Analysing territorial and consumption-based Greenhouse gas emission accounts
Case studies of Barcelona and Hamburg

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Abstract

Populations in cities have been growing and will continue to grow in the future. Therefore it is predicted that challenges related to resource depletion, waste production and increased GHG emissions are going to intensify. Although, the amount of mitigation strategies on city-levels is increasing and reduction successes are claimed on country and city-scales, global emissions are on the rise. This raises the concern, that the currently widespread use of territorial-based GHG inventories has disadvantages that need to be overcome to decrease emissions efficiently.
The purpose of the conducted research was to identify which effect a shift from territorial to consumption-based accounting would have on the GHG emissions and the mitigations strategies of Barcelona, Spain and Hamburg, Germany.
In order to establish the differences between these accounting methods literature review was undertaken outlining the pros and cons of each method. The theory was applied to the selected cases by modelling country and city-level territorial and consumption-based GHG accounts through the use of Input-Output tables and undertaking an analysis as to see which industrial activities and countries contribute to the consumption-based emission of each country. The city-level mitigation strategies were analysed to establish the current state of mitigation options and on that basis new actions were developed that responded to the consumption-based account.
Results show, that on a country and city-level consumption-based emissions exceed territorial-based emissions that currently form the basis for global mitigation action. A shift to consumption-based accounting calls for changes in the mitigation strategies.

Title image sources:
Krauß D. (2016), Skyline Hamburg, Graphic design,
Available at:
http://www.danielkrausz.de/skyline_silhouette.html

Muralesyvinilos (2015) Skyline Barcelona
Available at:
https://www.muralesyvinilos.com/cuadros-lienzos/barcelona/barcelona-skyline-18825456

Declaration of Authorship

I hereby declare that the Master Thesis presented here is, to the best of knowledge and belief, original and the result of my own investigation and has not been submitted in part or whole, for a degree at this or any other university.

All the information derived from the work of others has been acknowledged in the text and in the list of references.

Clara Kempken

Aalborg, 09th of June 2016.

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List of Abbreviations and Acronyms

CH_4	-	Methane
CO_2	-	Carbon dioxide
GHG	-	Greenhouse gas
GWP	-	Global Warming Potential
IPCC	-	Intergovernmental Panel on Climate Change
NEI	-	National Emission Inventory
OECD	-	Organisation for Economic Co-operation and Development
N_2O	-	Dinitrogen monoxide
ROW	-	Rest of World Regions (including Brazil, China, Africa, India etc.)
SNA	-	System of National Accounts
UNFCCC	-	United Nations Framework Convention on Climate Change
WL	-	Rest of Latin America (Latin American countries excluding Brazil)

1. Introduction

The world's population has reached around 7.4 billion people and 50% are currently living in cities. It is projected that by 2050 75% of the world population of 9 billion people will be living in cities. (Singh & Kennedy 2015; IPCC 2014b) This increase of about 3 billion people (around 80%) constitutes a significant challenge in respect to issues like resource consumption, waste production and Greenhouse gas (GHG) and other emissions. The global trend of urbanisation is associated with increased incomes, which is connected to higher energy consumption and GHG emissions (IPCC 2014b). GHG emissions are one of the main climate change impacts that can be attributed to cities. Therefore, when looking at the topic of climate change mitigation, cities and their activities have an important role (Ramaswami et al. 2012; Gouldson et al. 2015).

On the country level, a single GHG emissions inventory standard was developed by the Intergovernmental Panel on Climate Change (IPCC); and member countries are required to report their emissions through the United Nations Framework Convention on Climate Change (UNFCCC) (Dodman 2009). However, there is currently no standardised global framework applied for city inventories that is widely used and provides globally comparable results. Over the past years, several attempts have been made to develop standards for GHG inventories for cities. This includes the Greenhouse Gas Protocol for Community Scale emissions (Arikan et al. 2012). The importance of GHG emissions and the establishment of inventories has been recognised by cities worldwide and participation in the formulation of city-wide emission reduction targets is increasing (Ibrahim et al. 2012).

Although the number of implemented climate change mitigation policies and strategies for cities has been growing, global GHG emissions have continued to increase (IPCC 2014b). The willingness and effort of cities' governments to reduce emissions is evident; however, in order to develop appropriate climate mitigation strategies, it is necessary to apply effective GHG emissions measurement approaches to avoid burden shifting and allocate clear responsibility for generating emissions. The major sources and causes of emissions have to be identified in order to develop a strategy for emission reductions. GHG emissions can be measured using either territorial- or consumption-based accounting, namely focussing on sources and causes respectively.

1.1. Aims

The research conducted for this study focuses on the differences and problems related to the methods of measuring GHG emissions and the connection to climate change mitigation strategies of cities. According to the literature, undertaking GHG emissions accounting on a territorial basis has a number of drawbacks, resulting in the fact that not all emissions emitted by nations are taken into account in the method. This is related to the fact that the territorial-based approach does not take into account GHG emissions from products and services that are imported to territorial boundary and are consumed within the boundary. Additionally, emissions from exported products are also attributed to the territorial boundary they are produced in. This results in burden shifting, making it seem like some cities are performing better or worse than they actually do. Therefore it is questioned if it would be more effective to apply the consumption-based method, which takes the emissions of imported products and services into account.

For this thesis it is aimed to undertake an analysis of GHG emission accounting and climate change mitigation strategies in Barcelona, Spain and Hamburg, Germany. In its climate change mitigation strategy, that is based on territorial-based measurements, the city provides details on how it is currently reducing its emissions and which actions are taken in the future (Ministry for Urban Development and Environment 2011; Ajuntament de Barcelona 2013). The strategies also mention the targets that are set for the city and which reductions already have been achieved. It is aimed to assess if the provided information captures the causes and thereby the actual options for mitigating GHG emissions.

The consumption and the territorial-based approach are defined and the advantages and disadvantages of the approaches are discussed. It is investigated where the problem can be encountered in real life examples.

The territorial-based GHG accounts published by the cities are analysed regarding the type and accuracy of the provided information. It is intended to establish how the provided data can be misleading in terms of how the city is performing in their GHG emissions reduction. On the basis of territorial-based GHG emission data available, the consumption-based account is calculated in order to exemplify the differences of the methods. These results are used to establish whether the climate mitigation would still be useful for the city if a consumption-based account was applied and which changes would have to be made.

1.2. Problem formulation

Research questions:

The following main and sub-research questions were selected to provide research guidance. These questions are answered throughout undertaking the research.

- **Main question:**

What effect does the shift from territorial to consumption-based accounting have on the modelled GHG emissions of a city and its climate mitigation strategies?

- **Sub-questions:**

1. *What problems connected to fixed territorial boundaries are related to application of territorial-based accounting and what is the difference to the consumption-based approach?*
2. *What are the differences between consumption and territorial-based inventories of Hamburg (Germany) and Barcelona (Spain) and what are the main contributors to the emission generation?*
3. *Do the identified mitigation options, which are based on a territorial approach, still lead to net reductions when applying a consumption-based approach to GHG accounting?*

1.3. Objectives

The following objectives were set to be achieved during the course of this research:

1. Review problems in connection to fixed territorial boundaries and differences related to territorial and consumption-based approaches to GHG accounting
2. Quantitative establishment of a consumption-based account for a selected case study countries and cities on the basis of input-output (IO) tables and comparison to the territorial-based account
3. Analyse the current mitigation strategies of the cities and their connection to GHG emission reduction
4. Develop a new mitigation action to exemplify the effects on the consumption-and territorial-based account

2. Methodology

In order to be able to answer the research questions that were developed for guidance throughout the research, different methodologies are applied.

2.1. Definitions

Greenhouse Gases (GHGs)

GHGs trap heat in the atmosphere and there a number of gases that have the most significant effects on climate change:

- **Carbon dioxide (CO_2)**
  - Enters the atmosphere through burning of: fossil fuels, wood, solid waste
  - Removed from the atmosphere through the absorption by plants as part of the carbon cycle
- **Methane (CH_4)**
  - Emitted through producing and transporting coal, natural gas and oil
  - Produced through agricultural activities like livestock
  - Deterioration of organic materials in landfill
- **Dinitrogen monoxide (N_2O)**
  - Emitted through agricultural and industrial activities and burning fossil fuels and solid waste
- **Fluorinated gases (HFC, PFC)** (not further considered in this study)
  - Including Hydrofluorocarbons and perfluorocarbons
  - High Global Warming Potential Gases that are emitted in smaller quantities but are very potent in accelerating the warming process

  (US Environmental Protection Agency 2016)

Territorial-based accounting[1]

The basis for estimating GHG emissions by the territorial-based method is that the measurement takes place within a set geographical system boundary. In terms of accounting for emissions for a certain country or city it means that all emissions within the boundary are included while everything outside the boundary is excluded (Schmidt & Muños 2014).This means that only the GHG emissions generated by domestic production are considered. The responsibility for the emissions is taken by the producer not considering where the product or service is consumed (Boitier 2012; Peters 2008).

[1] This accounting method is either referred to as territorial or production-based accounting by the relevant literature. For ease of understanding only the term territorial-based accounting is used throughout this study.

Consumption-based accounting

The basic idea of consumption-based accounting is that emissions are measured within a product-orientated system boundary that considers all emissions sources related to the life cycle of a product. This means that the emissions from production, consumption and disposal of a product are included in the account, not depending on where the location of the emission is. (Schmidt & Muños 2014)

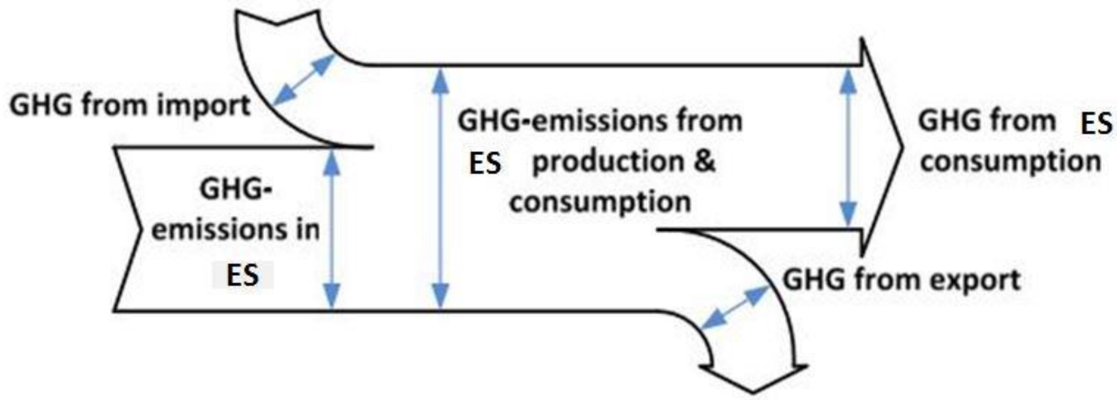

Figure 1 Territorial and consumption-based emissions (Spain (ES))
(Based on: Schmidt & Muños 2014)

Figure 1 shows how territorial and consumption-based emissions are formed. This shows that the total of GHG emissions from production and consumption include domestic GHG emissions as well as GHG from import and export.

In this approach, emissions allocation takes place according to the consumer country. This is usually based on final consumption which are recorded in the System of National Accounts (SNA) or as trade-adjusted emissions (Barrett et al. 2013). GHG emissions from final consumption include households, government and capital investments. In contrast to the territorial-based account, GHG emissions in the form of imports are considered while emissions from exports that were produced within the boundaries are not included (Chavez & Ramaswami 2011).

This approach calculates GHG emissions with the following formula:

$$GHG^{cons} = GHG^{domestic} - GHG^{exp} + GHG^{imp} \qquad \textbf{Equation 1}$$

National GHG emissions (GHG^{cons}) resulting from domestic final consumption ($GHG^{domestic}$) plus imports of GHG emissions (GHG^{imp}) minus GHG emissions that are resulting from exports (GHG^{exp}) (Boitier 2012).

Extraction-based accounting

For extraction-based, inventories emissions are allocated where fossil fuels are extracted. This approach has been developed more recently and is relevant due to the fact that 37 % of global emissions are caused by the trading of fossil fuels (Barrett et al. 2013). In the course of this research the focus was set on territorial and consumption-based accounting approaches. Therefore this approach will not be discussed in further detail.

National GHG Inventories

The ultimate goal of the UNFCCC[2] is to stabilise the concentration of GHGs at a level that prevents anthropogenic interference with the climate system, which could lead to dangerous effects on the planet. In order to achieve this goal, it is essential to estimate the levels of GHG emissions and removals regularly (UNFCCC 2014a).

Key documents like the National Inventory Report published yearly by the IPCC, which is the leading international body for the assessment on climate change, are using the territorial-based accounting framework (UNFCCC 2016). In the IPCC report it is stated that national inventories only include GHG emissions that are taking place within the national territory and offshore areas that are legally governed by the country (IPCC 2016).

The framework provided by the IPCC to compile inventories assesses the emissions produced by the main sectors: energy, industry, agriculture and forestry and waste (Dodman 2009). National GHG inventories have to be submitted yearly, take the year 1990 as the baseline of emissions and show the increase or decrease of emissions each year.

The IPCC provides guidelines and methodologies for estimating of GHG emissions by sources and removals by sinks which may assist Parties under the Convention to achieve their commitments (IPCC 2006).

2.2. Literature review

With the objective to uncover the issues related to the differences in production and consumption-based accounting and the problems arising from fixed territorial boundaries a review of related studies was conducted. Existing literature was reviewed in order to collect information about the current knowledge about the topic, the applied concepts and theories and the main contributors to the research.

The purpose of conducting a review on relevant literature is to answer the first research sub question: *What problems connected to fixed territorial boundaries are related to application of territorial-based accounting and what is the difference to the consumption-based approach?*

The data gathering process took places on the basis of secondary data collection in the format of a literature review. Secondary data were already collected by and is available in other sources. For this study, needed data were available in form of journal articles,

[2] United Nations Framework Convention on Climate Change (UNFCCC) is an international treaty with the goal to initiate cooperation between countries to fight climate change (UNFCCC 2014a).

governmental reports and books was gathered through the use of the databases Sciencedirect, Scopus, Google Scholar and the Aalborg University Library.

The reviewed literature is comprised of scientific papers, engineering textbooks, internet webpages and German standards for the performed experimental tests. Several scientific data bases were used to search for literature, including Scopus, Springer Link, Web of Science and Science Direct. The data bases were accessed via the Aalborg University library. The search engine of the library itself was also used to search for literature within all connected data bases.

During the search different keywords were used, including: consumption-based accounting, territorial-based accounting, GHG emission account, national GHG inventories, etc. Selection bias was avoided by choosing a wide range of search strings (e.g. by using synonyms, different combinations of words, etc.). In order to exclude papers unrelated to the research topic, the search results were manually analysed. The majority of the publications used are in English, however, a number of German and Spanish references are included related to the selected case studies. Time of publication was not included as a filter during the initial search, but was taken into consideration during the manual analysis, with priority given to more recent papers. Most of the literature selected for the review was published between 2006 and 2016.

The main contributors to the research undertaken in the field of territorial-based and consumption-based accounting include Glen Peters and Edgar Hertwich. They have published multiple papers discussing the need to move national GHG inventories from production to consumption-based approaches. Additionally, Peters was part of a major study that established a consumption-based emissions account for the UK. It is also important to mention the work of David Dodman, who contributed to the research on GHG emissions on the city-level, discussing the key issues of the application of different accounting methods.

The literature review provides a foundation for the research and allows the theory to be applied to a selected case. Before relevant literature can be reviewed it is necessary to introduce and define the most important terms related to the research.

2.3. IO tables and calculations

2.3.1. IO tables

One way to obtain data for the consumption-based accounting approach is the use of IO tables. These consist of large tables describing how industries, households and government entities in a certain area are interconnected through inputs and outputs (Hunt et al. 2014). IO tables can form the foundation to analyse the environmental implications of consuming goods and services. The interconnection of different production sectors is displayed and it is possible to trace production and consumption throughout an economy (Hertwich & Peters 2010).

Due to the fact that inputs into the economy of a country do not just come from the industrial production of the same country but also from other countries, a linkage between the IO tables of the countries is established. Figure 2 illustrates a trade-linked multi-regional IO-table for Spain. The IO-table links three countries/regions: Spain, the European Union (ex Es) and rest-of-the-world (RoW). The red boxes represent domestic product transactions (IO-table) and the blue ones emissions (extensions table), while the white boxes represent the trade with products (Schmidt & Muños 2014).

IO-table ES	Import to EU Union (ex ES) from ES	Import to RoW from EU Union
Import to ES from EU Union	IO-table: EU Union (ex ES)	Import to RoW from EU Union
Import to ES from RoW	Import to EU Union (ex ES) from RoW	IO-table RoW
ES emissions	EU Union (ex ES) emissions	ROW emissions

Figure 2 Trade- linked multi- regional IO- table (United Nations 2016) (Eurostat 2008) (Based on Schmidt & Muños (2014))

Figure 3 shows the common structure of a section within an IO table. The example country is Spain (ES) showing the imports from Australia (AU).

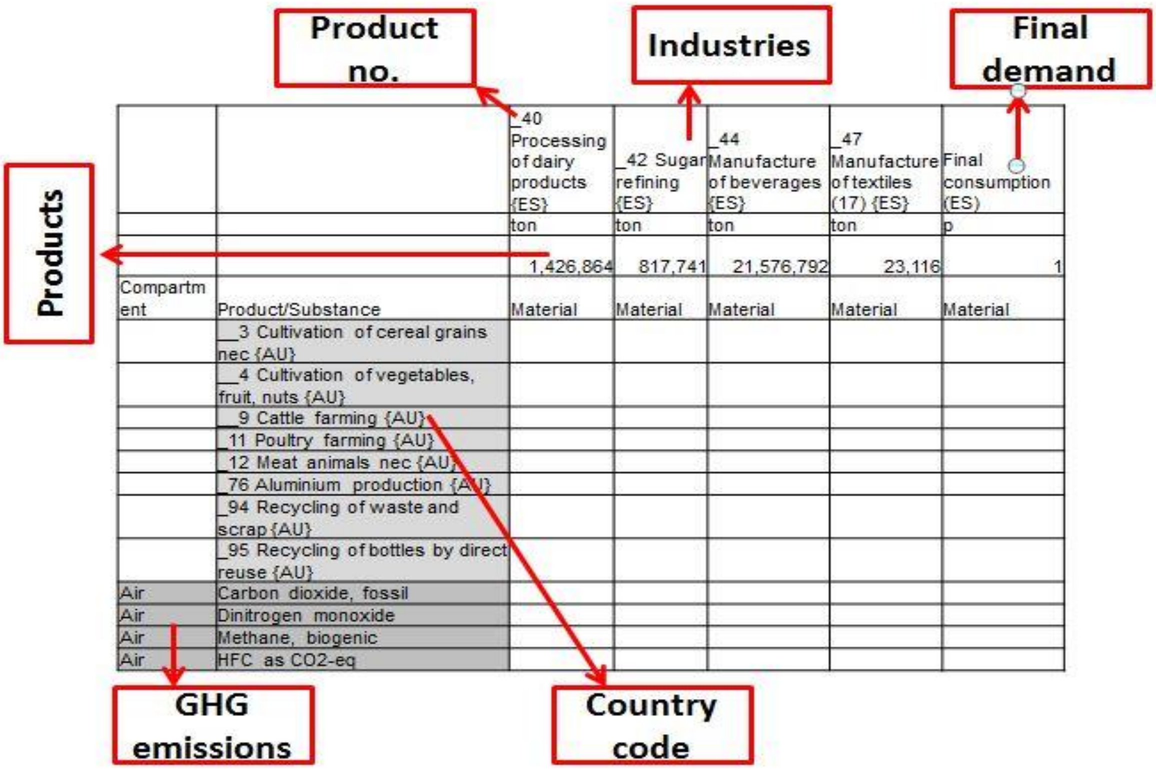

Figure 3 Structure IO table

2.3.2. Other tools used for consumption-based accounting

IO data are not the only available option for conducting consumption based accounting. Another tool that can be used is lifecycle assessment (LCA). The use of this quantitative environmental assessment tool allows the determination how a product, process or activity impacts the environment throughout its life time (ISO 1997). The aim is to identify and quantify the total amount of material and energy input and waste output to the environment and assess their environmental impact (Garner 1995). For a consumption-based account the focus would be set on household and industrial consumption activities of a city or a country and the GHG emissions caused by these activities. From the interpretation of the results conclusions and recommendations can be drawn that can be used by decision-makers where in the lifecycle of the activities the implementation of improvements is necessary the most to reduce emissions effectively.

It was found that the majority of studies use IO tables for setting up of consumption-based inventories. For this research the calculations undertaken for the consumption-based account are exclusively based on IO data. The existence of other data sources and tools is recognised but not considered in further detail.

2.3.3. Calculations

In order to establish the consumption-based account for a specific city, several calculations have to be undertaken. The consumption-based accounts use territorial-based accounts as a basis for the calculations.

Models and tools

One option that can be used to establish a GHG account for a city is an IO table. In this case, calculations are based on the EXIOBASE v3 model.

"EXIOBASE is a global, detailed Multi-regional Environmentally Extended Supply and Use / Input Output (MR EE SUT/IOT) database" (Exiobase Consortium 2015). That this IO table contains environmental extensions means that the table includes information about emissions generated by industries and households (Schmidt & Munos 2014). The international IO table is used to analyse the environmental impacts associated with the final consumption of product groups (Exiobase Consortium 2015).

The EXIOBASE model has the following features:

- 44 countries and five rest-of-world (RoW) regions,
- 200 products
- 164 industries
- 15 land use types
- Employment per three skill levels
- 48 types of raw materials
- 172 types of water uses

The IO tables for the case study countries and additionally needed data for the calculations were provided by 2.-0 LCA consultants[3], who were heavily involved in the development of Exiobase. The calculations were undertaken by using the tool MATLAB. This programming language was developed by Mathworks for numerical computing and allows plotting functions and data and the creation and manipulation of matrices.
The dataset provided by 2.-LCA consultants contains aggregated data for countries, industries and products, since not all data global data was necessary in detail for this study. Additionally, a smaller bulk of data made it easier and less time consuming to run the calculations through MATLAB. The data file is made up of the following sheets:

- **A:** provides the IO table containing data for 18 countries and two rest of world regions[4], 164 products and 164 industries, and 190 substances present in raw material, air, water and soil.
- **Z**: Input per unit of output for all industries and products (2969 rows)
- **B**: All substances and emissions emitted to raw material, water, soil and air. In the analysis of emissions the focus is set on the key GHGs emitted to air (190 rows)
- **f:** the final demand vector is added depending on the country for which the consumption-based account is to be established. The final demand (6 columns) for one country is added in 1 column and 2969 rows.
- **g:** Is the GHG emissions (B) life cycle inventory produced through running the calculation. (1 column and 190 rows). This Excel sheet shows the life cycle emissions related to the production of one unit of each product in the database. All substances and emissions emitted to raw material, water, soil and air are included in the table (1 column and 190 rows)

Process / Equations

This section discusses the processes and mathematical formulas behind the calculations that are run through MATLAB. This was based on the methods described in 'The Computational Structure of Life Cycle Assessment" (Heijungs & Suh 2002). A detailed description on the development of IO tables can be found in (Schmidt & Muños 2014).

[3] More information about the company: www.lca-net.com
[4] The regions aggregated are divided into rest of world (ROW) which are all countries that were not listed themselves in the table including Russia, China, India, Brazil, Africa and others. The second aggregated region is the rest of Latin America which includes all Latin American countries apart from Brazil

		_40 Processing of dairy products {ES}	_42 Sugar refining {ES}	_44 Manufacture of beverages {ES}	_47 Manufacture of textiles (17) {ES}	Final consumption (ES)
		ton	ton	ton	ton	p
		1,426,864	817,741	21,576,792	23,116	1
Compartment	Product/Substance	Material	Material	Material	Material	Material
	__3 Cultivation of cereal grains nec {AU}					
	__4 Cultivation of vegetables, fruit, nuts {AU}					
	__9 Cattle farming {AU}					
	_11 Poultry farming {AU}					
	_12 Meat animals nec {AU}					
	_76 Aluminium production {AU}					
	_94 Recycling of waste and scrap {AU}					
	_95 Recycling of bottles by direct reuse {AU}					
Air	Carbon dioxide, fossil					
Air	Dinitrogen monoxide					
Air	Methane, biogenic					
Air	HFC as CO2-eq					

Figure 4 Input-Output table (A)

The first step that is necessary to develop an equation is the nominalisation of the IO table meaning that Z is normalised to Zn. Equation 2 normalises the IO table so where A_n equals the Identity Matrix (I) minus the input per unit of output (Z).

$$A_n = (I - Z) \qquad \textbf{Equation 2}$$

Where:

A_n = Normalised Technology Matrix/ IO table

Z_n = Normalised Input per unit of output

I = Identity Matrix (square table with ones on the diagonal, and zeros in the remaining entries)

Equation 3 is used to calculate the scaling factors for all the activities in the IO table. The scaling factor is equal to the Identity matrix (I) minus the normalised input per unit of output (Z_n), which is the inverse of (I – Z) multiplied by the final demand vector.

$$\mathbf{s} = (\mathbf{I} - \mathbf{Z_n})^{-1} \times \mathbf{f} \qquad \textbf{Equation 3}$$

Where:

f = final demand vector for national-level

s = vectors of scaling factor, represents the production volume of each activity

The life cycle emissions are calculated by multiplying the scaling factor that was calculated in Equation 3 with the environmental extension (B_n) that is provided in the normalised IO table, which identifies the emissions per unit of output per activity.

$$\boldsymbol{g} = \boldsymbol{B_n} \times \boldsymbol{s} + \boldsymbol{g_{households}}$$ **Equation 4**

Where:

g = Vector of resulting emissions (life cycle emissions)

B = Extensions Matrix (GHG emissions)

B_n = Normalised GHG emissions

$g_{households}$ = vector of national household emissions

Equation 2 provides the results for the emissions on a national level. In order to scale down the emissions to city-level the scaling factor needs to be adjusted. Equation 5 is applied to calculate the life cycle emissions on a city-scale.

$$\mathbf{g} = \mathbf{B_n}(\mathbf{I} - \mathbf{Z_n})^{-1} \times \mathbf{f_{city}} + \mathbf{g_{city\ households}}$$ **Equation 5**

Where:

f_{city}= final demand vector for city-level

$g_{city\ househoulds}$ = vector of city household emissions

These equations form the foundation for the calculations that are run in MATLAB. A procedure was established defining the steps and tasks that have to be undertaken to answer the research question.

Procedure

The following main tasks were established:

1. Model consumption and territorial-based account for the national-level of Spain and Germany
2. Undertake a contribution analysis for both countries to establish which activities mainly contribute to key GHG emissions
3. Model consumption-based account for the city-level of Barcelona and Hamburg and discuss and compare the results

The following process had to be undertaken in order to establish a consumption-based account for a city.

TASK 1:

a) Save the provided Excel sheet Masterfile Exiobase v3 in the MATLAB folder
b) In addition to the Excel sheets A, Z, B add the sheet ‘f’ (final use) by adding all columns of the final household consumption of the chosen country together creating a sheet containing data in one column and 2969 rows
c) Enter the following script into MATLAB:

```
Zn=xlsread('master-file-Exiobase-v3.xlsx','Zn');
Bn=xlsread('master-file-Exiobase-v3.xlsx','Bn');
f=xlsread('master-file-Exiobase-v3.xlsx','f');
I=eye(2969);
An=(I-Zn);
s=inv(An)*f;
BLCI=Bn*s
xlswrite('BLCI.xlsx',BLCI)
```

This script corresponds with the Equations 2-5 explained in the calculation process

d) After MATLAB has run the calculation, an Excel sheet with the consumption-based account is created (g)
e) Add the emissions of the final use activities for Spain or Germany to the data provided in g to establish the consumption-based account
f) Add final use activities for households and industries to establish territorial-based account for Spain or Germany
g) Convert the key GHG emissions into kg CO_2 equivalent for comparability
h) Divide the total emissions by the number of citizens in the country to establish the emissions per capita

TASK 2

a) Add the sheet ‘f’ (final use) to the Excel table by adding all columns of the final household consumption of the chosen country (either Spain or Germany) together creating a sheet containing data in one column and 2969 rows
b) Enter the following script into MATLAB:

```
sdiag=diag(s);
BLCIcontribution=Bn*sdiag;
xlswrite('BLCIcontribution.xlsx',BLCIcontribution);
```

c) After MATLAB has run the calculation, an Excel sheet with the consumption-based account is created called BLCIContribution showing which countries and industrial activities influence the total upstream emissions of either Spain or Germany.
d) Transpose the table to have the industries presented on the left side of the table and the emissions to raw material, water, air and soil on the top.
e) Analyse the data provided for the key GHG emissions

TASK 3:

a) Scale national consumption and territorial-based GHG emissions to city level using population data
b) Scale national consumption and territorial-based GHG emissions to city level by using GDP data
c) Compare results for Barcelona and Hamburg for the emissions per capita

By following this procedure results are obtained to allow the comparison of the consumption and territorial-based account on a country and city-level. For the city-level, the territorial-based emissions are taken from the climate-change mitigation strategy of the Barcelona and Hamburg. This helps to establish whether the applied mitigation efforts that are based on territorial-based accounting are still applicable if the accounting method is changed.

2.4. Case studies

In order to be able to apply the theory researched in the literature to a real life situation it was decided to undertake case studies of two European cities. The broad research field is focused on particular cases in order to make the research topic clearer and the data volume more manageable. It was decided to pick two cities with different geographical locations and from different countries to see the effects of the estimations on different cases and investigate the similarities and differences in mitigation options. However, comparability was ensured by selecting European cities.

The purpose of using the selected case studies is to answer the sub- research questions 2 and 3:

- *What are the differences between consumption and territorial-based inventories of Hamburg (Germany) and Barcelona (Spain) and what are the main contributors to the emission generation?*
- *Do the identified mitigation options, which are based on a territorial approach, still lead to net reductions when applying a consumption-based approach to GHG accounting?*

In order to answer question 2 the consumption-based GHG account was modelled on a national and city scale and compared to the territorial-based account. A contribution analysis was conducted in order to find out which countries and industrial activities contribute to the consumption-based account. In order to answer question 2, the climate change mitigation strategy for each city was analysed and on that basis a new mitigation action was developed to identify the effects on consumption and territorial-based emissions.

2.4.1. City selection

A number of requirements were set in order to select cities for the case study research:

- Knowledge gathered through previous research *(3rd Semester project: "Accounting for GHG emissions: A review of various tools)* (Kempken 2016)
- Data availability (National GHG inventory, IO table, climate change mitigation strategy etc.)

- Willingness to undertake actions for GHG emission reduction
- Availability of a Climate Change Mitigation Strategy

On the basis of these criteria, the cities Hamburg and Barcelona were selected as appropriate case studies. These cities were part of the research undertaken in the 3rd Semester project and therefore basic knowledge about the cities' emissions and mitigation strategies has already been acquired. Both cities have, apart from the national climate change strategies for Germany and Spain, an action plan in place, which is adapted to the specific requirements of each city. Both cities are affiliated to the Joint European Master Programme in Cities and Sustainability (Jemes CiSu), providing contacts for possible cooperation and co-supervision for this Master thesis is provided by the Autonomous University of Barcelona. Additionally, Barcelona and Hamburg have similar characteristics like population size and the presence of a harbour and airport. They are also quite wealthy cities in comparison to the respective country average with a lot of economic activity.

The selected case study cities demonstrate major efforts to reduce emissions. Barcelona is part of the C40 network consisting of international megacities striving towards decreasing GHG emissions and mitigating climate change risks (C40 Cities 2015). The involvement in such a programme supports cities to set a focus on creating a sustainable future while collaborating globally to achieve local, national and international climate goals. Hamburg was elected as Green European Capital 2011, showing the city's great potential for sustainable development (European Comission 2011). Additionally, Hamburg responded to the surveys provided by the Carbon Disclosure Project (CDP) in 2013, 2014 and 2015 that provide information on the current status of the cities in terms of climate change mitigation and adaption.

In the decision process others cities were also considered for conducting case studies. For example, a comparison between Aalborg, Denmark and Sabadell, Spain, which are two towns of a similar size but very different locations and therefore suitable for a comparison. However, it was decided that for this type of study these towns were too small and especially for Sabadell, difficulties with access to data were predicted. Another city that was considered is Beijing, China due to a previous research project of the author and the rapid transition of the city. Again, concerns were raised about the access to the needed data and in addition to that, it was predicted that the language barrier would cause significant issues. Additionally, Beijing's size and population of around 20 million people puts it into a dimension not comparable to the biggest European cities. Also, in terms of resource consumption China is still a developing country basing its energy use mainly on coal, meaning Beijing is at a different state of development and deals with other environmental challenges than European cities.

The key background information about the cities is presented and the climate change mitigation strategies are analysed before establishing and comparing the territorial and consumption-based accounts.

2.5. Limitations to research

In the process of conducting the literature review, collecting data and evaluating the findings for this thesis, a number of limitations were encountered:

1. Information access

A number of different types of data were needed in order to conduct the different methodologies for the research. This data includes but is not limited to:

Literature review:

- Books
- Journals
- Governmental Reports
- Websites of key organizations

Case study:

- IO database
- Climate change mitigation strategies for a city
- Quantitative data for a city

Most of the information required for undertaking this study was available through the named means. However, some access restrictions were encountered for books that could have supported the research were not available online or in the library.

When looking more specific information like quantitative data for the case study cities some access limitations were encountered. Some city scale information was not available publically, meaning that data had to be scaled down from the national level. Especially consumption-based data for the city-level was very limited. Also on a national level the information about consumption-based inventories was relatively scarce.

2. Data quality

For the literature review it was made sure that data from reliable sources was used, for example books and articles that were cited numerous times to ensure that the discussed concepts and theories are supported widely. A large amount of the used data also came from governmental reports while sources like newspaper articles were tried to avoided due to concerns of biased or exaggerated information for the media.

3. Assumptions

For this study it was not possible to find information and have access to all data that is needed to conduct the research, therefore a number of assumptions had to be made throughout the study. This includes but is not limited to the following issues:

1. For the calculations of the consumption and the territorial-based GHG emissions accounts on a national level a simplified IO table was used not containing the full range of data for all countries.

2. IO data was only available for the city level, therefore the data was aggregated from the national inventories
3. To exemplify, the issues discussed in the literature review consumption and territorial-based data for single cities was presented. However, the amount of examples is limited due to restricted availability of information.

3. Literature Review

3.1. Purpose

This chapter is comprised of a review of existing literature dealing with the topic of consumption and territorial-based GHG emission accounting. It is attempted to establish the current view on the topic and the most common concepts and theories from key contributors to the research.

The purpose of conducting a literature review of relevant publications is answering the first research sub question: "*What problems connected to fixed territorial boundaries are related to application of territorial-based accounting and what is the difference to the consumption-based approach?"*

The following key literature was reviewed in order to answer the research sub question:

- Dodman, D., 2009. *Blaming cities for climate change ? An analysis of urban greenhouse gas emissions inventories.*
- Peters, G.P., 2008. *From production-based to consumption-based national emission inventories.*
- Peters, G.P. & Hertwich, E.G., 2008. Post-Kyoto greenhouse gas inventories: Production versus consumption.
- Schmidt, J. & Muños, I., 2014. *The carbon footprint of Danish production and consumption*

These papers and articles were identified as the most important references. Concerning the topic of territorial and consumption-based accounting, the work of Peters and Hertwich is the most referenced among the reviewed literature and forms the basis for various research studies conducted on the issue. Schmidt and Muños (2014) study on the territorial and consumption-based emissions of Denmark forms a good guidance for the methodology used to conduct this thesis. The models and equations used for the later case studies were mainly provided by this study. The reviewed literature mainly dealt with the topic of GHG emissions accounting on a national level. However, the focus of the thesis was set on city emissions and therefore it was important to find literature that discussed the issue on a city-level. Dondman (2009) provides a good insight into city emissions in developing and developed countries and issues related to the applied accounting methods.

The identified references all revolve around the topic territorial- vs. consumption-based accounting and all lead towards the latter approach, underlining that opinion by giving examples on the national and local level. The information and opinions represented in these references is assumed to be representative due to the fact the key advantages and disadvantages of the methods match between the sources.

Background information on the topic of GHG emission accounting and reduction is given. The advantages and disadvantages of territorial and consumption-based measurement approaches are discussed. In order to illustrate the differences between the approaches in more detail, examples are given for national and city emissions. The general thematic of

GHG emissions measurement approaches is then applied to the city level and which issues are related to that process.

3.2. Background of GHG emissions accounting

The United Nations Framework Convention on Climate Change (UNFCCC) was formed in 1992 with the goal to initiate cooperation between countries to fight climate change to reach the ultimate goal to prevent *"dangerous human interference with the climate system"* (UNFCCC 2014a). It was decided that average global temperature increases and the climate change effects resulting from this had to be limited and ways had to be found to cope with impacts that were already inevitable at that time. In 1994, the UNFCCC finally went into force and the Conference of the Parties took place in 1995 where discussion revolved around the fact that global response to climate change had to be intensified, leading to the adoption of the Kyoto Protocol in 1997. (UNFCCC 2014a) This international agreement states that global GHG emissions to the atmosphere have to be reduced (Munksgaard & Pedersen 2001).

The Kyoto Protocol came into force in 2005 and set binding emissions reduction targets for developed member Parties. Currently 197 Parties are members of the Convention and 192 Parties have ratified the Kyoto Protocol. The first commitment period of the Protocol went from 2008 until 2012. The second commitment period started in the beginning of 2013 and will run until 2020 (UNFCCC 2014b).

Since the formation of the UNFCCC several other climate conferences, agreements and amendments to existing treaties have taken place. The most recent development in the UN battle against climate change is the 2015 Paris Agreement. The central aim of this COP21 agreement is to limit the global temperature rise during this century below 2 °C above pre-industrial levels. Efforts are under taken to intensify climate change actions to such high levels in order to aim for a further reduction of the temperature limit to 1.5 °C.

Behind that background, most European countries have agreed to work towards the following emission reduction targets:

- 2020 target: 20% cut in greenhouse gas emissions from 1990 levels
- 2030 target: at least 40% reduction in greenhouse gas emissions from 1990 levels
- 2050 target: 80% emissions cut from 1990 levels
  (European Commission 2016b)

Parties under the Convention are divided into different categories depending on their commitment.

Annex I:

- Industrialized countries that were members of the OECD in 1992
- Countries with economies in transition (EIT Parties), which includes the Russian Federation, the Baltic States, and several Central and Eastern European States.
- Countries are required to publish National Inventories on a yearly basis.

Annex II:

- OECD members of Annex I without the EIT Parties.
- Required to provide financial resources to enable developing countries to undertake emissions reduction activities and to help them adapt to adverse effects of climate change

Non-Annex:

- Mostly developing countries
- Certain developing countries are recognised by the Convention as vulnerable (e.g. countries with low-lying coastal areas and those prone to desertification and drought) and facilitate support activities (investment, insurance, technology transfer) (UNFCCC 2014c)

For the set-up of consumption and territorial-based GHG inventories essentially the same data is needed, however, the approaches set a different focus in their application. As defined in the Kyoto Protocol, the IPCC uses territorial-based accounting methods, since they focus on point sources of emissions and form the basis for environmental regulation which is ultimately the goal of national inventories. Consumption-based accounting is founded on the method of Life Cycle Assessment (LCA) meaning that the GHG emissions are measured taking into account the environmental impact of all life cycle stages and not just focusing on the source.

In order to be able to undertake appropriate climate action, it has to be established which local, national and global activities have the biggest impact on emissions and how they can be reduced effectively. GHG inventories are normally established for countries but emissions are also measured for single cities in order to see the development of emissions over the years and check if progress is made in achieving the targets. Many countries claim that they are on a good track in achieving their reduction targets. Table 1 shows the reductions in CO_2 emissions of different countries.

Table 1 Reductions of CO_2 emissions in European Countries (UNFCCC 2015)

Country	Original level (1990) (million tons CO_2)	Reduced/ increased level (2013) (million tons CO_2)	Percentage
Denmark	70	56	20%
Germany	1250	950	24%
Netherlands	219	196	11%
Poland	580	394	32%
Ukraine	912	385	58%
Estonia	40	21	45%
Spain	290	322	-11%

It shows that many countries have managed to reduce their emissions substantially since the implementation of the Kyoto protocol. Especially countries whose economy is in transition including Poland, Ukraine and Estonia show great reductions in emissions. Ukraine shows the largest increase with almost 60%. These high percentages can be explained through a shift of production locations outside the territorial border of the countries. What is clearly noticeable is that Spain is the only country that has increased its emissions since the base year. Although not all European countries are presented in this table, the general trend is the reduction of emissions. However, this data is based on emissions measurements undertaken by the territorial-based accounting approach. The following paragraphs will clarify the reasons why this data should be handled carefully.

3.3. Comparison of GHG emissions accounting methods

3.3.1. Emission sources

The territorial-based account is focused on sources within a specific geographic boundary, meaning that all emissions that are coming from the production source are considered in the account. When considering the emissions of a specific country or city, this means that the sources of the considered emissions are close and easier to overview. The emissions estimated in territorial-accounts are also included in national climate and environmental regulation, which are the foundation for future plans of climate change mitigation and GHG emission reduction. The consumption-based approach sets its focus on the LCA approach meaning that all life-cycle stages of the emission progress are considered (Schmidt & Muños 2014). This also means that the emission sources are not identified as easily leading to a more complex problem-solving process to reduce emissions.

3.3.2. Carbon leakage

The term carbon leakage is used to describe a situation where companies move their production activities due to a tightening of climate policies into a region where climate measures are less ambitious. This can lead to negative impacts on global GHG emissions (European Commission 2016a).

Caro et al (2014) state that territorial-based accounting may encourage the shift of production from industrialised to developing countries and the responsibility for emissions from goods and services that are produced in one country and consumed in another is entirely allocated to the producer (Caro et al. 2014).

Grasso (2016) criticizes that territorial -based inventories encourage that the consumption of carbon-intensive products is shifted towards cheaper substitutes that are produced in parts of the world that are less regulated and are then mainly imported to the developed nations.

3.3.3. International trade

National GHG inventories only take into account the emissions that are produced within the territory under study but ignore the emissions that can be blamed to consumption within the territory through trade. Despite the fact that large amounts of CO_2 are traded internationally, they are not included in national GHG inventories.

According to Peters (2008), international trade is one of the main issues of carbon leakage. There are a number of matters connected to GHG emissions from international trade.

The fact that only domestically produced emissions are considered in national accounts can create a biased view. According to Boitier (2012) there is a problem with certain international activities like international trade and the related need for transport because it is difficult to allocate them properly. International transportation cannot be fixed to a certain geographical location which makes it difficult to assign responsibilities (Peters 2008).

A number of studies have found that the percentage of CO_2 emissions that are generated from products and services that are traded internationally is around 20-25% (Barrett et al. 2013; Davis & Caldeira 2010). These emissions can be blamed on the fact that large amounts of industry were moved to developing countries (Grasso 2016). This shows that it is fatal for the accuracy of the emissions measured globally to not consider international trade appropriately.

The issue of trade also has to be considered when measuring GHG emissions in cities. On a local level trade, commuting and shopping trips are key sources of emissions and have to be considered in the inventories (Hermannsson & Mcintyre 2014).

3.3.4. Competitiveness

The Kyoto protocol is about to expire and will be replaced by the Paris agreement (2015). However, the USA being the second largest emitter globally has never ratified the Kyoto protocol (Lenntech BV 2016; World Resource Institute 2015). If the Paris agreement will be ratified is still unknown. One of the key reasons of the delay of ratification is the *'loss of competitiveness in the absence of binding commitments in developing countries'* (Peters & Hertwich 2008). If the consumption-based approach is being applied, concerns about competitiveness can be addressed. The same environmental legislation is applicable for domestic and foreign producers. This means that the production process has to take place according to the same rules and frameworks.

3.3.5. Mitigation options

Peters and Hertwich (2008) also claim that consumption-based accounting offer a greater amount of options for GHG mitigation. This includes the fact that imports are taken into account, which encourages the production of goods and services in a location where environmental impacts can be minimised effectively and the lowest cost can be achieved.

Hertwich and Peter (2008) state that a pollution intensive resource base, which includes oil and gas, can be a significant disadvantage for a country if territorial-based emissions accounts are used. For example 69% of Norway's CO_2 emissions are caused by the exports. In order to meet its commitments under the Kyoto protocol, Norway would have to reduce its export outputs, but they make up a key part of the country's economy. Additionally, the country has strict environmental legislation and is mainly generating electricity through hydropower generation. This means that, in a consumption-based account, Norway's CO_2 emissions would be distributed differently between the emitting sectors and therefore different reduction methods may be applicable.

3.3.6. Responsibility allocation

Grasso (2016) states that the allocation of responsibility is done in a fairer manner for the consumption-based approach than for territorial-based accounting. Since the consumer takes responsibility for all emissions that are actually emitted through consumption, which also means that the consumer is in charge to reduce emissions as effectively as possible.

The use of consumption-based inventories also allocates a greater responsibility to developed countries since they are responsible for a greater share of the emissions. On the other hand lower results are shown for net exporters like China. These results can be explained because developed countries are looking to outsource their production into countries where production is cheaper and import the needed goods and services; while in the net exporter countries most of the services and goods that are produced and accounted for in the territorial-based account are not consumed within the country. As a result the commitments imposed on developing countries become less important. (Peters & Hertwich 2008)

3.3.7. System boundaries

One of the issues related to consumption-based accounting is that obstacles to implementation could occur due to the fact that political decision-making outside the standard geo-political region is necessary (Peters 2008). This may be met with political resistance because different countries may have different opinions on climate change (Peters & Hertwich 2008).

3.3.8. Complementing the accounting methods

According to Grasso (2016) a shift from territorial to consumption-based accounting is just a move from one extreme to another. Generally, it may not be the best idea to just allocate all responsibility to either consumers or producers. A number of sources suggest that consumption-based accounting should complement production-based accounting but is not suitable to replace inventories and targets entirely (Erickson et al. 2012; Barrett et al. 2013).

Territorial-based and consumption based accounts are calculated on the basis of the same data, however territorial-based are currently much more widely applied although the method has significant disadvantages. The inclusion of consumption-based approaches into the accounting method provides the opportunity to make national and regional emission reduction efforts more efficient.

3.4. City inventories

Unlike for countries, there is no global standard for GHG emissions inventories for cities that is widely accepted (Dodman 2009). The Greenhouse Gas Protocol has published the *Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC)* in 2014. There are several pilot projects undertaken in cities worldwide and some cities are testing the beta version of the GPC, however, it will take an extended amount of time until the application is as common as the UNFCCC framework (World Resource Institute 2014). The Kyoto protocol pledges that CO_2 emissions will be reduced by at least 50% in comparison to 1990 levels. Although treaties and targets may be set on a national level, cities are the places where changes take place due to the fact that a large part of the population agglomerates in cities. Mitigation strategies on national levels are additionally supplemented with city-wide actions against climate change (Ibrahim et al. 2012; Hermannsson & Mcintyre 2014). Table 2 shows the reduction of territorial-based emissions in cities that have mitigation strategies in place. As in the data presented in Table 1 showing the reductions on the country-level, significant decreases can also be seen here. All cities are located in developed countries, which means that it is likely that their success in emission reduction is related to a shift in the production location. However, parts of the reductions may also be linked to mitigation strategies like decrease of private vehicles in city centres, implementation of better public transport networks, more use of renewable energies in the grid etc.

Table 2 City-level territorial-based CO_2 reduction

City	Initial level (Mt CO_2)	Reduced level (Mt CO_2)	Percentage (%)	Reference
Copenhagen	2.5 (2005)	2 (2015)	20	(City of Copenhagen 2009)
Hamburg	20.7 (1990)	17.3 (2012)	16	(Ministry for Urban Development and Environment 2011)
Berlin	32.1 (1990)	29.6 (1995)	7.7	(Senate Department for Urban Development and the 2008)
London	50 (2000)	40 (2015)	20	(Greater London Authority 2015)
Glasgow	4 (2006)	3.5 (2012)	13	(Glasgow City Council 2014)
Barcelona	3.1 t CO_2 p.c.(1999)	2.28 t CO_2 p.c. (2012)	27	(Ajuntament de Barcelona 2013)

Measuring GHG emissions accurately in cities can therefore bring benefits on a national and global level. With a GHG inventory on a city-scale it can be indicated which sectors are especially emission-intensive and it provides a basis for setting climate policies with clear realistic targets. If climate change adaption and mitigation strategies are set without first analysing the city's activities and creating a GHG emissions inventory, the focus would not be set on the hotspots and locations where the highest emission reductions can be achieved (Ibrahim et al. 2012).

It is clear that cities contribute significantly to overall GHG emissions due to the fact that they are centres for economic activity. Cities with heavy industry and a lot of infrastructure show territorial-based per capita emissions that are higher than the country average. On the other hand, territorial-based per capita emissions are lower in cities which less industrial activity. There are also other factors that can have an effect on the reduction of city emissions. This includes for example that people are encouraged to walk, cycle or use public transport instead of private vehicles due to the provision of needed infrastructure and the vicinity of homes and businesses (Hermannsson & Mcintyre 2014; Dodman 2009). In addition, emissions vary significantly between cities, since emissions are partly dependent on many context specific issues including geophysical and technical factors like the climate, whether the city is a gateway or not, its ease of access to resources, urban design and waste treatment (Steinberger et al. 2009). However, the most important factor is whether there is heavy industry or energy production and large infrastructure present in the city. Therefore reduction policies to reduce local emissions have to be adapted to the activities in the selected region (Hermannsson & Mcintyre 2014).

In a city the use of territorial-based account can hide the high consumption lifestyles of certain areas that majorly contribute to the city's emissions. This happens due to the fact that areas with high consumption of goods and services differ from areas where production takes place where the responsibility for emissions is allocated. The city's GHG inventory fails to identify the areas where actions to reduce emissions are most necessary.

There are also logistical issues related to territorial-based emission accounts for cities. First of all there are large gaps in the information that can be acquired on city levels and also different information is available on different scales. For example data on the exports and imports of a single city is more difficult to acquire than for a country where IO tables are used to track the inputs and outputs of the industrial activity. It is also likely that the political boundary[5] of a city changes over time due to the increased move of population from rural areas to cities.

Dodman (2009) also blames the territorial-based approach for distorting the responsibility of cities in developed and developing countries for the generation of GHG emissions. Service-orientated cities and production-orientated cities are affected by this in different ways. The responsibility allocated to production-orientated cities mainly located in developing countries is exaggerated while service-orientated cities in developed countries are underestimated in their generation of emissions in comparison to the consumption-based account.

According to Chavez and Ramaswami (2011) consumption-based accounting has a number of advantages for the application on the city-level. In a city the major part of final consumption is caused by households. Consumption-based accounts allow to visualise the full transboundary impact of household consumption with is valuable information for environmental policy developments. It is an appropriate method to compare per capita emissions through household expenditure and provides thorough and detailed results. However, the results obtained are strongly dependent on data quality from IO tables. For many cities it is difficult to access IO data for the city level. Data may also be incomplete or not accurate due to the fact that it may have to be greatly scaled down.

In comparison to the territorial-based accounting method, consumption-based accounting has the advantage that deals appropriately with emissions from international trade and therefore the problem of carbon leakage is avoided (Boitier 2012; Peters & Hertwich 2008). Studies that have established consumption-based GHG inventories for different global case study cities show that consumption-based emissions are in some cases higher than territorial-based emissions. This is especially the case in cities in developed countries since consumed products are mainly imported from elsewhere meaning that the production does not take place in the city itself and therefore is not considered in the territorial-based account. However, the consumption-based account takes the increased consumption in these cities into accounts and therefore shows higher estimates. This includes but is not limited the examples presented in Table 3.

[5] The political boundary is the border that separates countries, states and cities. These borders can be changed through political decisions or if land is taken over during a war.

Table 3 Territorial vs. Consumption-based emissions in cities

City/Country	Territorial-based CO_2 emissions (million tons)	Consumption-based CO_2 emissions (million tons)	Year	Reference
Barcelona	10	14	2016	Calculations
Beijing	109	161	2007	(Feng et al. 2014)
Hamburg	20	22	2016	Calculations
London	44	90	2010	(Dhakal 2010)
Shanghai	200	209	2007	(Feng et al. 2014)

Table 3 shows that these cities have a higher contribution to the national and global carbon footprint as it is currently considered in their inventories and mitigation strategies. This means that the climate change mitigation strategies developed for the cities may not be appropriate to reduce emissions effectively.

3.5. Conclusions

The literature review was conducted in order to answer the sub-question: "*What problems connected to fixed territorial boundaries are related to application of territorial-based accounting and what is the difference to the consumption-based approach?*" In Table 4 and Table 5 the advantages and disadvantages of both accounting methods are presented to give a summarising overview.

Table 4 Summary of Pros for accounting methods

	Territorial-based	Consumption-based
Pros	Forms basis for countries' yearly GHG inventories	Avoidance of carbon leakage issues
	Common and wide knowledge and application	Consideration of emissions related to international trade
	Possible actions are close to the problem due to focus on sources within a certain geographic boundary	Developed countries take responsibilities for a greater share of emissions while pressure on developing countries is released
	Included in national climate regulations	Contributes to competitiveness between countries
		Increased options for climate change mitigation
		LCA approach means that all lifecycle stages are considered in the account

Table 5 Summary of Cons for accounting methods

	Territorial-based	Consumption-based
Cons	Many flaws that were uncovered in the literature may lead that this approach is prone to political resistance to the application	May be prone to political resistance due to opposing views on climate change in different countries
	Full responsibility for emissions lies on producer although consumption may take place in a different country/city	Unfair to allocate the full responsibility of emissions to consumer since a whole supply chain is involved
	Carbon leakage	Difficulties to access IO data for the city level.
	Emissions hotspots (in cities) are not represented accurately	Data may be incomplete or not accurate due to the fact that it may need to be scaled down from national to city level
	GHG emissions from international transport are not considered	

It can clearly be seen that none of the discussed accounting methods is ideal and each of them has their advantages and drawbacks. However, the relevant literature suggests that there is a preference toward the adoption of consumption-based approaching and a clear need to consider this option in further detail. However, the relevance of territorial-based accounting cannot be ignored. Therefore it is generally not recommendable to depend on one single method.

Although it is proven that consumption-based accounting is essential in order to estimate and understand emissions accurately, only few governments have decided to consider this approach for the formulation and appraisal of environmental policies (Barrett et al. 2013). A move toward consumption-based approach can lead to more efficiency in emission reduction and makes clear that in order to reduce the environmental load from production activities trading activities need to be reorganised. This means that the production of goods is much cheaper in developing countries; however, it is highly unsustainable to import the majority of products to developed countries (Mózner 2013).

Due to the fact that the current accounting system serves as a foundation for local, national and global climate action, resistance against a switch to consumption-based accounting is likely. Therefore the switch cannot take place rapidly but will require a relatively slow implementation (Grasso 2016).

However, Barrett (2013) states that territorial-based accounting is still the most accurate method to measure global aggregated emissions and can therefore not just be ignored. It has been suggested by multiple sources that a complementation of the territorial-based account with the consumption-based approach provides a sustainable solution to take all emissions into account.

Lastly, the debate about GHG emission inventories and reductions are mostly held on a national or global level. However, in order to achieve targets on national and international levels, action has to be taken locally in cities (Dodman 2009). The application of GHG emission accounts to cities is still relatively new, therefore, it can be expected that more accurate and simpler methods are going to be developed in the future (Chavez & Ramaswami 2011).

Based on what was found in the literature review on the differences of the GHG accounting methods and especially on the issues related to territorial-based inventories, an analysis on consumption and territorial-based GHG emission accounts on Barcelona and Hamburg will be conducted. The purpose of this analysis is to demonstrate the discussed issues on a case study and discuss potential causes and solutions.

4. Case Studies

4.1. Introduction

In order to be able to apply the theory researched in the literature to a real life situation it was decided to undertake two case studies. The broad research field is focused on particular cases in order to make the research topic clearer and the data volume more manageable.

It is aimed to undertake an analysis of GHG emission accounts and climate change mitigation strategies in Barcelona and Hamburg. In its mitigation strategy, which is based on territorial-based measurements, each city provides details on how it is currently attempting to reduce its emissions and which actions are taken in the future. The strategy also mentions the targets that are set for the city and which reductions already have been achieved. It is aimed to assess if this information capture the causes and thereby the actual options for mitigating GHG emissions. It is intended to establish how using the territorial-based account can be misleading in terms of how the city is performing in mitigating their climate.

On the basis of IO data from 2011, the consumption and territorial-based accounts were calculated on the national level for Spain and Germany, in order to exemplify the differences of the methods. For further analysis of the results for both nations and the case study cities, the focus was set on the main, most damaging GHGs (CO_2, N_2O, CH_4). The results were scaled down to city level according to population and GDP for Barcelona and Hamburg. These results were used to establish whether the climate mitigation strategy would still be useful for the city if a consumption-based account was applied and which changes would have to be made.

4.2. Modelling national-level GHG emissions

4.2.1. National-level GHG emissions accounts

Table 6 and Table 7 present a sample of the GHG emissions released to the air by Spain and Germany. For the territorial-based emissions, final household[6] emissions and final industry emissions are added together. The consumption-based emissions are obtained through MATLAB by the process detailed in the Methodology chapter.

Table 6 National emissions to air for Spain

GHG	Unit	Consumption-based	Territorial-based
Carbon dioxide, fossil (CO_2)	t	330,000,000	251,000,000
Dinitrogen monoxide (N_2O)	t	64,000	64,000
Methane, biogenic (CH_4)	t	2,000,000	838,000

[6] Final household emissions for a country include: transport (private vehicle and public transport), energy used for heating and cooling, electricity used for appliances, and waste disposal.

Table 6 clearly shows that key GHG emissions are significantly higher for the consumption-based account in comparison to the territorial-based account. This is specifically the case for CH_4 where the emissions are more than twice as high. Also the CO_2 emissions are almost 80 million tons higher.

Table 7 National emissions to air for Germany

GHG	Unit	Consumption-based	Territorial-based
Carbon dioxide, fossil (CO_2)	T	840,000,000	860,000,000
Dinitrogen monoxide (N_2O)	T	153,000	131,000
Methane, biogenic (CH_4)	T	6,000,000	2,000,000

Table 7 also shows that the territorial-based CO_2 emissions in Germany are a little higher than consumption-based CO_2 emissions. However, emissions of N_2O are slightly higher for the consumption-based account while CH_4 emissions are almost three times higher. CH_4 are mainly related to emissions from agricultural activities like livestock. This may mean that the territorial-based account excludes large amounts of imports of agriculture

The provided IO table presents the emissions in tons of each GHG. However, in order to be able to quantify the total emissions, they have to be converted to kg CO_2-equivalents (Table 8). The conversion factors were taken from the GWP100 factors from the 5th Assessment Report of the IPCC.

Table 8 Conversion factors for CO_2-eq (IPCC 2014a)

Emissions	Conversion
Carbon dioxide, fossil (CO_2)	1 kg CO_2 = 1 kg CO_2-eq
Dinitrogen monoxide (N_2O)	1 kg N_2O = 265 kg CO_2-eq
Methane, biogenic (CH_4)	1 kg CH_4 = 28 kg CO_2-eq

Table 9 and Table 10 show results for the conversion of each GHG, the sum of the GWP of the total emissions to air from Spain and Germany, as well as the emissions per capita. For the territorial-based emissions, final household[7] emissions and final industry emissions are added together. The consumption-based emissions are obtained through MATLAB by the process detailed in the Methodology chapter.

In order to calculate the emissions per capita the total GHG emissions of the country was divided by the population. Spain has a population of around 47 million people (2014) while Germany has a population of around 81 million people (2014) (World Bank 2016b).

[7] Final household emissions for a country include: transport (private vehicle and public transport), energy used for heating and cooling, electricity used for appliances, and waste disposal.

Table 9 National emissions to air for Spain in CO_2-eq

GHG	Unit	Consumption-based	Territorial-based
Carbon dioxide, fossil (CO_2)	t CO_2-eq	330,000,000	251,000,000
Dinitrogen monoxide (N_2O)	t CO_2-eq	17,000,000	17,000,000
Methane, biogenic (CH_4)	t CO_2-eq	68,000,000	24,000,000
Total (GWP)	t CO_2-eq	415,000,000	291,000,000
CO_2-eq per capita	t CO_2-eq	8.9	6.3

While the N_2O emissions are similar for the consumption and the territorial-based account of Spain, the biggest difference can be noted for the CH_4 emissions, which are around 3 times higher for the consumption-based emissions. The total emissions, as well as the per capita emissions, also show significantly higher results in the consumption-based account, which are around 100 million t CO_2-eq higher. This results in consumption-based per capita emissions of around 9 t CO_2-eq in contrast to a much lower 6 t CO_2-eq territorial-based per capita emissions. The higher consumption-based emissions can be explained by the fact that trade and transport activities are included while these emissions not considered in the territorial. As an economically developed country Spain imports are much higher than exports since production in developing countries is cheaper.

Tukker et al (2007) established that consumption-based emissions in Spain were around 577 million tons in 2005 resulting in around 13 t CO_2-eq per capita. The data that Tukker et al used for the estimations were collected prior to the financial crisis in 2008, while the estimations made for this study are based on data from 2011. The comparison shows that the total and per capita consumption-based emissions have decreased quite significantly which can mainly be attributed to the crisis. Spain was hit quite seriously by the crisis, which had devastating effects on the economic and industrial activity of the country. Additionally, different assumptions made while modelling the emissions also affect the results as for example the system boundary.

The World Bank's published CO_2 emissions per capita for Spain are 5.8 tons in 2011. Since 90% of the calculated territorial-based emissions are CO_2 emissions, the results are fairly similar (World Bank 2016).

Table 10 National emissions to air for Germany in CO_2-eq

GHG	Unit	Consumption-based	Territorial-based
Carbon dioxide, fossil (CO_2)	t CO_2-eq	840,000,000	860,000,000
Dinitrogen monoxide (N_2O)	t CO_2-eq	41,000,000	35,000,000
Methane, biogenic (CH_4)	t CO_2-eq	162,000,000	51,000,000
Total (GWP)	t CO_2-eq	1,043,000,000	946,000,000
CO_2-eq per capita	t CO_2-eq	12.9	11.7

Table 10 shows the total emissions in t CO_2-eq and the per capita emissions for Germany. The final results show that total and per capita consumption-based emissions in Germany are slightly higher than territorial-based emissions. Consumption-based emissions were estimated to be almost 13 t CO_2-eq per capita while territorial-based emissions are a bit less than 12 t CO_2-eq. Again the lower territorial-based emissions can be explained by the omitting of international trade and the related transport.

In 2005 carbon emissions were estimated to be around 16 t per capita and 1,340 million tons total emissions (Tukker et al. 2007). The results show that there also has been a reduction in emissions, meaning that the industrial and economic activity of Germany has been reduced due to the crisis. However, the reductions were not as significant as for Spain.

The estimation of the World Bank states that in 2011 around 8.9 tons of CO_2 per capita were emitted. Around 90% of the territorial-based emissions calculated can be attributed to CO_2, meaning that the calculated CO_2 estimations are higher (World Bank, 2016).

4.2.2. Contribution analysis

The contribution analysis is done in order to explain the contribution of different countries and industrial activities to the total consumption-based GHG account of Germany and Spain. It is also aimed to explain why consumption-based emissions are higher than territorial-based emissions for both countries. All values used for calculations and the resulting tables and graphs are approximated numbers.

Germany

As calculated in section 4.2.2, Germany's consumption-based GHG emissions sum up to a total of around 1 billion tons CO_2-eq (Table 11). Figure 5 shows that around 20% of the consumption-based emissions are from household activities while 80% can be allocated to industrial activities.

Table 11 Emissions distribution Germany

Source of consumption	Emissions (t CO_2-eq)
Industrial	834,000,000
Household	209,000,000
Total	1,043,000,000

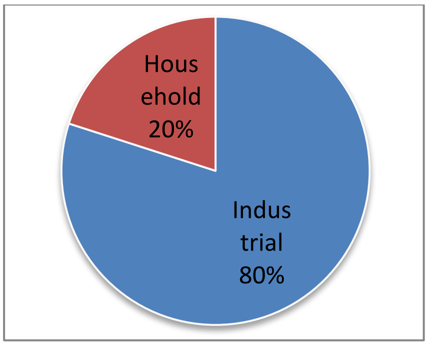

Figure 5 Distribution of consumption-based emissions (DE)

Table 12 and Table 13 present a sample of industrial activities and countries that have the highest contribution to Germany's consumption-based GHG emissions. Only the activities and countries that contribute the most are presented in the tables. The full tables can be found in Appendix C and D.

Table 12 Main contributing industrial activities to German emissions in tons of CO_2-eq

Industrial Activity	Product no.	GHG emissions	Percentage (from total)
Production of electricity by coal	_96	190,195,703	18%
Steam and hot water supply	112	97,610,263	9%
Manufacture of basic iron and steel and of ferro-alloys and first products thereof	_72	50,202,445	5%
Extraction of crude petroleum and services related to crude oil extraction, excluding surveying	_21	42,727,914	4%
Production of electricity by gas	_97	34,021,655	3%
Air transport	126	31,384,268	3%
Cattle farming	__9	28,063,240	3%
Raw milk	_14	27,833,678	3%
Sea and coastal water transport	124	25,452,852	2%
Biogasification of sewage sludge, incl. land application	149	23,350,784	2%
Other industrial activities		282,905,989.72	28%
Household (DE)		209,000,000	20%
Total		1043,000,000	100%

By far the industrial activity that contributes the most to Germany's consumption-based GHG emissions is the production of electricity by coal with over 190 million tonnes CO_2-eq. This is followed by steam and hot water supply with almost 100 million tonnes CO_2-eq.

Activities like air transport, cattle farming and raw milk production all have a contribution around 30 million t CO_2-eq.

The industrial activities for Germany were collected into broader groupings to have an overview about the contribution of industrial sectors. Sectors like agriculture, electricity, mining and manufacturing are split into a variety of activities. Appendix F presents the aggregated sectors for Germany.

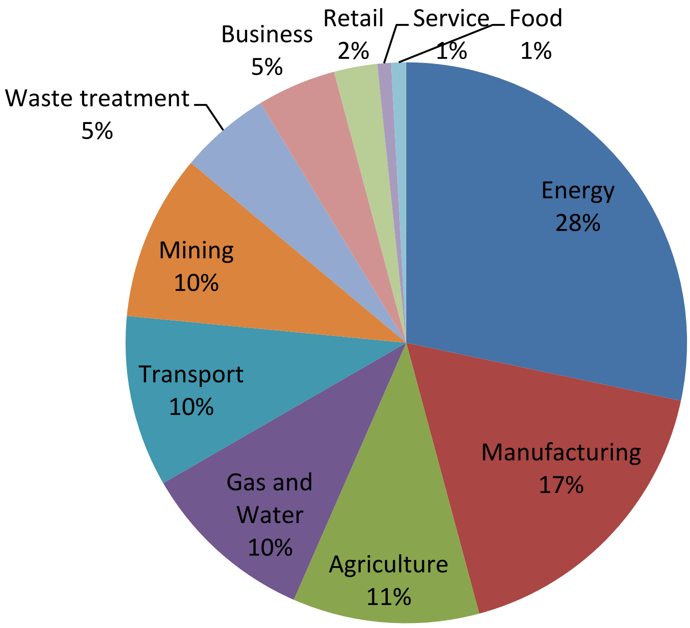

Figure 6 Contribution of aggregated industrial activities

The key sectors contributing to the consumption-based emissions of Germany are:

1. Energy (coal, gas, oil, renewables etc.) ~ 236 million tons
2. Manufacturing (metal, machinery, plastics, etc.) ~ 146 million tons
3. Agriculture animal farming, crop cultivation, fishing etc.) ~ 90 million tons
4. Gas and Water (water, steam and gas supply) ~ 84 million tons
5. Transport (air, water, rail, road etc.) ~ 82 million tons

Table 13 Main contributing countries to German GHG emissions

<table>
<tr><th>Countries</th><th>GHG emissions (CO_2-eq)</th><th colspan="2">Percent (from total)</th></tr>
<tr><td>Germany (DE) Industrial</td><td>401,332,288</td><td>39%</td><td rowspan="2">59%</td></tr>
<tr><td>Germany (DE) Household</td><td>208,951,768</td><td>20%</td></tr>
<tr><td>Rest of World (ROW)</td><td>282,118,397</td><td colspan="2">27%</td></tr>
<tr><td>United States (US)</td><td>70,732,644</td><td colspan="2">7%</td></tr>
<tr><td>Rest of Latin America (WL)</td><td>36,029,096</td><td colspan="2">3%</td></tr>
<tr><td>Italy (IT)</td><td>8,971,541</td><td colspan="2">1%</td></tr>
<tr><td>France (FR)</td><td>7,922,174</td><td colspan="2">1%</td></tr>
<tr><td>Czech Republic (CZ)</td><td>6,358,624</td><td colspan="2"><1%</td></tr>
<tr><td>South Africa (ZA)</td><td>6,092,447</td><td colspan="2"><1%</td></tr>
<tr><td>Canada (CA)</td><td>5,649,106</td><td colspan="2"><1%</td></tr>
</table>

Countries	GHG emissions (CO_2-eq)	Percent (from total)
Australia (AU)	5,319,805	<1%
Great Britain (GB)	5,273,765	<1%
All other countries	10,234,563	<1%
Total	1043,000,000	100%

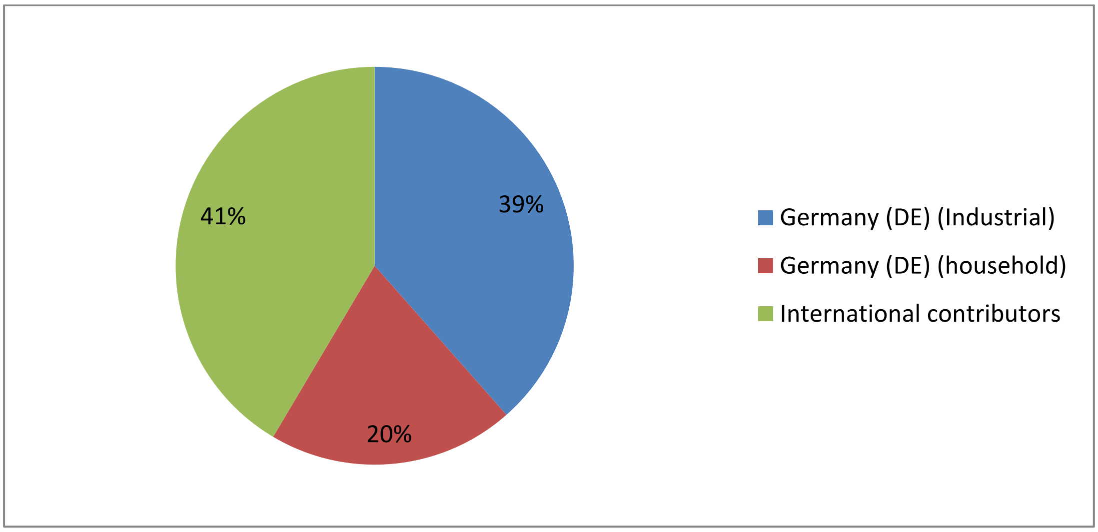

Figure 7 Contribution to German consumption-based emissions

After Germany's own industrial and household emissions, which represent 59% of the total, the rest of the contribution is made up from international contributors. This means that the production of a large number of goods and services that are consumed in Germany is done abroad and transported to the respective country. A lot of production sites are located in ROW due to cheaper production costs and less strict environmental policies.

Spain

As calculated in section 4.2.2, Spain's GHG emissions sum up to a total of around 415 thousand tons CO_2-eq (Table 14). Over 80% of the total consumption-based emissions of Spain emitted by industrial activities and the rest are emitted by households. (Fig. 8) Household contribution is slightly lower than in Germany which could be explained by the fact that Spain imports more industrial products which is creating higher impacts.

Table 14 Emissions distribution Spain

Source of consumption	Emissions t CO_2-eq)
Industrial	346,000,000
Household	69,000,000
Total	415,000,000

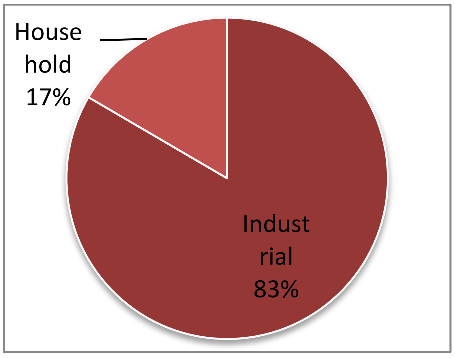

Figure 8 Distribution of consumption-based emissions (ES)

Table 15 and Table 16 present a sample of industrial activities and countries that have the highest contribution to Spain's consumption-based GHG emissions. Only the activities and countries that contribute the most are presented in the tables. The full tables can be found in Appendix A and B.

Table 15 Main contributing industrial activities to Spanish emissions in tons of CO_2-eq

Industrial activities	Product no.	GHG emissions	Percentage (from total)
Production of electricity by coal	_96	48,199,871	12%
Production of electricity by gas	_97	40,456,993	10%
Manufacture of basic iron and steel and of ferro-alloys and first products thereof	_72	25,324,459	6%
Extraction of crude petroleum and services related to crude oil extraction, excluding surveying	_21	17,925,362	4%
Steam and hot water supply	112	16,671,181	4%
Cattle farming	__9	13,888,320	3%
Air transport	126	11,878,633	3%
Production of electricity by petroleum and other oil derivatives	101	11,751,502	3%
Mining of coal and lignite; extraction of peat	_20	7,913,682	2%
Chemicals n.e.c[8]	_63	7,729,163	2%
Others		144,260,834	35%
Household (ES)		69,000,000	17%
Total		415,000,000	100%

[8] Not elsewhere classified

The industrial activities that contribute the most to Spanish consumption-based emissions is the production of electricity by coal (~50 million t CO_2-eq) and by gas (~40 million t CO_2-eq), Similar to the German consumption-based account, the manufacture of iron and steel also contributes majorly to the Spanish emissions with around 25 million t CO_2-eq. This is followed by crude petroleum extraction (~18 million t CO_2-eq) and steam and hot water supply (~17 million t CO_2-eq). Like for Germany, cattle farming and air transport are important contributors.

As for Germany, the industrial activities for Spain were collected into broader groupings to have an overview about the contribution of industrial sectors. The full list of aggregated sectors can be found in Appendix C.

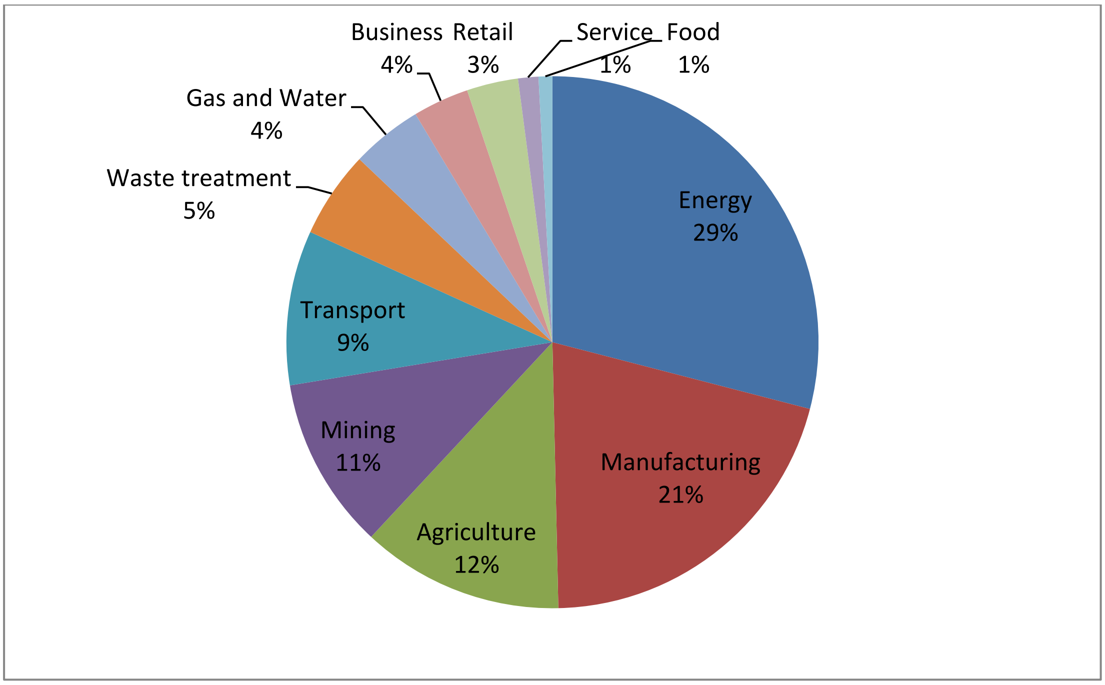

Figure 9 Contribution of aggregated industrial activities

The key sectors contributing to Spanish consumption-based emissions are:

1. Energy sector (coal, gas, oil, renewables etc.) ~ 100 million tons
2. Manufacture (metal, machinery, plastics, etc.) ~ 71 million tons
3. Agriculture (animal farming, crop cultivation, fishing etc.) ~ 43 million tons
4. Mining (coal, petroleum, oil etc.) ~ 36 million tons
5. Transport (air, sea, road, rail etc.) ~ 32 million tons

Table 16 Main contributing countries to Spanish GHG emissions

Countries	GHG emissions	Percent (from total)	
Spain (ES) Industrial	117,960,091	28%	
Spain (ES) Household	68,821,457	17%	45%
Rest of World (ROW)	144,963,333	35%	
Rest of Latin America (WL)	12,041,712	3%	
Germany (DE)	10,336,925	2%	
United States (US)	10,089,941	2%	
Great Britain(GB)	3,576,805	1%	
Italy (IT)	3,189,135	1%	
France (FR)	2,983,567	<1%	
Australia (AU)	2,888,111	<1%	
South Africa (ZA)	2,405,381	<1%	
Other	36,000,000	9%	
Total	415,000,00	100%	

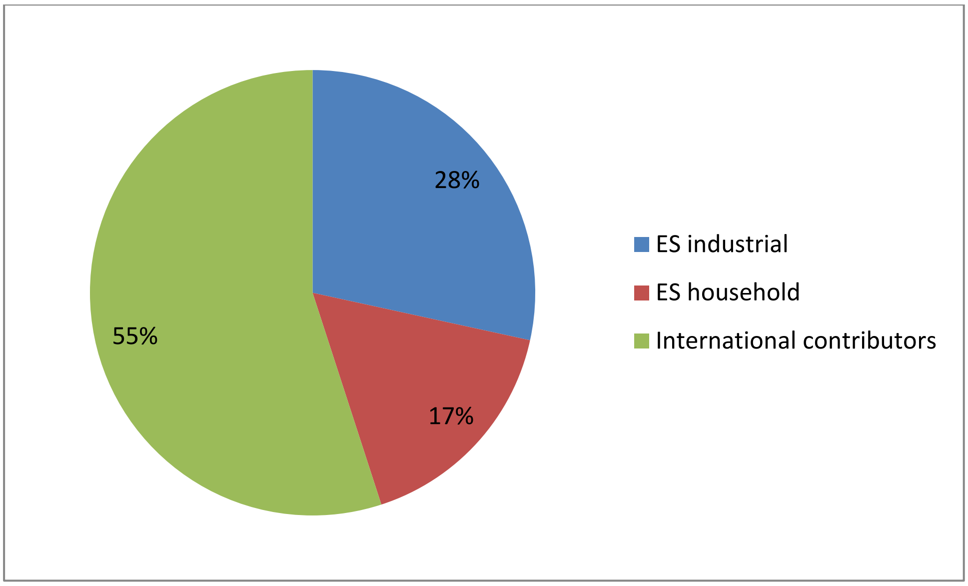

Figure 10 Contributors to Spanish Consumption-based emissions

As seen in figure 10, the main contribution to Spanish consumption-based emissions is made by the country itself through national industrial and household activities. They add up to almost 45%. Almost 1/3 of the emissions are generated through the consumption of industrial products and services that were produced in Spain.

55% of emissions are contributed by international imports which is higher than for Germany. Here the contribution of European countries, ROW, and WL regions mentioned in Table 16. This means that the production of a large number of goods and services that are consumed in Spain takes place abroad. A lot of production sites are located in ROW, which can be explained by cheaper production costs and less strict environmental policies in comparison to Spain.

4.2.3. Conclusion

At this point it can already be concluded that for both countries, for the main GHGs, the emissions are higher in the consumption-based account than in the territorial-based account. This also means that it is expected that the emissions in the case study cities Barcelona and Hamburg are also higher than suggested in the cities' climate change mitigation strategies, which may result in the need to make changes in the current mitigation actions.

Amongst the top 10 industrial activities contributing to consumption-based emissions in Spain and Germany are electricity production by coal, gas and petroleum, steam and hot water supply, manufacture of basic iron and steel air transport, cattle farming, raw milk production.

Germany's and Spain's consumption-based emissions are generated to a large part through products produced outside of these countries. This can be explained through the fact that the production in ROW regions is cheaper and under less strict environmental regulations.

When looking at IO table and the contribution analysis, it can be seen that the largest amounts of import to Spain and Germany that contribute the most to final consumption come from ROW regions. The key imports with the highest impacts are coal, petroleum, iron and steel, steam and hot water.

This shows that the industrial products that are consumed the most in both countries are produced under the cheapest conditions possible and are transported the furthest. Trade activities are not taken account for in the territorial-based account but in consumption-based accounts meaning that large amounts of emissions are left out of the account.

4.3. Modelling City-level GHG emissions

4.3.1. City-level emissions scaled by population

The consumption-based per capita emissions from Spain and Germany calculated previously were scaled down to the population of Barcelona and Hamburg respectively (Table 17). Barcelona has a population of around 1.6 million people (2014) and Hamburg has a population of around 1.7 million (2013).

Table 17 City level GHG emissions

	Unit	Consumption-based	Territorial-based
Barcelona total	t CO_2-eq	14,000,000	10,000,000
Barcelona per capita	t CO_2-eq	8.9	6.3
Hamburg total	t CO_2-eq	23,000,000	20,000,000
Hamburg per capita	t CO_2-eq	12.9	11.7

Since the consumption and territorial-based emissions per capita are higher for Germany it is logical that emissions for Hamburg are higher than for Barcelona, although the population is similar for both cities. This estimate is quite general and only gives a rough indication for the city emissions since specific factors that may influence the emissions in Barcelona or Hamburg are not considered. This may include differences in industrial activities, air and sea transport and agricultural activities in comparison to the country average.

4.3.2. City-level emissions scaled per income

The GHG emissions can also be scaled according to the GDP of the country. According to the World Bank, Germany's GDP is around \$3.9 trillion (2014) while Spain's GDP is around \$1.4 trillion (2014) (World Bank 2016a). The emissions per income are calculated by dividing the total emissions by the GDP of each country.

Table 18 Emissions per income for Germany and Spain

	Unit	Germany	Spain
GDP	Trillion US\$	3.9	1.4
Population	People	81,000,000	47,000,000
GDP per capita	US\$ per person	49,000	30,000
National Emissions per capita income (Consumption)	kg CO_2-eq	0.27	0.30
National Emissions per capita income (Territorial)	kg CO_2-eq	0.25	0.21

These results can be scaled to the city level of Barcelona and Hamburg by multiplying the emissions per capita income with the GDP of the respective city. In 2015, Barcelona had a GDP of 64.2 billion Euros (73 billion US\$) while Hamburg had a GDP of 109.3 billion Euros (124 billion US\$) (Statista 2016; La Vanguardia 2015). The GDP data for the cities was converted into US\$ for comparability with national data.

The consumption and territorial-based emissions per capita income is calculated by applying Equation 6:

$$\boldsymbol{country(\ t\ CO_2eq\ per\ capita)} \times \frac{\boldsymbol{GDPcapita\ city}}{\boldsymbol{GDPcapita\ country}} \qquad \textbf{Equation 6}$$

Table 19 City Emissions per Income for Barcelona and Hamburg

	Unit	Hamburg	Barcelona
GDP	US\$	124,000,000,000	73,000,000,000
Population	People	1,800,000	1,600,000
GDP per capita (city)	US\$ per person	71,000	46,000

	Unit	Hamburg	Barcelona
Consumption	t CO_2-eq/capita	19.0	13.6
Territorial	t CO_2-eq/capita	17.3	9.6
Consumption (total)	t CO_2-eq	32,000,000	22,000,000
Territorial (total)	t CO_2-eq	29,000,000	15,000,000

Table 19 shows that the per capita GDP for both countries is a lot higher than the national average meaning that higher incomes and more economic activity are taking place in the cities. However, Hamburg's total and per capita GDP is a lot higher than Barcelona's. Although both cities a regarded in their respective country as wealthy and as centres of economic activity the differences between total and consumption-based emissions are quite significant.

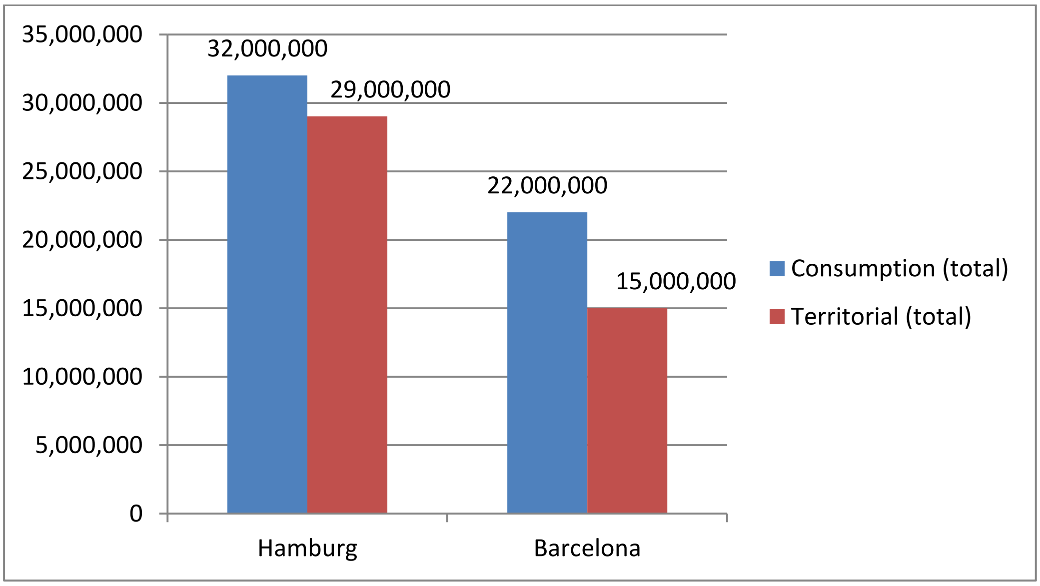

Figure 11 Total GHG emissions for cities

Figure 11 shows a comparison of the total consumption and territorial-based emissions of Hamburg and Barcelona.

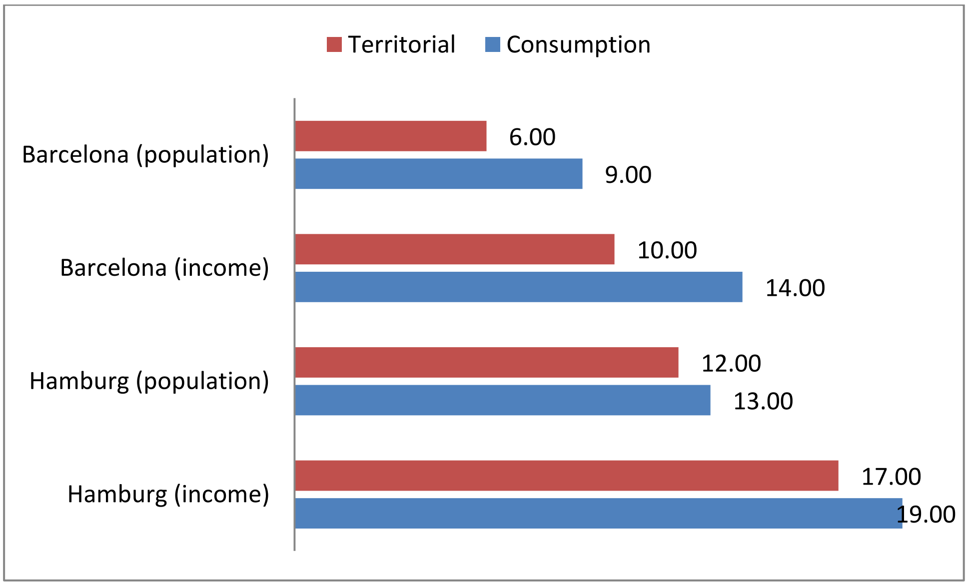

Figure 12 t CO_2-eq per capita

Figure 12 allows the comparison between the per capita emissions for Hamburg and Barcelona scaled according to population and according to income. Due to higher incomes in cities in comparison to the national average it was expected that per capita emissions are generally higher when scaled according to GDP.

The GDP of the city of Hamburg is considerably higher than the one of Barcelona although the population of the cities is similar. This difference is also noticeable in the GDP per capita which is around 71,000 US$ for Hamburg and only 46,000 US$ for Barcelona. This leads to the fact that territorial- and consumption-based per capita emissions for Barcelona are a lot smaller than the ones for Hamburg although the population size is similar.

4.3.3. City-level emissions detailed estimations

The estimations undertaken in sections 4.3.1 and 4.3.2 are quite general for the city-level. They do not take into account specific characteristics of Barcelona and Hamburg. In order to be able to make estimations for each city it is necessary to collect a large amount of quantitative data to clearly define the cities consumption and production patterns.

Figure 13 shows the sources and boundaries for GHG emissions on a city level that is used by the Greenhouse Gas Protocol. Scope 1 includes all activities that take place within the geographic boundary of a city. Scope 3 contains emissions that are linked to activities within the city but take place outside the city boundary. Scope 2 supplies energy from the grid to the activities in Scope 1 and 3. This schematic can be applied for the establishment of consumption and territorial-based inventories. For the consumption-based account all final industrial and household consumption is taken into account that takes within the scopes while the territorial-based account just considers production activities.

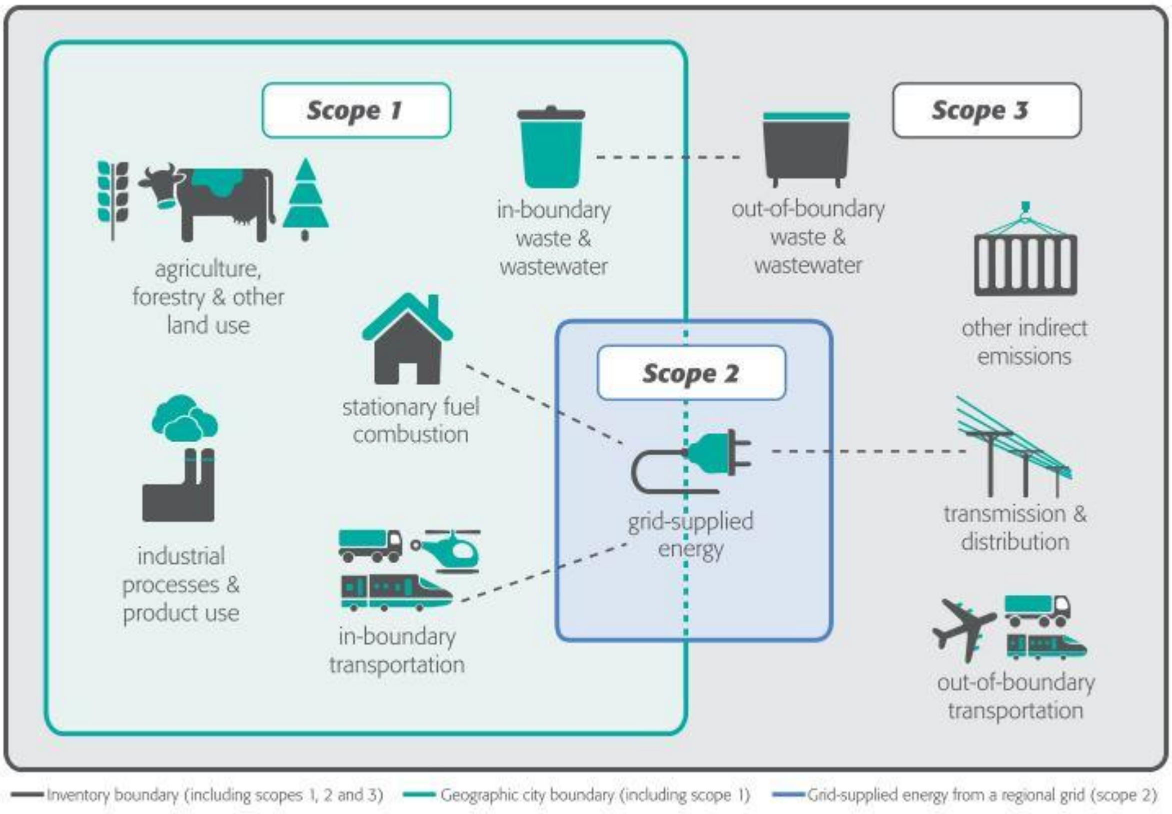

Figure 13 Sources and boundaries of emissions in cities (World Resource Institute 2014)

The data that has to be collected within these scopes includes but is not limited to the following list sorted according to priority:

Household activities

- Total inhabitants in the city and Inhabitants per household
- Transport (private vehicle and public transport),
- Estimates of the mix of renewables, coal, gas, nuclear in the energy grid of the municipality
- Energy used for heating and cooling
- Electricity used for appliances
- Waste disposal practices (recycling, incineration, landfill)

Industrial activities

- Agriculture (animal farming, fish cultivation, crop cultivation etc.)
- Manufacturing (metals, machinery, plastics, chemicals etc.)
- Mining (coal, gas, oil etc.)
- Transport (air, water, rail, road)
- Waste treatment (recycling, incineration, landfill etc.)
- Business (Communication, financial, insurance activities etc.)

4.4. Comparison with reported national GHG inventories

The United Nations have published data about the GHG emissions of both countries (UNFCCC 2013).

Table 20 National GHG emissions (without LULUCF)[9]

	GHG emissions without LULUCF (million tons CO_2-eq)	
	Spain	**Germany**
1990	284	1,248
2000	380	1,040
2012	341	939

Table 21 Calculated emissions

	Calculated GHG emissions (million tons CO_2-eq)	
2011	**Spain**	**Germany**
Territorial	291	946
Consumption	415	1,043

Table 20 shows that Spanish emissions have been increasing since the base year 1990. From 1990 to 2000 there was an increase of around 30% and until 2012 a slight decrease of 10%; which makes the total increase since the base year around 20%. On the other hand, Germany's GHG emissions have been decreasing around 20% since the base year from 1.25 billion to 940 million t CO_2-eq in 2012.

Table 21 shows the emissions calculated for 2011 in section National-level GHG emissions accounts. The closest year to compare the calculated data with the published data from the UN is 2012. The territorial-based account is slightly lower for the self-calculated estimated for Spain but slightly higher for Germany. The consumption-based emissions are in both cases clearly higher than the provided UN data. The differences in the territorial-based accounts can be explained by the fact that an IO table with limited data was used. Additionally, only the major GHG emissions CH_4, CO_2 and N_2O were considered in the calculations.

4.5. National climate change mitigation strategies

4.5.1. Introduction

National climate change action forms the guidance for the development of local strategies. Therefore, the strategies and Spain and Germany are summarised to give an overview of the framework that the strategies of Barcelona and Hamburg have to follow.

4.5.2. Spanish Climate Change and Clean Energy Strategy

The Spanish Government has recognised the increase in GHG emissions since 1990 and realised that the action to battle climate change is urgent. The strategy entered into force in 2007 and will run until 2020. Since Spain is a EU member, its climate policy principally aims to implement EU laws into the national legislation. Spain has the responsibility to reduce GHG emissions by 10% by 2020 (Grantham Research Institute on climate change and the

[9] The data provided by the United Nations for national GHG inventories exclude emissions and removals from Land use, land-use change and forestry (LULUCF) activities.

environment 2016). Certain focus areas for further climate change action were set and for each area, the objectives, measures and indicators were established. In the following paragraphs some of the focus areas for mitigation and some examples for specific action are presented:

Carbon Sinks

- Increase of wood stocks in order to increase the CO_2 sequestration capacity
- Adopt forestation and reforestation actions to increase forest surface
- Avoid forest fires by focussing on maintenance and improvement of fire extinguishing efficiency

CO_2 Capture and Geological Storage (CCS) [10]

- Determine the potential of the application of this technology in Spain including its cost and economic potential
- Quantification the amount of CO_2 available for capture and storage
- Investment in Research, development and innovation

Transport sector

- Develop a parking management and fares for cities, to encourage the reduce the use of private vehicles
- Introduce clean-air vehicles in public transport fleets in urban areas
- Expansion of the rail network

Residential, commercial and institutional sector

- Integrate measures in buildings to improve energy efficiency
- Promote the use of renewable energies in public and private buildings, such as solar panels
- Implement inspection systems of energy saving measures applied in the tertiary sector

Farming sector

- Improvement of energy efficiency in irrigation systems
- Annual inventory of GHG and the balance of Nitrogen in Spanish Agriculture
- Creation of a Cattle Registry with annual parameters that affect GHG emissions including, amount of cattle, cattle species, manure production etc.

Waste sector

- Increase awareness campaigns to decrease waste at domestic, commercial and institutional level
- Implement the Integrated Waste National Plan dealing with issues like, increasing recycling rates, promoting eco-packaging, closing and sealing uncontrolled landfills

(Ministerio de Medio Ambiente 2007)

[10] CCS is a three-step process including: 1.) Capturing CO_2 emitted by power plants and other industrial activities; 2.) Compressing the captured CO_2 and transporting it in pipelines 3.) Injecting and storing the CO_2 in the underground under rock formation located deep beneath the surface (EPA 2016).

4.5.3. The German Government's Climate Action Programme 2020

Since the baseline year, Germany has managed to significantly reduce its territorial-based GHG emissions. However, this preliminary success is only the beginning and it is determined to reach its goal to reduce CO_2 emissions by 40% from the 1990 levels until 2020. The government aims to cut greenhouse gas emissions by 40% by 2020 and up to 95% in 2050. By 2050, the share of renewables in final energy consumption is targeted to rise to 60 % (from 12.6% in 2015). Additionally, the goal is to achieve that renewables make up a minimum of 80% of Germany's gross power consumption by the middle of the century (Umwelt Bundesamt 2016).

In order to be able to achieve these ambitious targets certain sectors are specified in the strategy, that are the main focus for climate action. Over all the need for European and International cooperation is recognised.

Electricity sector

- Expansion of sourcing energy from renewables
- Development of combined heat and power networks (CHP)
- Increase use of low-energy light-emitting diodes (LEDs) for street lighting and interior lighting

Building and housing industry

- Tax incentives for energy-efficient refurbishment
- Development of new and stricter technical building standards
- Implementation of sustainability assessment systems at national, Land and municipal level

Transport sector

- Increase electrification of vehicle used in passenger and freight transport
- Expansion of rail freight transport and use of inland waterways
- Increase cycle transport by expanding cycling paths and improving traffic safety

Waste management

- Aerating landfills to achieve methane emissions reduction
- More stringent separate collection obligations, a requirement to pre-treat municipal waste and standards for sorting facilities
- Promote the reuse of electrical and electronic appliances

Agriculture

- Increased capacity for farm manure used for fertilization
- Prohibit use of fertilizer during certain periods (autumn and winter)
- Increase the percentage of land that is organically farmed

(Bundesministerium für Umwelt 2014)

4.6. City-level climate change mitigation strategies

4.6.1. Background information for case study cities

Table 22 Background information on cities

	Barcelona	Hamburg
Population (million)	1.6	1.7
Area (km^2)	101	755
Density (people per km^2)	15,685	2,300
Climate Zone	Mediterranean	Humid Moderate; No Dry Season
Annual Rainfall (mm/Year)	580	792
Heating Degree Days[11] (°C day)	1,201	Approx. 3,000
Cooling Degree Days[12] (°C day)	379	Approx. 50
Airport?	Yes	Yes
Harbour?	Yes	Yes

Although the cities have a quite similar population and both cities are served by an airport and a harbour, Hamburg and Barcelona differ quite significantly in other characteristics. While the population is similar, Hamburg is around 7 times larger in terms of area and therefore Barcelona's population density is around 7 times higher. This has an effect on the need for transportation needs since distances between residential, business and recreational areas may be smaller requiring less commuting. The cities are located in different climate zones meaning that different needs for heating and cooling can be expected.

4.6.2. Barcelona – A city committed to combating climate change (2013)

City-wide reduction action and targets

In the strategy it is claimed that Barcelona has one of the lowest GHG emissions per capita in the western world. According to the report, CO_2 emissions per capita have been reduced from 3.19 tons of CO_2 in 1999 to 2.28 tons of CO_2 in 2012. (Ajuntament de Barcelona 2013) In comparison to the calculations made in section 4.3. these per capita emissions are very low. The territorial- based emissions scaled according to population are around 6 t CO_2-eq while the results for the estimations according to GDP are around 10 t CO_2-eq.

The slogan/motto that is used to promote Barcelona's ambitious energy and climate change mitigation vision for the future is 'becoming a self-sufficient city with zero emissions'. It is suggested that the energy model of the city has to be changed, in order to reach full

[11] Heating degree days: Measure of how much (in degrees), and for how long (in days), the outside air temperature was below a certain level. This measure is used in calculations related to the energy consumption required to heat buildings.
[12] Cooling degree days: Measure of how much (in degrees), and for how long (in days), the outside air temperature was *above* a certain level. This measure is used in calculations related to the energy consumption required to *cool* buildings. (Bromley 2009)

sustainability. The intermediate target set in the Energy Self Sufficiency Plan of Barcelona is to achieve 10% energy self-sufficiency by 2024.

Therefore the following measures have been introduced or will be introduced in the future in order to reduce city-wide GHG emissions:

Domestic and tertiary sectors

- Promotion of retrofitting buildings and making their installations more energy efficient
- Provision of residual or renewable energy to existing buildings
- Encourage energy-saving and efficiency measures by involving private households, industries and businesses

Transport sector

- Electric and hybrid buses are already implemented in the city's bus fleet and this amount will be increased
- Electric vehicles should be used for commercial purposes like taxis, vans and vehicles and motorbikes
- Redesigning the supply chain to make goods distribution more efficient
- Provision of bike rentals throughout the city to promote more sustainable transport methods

Public spaces and infrastructure

- Integrate solar thermal energy supplies in the existing district heating and cooling (DH&C) networks
- Provision and extension of energy storage systems for heat and electricity
- Encourage the sourcing of energy from renewables

Municipal level

- Developing and implementing Energy Self-sufficiency plans for Municipal buildings
- Installation of smart street-lighting throughout the city which is brighter, more efficient and uses new technologies

Current status of emission reductions in Barcelona

The location and layout of Barcelona gives the city some advantages in the fight against climate change. The mild climate reduces the need for heating and the building and population density allows making better use of energy used for heating.

However, the city is affected by the heat island effect. This means the temperatures in the city are rising because heat is retained in pavement and buildings. Therefore the need for heating for households and offices in winter is decreased; however, cooling becomes more necessary in summer.

Barcelona is one of the most important Mediterranean harbor cities making it a center for economic activity. This activity has an effect not only on the city itself but on the entire region of Catalonia and leads to the increased emission of GHGs.

The strategy reports that in 2013 there has been any law passed that supports the use of renewable energies through tax reductions or incentives. Therefore, the strategy pushes for the introduction of such measures to further increase the use of renewable energies.

4.6.3. Hamburg – The Hamburg Climate Action Plan (2011)

City-wide reduction action and targets

The city has estimated its emissions and set ambitious reduction targets that are in line with the national framework.

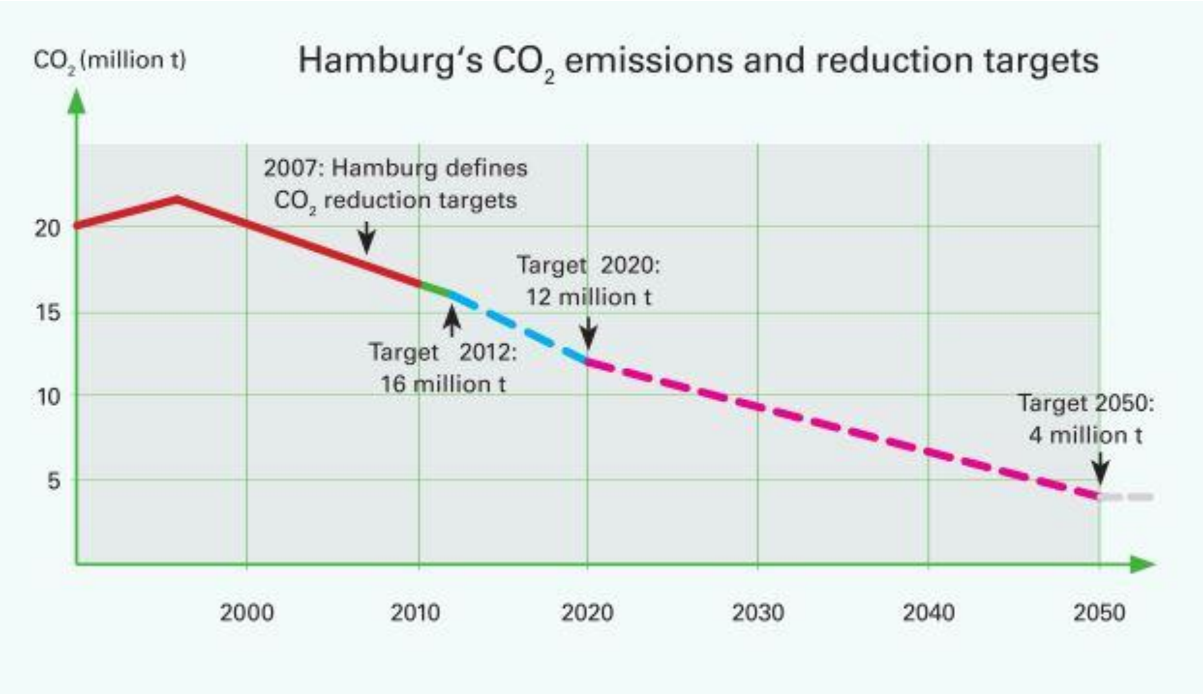

Figure 14 Hamburg's CO_2 emissions and reduction targets (Ministry for Urban Development and Environment 2011)

Figure 14 visualizes the estimated development of Hamburg's CO_2 emission reduction until 2050. The emissions reduction from 20 to 4 million tons is equivalent to an 80% reduction, which is very ambitious aim to realise until 2050. This means that the accurate estimation of emissions is essential to be able to achieve significant reductions. The reported emissions are only slightly lower compared to the calculations made in section 4.3.1 and 4.3.2 for the territorial-base account. For 2011 around 20 million t CO_{2}-eq were estimated.

The climate change mitigation strategy defines the following main action areas and products to reduce GHG emissions on the city-level.

Clean Energy

- Introduction and expansion of geothermal heating
- Expansion of the solar energy initiative
- Increase energy supply from wind power

Energy-efficient buildings

- Modernisation of rental housing
- Energy efficient public buildings
- Programmes that provide funding for energy efficiency and retro fitting measures
- Stricter building standards on the community scale, e.g. development of an ecolabel for the HafenCity (modern urban development project with residential and office spaces in the city centre adjacent to the river)

Sustainable mobility

- Expansion of public transport network
- Promoting e-vehicles, car-sharing and bike sharing systems to reduce emissions from private vehicles (CDP 2015)
- CO_2 emissions of public transport are reduced through the introduction of E-busses, H2-busses and the use of eco-power for the light rail system.

Industry and climate action

- Environment Partnership between the government and Hamburg businesses
- Self-commitment by industrial companies

(Ministry for Urban Development and Environment 2011)

Current status of emission reductions in Hamburg

According to the CDP survey filled out for the city in 2015, Hamburg has some positive prerequisites to reduce its emissions successfully and become more sustainable. It is stated that the city is an important location for business headquarters and installations for the renewable energy sector, especially for wind energy. The integrated public transport network allows 98% of the population to live in a 300 m radius of a public transport station. Additionally, 40% of Hamburg is covered in green spaces that form an almost continuous “green network”.

On the other hand, Hamburg has the third largest aviation industry in the world with the airplane manufacturer Airbus located in the city. The city also has an important role in sea and river trade and transport, since it is located on the river Elbe, which houses one of Europe’s busiest container ports. Europe’s largest fruit growing area is located adjacent to the river and next to its largest industrial area. Europe’s largest copper plant is situated there, as well as refineries, metal and petrochemical factories (CDP 2015).

This shows that Hamburg, on one hand, moves in the direction of a sustainable future, but on the other hand, has to deal with the GHG emissions of its industrial areas.

4.7. Analysis and discussion of the mitigation strategies

The actions proposed in the climate change mitigation strategies of Hamburg and Barcelona are similar. A major focus is set on greener energy production, greener buildings and greener public and private transport.

4.7.1. Barcelona

Barcelona reports in its strategy that the city was able to reduce its CO_2 emissions from 3.19 tons of CO_2 per capita in 1999 to 2.28 tonnes of CO_2 per capita in 2012. These numbers are based on the territorial-based emissions account. However, the territorial-based account calculated for Barcelona in this work according to the GDP per capita, is significantly higher, of around 9 t CO_2-eq per capita. On the national level, the territorial-based emissions per capita that were calculated as well as the ones reported by the World Bank are estimated around 6 t CO_2-eq. The emissions scaled according to income are around 10 t CO_2 per capita which is higher than the national average due to higher incomes in cities. Therefore it should be expected that the emission estimates for the city-level are higher, however it is not the case for the value reported by Barcelona. A possible explanation for this is the exclusion of certain emissions emitted by industries from territorial-city inventories.

The high deviation from the results presented in the mitigation strategy seems suspicious and the reported results seem very low. Since the calculated results are generally similar or only slightly higher than the results reported on city and national level, it can be assumed that Barcelona`s climate change mitigation strategy does not represent accurate data. The government claims that Barcelona has one of the lowest GHG emissions per capita in the western world. However, only the reductions of CO_2 emissions are mentioned and the initial emissions from 1999 seem already low. It can be assumed that this is not done deliberately but results due to exclusion of important emissions and general lack of information about the accounting method.

4.7.2. Hamburg

The territorial-based emissions calculated for Hamburg are similar to the ones mentioned in the mitigation strategy. However, only the total CO_2 emissions are mentioned, which were estimated to be around 16 million tons CO_2 in 2012. The calculated territorial-based GHG emissions for Hamburg, based on 2011 data, are estimated to be around 20 million tons CO_2-eq. Since around 80% of the emitted GHGs are CO_2 emissions, the calculated amounts are only slightly higher the reported numbers. The calculated per capita emissions were around 12 t CO_2-eq scaled according to population and 17 t CO_2-eq scaled according to income. The reported per capita emissions for 2012 are around 9 t CO_2. If N_2O and CH_4 emissions were added the results would still be lower than in the calculations. It can be assumed that different system boundaries and certain emissions were not considered causing slight deviations

Deviations in calculations

Deviations in the emissions calculated for the territorial- and consumption-based account can be expected due to a number of reasons:

- City-emissions were scaled from national-emissions according to population and GDP
- Estimations were only made for 2011, since the used IO data is from 2011
- System boundaries may be set differently
- Cut-off, meaning that industrial and agricultural activities that are taking place on the boundary of the cities are not accounted for
- Different accounting principles

Differences between the calculated territorial-based emissions and the ones reported by the cities occur due to the fact that the no specific characteristics of Barcelona and Hamburg were considered but it was based on the national levels. It can be noted that it is not likely that the per capita emissions for a city are the same as for the national average. Reasons for that is for example a different electricity mix in the energy supply grid, airport and port activities and more use of public transport than in remote areas.

However, it is clear that the consumption-based account for both cities is higher even if there is a small deviation due to calculations, i.e. the climate change mitigation strategies do not take into account the full emissions that the city's consumption is responsible for.

4.7.3. Mitigation actions not considered in the strategies

Another issue is that Barcelona's strategy only mentions CO_2 emissions and the reduction achievements related to that. Hamburg mentions the general issue of GHG emissions, however, talking about the success in reduction, only CO_2 emissions are mentioned, which is confusing for the reader. Especially CH_4 emissions are highly underestimated in the territorial-based accounts. CH_4 is mainly emitted by agricultural activities like animal farming and N_2O are connected to the burning of fossil fuels, The information provided within the mitigation strategies therefore seems more sustainable than it actually is depicting successful achievements by the cities, leaving important emissions out of the current territorial emissions. However, it can be assumed that this is not done on purpose but is related to the system boundaries excluding certain emissions and the unawareness of the flaws of territorial-based accounting.

Both cities set a major focus on the increase of using public transport including buses, metros and bike sharing. For the cities itself, this can decrease congestion and improve the air quality. Looking at the contribution analysis on the country level, air transport is one of the key contributors to consumption-based emissions. Since incomes in cities are higher, it can be assumed that the population is likely to take more flights for private but also for business purposes. For international connections, this can many times not be prevented; however, incentives to increase national and EU wide public transport could be effective.

There are some areas, like agricultural activities and food production that are not considered in the strategies. Industrial activities mainly take place outside the city parameter therefore governments may not set their focus on these activities for the climate change mitigation in cities. However, if a consumption-based account provided the basis for the mitigation action these activities have to be taken into account. Especially, because it can be expected that consumption in cities is higher due to higher incomes and greater and easier availability of products. Therefore the impact of the agriculture and the food sector is very important and not considering it in city mitigation fails reduce emissions efficiently.

4.8. Development of a city-level mitigation strategy

4.8.1. Introduction

In the previous sections the mitigation strategies of Barcelona and Hamburg were discussed, containing their current and future plan of action to reduce GHG emissions in the city. It was identified that the strategies do not even take full consideration of the territorial-based emissions and therefore, if the method was switched to consumption-based accounting, changes would have to be made to the strategy so that emissions can be reduced effectively.

For that purpose, a city-wide action was developed to be applied to Hamburg and Barcelona to complement the current strategies, with the aim to reduce consumption-based emissions. A number of different mitigation options were considered, however, due to time and data limitations, in this study it was decided to present the emission reduction results of the most significant option, which is to ban electricity production from coal. The following sections describe how the proposed action is implemented and how are its effects on GHG emissions.

4.8.2. Ban electricity produced from coal

The energy sector is the highest GHG contributing sector for Spain and Germany. The industrial activity contributing the most to consumption is the production of electricity by coal. Looking at the mitigation strategies of Barcelona and Hamburg, both cities are providing incentives to promote electricity generation from renewable energies. There is a general awareness that it is essential for the reduction of GHG emissions to move towards renewable energies and away from coal, gas and fossil fuels. However, the current action is not radical enough to achieve results.

A radical solution to decrease consumption-based accounting would be to ban coal as a source for electricity production. In addition to that, it is necessary to subsidize renewable energy in households, commercial and industrial activities, in order to prevent that switches are made to other resources like fossil fuels.

Action

For Germany, the electricity produced from coal contributes to total emissions by 18% and for Spain by 12%. In the suggested scenario, all electricity produced from coal is replaced by wind energy. In this scenario, territorial-emissions will not change because a simplified approach is used and the amount of emissions stays the same, just the source of the emissions is switched from coal to wind.

It may not be realistic to assume that the full impact from coal can be eliminated immediately. At least in the short run, it can be expected that fossil fuels will be used as a substitute. However, the long-term goal should be to fully replace these, depleting resources with renewable options. Although in the scenario the full replacement of electricity from coal by wind energy is considered, it is possible to introduce different scenarios considering solar and geothermal energy as replacements.

Consequences

Positive

- Reduction of consumption-based emissions
- Reduction of territorial-based emissions (due to the model used these emissions were kept stable in this case)
- Increase of renewables for electricity production e.g. solar, wind, biomass, heat from the ground
- More jobs in the renewable energy sector
- Improvement of air quality

Negative

- Duration of implementation since switch cannot take place from one day to another
- Closure of coal power plants would mean loss of workplaces

Effects on consumption-based emissions

Spain

Table 23 Change in emissions (ES)

GHG	Unit	Consumption (Reduced)	Consumption (Initial)	Territorial
CO_2	t CO_2-eq	320,000,000	330,000,000	251,000,000
N_2O	t CO_2-eq	17,000,000	17,000,000	17,000,000
CH_4	t CO_2-eq	67,000,000	68,000,000	24,000,000
Total	t CO_2-eq	404,000,000	415,000,000	291,000,000
Per capita	t CO_2-eq	8.70	8.93	6.27

Table 23 provides a summary for the impacts of the mitigation action on Spanish emissions. The total reduction for Spain is around 10 million tons CO_2-eq per capita, which results in a reduction of around 0.2 t CO_2-eq, which is quite small as it only represents 2.6%.

Looking at the city level of Barcelona, total emissions are reduced to around 13.9 million tons CO_2-eq, which is also a very small reduction. The initial per capita level of 13.7 t CO_2-eq is reduced to around 13.3 t CO_2-eq. This results in a reduction of the total level from 21.9 million t CO_2-eq to 21.3 t CO_2-eq.

Germany

Table 24 Change in emissions (DE)

GHG	Unit	Consumption (initial)	Consumption (reduced)	Territorial
CO_2	t CO_2-eq	840,000,000	785,000,000	860,000,000
N_2O	t CO_2-eq	41,000,000	40,000,000	35,000,000
CH_4	t CO_2-eq	162,000,000	160,000,000	51,000,000

GHG	Unit	Consumption (initial)	Consumption (reduced)	Territorial
Total	t CO_2-eq	1,043,000,000	985,000,000	945,000,000
Per capita	t CO_2-eq	12.9	12.2	11.7

Table 24 shows that most of the reductions are visible in the CO_2 emissions (around 55 million t CO_2-eq). This can be explained by the fact that in the process of burning coal, CO_2 is one of the main emissions, while N_2O and CH_4 have a lot smaller shares. The reduction that was achieved for German total emissions by replacing coal by wind energy was around 60 million tons. The per capita emissions were reduced from around 12.9 to 12.2 t CO_2-eq. The reductions are higher for Germany since the initial share of coal produced electricity is higher than for Spain. Therefore the opportunity for reduction is bigger.

Scaling these emissions to the level of Hamburg's population reaches around 21 million in comparison to the initially calculated 23 million t CO_2-eq. The reductions can also be scaled according to income, which results in around 17.6 t CO_2-eq per capita in comparison to the initial level of 18.7 t CO_2-eq of consumption-based emissions. This results in a reduction of total city emissions from 31.8 million tons t CO_2-eq to 29.9 million t CO_2-eq.

4.8.3. Summary

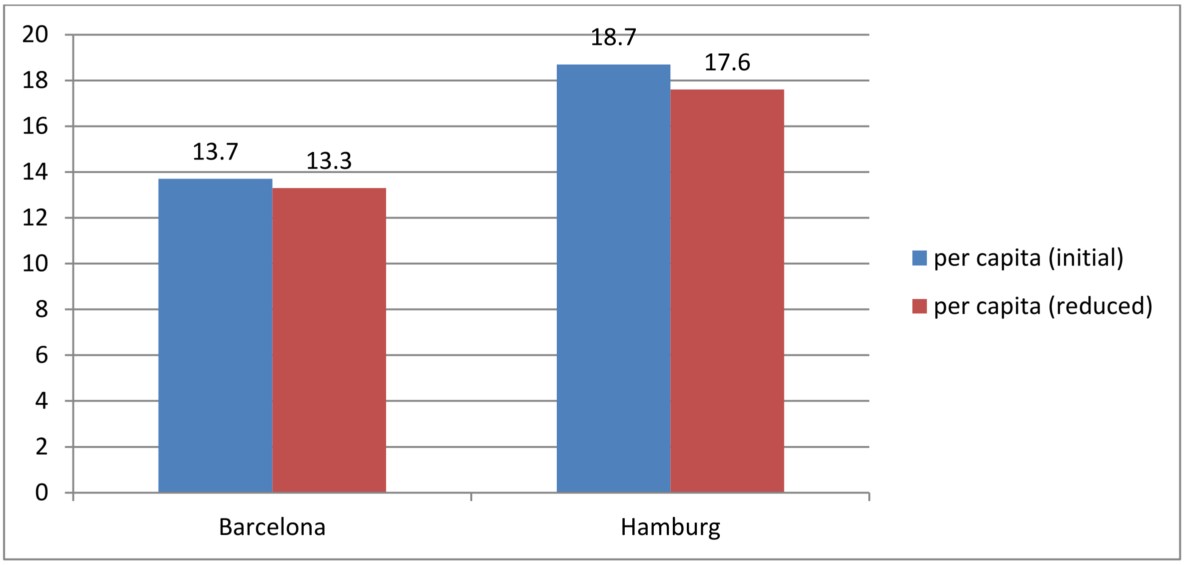

Figure 15 Comparison of reduction of city emissions

The reductions achieved on national and city level are relatively small which is partly related to the simplified estimation method. It is necessary to do further calculations to provide more specific estimations for the city level of Hamburg and Barcelona. Figure 15 shows the impacts of the coal ban are higher on Hamburg than on Barcelona due to the higher initial share of energy produced by coal. However, there are other environmental and social benefits related to this mitigation action. For future research, there are more opportunities to consider other mitigation actions and investigate their impact on territorial and consumption-based emissions.

5. Conclusions

At the start of this master thesis the following objectives were set:

1. Review problems in connection to fixed territorial boundaries and differences related to territorial and consumption-based approaches to GHG accounting
2. Quantitative establishment of a consumption-based account for selected case studies countries and cities on the basis of IO tables and comparison to the territorial-based account
3. Analyse the current mitigation strategies of the cities and their connection to GHG emission reduction
4. Develop a new mitigation action to exemplify the effects on the consumption- and territorial-based accounts

These objectives were achieved through the adoption of different methodologies and by following the guidance of answering the research questions. Three sub-questions were established and answered by the application of various methods with the aim to answer the main research question.

- **Main question:**

What effect does the shift from territorial to consumption-based accounting have on the modelled GHG emissions of a city and its climate mitigation strategies?

- **Sub-questions:**

1. *What problems connected to fixed territorial boundaries are related to the application of territorial-based accounting and what is the difference to the consumption-based approach?*

Through the literature review, the main features as well as advantages and disadvantages of consumption and territorial-based accounting were identified. In the literature, the majority of concerns were related to the territorial-based approach. One of the major issues discussed was that territorial-based accounting may encourage carbon leakage, meaning that production is moved to developing countries due to less strict environmental regulations and cheaper production. Additionally, emissions from international transportation and trade are not considered in the territorial-based account. This is an issue because large amounts of goods are produced in developing countries and are transported to developed countries. This can be blamed to the fact that trade cannot be allocated to a fixed geographic location. This problem also applies to inventories at city level. Neither the consumption-based method is flawless, but its advantages are outweighing the disadvantages. This can be explained by the fact that international trade and transportation is accounted for appropriately. However, territorial-based accounting is a widely used method and is well known while consumption-based accounting has not been extensively applied, yet. It is clear that a change in method is needed in order to reduce global, national and local emissions; however, the solution is rather a complementation of territorial-based accounting instead of its replacement.

2. *What are the differences between consumption and territorial-based emission accounts in Hamburg (Germany) and Barcelona (Spain) and what are the main contributors to the emission generation?*

In order to answer this question, calculations were undertaken to establish the national GHG inventories on the basis of IO data. Total and per capita emissions were estimated showing that consumption-based emissions are higher on the national and the city level. This can be explained due to the fact that territorial-based accounts do not consider emissions from international trade. However, Germany and Spain are developed countries that are importing a major part of the products consumed in the countries. Production in developing countries is cheaper and limited by fewer environmental regulations, so that carbon leakage is a common trait of territorial-based accounts. The contribution analysis established that the major parts of the consumption-based emissions are caused by the industrial and household activities of the countries themselves (Spain 45% and Germany 59%). The rest of the emissions are caused by imports from abroad, mainly ROW regions. The key industrial sectors contributing to consumption-based emissions are similar between Germany and Spain, including the sectors: energy, manufacturing, agriculture, mining and transport.

3. *Do the identified mitigation options, which are based on a territorial approach, still lead to net reductions when applying a consumption-based approach to GHG accounting?*

The fact that on the national and the city-scale level emissions on a consumption-based approach are higher becomes an issue in relation to the mitigations strategies. Current mitigation strategies are based on territorial- based emissions. This means that if a switch was made to a consumption-based account, which is much higher than the emissions currently considered, it is essential to make changes to the strategy in order to achieve more effective reductions.

The analysis of the mitigation strategies of Barcelona and Hamburg show that both cities set a focus on CO_2 emission reduction through more sustainable transport methods like cycling, electric public and private vehicles, through more energy efficient buildings that reduce the need for heating and cooling and through the supply of the energy grid mainly through renewables like solar, wind and geothermal heat. It becomes clear that none of the cities consider the importance of agricultural and other industrial activities because for territorial-based city accounts these activities are not taken into account. They may be located on the border of the city boundary or emissions may be seen as too big to add them to a single city. Consumption-based accounts take all industrial activities into account giving a more realistic image, since consumption in cities is often higher due to higher income. Therefore, it is necessary to especially consider agricultural activities and food production also for the city mitigation strategies. Therefore, the focus of mitigations strategies based on territorial-based accounts is different than if consumption-based accounts form the basis.

An own strategy with the aim to reduce consumption-based emissions was developed. For Germany and Spain, a ban on the electricity production by coal was introduced and entirely replaced by wind energy. This achieved a reduction of national per capita and total emissions for both countries. On the city level, the impact of the actions is slightly higher for Hamburg than for Barcelona.

The data presented in the climate change mitigation strategies of Barcelona and Hamburg does not fully represent the climate change impacts of the cities. The provided information seems to be represented in such a way that the cities can show off their emission reductions. Although this may not be done intentionally, city emissions often exclude certain industrial emissions since they are too high to include them for a single city.

Since the climate change mitigation strategies for cities are published by the municipality, it was planned to conduct interviews with experts to evaluate the awareness of the issue. Presenting the results to experts related to the development of strategies for Hamburg and Barcelona would make it possible to evaluate if there is a willingness to change. It was not possible during the course of this study due to time constraints and because the contacts in the municipality in Hamburg and Barcelona were not responsive to set up an interview in time.

The shift from territorial to consumption-based accounting shows a clearer image on the impact of the environmental impact of a country. It can be identified which industries and countries contribute the most to the GHG emissions. On a city level, consumption-based emissions are also generally higher than territorial-based emissions, since cities are commonly not the centres of production (in the western world). This means that the switch of accounting methods can lead to a change of focus for the city-level mitigations strategies. The reason for that is that industrial activities, which were not considered in the first may have a significant contribution to city-scale consumption-based emissions, especially because consumption in cities that are considered relatively wealthy like Barcelona and Hamburg can be expected to be higher than the country’s average.

6. Recommendations for future research

The IO table used to model consumption and territorial based GHG accounts for Spain and Germany was aggregated to around 18 countries and 2 ROW instead of 144 and 5 ROW regions. Although the data was aggregated the full global economy is covered in this table. This made the handling of the data and running the calculations easier and was considered sufficient for this study. However, this means that the contribution analysis to determine which countries mainly contribute to the GHG emissions provides general overview. In order to provide more detailed information on the worldwide contribution to the emissions the complete IO table should be used. With a more in-depth study it would also be possible to evaluate which countries are the main contributors for each industrial activity. This would give a more clear insight which mitigation strategies would be the most effective to reduce emissions.

Additionally, only the total final consumption of household emissions was represented in the IO table. Since in Spain and Germany around 20% of total emissions are generated through households it could be interesting to look at more detailed data on what activities are contributing to these emissions.

Another research part could be dedicated to establish more detailed estimations for the city levels. For this study the national-level estimations were scaled to the city level of Barcelona and Hamburg by the means of populations and GDP data. Considerations were made on which data would be necessary to estimate the emissions for the specific city and could form the foundations for further calculations.

The introduction of other mitigation actions to investigate the impact on consumption-based and territorial-based emissions may be another path for further research. First of all, it could be further investigated which effect the replacement of coal by a mix of wind, solar and geothermal energy would have. Additionally it could be interesting to look at mitigations connected to the agricultural and food sector since this is not considered in the city mitigation strategies A possible action is the reduction of meat consumption by 50%. The meat industry includes farming and feeding animals, processing meat, energy production for machinery etc. and therefore is a major contributor to consumption-based emissions. Additionally, it has large environmental impacts through resource consumption of water, energy and land.

Furthermore, conducting interviews with experts related to the publication of the climate change mitigation strategies in both cities would be very useful since it was not possible during this study. It has been found that the climate change mitigations strategies are underestimating territorial-based emissions. This means that the currently applied strategies cannot be effective in reducing emissions. However, the strategies claim low emissions are resulting through successful reductions, which may represent the city as ‘greener’ as it actually is, which may not be done intentionally. Since consumption-based emissions are even higher than territorial-based emissions the climate mitigation strategy needs to be adjusted in order to achieve effective results. It would be very interesting to confront experts with these results and find out if the municipalities are aware of these issues and if there is a willingness to change.

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