airport serves many cities – which it usual does.

Additionally, upstream GHG emissions occurring in the production of key urban materials like water, food, fuel and concrete, respectively construction material, have been ignored widely in case their production happens outside the boundary of the city. Moreover, when applying this method cities can claim credit for recycling but neglect the embodied energy associated with its production. This approach would actually always draw a negative picture of a producer city that produces essential material and draw a positive picture of a consumer city. Since GHG inventories are crucial for urban policies, the accounting of only operational emissions can be criticized as insufficient for drawing conclusions on sustainability levels. The chance to raise awareness of the severe impact of aviation or

the importance of fostering the development of recycling (or finding alternatives) of key urban materials is not sufficiently given (Ramaswami et al., 2008).

Anthropogenic stocks on the other hand, as materials that stay in the built environment for a longer time period, are the interface of the city and important for ensuring human development and environmental sustainability. They are utilized by households, governments, the public, or industries over a long lifetime to satisfy service demands like shelter and transportation and to enable industrial production. They drive the raw material demand and shape the physical appearance of the city, its economy and society. Therefore, they have lock-in effects on energy use and emissions, both directly and indirectly (Yu et al., 2018).

The building sector accounts for around 30 % of global energy consumption. Residential buildings alone represent 26 % of the energy consumption in the EU which makes them one of the largest single energy-consuming sectors. The embodied energy, also called grey energy in the German-speaking world, included in the former can represent up to 45 % of the life-cycle energy demand (comprising embodied and operational requirements) of a building over 50 years (Stephan & Crawford, 2014).

Furthermore, the attribute of a long lifetime of built environment stock seriously affects the drastic reduction of GHG emissions that will be necessary to limit the global temperature rise to 2°C, which is set in U.N. climate negotiations as level where human society can be dangerously interfered (Müller et al., 2013). This is, because the service of the stock provided over the lifetime is rigid and determines the operational emissions.

The field of socioeconomic metabolism research has developed methodologies to trace flows of energy and materials and to determine resource use and therewith eco-efficiency of socio-economic systems of various scales (cities and countries). The idea behind socioeconomic metabolism is to transfer the biological concept of metabolism – with the material and energy in- and outflows of organisms and the biochemical processing for providing energy, maintaining the biophysical structures, reproduction and functioning – to human society (Haberl, Wiedenhofer, Erb, Görg, & Krausmann, 2017). Using a top-down approach, data from statistical offices was proven sufficient enough to trace and account material and energy flows within our socio-economic system to determine the resource use of nations. This approach is standardized by *Eurostat* and called "economy-wide material and energy flow analysis", or EW-MEFA (Eurostat, 2001). More recently, the methodology has been applied to lower levels such as cities or regions. However, the numbers of so-called urban metabolism (UM) studies is comparatively lower than nationwide studies, which is mostly related to a great lack of data on the city level.

The approach applied in socioeconomic metabolism has revealed important insights into eco-

efficiency, i.e. the amount of resources used or pollutants respectively GHG emitted per unit of GDP (Haberl et al., 2017).

In Kalmykova et al. (2015) the resource productivity and evidence of economic decoupling were investigated on the basis of the time series 1996−2011 of material flow analysis for Sweden, Stockholm, and Gothenburg (Kalmykova, Rosado, & Patrício, 2015). For this, the GDP/domestic material consumption (DMC) indicator developed by Eurostat was used. The study showed that decoupling of the economy as a whole is not yet happening at any scale. The DMC continues to increase, in parallel with the GDP. However, in the three cases, absolute reductions in CO_2 emissions of approximately 20% were observed, meaning the energy consumption per capita decreased. Moreover, different metabolic profiles could be determined by this study, whereas Gothenburg as an industrial city has a rematerialization trend and Stockholm as a consumer-service city has a dematerialization trend.

Additionally, Rosado et al. (2017) used EM-MFA to identify urban metabolism characteristics based on urban MFA indicators, and to consequently characterize the urban metabolisms of Stockholm, Gothenburg and Malmo from 1996-2011 (Rosado, Kalmykova, & Patrício, 2017). Eight UM characteristics were determined allowing the identification of differentiated urban metabolism profiles. The urban profiles for Stockholm and Gothenburg stated in Kalmykova et al. (2015) were thus confirmed. Malmo´s metabolism was determined as transitioning. Malmo has a higher material demand in particular for construction materials. Moreover, since the economy and exports are based on domestically extracted non-metallic minerals and biomass, its dependency of imports is low.

Unfortunately, such described insights about resource productivity and profiles of UM´s did not yield in resource use reduction, as they were overcompensated by economic growth and rebound effects (Haberl et al., 2017). UM studies so far focused on flow research and neglected the processes in the city – saw the city as a “black-box” – hence more recently the role of in-use stocks is seen as more and more important to reveal climate mitigation options. The present research contributes to a more systematic and comprehensive approach to picture stock-flow relationships, since it intends to cover all resource flows and subsequent material stock dynamics. Haberl et al. (2017) claim that a combination of flow and stock research is also necessary since flows by themselves cannot provide services, only flows and stocks in combination (e.g. m² living space) can (Haberl et al., 2017).

In their most recent contribution to sociometabolic research Haberl et al. (2019) point out the importance of lock-in effects concerning built-up environment stocks, as Müller et a. (2013) and Yu et al. (2018) addressed (described above) (Haberl et al., 2019) . Haberl et al. (2019) estimated that future GHG emissions from fossil fuels required for the operation of the existing built environment until the end of their lifetime amount to approx. half of the remaining emission budget mentioned above. Over

50 % of the sociometabolic material flows is currently used to build up anthropogenic stocks, which induces that the mentioned lock-in effects may worsen. This emphasizes on the important role of the built environment for climate change mitigation options and motivated to critically evaluate the past flow centred research. More holistic may be a stock-flow-service nexus framework, which reflects that the combination of stocks and flows provides services such as shelter or mobility and not only a single one (Haberl et al., 2019).

UM studies so far also did not include the embodied emissions of flows. To include those, an input-output model is usually used, as applied in (Ns, Tionbase, Em, & On, 2018). Here, the C40 Cities Climate Leadership Group investigated the consumption-based GHG emissions of 79 Cities. They used sector-based GHG inventories to estimate GHG emission from household energy use in buildings and private vehicles and used an environmental extended input-output model to calculate GHG emissions from the consumption of goods. Based on financial flow data from national and regional economic accounts the model analyzed expenses from households, businesses and the government. Additionally, it estimated GHG emissions using average GHG emission factors for each consumption category depending on where the goods and services consumed in the city are produced. The results showed that most of the consumption-based GHG emissions of the 79 C40 cities are caused by the trade of materials and products. Around two-thirds of consumption-based GHG emissions are imported from regions outside the cities. This shows that the consumption activities by residents of C40 cities have a significant impact on the generation of GHG emissions beyond their boundaries (Ns et al., 2018).

When including material stock´s embodied emissions, which can then be summed up as carbon replacement value (CRV), what represents the carbon emissions that would be generated if the existing stock was replaced using current technologies, such an above-mentioned Input-Output Analysis or a Life-Cycle-Assessment (LCA) approach has to be applied. Several LCA studies have been developed to analyze the importance of embodied emissions. But most of these studies are focusing on the comparison of impacts of specific building types and do not have a wider scope, such as the evaluation of an entire city. Recently, studies target the assessment of new low-energy buildings, since it is known that they are built with a higher share of materials which are energy intensive in the production, but on the other hand have less energy demand in the use phase. Additionally, a number of studies Heinonen et al. (2001), for example, are going slightly further by incorporating GHG emissions from both construction and use phases covering not just one building, but a whole residential district including infrastructure, which is newly built for energy efficient living. This is illustrated on the example of Helsinki´s metropolitan area (Heinonen et al., 2011). The study estimates the life cycle GHG emissions of the construction phase of the selected district. 94 % of the emissions are caused by the building construction and 6 % by the infrastructure construction. The biggest

sources of embodied emissions in buildings are caused by the use of concrete (12 %), masonry (8 %) and steel (7 %) (Heinonen et al., 2011). This is in most of the cases also the order for the share of material used in the construction sector.

The analysis of the use- phase showed that the dominant source of carbon emissions is the housing energy consumption. The highly interesting outcome of the assessment is that in the assumed lifetime of 25 years, the share of the emissions occurring before the use- phase (embodied emissions) is close to 50 % (Heinonen et al., 2011).

Likewise, the interest of environmental assessments for pavements increased. So far LCA´s on roads and other pavements concentrated on assessing alternatives to the traditional hot mixed asphalt or concrete pavement. To lower the consumption of cement in concrete pavement for example, which greatly contributes to climate change, a new composition is considered with an almost complete substitution of the cement by fly ash, which occurs as waste in incineration processes.

Results show that ordinary concrete pavements cause a higher use of energy in comparison to ordinary asphalt pavements (Giani, Dotelli, Brandini, & Zampori, 2015).

However, to quantify the embodied emissions of a whole city, the complete material stock of the city has to be determined first. For such purpose, a bottom-up approach is preferred since it provides a specific overview and accurate estimations. This methodology uses determined material intensities and stock characteristics like floor area to estimate the material stock. Such approach is time- and data-intensive, which explains the relative few numbers of comprehensive studies. Top-down approaches so far used data of historical consumption of material and their corresponding lifetime to simulate the anthropogenic stocks. This brings along severe limitations due to data gaps, since trade data and consumption data is often not existing on regional level and furthermore the estimation of initial stock when it comes to buildings and infrastructure can be challenging due to their long lifetime (Yu et al., 2018). But there are new methods coming up which are not relying on such data. Nowadays satellite and remote sensing data and techniques showed that nighttime light images are correlating with anthropogenic stocks. This allowed Yu et al. (2018) to map the global anthropogenic stock based on a new set of historical anthropogenic material stock data.

An outstanding analysis (bottom-up approach) exists about Vienna´s material stock in buildings, which is based on data from Geographic Information Systems (GIS) and visualizes the spatial distribution of the material stock. The study was developed for the purpose of reflecting the amount of potential resource supply (urban mining) and planning waste management operations (Kleemann, Lederer, Rechberger, & Fellner, 2017). Information about utilization and construction period to each building provided by the municipality was combined with the data on building size and location from GIS.

The missing part on analyzing the implications on the embodied environmental requirements on an urban level using the quantified material stock is conducted by (Stephan & Athanassiadis, 2017) for the City of Melbourne. Stephan et al. 2017 as well conducted a bottom-up approach to quantify the material stock. The building´s geometry information supplied by GIS data was used to refine their bottom-up model and to estimate the material stocked in residential buildings. Each building archetype was determined based on land-use, age and height using expert knowledge in construction. Then the initial embodied energy and related GHG emissions associated with each material could be calculated using a process-based hybrid analysis approach developed by (Treloar, 1997).

The research gap this study wants to address is the lack of a holistic analysis of the embodied and operational emissions of the anthropogenic stock of an urban metabolism (UM), and especially the relation between those two types of emissions. The city of Odense is used as a case study.

(Goldstein, 2012) already addressed existing shortcomings in UM's ability to capture the embodied environmental load in goods consumed by a city, and therewith, fully quantified a city's (un)sustainability. In the study, a hybrid UM-LCA model is developed and applied to analyze five case cities (Beijing, Cape Town, Hong Kong, London, and Toronto). Like in most UM studies – Goldstein (2012) models the city as a black-box and does not analyze the city´s internal activities, but rather focuses purely on the in- and outflows. In the present study however, the focus is on the anthropogenic stock and the service demand by inhabitants, which are defined as driver for embodied emissions.

In conclusion, determining embodied emissions implies combining MFA and LCA methodologies. This sort of hybrid approach is further explained in the method part.

This study is developed on the hypothesis that the investigation of both embodied and operational emissions in an urban metabolism can reveal more options for climate mitigation than the traditional investigation of only operational emissions. Moreover, by quantifying the contribution of embodied emissions, a possible trade-off can be detected, and counter measurements considered.

According to the above, the thesis aims at answering following research questions:

1) What is the total amount of emissions caused by the City of Odense? (embodied and operational)

2) How much do the embodied emissions contribute to the aggregated emissions?

3) What is the Carbon Replacement Value (CRV) of the built environment?

4) What does this indicate for future planned low carbon city development and policy making?

2 Method

2.1 System Boundary

It is crucial to make clear cut-offs when defining a system, and its spatial, temporal and material boundary.

Figure 1 visualizes the socio-economic metabolism of Odense in a wider perspective, including its connection and dependency to the regional (and global to some extent) environment for securing resource and consumer goods supply. Embodied emissions first occur with the processes to provide materials, in agricultural processes, the extraction and processing of materials and the supply of water. The materials then enter the municipality and are incorporated to the anthropogenic stock, i.e. built environment and mobile stock. In Odense´s metabolism, operational emissions are occurring while operating the stock and – to a lower extent – during the end-of-life (EoL) phase (waste management). But since energy recovery and recycling are implemented in the waste management system of Odense, the EoL phase is also a secondary source for energy and material. Accordingly, those flows are returning to the use phase.

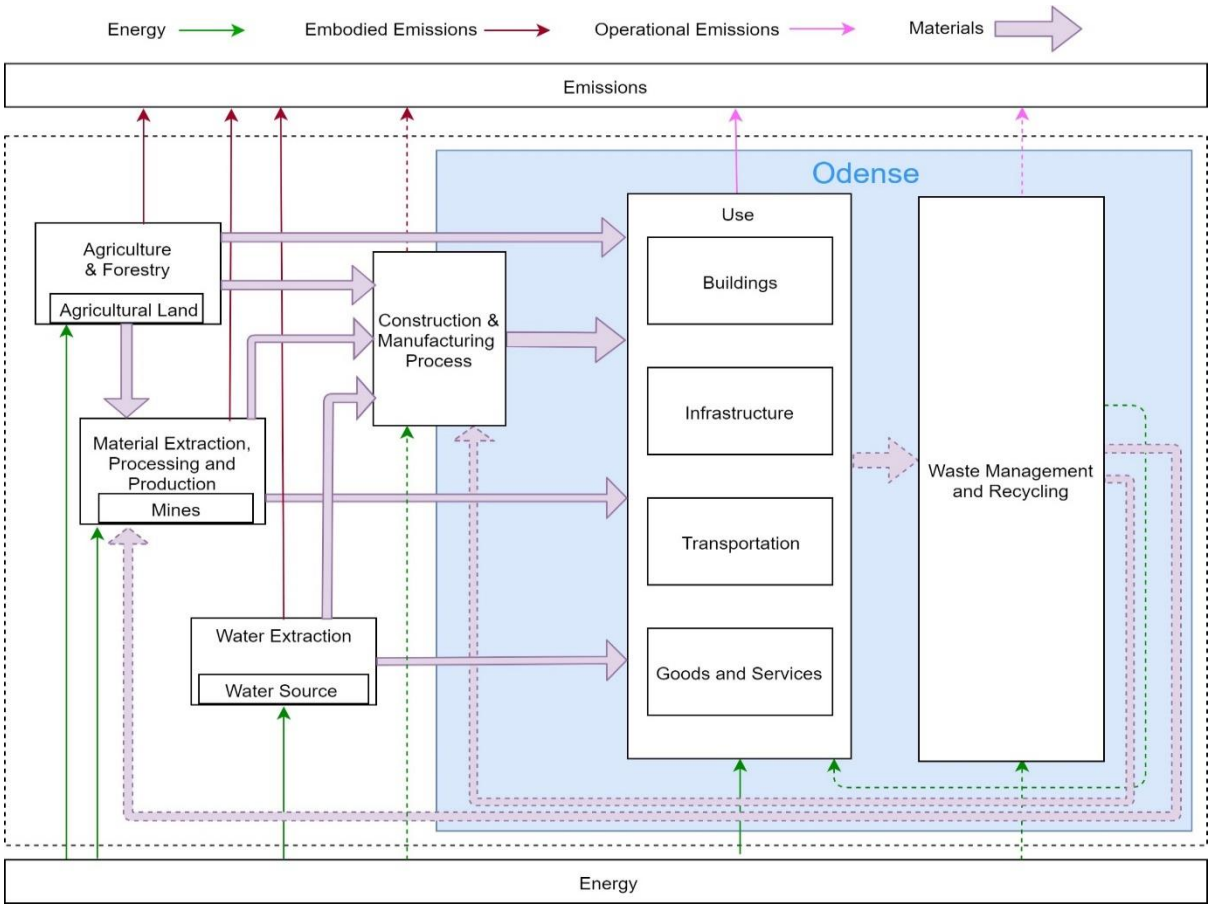


Figure 1: The socio- metabolic system of Odense in a wider perspective with incoming energy which is incorporated into materials for erecting and maintaining the built environment and satisfying the needs of consumers in Odense (spatial boundary blue) and incoming energy for the use of stocks (mobile and built environment) in the UM (inspired by (Müller et al., 2013)*).*

To quantify the embodied emissions caused by the city it is necessary to determine the material inflows of the urban metabolism and the city´s material stocks. Stock can here be thought of as, the accumulated materials within the city, that entered the system as material inflows in the past and are still within the city´s boundaries. The material outflows usually considered in an urban metabolism – solid waste, demolition waste and wastewater - are not quantified in this study (dashed symbols), since emissions from outflows are covered with the operational emissions occurring in the city. Emissions which occurred during the construction phase, are not included in the estimation (dashed arrows). This is, due to the complexity of the estimation and furthermore it is assumed that it will contribute only marginal. (Stephan & Crawford, 2014) conclude in their study that the construction works contribute insignificantly with 1.3 % to the carbon replacement value.

To determine the embodied emissions in flows, first an economy wide material flow accounting is conducted at the municipality level or flows derived from the stock data through outflow and historic inflow modelling. Then data for emission intensities from existing LCA studies and databases are obtained and multiplied by the magnitude of the observed flows.

2.1.1 City of Odense

The case city Odense is the third biggest city in Denmark after Copenhagen and Aarhus and is located on the island of Funen in between the peninsular Jutland (west) and the island Zealand (east) with Denmark´s capitol. Since the island is surrounded by the Baltic Sea, the climate can be defined as mild. Odense is a continuously growing city. In 2007 Odense´s population amounted to 186 745 people, ten years later in 2017 the city had 200 563 inhabitants. Over this period of ten years an average growth rate per year of 0.72 % could be documented. The growth of population accelerated the growth of economic activity and the city is willed to invest 34 billion DKK – converted around 5.18 billion US dollars- in urban development in the coming years (Odense Kommune, 2017b). Sustainability and efficiency are important factors considered in the plans of the municipality which is for example reflected by the initiative *Smart City Odense*, where aspects like better mobility by bike to reduce the CO_2 emissions and more efficient energy and water use are considered, but also how to guarantee a clean urban environment (Odense Kommune, 2015).

Table 1 presents the recent general properties of Odense.

Table 1: Properties of Odense (References in Appendix 7.1) GDP: Gross Domestic Product, HDI: Human Development Index.

	2016	2017	2018
Population	198 972	200 563	204 080
Population density [cap/km²]	657.4	661.8	667.8
GDP per Capita [USD/cap]	60670	61582	
GDP growth rate [%]	1.5		
HDI Value	0.928 and Rank 11	0.929 and Rank 11	
Ave. Daily Temperature [°C]	8.4		

Spatial Boundary

Even though, some of the outer areas of Odense´s municipality are rather rural, the municipal border is chosen to be the spatial boundary (Figure 2(Odense Kommune, 2018)). This is since statistical data is collected and documented for the whole municipality.

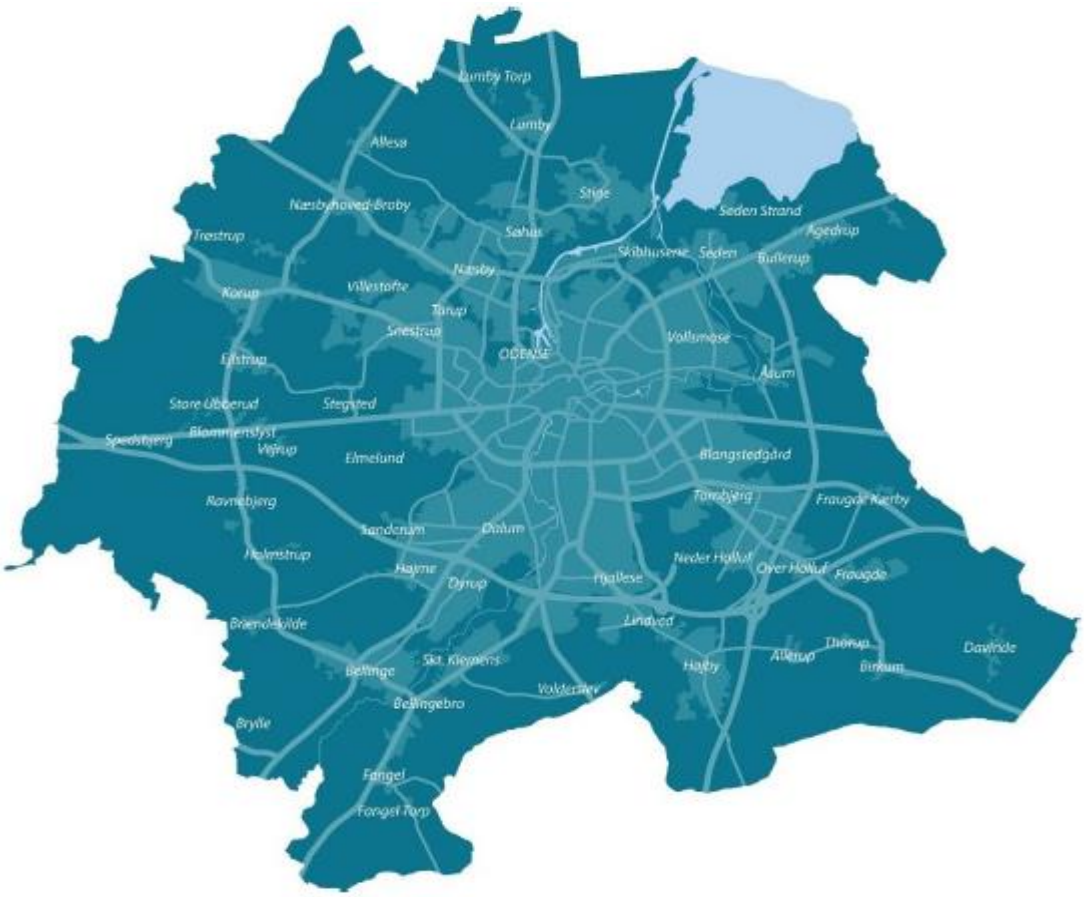


Figure 2: Municipality of Odense (Odense Kommune, 2018)

2.1.2 Stock Categories

Table 2 shows the material stock categories considered in this study. Railways are not considered in the transportation infrastructure. Data on pipe networks for drinking water, wastewater or heating was not available and as well no on cable networks.

Table 2: Material Stock Types

Category	Type
Buildings	- Residential
	- Non-Residential
Transportation infrastructure	- Roads
Mobile Stock	- Vehicles
	- Electronic Appliances

2.1.3 Urban Metabolism Inflows

Following inflows of the UM are considered:

- Energy
- Construction Material
- Food
- Water
- Consumption of Goods
    - Including packaging, vehicles and electronic appliances

2.1.4 Temporal Boundary

Inflows into the municipality were gathered for the years 2010 to 2018. Unfortunately, data on energy consumption in the municipality could only be obtained for the years 2010 to 2015 as well as for packaging. Because of that, for the comparison of embodied and operational emissions the base year 2015 was selected.

The embodied emissions in the built environment respectively the CRV was estimated for the year 2018.

2.1.5 Emission Factors for Carbon Replacement Value and Embodied Emissions

The CRV reveals the amount of CO_2 emissions resulting from erecting the whole built environment of Odense from scratch, under today's status quo conditions and to provide the same level of services

through inflows. In order to calculate Odense's CRV, data on emission factors for material or product are used.

In case of missing data, the embodied emissions were calculated with the current Danish energy mix applied on the electricity needed for providing the material.
(Energinet, 2018) states that, in 2017, the provision of one kWh caused 0,190 kg of CO_2. The Danish Energy Agency (DEA) states a value of 0,290 kgCO_2/kWh (Danish Energy Agency, n.d.). The difference between these two numbers can be explained by the difference in scope in the calculation of these values: while the DEA's value represents the average emission of a produced kWh in Denmark (Danish Energy Agency, n.d.), *Energinet* also includes export and import of electricity. For these reasons, *Energinet's* value was deemed the most relevant in depicting representative Danish conditions.

2.2 Stock Characterization

The methodology to estimate the stock in the built environment and the mobile stock as well as the estimation of their embodied emissions is described in the following.

All stocks were quantified in a bottom-up fashion, estimating material intensity and determining the number of units. Consequently, following formulae summarizes the methodology:

$$Weight\ (kg) = Number\ of\ units\ (unit) \cdot Material\ Intensity\ (\frac{kg}{unit})$$

Due to the time-intensity of a bottom-up approach, the work of estimating the material intensity of residential buildings was shared between members of a founded taskforce, consisting of six members (including the author) which were following:

- Maud Lanau Ph.D Student (SDU Life-Cycle-Engineering)
- Zhi Cao Ph.D Postdoc (SDU Life-Cycle-Engineering)
- Sven Kapfer Master´s Student (SDU M.Sc. Environmental Engineering)
- Jeppe Rossen Moller Master´s Student (SDU M.Sc. Environmental Engineering)
- Julija Metic Master´s Student (SDU M.Sc. Environmental Engineering)
- Luca Herbert Master´s Student (SDU M.Sc. Environmental Engineering)

2.2.1 Residential Buildings

To quantify the material intensity of residential buildings (RB) in Odense in a bottom-up fashion, several steps were needed.
First, representative archetypes were selected. The *Intelligent Energy Europe (IEE) Project TABULA 2009-2012* already developed representative archetypes for Danish residential buildings to display

their energy related features and the possible energy savings by implementing refurbishment measures (IEEP European Union, 2012). Therefore, those were chosen here as well.

Table 3 presents the developed archetypes from the TABULA project and their occurrence in Odense.

Table 3: Number of Buildings per Residential Building Archetypes (IEEP European Union, 2012)

Time cohorts	Single Family House (SFH)	Terraced House (TH)	Apartment Block (AB)
< 1850	448	114	74
1850 – 1930	5494	1311	2211
1931 – 1950	4082	623	1327
1951 – 1960	3804	1639	304
1961 – 1972	8904	3023	194
1973 – 1978	3721	2036	50
1979 – 1998	2999	3320	368
1999 – 2006	793	665	95
2007 – 2010	547	239	66
2011 – present	764	338	112

Second, all Odense's buildings were classified according to the developed archetypes. In the building registry Bygnings- og Boligregistret (BBR) set up by the Ministry for Development and Simplification (Udviklings og Forenklingstyrelsen) all buildings of Denmark and therewith Odense are registered. Odense BBR data was provided by the municipality of Odense. Among other attributes, the BBR register includes the year of construction of each registered building and uses a coding system reflecting each building's end-use (Udviklungs og Forenklingsstyrelsen, n.d.). The coding system was used to classify buildings into the archetypes' end-uses, namely Single-Family-Houses, Terraced-Houses and or Apartment-Buildings. Table 4 below shows the correspondence between BBR and archetype end-uses.

Table 4: BBR codes assigned to end-use from TABULA

BBR codes and description	Archetype end-use TABULA
110-119: Farmhouses 120-129: Single Family houses	SFH
130-139: Terraced, linked or semi-detached houses	TH
140-149: Multi-dwelling houses	AB

With the information of the year of construction the buildings were assigned to the final archetypes. For each archetype end-use a spreadsheet in Excel was created. The order of each of the spreadsheets was randomized with the random-function of Excel. A column was added with the produced number of the random-function and then the spreadsheet sorted by smallest to biggest number. To select sample buildings, it was successively run through each archetype database with selected time-cohort and the addresses used to search in the building plan archive *Weblager.dk* for information (weblager.dk, n.d.). In case enough information about the construction of the building existed, the building could be selected for further analysis. This analysis consisted of quantifying the volumes of the materials the individual buildings are composed of. It was a highly time-consuming work also because in more than a few cases the building plans lacked details (also due to their age e.g. before 1850). Every member of the taskforce was working around 1.5 months on 15 buildings each. Furthermore, to complete the analysis several assumptions had to be done. Those are stated in the attached pdf-file "Annex for RB stock estimation". Lastly, when the volumes were determined they were translated into the total masses applying the individual density.

To determine the embodied emissions of the material built up in Odense´s building stock, values for their global warming potential (GWP) in kg CO_2-Equivalent per kg material were taken from the database *ÖKOBAUDAT* established by the German Federal Ministry of the Interior, Building and Community. The Database serves as mandatory data source within the Assessment System for Sustainable Building (BNB) (ökobaudat.de, 2019). All *ÖKOBAUDAT* datasets are compliant to EN 15804 and have been generated based on GaBi background data. Figure 3 visualizes the methodological steps for determining the material intensity of the built environment stock of Odense and its embodied emissions. Since *ÖKOBAUDAT* is established in Germany, the GHG emissions are calculated with the emission factor for the German energy mix. This factor is usual higher than the Danish. However, it was not possible to find consistent data which considered the Danish energy mix, hence the data from *ÖKOBAUDAT* was preferred.

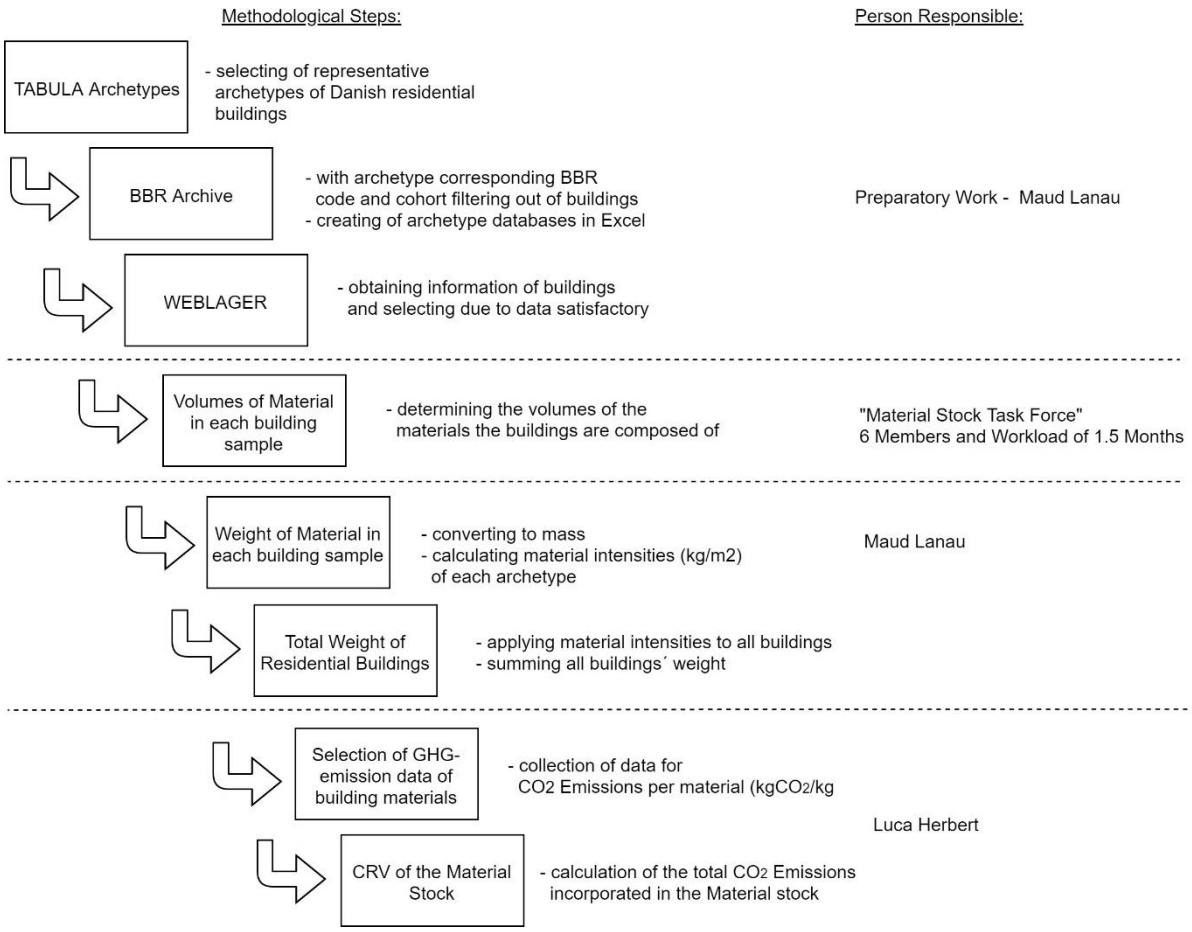


Figure 3: Methodology for determining the material intensity in Odense´s residential building stock and the CRV

2.2.2 Non-Residential Buildings

The data of the material stock in non-residential buildings (NRB) was provided by Maud Lanau and Zhi Cao.

In order to model the non-residential building stock of Odense, they used material intensity data from three sources: Gontia's ongoing work on non-residential buildings in Sweden (personal communication), Ecoinvent database, and formerly calculated material intensities of Odense's residential buildings. They assigned the relevant material intensities to the different end-uses of Odense's non-residential buildings.

The CRV was calculated with the emission factors provided by *ÖKOBAUDAT* as used for the calculation of embodied emission in materials in residential buildings (2.2.1).

2.2.3 Roads

The material stock data on roads was obtained from the master thesis of Miina Mälgand, who was estimating the weight of the city Odense (the total material stock) in a pilot project (Mälgand, 2017).

Mälgand proceeded like following. Data to estimate the road material stock was obtained from the Danish Road Directory´s web geo-spatial data inventory and used in a GIS program. The inventory gave information about the type of road (motorway, traffic way, parking lot etc.), length of road, as well as whether roads have cycle and pedestrian pavement included and how many. Information on the width of roads was available for 38 % of the roads.

Information on specific material compositions of the roads in Odense was not available, why Mälgand used data from (Birgisdóttir, Pihl, Bhander, Hauschild, & Christensen, 2006). Data from (Djuurhus, 1998) was used for the width of the roads, in case the width was not given in the first place.

The CRV of the material stock in roads was estimated with CO_2-emissions factors obtained from *ÖKOBAUDAT* like for the other above described building stock types.

2.2.4 Mobile Stock

In the following, the methodologies for the calculation of material stocked in different mobile stocks are presented.

Electronic Appliances

Figure 4 presents the methodology used to estimate the material stock in consumer electronics and house appliances (summarized electronic appliances).

Figure 4: Methodology to quantify the Material Stock in Electronics

Statistics about the possession (in %) of electronic products in family households, meaning in how many households the product can be expected, were obtained from *Statbank* (A 7.3.2) (StatBank, n.d.-f). The statistics are based on a national survey, but were used to obtain the quantity of electronic products in Odense, with the number of family households in Odense also obtained from *Statbank* (StatBank, n.d.-d). The difference between Odense and the national level regarding the possession of electronic products is assumed to be from minor degree. Data on material composition of electronic products were extracted from the literature (Table 47 and Table 48 , Appendix 7.3.2), and used to estimate the final material amount of electronic products in Odense.

The final embodied emissions were estimated with data on emission factors per product obtained from several sources from the literature (Appendix 7.3.2, Table 52).

Vehicles

The below stated vehicle types were considered for the stock estimation:

- Passenger cars
- Buses
- Vans
- Lorries
- Road tractors
- Trailers for lorries and passenger cars
- Trailers for agricultural tractors
- Semi-trailers
- Motorcycles
- 45-Mopeds
- Agricultural tractors
- Caravans

The number of vehicles in Odense was obtained from *Statbank* for the period 2010 to 2018 (StatBank, n.d.-b). Data on material composition of the existing stock was extracted from the literature (Appendix 7.3.1). Information could be found for passenger cars, vans, buses and lorries. Additionally, data related to the upcoming light rail trains were retrieved through personal communication with the municipality (Odense Letbane, 2019). For the material composition of other vehicle types, assumptions were made (Appendix 7.3.1). For the estimation of embodied emissions per vehicle type the Ecoinvent v3 database (Allocation Cut-off) in SimaPro was used. The corresponding assumptions are presented in the Appendix 7.3.1 as well.

2.3 Inflows

2.3.1 Consumption of Goods

The inflow of consumption of goods includes packaging materials, vehicles and electronic appliances.

Packaging

The consumption of packaging was derived from the national waste statistics of *Statbank* (StatBank, n.d.-a), where data was available for the timespan 2010 to 2015. It is assumed that the waste generation is representative of the inflow of packaging into the urban metabolism of Odense. Packaging is likely produced somewhere outside of the municipality and is imported together with goods. Export of packaging waste and goods from Odense is deemed to be minor.

The waste generation was stated in total for Danish households. With the number of Danish households in total, the generation by households (t/households) was calculated and afterwards the total amount generated by Odense with the number of households in the municipality. Data on the number of households was derived from *Statbank*, too (StatBank, n.d.-d).

Only data on the household sector could be used, not on industry or public, since the original numbers are national and waste by industry or other sectors are impossible to convert to estimate the amount in Odense.

Vehicles

The data on inflows of vehicles was derived from the stock data (2.2.4). A static lifetime of 13 years for vehicles was assumed, with a standard deviation of 2.6 years. A normal lifetime distribution was applied. Using the growth rate, the historic stock until 1950 was calculated. With the stock data and the lifetime distribution it was possible to model the outflows, what allowed to determine the surviving historic inflows. The stock at year "X" minus the sum of the surviving historic inflows equals then to the inflow at year "X".

Electronic Appliances

The data on inflows for electronic appliances was derived from the stock data (2.2.4). For house appliances a static lifetime of 9.28 years was assumed, with a standard deviation of 1.86 years. A normal lifetime distribution was applied. Historic stock data existed for most of the appliances and if not, assumptions were made, and growth rates used (Appendix 7.4.3). In case there were fluctuations in the stock data, which would mean a negative inflow, the moving average tool in excel was used to smoothen the fluctuations (Appendix 7.4.3).

For consumer electronics a static lifetime of 4.55 years was assumed, with a standard deviation of 0.91 years. A normal lifetime distribution was applied. Historic stock data was calculated using growth rates. For several products the stock was decreasing, because the technology was outdated. For those it was assumed, that from the turning point when the stock data decreased the inflows equal zero. In case of fluctuations in the stock data, the mentioned, moving average tool was used to smoothen the data (Appendix 7.4.3).

Using the edited stock data and the lifetime distributions, the outflows and hence the surviving historic inflows could be modelled. The stock at year "X" minus the sum of the surviving historic inflows equals then to the inflow at year "X".

2.3.2 Water

Data for the water consumption was obtained from the annual report of Odense municipality (Odense Kommune, 2018). Godskesen et al. (2013) conducted an LCA of the water consumption in Copenhagen, and those results are deemed appropriate to use for Odense (Godskesen, Hauschild, Rygaard, Zambrano, & Albrechtsen, 2013). The water is extracted from groundwater sources located outside the city and then treated ate the waterworks (aeration and sand filtration) before distribution, resulting in an energy consumption of 0.27 kWh per m^3 of water consumed. The final emissions are then calculated with the conversion factor of 0.190 $kgCO_2$/kWh (mentioned in chapter 2.1.5).

2.3.3 Food

Statistics about food consumption in Odense do not exist. However, a Danish national survey about diets was conducted between 2011 and 2013 (Pedersen et al., 2015). Even though the survey did not specifically target citizens of Odense and is now a few years old, the data can be seen as representative. Indeed, diet habits are assumed to be similar between the different regions of Denmark, and to not have significantly changed in the last years.

Table 5 shows the values stated in the food survey. The results of the total consumption are calculated using the consumption per age interval and the number of inhabitants in that interval per that particular year. The consumption of people above the age of 75 was assumed to be the average of the consumption of the defined age intervals, this means a lower consumption than the one for adults but a higher than for children. This seems representative for elderly diet habits. The consumption for children below the age of four was calculated with the values for consumption for the age interval 4 to 9. This is likely an overestimation, but the number of children in that age interval are comparatively very small.

Table 5: Danish food consumption by age interval and food category (Pedersen et al., 2015)

Food Product (g/day/cap)	Consumption by age Interval			Average Consumption
	4 to 9	10 to 17	18 to 75	
Milk and milk products	428	407	304	380
Cheese and cheese products	21	25	44	30
Bread and other cereals	216	219	218	218
Potatoes and potato products	40	74	91	68
Vegetables and vegetable products	157	144	199	167
Fruit and fruit products	188	141	190	173
Juice	59	75	56	63
Meat and meat products	87	120	134	114
Poultry and poultry products	16	27	26	23
Fish and fish products	16	15	37	23
Egg	18	17	24	20
Fatty substances	37	36	41	38
Sugar and Candy	35	38	37	37
Beverage	758	1120	2180	1353
Total	**2076**	**2458**	**3581**	**2705**

To estimate the embodied emissions however, the exact amount of food per category was not being used, because data could not be obtained with one consistent system boundary for all categories. The emissions were then estimated using the energy consumption for providing food determined in an Input-Output-Analysis conducted by (Girod & de Haan, 2010), whose study is about the GHG emissions driven by the consumption of Swiss households. The energy consumption was converted into CO_2-eq with the value of the Danish energy mix. The Swiss diet habits are considered to be similar to Danish, both countries are similarly developed and, have a high HDI, and diet differences between middle and north European can be considered small. (Girod & de Haan, 2010) considers beside the consumption of food as well beverages.

2.3.4 Construction Material

The inflow of construction material were estimated with the material intensity (2.2.1) for RB and NRB and data from the statistics about completed floor area per year in Odense (Appendix 7.4.1) (StatBank, n.d.-c). The material intensity per m² of the most recent archetype was taken and multiplied with the newly added floor area per year. Residential buildings and non-residential buildings are considered, data on materials for infrastructure construction was not available. Assumptions on material intensities for building types are attached (Table 56, Appendix 7.4.1)

The methodology can be summarized with following formulae:

$$material\ weight\ \left(\frac{kg}{a}\right) = material\ intensity\ \left(\frac{kg}{m^2}\right) \cdot floor\ area\ added\ (\frac{m^2}{a})$$

The embodied emissions in the construction material was estimated same as for the materials in the stock with the emission factors obtained from *ÖKOBAUDAT*.

Furthermore, data on the currently ongoing big construction projects in Odense - the light rail system and the new hospital - was collected to display future construction material demands.

2.3.5 Energy and Operational Emissions

Data was retrieved from the Danish Ministry for Energy and its portal *Sparenergi.dk* (Energistyrelsen, n.d.). The ministry provides detailed information about the sources of the emissions and energy consumption. Data exists for the years 2010 to 2015 and is visualized to capture the trend over the years.

3 Results

3.1 Built Environment Stocks

In the following, the material stock of the built environment of Odense is presented.

3.1.1 Residential Buildings

Figure 5 visualizes the material stock in residential buildings (2018) aggregated into six material categories (disaggregated results can be found in (Appendix 7.2.2)). In total, 14 473 kt are built up in residential buildings in Odense. As shown in Figure 5, the majority of the stock are non-metallic minerals, which is not surprising as the category includes concrete and concrete elements. The second biggest material category is ceramics and bricks, which includes clay bricks. Clay bricks are the most used building elements for outer masonry in Denmark.

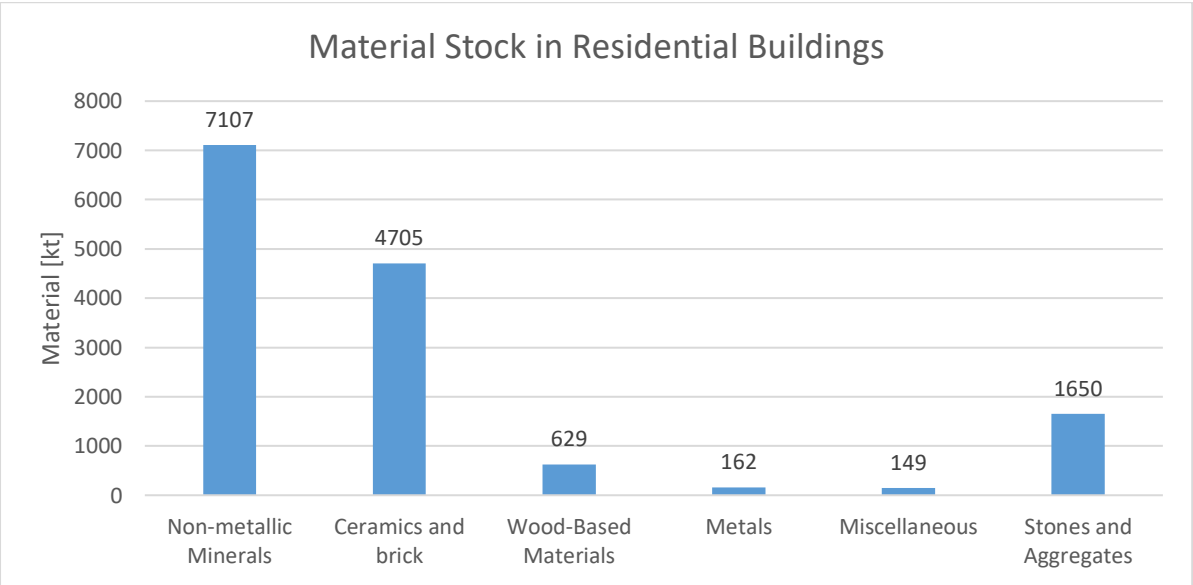


Figure 5: Material Stock in Residential Buildings in Odense 2018

Following Figure 6 shows the CRV in the material stock in residential buildings. It is visible, that most of the carbon is stored in ceramics and bricks, followed by non-metallic minerals, although they make up the biggest share in materials absolute. This is, due to very low emission factors for the materials in that category. Apparently, the production of concrete causes 0.11 $kgCO_2/kg$ (ökobaudat.de, 2019). In contrast, for clay brick an emission factor of 0.271 $kgCO_2/kg$ is given.

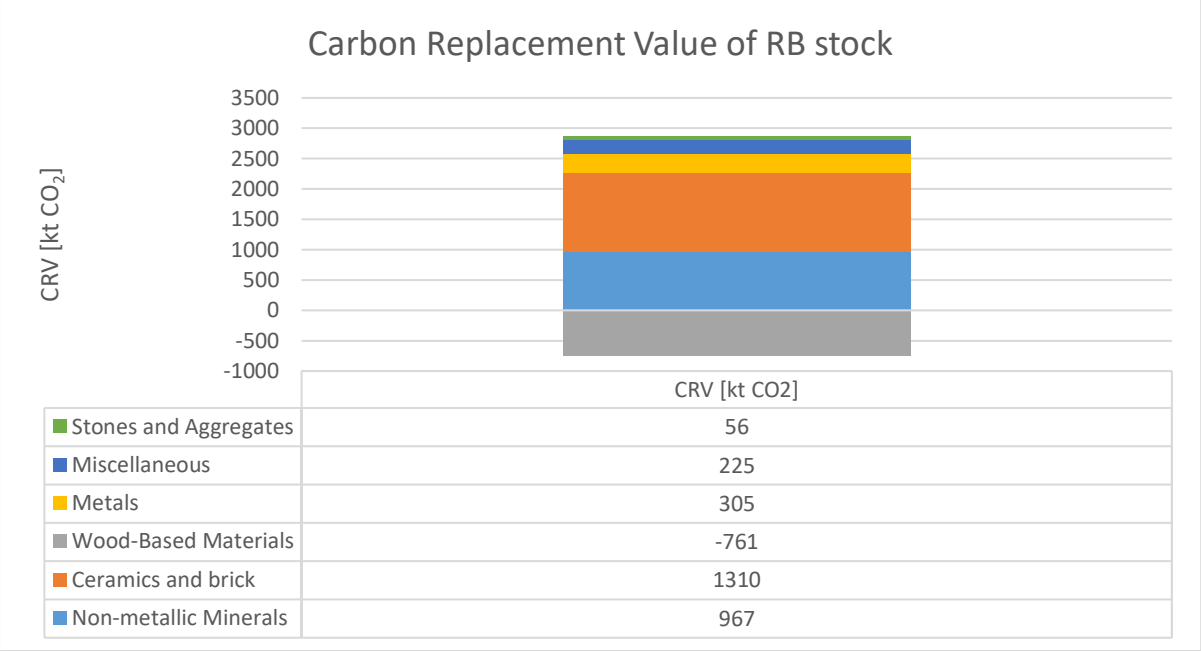


Figure 6: The Carbon Replacement Value of the Residential Building Stock 2018

Wood-based materials are contributing negatively to the total CRV, due to the negative emission factors provided by *ÖKOBAUDAT*. The total CRV of the residential building material stock amounts to 2103 kt CO_2.

3.1.2 Non-Residential Buildings

Figure 7 visualizes the material stock in NRB´s aggregated into six material categories, the disaggregated results are attached (Appendix 7.2.3). In total 14 182 kt are built up in NRB´s in Odense. As shown in Figure 7, most of the stock are non-metallic minerals as for residential buildings. Also, like for RB´s, the second biggest material category are ceramics and bricks, though they take a lower share in comparison. This seems reasonable, because for non-residential buildings aesthetic as criteria is less important and thus the masonry does not have to be from clay brick and can be plane concrete. Function is seen more important in NRB´s. Furthermore, the data on material intensities used is originates from Sweden, where comparatively less clay bricks are used as in Denmark (Lanau, 2019). The ratio between the category´s ceramic and bricks and non-metallic minerals is therewith plausible (in comparison with RB´s). Furthermore, metals contribute higher for these building types, which can be explained with the more complex building structures, especially regarding heavy loads.

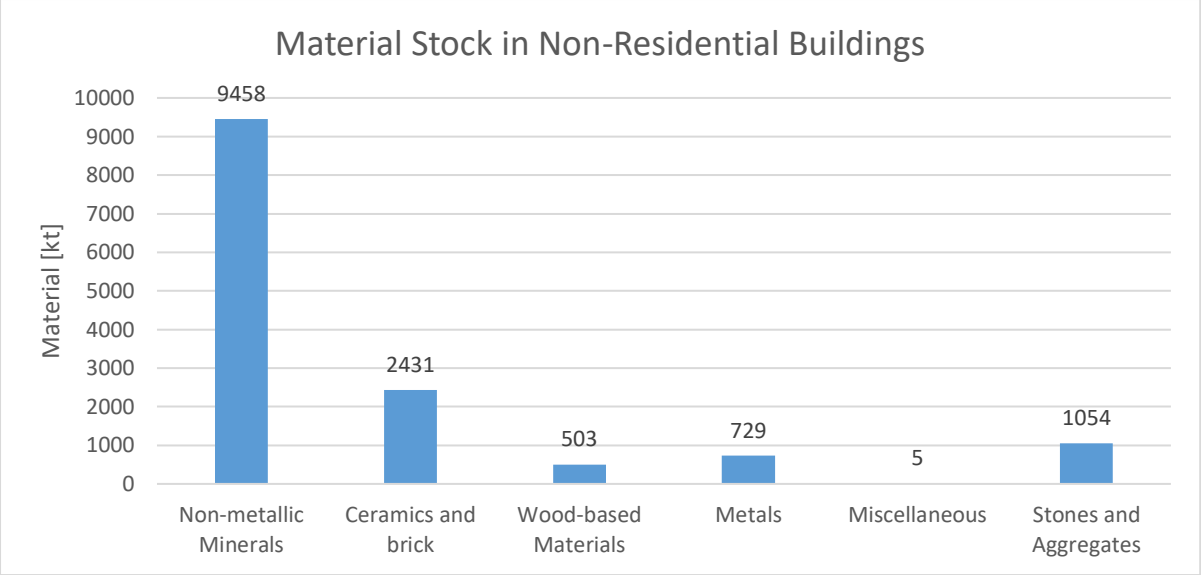


Figure 7: Material Stock in Non-residential Buildings in Odense 2018

Following Figure 8 shows the CRV in the material stock in NRB´s. It shows, that most of the carbon is stored in ceramics and bricks, followed by non-metallic minerals, although they make up the biggest share in materials overall. This is, due to very low emission factors for the materials in that category as mentioned in 3.1.1.

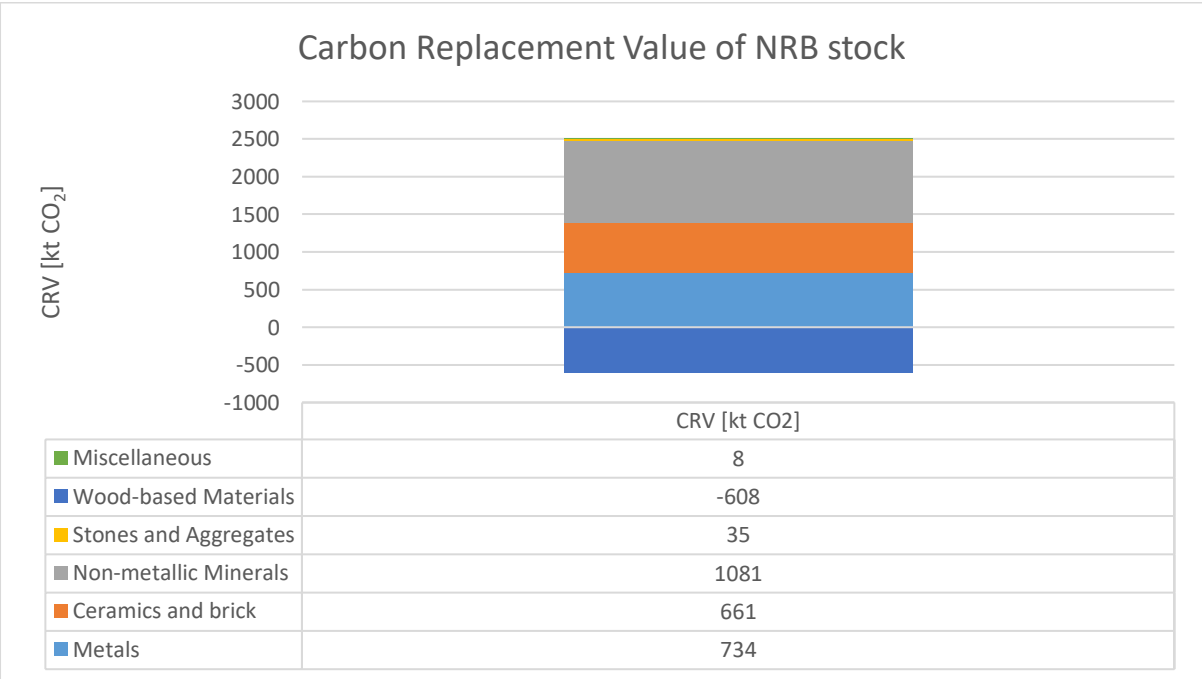


Figure 8: The Carbon Replacement Value of the NRB Stock in 2018

The total CRV of the NRB material stock amounts to 1911 kt CO_2.

3.1.3 Roads

The results of the material stock analysis for roads are listed in following Table 6. The total stock in roads amounts to 23.6 million tons. 85 % of the stock is gravel, which seems reasonable as it functions as basis for roads.

Table 6: Material Stock and related CRV in Roads in YEAR XX

Material	Mass [kt]	CO_2 emission factor $kgCO_2/kg$ [1]	CRV [kt CO_2]
Concrete	3275	0.111	363
Asphalt	182	0.074	13
Gravel	20 146	0.033	670
Total	23 603		1047

[1] References (Table 24, Appendix 7.2.4)

The CRV of the stock in roads is equal to 1047 $ktCO_2$.

3.2 Mobile Stock

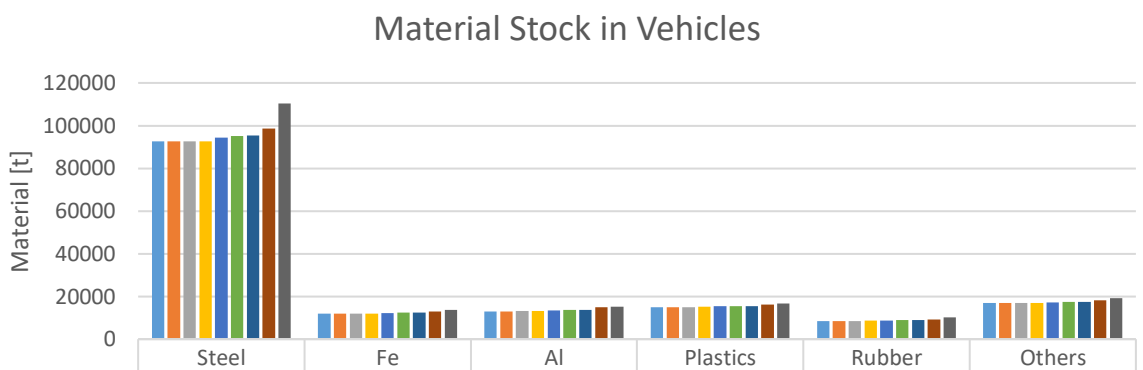
In the following, the results for the two mobile stock types - vehicles and electronic appliances – are presented.

Vehicles

The private car fleet in Odense increased over the last 8 years from 64 837 cars in 2010 to 75 617 cars in 2018 according to the statistics (Table 25, Appendix 7.3.1).

This is compliant with the statements in the mobility plan of Odense. The municipality even estimates an increase of the car fleet by 37 % from 2014 to 2024 (Odense Kommune, 2017a). Caravans, 45-Mopeds and Vans were decreasing in number, however they do not make up for a significant share. The number of motorcycles increased slightly as well as the number of trailers. Trailers are high in number and increasing due to their correlation with the car fleet.

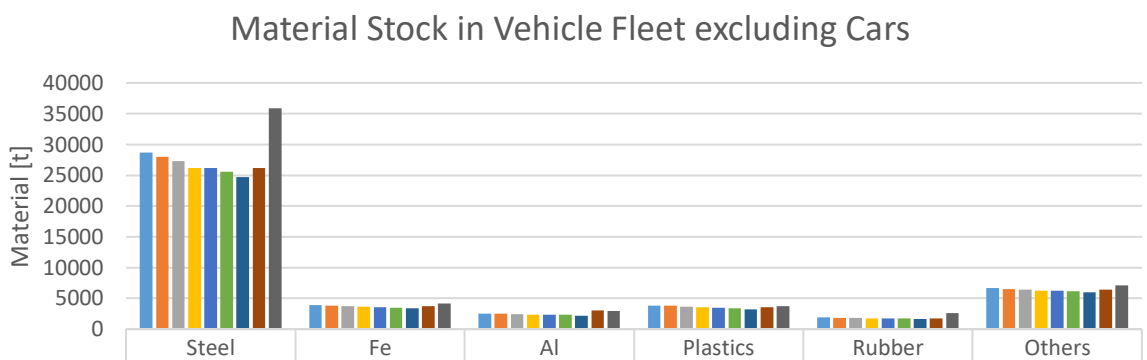
The material stock for the total vehicle fleet is visualized in Figure 9. A rising trend is visible throughout the years. The highest amount, by far, of material in the vehicle stock is steel, followed evenly by plastics, iron and aluminum.



	Steel	Fe	Al	Plastics	Rubber	Others
2010	92586	12045	12920	14940	8475	16946
2011	92627	12052	13073	15003	8498	16970
2012	92604	12029	13109	14994	8528	16934
2013	92728	12069	13209	15083	8582	16978
2014	94435	12259	13524	15348	8761	17254
2015	95197	12338	13684	15470	8869	17360
2016	95493	12344	13785	15529	8934	17378
2017	98520	12877	14872	16120	9180	18077
2018	110396	13591	15154	16705	10219	19174

Figure 9: Material Stock in Vehicles 2010-2018

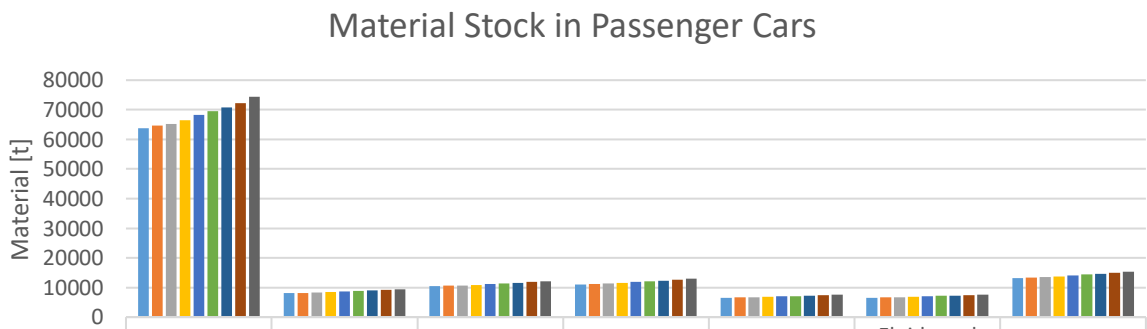
Out of the total vehicles stock, the highest share is made by the car fleet. When excluding this share from the total stock in vehicles it gets visible that the car fleet (Figure 11) is the main responsible for the increase of vehicles material stock. Figure 10, displaying the material stock of non-car vehicles, shows a general decreasing tendency. The last two years though, have to be observed with caution. In 2017 a sudden jump in bus stock is stated in the statistics from 174 buses in 2016 to 520 buses in 2017. As well the number of lorries increased extraordinarily from 385 in 2017 to 721 lorries in 2018. The reason for the sudden rises is likely a change in the counting method.



	Steel	Fe	Al	Plastics	Rubber	Others
2010	28721	3940	2482	3853	1926	6644
2011	27969	3847	2505	3778	1869	6539
2012	27289	3740	2433	3655	1831	6395
2013	26153	3620	2328	3525	1756	6235
2014	26171	3596	2366	3497	1761	6238
2015	25582	3504	2305	3385	1731	6125
2016	24714	3362	2216	3241	1677	5955
2017	26163	3694	3045	3559	1761	6399
2018	35913	4138	2980	3774	2582	7152

Figure 10: Material Stock in Vehicle Fleet excluding Cars

Following Figure 11 shows the material stock for the car fleet only. A steady increase is visible.



	Steel	Fe	Al	Plastics	Rubber	Fluids and Lubricants	Others
2010	63837	8105	10439	11086	6528	6557	13203
2011	64630	8205	10568	11223	6609	6639	13367
2012	65287	8289	10676	11337	6676	6706	13502
2013	66546	8449	10882	11556	6805	6835	13763
2014	68235	8663	11158	11849	6978	7009	14112
2015	69585	8834	11379	12084	7116	7148	14391
2016	70749	8982	11569	12286	7235	7267	14632
2017	72325	9182	11827	12559	7396	7429	14958
2018	74451	9452	12174	12929	7613	7647	15398

Figure 11: Material Stock in Passenger Cars 2010-2018

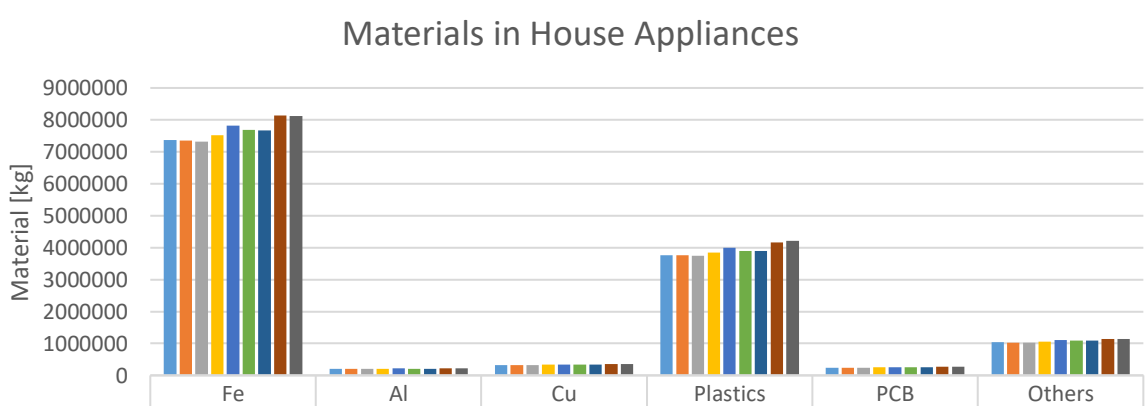
In total, the vehicles material stock increased from 180 869 tons in 2010 to 212 541 tons in 2018, meaning a gain by 18 % in 8 years.

Using Ecoinvents database in SimaPro, the CRV of the mobile stock in 2018 amounted to 727.5 kt CO_2.

Because of the opening of the light rail system, the vehicle fleet in Odense will grow in 2020 by 16 light rail trains from the model Variobahn by manufacturer Stadler (Odense Letbane, 2019). The train will have a tare weight of 41.8 tons, meaning a total addition to the material stock in the vehicle fleet in 2020 by 668.8 tons (strassenbahn-online.de, 2019).

Electronic Appliances

According to the statistics (Table 45, Appendix 7.3.2), the possession of the most common house appliances (e.g. dryer, washing machine, dishwasher and microwave) per family households stayed the same over the last 8 years. The absolute number however increased, driven by the population rise. The increasing number of those common appliances also caused a raise in the material stock of the city. As Figure 12 indicates, the amount of the materials majorly used in the appliances, such-as iron, aluminium, copper and plastics continuously rose over the period.

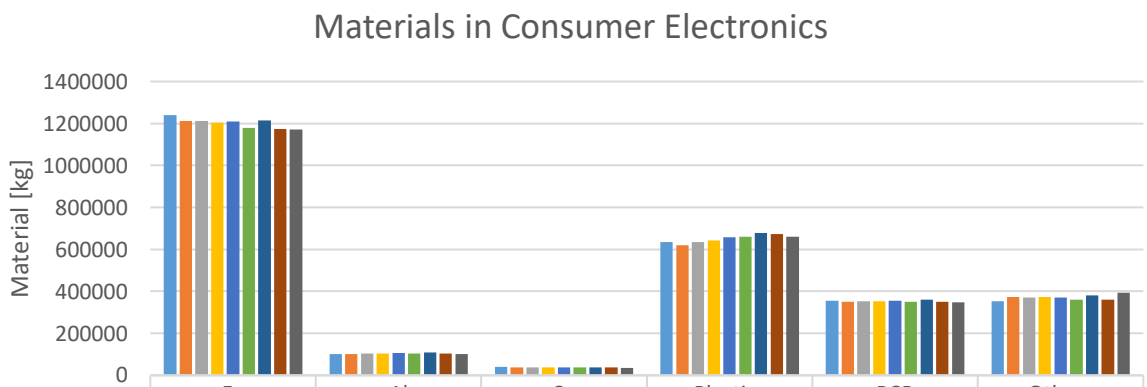


	Fe	Al	Cu	Plastics	PCB	Others
2010	7372038	201378	324170	3756185	239832	1034083
2011	7347191	201529	324841	3754927	239523	1029038
2012	7312711	199846	321267	3738336	238394	1028873
2013	7520986	205276	332089	3837900	246898	1058799
2014	7815186	213804	344090	3997393	255091	1098989
2015	7685553	207770	334878	3896506	251047	1086263
2016	7661849	207604	333505	3892524	249384	1081784
2017	8129646	222815	358505	4165953	265487	1142955
2018	8126800	229517	359866	4210531	265808	1142371

Figure 12: Material Stock in House Appliances

The statistics for consumer electronics (Table 45, Appendix 7.3.2) indicate the common technological change of the last years. There is a decreasing trend for electronics like digital camera, DVD- and CD-Player or landline telephone, and a rising trend for products like smartphone, tablet and laptop. This

is also visible in the material stock change in Odense over the time period (Figure 13). The outdated products are more material intensive than the modern ones, so a decrease in iron is visible. The other materials are steadily present in the material stock over the period. This is likely due to the population rise.



	Fe	Al	Cu	Plastics	PCB	Others
2010	1239183	102311	39980	635546	356640	352944
2011	1212734	101512	38311	620943	349374	372040
2012	1212343	103072	38542	634662	352211	369891
2013	1205454	103563	38599	642788	352757	373607
2014	1209799	107088	38372	657686	355874	370704
2015	1178213	104406	37676	661177	349274	360941
2016	1214678	108551	38218	679366	360847	381540
2017	1172985	103980	37022	672276	349201	359906
2018	1170623	100856	36382	659619	347712	393222

Figure 13: Materials in Consumer Electronics 2010-2018

Table 7 below shows the total material stock in consumer electronics and house appliances in the years 2010 to 2018. The slight increase in stock over the years resulted in a total stock of 17 043 t material in 2018.

Table 7: The Weight of Material Stock of Electronic Appliances

	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Consumer Electronics [t]	2727	2695	2711	2717	2740	2692	2783	2695	2708
House Appliances [t]	12 928	12 897	12 839	13 202	13 725	13 462	13 427	14 285	14 335
Total [t]	*15 654*	*15 592*	*15 550*	*15 919*	*16 464*	*16 154*	*16 210*	*16 981*	*17 043*

3.3 Total Stock

The absolute amounts of all considered stock types are summarized below (Table 8). 99.3 % of the materials are in the built environment (RB, NRB and roads). In year 2018 the total stock in Odense amounts to 52.6 Mt.

Table 8: Weights of all considered stock types (2018)

Stock type	Mass [kt]
Vehicles	201
Electronics	17
RB	14 473
NRB	14 182
Roads	23 603
Total	*52 576*

3.4 Carbon Replacement Value 2018

Embodied emissions in stock can be basically seen as CRV, since they represent the emissions it took to extract, to produce and to install the materials.

Following Figure 14 visualizes the CRV respectively embodied emissions of the stock – mobile and from built environment – in year 2018. It would cause 6 039 kt of CO_2 emissions to provide the service of the built environment and the mobile stock in Odense in year 2018.

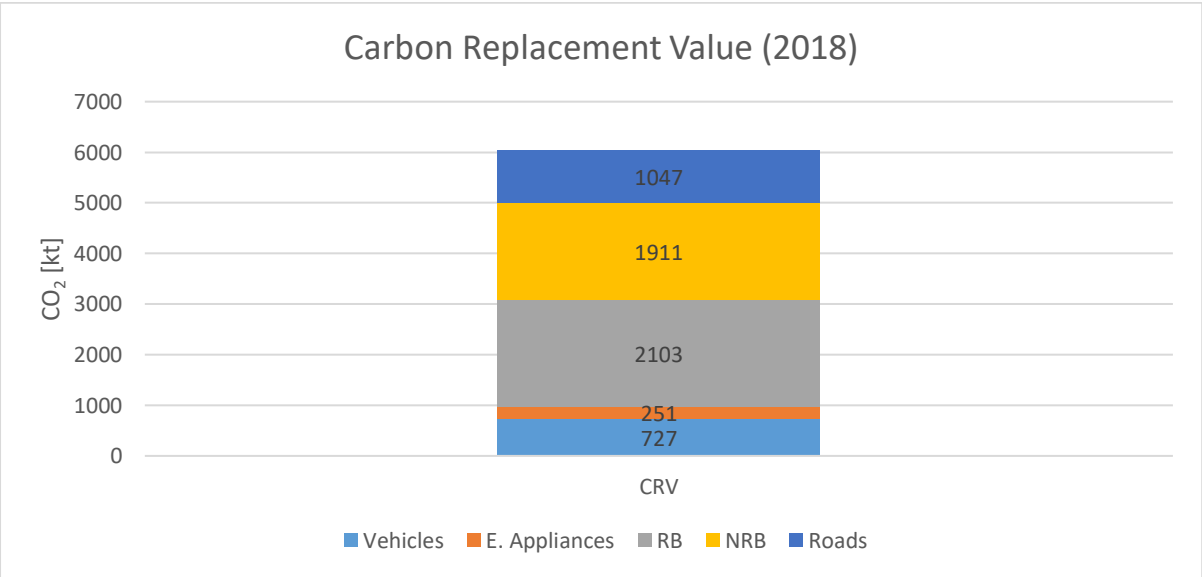


Figure 14: Carbon Replacement Value of stocks in Odense 2018

As visible in Figure 14 the majority of carbon is embodied in RB and NRB which appears to be logical since the majority of the materials are erected in the built environment. Nevertheless, interesting is that the contribution of the mobile stock is quite high with around 16 %, keeping in mind that mobile

stock is only 0.4 % of the total material weight in the stock. This is pointing out the high energy requirements to provide goods like vehicles and electronics.

3.5 Inflows

3.5.1 Water

Table 9 shows the water consumption in Odense over the period 2011 to 2017.

Table 9: Water Consumption (Odense i tal 2018) and corresponding embodied emissions over the period 2011-2017

Year	2011	2012	2013	2014	2015	2016	2017
Private [kt]	6110	6141	6041	6052	5959	6015	5999
Business/Industry [kt]	2082	1940	2119	2173	2126	2151	2226
Total [kt]	8192	8081	8160	8225	8085	8166	8225
Emissions from Distribution [t CO_2]	420	415	419	422	415	419	422

The water consumption over the years from 2011 to 2017 stays fairly constant (Figure 15). The consumption remains on one level. This means a gain in efficiency, since the population rise did not have an impact on the total consumption. This is as well claimed by the municipality (Kommune Odense, 2018). To reduce the consumption of water, water measurement tools were installed in households, which helped both the consumer and the municipality to follow the consumption. As well a more efficient toilet flush system was installed in many households and they implemented that water which does not fulfil the requirements of drinking water is used by industries with special permission. Lastly, the piping system was renewed to reduce the losses in the network (Kommune Odense, 2018).

According to the steadily consumption of water throughout the years, the emissions from distribution of the water are on a similar level over the period. In 2017 they amounted to 422 ton of CO_2.

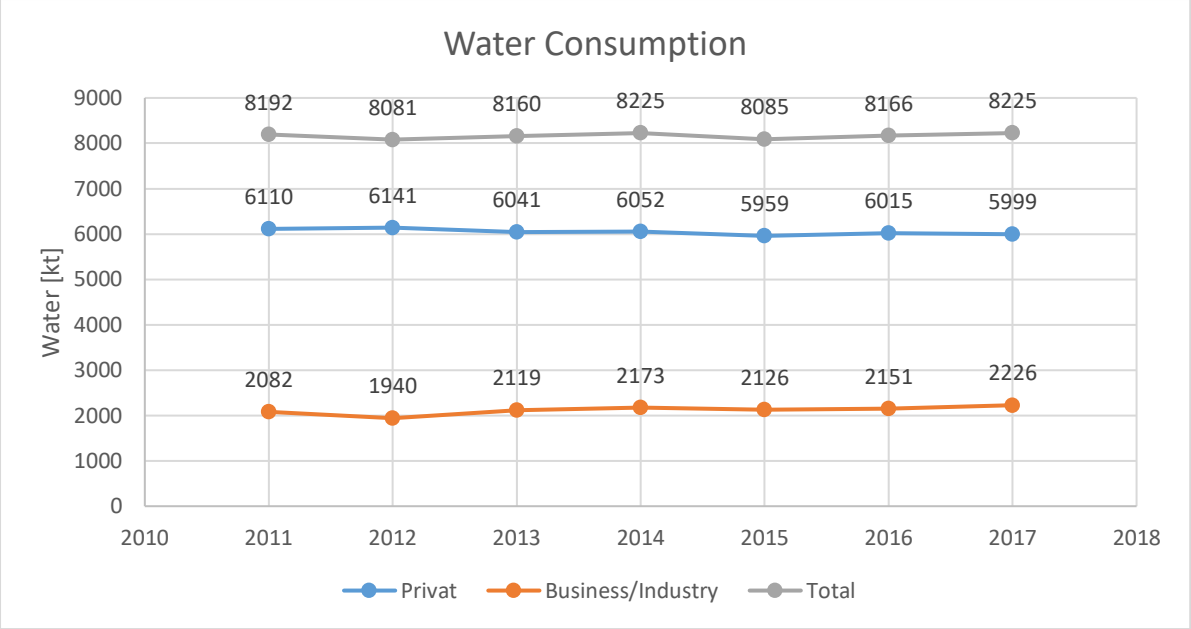


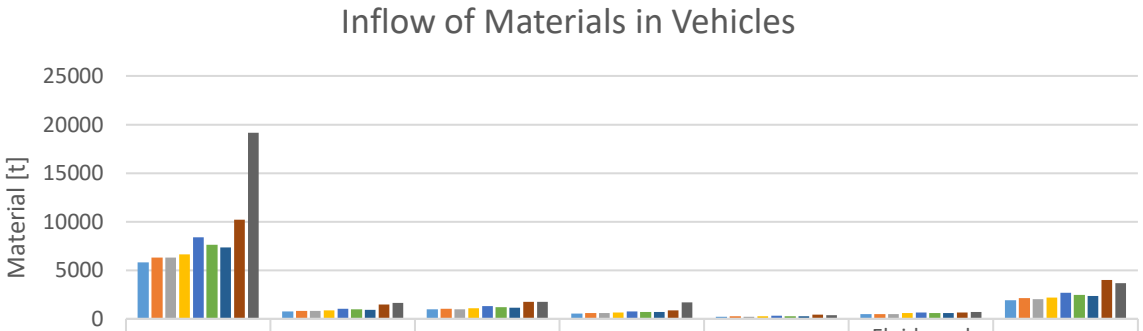
Figure 15: Water consumption in Odense in the years 2011 to 2017

3.5.2 Consumption of Goods

The results for the inflow of consumption of goods, considering vehicles, electronic appliances and packaging are displayed below.

Vehicles

The increasing trend in the vehicle fleet (mostly of cars) is visible in the trend of the incoming materials (Figure 16). The growth between 2010 and 2016 was quite linear, followed by sudden jumps in inflows for mostly all of the materials, but very significant for steel. This can be explained by the strong increase of the fleet of buses and lorries, which is as prior mentioned probably resulting from a change in the counting method.



	Steel	Fe	Plastics	Rubber	Glass	Fluids and Lubricants	Others
2010	5796	747	962	558	224	489	1925
2011	6281	823	1059	589	244	505	2161
2012	6320	801	1000	606	231	498	2017
2013	6610	881	1117	644	256	572	2206
2014	8369	1053	1321	785	303	629	2699
2015	7611	965	1207	732	281	607	2439
2016	7327	916	1173	706	276	603	2355
2017	10208	1463	1734	901	409	659	4029
2018	19154	1658	1748	1704	377	727	3686

Figure 16: Inflow of Materials in Vehicles (2010-2018)

Electronic Appliances

Figure 17 illustrates the inflow of materials from consumer electronics. The inflow of materials fluctuates fairly strong over the shown period 2010 to 2018. The graph does not induce a clear trend.

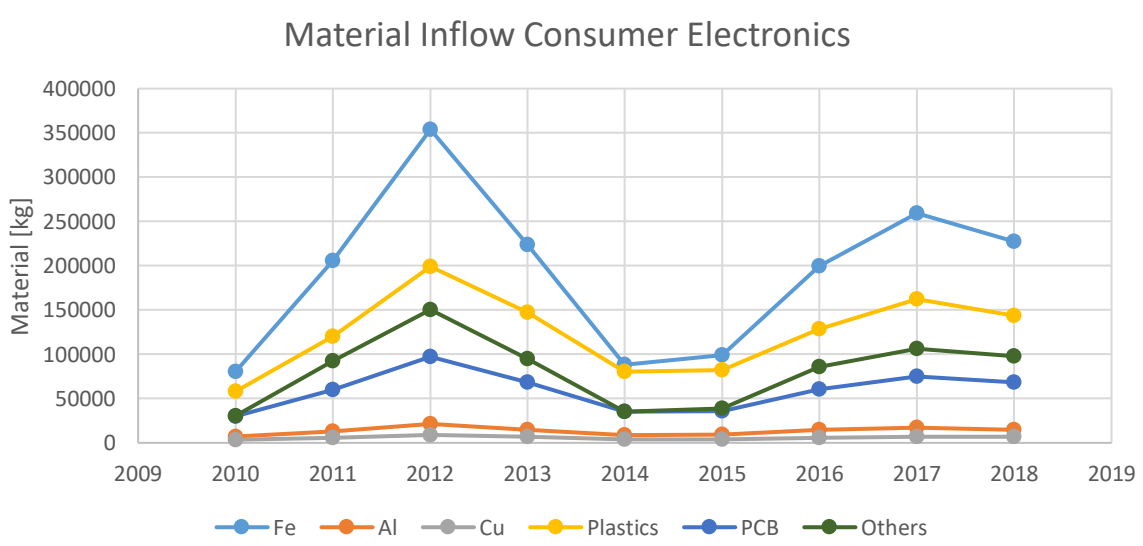


Figure 17: Material Inflow from Consumer Electronics

Figure 18 shows the inflows of material from House Appliances in the period from 2010 to 2018. In the years until 2014 a clear increase is visible, followed by a decrease until 2018 which is from a lower slope, though. In overall, a slight increase of the flow can be interpreted.

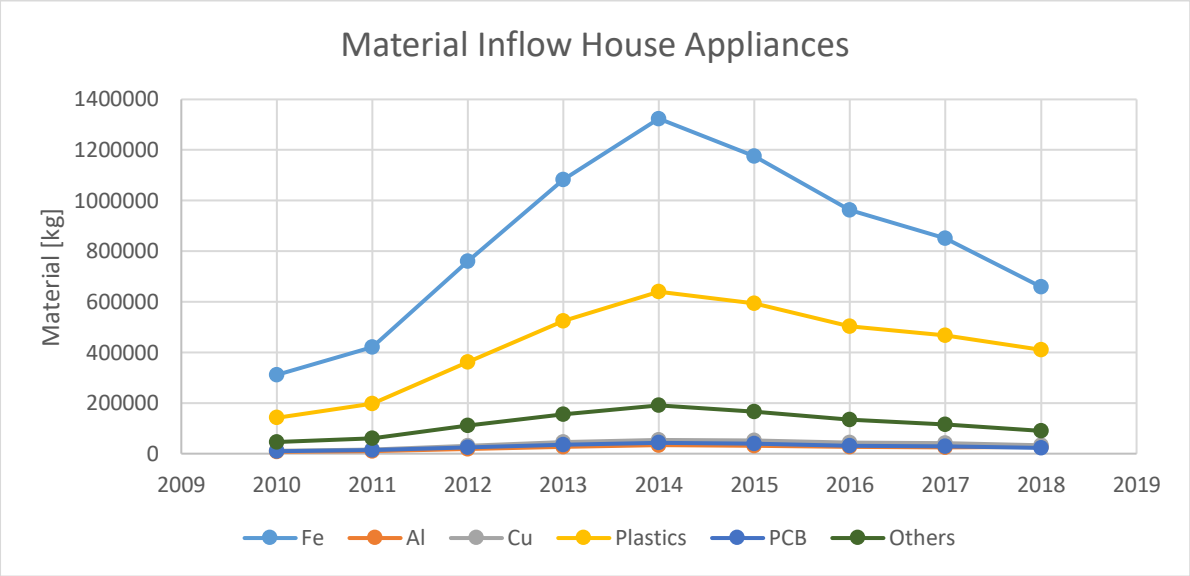


Figure 18: Material Inflow from House Appliances

Table 10 summarizes the results of the material inflow of electronic appliances in the period 2010 to 2018. In 2015 a peak is visible with 2536 t. House appliances making up for the majority of the inflow in all years. This seems reasonable, since they include bulky appliances like washing machines etc.

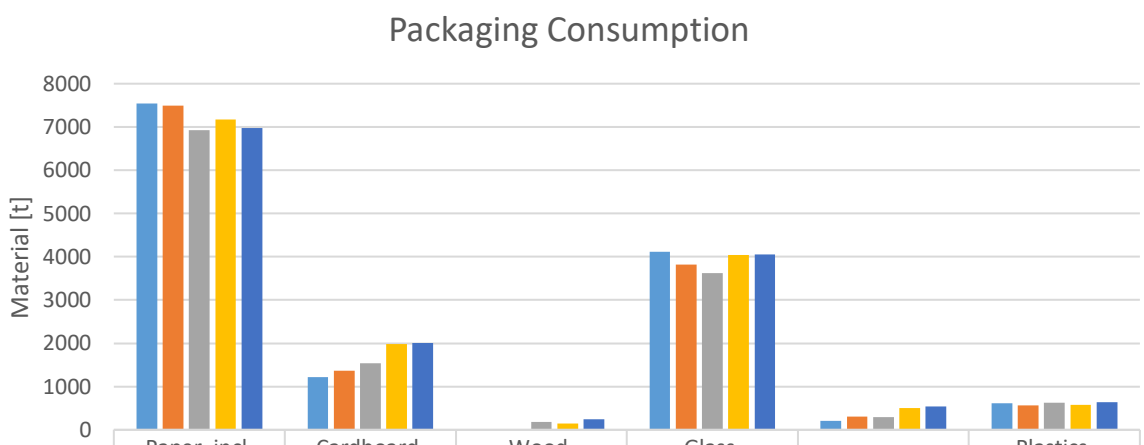
Table 10: Summarized results for the material inflow of Electronic Appliances

	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Consumer Electronics [t/a]	242	532	829	555	251	269	495	627	559
House Appliances [t/a]	528	722	1307	1871	2285	2056	1703	1529	1243
Total [t/a]	*770*	*1255*	*2136*	*2427*	*2536*	*2325*	*2197*	*2156*	*1802*

Packaging

Figure 19 shows the packaging consumed in Odense in the years 2010 to 2015. It is visible that the paper consumption has a decreasing trend over the time, which is likely because of the development of digitalization, however it is still consumed the most from all the packaging materials with 6 976 tons in 2015. For cardboard on the other hand, a growth is visible. This is likely because of the trend of more home deliveries, where typically cardboard is used as packaging material. Wood packaging increased as well in magnitude, though it is still rather little used in comparison with 246 tons in 2015. Amount of glass packaging fluctuates slightly in magnitude but overall stays on the same level. Plastics

in general show an increasing trend over the time period, whereas plastic packaging is stagnant on one level.



	Paper, incl. packaging	Cardboard, incl. packaging	Wood, packaging	Glass, packaging	Plastics	Plastics, packaging
2011	7545	1220	14	4110	211	609
2012	7494	1364	14	3813	305	562
2013	6925	1534	183	3624	290	626
2014	7171	1979	139	4045	502	575
2015	6976	2009	246	4053	545	643

Figure 19: Packaging Consumption in Odense 2010 to 2015

3.5.3 Food

Table 11 shows the food consumption in Odense and the related embodied emissions over the period from 2010 to 2018. An increasing trend is visible, which is basically driven by the population increase in Odense, since the same consumption per person per age interval is assumed in all the years.

The energy consumption for providing food and beverages is estimated to be 5 598 kWh/capita/year which equals to 1 064 kgCO_2/capita/year with the Danish energy mix, resulting in 204 kt CO_2 which is emitted in 2018.

Table 11: Food consumption and related embodied emissions in Odense 2010-2018

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018
Food inc. beverage(kt)	226	227	230	233	235	237	240	242	244
Food exc. beverage (kt)	96	97	98	99	100	100	101	102	103
embodied emissions (kt CO_2)	202	204	205	208	210	210	212	213	217

A detailed Table showing the consumption per food category per year is attached (Table 59, Appendix 7.4.2)

3.5.4 Construction Material

Figure 20 visualizes the inflow of construction material in the years 2010 to 2018. In general, a growth is visible, however fluctuations between the years are present. These fluctuations are mainly caused by the completion of constructions of apartment blocks, office buildings and factories which have typically a high floor area. As well as they are not demanded in Odense in an extent that every year a high number of such buildings have to be constructed. The newly finished floor area for big contributors like single family houses and terraced houses is more homogenous over the years.

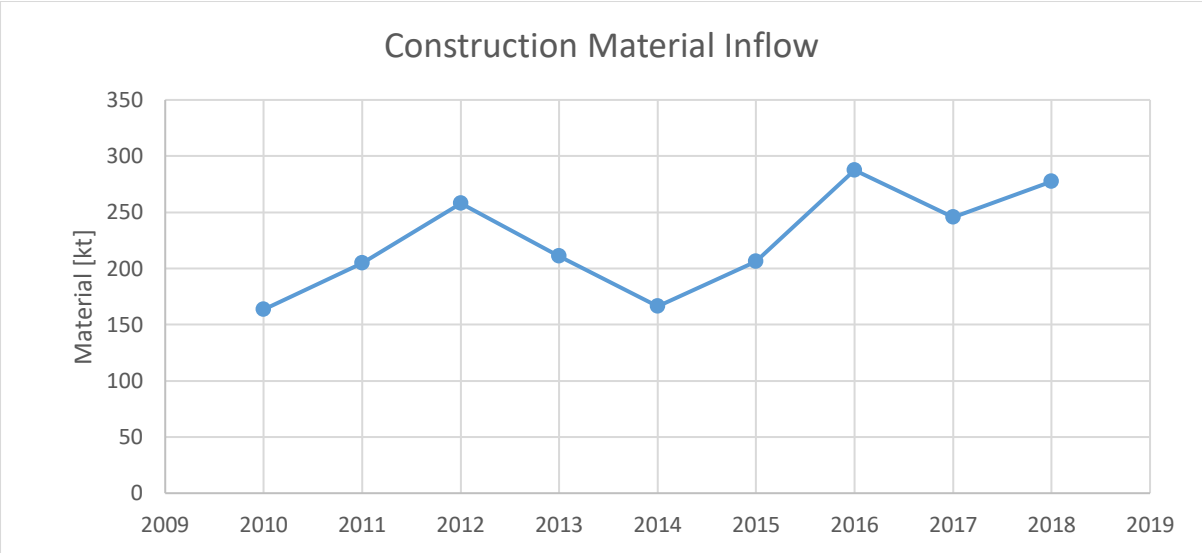


Figure 20: Construction Material Inflow 2010-2018

When looking into the contribution of the materials (Table 57, Appendix 7.4.1) to the total weight, it becomes apparent, that non-metallic materials dominate. Concrete contributes by far most to the total weight, followed by clay brick for masonry and gravel and sand as base layer for the foundation. This contribution was expected.

In baseline year 2015, the emissions embodied in construction material amounted to 24 kt CO_2. The total embodied emissions per year estimated per individual material are attached (Table 58, Appendix 7.4.1).

Light rail

In August 2017 the construction of the light rail network in Odense started and it is estimated that the light rail will be in operation in its test phase and all constructions finished in April 2020 (Odense Kommune, n.d.). The civil and environmental engineering specialized consultancy COWI assessed the

project on its environmental impact and estimated the construction material and demolition waste occurring in the construction process (COWI, 2013). COWI claims that the need for raw materials and the generation of waste in the construction phase will not have magnificent impacts on the environment. This is because, the waste is mostly recycled, and the raw materials are already recyclables. To fulfill this, the complete waste generation will be documented, during the construction and the operation phase. Table 12 lists the construction material expected to be demanded by the construction of the light rail network.

Table 12: Construction material necessary for erecting the light rail infrastructure (COWI, 2013)

Material	**Amount [t]**
Gravel	189 000
Asphalt	46 000
Concrete	112 000
Granite	240
Crushed Rock	11 300
Steel rails and masts	4 600
Copper	510
Plastic	260

COWI further claims that the required amount of gravel equals 0.5% of the total annual recovery in Denmark. 43 000 tons of asphalt are expected to remain broken up on site and will be recycled, so the net consumption of new asphalt is about 3 000 tons. Crushed rock and granite cannot be delivered locally but can be imported from Bornholm or Norway. The remaining quantities are small compared to Denmark's annual turnover.

New Hospital - Nyt OUH

On the 28th of April 2016 the construction process for the new hospital started, which will then be - by around November 2022 - the biggest hospital in Denmark. Also for this construction project an environmental assessment was conducted and it is intended that the project is based on sustainable principles (Naturstyrelsen, 2014). The standard of the German Sustainable Building Council for sustainable construction is a requirement for the project. Furthermore, it is claimed that materials with, in comparison lowest resource and energy consumption are selected, that those materials are preferable local, and the materials are recyclable. Table 13 shows the estimation of the materials which are being consumed during the construction. The amount of concrete however seems very low when considering the dimension of the hospital with its new floor area of 284 000 m² and also in

comparison with the amount of concrete used in the construction of the light rail, which is almost double.

Table 13: Estimation of Materials used in the construction of the new hospital (Naturstyrelsen, 2014)

Material	**Amount**
Concrete	60 000 t
Steel (including reinforcement)	5 000 t
Cortensteel	5 000 m²
Zink	50 m²
Glass outer wall	17 400 m²
Glass inner wall	12 000 m²
Timber	1 400 doors
Bitumen felt	16 000 m²
Linoleum flooring	16 400 m²
Painted flooring	6 000 m²
Ceramic tiles flooring	9 100 m²
Vinyl flooring	11 000 m²
Paint inner walls	40 000 m²

3.6 Energy and Operational Emissions

Data for the operational emissions of Odense were obtained from the Danish Energy Ministry (Energistyrelsen, n.d.). According to the ministry, the CO_2-Emissions caused by the municipality decreased except in year 2012 gradually from 2010 to 2015 as visualized in Figure 21. In 2010, 1084 kt CO_2 were released to the atmosphere whereas in 2015 it was 840 kt CO_2. Looking at the two biggest contributors of the total emissions – the energy and the transport sector – it becomes clear why the numbers dropped. The contribution by the energy sector, which represents the provision of heat and electricity, significantly decreased over the years. Though, the emissions due to transport were slightly higher in some years why the total emissions did not drop as strong. However, looking at the emissions in 2010 and 2015 caused by the transport sector, they are on a similar level. The emissions slightly increased in some years, probably due to the increasing car fleet in Odense and the burning of more fuel (StatBank, n.d.-e).

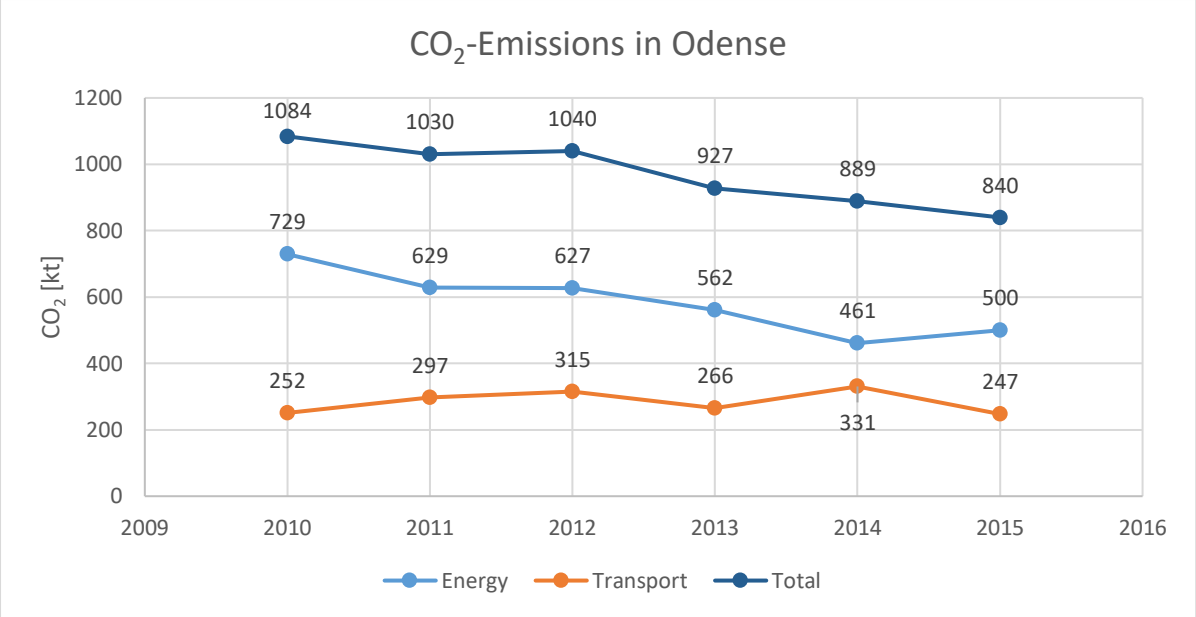


Figure 21: CO_2-Emissions in Odense in the years 2010-2015

Figure 22 shows the contribution to the total emissions by the residual smaller contributors – agriculture, landfills and the chemical industry. A significant decrease can be seen in the chemical industry by almost a quarter of the emissions from 42 kt to 33 kt. This is likely due to an increase of efficiency in the industrial processes. The emissions due to landfilling also decreased slightly, whereas the emissions from agriculture marginal increased from 35 kt to 37 kt.

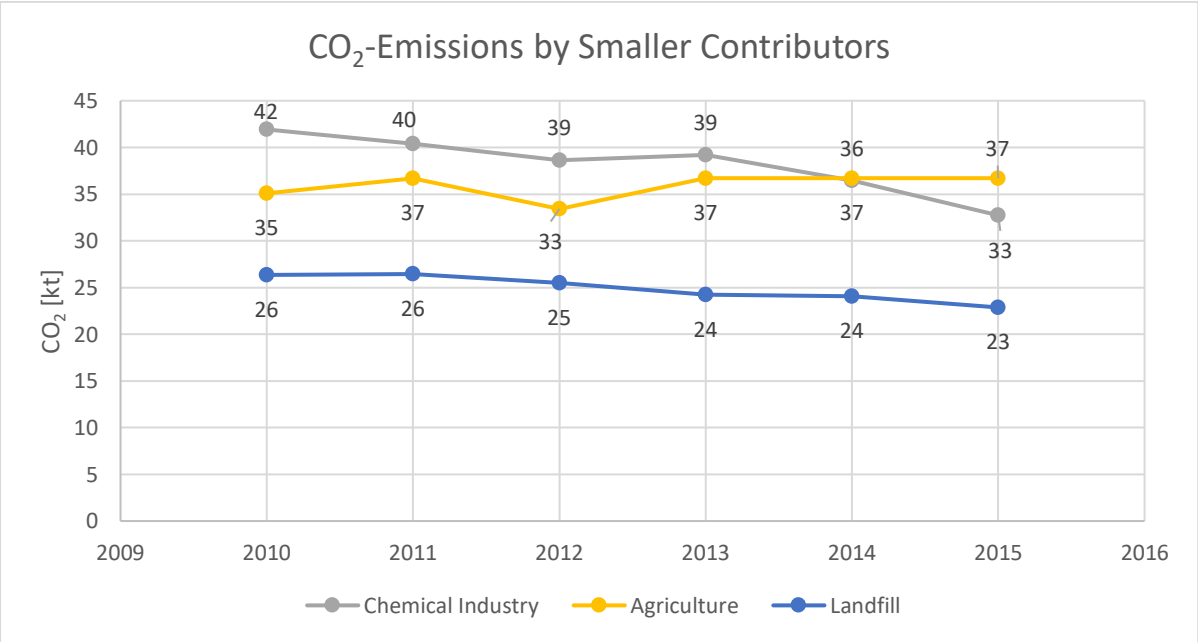


Figure 22: CO_2-Emissions in Odense in the years 2010-2015 by smaller Contributors

As visualized in Figure 21, the emissions caused by the energy sector in Odense significantly decreased over the years 2010 to 2015. Interestingly, the total consumption of heat and electricity in the city increased over the given period, as can be seen in Figure 23. The graph shows a strong increase in energy consumption which is mainly due to households (orange graph). The energy consumption by business/industrial and by the public sector increased only slightly.

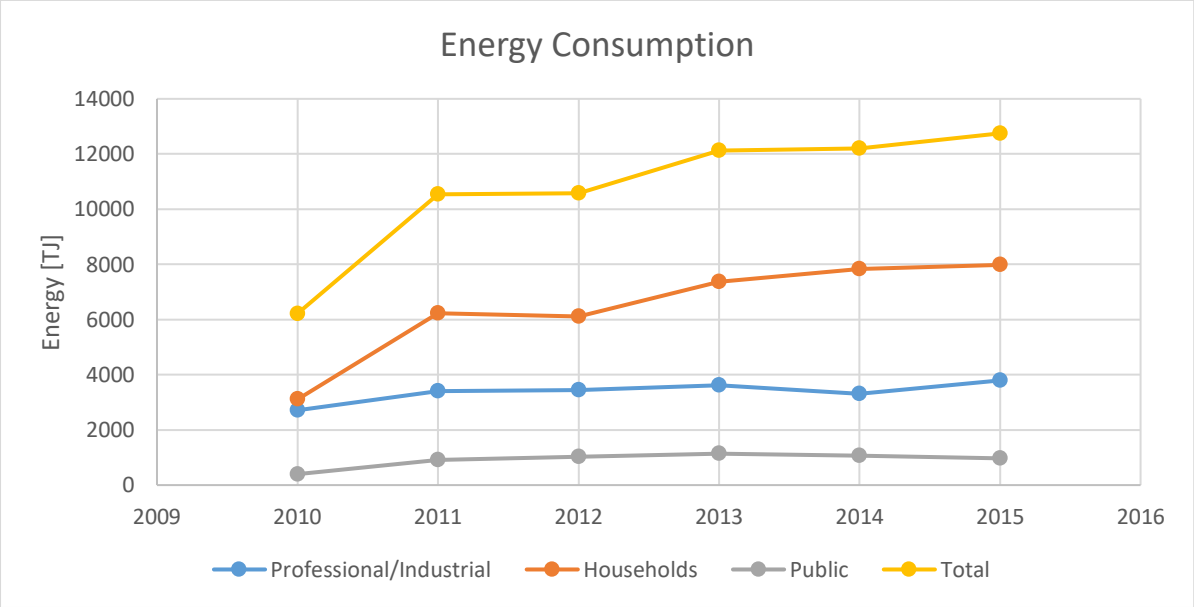


Figure 23: Energy consumption in Odense in the years 2010-2015 (heat & electricity)

Looking closer at the energy consumption from households (Figure 24), it reveals that the rise is mainly because of more demand for district heating. This could be explained by the growth of the municipality, meaning the expansion and incorporation of districts and the rising number of citizens as well as the increase of floor area per dwelling per person (Statistics Denmark, 2018). The consumption of electricity by households increased just minimal.

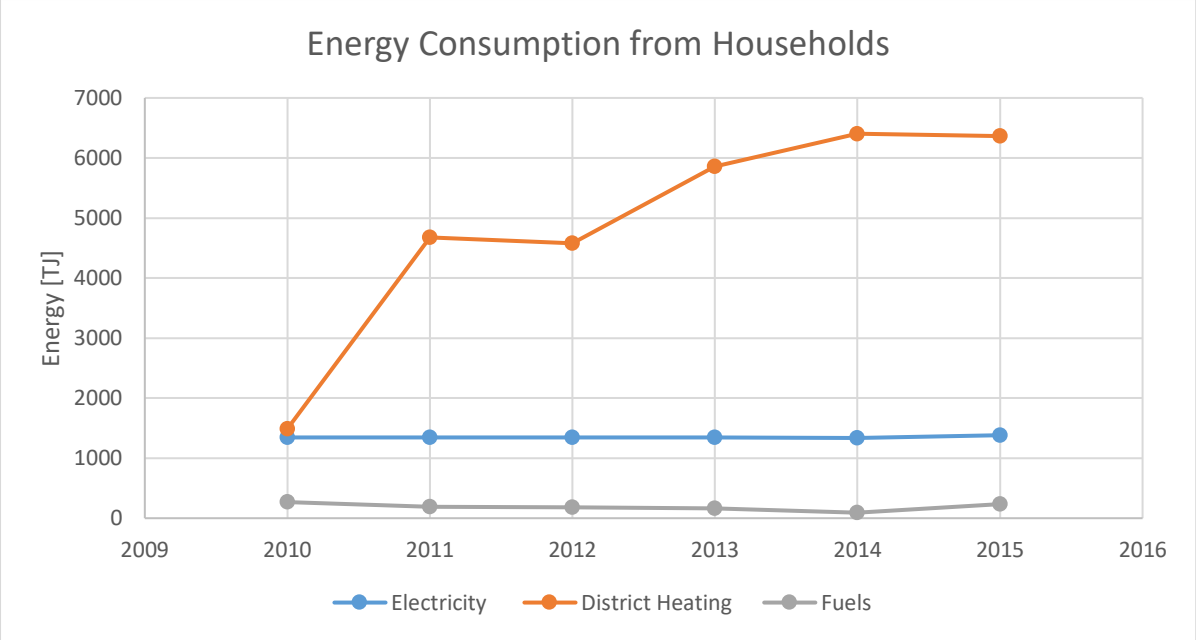


Figure 24: Energy Consumption from Households by Source in the years 2011-2015

The reason that the total CO_2 emissions dropped even though the energy consumption more than doubled is due to changes in technology. Heat and especially electricity as shown in Figure 25 was increasingly produced in the local combined heat and power (CHP) plant. With a CHP plant, higher efficiency is reached. Moreover, more and more biogenic and alternative carbon sources were used in the CHP plant over the years, like wood chips, straw, biowaste, waste and biogas and on the other hand the share of coal dropped. In 2013 the production of electricity from the CHP plant even exceeded the demand and electricity was exported. The renewables wind and solar also visualized in Figure 25 contribute only marginally to the total production, with 75 TJ from wind and 25 TJ from solar power in 2015.

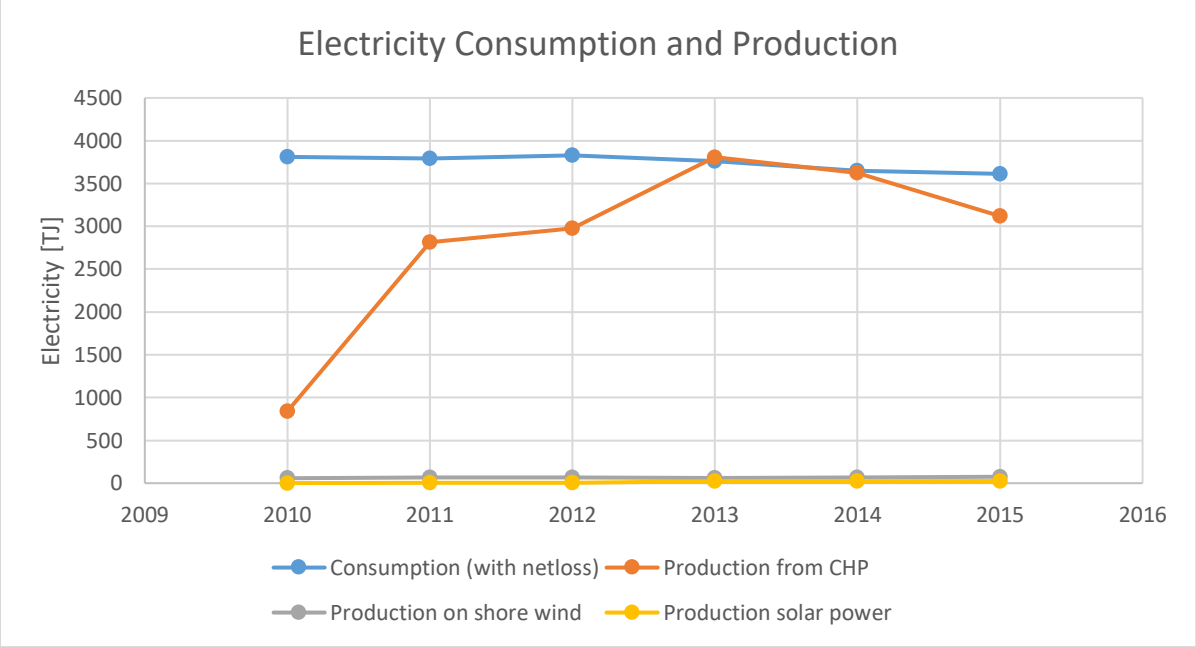


Figure 25: Electricity Consumption and Production in Odense in the years 2011-2015

The reasoning that the CO_2 emissions dropped because of a higher share of electricity production by the CHP plant can be emphasized with following Figure 26. The emissions from electricity usage dropped significantly. The emissions from district heating increased, but only due to the expansion of the heated floor area.

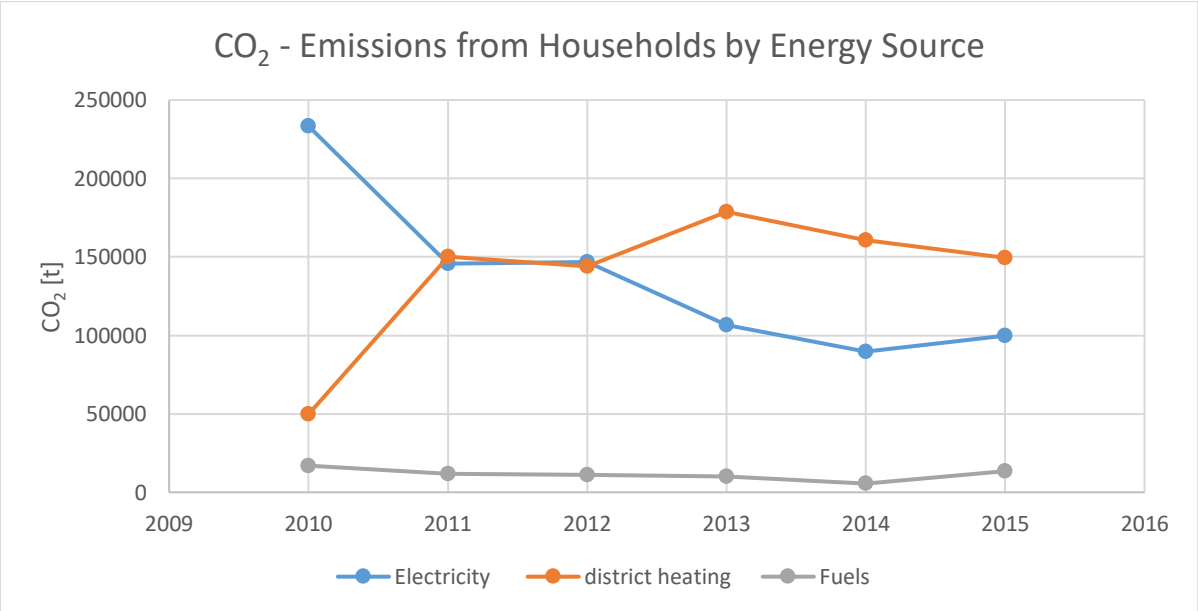


Figure 26: CO_2 emissions from household by energy source

The CO_2 emissions from the transport sector are preliminary caused by road traffic as visualized in Figure 27. The airport in Odense is running only seasonally as a commercial airport.

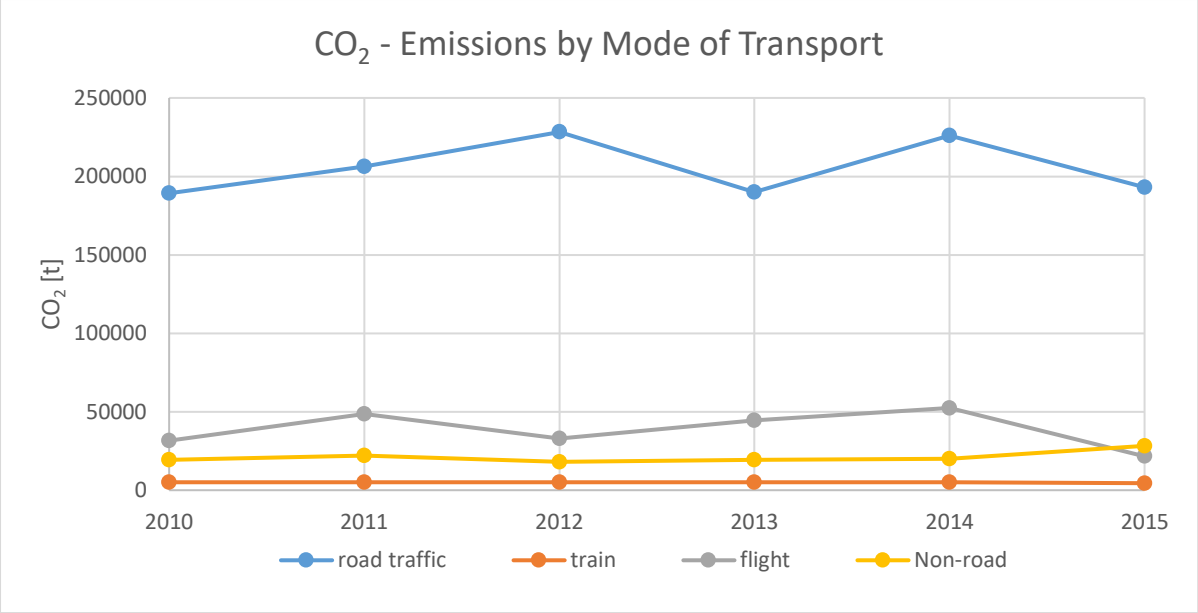


Figure 27: CO_2-emissions by mode of transport

The biggest contributor to the emissions from road traffic are passenger cars (Figure 28), for an overall an increasing trend is visible. This correlates with the rising of car ownership per citizen in Odense.

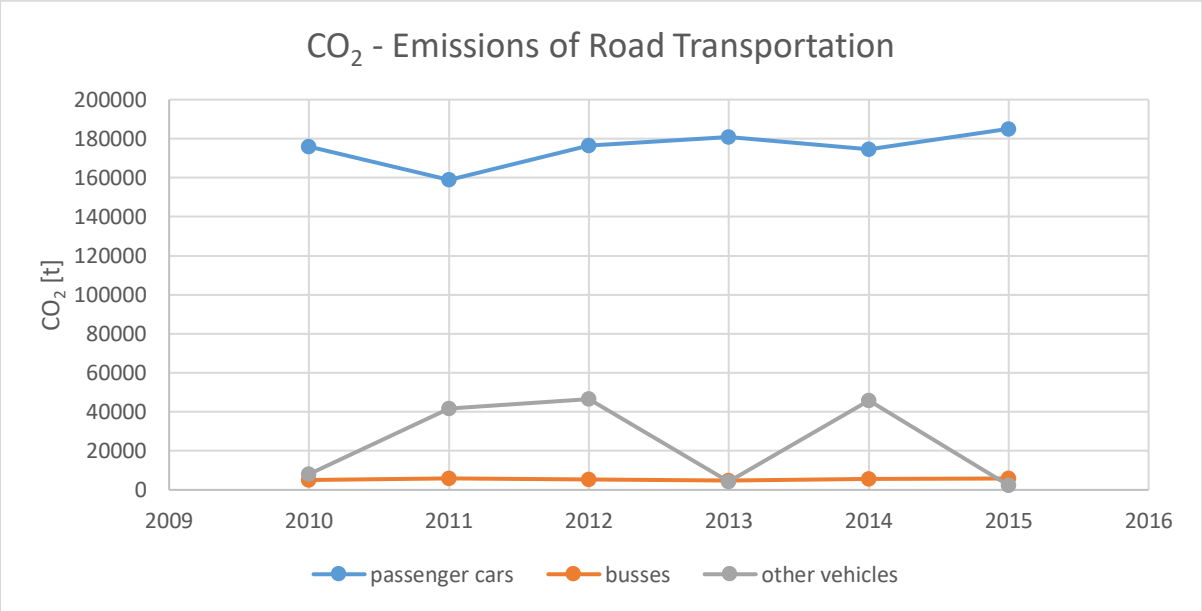


Figure 28: CO_2-emissions of road transportation

Analysing the contributors to the emissions of non-road transportation mode reveals, that the biggest contributor is transport related to constructions, where an increasing trend is noticeable. This seems reasonable, since Odense currently undergoes vast construction projects and will undergo bigger construction projects with the erection of the tramway until 2020 and the erection of the new hospital until at least 2022 (Odense Kommune, n.d.), (Region Syddanmark, n.d.). The other emitters stay mostly

on the same level over the years with agriculture as second biggest contributor. Emissions increased in the year 2015 due to transport concerning gardens and parks and remaining professional transport.

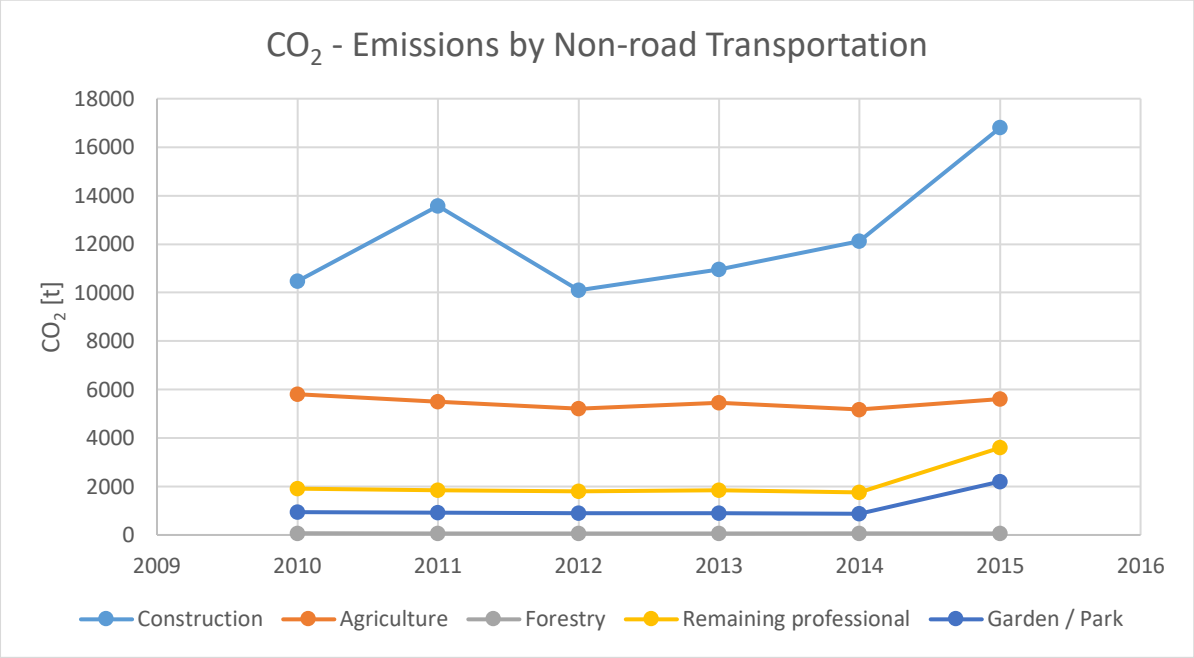


Figure 29: CO_2-emissions by non-road transportation

3.7 Urban Metabolism Baseline 2015

In the following, the inflows of the UM of Odense in year 2015 are presented and their embodied emissions. Furthermore, the results are analyzed including the operational emissions to see the relationship between these two types of emission in the UM.

Table 14 below shows the inflows into the city of Odense in the year 2015.

Table 14: Inflows into the Urban Metabolism 2015

Inflow	**Energy [TJ]**	**Op. Emissions [kt CO_2]**
Energy	12749	840
	Mass [kt]	**Emb. Emissions [kt CO_2]**
Water	8085	0.415 [1]
Packaging (Consumption of Goods)	15	31
Vehicles (Consumption of Goods)	10	35
Electronics (Consumption of Goods)	2.3	27
Construction Material	206	24
Food	100	210

[1] emissions occurring due to the extraction and distribution of drinking water

As expected, water makes the biggest share of the inflows into the city, followed by construction material. Food contributes in a high magnitude as well with 100 kt. The inflow of packaging and vehicles, representative for consumption of goods contribute lowest to the total inflow, however still significantly with 25 kt combined.

When analyzing the embodied emissions of the inflows another trend is apparent. CO_2 emissions occurring to provide food amount highest with 210 kt, consumption of goods is causing upstream 66 kt CO_2 emissions and construction material 34 kt CO_2. The extraction and distribution of water causes comparable small CO_2 emissions with 0,415 kt, which is due to low energy demand in the processes to supply the water. Emissions caused by the inflow of construction material are as well comparable low, which is due to low energy requirements and emission for the bulk materials like concrete and clay brick. In contrast to provide food requires high amounts of energy what is displayed in the final embodied emissions of the inflow.

Figure 30 shows the emissions caused by the urban metabolism. It furthermore shows the relation of the embodied emissions of the inflows and the operational emissions which are occurring in the city when using (operating) the stock and services.

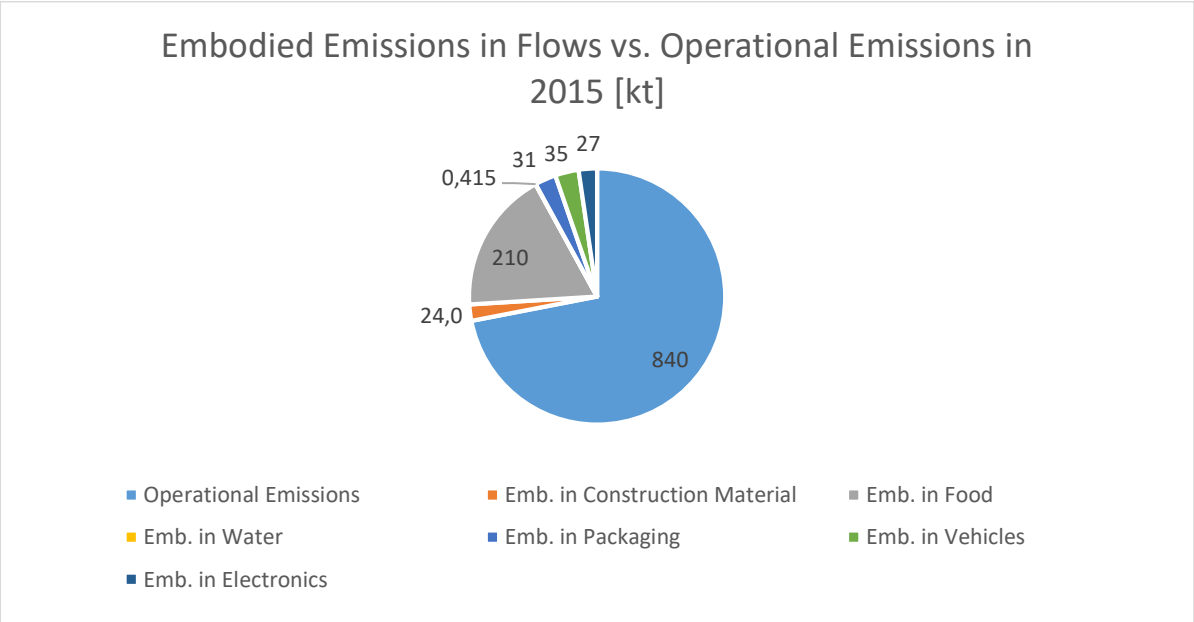


Figure 30: Embodied Emissions in Flows vs. Operational Emissions of the municipality in base year 2015

Figure 30 shows that embodied emissions in flows make up for around one fourth of the total emissions which amount to 1 167 kt CO_2 in year 2015.

Figure 31 compares the operational emissions of Odense in 2015 with the CRV of the material stock in Odense 2018. The CRV of the stock is the sevenfold of the operational emissions, meaning it is "worth" seven years of operational emissions, considering the status in 2015.

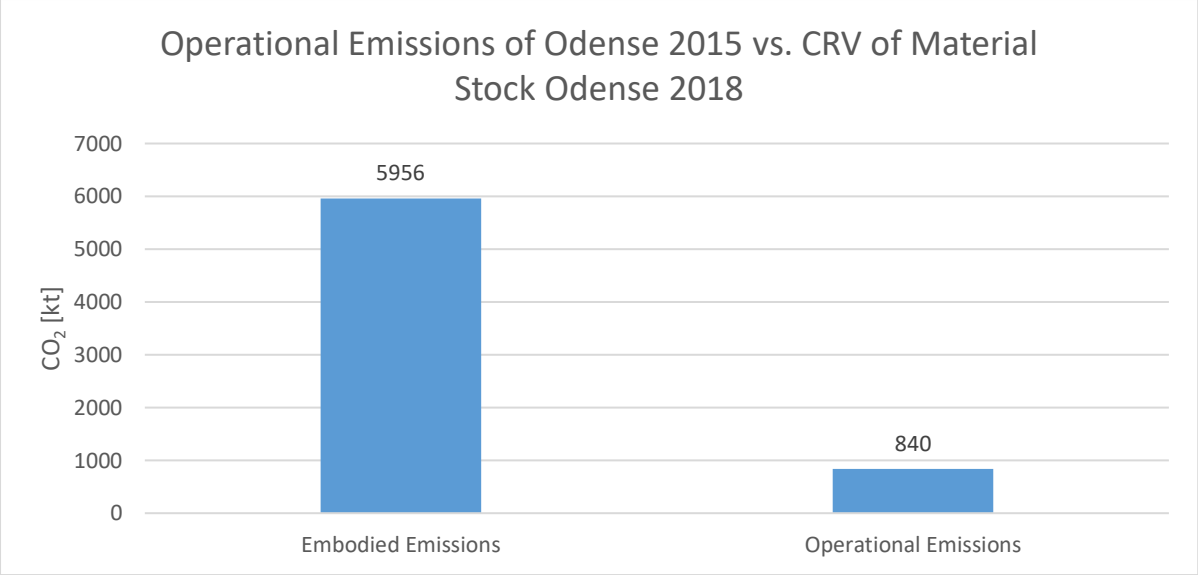


Figure 31: Operational Emissions of Odense 2015 vs. the CRV of material stock in Odense 2018

3.7.1 Emissions of the Transportation Sector

The comparison of the operational emissions in the transport sector (2015) with the CRV of the vehicle fleet which is erected to provide the service of transportation shows, that the embodied emissions are only about threefold higher than the operational (Figure 32). This leads to the conclusion that the use phase of vehicles is from significant importance when considering CO_2 emissions, which is also commonly known.

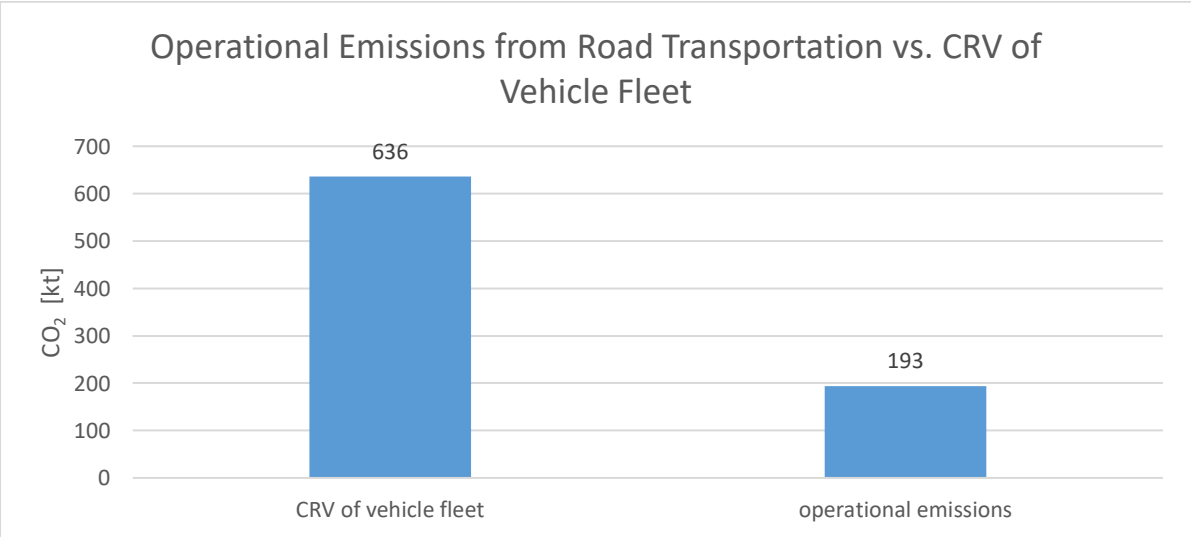


Figure 32: Operational emissions from road transportation vs. CRV of vehicle fleet (2015)

When looking at the operational emissions by passenger cars only and the CRV of the passenger car fleet the significance of the use phase becomes even more apparent (Figure 33).

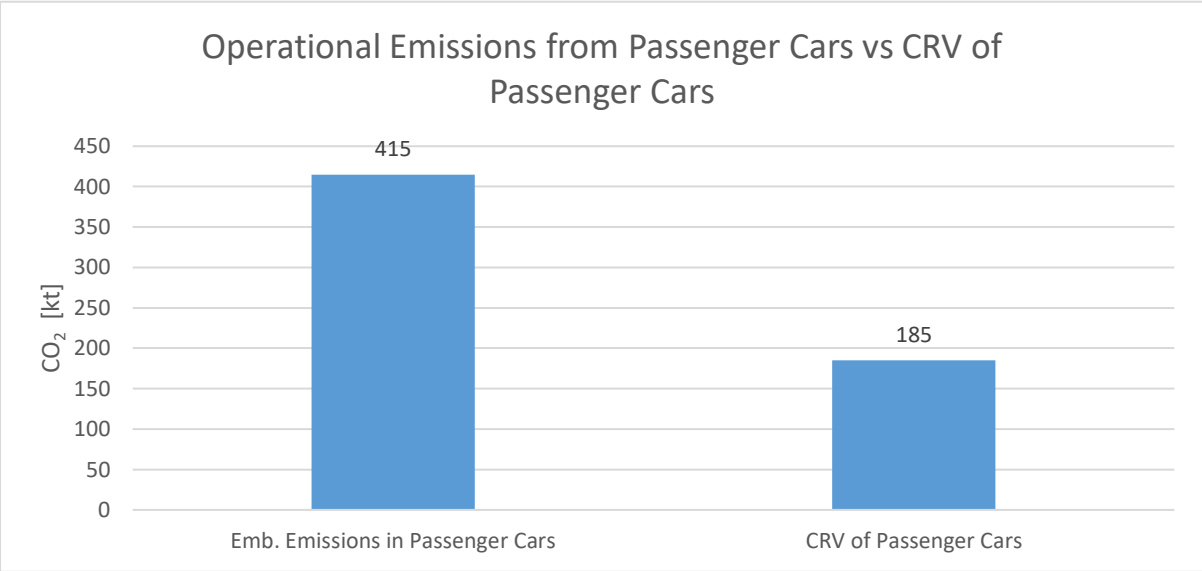


Figure 33: Operational emissions from passenger cars vs CRV of passenger cars (2015)

3.7.2 Emissions from Households

The comparison of the operational emissions from households and the embodied emissions in RB is visualized in Figure 34.

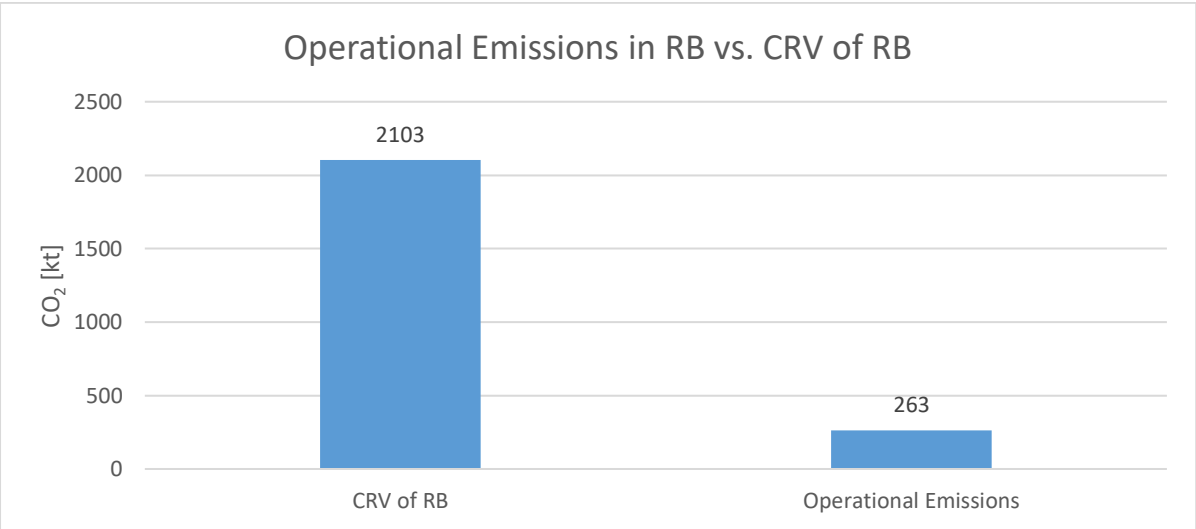


Figure 34: Operational Emissions in RB vs. CRV of RB

The comparison shows that the operational emissions from households in year 2015 are around an eighth of the CRV in the material stock in RB.

4 Discussion

In the following, limitations in the methodology are pointed out and uncertainties analyzed, as well as results compared to values from the literature and options for climate mitigation discussed. Additionally, possible further studies are listed and indications on policy making, which can be derived from this study are presented.

4.1 Uncertainties and Limitations

4.1.1 Residential Buildings

Weight of RB Stock

A thoroughly detailed bottom-up approach was conducted; however, archetypes were created to reduce the otherwise not bearable workload. Material intensities for archetypes could be developed but no material intensities for all individual buildings. Though, on the total material stock this will have a minor impact.

Furthermore, it was often not possible to estimate all building materials through measuring, especially those from minor absolute weight and especially for older buildings due to not detailed building plans. Hence assumptions had to be done. This issue was for instance severe concerning the material steel. The estimation of steel as reinforcement is mostly based on assumptions. Moreover, pipes and wires are not included in the estimation.

To estimate the final weight of the material stock building footprint data from the BBR register was used. There is an uncertainty, that owners did not register their building. Concerning the assumptions taken for non-bulky materials as mentioned in the limitations (e.g. steel), there are uncertainties about the absolute weight.

CRV of RB Stock

For a few similar building materials, the same emission factor was selected (Appendix 7.2.1)

It is impossible to have a complete accurate emission factor per material, since only in rare cases (newly constructed buildings) information on the exact type and property of the building material is available (e.g. concrete and compressive strength). Furthermore, emission factors are based on LCA´s where the system boundary and the assumptions taken are very important for the final result.

4.1.2 Non-residential Buildings

Weight of NRB stock

NRB material intensities for Odense were not estimated due to the lack of time. The material intensities were provided from Gontia (Chalmers University) who is about to finish a study about the non-residential building stock in Gothenburg (Sweden) (Gontia, 2019).

Because the material intensities are based on the NRB stock of Gothenburg (Sweden), uncertainties do exist. Those are regarding the absolute weight probably small, since function is from main

importance in NRB´s and thus NRB´s should not be very diverse. Regarding the material composition though, uncertainties can be higher. For instance are clay bricks less used in masonries in Sweden as in Denmark (Lanau, 2019).

CRV of the NRB Stock

See above in "CRV of RB Stock"

4.1.3 Roads

Weight of Road stock

No material intensity data for roads in Odense was available. Hence, they are based on assumptions and high uncertainty exists.

CRV of Road stock

Since high uncertainty in material intensity, a high uncertainty is here to be expected as well. Furthermore, emission factors are based on LCA´s where the system boundary and the assumptions taken are very important for the final result.

4.1.4 Vehicles

Number of Vehicles

The number of vehicles was obtained from *Statbank* and the statistics were collected specifically for Odense. Nevertheless, regarding the vehicle types bus and lorry sudden jumps in number were observed which can lead to the conclusion that an inconsistent counting method was applied.

Material Composition and Emission factors

Generic material compositions were used for several vehicle types including the most common passenger cars and for others, assumptions were made. Different models and therewith dimensions were not considered, why the uncertainty for the absolute material stock can be noticeable. Emission factors were obtained from the Ecoinvent database, which were generic emission factors. Here high uncertainty can be seen, because dimension model differences are not taken into account.

4.1.5 Electronic Appliances

Number of Electronic Appliances

The number of electronic appliances was estimated using statistics about the possession of those in family households (%). The statistics were national but the differences between country level and Odense are assumed to be low. However, a significant issue with this approach of estimation is that the statistics about the possession are not giving any information, if in those households, where such an appliance is present, more than one is present.

Material Composition and emission factors of Electronic Appliances

Except for the appliances – GPS-navigation, Activity-tracker watch, GPS-watch and MP3-Player – individual material compositions could be obtained from the literature. For those above mentioned, a generic composition for small electronics was used. It is assumed though, that there are no big differences in material composition and dimensions, nevertheless there is uncertainty.

Data on embodied emissions was not available for all appliances considered, why assumptions had to be made (Appendix 7.3.2, Table 52). Here a high uncertainty exists.

4.1.6 Water Inflow and Embodied Emissions

The data was provided from the local water supply company and is assumed to be accurate. Regarding embodied emissions due to the water inflow; Data on energy (or emissions) required to extract water and to distribute water into the municipality of Odense does not exist. Data is taken from an LCA on the water supply in Copenhagen. Because the data is taken from an LCA on water supply in Copenhagen, there are uncertainties due to system boundary issues. Those however can be estimated to be low, since there are no big differences between applied technologies in Denmark concerning water supply.

4.1.7 Consumption of Goods

Packaging Inflow

Packaging material inflows are derived from statistics about packaging waste, however it is assumed, that the difference between inflow and outflow (waste) is minor, since waste is not likely to be transported.

Vehicle Inflow

The inflow data was derived from the stock data via modelling. No data on inflows could be obtained from statistics, therefore high uncertainty exists. The same limitations and uncertainties for the material composition and emission factors as for the stock data (4.1.4) are here to mention.

Electronic Appliances Inflow

The inflow data was derived from the stock data via modelling. Due to inconsistency in the data and fluctuations in the data, the data for most of the products had to be smoothened with the moving average tool in Excel, as well for outdated technologies inflows of zero were assumed to simplify the model and because very low inflow rates are assumed. The uncertainty is therewith very high. The same limitations and uncertainties for the material composition and emission factors as for the stock data (4.1.5) are here to mention.

Even though the uncertainty is very high. The impact on the total results is low. Electronic Appliances made up for only 0.03 % of the mass inflow in 2015 and 2 % of the total emissions respectively 9 % of the total embodied emissions in flows.

4.1.8 Food Inflow

Even though, the consumption per person is derived from a national survey from 2013, the uncertainty is assumed to be low, since minor differences can be expected. The uncertainty of the results for the embodied emissions though has to be seen higher, since the data was obtained from an IOA regarding Swiss households, as well as the data was on energy requirements for food consumption per person and not on specific food categories.

4.1.9 Construction Material

The uncertainties and limitations concerning the material intensity are those mentioned in 4.1.1 RB stock and 4.1.2 NRB stock. The data on newly added floor area was obtained from *Statbank* and because this data was originally collected from BBR the same issue as in 4.1.1 concerning the registration of newly added floor area is assumed.

4.1.10 Outflows

Due to data gaps and limited time, outflows of the UM were not included and important factors like recycling and energy recovery could not be considered. However, energy used in EoL processes and occurred emissions are covered with the operational emissions presented here.

4.1.11 Emission Factors per Material

A throughout difficult task in setting up the results in this report was the selection of emission factors per material or good. The preference was to find data from Danish LCA´s, but unfortunately those were in most of the cases not available. This brings uncertainty, since then another energy mix was applied to estimate the emission factor. Furthermore, concerning the number of materials included in this study, it was impossible to collect the data from just one study or database, what means there is uncertainty due to different system boundaries in the studies.

4.2 CRV of Wood-based Materials – different Scenarios

A significant part of the material stock are wood-based materials respectively timber. For such biomaterials widespread disagreement exists under LCA experts on how the embodied emissions have to be calculated. This is, because biomaterials store carbon in the process to build up biomass. Some account the amount of stored carbon, others neglect them, again others have another solution. In this report the CRV of wood-based materials is calculated with the data obtained from *ÖKOBAUDAT* (as mentioned above). *ÖKOBAUDAT* accounts the stored carbon and hence provides a negative emission factor for construction timber (-1.21 $kgCO_2/kg$) (ökobaudat.de, n.d.). Setting up a scenario where the impact of timber on the CRV of the building stock is excluded - assuming an emission factor of 0 $kgCO_2/kg$ - the total CRV of the stock in Odense would increase by 23 % from 6 039 kt CO_2 to 7 398 kt CO_2. Selecting the highest emission factor provided by the literature (1.1 $kgCO_2/kg$,(Huang et al., 2019)), the total CRV of the baseline scenario would increase by 43 % and amount to 8 653 $ktCO_2$.

Thus, it is to conclude, that the emission factors of wood-based materials are from high importance estimating the CRV. Since the CRV can be considered as parameter for making policies, it is crucial to further debate about the estimation of the emission factors respectively embodied emissions of biomaterials and to standardize a methodology.

4.3 CRV as Parameter for Policy Making

As described above (3.7, Figure 31) the CRV is about the sevenfold of the operational emissions of the municipality in 2015. Though, the operational emissions are currently in the focus of the policy makers. This seems reasonable from the first place, since the stock (and the corresponding CRV) is already built-up, nonetheless the quantification is important especially for policy making in the developing countries or when thinking in a global scale. The built environment of developing countries is far from being as advanced as the one in industrialized countries. But developing countries will, in the future, demand the same service the built environment provides in industrialized countries nowadays. (Müller et al., 2013) estimated in their study the carbon footprint of the existing global infrastructure in 2008, and they conclude that a globalization of the Western infrastructure stocks using back then current technologies would cause emissions of approx. 350 Gt CO_2, which corresponds to about 35-60% of the remaining carbon budget available until 2050 (keeping the 2°C target in mind). Here the policy makers in developing countries have the opportunity for mitigating climate change and for setting guidelines to low carbon city development. Obtaining knowledge from studies on CRV´s of the built environment can thus lead to conclusions on what measurements are (material choices, resource reduction potential) necessary to leapfrog unsustainable urban development.

Furthermore, the relationship of the CRV and the operational emissions of cities with considering the factor of urban form could also reveal policy making options for industrialized countries and cities. Identifying patterns which are giving answers on why the CRV is high, or why the operational emissions are high in ratio could create opportunities for sustainable development.

4.4 Comparison to Values from the Literature

Comparing the results for the CRV per capita of the built environment with the results from (Müller et al., 2013), potential shortcomings of the estimation in this study become apparent. Whereas (Müller et al., 2013) estimated 56.54 tCO_2/cap, here it is 24.8 tCO_2/cap. This is likely because piping networks for water and heating and the electricity networks were not included in the estimation, as well as an accurate estimation for steel and aluminum (which were beside cement the other materials considered in (Müller et al., 2013)) was restricted due to lacks of information in building plans. Moreover, no metals were considered in the material stock estimation of roads.

4.4.1 Gothenburg

Gothenburg is the second-largest city in Sweden, with 571 868 citizens in 2018 (Statistics Sweden, n.d.). The Gothenburg region which spans 13 municipalities in Greater Gothenburg, has a population of 1.1 million. The city is strategically located between Oslo and Copenhagen and is Scandinavia´s largest port. Since years Gothenburg is in a major development boom. The municipality is growing strongly to make space for 700 000 residents by 2035 – which is around 130 000 more than at present (City of Gothenburg Executive Board, 2017).

Gothenburg has a different economy than the national average and the capital Stockholm. The industrial sector in the city is very strong: where only 9 % of the workforce are employed in the industrial sector in Stockholm, the number rises to 16 % in Gothenburg. Additionally, 30 % of the Swedish foreign trade passes through the large port. This induces significant material flows and emissions (Kalmykova et al., 2015).

Table 15 below shows the current properties of Gothenburg.

Table 15: Properties of Gothenburg (References in Appendix 7.5,Table 66)

	2016	2017	2018
Population	556 600	564 000	571 868
Population density [cap/km²]	1 242.8	1 259.3	1 276.9
GDP per Capita [USD/cap]	56 473	66 935	
GDP growth rate (average) [%]	2.62		
HDI value		0.933 Rank 7	
Ave. Daily Temperature [°Celsius]	7.7		

In Table 16 the results for the CRV per capita (only RB) and the operational emissions of Gothenburg and Odense are compared. Odense has a 10 % higher CRV of the built environment per capita than Gothenburg. The higher value for the CRV per capita in Odense is probably because the population density of Odense is around twice as low as Gothenburg's and in the statistics about floor area per person, Denmark (77 m²/person) ranks before Sweden (58 m²/person) (entranze.enerdata.eu, 2008). Here is to regard though, that the material stock for Gothenburg was aggregated to material categories, why emission factors had to be generalized as well and the uncertainty is higher (Appendix 7.5.1).

That the operational emissions per capita in Gothenburg (Göteborgs Stad, 2014) are lower as in Odense in year 2011 is surprising though. A higher value was expected due to the high industrial activity in Gothenburg and the large port. But the value of the emissions in Gothenburg have to be

observed with caution, too. Contradicting values are published from official websites, so is (Smart City Sweden, n.d.) claiming, that Gothenburg released more than 8 t CO_2 per capita in 2012 and the goal is to reduce the emissions to 3.5 t CO_2 by 2035 and 1.9 t CO_2 by 2050. Likely, here exists also a boundary issue in accounting the emissions as mentioned before.

Table 16: Comparison of the Results Gothenburg vs. Odense (References and Assumptions for Gothenburg in Appendix 7.5.1)

	Gothenburg	Odense
CRV 2018 [tCO_2/cap]	9.32	10.30
Operational Emissions 2011 [tCO_2/cap]	4.91	5.38

4.5 Mitigation Options to lower the Carbon Replacement Value in Building Stocks

This chapter is especially interesting for policy making in developing countries, where the built environment is not yet as advanced as in industrialized countries and leapfrogging is possible, but it is also from interest regarding renovations of buildings in the Western infrastructure.

The CRV of wood-based materials (generic biomaterials) was extensively discussed in 4.1. From that can be concluded that there is a great potential to mitigate climate change using biomaterials, since they can function as temporary carbon sink. Few studies already exist, which estimate the impact of using wood-based materials on a bigger scale. (Pittau, Lumia, Heeren, Iannaccone, & Habert, 2019) for example investigated the effect of the extensive use of biomaterials in construction processes and if it is an important strategy for meeting the 2°C target for 2050. (Pittau et al., 2019) concludes, that fast-growing biogenic materials have an increased potential to act as a carbon sink compared to ordinary construction timber and that this method of storing carbon in a short term is an important strategy towards the climate goals.

Moreover, several other studies addressed the issue of embodied carbon and pointed out solutions for a low-carbon built environment. (Pomponi & Moncaster, 2016) summarized the findings of 102 studies concerning mitigation options and presented them in a literature review.

The obvious and therefore often mentioned solution to mitigate the contribution of the built environment to climate change, is the use of alternative materials with low embodied energy respectively emissions (Pomponi & Moncaster, 2016). One study showed that a reduction by 50 % of embodied energy could be reached with substituting load bearing brickwork with stabilized mud blocks (Venkatarama Reddy, 2009). This could be from high interest especially for the Danish building sector, where brick is after concrete and aggregates the most often used building material. A study on Chinese buildings and the usage of alternative building materials as well could reveal a high mitigation potential with a reduction by 34.8 %. (Pomponi & Moncaster, 2016) as well presents studies on

biomaterials as alternatives, as mentioned above and is pointing out the remarkable results. In a comparison of a typical brick cladding house in Canada, a wood-intensive constructed house reduced the impact from 72 tCO_2 to 20 tCO_2 for instance.

As second mitigation option Pomponi et al. (2016) names better design. Studies quantified the reduction of embodied emissions through better design by up to 20 % (Pomponi & Moncaster, 2016).

Thirdly, optimizing the buildings dimensions (foundation piles etc.) and therewith reducing the resource use is a promising approach (Pomponi & Moncaster, 2016).

Furthermore, (Pomponi & Moncaster, 2016) goes on with listing mitigation options which are here however from minor importance.

4.6 Future Scenarios

Odense is currently in a construction boom and takes measures to create a more urban and livelier city to attract more people to reside in Odense. This induces that the built environment in Odense in the upcoming years will grow in similar extent as in the moment. The construction material inflow will grow or remain on the currently high level, as well as the CRV of the built environment will increase. One project which will likely have a high impact on both, the CRV and the operational emissions, is the new light rail system. The project demands vast amount of resources. Beside common construction materials like non-metallic minerals and stones and aggregates, high amounts of metal are required, due to the railway and electrification. On the other hand, it will impact the transportation sector. Bus lines are going to be substituted, which were implemented by the municipality and attract people who were used to commute by car to use the light rail. A reduction of the GHG emissions by the municipality in the transportation sector can be expected. Another parameter to consider is the impact of the light rail system on the development of the city and its businesses. Odense municipality hopes and predicts (based on experiences from other cities) that the light rail system will attract businesses around stations and increase interest in real estate (COWI, 2013). A clear conclusion on how this will influence the here studied parameters cannot be drawn, but a prognoses is that Odense will shift to a more compact city which increases the CRV, where a new factor is the height of the buildings (increases the embodied energy demand), and that the transportation by car will be reduced even more. Moreover, analyzing the transportation sector (3.7.1) induced that the use phase of vehicles is from significant importance, since the operational emissions are high in comparison. A shift of this relationship between CRV and operational emissions can be predicted for the future, since more and more of the vehicle fleet will be electricity driven which means lower emissions in the use phase. Though, electric vehicles usual have a higher CRV (Messagie, 2017).

Concerning the inflows into the UM several different trends could be analyzed. The water

consumption stayed on the same level in the recent years, which was due to several measures to reduce water consumption and because of measures to increase the efficiency of the water supply network. In the future it is likely that the consumption will stay for several more years on the same level but will then increase slightly due to the predicted population rise. The driver population will also be responsible for a further increase in total food consumption in the next years. A reduction of food consumption per person cannot be expected (at least not in the near future). The consumption of packaging material showed different trends. A reduction of paper was visible and can be also forecasted, because of digitalization but on the other hand an increase for cardboard was visible and can be expected in the next years due to the rising number of home deliveries. The material inflow through vehicles will likely increase, since the car ownership is increasing and is predicted to increase. And lastly, regarding electronic appliances it was not possible to obtain a trend from the data, hence it is difficult to forecast a scenario. However, what can be considered, is that through technological development the dimensions of electronic appliances (excluding house appliances) will decrease further and hence the total material inflow will decrease. To consider here is though, that also the complexity of the products increases (bigger PCB´s) and this may result in a higher inflow of rare earths and materials.

4.7 Possible Further Studies

4.7.1 Stocks in the Built Environment

To have a more accurate estimation of the material stock in NRB, a bottom-up approach as for RB could be applied in the future. Regarding materials in roads, it would be beneficial to find a more accurate way of estimating the material intensities of the specific roads in the municipality.

Furthermore, in further studies piping networks for water and heating as well as wire networks should be included in the material stock estimation of the city.

4.7.2 Mobile Stock

Electronic Appliances

As mentioned above (4.1.5), the limitations of the method applied to estimate the stock of electronic appliances are substantial. To overcome those, an accounting using international statistics could be conducted. The statistical agency of Germany provides a holistic survey including important information as multiple possession of goods (Statistisches Bundesamt, 2018).

Other Types of Mobile Stocks

To conduct a more holistic study more types of mobile stocks should be considered. Even though, data on - for instance - agricultural and industrial machinery as well as furniture could not be obtained, an estimation based on international data would be an opportunity. The stock of bicycles is important to

include too, especially concerning the aluminum stock and because of the high number in possession in Odense.

4.7.3 Outflows

Another parameter to include, to make a more holistic UM study, would be outflows of the UM. It is important to know recycling rates and in case of Odense especially important to know the energy recovered from waste outflows. Odense´s incineration plant utilizes besides coal and straw as well waste as fuel.

4.7.4 Input-Output-Analysis

To overcome mentioned data gaps, another opportunity is an Input-Output-Analysis (IOA). Since IOA´s are based on economical flows, data should be available for all inflows. The issue though, is that the data is mostly aggregated, and a high resolution is not possible, as well as to translate the flows into emissions, a hybrid with an LCA should be considered.

Furthermore, the IOA approach would solve the system boundary issue described in the introduction. It would be clear what is extracted and produced inside the boundary of the municipality and what imported. This would be especially useful for the inflow of food, because it contributes largely to the total of the embodied emissions. A consumption- based emission accounting could be conducted like in the study of the C40 cities, mentioned in the introduction, to make the results comparable and to reveal patterns.

4.7.5 Finding Patterns through the Inclusion of Urban Form Studies

It would be beneficial to compare the results with all available data from other cities and to include the factor of urban forms into the evaluation of the results. This could reveal patterns concerning the ratio between the CRV and the operational emissions and reveal options for sustainable development respectively point out unsustainable urban form parameters.

Julija Metic conducts currently a study about the urban form of Odense, which is about to be done by September 2019. Her results and findings should be highly enlightening and might give answers on questions about the relationship on CRV of the built environment and the operational emissions.

5 Conclusions

In the following, the research questions established – and listed below - are answered briefly and subsequently the key take-aways presented.

1) What is the total amount of emissions caused by the City of Odense? (embodied and operational)
2) How much do the embodied emissions contribute to the aggregated emissions?
3) What is the Carbon Replacement Value of the built environment?
4) What does this indicate for future planned low carbon city development and policy making?

To answer the first research question of the total amount of emissions caused by the City of Odense, first the incoming material flows had to be quantified and subsequent emission factors per material applied. The results show that a total of 1 167 kt CO_2 were emitted by the municipality in 2015. Thereof 840 kt CO_2 (73 %) are operational emissions, the residual 327 kt CO_2 are based on consumption and embodied in inflows. 60 % of the operational emissions occurred due to energy provision and 29 % in the transportation sector. Concerning the energy sector, a strong decrease in emissions over the years 2010 to 2015 could be observed and the trend indicates a further decrease. Contrarily, the emissions of the transportation sector, in the mentioned period, indicate a slight increasing trend which is rooted in the increase of the vehicle fleet.

The second research question investigates the amount of embodied emissions in the aggregated emissions. Here it is found that the highest contribution of embodied emissions is based on the consumption of food and amounts to 64 %. Construction materials contribute 7 % only, even though they are highest in weight (excluding the inflow water), which is due to low energy requirements in upstream processes. Very high upstream energy requirements are noticeable in the emissions due to the inflow of electronic appliances. Even though they make up for less than 1 % of the total weight of inflows, they contribute with 9 % to the total emissions.

Regarding the third research question, the CRV of the built material stock of Odense in 2018 is equal to 24.8 t CO_2 per capita. It amounts to 6 039 kt CO_2 in total and is around sevenfold the operational emissions.

The majority of carbon is embodied in RB and NRB which does not surprise, since the majority of the materials are erected in the built environment. Nevertheless, interesting is the contribution of mobile stocks to the total CRV with 16 %, keeping in mind that mobile stock is only 0.4 % of the total material

weight of all stock. This is pointing out the high energy requirements to provide goods like vehicles and electronics.

Having analyzed the CRV, the final research question shall be answered by providing indications for the development and policy making for future planning of low carbon cities.

The CRV basically indicates how much emissions would occur, applying current technologies, to rebuild or replace the stock of the built environment. This information is important, since it can be used to estimate the future GHG emissions which will occur with rising population and development. The parameter of CRV per capita especially is useful for local city planning and the estimation of future emissions. Through the comparison of this parameter with other cities conclusions can be drawn about the sustainability of the building industry (material choices) and of consumption behaviors (floor area).

On a global scale the parameter CRV is very important. Developing countries respectively cities will demand the same service provided by the built environment as there is currently in industrialized countries. Keeping in mind the magnitude of the CRV in this study, the sevenfold of the operational emissions, it is a parameter which is crucial when thinking of the 2°C target for climate change in 2050. Furthermore, the relationship of the CRV and the operational emissions of cities with considering the factor of urban form could also reveal policy making options for industrialized countries and cities. Identifying patterns which are giving answers on why the CRV is high, or why the operational emissions are high in ratio could create opportunities for sustainable development.

As every scientific work, also this research paper on the estimation of the CRV presents some shortcomings. Material compositions had to be assumed for the material stock in roads. Moreover, the stocks for piping networks and electrification could not be included and only two types of mobile stock could be included.

Furthermore, concerning the estimation of embodied emissions in inflows shortcomings are present regarding the consumption of goods, which were derived from the mobile stock data.

The essential take-away message from this study is the necessity to reflect on the current method of measuring GHG emissions in cities. Accounting the emissions occurring inside the boundary of a city only, is not sufficient because it does not draw a holistic picture. As (Ramaswami et al., 2008) describes, *such an approach may effectively penalize "producer cities" that produce critical urban materials and goods, while giving credit to "consumer cities" for end of life recycling* for goods they did not produce. This fosters a trade-off. The idea though to account emissions based on consumption and the provision of service does draw a holistic a real picture because it does not benefit any type of economy.

A more general and simpler take-away message which is however essential as well, is the plea for a more conscious consumption. A vast amount of emissions can be cut out if we think twice about our consumption and if we need the product or the service. It is for instance surely nice, if we have a house or flat which requires a very small amount of energy, but if we then demand an over dimensional floor area, we miss the target. The energy and emissions it took to provide this service of shelter and to erect this building (CRV) need to be considered. This holds for any other good as well.

Awareness campaigns with the aim of educating the public regarding this topic can present a way to reach this goal.

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7 Appendix

7.1 City of Odense

Table 17: References for Table 1 - Properties of Odense

Information	Reference
Population	StatBank. (2018). FOLK1B: POPULATION AT THE FIRST DAY OF THE QUARTER BY REGION, SEX, AGE (5 YEARS AGE GROUPS) AND CITIZENSHIP. Retrieved from http://www.statbank.dk/statbank5a/default.asp?w=1366
Population density:	Odense Kommune. (2018). *Odensen i tal 2018*. Retrieved from https://www.odense.dk/om-kommunen/statistikker-og-regnskaber/odense-i-tal/odense-i-tal Odense Kommune. (2017). Odense i tal 2017, 1–32. Retrieved from https://www.odense.dk/om-kommunen/statistikker-og-regnskaber/odense-i-tal/odense-i-tal
GDP per capita (for national level):	Trading Economics. (2018). Denmark, historical GDP per Capita. Retrieved from https://tradingeconomics.com/denmark/gdp-per-capita
GDP growth rate per region:	StatBank. (2017). NYT: Højest økonomisk vækst i Københavns omegn - Danmarks Statistik. Retrieved from https://www.dst.dk/da/Statistik/nyt/NytHtml?cid=25769
HDI	United Nations. (2018). Human development indices and indicators: 2018 statistical update. Retrieved from http://hdr.undp.org/sites/default/files/hdr2018_technical_notes.pdf
Average daily temperature	Wikipedia. (2018). Odense Climate. Retrieved from https://en.wikipedia.org/wiki/Odense#Climate

7.2 Stock

7.2.1 Emission Factors for Building Materials

Table 18: Emission factors obtained from ÖKOBAUDAT (ökobaudat.de, 2019)

Material	CO_2-factor [$kgCO_2/kg$]	Name	Data owner
Aluminum	17.600	Türbeschläge aus Aluminium (en)	Fachverband Schloss und Beschlagindustrie
Aluminum+PE	17.600	Türbeschläge aus Aluminium (en)	Fachverband Schloss und Beschlagindustrie

Carpet	7.432	Carpet floor covering (1400 g/m²) (en)	thinkstep
Ceramic	0.702	Ceramic tiles	Bundesverband Keramische Fliesen e. V.
Cement roof tile	0.214	Dachsteine (en)	Nehlskamp GmbH
Clay	0.102	Clay plaster; 1600 kg/m³ (en)	thinkstep
Clay Brick	0.271	facade clinker	thinkstep
Clay brick rooftile	0.350	Roof tile; 1800 kg/m³	thinkstep
Concrete	0.111	average from: Beton der Druckfestigkeitsklasse C 20/25 and Beton der Druckfestigkeitsklasse C 50/60 (en)	Informationszentrum Beton GmbH
Concrete Brick	0.121	Concrete masonry brick; 2000 kg/m³	thinkstep
Concrete - screeds	0.108	Calcium sophat screed	thinkstep
Fiber cement roof plates	0.538	Fibre cement facade panel	thinkstep
Fiber cement	0.538	Fibre cement facade panel	thinkstep
Aerated Concrete	0.479	Aerated concrete P2 04 non-reinforced; average density 380 kg/m³	thinkstep
Glass	1.796	Insulated glazing, double pane; double glass	thinkstep
Gypsum	0.260	Gypsum (CaSO4 alpha semihydrate); grinded and purified product	thinkstep
Leca beton (light weight concrete)	0,322	Expanded clay concrete block inner wall; Plan stone interior wall, density class 0,7, 700 kg/m³	thinkstep
Leca nuts	0.949	Expanded clay granulation; grain size 4/16 thinkstep	thinkstep
Linoleum flooring	1.256	Linoleum flooring	thinkstep
Mineral wool	1.509	Mineral wool (facade insulation)	thinkstep
Mortar (lime mortar) <1970s	0.111	Lime cement mortar	thinkstep
Mortar (limestone cement) >1970s	0.111	Lime cement mortar	thinkstep
PE, PP	1.997	Damp insulation PE	thinkstep
Plywood	-1.513	Plywood board; 5% moisture	thinkstep
PVC	4.000	PVC roofing membrane	thinkstep
Sand and gravel	0.033	Gravel 2/32 dried	thinkstep
Slag	0.000	Slag-tap granulate; granulate	thinkstep
Steel	1.000	Steel section; Steel sections	thinkstep
Stones	0.192	Natural stone slab, rigid, outdoor usage (80 mm); 208 kg/m2 (en)	thinkstep
Straw	-1.280	FASBA e.V. Baustroh 100 kg/m³; 100 kg/m³	FASBA e.V.

Sundolit (X-EPS)	2.894	Extruded polystyrene (XPS); 32 kg/m^3	thinkstep
Tared paper (bitumen + PE)	0.867	Bitumen sheets PYE-PV 200 S5 ns (slated); 6,2 kg/m^2 (en)	thinkstep
Timber	-1.210	Solid construction timber (15 % moisture / 13 % H2O content); 529 kg/m^3 at 15% moisture	thinkstep
Zinc	1.710	NedZink Naturel (en)	NedZink B.V

7.2.2 Residential Buildings

Table 19: Material Stock in Residential Buildings assigned to Material Categories

Material Category	Material	Mass [t]
Metals	Steel	152 733
	Zinc	210
	Aluminum	8 553
	Aluminum + PE	83
Ceramics and brick	Ceramic	9 410
	Clay	255 345
	Clay Brick	4 301 332
	Clay brick rooftiles	138 706
Non-metallic Minerals	Concrete	5 006 358
	Concrete - screeds	110 669
	Concrete brick	8 209
	Fiber cement roof plates	77 612
	Fiber cement	111
	Aerated concrete	146 040
	Cement rooftiles	63 640
	Gypsum	117 159
	Leca beton (light weight concrete)	177 672
	Leca nuts	71 848
	Mortar (lime mortar) <1970s	1 080 862
	Mortar (limestone cement) >1970s	318 667
Stones and Aggregates	Sand and gravel	1 643 817
	Stones	6 321
Wood-based Materials	Straw	15
	Timber	628 805
	Wood wool cement	121
Miscellaneous	Carpet	865
	Sundolit (X-EPS)	3 418
	Tared paper (bitumen + PE)	30 334
	Slag	153

	PE, PP	5 175
	PVC	428
	Glass	25 700
	Linoleum	2 293
	Mineral wool	80 296
Total		14 472 961

Table 20: Carbon Replacement Values of the Material Stock in Residential Buildings

Material	Mass [t]	CO_2-emission factor [kgCO_2/kg]	CRV [ton CO_2]
Aluminum	8 553	17.600	150 538
Aluminum + PE	83	17.600	1 460
Carpet	865	7.432	6 427
Cement rooftiles	63 640	0.702	44 702
Ceramic	9 410	0.214	2 014
Clay	255 345	0.102	25 966
Clay Brick	4 301 332	0.271	1 165 661
Clay brick rooftiles	138 706	0.350	48 547
Concrete	5 006 358	0.111	554 871
Concrete - screeds	110 669	0.108	11 952
Concrete brick	8 209	0.121	993
Fiber cement roof plates	77 612	0.538	41 791
Fiber cement	111	0.538	60
Aerated Concrete	146 040	0.479	69 907
Glass	25 700	1.796	46 160
Gypsum	117 159	0.260	30 461
Leca beton (light weight concrete)	177 672	0.322	57 230
Leca nuts	71 848	0,949	68 212
Linoleum	2 293	1.256	2 881
Mineral wool	80 296	1.509	121 198
Mortar (lime mortar) <1970s	1 080 862	0.111	120 093
Mortar (limestone cement) >1970s	318 667	0.111	35 407
PE, PP	5 175	1.997	10 335
PVC	428	4.000	1 711
Sand and gravel	1 643 817	0.033	54 706
Slag	153	0.000	0
Steel	152 733	1.000	152733
Stones	6 321	0.192	1216
Straw	15	-1.280	-19
Sundolit (X-EPS)	3 418	2.894	9892
Tared paper (bitumen + PE)	30 334	0.867	26293
Timber	628 805	-1.460	-918055
Wood wool cement	121	-0.818	-99

Zinc	210	1.710	359
Total [t]	**14472961**	**Total [kt CO_2]**	**1946**

7.2.3 Non-residential Buildings

Table 21: Assumptions on Material Intensities for non-residential building stocks

Non-residential building type	**Assumptions**
Non-residential farm buildings	Industrial – Sweden [1]
Factories, workshops, etc.	Industrial – Sweden [1]
Power stations, gaswork, etc.	Industrial – Sweden [1]
Other building used for production	Industrial – Sweden [1]
Transportation or garage	Public – Sweden [1]
Office, trade, inventory, incl. public administration	Public – Sweden [1]
Hotel, restaurant, hairdresser and other services	Commercial – Sweden [1]
Unspecified transport and trade	Public – Sweden [1]
Library, church, museum etc.	Public – Sweden [1]
Building for education and research (schools, laboratory etc.)	Public – Sweden [1]
Building for hospital, home, maternity home etc.	Public – Sweden [1]
Day-care institution	Public – Sweden [1]
Non-specified welfare institutions	Public – Sweden [1]
Weekend cottages	SFH – samples [2]
Unspecified holiday purposes	SFH – samples [2]
Sports centres, club houses	Public – Sweden [1]
Allotment garden house	SFH – samples [2]
Garage with room for one or two vehicles	Garage [1]
Carports	Garage [1]
Outhouses	Garage [1]
Unspecified recreational purposes	Commercial – Sweden [1]
Under construction, Unlisted	not taken into account

[1] The material intensities were obtained from Paul Gontia, Chalmers University (Sweden) (Gontia, 2019)
[2] Material intensity data from our estimation on RB material intensity

Table 22: Material Stock in Non-Residential Buildings assigned to Material Categories

Material Category	Material	Mass [t]
Metals	Steel	729190
	Zinc	3
	Aluminum	274
	Aluminum + PE	7
Ceramics and brick	Ceramic	1023

	Clay	5595
	Clay Brick	2415107
	Clay brick rooftiles	9100
Non-metallic Minerals	Concrete	9333166
	Concrete - screeds	11699
	Concrete brick	29
	Fiber cement roof plates	6558
	Fiber cement	61628
	Aerated Concrete	3633
	Cement rooftiles	197
	Gypsum	1639
	Leca beton (light weight concrete)	11199
	Leca nuts	1763
	Mortar (lime mortar) <1970s	17150
	Mortar (limestone cement) >1970s	11004
Stones and Aggregates	Sand and gravel	1053972
	Stones	117
Wood-based Materials	Straw	1
	Timber	502718
	Wood wool cement	10
Miscellaneous	Carpet	1
	Sundolit (X-EPS)	74
	Tared paper (bitumen + PE)	814
	Slag	15
	PE, PP	83
	PVC	135
	Glass	866
	Linoleum	63
	Mineral wool	3209
Total		**14182040**

Table 23: Carbon Replacement Values of the Material Stock in Non-Residential Buildings

Material	Mass [t]	CO_2 emission factor [kgCO_2/kg]	CRV [t CO_2]
Aluminum	274	17.600	4818
Aluminum + PE	7	17.600	117
Carpet	1	7.432	9
Ceramic	1023	0.702	719
Cement rooftiles	197	0.214	42
Clay	5595	0.102	569
Clay Brick	2415107	0.271	654494

Clay brick rooftiles	9100	0.350	3185
Concrete	9333166	0.111	1034426
Concrete - screeds	11699	0.108	1264
Concrete brick	29	0.121	3
Fiber cement roof plates	6558	0.538	3531
Fiber cement	61628	0.538	33184
Aerated concrete	3633	0.479	1739
Glass	866	1.796	1555
Gypsum	1639	0.260	426
Leca beton (light weight concrete)	11199	0.322	3607
Leca nuts	1763	0.950	1673
Linoleum	63	1.256	79
Mineral wool	3209	1.509	4844
Mortar (lime mortar) <1970s	17150	0.111	1906
Mortar (limestone cement) >1970s	11004	0.111	1223
PE, PP	83	1.997	166
PVC	135	4.000	539
Sand and gravel	1053972	0.033	35076
Slag	15	0.000	0
Steel	729190	1.000	729190
Stones	117	0.192	22
Straw	1	-1.280	-1
Sundolit (X-EPS)	74	2.894	215
Tared paper (bitumen + PE)	814	0.867	705
Timber	502718	-1.460	-733968
Wood wool cement	10	-0.817	-8
Zinc	3	1.710	5
Total [t]	**14182040**	**Total [kt CO_2]**	**1785354**

7.2.4 Roads

Table 24: Emission factors of construction materials used in road material stock

Material	$kgCO_2/kg$	Reference in ÖKOBAUDAT	Data owner
Asphalt	0.074	Stone mastic Asphalt SMA	thinkstep
Gravel	0.033	Gravel 2/32 dried	thinkstep
Concrete	0.111	average from Beton der Druckfestigkeitsklasse C 20/25 and Beton der Druckfestigkeitsklasse C 50/60 (en)	Informations zentrum Beton GmbH

7.3 Mobile Stock

7.3.1 Vehicles

Table 25: Stock of vehicles per 1 January in Odense (Statbank,BIL707)

Vehicle Type	2010	2011	2012	2013	2014	2015	2016	2017	2018
Cars	64837	65642	66309	67588	69304	70675	71857	73458	75617
Buses	130	166	165	148	177	178	174	520	410
Vans	9325	9008	8532	8173	8033	7645	7182	7005	7395
Lorries	438	400	409	415	411	426	417	385	721
Road tractors	127	131	126	117	125	124	111	101	298
Trailers for lorries and cars	20178	20745	21366	20846	21498	22143	22760	22338	24408
Trailers for agriculture	95	86	80	70	66	66	67	286	96
Semi-trailers	366	355	354	329	325	321	304	301	467
Motorcycles	3841	3864	3768	3820	3879	3858	3921	4054	4121
45-mopeds	1738	1639	1493	1431	1381	1257	1280	1244	1174
Agricultural tractors	764	736	727	672	685	673	673	674	1348
Caravans	3782	3754	3724	3619	3521	3409	3338	3256	3147
Vans & lorries for rescue	14	15	15	14	14	16	15	37	38

Table 26 shows the average material composition of a car constructed in 2011. The values of 2011 were taken, due to the fact, that the average car in Denmark is 8 years old according to Statbank (StatBank, n.d.-b).

Table 26: Average Material Composition of a Car constructed in 2011 (Dai, Kelly, & Elgowainy, 2016)

Material	Mass (kg)
Steel	985
Iron	125
Aluminum	161
Magnesium castings	5
Copper and brass	30
Lead	19
Zinc castings	4
Powder metal parts	19
Other metals	2
Plastics and plastic composites	171
Rubber	101
Coatings	15

Textiles	22
Fluids and lubricants	101
Glass	44
Other materials	43
Total	***1847***

Table 27: Average material composition of heavy duty vehicles (Ricardo AEA, 2015)

Material (kg)	**Van (5tGVW) = Van**	**Coach (19 t GVW) = Bus**	**Artic Truck (Curtainsider) (40t GVW) = Lorry**
Fe	232	1273	1543
Steel	1011	5667	8750
HS Steel	268	476	465
Al	141	2544	519
Cu	23	34	70
Plastics	249	1174	815
Rubber	69	388	844
Glass	14	300	43
Water	15	120	60
Lead	16	156	156
Other	263	1269	1285
Total	2300	13 400	14 550

Table 28: Material Composition for Road and Agriculture Tractors, originally for Wheel Loader(Volvo, 2018)

Material	Mass [kg]
Steel and Iron	8010
Pb	24
Other non-iron metals	55
Tires	444
Rubber	200
Glass	60
Oil	230
Total	9023

For road tractors and agricultural tractors the composition of a compact wheel loader was taken (Volvo, 2018).

Table 29: Material Composition for Motorcycles and Mopeds derived from Car Material Composition with Adjustments

Motorcycle		Moped	
Material	Mass [kg]	Material	Mass [kg]

Steel	99.2	Steel	42.6
Fe	12.6	Fe	5.4
Al	16.2	Al	7.0
Cu and Brass	3.1	Cu and Brass	1.3
Pb	1.9	Pb	0.8
Powder Metals	1.9	Powder Metals	0.8
Plastics	17.2	Plastics	7.4
Rubber	5.1	Rubber	4.4
Fluids and Lubricants	10.2	Fluids and Lubricants	4.4
Others	9.2	Others	4.0

For mopeds and motorcycles the same material composition as for cars was taken, except that the amount for rubber was halved, because of only two existing wheels and also glass was not considered as material compound. The windshield of motorcycles and mopeds is usual made out of acryl glass – a polymer. The total weights of the two vehicles are set after a market research (Survival Techshop, n.d.), (idealo.de, n.d.).

Table 30: Material Composition assumed for Agricultural Trailers

Material	Mass [kg]
Steel	4392
Plastic	488
Rubber	120

To make appropriate assumptions for the material composition of agricultural trailers, a agricultural trailer typical for the market was selected from the internet (metalltech.com, n.d.). The trailer weighs around 5000 kg and consists mostly out of steel. It has two axis and hence is a four-wheeler. The weight of the tires is estimated with 30 kg each. For the rest 90 % of steel are estimated and 10 % plastics.

Table 31: Material composition assumed for trailers used by cars (and lorries)

Material	Mass [kg]
Steel	115.43
Al	57.71
Rubber	40.00
Plywood	399.62
Plastics	19.24

To make assumptions of the material composition of trailers for cars and lorries It was searched for typical trailers for cars, it is assumed, that trailers for lorries are in minority in this category. The weight of a such a trailer amounts to 632 kg. Taking the measures of the trailer from the manufacturer (300X155X185 cm), the area of the housing (plywood) was calculated and amounts to around 21 m². Assuming the thickness to be 3 cm and applying the density (620 kg/m³ (Woodproductsfi, n.d.)) the weight could be estimated with 399.62 kg. The trailer is a four-wheeler with a small tire size (14inch), hence the weight for the tires is estimated with 10 kg each. For the rest composition of the trailer it is

estimated, that 60 % is steel (axis, base construction), 30 % is aluminum (connection parts housing) and 10 % plastics.

Other assumptions are, that semi-trailers are not considered as individual unit, since it is assumed that they are included in the material composition of the lorries. And for Caravans the same material composition was assumed as for normal Vans (5t GVW)

Table 32: Material Stock in Cars in Odense 2010-2018

Material (t)	2010	2011	2012	2013	2014	2015	2016	2017	2018
Steel	63837	64630	65287	66546	68235	69585	70749	72325	74451
Fe	8105	8205	8289	8449	8663	8834	8982	9182	9452
Al	10439	10568	10676	10882	11158	11379	11569	11827	12174
Mg	353	357	361	368	377	385	391	400	412
Cu and brass	1970	1995	2015	2054	2106	2147	2183	2232	2298
Pb	1206	1221	1233	1257	1289	1314	1336	1366	1406
Zn	265	268	271	276	283	288	293	300	309
Powder metals	1206	1221	1233	1257	1289	1314	1336	1366	1406
Other metals	147	149	150	153	157	160	163	167	171
Plastics	11086	11223	11337	11556	11849	12084	12286	12559	12929
Rubber	6528	6609	6676	6805	6978	7116	7235	7396	7613
Coatings	1000	1012	1022	1042	1069	1090	1108	1133	1166
Textiles	1411	1429	1443	1471	1509	1539	1564	1599	1646
Fluids and lubricants	6557	6639	6706	6835	7009	7148	7267	7429	7647
Glass	2882	2917	2947	3004	3080	3141	3194	3265	3361
Other materials	2764	2798	2827	2881	2954	3013	3063	3132	3224
Total (kt)	119.7	121.2	122.4	124.8	127.9	130.5	132.7	135.6	139.6

Table 33: Material Stock in Vans in Odense 2010-2018

Material [t]	2010	2011	2012	2013	2014	2015	2016	2017	2018
Steel	11927	11521	10912	10453	10274	9778	9186	8959	9458
Fe	2163	2090	1979	1896	1864	1774	1666	1625	1716
Al	1315	1270	1203	1152	1133	1078	1013	988	1043
Cu	214	207	196	188	185	176	165	161	170
Plastics	2322	2243	2124	2035	2000	1904	1788	1744	1841
Rubber	643	622	589	564	554	528	496	483	510
Glass	131	126	119	114	112	107	101	98	104
Water	140	135	128	123	120	115	108	105	111

Pb	149	144	137	131	129	122	115	112	118
Other	2452	2369	2244	2149	2113	2011	1889	1842	1945
Total	21448	20718	19624	18798	18476	17584	16519	16112	17009

Table 34: Material Stock in Buses in Odense 2010-2018

Material [t]	2010	2011	2012	2013	2014	2015	2016	2017	2018
Steel	799	1020	1014	909	1087	1093	1069	3194	2519
Fe	165	211	210	188	225	227	222	662	522
Al	331	422	420	377	450	453	443	1323	1043
Cu	4	6	6	5	6	6	6	18	14
Plastics	153	195	194	174	208	209	204	610	481
Rubber	50	64	64	57	69	69	68	202	159
Glass	39	50	50	44	53	53	52	156	123
Water	16	20	20	18	21	21	21	62	49
Pb	20	26	26	23	28	28	27	81	64
Other	165	211	209	188	225	226	221	660	520
Total	1742	2224	2211	1983	2372	2385	2332	6968	5494

Table 35: Material Stock in Lorries in Odense 2010-2018

Material [t]	2010	2011	2012	2013	2014	2015	2016	2017	2018
Steel	4036	3686	3769	3824	3787	3926	3843	3548	6644
Fe	676	617	631	640	634	657	643	594	1113
Al	227	208	212	215	213	221	216	200	374
Cu	31	28	29	29	29	30	29	27	50
Plastics	357	326	333	338	335	347	340	314	588
Rubber	370	338	345	350	347	360	352	325	609
Glass	19	17	18	18	18	18	18	17	31
Water	26	24	25	25	25	26	25	23	43
Pb	68	62	64	65	64	66	65	60	112
Other	563	514	526	533	528	547	536	495	926
Total	6373	5820	5951	6038	5980	6198	6067	5602	10491

Table 36: Material Stock in Caravans 2010-2018

Material [t]	2010	2011	2012	2013	2014	2015	2016	2017	2018
Steel	4837	4801	4763	4629	4503	4360	4269	4164	4025
Fe	877	871	864	840	817	791	774	755	730
Al	533	529	525	510	496	481	471	459	444
Cu	87	86	86	83	81	78	77	75	72
Plastics	942	935	927	901	877	849	831	811	784
Rubber	261	259	257	250	243	235	230	225	217
Glass	53	53	52	51	49	48	47	46	44

Water	57	56	56	54	53	51	50	49	47
Lead	61	60	60	58	56	55	53	52	50
Other	995	987	979	952	926	897	878	856	828
Total	8699	8634	8565	8324	8098	7841	7677	7489	7238

Table 37: Material Stock in Mopeds 2010-2018

Material [t]	2010	2011	2012	2013	2014	2015	2016	2017	2018
Steel	74.12	69.90	63.67	61.03	58.89	53.61	54.59	53.05	50.07
Fe	9.41	8.87	8.08	7.75	7.48	6.81	6.93	6.74	6.36
Al	12.12	11.43	10.41	9.98	9.63	8.77	8.93	8.67	8.19
Cu and Brass	2.29	2.16	1.96	1.88	1.82	1.65	1.68	1.64	1.55
Pb	1.40	1.32	1.20	1.15	1.11	1.01	1.03	1.00	0.95
Powder Metals	1.40	1.32	1.20	1.15	1.11	101	1.03	1.00	0.95
Plastics	12.87	12.14	11.06	10.60	10.23	9.31	9.48	9.21	8.69
Rubber	7.58	7.15	6.51	6.24	6.02	5.48	5.58	5.42	5.12
Glass	3.35	3.16	2.87	2.75	2.66	2.42	2.46	2.39	2.26
Fluids and Lubricants	7.61	7.18	6.54	6.27	6.05	5.51	5.61	5.45	5.14
Others	6.90	6.50	5.92	5.68	5.48	4.99	5.08	4.94	4.66
Total	139	131	119	114	110	100	102	99.5	93.9

Table 38: Material Stock in Motorcycles

Material [t]	2010	2011	2012	2013	2014	2015	2016	2017	2018
Steel	381	383	374	379	385	383	389	402	409
Fe	48	49	47	48	49	49	49	51	52
Al	62	63	61	62	63	63	64	66	67
Cu and Brass	12	12	12	12	12	12	12	12	13
Pb	7	7	7	7	7	7	7	8	8
Powder Metals	7	7	7	7	7	7	7	8	8
Plastics	66	67	65	66	67	66	68	70	71
Rubber	20	20	19	19	20	20	20	21	21
Glass	17	17	17	17	17	17	18	18	18
Fluids and Lubricants	39	39	38	39	40	39	40	41	42
Others	35	36	35	35	36	36	36	37	38
Total	695	699	682	691	702	698	710	734	746

Table 39: Material Stock in Road and Agriculture Tractors

Material [t]	2010	2011	2012	2013	2014	2015	2016	2017	2018
Steel and Iron	7137	6945	6833	6320	6488	6384	6280	6208	13184
Pb	21	21	20	19	19	19	19	19	40
Other non-iron metals	49	48	47	43	45	44	43	43	91
Tires	396	385	379	350	360	354	348	344	731
Rubber	178	173	171	158	162	159	157	155	329

Glass	53	52	51	47	49	48	47	47	99
Oil	205	199	196	181	186	183	180	178	379
Total	8039	7823	7697	7119	7309	7191	7074	6993	14852

Table 40: Material Stock from Trailers for Cars

Material [t]	2010	2011	2012	2013	2014	2015	2016	2017	2018
Steel	2329	2395	2466	2406	2481	2556	2627	2700	2817
Al	1165	1197	1233	1203	1241	1278	1314	1350	1409
Rubber	807	830	855	834	860	886	910	935	976
Plywood	8064	8290	8538	8330	8591	8849	9095	9346	9754
Plastics	388	399	411	401	414	426	438	450	470
Total	12752	13111	13503	13175	13587	13994	14384	14781	15426

Table 41: Material Stock from Agricultural Trailers

Material [t]	2010	2011	2012	2013	2014	2015	2016	2017	2018
Rubber	11	10	10	8	8	8	8	34	12
Steel	417	378	351	307	290	290	294	1256	422
Plastic	46	42	39	34	32	32	33	140	47
Total	475	430	400	350	330	330	335	1430	480

Table 42: Processes used in SimaPro for GHG emissions estimation

Vehicle	Simapro reference (Ecoinvent v3 Allocation cut-off)	$kgCO_2$/unit
Moped	Motor scooter, 50cubic cm engine [RER] motor scooter production	414
Motorcycle	Motor scooter, 50cubic cm engine [RER] motor scooter production [1]	828
Lorry	Lorry, 28 metric ton [RER] production	29161
Car	Light commercial vehicle [RER] production	5873
Van	Passenger Car petrol/natural gas [GLO]production [2]	12091
Bus	Bus [RER] production	29465
Road and Agricultural Tractor	Tractor, 4-wheel, agricultural [GLO] production [3]	63605
Caravans	Passenger Car petrol/natural gas [GLO] production [4]	
Agricultural Trailer	Agricultural trailer {RoW}| production | Alloc Rec, U [5]	39480

[1] For Motorcycles the process for Motor scooters is taken but doubled. The weight of a motorcycle (Survival Techshop, n.d.) is approximately twice the one of a motor scooter (idealo.de, n.d.).

[2] For vans the process for a petrol car was chosen and the weight adjusted. 2000 kg were assumed for a van.

[3] For the input weight it was assumed that a tractor weighs 9023 kg. That is as much as the wheel loader from Volvo weighs (Volvo, 2018)

[4] For Caravans the same process as for Vans was assumed, with the same weight.

[5] It is estimated that the agricultural trailer weighs 5000 kg (metalltech.com, n.d.)

Table 43: Embodied Energy Values from the Literature for Materials in Trailers

Material	Embodied Energy [kWh/kg]
Steel	5.34 [1]
Aluminum	23 [1]
Rubber	5.94 [1]
Plastics [2]	23.24 [1]
Plywood	0.24 [3]

[1] Derived from an LCA for automotive parts (Pryshlakivsky & Searcy, 2017)
[2] Average from CO2 emission factor for HDPE, PP and PET
[3] Derived from Simapro database Ecoinvent v3 Allocation cut off for process: Plywood, for outdoor use {RER}| market for | Alloc Rec, U (482 kg CO2/m³) then converted with the average density of plywood of 620 kg/m³ (Woodproductsfi, n.d.) to 0.77 kgCO2/kg.

Table 44: CO_2 emissions embodied in Vehicle Fleet in 2018 (CRV)

Vehicle type	Vehicles in 2018 [nb]	CO_2 [t]
Passenger cars	75617	444080
Buses	410	12081
Vans	7395	89413
Lorries	721	21025
Road tractors	298	18954
Trailers (agricultural and for cars)	24504	14241
Semi-trailers	467	0
Motorcycles	4121	3412
45-mopeds	1174	486
Agricultural tractors	1348	85739
Caravans	3147	38050
Vans and lorries for rescue	38	0
Total [t CO_2]		**727 480**

7.3.2 Electronic Appliances

Table 45: The families possession of home appliances by type of consumption and time (Statbank Varforbr)

House Appliances [% of families]	2010	2011	2012	2013	2014	2015	2016	2017	2018
Dryer	53	54	52	52	54	52	52	54	54
Washing machine	82	80	79	81	82	78	76	83	81
Dishwasher	69	67	67	67	69	69	68	69	68
Microwave oven	76	75	73	77	76	76	73	76	74
Espresso machine, espresso capsule maker	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	36
Robot vacuum cleaner	n.a.	n.a.	7	8	7	9	8	8	7
Consumer Electronics [% of families]	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Video camera	32	28	n.a	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Digital video camera	26	22	31	25	24	26	23	21	20
Digital camera	77	79	76	71	73	65	59	56	49
CD-player	84	84	82	77	74	64	66	60	60[1]
Video recorder	55	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
DVD-player	85	78	68	65	61	53	52	44	44 [2]
HDD-recorder	32	26	28	27	28	26	26	25	30
BluRay-player	10	16	23	24	27	30	32	32	32 [3]
Flatscreen Tv	70	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Tv [4]	96	96	96	95	98	98	98	94	94
Digital Tv	60	74	n.a	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
3D-tv	n.a	4	14	17	17	19	19	18	19
Smart-tv	n.a.	n.a.	n.a.	24	34	40	45	53	53
PC	n.a.	91	92	93	95	92	95	91	94
Desktop PC	53	53	49	47	41	39	39	37	42
Laptop PC	72	78	81	81	86	85	91	87	90
Tablet PC	n.a.	9	19	33	45	50	61	52	60
Mobile phone	97	97	97	98	98	98	96	96	96
Smartphone	n.a.	33	50	63	73	77	83	84	88
Landline telephone	64	58	51	50	42	39	30	26	20
MP3 Player	50	48	46	45	40	36	33	28	28 [5]
DAB radio	33	32	35	37	35	36	37	38	33
GPS navigation	46	52	54	50	53	54	54	49	51
Activity tracker watch	n.a.	n.a.	n.a	n.a	n.a	n.a.	n.a.	n.a.	30
GPS-watch	8	10	11	11	12	13	17	17	19
Game console	35	40	40	42	39	39	42	40	39
E-book reader	2	2	4	5	6	8	6	10	9

[1] no value was given. It is assumed the stock stays the same and was just not counted.
[2] no value was given. It is assumed the stock stays the same and was just not counted.
[3] no value was given. It is assumed the stock stays the same and was just not counted.

[4] Obtained from (Statistisches Bundesamt, 2019) due to inconsistency in data of *Statbank*
[5] no value was given. It is assumed the stock stays the same and was just not counted.

Assumptions and Simplifications:

- Information on TV devices in general only exists for 2011 (98%) in Statbank. Thus, data was obtained from German statistics (Statistisches Bundesamt, 2019).
- No data on material composition for dryer was found, hence the same material composition as for washing machines was assumed
- No data on material composition for GPS – navigation devices, Activity tracker watch and GPS watch was found, hence a general composition from the literature was used for small WEEE (Dimitrakakis, Janz, Bilitewski, & Gidarakos, 2009).
- For the Hard disk-recorder, CD-Player and BluRay-Player the same material composition stated by (Oguchi, Sakanakura, & Terazono, 2013) for the DVD-player was assumed.
- In 2018 data for CD-Player, BluRay-Player and DVD-Player was not given. It is assumed that the goods are still there as stock and hence the same data for 2018 as for 2017 is assumed.

Table 46: Estimated stock of Electronic Appliances in family households in Odense

	2010	2011	2012	2013	2014	2015	2016	2017	2018
Families Odense	101093	102148	103406	104669	106635	107820	109475	110413	112092
House Appliances [nb of units]									
Dryer	53579	55160	53771	54428	57583	56066	56927	59623	60530
Washing machine	82896	81718	81691	84782	87441	84100	83201	91643	90795
Dishwasher	69754	68439	69282	70128	73578	74396	74443	76185	76223
Microwave oven	76831	76611	75486	80595	81043	81943	79917	83914	82948
Esp. machine	n.a	n.a	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	40353
Robot vac. cleaner	n.a	n.a	7238	8374	7464	9704	8758	8833	7846
Consumer Electronics [nb of units]									
Digital video camera	26284	22473	32056	26167	25592	28033	25179	23187	22418
Digital camera	77842	80697	78589	74315	77844	70083	64590	61831	54925
CD-player	84918	85804	84793	80595	78910	69005	72254	66248	66248
Video recorder	55601	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
DVD-player	85929	79675	70316	68035	65047	57145	56927	48582	48582
Hard disk-recorder	32350	46988	48601	49194	51185	48519	50359	47478	33627
BluRay-player	10109	16344	23783	25121	28791	32346	35032	35332	35332
Tv	97251	98266	99683	99540	103969	105556	107176	107984	105703
PC	88962	92955	95134	97342	101303	99194	104001	100476	105366

Desktop PC	47150	49266	46615	45751	41534	38686	40560	37176	44254
Laptop PC	64053	72505	77058	78847	87121	84315	94641	87414	94830
Tablet PC	n.a.	9193	19647	34541	47986	53910	66780	57415	67255
Mobile phone	98060	99084	100304	102576	104502	105664	105096	105996	107608
Smartphone	n.a.	32698	50152	64623	76287	81361	87230	89037	94695
Landline Telephone	64700	59246	52737	52335	44787	42050	32843	28707	22418
MP3 Player	50547	49031	47567	47101	42654	38815	36127	30916	30916
DAB radio	33361	32687	36192	38728	37322	38815	40506	41957	36990
GPS navigation	46503	53117	55839	52335	56517	58223	59117	54102	57167
Activity tracker	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	33628
GPS-watch	8087	10215	11375	11514	12796	14017	18611	18770	21297
Game console	35383	40859	41362	43961	41588	42050	45980	44165	43716
E-book reader	2022	2043	4136	5233	6398	8626	6569	11041	10088

Table 47: Material compositions of Consumer Electronics

Material Compositions derived from (Oguchi et al., 2013)

Product	Fe [%]	Al [%]	Cu [%]	Plastics [%]	PCB [%]	Ave weight [kg]
LCD TV	43.0	3.8	0.8	31.8	11.6	11.3 [1]
Desktop PC	47.2	–	0.9	2.8	9.4	10.0 [1]
Notebook PC	19.5	2.4	1.0	25.8	13.7	1.9 [2]
Telephone	–	–	10.3	53.2	12.6	0.5 [1]
Digital camera	5.2	4.3	0.3	31.8	20.2	0.2 [3]
Camcorder	5.0	–	2.9	29.0	17.7	0.5 [1]
Video game	19.9	2.3	1.6	47.8	20.6	2.8 [1]
Microwave oven	71.9	0.4	4.0	6.5	4.7	16.0 [1]
Washing machine	51.7	2.0	3.1	35.3	1.7	65.0 [1]

Material Compositions taken from (Parajuly & Wenzel, 2017)

Product	Fe [g]	Cu [g]	Al [g]	Plastic [g]	PCB [g]	Other [g]
DAB Radio	1207	88.8	19	1320.2	365	40
Mobile Phone	316	44.8	0	514.2	239	3
DVD-Player	1633	43	226	203	379	13

Material Composition of Smart Phones from (Magyar, Nagy, Őrsi, & Papp, 2018) **and (Öko-Institut & Buchert, 2012)**

Material	Multitouch Panel	Plastic	Fe	PCB	Ag	Au
[g]	23.79	45.7	0.53	11.48	0.305	0.3

Material	Palladium	Cobalt	Neudymium	Praseoydium	OLED
[g]	0.11	6.3	0.05	0.01	7.87

Material Composition of E-readers derived from (Ding et al., n.d.)

Material	PVC	Copper	Aluminum	Lithium	Glass	Zinc	Fe
[g]	72.5	37.77	31.31	0.459	42.3	10.83	143.22

Material Composition of Tablets (Ipad) derived from (Naicker & Cohen, 2016)

Material	Glass	LCD	Al	Battery, Lithium	ABS	PS	PCB
[g]	61	109	86	161	33	66	32

Material Composition of small WEEE used for GPs-navigation device, Activity tracker watch and GPS-watch derived from (Freegard & Claes, 2009)

Material	Fe	Cu	PCB	Plastics	Batteries	LCD	Glass	others
%	0.48	0.061	0.081	0.0315	0.007	0.003	0.008	0.044

[1] (Sustainablility-Exchange, n.d.)
[2] (Zeng, Gong, Chen, & Li, 2016)
[3] (Park, Tahara, & Inaba, 2007)

Table 48: Material Compositions of House Appliances

Material Composition of Dishwashers derived from (Öko-Institut e.V, 2011)

Material	stainless steel	steel sheet galvanized	Cast iron	Polypropylen	Plastics
[g]	24560	403	2303	4980	1165
Material	ABS	PS	Copper wire	PVC	EPDM-rubber
[g]	751	512	1006	403	524
Material	Aluminum	CuZn38 cast	Chrome	Bitumen	Concrete
[g]	273	23	71	6089	1263
Material	Cotton	Epoxy	Wood	others Paper	PCB electronic control
[g]	452	609	2034	285	448

Material Composition of Espresso Machines derived from (Parajuly & Wenzel, 2017)

Material	Fe	Cu	Al	Plastic	PCB	Other
[g]	141.17	46.12	165.50	1124.55	27.00	36.00

Material Compositions derived from (Oguchi et al., 2013)

Product	Fe [%]	Al [%]	Cu [%]	Plastics [%]	PCB [%]	Ave weight [kg]
Microwave Oven	71.9	0.4	4.0	6.5	4.7	16.0 [1]
Washing Machine	51.7	2.0	3.1	35.3	1.7	65.0 [1]

Material Composition of Robot Vacuum Cleaners derived from (Parajuly, Habib, Cimpan, Liu, & Wenzel, 2016)

Material	Polymers (ABS&PC)	Fe-metals	Non-Fe metals and magnet	Battery	PCB
[g]	1.45	0.425	0.075	0.45	0.125

[1] (Sustainablility-Exchange, n.d.)

Table 49: Material Stock in House Appliances in Odense (a)

Material (t)	Fe	Non-Fe	Al	Cu	Plastics	PCB	Others	PP	ABS	PS	PVC	EPDM-rubber
2010	7372	0	201	394	3293	240	0	347	52	36	28	37
2011	7347	0	202	394	3300	240	0	341	51	35	28	36
2012	7310	0.0005	200	391	3267	237	0	345	52	35	28	36
2013	7517	0.0006	205	403	3360	246	0	349	53	36	28	37
2014	7623	0.0006	209	409	3432	249	0	349	53	36	28	37
2015	5797	0.0007	208	410	3301	250	0	370	56	38	30	39
2016	7658	0.0007	208	408	3385	248	0	371	56	38	30	39
2017	8126	0.0008	223	435	3647	236	0	379	57	39	31	40
2018	8123	0.0007	225	441	3693	265	1,45	380	57	39	31	40

Table 50: Material Stock in House Appliances in Odense (b)

Material (t)	CuZn38 cast	Chrom	Bitumen	Concrete	Cotton	Epoxy	Wood	others Paper	Total
2010	2	5	425	88	32	42	142	20	***12755***
2011	2	5	417	86	31	42	139	20	***12714***
2012	2	5	422	88	31	42	141	20	***12652***
2013	2	5	427	89	32	43	143	20	***12993***
2014	2	5	427	89	32	43	143	20	***13185***
2015	2	5	453	94	34	45	151	21	***11305***
2016	2	5	453	94	34	45	151	21	***13247***
2017	2	5	464	96	34	46	155	22	***14037***
2018	2	5	464	96	34	46	155	22	***14120***

Table 51: Material Stock in Consumer Electronics in Odense 2010-2018

Material stock [kg]	Fe	Al	Cu	Plastics	PCB	Others	Battery	LCD	Precious Metals	Total [t]
2010	1239183	102311	39980	635546	356640	352750	136	58	0	*2727*
2011	1212734	101512	38311	620943	349374	369112	1630	1066	232	*2695*
2012	1212343	103072	38542	634662	352211	364009	3319	2207	356	*2711*
2013	1205454	103563	38599	642788	352757	363611	5710	3828	459	*2717*
2014	1209799	107088	38372	657686	355874	356986	7881	5296	542	*2740*
2015	1178213	104406	37676	661177	349274	345584	8837	5942	578	*2692*
2016	1214678	108551	38218	679366	360847	362666	10909	7345	619	*2783*
2017	1172985	103980	37022	672276	349201	343566	9389	6318	632	*2695*
2018	1170623	100856	36382	659619	347712	374162	10990	7398	672	*2708*

Table 52: Energy Input and Emission Factors per Product for Consumer Electronics and House Appliances

Consumer Electronics		
	Energy Input [kWh]	Emission factor [kg/unit]
Digital videocamera	833 [1]	79
Digital camera	833 [1]	25
CD-player	833 [1]	395
DVD-player	833 [1]	395
Hard disk-recorder	833 [1]	396
BluRay-player	833 [1]	395
TV (LCD)		308 [2]
Desktop-PC	2200[2]	418
Laptop-PC	840[2]	160
Tablet PC	70[3]	13
Mobile phone	53[2]	10
Smartphone	53[2]	10
Landline Telephone	833 [1]	79
MP3 Player	833 [1]	16
DAB radio	833 [1]	481
GPS navigation	833 [1]	48
Activity tracker watch	833 [1]	6
GPS-watch	833 [1]	6
Game console	833 [1]	437
E-book reader	42 [4]	8
House Appliances		
Dryer	1083 [5]	206
Washing machine	1083 [5]	206
Dishwasher	1083 [5]	206
Microwave oven	1083 [5]	206
Espresso machine, espresso capsule maker	51 [5]	10
Robot vacuum cleaner	833 [1]	396

[1] kWh per kg product for general small electronic devices. Derived from: Ashby, M. F. (2013). *Materials and the Environment* (2nd ed.). Butterworth-Heinemann.

[2] Andrae, A. S. G., & Andersen, O. (2010). Life cycle assessments of consumer electronics - Are they consistent? *International Journal of Life Cycle Assessment*, *15*(8), 827–836. https://doi.org/10.1007/s11367-010-0206-1

[3] Naicker, V., & Cohen, B. (2016). A life cycle assessment of e-books and printed books in South Africa. *Journal of Energy in Southern Africa*, *27*(2), 68. https://doi.org/10.17159/2413-3051/2016/v27i2a1343

[4] Ding, P., Evans, S., Hong, C., Lin, Y.-C., Environment, A. N., & Rajagopal, D. (n.d.). Life Cycle Analysis: E-reader and Printed Books, 1–36.

[5] For Dryer, Dishwasher and Microwave it is assumed to have the same embodied energy as for a Washing Machine. Derived from Ciceri, N. D., Gutowski, T. G., & Garetti, M. (2010). A tool to estimate materials and manufacturing energy for a product. *Proceedings of the 2010 IEEE International Symposium on Sustainable Systems and Technology, ISSST 2010*, (September). https://doi.org/10.1109/ISSST.2010.5507677

Table 53: CO_2 emissions embodied in Electronic Appliances in 2018 (CRV)

Electronic Appliance	**Amount [nb]**	**CRV [t CO_2]**
Digital video camera	22418	1775
Digital camera	54925	1385
CD-player	66248	26195
DVD-player	48582	19210
Hard disk-recorder	33628	13311
BluRay-player	35332	13971
TV (LCD)	109850	33834
Desktop-PC	44254	18498
Laptop-PC	94830	15135
Tablet PC	67255	890
Mobile phone	107608	1084
Smartphone	94695	954
Landline Telephone	22418	3550
MP3 Player	30916	4895
DAB radio	36990	5857
GPS navigation	57167	9051
Activity tracker watch	33628	5324
GPS-watch	21297	3372
Game console	43716	6922
E-book reader	10088	80
Dryer	60529,68	12459
Washing machine	90795	18689
Dishwasher	76223	15689
Microwave oven	82948	17073
Espresso machine, espresso capsule maker	40353	392
Robot vacuum cleaner	7846	1242
Total [t CO_2]		**250836**

7.3.3 Packaging

Table 54: Embodied Emissions Factors for Packaging Material

Material	Emission factor [$kgCO_2/kg$]

Paper, incl. packaging	3.65 [1]
Cardboard, incl. packaging	1.08 [2]
Wood, packaging	0.24 [3]
Glass, packaging	1.51 [4]
Metals, packaging	2.81 [5]
Plastics, packaging	2.13 [6]
Plastics	2.13 [6]

[1] average from Econinvent Database v3 in Simparo for following processes:

- Tissue Paper [RER] production 1.02 $kgCO_2/kg$
- Paper, melamine impregnated {RER}| melamine impregnated paper production | Alloc Rec, U 3.11 $kgCO_2/kg$
- Kraft paper, unbleached {RER}| production | Alloc Rec, U 2.876 $kgCO_2/kg$
- Kraft paper, bleached {RER}| production | Alloc Rec, U 2.83 kg CO_2/kg

[2] average from Ecoinvent Database v3 in Simapro for following processes:

- Liquid packaging board container {RER}| production | Alloc Rec, U 3.23 kgCO2/kg
- Solid unbleached board {GLO}| market for | Alloc Rec, U 3.22 kgCO2/kg

[3] from Ecoinvent Database v3 in Simapro for Plywood, for indoor use {RER}| market for | Alloc Rec, U with 375 $kgCO_2/m3$, subsequent converted with the average density of 620 kg/m^3 (Woodproductsfi, n.d.) to 0.77 $kgCO_2/kg$

[4] average from Ecoinvent Database v3 in Simapro for following processes:

- Packaging glass, white [GLO] market for: 0.986 kg CO2/kg
- Packaging glass, green [GLO] market for: 0.959 kgCO2/kg
- Packaging glass, brown [GLO] market for: 0.991 kgCO2/kg

[5] from Ecoinvent Database v3 in Simapro for *steel, low alloyed.* It is assumed that this category mostly concerns can containers out of steel.

[6] The average of the emission factors of the most common plastic packaging types were considered(Chemicalsafetyfacts.org, n.d.). The values were obtained from the Ecoinvent v3 Allocation cut-off database in SimaPro:

- HDPE: Polyethylen, high density granulate [RER] production1.57 kgCO2/kg
- PET: Polyethylen terephtalate, granulate, bottle grade [RER] production 2.61 kgCO2/kg
- PVC, suspension, bottle grade 1.86 kgCO2/kg
- PP: Polypropylen, granulate [RER] production 1.68 kgCO2/kg
- Packaging film, low density polyethylene [RER] production 2.34 kgCO2/kg
- Polystyrene, general purpose [RER] production 2.74 kgCO2/kg

7.4 Inflows

7.4.1 Construction Material

Table 55: Newly added floor area per year in Odense 2010-2018 (StatBank, n.d.-c)

Newly added floor area [m²/year]	2010	2011	2012	2013	2014	2015	2016	2017	2018
Farmhouses	2006	1766	1630	1538	1112	2087	1243	1280	696
Detached houses	28520	19212	27080	24954	23955	27311	30598	45194	26656
Terraced, linked or semi-detached houses	3159	21453	12067	8407	14731	11465	11346	23766	9443
Multi-dwelling houses	13123	4460	33182	12636	10810	20497	31254	40401	51141
Student hostels	837	1865	5456	1029	0	0	21007	0	7518
Residential buildings for communities	894	83	3555	16	661	1162	0	34	73
Other residential building	911	52	41	365	302	500	117	0	100
Non-residential farm buildings	14123	8065	9605	32422	12867	21798	34890	10354	19098
Factories, workshops, etc.	8556	30633	23727	4771	4685	6766	27833	7692	7249
Power stations, gaswork, etc.	158	179	473	1320	107	1315	224	0	395
Other building used for production	0	0	0	0	0	0	0	0	0
Transportation or garage	222	14464	1996	579	816	0	138	456	16396
Office, trade, inventory, incl. public administration	30860	29878	39996	29106	21989	39852	14139	23380	18901
Hotel, restaurant, hairdresser and other services	244	15349	237	1075	344	124	195	852	239
Unspecified transport and trade	67	6	28	0	15	0	0	0	0
Library, church, museum etc.	208	91	0	2165	320	1153	20220	59	476
Building for education and research (schools, laboratory etc.)	4191	11541	11418	9844	20089	20566	2479	1813	5346
Building for hospital, home, maternity home etc.	3874	1597	9515	2040	78	118	0	819	5190
Day-care institution	2177	945	453	16	783	27	789	319	858
Non-specified welfare institutions	0	1648	0	407	0	0	0	0	0
Weekend cottages	0	218	0	0	0	0	0	0	0
Unspecified holiday purposes	0	122	0	23	0	0	1031	0	0

Sports centres, club houses	356	0	1281	359	8473	1960	603	1276	7500
Allotment garden house	0	512	0	0	0	0	0	0	0
Garage with room for one or two vehicles	3175	2379	3548	4370	2784	2051	2348	3556	2301
Carports	8601	7618	5982	8861	5700	5942	5606	5940	4470
Outhouses	8248	8606	5938	26087	9069	6747	8406	9684	11403
Unspecified recreational purposes	1499	1869	835	794	48	307	918	0	20

Table 56: Assumptions for Material Intensity per Building type for Construction Material Inflow

Building type	**Assumptions on Material Intensity**
Farmhouses	SFH – samples [1]
Detached houses	SFH – samples [1]
Terraced, linked or semi-detached houses	MFH – samples [1]
Multi-dwelling houses	AB – samples [1]
Student hostels	AB – samples [1]
Residential buildings for communities	AB – samples [1]
Other residential building	Average of all RB- samples [1]
Non-residential farm buildings	Industrial – Sweden [2]
Factories, workshops, etc.	Industrial – Sweden [2]
Power stations, gaswork, etc.	Industrial – Sweden [2]
Other building used for production	Industrial – Sweden [2]
Transportation or garage	Public – Sweden [2]
Office, trade, inventory, incl. public administration	Public – Sweden [2]
Hotel, restaurant, hairdresser and other services	Commercial – Sweden [2]
Unspecified transport and trade	Public – Sweden [2]
Library, church, museum etc.	Public – Sweden [2]
Building for education and research (schools, laboratory etc.)	Public – Sweden [2]
Building for hospital, home, maternity home etc.	Public – Sweden [2]

Day-care institution	Public – Sweden [2]
Non-specified welfare institutions	Public – Sweden [2]
Weekend cottages	SFH – samples [1]
Unspecified holiday purposes	SFH – samples [1]
Sports centres, club houses	Public – Sweden [2]
Allotment garden house	SFH – samples [1]
Garage with room for one or two vehicles	Garage [2]
Carports	Garage [2]
Outhouses	Garage [2]
Unspecified recreational purposes	Commercial – Sweden [2]
Under construction, Unlisted	not taken into account

[1] Material intensity from RB stock estimation

[2] Material intensity data from Paul Gontia Chalmers University

Table 57: Construction Material Inflow 2010-2018

Material [t]	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Aluminum	26	25	36	25	26	30	42	52	39
Aluminum + PE	0	0	0	0	0	0	0	0	0
Carpet	0	0	0	0	0	0	0	0	0
Cement rooftiles	1535	1554	1647	1462	1547	1676	1827	2769	1520
Ceramic	182	129	169	157	148	174	194	274	161
Clay	0	0	0	0	0	0	0	0	0
Clay Brick	6813	9653	9522	7774	7646	8671	11523	13138	9046
Clay brick rooftiles	189	80	526	172	144	272	652	504	733
Concrete	118038	154437	195718	150496	120773	154818	214559	168347	209379
Concrete - screeds	3149	1719	6267	2804	2475	3885	7649	6834	8174
Concrete brick	0	0	0	0	0	0	0	0	0

Fiber cement roof plates	1088	461	3030	991	831	1567	3755	2903	4219
Fiber cement	911	855	708	1790	804	675	748	882	830
Aerated Concrete	1751	2692	2307	1935	2345	2313	2456	4054	2044
Glass	80	77	101	77	80	91	115	153	105
Gypsum	758	593	1121	696	679	870	1320	1478	1296
Leca beton (light weight concrete)	1545	1756	3064	1613	1763	2172	3574	3927	3641
Leca nuts	0	0	0	0	0	0	0	0	0
Linoleum	0	0	0	0	0	0	0	0	0
Mineral wool	604	533	1046	581	587	758	1234	1328	1247
Mortar (lime mortar) <1970s	202	250	316	211	237	264	357	465	337
Mortar (limestone cement) >1970s	2432	3170	3440	2555	2930	3117	3810	5439	3424
PE, PP	11	20	16	13	16	16	17	29	15
PVC	1	1	1	2	1	1	1	1	1
Sand and gravel	13577	13828	16116	21060	13324	13644	17252	19590	18262
Slag	0	0	0	0	0	0	0	0	0
Steel	3585	5964	5493	5339	3112	4600	8299	3906	5044
Stones	0	0	0	0	0	0	0	0	0
Straw	0	0	0	0	0	0	0	0	0
Sundolit (X-EPS)	216	226	387	218	232	285	451	507	453
Tared paper (bitumen + PE)	147	180	237	153	172	194	269	342	257
Timber	6613	6764	6585	10975	6210	5992	7395	8597	7249
Wood wool cement	0	0	0	0	0	0	0	0	0
Zinc	0	0	0	0	0	0	0	0	0
Total [kt]	**163**	**205**	**258**	**211**	**166**	**206**	**288**	**246**	**277**

Table 58: Embodied Emissions in the Construction Material Inflow 2010-2018

Material	CO_2-emission factor [kgCO_2/kg]	2010	2011	2012	2013	2014	2015	2016	2017	2018
Aluminum	17.600	451	438	635	435	453	533	731	911	689
Aluminum + PE	17.600	0	0	0	0	0	0	0	0	0
Carpet	7.432	0	0	0	0	0	0	0	0	0
Cement rooftiles	0.702	1078	1091	1157	1027	1087	1177	1283	1945	1068
Ceramic	0.214	39	28	36	34	32	37	42	59	35
Clay	0.102	0	0	0	0	0	0	0	0	0
Clay Brick	0.271	1846	2616	2580	2107	2072	2350	3123	3561	2452
Clay brick rooftiles	0.350	66	28	184	60	51	95	228	176	256
Concrete	0.111	13083	17117	21692	16680	13386	17159	23780	18658	23206
Concrete - screeds	0.108	340	186	677	303	267	420	826	738	883
Concrete brick	0.121	0	0	0	0	0	0	0	0	0
Fiber cement roof plates	0.538	586	248	1631	534	447	844	2022	1563	2272
Fiber cement	0.538	491	460	381	964	433	363	403	475	447
Aerated Concrete	0.479	838	1288	1104	926	1123	1107	1175	1941	978
Glass	1.796	145	139	182	137	143	164	207	275	188
Gypsum	0.260	197	154	291	181	177	226	343	384	337
Leca beton (light weight concrete)	0.322	498	566	987	520	568	700	1151	1265	1173
Leca nuts	0.949	0	0	0	0	0	0	0	0	0
Linoleum	1.256	0	0	0	0	0	0	0	0	0
Mineral wool	1.509	912	804	1579	877	886	1144	1863	2004	1883
Mortar (lime mortar) <1970s	0.111	22	28	35	23	26	29	40	52	37
Mortar (limestone cement) >1970s	0.111	270	352	382	284	326	346	423	604	380
PE, PP	1.997	22	39	33	26	33	32	35	57	30
PVC	4.000	4	4	3	9	4	3	4	4	4
Sand and gravel	0.033	452	460	536	701	443	454	574	652	608
Slag	0.000	0	0	0	0	0	0	0	0	0

Steel	1.000	3585	5964	5493	5339	3112	4600	8299	3906	5044
Stones	0.192	0	0	0	0	0	0	0	0	0
Straw	-1.280	0	0	0	0	0	0	0	0	0
Sundolit (X-EPS)	2.894	626	653	1121	630	671	826	1307	1466	1310
Tared paper (bitumen + PE)	0.867	127	156	206	133	149	168	234	297	223
Timber	-1.460	-9655	-9876	-9615	-16024	-9067	-8749	-10797	-12552	-10583
Wood wool cement	-0.818	0	0	0	0	0	0	0	0	0
Zinc	1.710	0	0	0	0	0	0	0	0	0
Total [t CO_2]		**16 023**	**22 943**	**31 313**	**15 905**	**16 821**	**24 028**	**37 296**	**28 442**	**32 919**

7.4.2 Food

Table 59: Food Consumption per food category considering the demography in Odense (2010-2018)

Food Category [t]	2010	2011	2012	2013	2014	2015	2016	2017	2018
Milk and milk products	23056	23192	23389	23655	23872	24021	24256	24401	24611
Chees and cheese products	2692	2712	2741	2780	2810	2834	2864	2886	2914
Bread and other cereals	15119	15219	15360	15553	15705	15816	15976	16082	16228
Potatoes and potato products	5708	5750	5807	5888	5950	5998	6061	6108	6168
Vegetables and vegetable products	12992	13085	13214	13392	13530	13635	13775	13871	14000
Fruit and fruit products	12787	12875	13001	13171	13304	13403	13539	13629	13750
Juice	4062	4087	4123	4171	4211	4238	4281	4309	4348
Meat and meat products	8753	8815	8900	9018	9111	9180	9275	9343	9432
Poultry and poultry products	1719	1731	1747	1770	1788	1801	1820	1833	1851
Fish and fish products	2201	2219	2243	2276	2301	2322	2346	2364	2387
Egg	1555	1566	1582	1604	1620	1633	1650	1661	1677
Fatty substances	2769	2788	2815	2851	2880	2901	2931	2951	2977
Sugar and Candy	2557	2574	2598	2630	2656	2675	2702	2720	2745
Beverage	129796	130831	132223	134180	135660	136838	138301	139399	140782
Total including Beverages	**225767**	**227444**	**229743**	**232941**	**235398**	**237295**	**239776**	**241557**	**243871**
Total excluding Beverages	**95971**	**96614**	**97520**	**98761**	**99738**	**100457**	**101474**	**102158**	**103089**

7.4.3 Electronic Appliances

Table 60: Stock data used for modelling Inflows of Electronic Appliances (a)

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
House Appliances [nb of units]											
Dryer	0	0	0	0	0	0	0	0	0	45365	47344
Washing machine	0	0	0	0	0	0	75486	76233	77313	78232	78165
Dishwasher	0	0	0	0	0	0	52752	54237	57403	58836	60669
Microwave oven	0	0	0	0	0	0	58242	61517	64712	67955	70221
Robot vacuum cleaner	0	0	0	0	0	0	0	0	5245	5423	5610
Consumer Electronics [nb of units]											
Video camera	0	0	18434	19347	20325	20593	21695	22585	24694	26560	27627
Digital video camera	0	0	0	0	0	0	0	0	13276	16974	19685
Digital camera	0	0	0	0	0	0	34514	47548	60740	64903	70068
CD-player	0	0	0	0	0	0	0	0	0	0	0
DVD-player	0	0	0	0	0	0	0	0	0	0	0
Hard disk-recorder	0	0	0	0	0	0	4930	7924	12944	13979	24023
BluRay-player	0	0	0	0	0	0	4258	4920	5688	6561	7566
Tv	0	0	0	0	0	0	0	0	0	94289	94564
Desktop-PC	0	0	0	0	0	0	0	0	0	0	60247
Laptop-PC	0	0	0	0	0	0	0	63485	65181	66761	68358
Tablet PC	0	0	0	0	0	0	0	779	1143	1672	2446
Mobile phone	36817	46259	53685	60828	69379	75999	81849	86925	89866	92612	94092
Smartphone	0	0	0	0	0	0	11251	13153	15388	17959	20953
Fixed line telephone	0	0	0	0	0	0	0	0	0	0	0
MP3 Player	0	0	0	0	0	0	34892	37266	39830	46930	48047

DAB radio	0	0	0	0	0	0	0	0	0	14386	17890
GPS navigation	0	0	0	0	0	0	0	0	0	0	33505
Activity tracker watch	0	0	0	0	0	0	18405	19126	19888	20631	21395
GPS-watch	0	0	0	0	0	0	3885	4392	4968	5606	6324
Game console	0	0	0	0	0	0	0	0	0		33505
E-book reader	0	0	0	0	0	0	0	388	526	711	960

Table 61: Stock data used for modelling inflows of Electronic Appliances (b)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
House Appliances [nb of units]										
Dryer	48876	50321	51087	51892	52876	53726	54868	55102	55892	56761
Washing machine	79066	79994	80405	81167	82108	83706	83946	84243	86233	87436
Dishwasher	60703	63559	64700	66375	67388	70236	71165	72365	73746	74965
Microwave oven	71687	73581	74763	75283	76387	78113	79136	79797	81482	81953
Robot vacuum cleaner	5808	6014	6232	6466	6833	7042	7543	7876	8187	8317
Consumer Electronics [nb of units]										
Video camera	29367	31136	0	0	0	0	0	0	0	0
Digital video camera	21790	23588	24516	27230	0	0	0	0	0	0
Digital camera	73417	77841	80697	0	0	0	0	0	0	0
CD-player	92023	88456	85804	85827	83212	80509	74396	71159	69560	67255
DVD-player	86492	85929	79675	70316	68035	65047	57145	56927	48582	49320
Hard disk-recorder	28160	32349	0	0	0	0	0	0	0	0
BluRay-player	8743	10109	16344	23783	25121	28791	32346	35032	35332	35869
Tv	95298	95912	96540	97912	98685	100365	102187	104060	106171	106605
Desktop PC	58508	56825	55598	54038	52537	50260	47954	45666	43703	43279

Laptop-PC	70152	72024	76611	82208	84782	89040	92186	96338	98268	99201
Tablet PC	3585	5256	7748	14477	27214	41588	51215	60759	62383	62772
Mobile phone	96046	97302	98828	100562	101791	103969	105394	106738	107101	108169
Smartphone	24502	28664	33709	51703	65941	77844	83021	90864	92747	98641
Fixed line telephone	0	0	0	0	0	0	0	0	0	0
MP3 Player	48274	50546	0	0	0	0	0	0	0	0
DAB radio	22125	27042	30389	33348	35849	37056	38546	39685	40301	40353
GPS navigation	34043	34604	36300	38020	40111	41801	43128	44228	44607	44613
Activity tracker watch	22238	23124	24171	25312	26505	27934	29218	30689	32020	33628
GPS-watch	7150	8087	10215	11375	11514	12796	14017	18611	18770	21297
Game console	34043	34604	36300	38020	40111	41801	43128	44228	44607	44613
E-book reader	1300	1761	2043	3102	4710	5865	7547	7663	8833	10649

Assumptions:

- Data for all products except of following had to be smoothened with the moving average tool in Excel:
    - BluRay-Player
    - Smartphone
    - Activity tracker watch
    - GPS-watch
- For following products inflows were considered being zero from the turning point of the stock:
    - Video camera – inflow equals zero from 2011
    - Digital video camera - inflow equals zero from 2013
    - Digital camera - inflow equals zero from 2012

- CD-Player – turning point already before 2010: no inflow in all the considered period
- Hard-disk recorder - turning point already before 2010: no inflow in all the considered period
- Fixed line telephone - turning point already before 2010: no inflow in all the considered period
- MP3 Player - inflow equals zero from 2011

Table 62: Inflows of Electronic Appliances 2010-2018

	2010	2011	2012	2013	2014	2015	2016	2017	2018
House Appliances [nb. of Products]									
Dryer	1459	851	1187	2276	4144	7490	9501	11096	9709
Washing machine	3053	5807	11087	15858	17902	13809	9091	6874	4422
Dishwasher	4354	4961	9036	11777	14865	11328	8460	5958	4600
Microwave oven	3561	5446	8769	13240	15406	13063	9315	7353	4663
Espresso machine	0	0	0	0	0	0	0	0	40353
Robot vacuum cleaner	359	605	973	1429	1360	1452	959	697	448
Consumer Electronics [nb. of Products]									
Video camera	8755	0	0	0	0	0	0	0	0
Digital video camera	4993	7427	8392	0	0	0	0	0	0
Digital camera	21960	15417	0	0	0	0	0	0	0
CD-player	0	0	0	0	0	0	0	0	0
DVD-player	0	0	0	0	0	0	0	0	0
Hard disk-recorder	7925	0	0	0	0	0	0	0	0
BluRay-player	2954	7281	8723	3344	6549	7731	8794	7014	6385
Tv	4548	22190	40783	25396	9124	11143	22741	31217	25192
Desktop PC	957	13143	23852	13253	709	948	9637	14025	13452
Laptop PC	28801	22096	11782	10097	19802	25118	24733	17225	15031

Tablet PC	2104	3000	7329	13631	15789	11914	13686	9362	12240
Mobile phone	18485	17874	20220	21996	23111	20973	20331	20429	22593
Smartphone	8482	8012	21657	19875	19493	14039	19648	18813	25235
Fixed line telephone	0	0	0	0	0	0	0	0	0
MP3 Player	13144	0	0	0	0	0	0	0	0
DAB radio	5526	6792	9948	8853	6199	7103	8272	9095	8384
GPS navigation	645	3095	9401	16213	10757	4615	5550	9289	11987
Activity tracker watch	6140	3101	3602	5965	7959	7204	5892	5685	7329
GPS-watch	2311	2960	2169	1750	3477	3702	7135	2502	4938
Game console	645	3095	9401	16213	10757	4615	5550	9289	11987
E-book reader	663	493	1273	1903	1589	2255	888	2369	3421

Table 63: Material inflow of Consumer Electronics

Material [kg]	Fe	Al	Cu	Plastics	PCB	Others
2010	104688	11023	4044	56896	34678	30561
2011	230690	16245	6192	121621	64581	92782
2012	353670	21443	8850	198264	96761	150346
2013	223833	14491	6683	147031	68228	95048
2014	88052	8470	3878	80608	35028	34909
2015	99044	9152	3855	82035	35679	38765
2016	199462	14524	5806	128783	60243	85750
2017	259283	17338	7103	162112	75219	105993
2018	227536	14961	6694	143636	68056	97954

Table 64: Material inflow of House Appliances

Material [kg]	Fe	Al	Cu	Plastics	PCB	Others
2010	311478	7283	11372	141769	9660	46121

2011	421895	10358	16901	198050	13750	61538
2012	760131	18984	30344	362729	24327	110316
2013	1083384	27636	45012	523895	35448	156092
2014	1323977	33704	54283	639955	42776	190787
2015	1175525	31617	51278	592883	38615	166385
2016	963048	27076	43425	503767	31460	134138
2017	851193	25457	40914	467498	28142	115712
2018	659833	26603	33320	411051	22328	89752

Table 65: Inflows of Electronic Appliances in year 2015 and related embodied emissions

	Product [unit]	Emission factor $kgCO_2/kg$	Embodied Emissions [t CO_2]
House Appliances			
Dryer	7490	205.83	1542
Washing machine	13809	205.83	2842
Dishwasher	11328	205.83	2332
Microwave oven	13063	205.83	2689
Coffee machine	0	9.71	0
Robot vacuum	1452	395.83	575
Consumer Electronics			
Video camera	0	0.00	0
Digital video camera	0	79.17	0
Digital camera	0	25.22	0
CD-player	0	395.41	0
DVD-player	0	395.41	0
Hard disk-recorder	0	395.83	0
BluRay-player	7731	395.41	3057
TV (LCD)	11143	308.00	3432
Desktop-PC	948	418.00	396
Laptop-PC	25118	159.60	4009
Tablet PC	11914	13.23	158
Mobile phone	20973	10.07	211
Smartphone	14039	10.07	141
Fixed line telephone	0	79.17	0
MP3 Player	0	15.83	0
DAB radio	7103	481.33	3419
GPS navigation	4615	47.50	219
Activity tracker watch	7204	6.33	46
GPS-watch	3702	6.33	23
Game console	4615	437.00	2017
E-book reader	2255	7.97	18
Total [t CO_2]			**27126**

See for references and assumptions the appendix chapter for electronic appliances stock 7.3.2.

7.5 Gothenburg

Table 66: References for the properties of Gothenburg

Population	Statistics Sweden. (n.d.). Population Gothenburg. Retrieved from http://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__BE__BE0101__BE0101A/BefolkningNy/table/tableViewLayout1/?rxid=476946b5-770a-41b6-a83d-2471fdeac9fe
Population Density	Statistics Sweden. (n.d.). Population Density Gothenburg. Retrieved from http://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__BE__BE0101__BE0101C/BefArealTathetKon/?rxid=9877bd91-04e9-4a1c-aab5-9afd7e51e06e
GDP per Capita	Trading Economics. (n.d.). GDP per Capita Sweden. Retrieved from https://tradingeconomics.com/sweden/gdp-per-capita
GDP growth rate	Trading Economics. (n.d.). GDP Annual Growth Rate Sweden. Retrieved May 22, 2019, from https://tradingeconomics.com/sweden/gdp-growth-annual
HDI	United Nations. (2018). Human development indices and indicators: 2018 statistical update. Retrieved from http://hdr.undp.org/sites/default/files/hdr2018_technical_notes.pdf
Average Temperature	Wikipedia. (n.d.). Gothenburg. Retrieved from https://en.wikipedia.org/wiki/Gothenburg

7.5.1 CRV and Operational Emissions per Capita

Table 67 shows the data on material stock in RB in Gothenburg, aggregated into material categories (Gontia, 2019).

Table 67: Material Stock in RB in Gothenburg, aggregated into material categories

	Wood-based materials	**Ceramics and brick**	**Non-metallic Minerals**	**Stone and aggregate**	**Iron and steel**	**Others**	**Total**
Mass (kt)	Con.	Con.	Con.	Con.	Con.	Con.	Con.

Table 68 lists the materials included in the material category “Others” as well as their emission factor and related CRV in kt CO_2.

Table 68: Material Category "Others" disaggregated, listed CRV per material

Material	Share	Ökobaudat Reference	Emissions kg CO_2/kg	Mass [kt]	CO_2 [kt]
Coke ash	Con.	Fly ash	0	Con.	0
Copper sheet	Con.	Blanke Kupfer-Hausinstallationsrohre	1.970	Con.	128
EPS insulation	Con.	Extruded polystyrene (XPS); 32 kg/m3	2.894	Con.	48,6
Glass	Con.	Insulated glazing, double pane; double glass	1.796	Con.	41,6
Mineral wool	Con.	Mineral wool (facade insulation)	1.509	Con.	320
Peat	Con.	n.a.	0	Con.	0
Reed	Con.	n.a.	0	Con.	0
Slag	Con.	Slag-tap granulate; granulate	0	Con.	0
Wood wool	Con.	Lightweight wood fibre panel; 360 kg/m3	-0.083	Con.	-3,0
Total	**100%**			Con.	**536**

Table 69 lists the materials included in the material category “Non-metallic Minerals” as well as their emission factors and related CRV in kt CO_2.

Table 69: Material Category "Non-metallic Minerals” disaggregated, listed CRV per material

Non-Metallic Minerals	Share	Ökobaudat Reference	Emissions kg CO_2/kg	Mass [kt]	CO_2 [kt]
Concrete	Con.	average from: *Beton der Druckfestigkeitsklasse C 20/25* and *Beton der Druckfestigkeitsklasse C 50/60 (en)*	0.11	Con.	2078
Gypsum	Con.	Gypsum (CaSO4 alpha semihydrate); grinded and purified product	0.26	Con.	271
total				Con.	2350

Con. = confidential