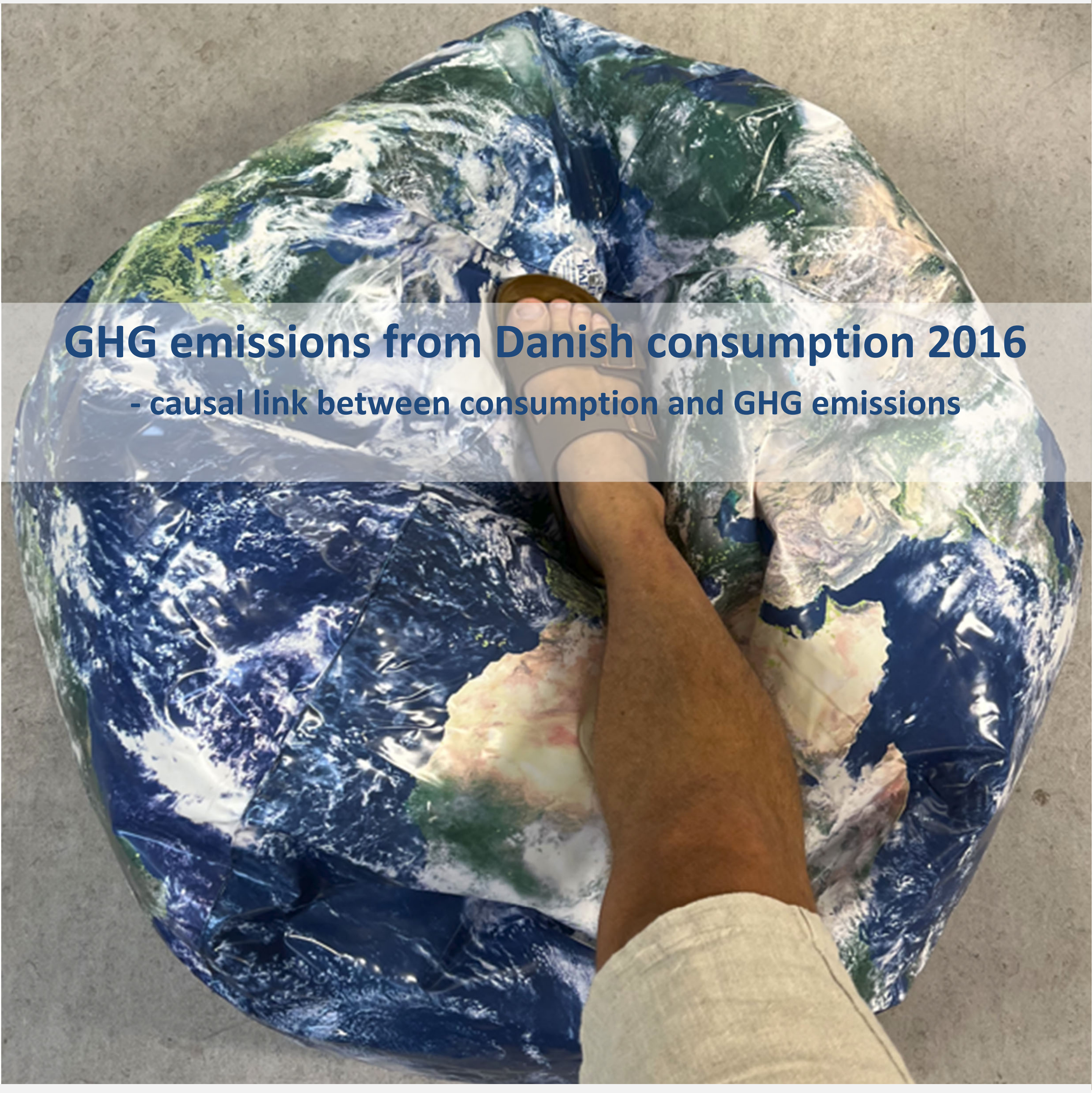
Technical report



GHG emissions from Danish consumption 2016

- causal link between consumption and GHG emissions

by Jannick Schmidt, Stefano Merciai, 2.-0 LCA consultants, Aalborg, 24th August 2023

Preface

This report documents a calculation of Danish consumption-based GHG emissions. The study is carried out by 2.-0 LCA consultants, it is commissioned by CONCITO, and it benefits from modelling and data acquired as part of the 'Getting the Data Right' project[1] (funded by the KR Foundation) and the EXIOBASE update club[2] (crowdfunded project lead by 2.-0 LCA consultants). The study has been carried out May 2022 – August 2023.

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When citing the current report, please use the following reference:

Schmidt J, Merciai (2023). Technical report: GHG emissions from Danish consumption 2016 - causal link between consumption and GHG emissions. CONCITO, Denmark.

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[1] Getting the Data Right is a large project lead by Aalborg University and funded by the KR Foundation: https://www.en.plan.aau.dk/research/the-danish-centre-for-environmental-assessment/getting-the-data-right

[2] EXIOBASE Update Club: https://lca-net.com/clubs/exiobase-update/

CONTENTS

Abbreviations and terms

Abbreviations

Country codes

CN	China
DE	Germany
DK	Denmark
IN	India
NO	Norway
SE	Sweden

Units

EUR	Euros
MJ	Megajoules

Other

ALCA	Attributional LCA
CHP	Combined heat and power
CLCA	Consequential LCA
dLUC	Direct land use changes
GFCF	Gross Fixed Capital Formation
GHG	Greenhouse gas
GWP	Global warming potential
iLUC	Indirect land use changes
IO	Input-output
N_2O	Nitrous oxide
NGO	Non-Governmental Organization
NPISH	Non-profit institutions serving households
NPP_0	Potential net primary production

Commonly used terms

Activity	Part of the technosphere. The doing or making something. Usually, an activity refers to productive activities that aim at selling the resulting products to other activities. In LCA literature, LCA activities are sometimes referred to as processes.
Attributional modelling	"System modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule." (Sonnemann & Vigon, 2011, p 132). In the current study attributional modelling is modelled by assuming that the products are produced using existing production capacity (current or historical market average), and multiple-output activities are dealt with by applying allocation factors based on economic value.
By-product	Non-determining product that directly (i.e. without further processing) is used in place of other products.
Consequential modelling	"System modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit." (Sonnemann & Vigon, 2011, p 133). Hence, in consequential modelling it is generally a change in demand of the product under study that is modelled. A cause-effect relationship between a change in demand and the related changes in supply is intended to be

	established. This implies that the product is produced by new capacity (if the market trend is increasing). It is additionally taken into account that the affected production capacity must be the actual affected, i.e. it is not constrained. Multiple-output activities are dealt with using substitution. The modelling principles are comprehensively described in Weidema et al., (2009) and Weidema (2003).
dLUC	Direct land-use change. dLUC are defined as those changes that occur on the same land as the land use (Schmidt et al., 2015).
Exchanges with the environment	Exchanges between the technosphere and the environment. Emissions, resource inputs, land use exchanges (occupation and transformation), and other such as radiation, noise, odour, vibrations, aesthetical effects on landscape etc.
GWP100	Global warming potential calculated using a time horizon of 100 years. This is defined in IPCC (2013, table 8.A.1).
iLUC	Indirect land-use changes. iLUC are defined as the upstream life cycle consequences of the land use, regardless of the purpose of the land use (Schmidt et al., 2015).
IO model	Life cycle model based on national supply-use tables.
Material for treatment	Output flow of a human activity that remains in the technosphere and cannot directly (i.e. without further processing in a treatment activity) displace a reference product
Product	Output flow from a human activity with a positive either market or non-market value. Further distinction of the products can be made in terms of determining products and by-products.
Reference product	Product for which the production volume changes in response to changes in demand. In consequential modelling reference product is equivalent to determining product.

1 Introduction

This report presents a very detailed calculation of the greenhouse gas (GHG) footprint of Danish consumption for 2016. The results and scenarios reflect best available estimates of changes in the GHG concentrations in the atmosphere caused by consumption and changes hereof.

Compared to the official reporting of Danish GHG emissions (see Figure 1.1), which represents emissions occurring from Danish territory, the results presented here refer to Danish consumption. Consumption-based emissions are the emissions caused by the production, use and disposal of all products consumed by Danish households and government, which is the same as emissions occurring from Danish territory plus emissions caused by import minus emissions caused by export.

Compared to other consumption-based footprints, the current study establishes a causal link between consumption and production (and associated emissions). Opposed to other consumption-based footprint studies, the current study can therefore be used to predict the effect on global GHG emissions caused by changes in production and consumption.

It should be noted that the purpose of the current technical report is to document the methods and data used for the calculation of the Danish consumption-based footprint – not to provide a detailed interpretation of the results. The latter is provided in a separate report authored by CONCITO.

1.1 Consumption-based footprints

National GHG emissions are an important indicator of the sustainability of a country's economy. The Danish Government publishes the national GHG emissions of Denmark every year (Danish Energy Agency 2023a). The emission inventories include all emissions occurring within Danish borders within the accounting year. In this way, the Danish Energy Agency (2023a) has reported that the Danish GHG emissions in 2021 are 46.2 million t CO_2-eq. These emission inventories are used to measure progress in terms of Denmark's GHG emission reduction commitments and targets (Danish Ministry of Climate, Energy and Utilities 2020). The development in Denmark's GHG emissions 1990-2021 is presented in Figure 1.1. These data show that Denmark has reduced its emissions by 39%.

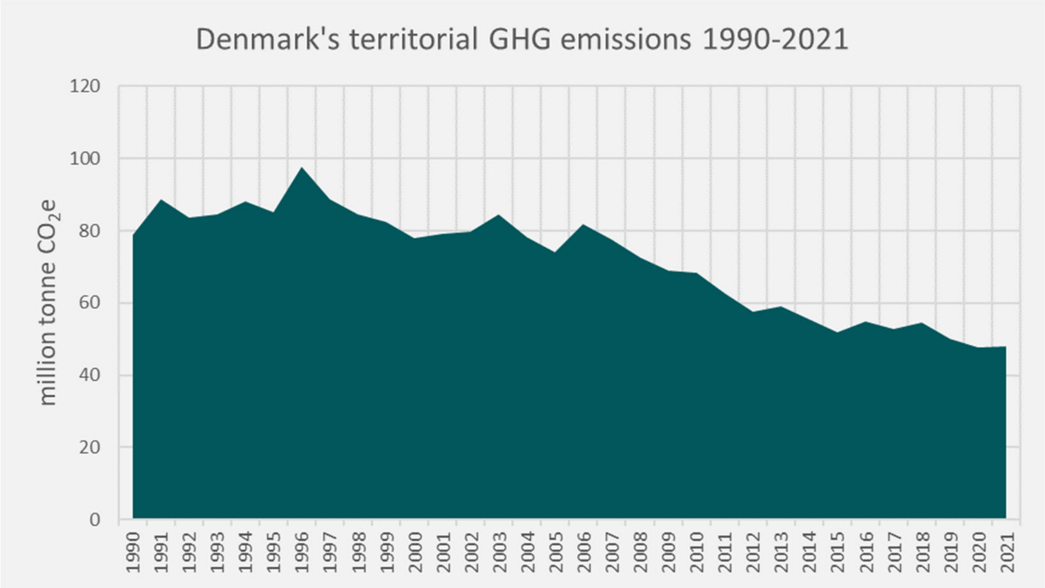

Figure 1.1: Denmark's official GHG emissions as reported under the United Nations Framework Convention on Climate Change (UNFCCC 2023).

One problem of measuring national GHG emissions as the direct emissions occurring in Danish territory within the accounting year is that reported reductions may not represent the actual changes in GHGconcentrations in the atmosphere. Why is that? This is because of so-called leakage effects. If emission intensive activities are reduced in Denmark, e.g. a reduction in the number of dairy cows, then the calculation does not take into account that the consumption of milk may not have reduced, and that the reduced production is compensated by increased import (or reduced export) and associated emissions outside Denmark.

The solution to the abovementioned problem related to the way countries measure their GHG emission performance is to calculate emissions caused by consumption instead of the country's territorial direct emissions. Hereby, all emissions related to the production of imported products are included, as well as Danish emissions related to exported products. Since 2021, the Danish Energy Agency has published the Danish GHG emissions related to total Danish consumption (Danish Energy Agency 2023b), see Figure 1.2. According to Figure 1.2, the reduction in Danish consumption-based GHG emissions from 1990 to 2021 is 21%. It appears that this reduction is only around half of the corresponding reduction in territorial emissions in the same period. This illustrates that around half of the reduction in Danish GHG emissions from 1990 to 2021 are achieved through "exporting" the emissions to other countries.

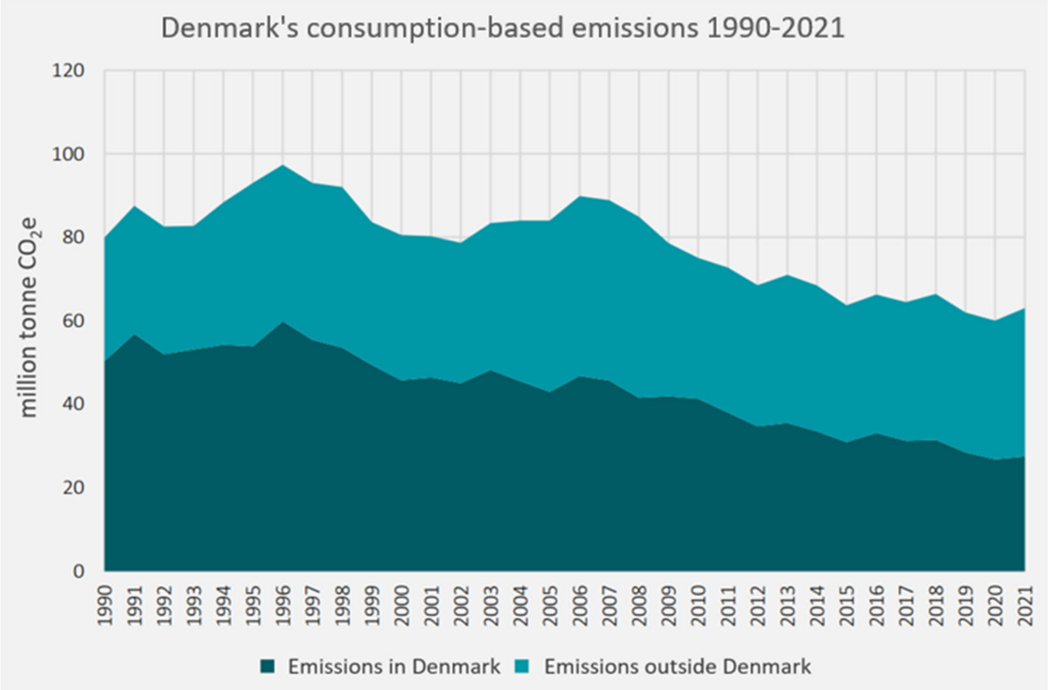

Figure 1.2: Denmark's consumption-based GHG emissions as reported by the Danish Energy Agency (Danish Energy Agency 2023b, p 17).

1.2 Common problems of consumption-based footprints

A problem related to most consumption-based footprints, including the footprint published by the Danish Energy Agency, is that the results do not represent a causal link between consumption and GHG emissions. This means that the calculated GHG emissions from a change in the consumption will be different from the emissions that will end up in the atmosphere. Why is that? This is because most consumption-based footprints are based on "as is" average supply-mixes of products and that by-products are modelled by artificially partitioning the industries that produce more than one product output. An example of an average supply mix is electricity. According to Danish Energy Agency (2023c), 12% of the electricity supply in 2021 come from Danish coal-fired electricity production. However, since coal is being phased out, while electricity supply at the same time is increasing (and expected to increase in the future), it is unlikely that changes in demand for electricity will cause more coal-based electricity. A related example of artificial partitioning of a process that produce more than one product output is the supply of heat from combined heat and power production. According to the Danish Energy Agency (2023c), more than 40% of the Danish electricity production come from combined heat and power (CHP) units. In the Danish consumption-based footprint provided the Danish Energy Agency (2023b), part of the emissions from these CHP units are allocated to the electricity supply (however it is not clear how). Also, the activities related to heat-supply do not include the substitutions of electricity when the heat is supplied from CHP. Summarizing, if the results and models of most footprints, such as Danish Energy Agency (2023b), are used to identify improvement options or to perform scenario analysis, the calculated emissions will be based on suppliers of energy, which will not react to changes in demand. Further, emissions related to some products, such as electricity, include emissions from other non-related activities (heat activities), and substitutions in the market are ignored.

Besides the abovementioned general lack of causality between demand and supply, consumption-based footprints are often incomplete and misallocate the emissions associated with investments:

- Exclude the impacts caused by land-use, i.e. land use changes.
- Exclude the temporal radiative forcing effects from the use of biomass.
- Exclude the contribution to global warming from aviation contrails.
- Allocates all emissions embodied in investments to national consumption, and thereby exclude embodied investments in import and export.

Furthermore, most consumption-based footprints are purely based on relatively aggregated monetary national accounts and trade data combined with national emission accounts. The disadvantage of using purely monetary accounts is that it is very difficult to check and validate the transactions within economy. For example, if Danish households use 1 billion DKK electricity or if Denmark imports 500 million DKK wheat, it is hard to cross check and to make sanity checks whether this represent the actual physical flows of products. Furthermore, the monetary accounts cannot take into account that the price of products vary depending on the user, e.g. large industries pay less per kWh than other users in the market. Hence, the use of pure monetary accounts makes it impossible to ensure mass and energy balances, which should be fundamental for models of physical flows. The footprint from Danish Energy Agency (2023b) is based on an industry resolution of 117 for Danish Industries and of 164 for industries outside Denmark. This means that many products are highly aggregated, e.g. the model cannot distinguish Danish production of beef and broccoli – they have the same impact per DKK.

1.3 The model used in the current study: EXIOBASE v4.0 – hybrid version

The current study aims at establishing a causal link between Danish consumption in 2016 and changes hereof and the related GHG emissions emitted to the atmosphere. The study is based on a new fully updated hybrid version of EXIOBASE, version 4.0. “Hybrid” here refers to the units of the flows in the model, which are mass for tangible products, energy for energy products (electricity and steam/hot water), amounts/number for vehicles, and monetary units for all remaining product flows.

EXIOBASE v4 is created as part of the crowdfunded project: “EXIOBASE Update Club”[3] as well as the “Getting the Data Right” project[4]. The data collection for EXIOBASE v4 is funded by the EXIOBASE Update Club, while algorithms for data handling and model generation are developed within the “Getting the Data Right” project. The EXIOBASE v4 used in the current study is similar as the first version of the BONSAI model[5], which is delivered as part of the “Getting the Data Right” project.

The study consistently addresses the common problems in consumption-based footprints described above.

Why 2016, and not more recent data? The establishment of supply-use tables in monetary, mass and energy layers takes a considerable amount of time. Furthermore, the data on which the model is based are published with some delay. In the future, however, updates to the model will be made with much shorter delays, as the ‘Getting the Data Right’ project, a large project focusing on production and consumption GHG footprints for all

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[3] EXIOBASE Update Club: https://lca-net.com/clubs/exiobase-update/

[4] Getting the Data Right is a large project lead by Aalborg University and funded by the KR Foundation: https://www.en.plan.aau.dk/research/the-danish-centre-for-environmental-assessment/getting-the-data-right

[5] BONSAI: https://bonsai.uno/

product groups and for all countries, is aiming at automating the update procedure with the use of APIs to statistical data and with generalized algorithms for transforming the input data to the final model.

2 Goal and scope of the model

This chapter describes the overall goal and scope of the study. Details on the used model for the calculations (EXIOBASE v4, hybrid version) and specific modules for land use changes, electricity markets or aviation contrails, among others, are described in chapter 3.

2.1 Goal of the study

The current study aims at establishing a causal link between Danish consumption in 2016 and changes hereof and the related GHG emissions emitted to the atmosphere.

GHG emissions from Danish consumption are presented as total emissions as well as normalized per capitata. Besides, establishing a result for the Danish consumption footprint, the study aims at breaking the result down into contributing elements of consumption. For this purpose, results are both broken down in terms of product classification in EXIOBASE v4 as well as in terms of consumption categories as of official Danish consumption statistics (Statistics Denmark 2023b). These breakdowns point to the potential elements for GHG mitigation from a consumer perspective, i.e. how can consumers change behaviour to reduce GHG emissions.

It should be noted that the purpose of the current technical report is to document the methods and data used for the calculation of the Danish consumption-based footprint – not to provide a detailed interpretation of the results. The latter is provided in a separate report authored by CONCITO.

To illustrate the model's ability to estimate the life cycle GHG emissions related to different mitigation efforts, the following scenarios are included:

- GHG effect if one million conventional cars are replaced by electric cars.
- GHG effect if 90% of Danish beef consumption in households is replaced with pork and chicken.

2.2 Modelling approaches: Consequential and attributional models

The study uses a cause-effect based model, which follows the overall requirements in the international standard on Life Cycle Assessment (LCA), ISO 14040 and 14044, combined with a consequential modelling approach as described in Weidema et al. (2009). A consequential model is often seen as the contradictory of an attributional model. An example of an attributional consumption-based footprint is the footprint of Danish consumption published by the Danish Energy Agency referred to in the introduction (Danish Energy Agency 2023b). The terms consequential and attributional can be used both for national consumption-based footprints and for product footprints, which are more commonly called LCA. Below, the two approaches are described.

According to Sonnemann & Vigon (2011, p 133), consequential modelling is defined as a "*system modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit.*" Hence, in consequential modelling it is generally a change in demand of the product under study that is modelled. A cause-effect relationship between a change in demand and the related changes in supply and associated emissions is intended to be established. This implies that the mix of suppliers only includes those that are expected to react to a change in demand. This implies that constrained suppliers are excluded from the supply mix. For example, electricity from coal and natural gas is currently being phased out in Denmark. This means that a change in demand for electricity will not influence that new capacity is installed. Instead, changes in demand for electricity will affect the number of installed wind power mills and solar plants. Whenever activities are associated with by-products, e.g. production of district heating is often done in combination with electricity (in combined heat and power plants, CHP), then the output of the by-product will reduce the demand for other production hereof. In the case of the CHP the demand for heat will cause substituted electricity, i.e. the more heat from CHP we demand, the less electricity capacity is needed from other sources such as wind and solar. The modelling principles are comprehensively described in Weidema (2003), Weidema et al. (2009), and Weidema et al. (2013).

According to Sonnemann & Vigon (2011, p 132), attributional modelling is defined as a "*system modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule*". Most often, attributional studies assume that the products are produced using existing production capacity (current or historical market average), and multiple-output activities are dealt with by applying allocation factors based on economic, mass or energy content of the product outputs.

The characteristics of the used consequential approach and a typical attributional approach are summarised in Table 2.1**.**

Table 2.1. Description of the key features of consequential and attributional footprints.

Elements in modelling	Description
ISO 14040/44: Consequential modelling (International Organization for Standardization, 2006a, 2006b; Weidema et al. 2009; Weidema et al., 2013)	
Included suppliers	The included suppliers represent the actual production mix (ISO14044, section 4.3.3.1). This is interpreted as the actual suppliers affected by a change in demand. As default, the actual production mix is regarded as the average product mix where constrained suppliers are excluded (Weidema et al., 2009). This approach is used by default in the current study. However, for electricity, the trend of new installed capacity is used to compose the mix. Also, for land use changes, the trend in expansion of cropland and increase in yields is used to predict how much and in which countries deforestation and intensification is caused by changes in demand for land.
Multiple-output activities	Whenever possible, allocation should be avoided (ISO 14044, section 4.3.4.2). The reference product(s), i.e. the determining co-product(s) is determined, and the remaining co-products are regarded as by-products which can directly substitute other products or as material to treatment. All exchanges are ascribed to the reference product(s) including the avoided exchanges related to the displaced activities due to by-products.
Attributional modelling (Weidema et al., 2013)	
Included suppliers	The included suppliers represent the average market mix including constrained suppliers.
Multiple-output activities	Allocation is carried out for all co-products. It should be noted that allocation is only carried out for products for which there a market exists, i.e. allocation is not carried out between co-products and materials to treatment. In such cases the allocation is usually carried out between the products at the point of substitution, i.e. after the treatment activities.

There are pros and cons of both consequential and attributional modelling. In view of the authors, the most important ones are listed in Table 2.2. The table is based on Schmidt and de Saxcé (2016) and supported by Weidema et al. (2018), Weidema (2018), Weidema (2014), and Weidema and Schmidt (2010).

Table 2.2: Pros and cons of consequential and attributional modelling.

Consequential modelling	Attributional modelling
Pros	
• Strives towards identifying the consequences of demanding the functional unit. • Follows ISO 14044 allocation hierarchy, i.e. the highest priority to model by-products is followed. • Based on scientific criteria. • Mass balances are maintained. • Relatively simple to apply consistent modelling of by-products throughout the product system.	• Seemingly easy: Since the approach is normative, ad hoc choices can be made to exclude complex issues. • Most industry specific LCA and GHG guidelines are based on attributional modelling, e.g. many national consumption-based footprints (Danish Energy Agency 2023b) and the EU PEF Guideline.
Cons	
• Uncertainties associated with the identification of affected market mixes, i.e. "marginal" suppliers. • Hard to communicate: Since constrained suppliers are excluded, the directly economically connected product chain is not always followed. Negative impacts may be misunderstood.	• Complicated (or impossible) to consistently apply same allocation approach throughout a product system. • Allocated systems do not exist in reality – experts cannot recognise allocated product systems. • Applied market mixes, i.e. "average" suppliers may not represent the consequences of demanding products from the market – because some suppliers are more likely to respond to changes than others. • Uncertainties hidden behind allocation factors, i.e. substitutions are represented by crude proxy/random allocations between co-products. • Most often, the lowest priority to model by-products with regard to the ISO 14044 hierarchy on allocation is followed. • Mass, substance, energy, and other balances are not maintained when allocating. • May lead to misleading results – because of allocation, market averages and normative models. • Hard to communicate beyond the final numbers: Since allocated product systems do not exist in reality, the modelled system can be difficult to communicate. • It is very difficult to describe what attributional results refer to, i.e. which question should be asked in order to logically produce the results as an answer on this question.

2.3 Functional unit

The functional unit of the current study is the Danish final consumption in 2016. Results are also presented normalized by the number of citizens in Denmark in 2016[6]. This includes consumption by households, government, and non-profit institutions serving households (NPISH). Household consumption relates to the spending of money in private households. Government consumption relates to the use of money collected by the government via taxes, i.e. the spendings on healthcare systems, education and public research, defence and police, public infrastructure etc. NPISH refers to e.g. sports associations, private charity organisations, and trade unions.

The functional unit is illustrated as 'Final DK' in Figure 2.2.

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[6] In 2016, the number of citizens in Denmark was 5,728,000 (Statistics Denmark 2023a). The population is determined as the average of the number in January 2016 and January 2017.

2.4 System boundaries

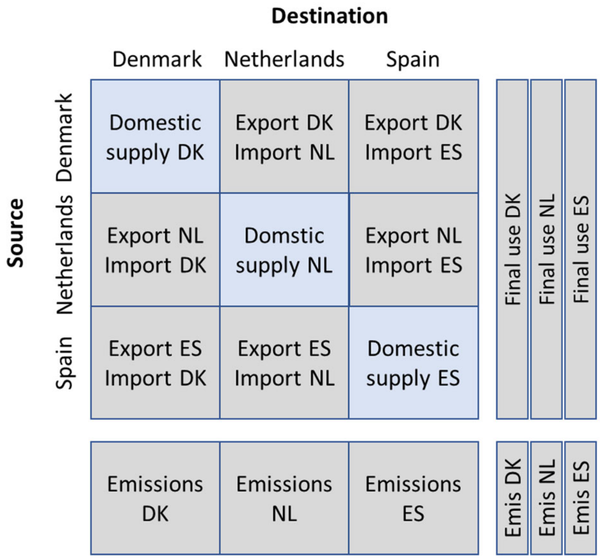
Danish consumption influences the production of all products on the Danish market as well as all upstream production processes. Furthermore, products may in principle come from all countries, or at least they have upstream processes in all countries. Therefore, the modelled production system to quantify the GHG emissions related to Danish consumption is global.

The Danish consumption-based emissions can, in a simplified way, be described as:

Equation 1

DK consumption GHG emissions = DK GHG emissions + GHG emissions embodied in import – GHG emissions embodied in export

However, this way of organising the calculations does not enable for breaking down the result into products used by households and government in Denmark. Instead, the calculations are organized using a multiple regional input-output format. A basic version of such a system is described in Stadler et al. (2018), which is also illustrated below in Figure 2.1 using Denmark, The Netherlands and Spain as examples.



Destination

Source	Denmark	Netherlands	Spain			
Denmark	Domestic supply DK	Export DK Import NL	Export DK Import ES	Final use DK	Final use NL	Final use ES
Netherlands	Export NL Import DK	Domstic supply NL	Export NL Import ES			
Spain	Export ES Import DK	Export ES Import NL	Domestic supply ES			
	Emissions DK	Emissions NL	Emissions ES	Emis DK	Emis NL	Emis ES

Figure 2.1. Illustration of multiregional input output table – here illustrated with three countries: Denmark (DK), Netherlands (NL), and Spain (ES). The central table that consists of nine square tables is what is referred to as the input output table. This is also called the Z matrix.

The model used in the current study is an expanded and refined version of the conventional way of organizing input-output tables. The model as illustrated in Figure 2.1 includes a lot of redundant information, i.e. the trade mix of each product is repeated for all industries in a country that is using this product. To avoid this repetition, the production recipes of products (columns in Figure 2.1) is divided into a) a production recipe and a market mix of each product in each country. This is illustrated in Figure 2.2.

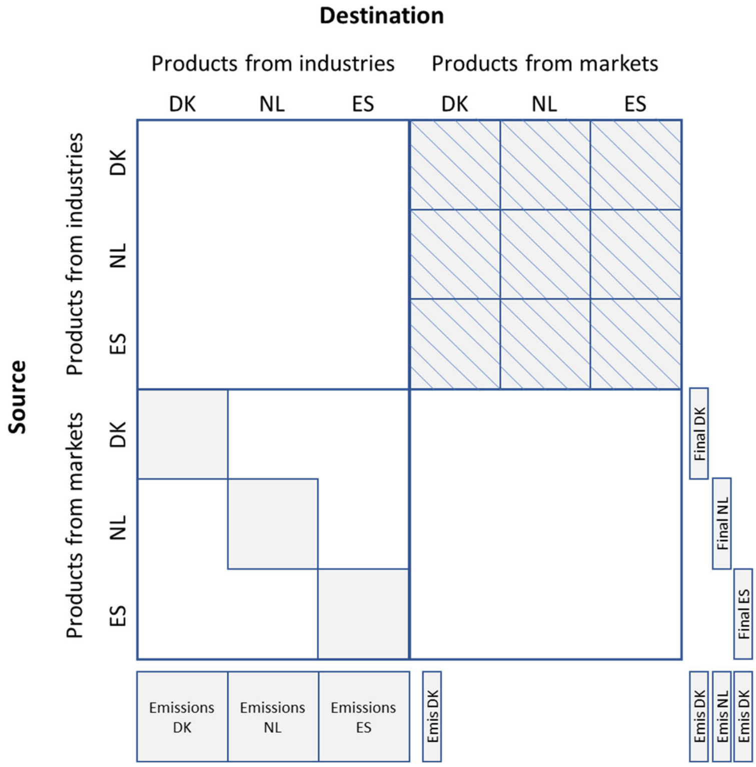


Figure 2.2. Illustration of refined and expanded version of conventional multiregional input output table – here illustrated with three countries: Denmark (DK), Netherlands (NL), and Spain (ES). The lower left part represents national input output tables, where the inputs are the relevant supply mix of the products, and the upper right part represents the input to the product markets. In the product markets, each market product has inputs of products from different suppliers (countries), this is illustrated with the diagonal stripes.

The refined and expanded version of the multiregional input output table in Figure 2.2 is more transparent and better suited for contribution analysis than the conventional representation of input output tables in Figure 2.1.

As the system boundaries include the entire global economy as well as all global GHG emissions (CO_2, CH_4, N_2O), there is in principle nothing that is left out of the study. In LCA terms: the cut-off is 0%.

2.5 Geographical and temporal scope

The current study presents a life cycle calculation of Danish consumption in 2016. Since this potentially involves producing activities in all countries in the World, the geographical scope is global. The used model, EXIOBASE v4, divides the global economy into 43 countries and five rest-of-world regions.

All data in the calculation refer to 2016. In identifying the most likely suppliers to react to changes in demand, time series are used for 2011 to 2016 to calculate trends in production volumes. This is done to identify the electricity mixes on each electricity market in each country/region as well as to identify which suppliers of land (transformation of non-used land to productive land as well as intensification in different countries/regions) will react to a change in demand for land. The modelling of electricity mixes and land use changes are further described in sections 3.1 and 3.2 respectively.

3 EXIOBASE v4: Hybrid input-output model and modifications hereof

This study is based on a new fully updated hybrid version of EXIOBASE, version 4.0. “Hybrid” here refers to the units of the flows in the model, which are mass for tangible products, energy for energy products (electricity and steam/hot water), amounts/number for vehicles, and monetary units for all remaining product flows.

EXIOBASE v4 is created as part of the crowdfunded project: “EXIOBASE Update Club”[7] as well as the “Getting the Data Right” project[8]. The data collection for EXIOBASE v4 is funded by the EXIOBASE Update Club, while algorithms for data handling and model generation are from the “Getting the Data Right” project. The EXIOBASE v4 used in the current study is similar as the first version of the BONSAI model[9], which is delivered as part of the “Getting the Data Right” project. A technical description of the BONSAI model is available in Schmidt et al. (2023).

EXIOBASE is a global hybrid multi-regional environmentally extended input-output (IO) database. The advantage of using an IO-database instead of a process database, such as e.g. ecoinvent, is that it operates with a cut-off criterion at 0% and that it has a much more complete geographical scope than any process database, as well as IO models consistently refer to a specific year. Furthermore, since IO-models represent balanced accounts of economy, they include the needed data on total consumption to perform the national consumption-based footprint.

EXIOBASE v4.0 has the following characteristics:

- 789 Product flows in hybrid units: EUR, kg, MJ.
- 490 Activities (this is equivalent to LCA processes in a conventional LCA database), of which
  - 103 are (waste) treatment activities (e.g. recycling of steel scrap, incineration of food waste).
  - 40 are combustion activities (makes energy usage modelling easier).
  - 3 are other activities featuring energy modelling.
  - 9 are land use change activities.
- 43 countries and 5 Rest-of-the-world regions.
- Base year: 2016
- GHG emissions: carbon dioxide (CO_2), biogenic and fossil methane (CH_4), nitrous oxide (N_2O), preponed CO_2 (moving CO_2 emissions in time).

‘Appendix 1: Main data for EXIOBASE v4’ provides an overview of the main data sources used to construct EXIOBASE v4.

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[7] EXIOBASE Update Club: https://lca-net.com/clubs/exiobase-update/

[8] Getting the Data Right is a large project lead by Aalborg University and funded by the KR Foundation: https://www.en.plan.aau.dk/research/the-danish-centre-for-environmental-assessment/getting-the-data-right

[9] BONSAI: https://bonsai.uno/

The predecessor of EXIOBASE v4 hybrid, i.e. v3 hybrid, is documented in two core papers: Stadler et al. (2018) and Merciai & Schmidt (2017a). Compared to the scope of EXIOBASE v3, which is described in the two mentioned papers, the following elements are added in EXIOBASE v4.0:

- **A model for indirect land use (iLUC) changes** is integrated in EXIOBASE: The applied iLUC method (Schmidt et al., 2015) has been integrated in EXIOBASE (Schmidt & De Rosa, 2018). See further description in section 3.1.
- **A cause-effect based electricity model** is integrated in EXIOBASE: The electricity model methodology is described in Muñoz et al. (2015) and its implementation in EXIOBASE is described in Merciai & Schmidt (2017b). See further description in section 3.2.
- **Investments are integrated in the core input-output table**. In the source data from statistical agencies these data is represented as part of final consumption. The values in the column of gross fixed capital formation (GFCF) are distributed into the IO-table (endogenized) based on: a) The recipes of the activities, and b) the consumption of fixed capital in the value added of activities. Each flow is distributed proportionally to the consumption of fixed capital reported. An iterative procedure is finally implemented to redistribute the GFCF flows to achieve balance.
- **Aviation contrails Global Warming Potential (GWP)** are added as contributing to GHG emissions. This is based on Lee et al. (2021). Based on global average data for aviation, the contrail GWP100 corresponds to 0.74 relative to aviation CO_2 emissions. Hence, when an aircraft emits 1 kg CO_2, the GWP100 is 1 kg CO_2 plus 0.74 kg CO_2-eq from contrails.

3.1 Electricity and district heating modelling

LCI data for the production of electricity based on several technologies (coal, gas, wind, photovoltaic, biomass etc.) in each country is available in EXIOBASE v4. The market for electricity in each country in EXIOBASE is modelled following the procedure described in Muñoz et al. (2015) and Merciai & Schmidt (2017b). This procedure is also nicely exemplified in the consequential-lca.org webpage[10]. The electricity mix is composed based on data for 2016 and 2025 obtained from the International Energy Agency (IEA 2022).

It should be noted that a considerable share of the reported electricity generation from coal, biomass, and natural gas is produced in combined heat and power plants (CHP). The determining product[11] of CHP is heat generation, and the electricity is a by-product. Hence, the electricity produced in CHPs should be taken out of the total electricity generation by source from the IEA statistics, before calculating the marginal electricity mix. Since electricity from the above-mentioned fuels in many countries is mainly produced in CHPs, the share of these electricity sources become relatively small in the calculated marginal electricity mixes. For example, electricity from coal only account for 11% of the marginal electricity mix in China (see Table 3.1). This is partly because around half of the coal used in the energy sector in China is in CHP, and partly because the installation of wind and solar power is rapidly increasing.

Table 3.1 shows the applied electricity mixes for some of Denmark's most important trade partner countries.

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[10] Marginal electricity mix example calculation: https://consequential-lca.org/clca/marginal-suppliers/the-special-case-of-electricity/example-marginal-electricity-in-denmark/

[11] Determining product: https://consequential-lca.org/glossary/#determining-product

Table 3.1. Applied consequential electricity mix from EXIOBASE.

Country: Source:	Denmark (DK)	China (CN)	Germany (DE)	India (IN)	Norway (NO)	Sweden (SE)	United States (US)
Biomass			6%		1%		3%
Coal		11%					
Gas		5%	14%	10%	3%		23%
Geothermal		1%	1%				5%
Hydro	1%	1%	1%	3%	8%	14%	<1%
Nuclear		7%	2%	16%			1%
Oil	3%	1%	2%	13%	<1%	3%	1%
Solar		33%	30%	27%		31%	25%
Wind	96%	41%	44%	32%	88%	52%	42%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

3.2 Indirect land use changes (iLUC)

According to IPCC (2020), 11% of global GHG emissions (GWP100) are caused by CO_2 emissions from land use changes. We use a model for iLUC proposed by Schmidt et al. (2015). This model has been used for a large number of LCA studies and carbon footprints[12] and the model is rated as the best among a comparison of six major LUC models by De Rosa et al. (2016). The ranking considers completeness, impact assessment relevance, scientific robustness, and transparency. The current study uses the same modelling approach as described in Merciai and Schmidt (2017b) and Schmidt and De Rosa (2018), but here it is based on data in EXIOBASE v4.0. The applied iLUC model has been and is currently being developed through an initiative lead by 2.-0 LCA consultants: The 2.-0 iLUC club (http://lca-net.com/clubs/iluc/). The initiative is supported by more than 25 partners including large multinational companies, national research centres, non-governmental organizations (NGOs) and universities. The partners are located in 11 different countries in Europe, Asia, North America and Australia.

The iLUC model has several key characteristics that make it more complete and precise to many of the other models:

- It is applicable to all crops (also forest land, range land, built land etc.) in all regions in the world.
- It avoids arbitrary allocation/amortization of transformation impacts.
- It is based on modelling assumptions that follow cause-effect relationships consistent with the way any other links between LCA-processes are modelled.

1 ha*year average global arable land is associated with 1.77 t CO_2-eq. (calculated with the EXIOBASE v4.0 implementation of the iLUC model) when using GWP100.

According to Schmidt et al. (2015), changes in the demand for land are the cause of land transformation. The mechanism linking the drivers (demand for land) with effects (land use changes) is illustrated in **Figure 3.1**. The figure uses the example of adding a demand for land for rapeseed in Denmark of 1 ha*year. It appears from the figure that the land use effects can be divided into direct and indirect land use changes. This is further explained in the following.

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[12] See list of examples of application areas at: https://lca-net.com/projects/show/indirect-land-use-change-model-iluc/

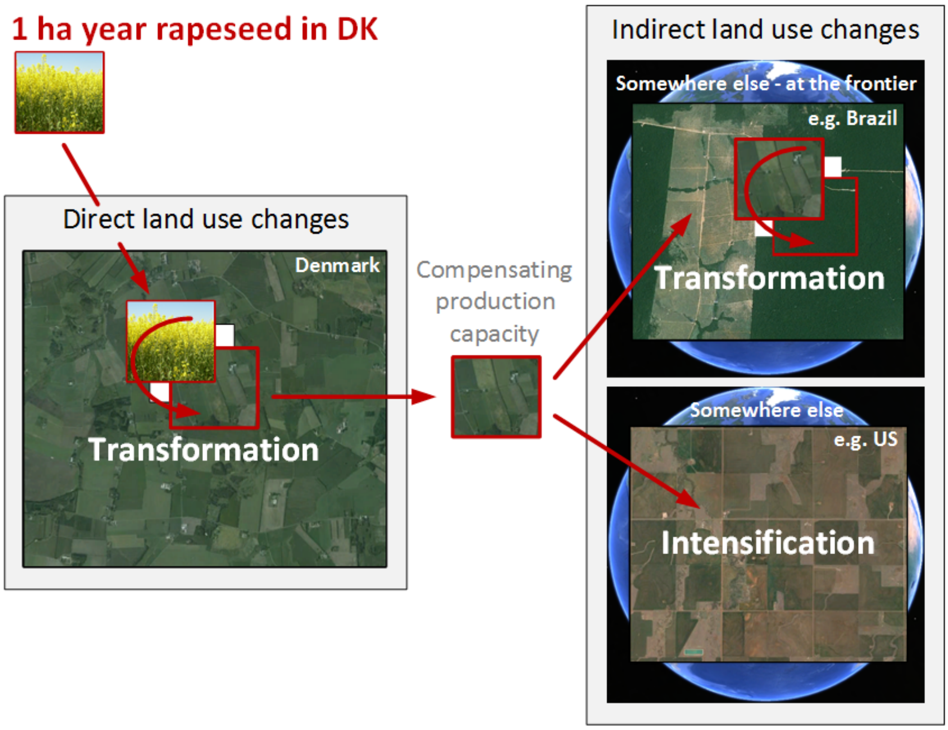

Figure 3.1. Illustration of the effects of adding a demand for land in Denmark of one hectare*year. The effects include indirect transformation of land and intensification to compensate for the production capacity in Denmark that is now no longer available due to being occupied by the new demand.

Direct land use changes (dLUC)

In the example in Figure 3.1, the dLUC is the effect of changing from a reference situation to rapeseed. The reference situation is the current marginal use of the affected land, which will be arable land in most cases (Schmidt et al. 2015).

Obviously, any arable cropping will affect arable land, but also many other human activities are located on arable land, so that when demanding land for buildings, infrastructure, sites for resource extraction, etc., arable land is often affected. An example is the use of land for a residential house in an urban area. This change in demand for land will put equivalent pressure on the boundaries of the urban area that will likely expand into the surrounding arable land.

When the occupied land under study is associated with a carbon stock that is equal to the reference in that country, then the dLUC are not associated with any change in carbon stock. However, if the land under study stores more carbon than the reference, then the land under study contributes to an increase of stored carbon in that country. This is the case of fruit plantations, which stores more carbon than reference (average arable land).

In the current study, direct land use changes are not considered because they contribute insignificantly to the results.

Indirect land use changes (iLUC)

As illustrated in Figure 3.1, the indirect consequence of the dLUC is the occupation of production capacity somewhere else to compensate for the production capacity now occupied by the additional demand. According to Schmidt et al. (2015), this compensation is partly expansion of arable land at the agricultural frontier, and partly intensification of land already in use. The use of land by the crop under study is what is considered as dLUC, while the supply of new land caused by the need for compensating the production capacity of the land required by the new demand is considered as iLUC. The link between the supply-side and the use-side of land is further elaborated in the next section.

Supply and use of land linked via the global market for land

The iLUC model described in Schmidt et al. (2015) assumes there is a global market for land. To be more precise, the market is not mainly concerned with the area of land but rather its production capacity. Hence, 1) all countries that expand their arable land, supply land into this market; 2) all countries that intensify their existing productive land, supply arable land into the global market for arable land. This supply-side to the global market for land is illustrated in **Figure 3.2**.

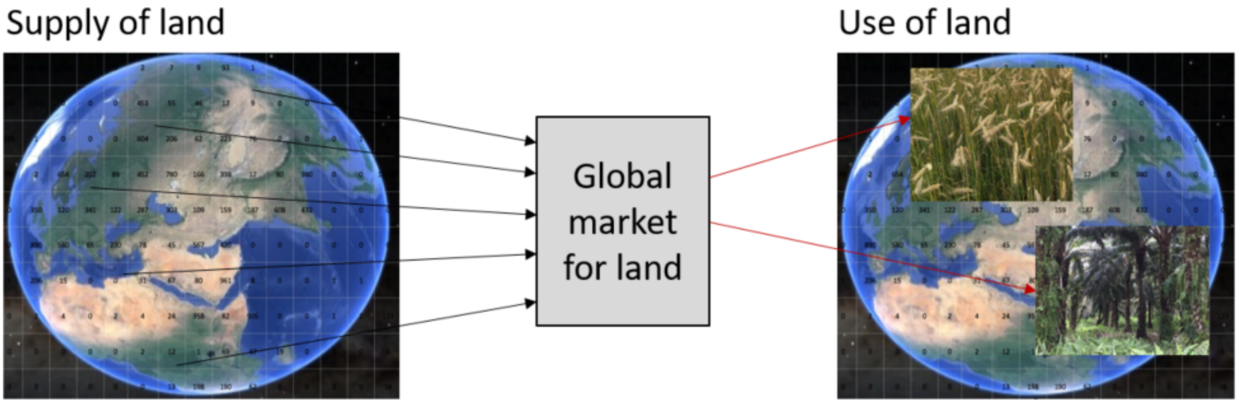

Figure 3.2. Illustration of the global supply and demand of land (Schmidt and De Rosa 2018).

The supply-side of land is modelled using the EXIOBASE model, and the approach and data are described in Schmidt and De Rosa (2018) and Merciai and Schmidt (2017b).

The supply of land in the applied iLUC model is modelled by using data in the multi-regional hybrid input-output model EXIOBASE (Merciai and Schmidt 2017a). The procedure for the integration of the iLUC model in EXIOBASE is described in Merciai and Schmidt (2017b) and Schmidt and De Rosa (2018). The land market modules of the model contain data on time-series of land use data and agricultural production data for all countries. The EXIOBASE data allow identifying the land supplied by each country, by expansion of the cultivated area as well as by intensifying existing agricultural land and linking the production trends with the land use trends. In EXIOBASE, the complete global economy is divided in 47 countries and regions, and each of them is divided in 164 industrial sectors. The agricultural and land use module in EXIOBASE make use of FAOSTAT (2022), which provide time series on area and production per crop. The time-series used for the integration of the iLUC model in EXIOBASE v4.0 is 2011 and 2016. To have comparative yields, all crops are converted to dry matter. These data allow modelling the global supply of land (Figure 3.2) to the global market for land, distinguishing between land expansion (land transformation) and land intensifications (increased production per unit of land). Analogously, the demand side is modelled for every country using land for crop cultivation, pasture, forestry and other purposes.

Adjustment for differences in potential productivity

To calculate how much land that needs to be compensated from occupying 1 ha*year in a specific country/region, its productivity must be adjusted for. Schmidt et al. (2015) use the potential net primary production (NPP_0) for this adjustment. Hence, the adjustment factor is calculated as the actual NPP_0 divided by the global average NPP_0 for arable land. When this adjustment is done, the unit is changed from ha*year to ha*year-equivalents, where 1 ha*year-equivalent refer to land with average global potential productivity.

The potential productivity of arable land in different countries is based on high resolution maps that allow to determine how much iLUC is induced by using land in different regions. For example, 1 ha arable land in Indonesia gives a potential productivity that is 1.9 times greater than in EU28, hence the induced iLUC emissions from 1 ha in Indonesia is 1.9 times higher than in EU28. The data used to determine national average potential productivity of arable land relative to global average arable land is a detailed overlay analysis in GIS, with the following data sources:

- 10 x 10 km grid of potential net primary production (NPP_0) (Haberl et al. 2007)
- 0.05 x 0.05 km grid of land cover data (Friedl et al. 2010)
- National borders

Different land markets

Schmidt et al. (2015) operate with different markets for land: 1) Arable land, 2) Intensive forest land, 3) Extensive forest land, and 4) Grassland. This delimits land types with different potential uses. The potential uses represent the reference for each land type, e.g. grassland in the dry Brazilian Cerrado, which is to a large extent used for cattle grazing, cannot be used for forestry or arable cropping because it is too dry for these purposes. Therefore, a change in the use of these grasslands will not have any indirect effects on the markets for forest land or arable land. Similarly, forest land in some countries may not be fit for arable cropping because the land is too cold, rocky or hilly for that purpose. Therefore, the use of this land will only affect the market for forest land. Sometimes land is used for less productive purposes (economically) than the land's potential use, e.g. when potential arable land in Indonesia and Malaysia is used for extensive forestry. In this case, using this land will still affect the market for arable land (Schmidt and de Saxcé 2016). The definitions of markets for land are presented in Table 3.2.

Table 3.2. Different markets for land based on Schmidt et al. (2015)

Markets for land	Description
Market for arable land (fit for arable and other)	Fit for arable cropping (both annual and perennial crops), for intensive or extensive forestry, and pasture.
Market for forest land (fit for intensive/extensive forestry and grazing)	Fit for forestry and pasture, but unfit for arable cropping e.g. because the soil is too rocky or because the climate is too cold. Forest land may also be used for other uses, e.g. livestock grazing.
Market for grassland (fit for grazing)	Too dry or cold for forestry and arable cropping. Grassland is most often used for grazing.

Temporal aspects: Avoiding amortization of land transformation

A challenge when modelling land use changes is that transformation of land (in unit ha), e.g. from forest to oil palm, is not proportional with fresh fruit bunches (FFB) production (which is proportional with land occupation in unit ha*year). A common approach to overcome this is to amortize (allocate) impacts related to land transformation over a normatively defined period of time, e.g. 20 years. This approach is used in several LCA and carbon footprint guidelines, e.g. the PEF guideline, the GHG protocol, PAS2050 and the PalmGHG.

However, this approach does not reflect a cause-effect relationship, the amortization period is arbitrarily defined, and by allocating historical land use change impacts to current oil palm cultivation it implies a causality that goes backwards in time (current demand for crops causes deforestation 20 years ago), which is obviously not possible in reality.

The applied iLUC model overcomes this problem by modelling land transformation as accelerated denaturalisation (Schmidt et al. 2015). This approach models the observed and current relationships only: that deforestation is taking place as long as the demand for land grows and as long as deforestation is not stopped. To grow the functional unit under study in an LCA, the indirect effect could be an additional demand for 1 ha*year. When this demand is added to the background demand causing the current deforestation, the effect is that in year 0, an additional hectare of deforestation is taking place, while after one year when the functional unit is produced, the cleared land can be handed over to the next crops, which can then be grown without deforestation. The handing over of the land after 1 year thus avoids 1 ha deforestation. The net effect of the additional demand for 1 ha*year is thus a preponement of 1 ha deforestation by 1 year, i.e., the deforestation that would have taken place in year 1 is now taking place in year 0 because of the demand for the functional unit under study. When moving deforestation and associated CO_2 emissions in time, the impact on global warming can be calculated by using the time-dependent global warming potential. This is further described in section 3.3.

How does Danish consumption affect GHG emissions from iLUC?

The life cycle calculation with EXIOBASE v4 hybrid, show that Danish consumption is associated with land occupation as presented in Table 3.3. The table also presents the calculated GHG emissions caused by the land use, as well as a comparison with actual direct land cover in Denmark is shown.

Table 3.3. Land use related to Danish consumption 2016 broken down in occupation of cropland, forest land and grassland (calculated using EXIOBASE v4). The actual land cover in Denmark is also shown (FAOSTAT 2022).

Land use category	Land use DK consumption (km^2)	iLUC related to DK consumption (million t CO_2-eq.)	Actual land cover in Denmark (km^2)
Cropland	14,712	2.66	23,995
Forest (biomass)	7,393*	1.31*	6,247
Forest (wood)	20,051*	0.94*	
Grass	15,421*	1.12*	2,260
Other, e.g. protected non-productive land	n.a.	n.a.	7,499
Total	**57,577**	**6.04**	**40,000**

**Land occupation of forest land and grassland related to Danish consumption is related to large uncertainties. This is because statistical data on grass and timber yields are associated with uncertainties. It has been assumed that half if woody biomass used in Denmark affects forest plantations, while the remaining affects the harvest of forest residues. It should be noted that forest residues will become a constrained by-product of forestry when it is fully utilized.*

Table 3.3 shows that the total land use related to Danish consumption is considerably larger than the territory of Denmark. This applies to the use of forest land and grassland. The higher use of forest land than the Danish forest area relates to import of construction wood, biomass, and wood via paper. For grassland, the higher land use relates to extensive grass for cattle. The occupation of cropland related to Danish consumption is considerably lower than the actual land cover of cropland on Danish territory. This is because Denmark is a large exporter of agricultural products, namely animal products, which have large upstream land use largely taking place outside Denmark.

It should be noted that the calculation of iLUC caused by Danish consumption is associated with uncertainties. Especially, the contribution from forest and grassland.

3.3 Biomass from forest and residues

This section explains how the use of biomass from forest products and residues has an effect on global warming. The CO_2 emissions and uptake related to biomass are biogenic. It is common to assign no GWP effect from biogenic CO_2. However, in the following, it is explained how this affects global warming, and how it is included in the current model.

CO_2 fluxes related to biomass from forest products

When biomass is sourced from forest products, the effect is that trees are harvest and burned, and new trees are planted. This means that the time of the demand for forest biomass, there will be CO_2 emissions from the burning of the biomass. When new trees are planted, they will take CO_2 from the atmosphere for the growths. When the trees are fully grown, the CO_2 uptake equals what was emitted when the tress were felled and burned. Hence, in the long term, biomass is CO_2 neutral, but from the time of emissions (at burning) till the CO_2 is again taken up by new trees, there will be more CO_2 in the atmosphere compared to a situation, where the biomass was not demanded (counterfactual). Hence, a carbon balance of CO_2 emissions and uptake can be established as a function of time, see examples in Schmidt and Brandão (2013, section 3.4). The establishment of forest carbon balances is made using the model described in De Rosa et al. (2016). Since the CO_2 has a radiative forcing effect during this period, this has a warming effect. The GWP100 effect is based on a temporal CO_2 emission and uptake account of the forest system and GWP metrics as described in section 3.4.

CO_2 fluxes related to biomass from forest and agricultural residues

When biomass is sourced from forest and agricultural residues, the effect is that the biomass is collected and burned. If there is an excess of residues available, the net effect of demanding biomass is the inducement of CO_2 emissions from burning while decay of the residues is avoided. Decay functions of residues are calculated using the RothC model (Jenkinson et al. 1990). Decay of agricultural residues (straw) in Europe has a halftime of less than one year, and after 100 years approximately only 2% of the carbon is left in the soil. Decay of forest residues in Europe has a halftime of around four years, and after 100 years approximately 4% of the carbon is left in the soil.

As for the forest biomass, this means that the time of the demand for forest biomass, there will be CO_2 emissions from the burning of the biomass, while the counter factual leads to net CO_2 uptake (which is in reality avoided CO_2 from decay). Hence, in the long term, biomass is CO_2 neutral, but from the time of emissions (at burning) till the CO_2 is again taken up, there will be more CO_2 in the atmosphere compared to a situation where the biomass was not demanded (counterfactual). Similar to the forest biomass, a carbon balance of CO_2 emissions and uptake can be established as a function of time, see examples in Schmidt and Brandão (2013, section 3.4). The GWP100 effect is based on a temporal CO_2 emission and uptake account of the forest system and GWP metrics as described in section 3.4.

3.4 GHG metrics and temporal aspects

The method used for calculating GHG emissions, measured as CO_2-equivalents, is the IPCC 100 year GWP or GWP100 (IPCC 2013). The sub-sections below describe how biogenic CO_2 is dealt with and how temporal aspects of emissions and uptake are accounted for. Table 3.4 summarizes the GWP100 characterization factors used to calculate CO_2-eq.

In addition to the default results using GWP100, results are also calculated using GWP30. The characterization factors for this are calculated based on the supplementary files from IPCC (2013), where all formulas and data for calculating GWP are available. The GWP30 factors are also presented in Table 3.4.

Table 3.4. GWP100 and GWP30 characterization factors (IPCC 2013).

Emission	GWP100 (kg CO_2-eq/kg)	GWP30 (kg CO_2-eq/kg)
Carbon dioxide, fossil	1	1
Methane, biogenic	27.75	69
Methane, fossil	30.5	72
N2O	265	290
Dinitrogen monoxide	265	290
Preponing CO_2 by 1 year	0.00772*	0.0265

** This is calculated as GWP for CO2 emitted at time t=1 year minus GWP for CO2 emitted at time t=0 year. See GWP(t) in Table 3.5.*

Biogenic CO_2

Generally, inputs and outputs of biogenic CO_2 are considered as having no effect on global warming. This includes natural carbon cycles such as animals eating feed, the feed being excreted, manure being applied to the field to grow crops which the animals then eat again, etc. However, in some cases biogenic CO_2 is relevant and included, which applies when a defined timing (usually yearly basis) of emissions and uptake differs. This is relevant for land use changes and biomass as described in sections 3.2 and 3.3.

Temporal aspects of CO_2 emissions

Generally, all emissions are modelled as if they are emitted at the same time, i.e. at the time of demand (Danish consumption). This means that it is assumed that emissions today have the same importance as emissions taking place in 100 years. However, for biogenic emissions related to indirect land use changes (iLUC) and biomass for energy, the time effects are included.

When accounting for emissions taking place at different times other than at year zero (= the time of Danish consumption), the GWP100 formula (IPCC 2013, p 710-732 and supplementary material 8SM-14 - 8SM17) is consistently applied. The characterization factors are summarized in Table 3.5.

Table 3.5. GWP100 characterization factors for CO2 emitted at different times. Calculated based on: (IPCC 2013, p 710-732 and supplementary material 8SM-14 - 8SM17).

Timing of CO_2 emission (t), year	GWP100 (kg CO_2-eq/kg CO_2 at time t)
0	1.0000
1	0.9923
2	0.9846
3	0.9768
…	…
99	0.0365
100	0.0188
101	0

4 Results

The results presented in the current study refer to marginal changes in emissions as a consequence of marginal changes in consumption. This also means that the calculated total consumption-based footprint in itself makes little sense because you would not change the entire Danish consumption in one go. When presenting results per capita, the results represent the annual impact of one additional or one less Danish average citizen. Again, this does not represent a relevant decision context, unless the question at stake was to decide on changing the birthrate in Denmark and that the results should represent the long-term effects hereof. However, it has still been decided to present results as total Danish consumption-based emissions as well as per capita results since this gives a good indication of the potential influence on GHG emissions by changing production and Danish consumption. The current model is fit for predicting the effects on GHG emissions from any marginal change in production or consumption, so the presented results can be used as a baseline. And calculated changes in in emissions caused by changes in consumption or production can then be compared to the baseline to obtain an idea of their relative importance of the analyzed change.

The calculated consumption-based footprint of Denmark 2016 is **73.9 million tonne CO_2-eq**. This corresponds to **12.9 tonne CO_2-eq. per capita**.
It should be noted that a more elaborated and detailed interpretation of the results is provided in a separate report authored by CONCITO.

4.1 Contribution analysis

The total result is broken down into contributing products and services in final consumption in Denmark 2016 is presented in Table 4.1 and Figure 4.1. The classification used for the breakdown in Table 4.1 is manually made by the authors to provide an overview of not too many and relative homogeneous product categories. Breakdown of results for other classifications are available in 'Appendix 2: Breakdown of results'.

It appears from Table 4.1 and Figure 4.1 that food, transport and housing are the most important contributors to the overall impact. It should be noted that the transport here includes both car-driving in the households ('Households direct emissions') as well as the transport of goods used by households ('Transport services'). Other important contributions are heating (of houses) and 'Health and social work services'.

Table 4.1. Breakdown of the Danish consumption-based footprint 2016. Results broken down in different levels of aggregation are available in ‘Appendix 2: Breakdown of results’ (excel file).

Product/service	**million t CO2-eq.**	**t CO_2-eq. per capita**
Food	11.3	1.97
Apparel and textiles	2.6	0.45
Domestic appliances, electronics, machinery	1.7	0.30
Vehicles	2.2	0.38
Other materials: paper, plastics, chemicals, furniture; other manufactured goods	3.0	0.52
Electricity	0.7	0.12
District heating	5.5	0.97
Fuels	0.4	0.07
Construction work and real estate	6.5	1.14
Hotel and restaurant services	4.2	0.73
Transport services	10.1	1.76
Post and telecommunication services	1.3	0.23
Public administration, defence, social security	4.5	0.78
Education services	2.4	0.42
Health and social work services	6.1	1.07
Waste treatment and recycling	0.6	0.10
Recreational, cultural and sporting services	2.0	0.34
Other services	3.5	0.61
Household direct emissions (transport and heating)	5.4	0.94

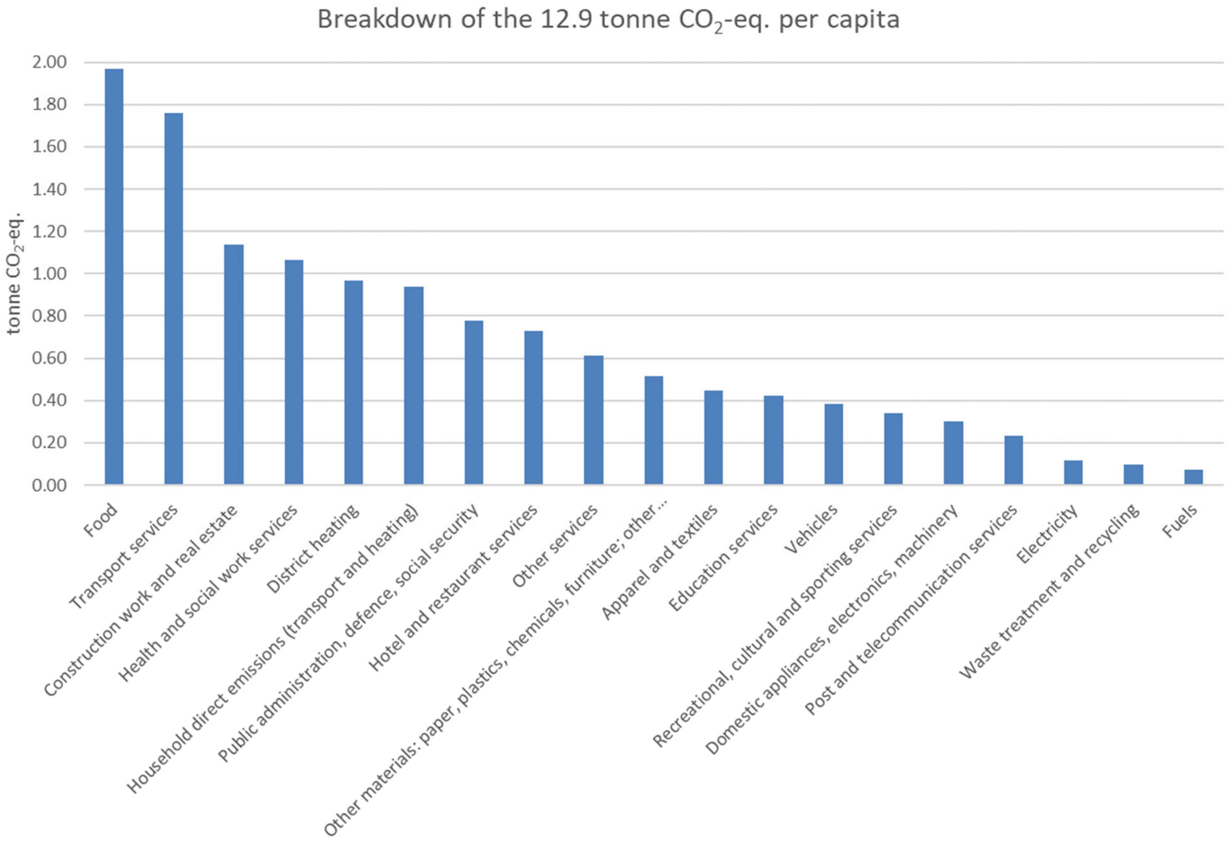

Figure 4.1. Breakdown of the Danish consumption-based footprint 2016. Results broken down in different levels of aggregation are available in ‘Appendix 2: Breakdown of results’ (excel file).

4.2 How do the results differ from other consumption-based footprints

In section 1.2, several problems related to most common consumption-based footprints are described. The used model in the current study, i.e. EXIOBASE v4 hybrid, consistently addresses these problems. The addressed common problems in consumption-based footprint include:

- iLUC arable land and biomass (see section 3.2)
- Biomass effects (see section 3.3)
- Change from average to marginal electricity (see section 3.1)
- Endogenization of fixed capital (see section 3)
- Contrails from air transport (see section 3)

In this section, it is described how the changes in modelling according to the above-mentioned bullets affect the results of Denmark's consumption-based GHG footprint. Further, it is described how the changes in modelling should affect decisions to reduce GHG emissions - compared to a situation, where conventional models are used for decision support.

Table 4.2 and Figure 4.2 show how each of the addressed items above affect the overall DK consumption-based footprint. The first row in the table shows the results of EXIOBASE v4 before any of the changes in modelling have been implemented. Then each of the following five rows show how the results are affected by changes in modelling. The bottom-line of the table show the result after the changes have been implemented.

Table 4.2. Difference between conventional IO-model and the current IO model.

Contribution	DK consumption million t CO_2-eq.
Conventional IO model	**69.2**
iLUC arable land and biomass	+6.0
Biomass	+1.3
Change from average to marginal electricity	-3.2
Endogenization of fixed capital	-1.1
Contrails from air transport	+1.6
Current IO model	**73.9**

It appears from Table 4.2 and Figure 4.2 that the overall result does not change a lot. However, this is because some of the changes in modelling increase the result while others do the opposite. The most important change is the inclusion of iLUC, which adds 6 million tonne CO_2-eq. to the result achieved using the conventional approach. Also, accounting for the biogenic CO_2 emitted from biomass (which is taken up again later during regrowth) as well as aviation contrails adds a considerable amount of CO_2-eq.

On the contrary, the change from average electricity to marginal electricity reduces the CO_2-eq. significantly. Also, the endogenization of fixed capital reduces DK consumption-based GHG emissions.

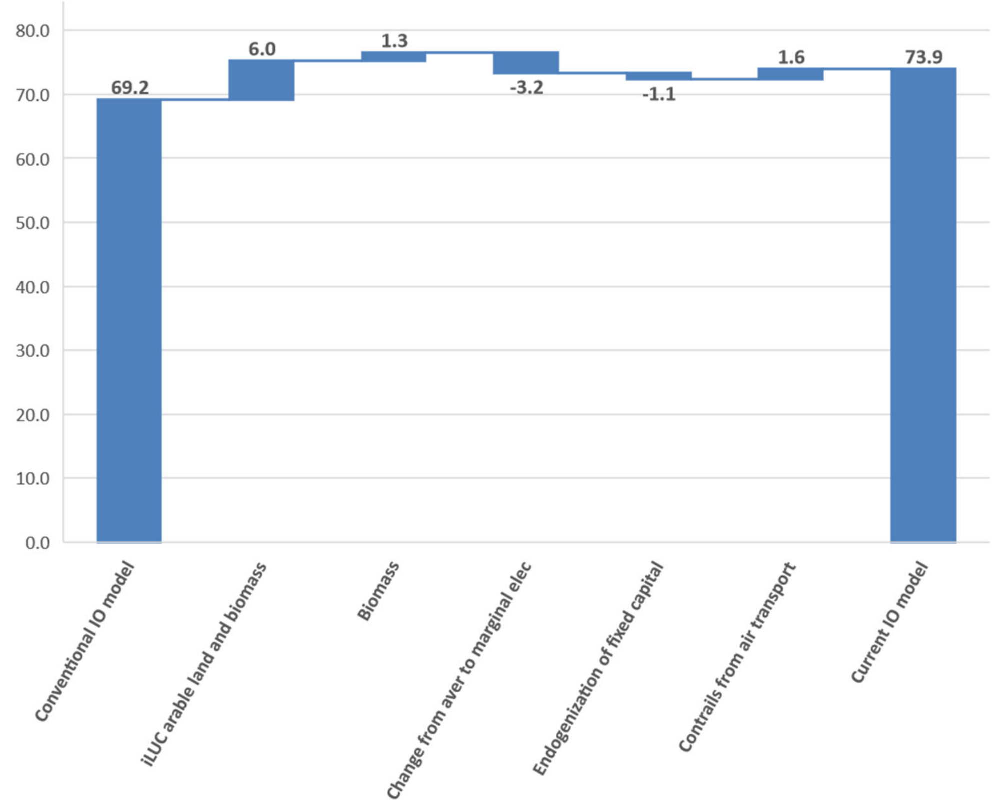

Figure 4.2. Difference between conventional IO-model and the current IO model.

Below, it is briefly summarized how each of the items addressed affect the calculated impacts of certain product groups in Denmark.

- iLUC arable land and biomass
    - iLUC significantly increases the impact of all products that require land for their production, such as food and biofuels. This means that land-intensive food, such as meat, and especially beef, has significantly higher impacts than a traditional footprint model would show. Also, biofuels associated with land use become more GHG intensive.
    - Decisions to reduce GHG emissions should focus on minimizing the use of land throughout the life cycle of products. The less land we use, the more forests, which contain carbon, will remain. Important to acknowledge that land is not a carbon free resource.
- Biomass effects
    - The inclusion of the effects of biogenic carbon from biofuels increases the GHG intensity of biomass. Especially biomass based on carbon pools, which take long time to recover, e.g. wood plantations, but also forest residues decays relatively slow.
    - Decisions to reduce GHG emissions should focus on minimizing the use of biomass, which involves that CO_2 is emitted, while it takes long to recover the carbon stock: from the time of emissions (at burning) till the CO_2 is again taken up by new trees, there will be more CO_2 in the atmosphere compared to a situation, where the biomass was not demanded.
- Change from average to marginal electricity
    - The marginal electricity mix is considerably cleaner than the average mix. This means that the use of electricity is associated with less GHG emissions than calculated in conventional IO models.
    - Decisions to reduce GHG emissions should focus less on reducing electricity use. Electricity has become a relative clean source of energy, while other forms of energy are more problematic: fuels for transport and industrial processes involving high temperatures.
- Endogenization of fixed capital
    - The negative change in results by endogenizing capital formation means that Denmark import less capital intensive products compared to the products exported by Denmark. One example could be Denmark’s large export of pharmaceuticals, which requires relatively large investments compared to imported products.
    - This change does not have any specific consequences for decision support besides that the results of the used model in the current study are much more accurate compared to conventional IO models. For example, the impacts of wind power are highly underestimated in conventional IO models, because these do not include the production of the used windmills.
- Contrails from air transport
    - The inclusion of aviation contrails increases the climate impact from aviation by 75%.
    - Decisions to reduce GHG emissions should put more emphasis on reducing aviation since the impact of this is much higher compared to what more conventional calculations typically show.

5 Scenarios

This chapter presents two “what-if” scenarios of changes in production/consumption, which will affect GHG emissions:

- One million conventional cars are replaced by electric cars.
- 90% of Danish beef consumption in households is replaced with pork and chicken.

The scenarios mentioned above serves as illustrative examples of what the model can be used for. It should be noted that the model used in the current study is especially fit for this kind of scenario analysis. Most of the conventional IO models used for consumption-based footprints are not fit for this kind of analysis, i.e. they cannot be used for predicting the effect of different changes in production and consumption.

5.1 One million conventional cars are replaced by electric cars

This scenario calculates the GHG effect of replacing one million conventional combustion cars in Denmark with electric cars. The calculation shows that this reduces the GHG emissions by 4.3 million tonne CO_2-eq. Normalising this to the Danish population, this corresponds to a reduction of the Danish consumption-based GHG footprint of 0.76 tonne CO_2-eq (from 12.9 to 12.1 tonne CO_2-eq per capita). This corresponds to a 6% reduction in the Danish consumption-based footprint.

The calculation is based on data on the Danish car fleet in 2021: distribution of gasoline and diesel cars, their fuel efficiency (fuel per km), driven distances in 2021 (km), the use of batteries (kg battery per kWh electricity), and GHG intensities related to fuels and their combustion as the production of batteries (kg CO_2-eq. per unit of fuel and battery).

The fuel efficiencies and use of batteries are given in Table 5.1. This table also shows the use of batteries for electric cars.

Table 5.2 shows the GHG intensities used for the calculation. The GHG intensities are calculated using EXIOBASE v4. It has been assumed that batteries can be represented by ‘Electric machinery’ produced in China.

Table 5.3 show the GHG emissions for the Danish car fleet in 2021 as it is and for the scenario, where one million of the gasoline and diesel cars have been replaced by electric cars.

Table 5.1. Fuels efficiencies for transport (Statistics Denmark 2022; Bilbasen 2021; Electric Vehicle Database 2022). The use of batteries is obtained from Bieker (2021) and an assumed weight of a battery at 500 kg.

Fuel	Unit	Fuel efficiency
Combustion cars		
Gasoline	litre/100 km	5.23
Diesel	litre/100 km	4.71
Electric cars		
Electricity	kWh/km	0.20
Battery use	kg/kWh	0.00135

Table 5.2. GHG intensities of fuels. Data are calculated using EXIOBASE v4 hybrid.

Fuel	Unit	GHG intensity
Gasoline	t CO2-eq./ton gasoline	3.92
Diesel	t CO2-eq./ton diesel	4.38
Electricity	t CO2-eq./MWh elec	0.038
Battery	t CO2-eq./t battery	8.5

Table 5.3. GHG emissions related to replacing one million gasoline and diesel cars in Denmark with electric cars.

Baseline scenario			
Fuel	**Car fleet 2021 (units)**	**Transport (million km)**	**GHG emissions (million t CO_2-eq.)**
Gasoline	1,840,349	57,560	8.83
Diesel	802,420	25,097	4.31
Electricity	66,610	2,083	0.016
Battery			0.0048
Total	**2,709,379**	**84,741**	**13.2**
1 million electric cars scenario			
Fuel	**Car fleet 2021 (units)**	**Transport (million km)**	**GHG emissions (million t CO_2-eq.)**
Gasoline	1,190,363	37,231	5.71
Diesel	519,016	16,233	2.78
Electricity	1,000,000	31,277	0.237
Battery			0.0719
Total	**2,709,379**	**84,741**	**8.8**
Effect of scenario = Scenario minus baseline			
Fuel	**Car fleet 2021 (units)**	**Transport (million km)**	**GHG emissions (million t CO_2-eq.)**
Gasoline	-649,986	-20,329	-3.12
Diesel	-283,404	-8,864	-1.53
Electricity	933,390	29,194	0.22
Battery			0.07
Total	**0**	**0**	**-4.35**

Limitations of the calculation:

- It has been assumed that the only difference in GHG emissions related to the production and disposal of combustion and electric cars is the battery, which needs to be added to the electric cars. Since it is the difference between the one million and the baseline scenario that is of interest, items which are the same in both scenarios have not been included in the calculation. Therefore, Table 5.3 only shows the batteries and not other parts of the cars that need to be produced.
- The calculation includes the total car fleet in Denmark in 2021. However, 78,000 hybrid cars have not been included in the calculation since these are assumed to be the same in both scenarios.
- It has been assumed that the conventional cars replaced by electric cars are new cars. This is because the decision context is assumed to be best represented by a situation where consumers decide to either buy a new electric car or a new combustion car. Of course, there could also be situations where additional incentives to phase out combustion cars were introduced by financial subsidies. If such a situation was considered, the shortened lifetime of the old cars, would also need to be considered. This should be compensated by the production of additional new electric cars. This scenario could be carried out, but it would need data on: how much product lifetime is lost from outphasing existing combustion cars, average product lifetime, and average total kilometres driven by electric cars.
- It should be noted that the price difference in using combustion and electric cars is not considered. This means that potential rebound-effects are not addressed. Since the life cycle costs of electric cars are currently higher than combustion cars, the GHG savings would be higher if rebound effects were included.

5.2 90% of Danish beef consumption in households is replaced with pork/chicken

This scenario calculates the GHG effect of replacing 90% of the beef consumption in households with pork and chicken meat. The calculation shows that this reduces the GHG emissions by 6.8 million tonne CO_2-eq. Normalising this to the Danish population, this corresponds to a reduction of the Danish consumption-based GHG footprint with 1.2 tonne CO_2-eq from 12.9 to 11.7 tonne CO_2-eq per capita. This corresponds to a 9% reduction in the Danish consumption-based footprint.

The calculation is fully based on data in EXIOBASE v4, and by assuming that beef, pork and chicken products used by Danish households are fully substitutable, i.e. 1 kg beef can be fully replaced by 1 kg pork or chicken, without affecting losses, uses of other food items, and energy for storage and preparation.

The calculation is summarised in Table 5.4.

Table 5.4. GHG emissions related to replacing 90% of the beef consumption in households with pork and chicken meat. “All other products” refer to the residual Danish consumption-based emissions.

Baseline scenario			
Product	**Consumption (tonne)**	**GHG intensity (tonne CO2-eq./tonne)**	**GHG emissions (million tonne CO2-eq.)**
Beef	91,164	87.3	7.96
Pork	22,666	5.2	0.12
Chicken	94,498	3.0	0.28
All other products			65.5
Total	**208,329**		**73.9**
Reduced beef scenario			
Product	**Consumption (tonne)**	**GHG intensity (tonne CO2-eq./tonne)**	**GHG emissions (million tonne CO2-eq.)**
Beef	9,116	87.3	0.80
Pork	63,690	5.2	0.33
Chicken	135,522	3.0	0.40
All other products			65.5
Total	**208,329**		**67.0**
Effect of scenario = 1 million elec cars minus baseline scenario			
Product	**Consumption (tonne)**	**GHG intensity (tonne CO2-eq./tonne)**	**GHG emissions (million tonne CO2-eq.)**
Beef	-82,048	87.3	-7.16
Pork	41,024	5.2	0.21
Chicken	41,024	3.0	0.12
All other products			0.00
Total	**0**		**-6.8**

Limitations of the calculation:

- The scenario applies only to meat consumption in households, i.e. the use of meat in catering and restaurants is not changed.
- The calculation is applied proportionally to average meat production and consumption of beef, pork and chicken respectively. Hence, variations in different cuts are not considered.
- It should be noted that the price difference in using beef, pork and chicken products is not considered. This means that potential rebound-effects are not addressed. Since the life cycle costs of pork and chicken products are currently lower than for beef products, the GHG savings would be smaller if rebound-effects were included.

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Appendices

Appendix 1: Main data for EXIOBASE v4

The table below summarises the main data sources used to construct EXIOBASE v4.

Bilateral trade		
Products:	**Dataset**	**external link**
agricultural products	FAOSTAT: Detailed trade matrix	https://www.fao.org/faostat/en/#data/TM
Auto, bus, truck	COMTRADE	https://comtrade.un.org/data/
Other physical flows	BACI	http://www.cepii.fr/cepii/en/bdd_modele/presentation.asp?id=37
Monetary flows	Exiobase Monetary	https://zenodo.org/record/4277368#.YlV9EchBxaQ
Trade (Total Imports and Exports)		
Products:	**Dataset**	**external link**
Agricultural and food products	FAOSTAT: Supply Utilization Accounts	https://www.fao.org/faostat/en/#data/SCL
Energy products	IEA: World Energy balances	https://www.iea.org/data-and-statistics/data-product/world-energy-balances
Monetary flows	Exiobase Monetary	https://zenodo.org/record/4277368#.YlV9EchBxaQ
Production		
Products:	**Dataset**	**external link**
Agricultural products	FAOSTAT: Crops and livestock products	https://www.fao.org/faostat/en/#data/QCL
Fishery	FAOSTAT: Fisheries and Aquaculture	https://www.fao.org/fishery/en/home
Mining and metal products	Global Material Flows Database (UN IRP (2021) - International Resource Panel)	https://owncloud.wu.ac.at/index.php/s/JTtaoj9jxLqfxEX
	British geological survey - Minerals UK	https://www2.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS
	US geological survey	https://www.usgs.gov/centers/national-minerals-information-center/commodity-statistics-and-information
Secondary steel	Worldsteel	https://worldsteel.org/wp-content/uploads/Steel-Statistical-Yearbook-2017.pdf
Manufactured products	PRODCOM (UE)	https://ec.europa.eu/eurostat/web/prodcom/data/database
	UN Industrial Commodity Statistics	http://data.un.org/Explorer.aspx
	Chinese Bureau of Statistics	http://www.stats.gov.cn/english/
Auto, bus, truck	International Organization of Motor Vehicle Manufacturers	https://www.oica.net/category/production-statistics/2016-statistics/
Energy products	IEA: World Energy balances	https://www.iea.org/data-and-statistics/data-product/world-energy-balances
Fertilisers	FAOSTAT: Fertilizers by Nutrient	https://www.fao.org/faostat/en/#data/RFN
	FAOSTAT: Fertilizers by Product	https://www.fao.org/faostat/en/#data/RFB
Monetary flows	Exiobase Monetary	https://zenodo.org/record/4277368#.YlV9EchBxaQ

Appendix 2: Breakdown of results

The following breakdown of results are available in an excel file:

- 19 product categories: classification defined manually: ensuring few, homogeneous categories.
- 69 product categories: classification defined manually.
- DST 44 product categories: classification following the product categories in DST: Statistics Denmark (2023b).
- EXIO 282 product categories: most detailed breakdown based on calculation.