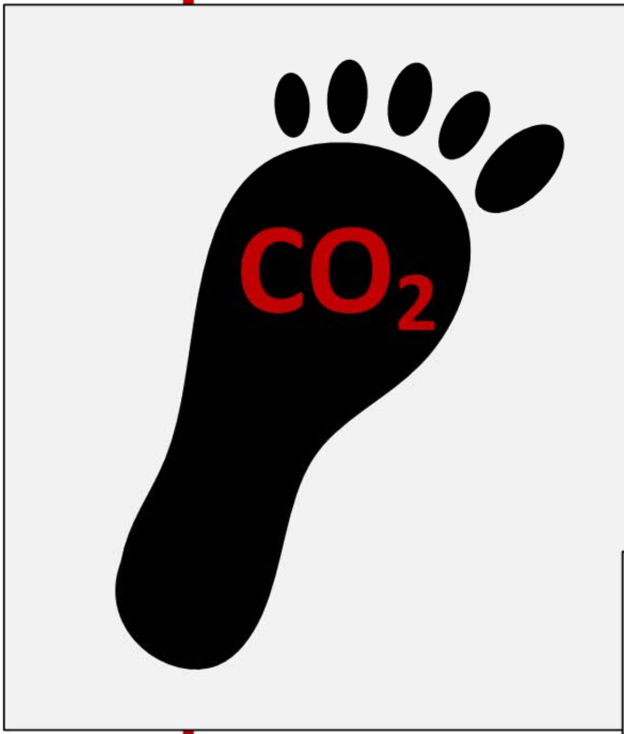
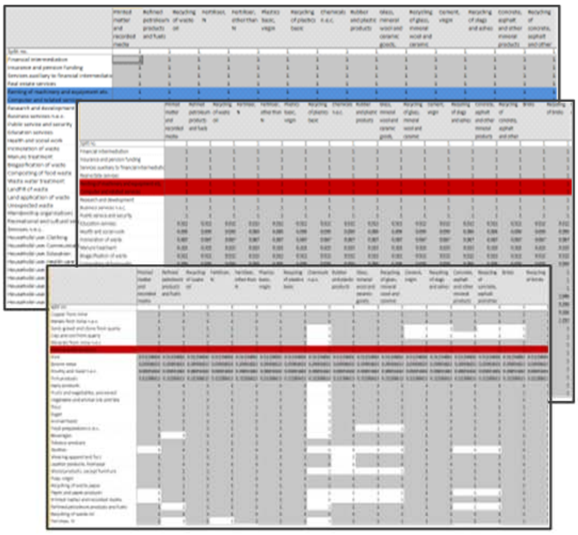
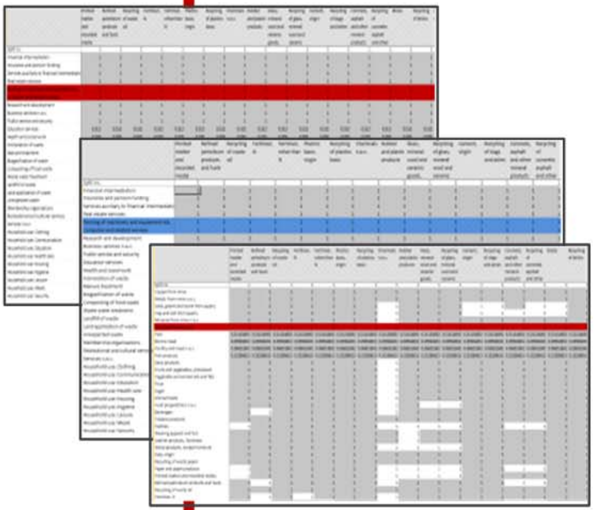
The carbon footprint of Danish production and consumption

- Literature review and model calculations







DANISH ENERGY AGENCY

Preface

The report is carried out for the Danish Energy Agency by 2.-0 LCA consultants.

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Table of Contents

Dansk resume

Baggrund og formål

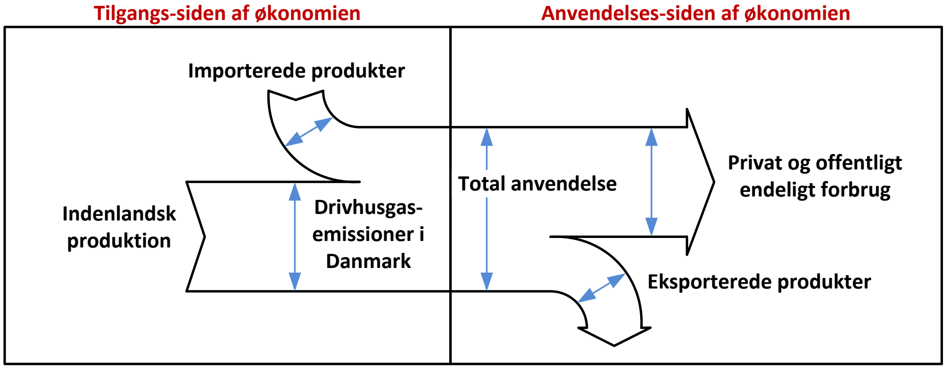
For at forbedre kendskabet til Danmarks ”carbon footprint” har Energistyrelsen fået udarbejdet nærværende studie, som omhandler Danmarks forbrugsrelaterede drivhusgasudledninger. Udover at projektet tilvejebringer nye resultater, består projektet også af et review af eksisterende studier. Fokus i reviewet er at fremhæve metodologiske forskelle og andre aspekter, som kan være årsag til forskelle i resultater studierne imellem.

Projektets primære formål er at tilvejebringe det bedst mulige estimat for Danmarks forbrugsrelaterede ”carbon footprint”. Med carbon footprint menes drivhusgasemissioner udtrykt i kuldioxidækvivalenter (CO_2-ækv.). Forbrugsrelaterede drivhusgasemissioner er i dette projekt defineret som udledninger fra dansk økonomi inklusiv import og fratrukket emissioner fra eksport. Således er hele livscyklus for produkter importeret til Danmark medregnet, og dermed er det ikke kun emissioner udledt i Danmark, som er medregnet. Data vedrørende produktion, import og eksport af varer og serviceydelser er fra input-output (IO)-tabeller, som er udvidede med miljødata. Et andet formål i projektet er, at give et overblik over importerede/eksporterede produkter og serviceydelser, samt drivhusgasudledningerne relateret til dette.

En input-output tabel er en tabel, som indeholder data for alle transaktioner af produkter mellem forskellige industrisektorer og husholdninger. Udvidelse af en input-output tabel med miljødata betyder, at der til hver industri- og husholdningssektor tilføjes emissioner. De udvidede input-output tabeller kan anvendes til beregning af nationale forbrugs- og produktions-carbon footprints i et livscyklusperspektiv.

Danmarks carbon footprint er estimeret ved: 1) Evaluering af allerede eksisterende studier, som omhandler Danmarks carbon footprint, og 2) detaljerede modelberegninger med udgangspunkt i en eksisterende model, som er tilpasset for at opnå en højere grad af fuldstændighed og nøjagtighed. Modellen, som er valgt til de videre beregninger, er FORWAST modellen, som er en dansk/europæisk input-output model, der er udvidet med miljødata. Modellen blev udviklet i forbindelse med et EU finansieret forskningsprojekt under det 6. rammeprogram. Den oprindelige model er, i nærværende projekt, tilpasset. Tilpasningerne inkluderer forbedret modellering af importerede produkter, tilføjelse af emissioner fra ”indirect land use changes” (iLUC), samt tilføjelse af forhøjet drivhuseffekt fra flyudstødning i stor højde.

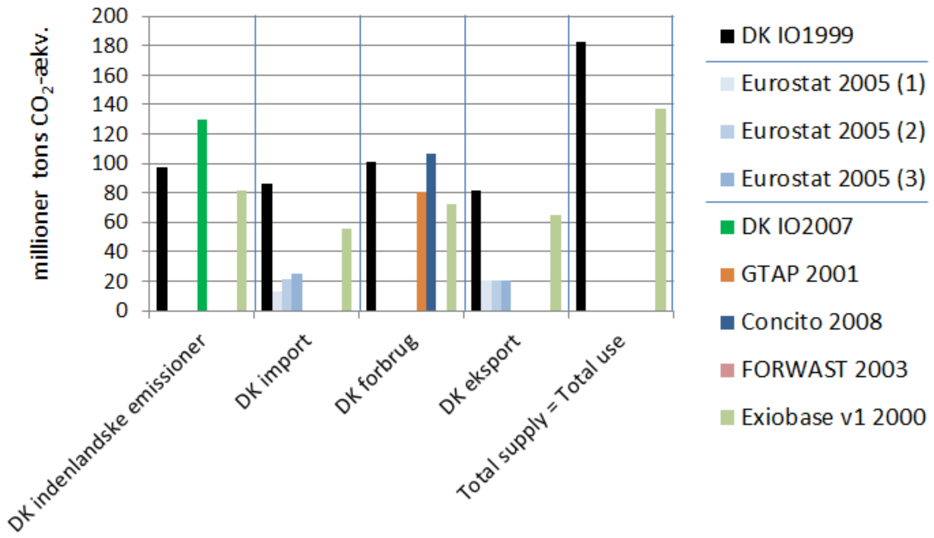
Et lands carbon footprint kan analyseres i forskellige perspektiver. På ’supply’-siden af landets økonomi skelnes mellem indenlandske emissioner og emissioner udledt i forbindelse med produktion af importerede produkter. På ’use’-siden skelnes mellem emissioner fra dansk forbrug og eksporterede produkter. De forskellige perspektiver er illustreret i **Figur 0.1** herunder.



Figur 0.1: Forskellige perspektiver som kan anvendes til analyse og opgørelse af emissioner relateret til landes carbon footprint.

Review af eksisterende studier

Syv eksisterende studier /databaser omhandler drivhusgasudledninger fra den danske økonomi, og i disse er primært anvendt en input-output tilgang. Nogle af dem fokuserer udelukkende på Danmark, mens andre har et europæisk eller globalt perspektiv. Studierne omfatter perioden 1999-2008, men en sammenhængende tidsserie kan dog ikke etableres ved brug af disse studier. Det skyldes at de anvendte metoder er forskellige. **Figur 0.2** viser en oversigt over de danske carbon footprint resultater, som er undersøgt nærmere i gennemgangen af eksisterende studier. Bemærk at resultatsøjlerne i **Figur 0.2** er grupperede, således at de matcher de forskellige perspektiver (blå pile) i **Figur 0.1**: ’Privat og offentligt endeligt forbrug’ svarer til ’DK forbrug’, og ’Total anvendelse’ svarer til ’Total supply = Total use’.



Figur 0.2. Oversigt over resultater for dansk økonomis drivhusgasudledninger baseret på review af eksisterende studier.

De fleste af de evaluerede studier inkluderer de vigtigste drivhusgasser, som er CO_2, CH_4 og N_2O. Emissioner fra skibe og fly udenfor landets grænser er også inkluderet i de fleste af studierne, dog med undtagelse af Eurostat 2005-studiet. Med hensyn til luftfart tager ingen af de eksisterende studier højde for den forhøjede drivhuseffekt fra flyudstødning i stor højde.

En af de største forskelle mellem studierne er modellering af emissioner fra importerede produkter. Tilgangene spænder lige fra slet ikke at inddrage emissionerne, til at antage at importerede varer har samme drivhusgasintensitet som danske varer, og videre til at anvende landsspecifikke IO-tabeller for de lande hvorfra produkter importeres. En anden forklaring på forskelle i resultater er hvorvidt LULUCF[1] emissioner er inddraget eller ikke. Det eneste studie som forholder sig specifikt hertil er Concito-studiet.

Hvad angår indenlandske emissioner varierer studiernes resultater mellem 80 og 130 millioner tons CO_2-ækv. De højeste emissioner er rapporteret i DK IO2007-studiet, og kan forklares med at biogene CO_2-emissioner[2] er medregnet. Set i forhold til import og eksport af varer, viser Eurostat 2005-studiet markant lavere resultater end de øvrige. Resultaterne for dansk forbrug er omtrent det samme for DK IO1999- og Concito-studiet; omkring 100 millioner tons CO_2-ækv. De øvrige studier (GTAP, FORWAST og Exiobase) viser forbrugsbaserede emissioner på 68-81 millioner tons CO_2-ækv. Med hensyn til total produktion og forbrug ligger Exiobase-studiet lavest med 138 millioner tons CO_2-ækv., mens DK IO1999- og FORWAST-studierne begge viser udledninger på omkring 180 millioner tons CO_2-ækv. Disse studier er i god overensstemmelse på supply-siden (indenlandske emissioner og import) men i mindre grad på use-siden (forbrug og eksport).

Overordnet set viser reviewet, at resultaterne fra studierne er forskellige, og at de anvendte metoder og antagelser er årsag hertil. Det skal bemærkes, at konceptet med input-output tabeller udvidet med miljødata er forholdsvist nyt, og det forventes, at i takt med at interessen for denne tilgang øges, vil resultaterne fra forskellige studier også komme nærmere på hinanden.

Data og metoder

På baggrund af reviewet af de eksisterede studier blev FORWAST-modellen valgt til brug for nærværende studie. En række modificeringer af modellen blev foretaget for at forbedre modelleringen og medtage manglende aspekter. FORWAST-projektet er et EU forskningsprojekt under det 6. rammeprogram og blev afsluttet i 2010. Som en del af projektet blev der udviklet input-output modeller med miljødata for alle EU27-lande. Udgangspunktet for den danske input-output tabel i FORWAST-modellen var en detaljeret supply-use tabel (dansk: tilgang-anvendelses-tabel) for 2003 fra Danmarks Statistik. Denne blev tilpasset til det generelle format anvendt i FORWAST (134 produkter og 134 industrisektorer). Ud over data for økonomiske transaktioner, inkluderer FOREWAST-projektet også data for massestrømme af både produkter og affald. Desuden blev nogle af produkterne/industrisektorerne underopdelt ved brug af detaljerede livscyklus-opgørelser og andre datakilder. I FORWAST-projektet blev nationale emissionsopgørelser fra Danmarks Statistik (2009) anvendt. Endvidere blev ressourceinput til dansk økonomi også inkluderet i de udvidede tabeller.

FORWAST input-output modellen er en såkaldt hybridmodel, da den er baseret på både økonomiske data fra nationalregnskabet og processpecifikke data fra livscyklusopgørelse (anvendt til underopdeling). Samtidig optræder transaktionerne i modellen i forskellige enheder: masse for fysiske produkter, energienheder for elektricitet/varme/damp og monetære enheder for andre flows så som serviceydelser. Produkter som importeres af Danmark er alle modelleret, som om de var produceret i EU27.

I nærværende studie blev den oprindelige FORWAST model modificeret med henblik på:

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[1] LULUCF (land use, land use change and forestry) refererer til emissioner forårsaget vedligeholdelse/bearbejdning af land (fx dræning) og ændringer i arealanvendelsen (fx skovrydning).

[2] Biogene CO_2-emissioner er emissioner fra forbrænding/nedbrydning af organisk materiale

- at tage bedre højde for produkter importeret fra lande udenfor EU27
- at omfatte emissioner, der er forbundet med indirect land use changes (iLUC)[3], og
- at inkludere den forhøjede drivhuseffekt fra flyudstødning i stor højde.

Den danske input-output tabel, såvel som EU27 tabellen, skelner mellem produkter importeret fra EU27 og lande udenfor EU27. Modificeringen vedrørende modellering af produkter importeret fra lande udenfor EU27, blev udført ved at kopiere EU27-tabellen, og herefter tilpasse energisektoren for i højere grad at afspejle elektricitetsmixet udenfor EU27.

Emissioner fra ’indirect land use changes’ (iLUC) er oftest ikke inkluderet i livscyklusvurderinger og input-output-analyser. Det er en betydelig mangel på fuldstændighed, da skovrydning bidrager betragteligt til den globale drivhusgasudledning. Nogle af de seneste studier indikerer, at skovrydning (LULUCF) udgør omkring 9% af de globale CO_2-emissioner.

Når iLUC modelleres, er det vigtigt at tage højde for, at den væsentligste skovrydning sker langt væk fra de drivende kræfter bag skovrydningen. Det er i den anvendte iLUC model antaget, at skovrydning er forårsaget af ændringer i den generelle efterspørgsel på land. Derfor fører efterspørgsel på land i Danmark også til effekter i andre dele af verden.

De vigtigste årsager til den forhøjede drivhuseffekt fra flyudstødning i stor højde er dannelse af lineære kondensskyer og øget dannelse af cirrus skyer. Bidrag til global opvarmning herfra er medtaget som en modifikation af modellen.

Tilpasningerne af den originale FORWAST model beskrevet i ovenstående øgede drivhusgasudledninger fra det danske forbrug med 18%, hvoraf langt det meste er relateret til iLUC.

Resultater

Eftersom FORWAST-modellen er baseret på år 2003, repræsenterer alle resultater også 2003. En simpel makroøkonomisk og miljømæssig analyse er udført for at se, om der er indikationer på at Danmarks forbrugsrelaterede emissioner er ændret siden 2003 (**afsnit 5.2**). Analysen fokuserede på følgende indikatorer: Indenlandske emissioner, bruttonationalproduktet og importandelen af den samlede forsyning af varer og tjenester. På baggrund af de observerede indikatorer har det ikke været muligt, at afgøre om Danmarks forbrugsrelaterede emissioner er steget eller faldet siden 2003. Baseret på de tilgængelige data og modeller vurderes det, at det bedste estimat på Danmarks forbrugsrelaterede emissioner i dag (2013) formentlig er omtrent det samme som i 2003, som er modellens referenceår.

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[3] iLUC: Al anvendelse af produktivt land øger det generelle pres på grænsen mellem ”natur” og land forvaltet af mennesker. Anvendelse af land i Danmark påvirker således, via eksempelvis afgrødesubstitutioner, skovrydningen i andre dele af verdenen samt takten hvormed landbrugsland intensiveres. Disse effekter kaldes ’indirect land use changes’ (iLUC). At effekterne er *indirekte* refererer til, at årsagen (anvendelse af land) til effekterne (afskovning og emissioner fra intensivering af landbruget) oftest foregår vidt forskellige steder i verden.

Danmarks forbrug

Emissioner fra dansk forbrug er 80,5 millioner tons CO_2-ækv. Dette svarer til 15,0 tons CO_2-ækv per indbygger i Danmark og 0,0575 kg CO_2-ækv. per DKK[4] BNP.

Det forbrugsbaserede danske carbon footprint er beregnet som indenlandske emissioner plus emissioner fra importerede produkter fratrukket emissioner fra eksporterede produkter. Hertil er tilføjet bidrag fra iLUC og den forhøjede drivhuseffekt fra flyudstødning i stor højde.

Danske indenlandske emissioner rapporteres til FN's konvention om klimaændringer (UNFCCC) og Kyotoprotokollen. I 2003 var disse emissioner 74,1 millioner tons CO_2-ækv. (Statistics Denmark 2003a). Når emissioner fra international transport[5] er medregnet, så er 'de officielle danske emissioner' 100,6 millioner tons CO_2-ækv. De tilsvarende emissioner i den oprindelige FORWAST-model er 94,4 millioner tons CO_2-ækv. Årsagen til denne forskel er: 1) I FORWAST-modellen er affaldssektoren modelleret på en særlig måde, som afviger fra de 'officielle' rapporterede emissioner. Dette indebærer, at mængden af alle affaldsflows beregnes, hvorefter dette kombineres med emissioner fra de forskellige typer affaldsbehandling af hver affaldsfraktion. 2) En forbedret opgørelse over dansk landbrugs emissioner er implementeret i FORWAST-modellen (Hermansen et al. 2010). Det skal bemærkes at indenlandske emissioner fra 'land use change' (LUC) og skovbrug (tilsammen LULUCF) i Danmark ikke er inkluderet. Dette skyldes, at det i input-output-modeller til analytiske formål ikke giver mening at inkludere LULUCF for enkelte lande. Hvis dette var inkluderet, ville man se mærkeligt resultater. Fx ville en analyse af et øget forbrug af landsbrugs- og skovbrugsprodukter i Danmark resultere i negative LULUCF emissioner, fordi skovarealet i Danmark er stigende, hvilket medfører negative LULUCF emissioner. Men bare fordi et land har et stigende skovareal/faldende landbrugsareal, betyder det jo ikke, at en øget efterspørgsel på arealforbrugende produkter resulterer i at der vil lagres yderligere kulstof i skovene. I forhold til LULUCF, så sker de helt store ændringer udenfor Danmarks grænser (fx skovrydning i Sydamerika, Sydøstasien og Centralafrika), og disse ændringer sker på grund af ændringer i den globale efterspørgsel på produktivt land. Derfor modelleres LULUCF som et rent globalt marked, hvor LULUCF i Danmark antages at skyldes andre forhold end forbrug, fx regulering af skovarealet og landbruget.

Emissioner fra importerede produkter udgør i den oprindelige FORWAST-model 83,6 millioner tons CO_2-ækv. Modelleringen af importerede produkter er, som tidligere beskrevet, tilpasset i nærværende studie. Når der tages højde for at energimixet i EU27 og i resten af verden (RoW) er forskelligt, udgør emissioner relateret til importerede produkter i Danmark 87,2 millioner tons CO_2-ækv.

De totale emissioner fra dansk økonomi kan beregnes som de indenlandske emissioner på 94,4 millioner tons CO_2-ækv. plus emissioner fra importerede produkter svarende til 87,2 millioner tons CO_2-ækv. Dette giver en total udledning på 182 millioner tons CO_2-ækv. For at opnå et resultat, som repræsenterer det samlede danske forbrug, skal vi fratrække emissioner fra eksporterede produkter. De eksportrelaterede emissioner udgør 112 millioner tons CO_2-ækv. Emissioner relateret til dansk forbrug kan hermed beregnes til 182 millioner tons CO_2-ækv. fratrukket 112 millioner tons CO_2-ækv, hvilket giver 70 millioner tons CO_2-ækv.

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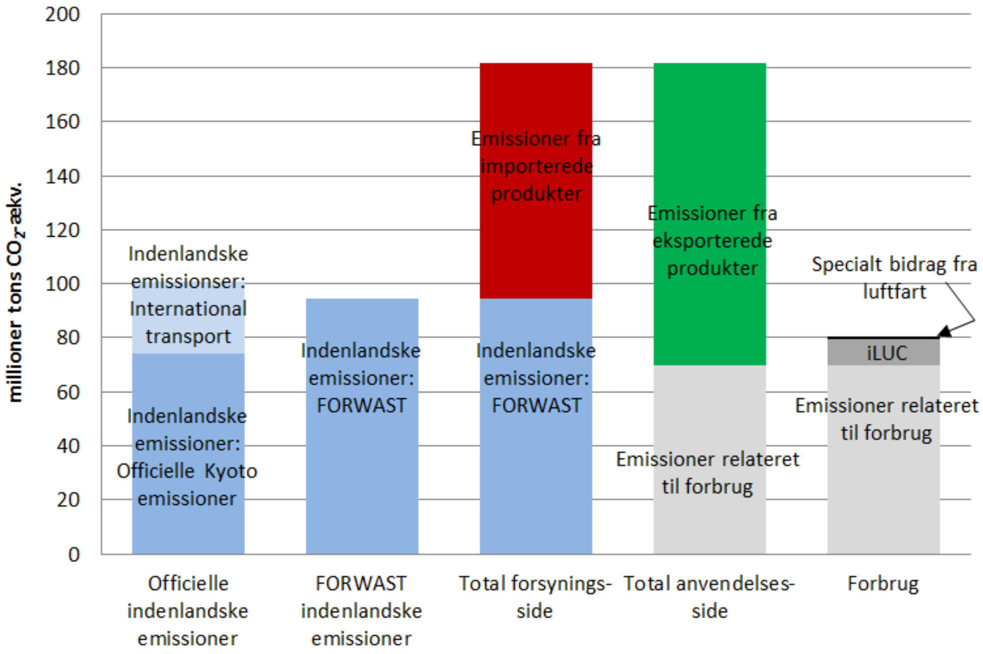
[4] DKK2003 valuta.

[5] Dette omfatter emissioner fra danske skibe, fly, lastbiler m.m., som tankes op i udlandet.

Vi vil nu også medregne bidraget fra ’indirect land use changes’ (iLUC), som udgør 9,9 millioner tons CO_2-ækv. Når bidraget fra iLUC er medregnet, udgør emissioner fra dansk forbrug således 80 millioner tons CO_2-ækv.

For at komme til det endelige estimat på det danske forbrugsrelaterede carbon footprint, mangler vi kun at tilføje den forhøjede drivhuseffekt fra flyudstødning i stor højde, som udgør 1,2 millioner tons CO_2-ækv. Det endelige estimat for carbon footprint af dansk forbrug udgør hermed cirka 81 millioner tons CO_2-ækv.

Ovenstående beskrivelse/beregning er illustreret i **Figur 0.3**.



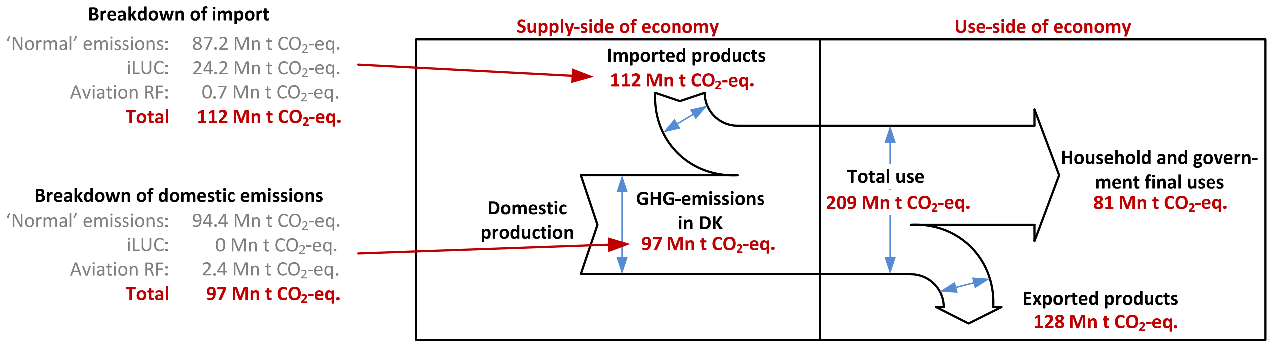
Figur 0.3. Danmark 2003. Trinvis beskrivelse af, hvorledes det endelige forbrugsrelaterede resultat nås ved start i de officielle nationale emissionsopgørelser. Hver resultatkolonne repræsenterer et skridt som beskrevet i teksten over figuren. Udgangspunktet er kolonnen til venstre, og det endelige resultat kan aflæses i kolonnen til højre.

Figur 0.3 beskriver trinnene for at komme fra de officielle Kyoto-emissionsopgørelser til det endelige forbrugsrelaterede resultat. **Tabel 0.1** opsummerer virkningen af de tre modificeringer af den oprindelige FORWAST-model.

Tabel 0.1: Virkningen på resultater fra de tre modificeringer af den originale FORWAST-model.

	Original version	**Modificering 1:** modificeret import	**Modificering 1+2** modificeret import og inkludering af iLUC	**Modificering 1+2+3** modificeret import, inkludering af iLUC, og forhøjet drivhuseffekt fra flyudstødning
Modificering af den oprindelige FORWAST-model				
År	2003	2003	2003	2003
Importdata	EU27	**EU27 + RoW**	**EU27 + RoW**	**EU27 + RoW**
Inkl. iLUC	nej	nej	**Ja**	**Ja**
Inkl. forhøjet drivhuseffekt (flyudstød.)	nej	nej	nej	**Ja**
Resultater	millioner tons CO_2-ækv.	millioner tons CO_2-ækv.	millioner tons CO_2-ækv.	millioner tons CO_2-ækv.
'Supply side '				
DK indenlandske emissioner	94,4	94,4	94,4	96,8
DK import	83,6	87,2	111	112
'Use side'				
DK forbrug	68,2	69,5	79,3	80,5
DK eksport	110	112	126	128
'Total supply' = 'total use'	**178**	**182**	**206**	**209**

Kolonnen længest til højre i **Tabel 0.1** repræsenterer de endelige resultater for den danske økonomi. Disse resultater er illustreret visuelt i nedenstående figur, der viser drivhusgasemissionerne fra forskellige analytiske perspektiver. De særlige bidrag fra iLUC og flyudstødning er specificeret i 'Breakdown' af emissioner til venstre i figuren. Det fremgår, at alle iLUC emissioner er placeret som import. Det betyder, at al skovrydning og intensivering landbrugsproduktionen foregår uden for Danmark. Bemærk, at det ikke betyder, at kun importerede produkter er forbundet med iLUC; iLUC er forårsaget af enhver efterspørgsel på produktiv land - også i Danmark.



Figur 0.4. Danmark 2003. Illustration af drivhusgasemissionerne vedrørende dansk økonomi for forskellige perspektiver i analysen. Bidragene fra iLUC og særlig bidrag fra luftfarten, er vist i 'breakdown' af import-og indenlandske emissioner til venstre.

Sammenlignet med de reviewede studier vedrørende danske økonomis drivhusgasemissioner i **Figur 0.2**, så er de beregnede emissioner højere end i FORWAST- og Exiobase-studierne, svarer til emissionerne i GTAP-studiet og lavere end resultaterne i DK IO1999 og Concito-studierne.

Omkring 58% af emissionerne fra det danske forbrug forekommer i Danmark. De væsentligste indkøbte produkter i husholdninger/staten i forhold til drivhusgasemissioner er: el/varme, direkte emissioner fra forbrænding af brændstoffer (hovedsageligt fra personbiltransport), og ejendomsvirksomhed, dvs boliger. Det fremgår også, at sociale ydelser som sundhed og socialt arbejde, offentlig service og sikkerhed og uddannelse er blandt indkøb, der forårsager betydelige emissioner.

I forhold til arealanvendelse (beslaglæggelse af areal målt i hektarår), er det danske forbrug forbundet med et arealforbrug på ca. 1,6 gange Danmarks areal. Dette arealforbrug vedrører produktivt areal (plante-, dyre-og træproduktion og bebyggede arealer) for at producere alle de produkter, der forbruges af de danske borgere.

Eksport

Drivhusgasemissionerne forbundet med produktion af eksportvarer er 128 mio ton CO_2-ækv. De eksporterede produkter med de højeste drivhusgasemissioner er skibstransport, kødprodukter (svinekød), og elektricitet.

Import

De samlede drivhusgasemissioner relateret til importerede produkter er 112 mio ton CO_2-ækv. De vigtigste udledere af drivhusgasser i produktsystemet relateret til dansk import er: el/varmeproduktion (i RoW), transport med skib i EU27, og indirect land use changes (iLUC).

Indenlandske emissioner

Indenlandske emissioner er hvad der typisk rapporteres som de officielle nationale emissioner. Ifølge modelberegningerne, er de indenlandske emissioner 97 mio ton CO_2-ækv. (inklusiv emissioner fra international transport). De vigtigste udledere af drivhusgasser i Danmark er: el/varmeproduktion, transport med skib, og direkte emissioner fra husholdninger/regeringen (dvs. hovedsageligt fra personbiltransport).

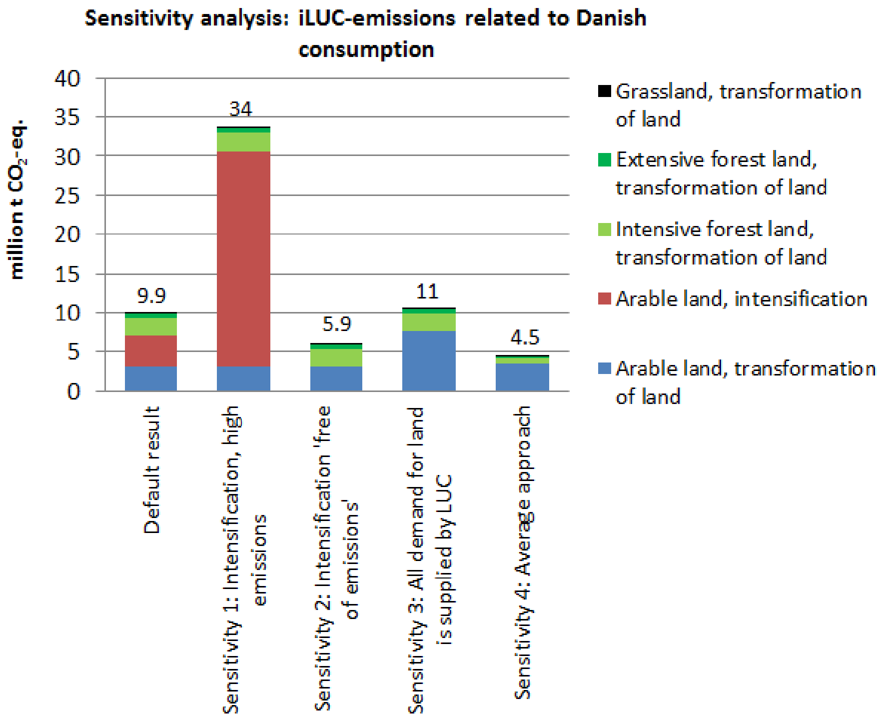
Usikkerheder i forhold til 'indirect land use changes' (iLUC)

Drivhusgasemissionerne fra iLUC har vist sig at være væsentlige; omkring 12% af emissionerne fra dansk forbrug. Den anvendte iLUC-model er baseret på en marginal tilgang, hvor iLUC-resultaterne repræsenterer emissionerne i forhold til en situation, hvor det danske forbrug ikke eksisterede. For at illustrere forskellen til en gennemsnitsbetragtning er en forenklet udgave heraf også gennemregnet (se følsomhedsanalyse 4 i **Figur 0.5** nedenfor). Gennemsnitsbetragtningen fordeler ligeligt alle LULUCF emissioner (som det er, uden at tage højde for tidsmæssige aspekter ved emissioner fra skovrydning) ud på alle arealer i brug globalt. Det kan nemt påvises, at denne tilgang mangler en årsagssammenhæng; hvis de globale LULUCF-emissioner var negative, dvs. en situation med genplantning af skov, så ville modelresultatet af et øget forbrug af produkter (som kræver land, fx landbrugsprodukter) føre til flere negative emissioner/mere genplantning af skov. Dette er naturligvis ikke sandsynligt.

De væsentligste usikkerheder i forbindelse med modellering af iLUC er vurderet til at være:

- identificering af hvor meget en ændring i efterspørgslen på land forårsager henholdsvis skovrydning og intensivering af land, der allerede er i brug
- modellering af tidsmæssige aspekter vedrørende emissioner fra skovrydning
- kulstoflagre i land før og efter ændring i arealanvendelsen
- identifikation af hvorledes intensivering opnås samt de relaterede emissioner

Usikkerhederne i forhold til identificering af hvorledes intensivering opnås samt de relaterede emissioner er vurderet at udgøre den største usikkerhed i modellen. Derfor er en række følsomhedsanalyser gennemregnet for at analysere dette. Nedenfor i **Figur 0.5** belyser følsomhedsanalyse 1, 2 og 3 forskellige aspekter i forbindelse med emissioner fra intensivering.



Figur 0.5. Resultat af følsomhedsanalyser vedrørende modellering af iLUC. Resultaterne viser ILUC drivhusgasemissioner relateret til det danske forbrug 2003. Enhed: millioner tons CO_2-ækv.

Det fremgår af ovenstående følsomhedsanalyser, at standardantagelsen (default resultat) fører til et resultat, som ligger indenfor de udførte følsomhedsanalyser. Forskellene i resultaterne fra følsomhedsanalysen indikerer, at usikkerhederne vedrørende iLUC er væsentlige.

Executive Summary

Background and goal

In order to improve the knowledge of Denmark's "carbon footprint", the Danish Energy Agency (DEA) has commissioned a study on the national consumption-related greenhouse gas (GHG) emissions. Besides providing new results, this study does also provide a critical review of previous studies. The focus of the review is highlighting methodological differences and any other aspects causing differences in the results obtained.

The main goal of this project is to provide the best possible estimate of Denmark's consumption-related "carbon footprint". By carbon footprint is meant GHG-emissions, expressed as carbon dioxide equivalents (CO_2-eq.). Consumption-related is defined as GHG-emissions from the Danish economy including imports, while emissions associated with exports are excluded. In this respect, the limitations of the traditional geographical approach to account for national emissions are addressed by taking into account the full life cycle of imported products to Danish economy. Data on production, imports, and exports of goods and services are obtained from environmentally-extended input-output (IO) tables. An additional goal of the project is to provide an overview of the products and services imported to and exported from Denmark, and their embedded GHG-emissions.

An input-output (IO) table is a table accounting for all transactions of products between industries and households in economy. When an IO-table is environmentally extended, this means that information on the emissions (and sometimes also other exchanges with the environment) by each industry and households are added to the table. Environmentally extended IO-tables can be used to calculate life cycle carbon footprints of national consumption and production.

Denmark's carbon footprint is studied by 1) reviewing existing studies focusing on Denmark's carbon footprint and 2) detailed model calculations using an existing model which is modified to obtain a higher degree of completeness and accuracy. The chosen model which is used for the detailed calculations is the FORWAST model, which is a Danish & European environmentally extended input-output model that was developed through an EU funded research project under the sixth framework programme. The original version of this model is associated with a number of limitations which are sought reduced by several modifications. These modifications include; improved modelling of imported products, inclusion of emissions from indirect land use changes (iLUC) and inclusion of special global warming potential from aviation. The applied iLUC model is comprehensively described and integrated with the FORWAST model.

The carbon footprint of a nation can be analyzed using different perspectives. In the supply side of economy, distinction is made between domestic emissions and emissions associated with imported products, and on the use side of economy distinction is made between emissions associated with Danish consumption and exported products. The different perspectives are illustrated in **Figure 0.1** below.

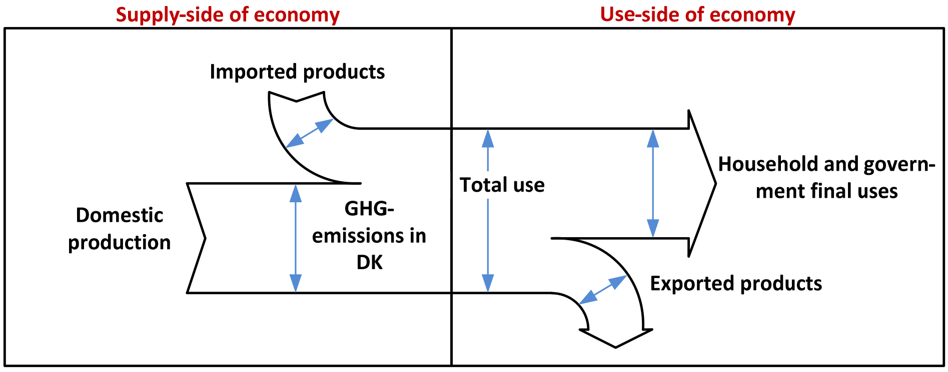


Figure 0.1: Different perspectives for analysing and accounting emissions related to national carbon footprints.

Review of previous studies

Seven studies/projects/databases have addressed the topic of GHG-emissions of the Danish economy, mostly through an IO approach. Some of them had the purpose of looking at Denmark specifically, whereas others had a wider scope, such as Europe, or even the world. From a time perspective, the studies cover the period from 1999 to 2008, however a consistent time series for Danish GHG-emissions cannot be derived, not only because there are some years not covered in this period, but most importantly, because of the lack of methodological harmonization between studies. The identified carbon footprint results for Danish economy in the review are summarized in **Figure 0.2**. Note that the groups of results columns in **Figure 0.2** match with the different perspectives (blue arrows) in **Figure 0.1**: household and government final uses corresponds to consumption.

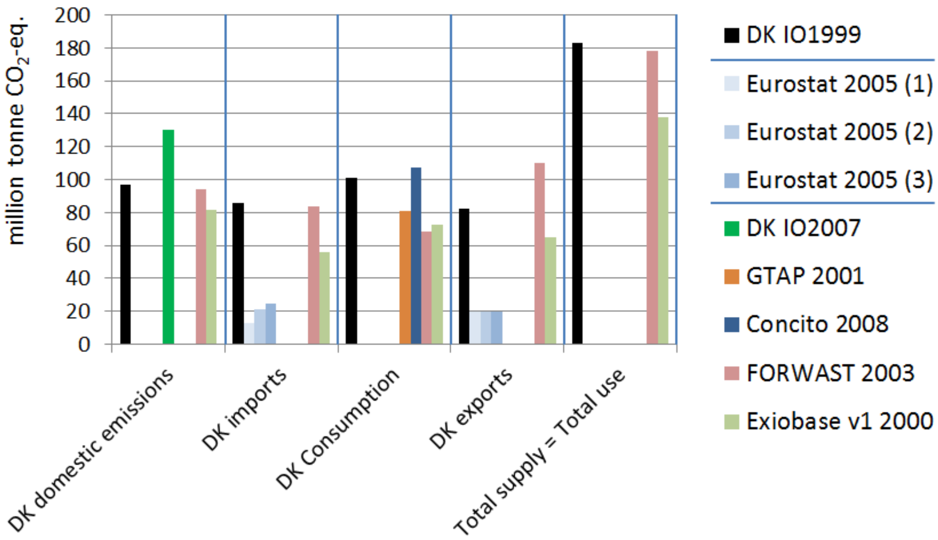


Figure 0.2. Summary of the results on GHG-emissions related to Danish economy based on the review of existing studies/models.

In terms of GHG-emissions covered, most studies include the main ones, namely CO_2, CH_4 and N_2O. Most studies also address emissions from ships and aircraft abroad, only with the exception of the Eurostat study. With regard to aircraft, the review shows that none of the studies take into account the specific impact of emissions at high altitude.

One of the main areas where studies differ is the way emissions from imports are considered. The approaches range from not considering these emissions at all, to inclusion with different levels of resolution, the lowest being the assumption that imports have the same GHG intensity as Danish production, and the highest being the consideration of country-specific efficiencies. Another source of potential disagreement in results is whether or not LULUCF[6] is included. The only study to address this explicitly is the Concito study.

For domestic emissions, the studies show results between 80 and 130 million tonne CO_2-eq. The highest emissions are reported by the DK IO2007 study, and this is explained by the fact that this study includes biogenic CO_2 emissions. For imports and exports, the Eurostat study show significantly lower results than the other studies. For Danish consumption, the DK IO1999 study and the Concito study show similar results at around 100 million tonne CO_2-eq. The other studies (GTAP, FORWAST and Exiobase) show consumption-based emissions at 68-81 million tonne CO_2-eq. For total supply = total use, Exiobase shows the lowest value, of 138 million tonnes, whereas the DK IO1999 study and FORWAST provide similar figures of around 180 million tonnes. These studies are in good agreement from the supply side (domestic emissions and imports), while the match from the use side (consumption and exports) is not as good.

In general the review shows that heterogeneous results are obtained by different studies, due to different underlying methods and assumptions. It should be noted that the concept of environmentally-extended input output tables is relatively new, and it is expected that as the interest in this approach increases, harmonization among studies will, too.

Data and methods

Based on the literature review the FORWAST model was chosen as the model for the current study, although several modifications have been made. The FORWAST project is an EU FP6 project that was finalised in 2010. As part of the project environmentally extended IO-models were developed for all EU27 countries. The starting point of the Danish IO-table in the FORWAST model was a detailed supply-use table for 2003 (~2000 products by 134 industries) provided by Statistics Denmark. This was turned into square tables (134 products by 134 industries). In addition to the accounting for economic transactions in economy, the FORWAST project also included accounting in physical (mass) transactions of products and waste flows. Also, some of the products/industries were disaggregated (subdivided). The latter was done based on data from detailed life cycle inventories, among other sources. Further, in order to harmonise the level of detail with the supply-use tables for other EU27 countries, some of the products/industries in the Danish tables were aggregated (merged). In the FORWAST project, the emissions for Denmark were obtained from the national emission inventories as provided by Statistics Denmark (2009), including those from bunkering. Further, the resource inputs to the economy were also included in the extension tables.

The FORWAST IO-model is a so-called hybrid model as it is based on economic data from the national account as well as process-specific data from life cycle inventories (used for the disaggregation), and secondly because the transactions in the model are in different units: dry matter for physical products,

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[6] LULUCF (land use, land use change and forestry) refer to emissions from maintenance/treatment of land (e.g. draining of organic soils) and changes in the land use (e.g. transformation of forest to arable land).

energy units for electricity/heat/steam and monetary units for other flows such as services. Products imported to Denmark are modelled as if they were all produced in EU27.

In the current study, the original FORWAST model was modified in order to:

- better account for products imported from outside EU27,
- include emissions associated with indirect land use changes (iLUC)[7], and
- include special radiative forcing from aviation

The Danish as well as the EU27 IO-tables specifically distinguish between import intra and extra EU27. The modifications regarding imported products from outside EU27 included a copy of the EU27 table where the energy sector was modified in order to better represent an electricity mix outside EU27.

Most often emissions from land use changes are not included in life cycle assessment and input-output analysis. This is regarded as a major lack of completeness since land use changes, such as deforestation, constitute a major contributor to global GHG-emissions. Some of the most recent studies indicate that land use changes account for around 9% of global CO_2-emissions. When modelling land use changes it is important to note that the driving forces are located far from the actual deforestation processes. The applied model assumes that land use changes are caused by the general demand for land. Hence, demanding land in Denmark does also cause deforestation somewhere else in world.

The most important of the special contributions to global warming from aviation includes radiative forcing from the formation of persistent linear contrails and contrail-cirrus.

Overall, the above modifications increased the GHG-emissions related to Danish consumption by 18% of which the contribution from indirect land use change is by far the most important.

Results

Since the FORWAST model is based on 2003, all results are presented for this year. Based on a brief macro-economic and environmental analysis in **section 5.2**, it was not possible to establish whether the total life cycle GHG-emissions related to the Danish economy has changed from 2003 to today. The observed indicators go in different directions and the different contributing trends may level each other out. Therefore, given the present data, the best estimate of GHG-emission related to Danish economy today (2013) are in the same range as in 2003 which is the base year of the FORWAST IO-model.

Danish consumption

The emissions from Danish consumption are 80.5 million tonne CO_2-eq. This corresponds to 15.0 tonne CO_2-eq. per citizen in Denmark and 0.0575 kg CO_2-eq. per DKK[8] GDP.

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[7] iLUC: Any use of productive land increases the overall pressure on the frontier between ‘nature’ and land managed by humans. In this way, use of land in Denmark affects, through e.g. crop substitutions, deforestation in other parts of the world as well as the rate at which agricultural land is intensified. These effects are here referred to as 'Indirect land use changes' (iLUC).The term ‘*indirect*’ refer to the fact that the cause (use of land) and the effects (deforestation and emissions from agricultural intensification) usually takes place in different parts of the world.

[8] DKK2003 currency

The consumption based Danish carbon footprint is calculated as emissions in Denmark plus emissions from imported products minus emissions associated with the production of exported products. On top of this is then added the contribution from indirect land use changes (iLUC) and special global warming potential from operation of aircrafts at high altitudes.

Danish domestic emissions as reported to UNFCCC as part of the Kyoto obligations. According to Statistics Denmark (2013a), these emissions were 74.1 million tonne CO_2-eq. in 2003. When adding the emissions from international transport[9], the official Danish emissions arrive at 100.6 million tonne CO_2-eq. The corresponding emissions in the original FORWAST model are 94.4 million tonne CO_2-eq. The reason for this difference is 1) The FORWAST model applies a special modelling of the waste sectors, which changes the emissions, and 2) an improved emission inventory for Danish agriculture has been implemented in the FORWAST model (Hermansen et al. 2010). It should be noted that domestic emissions from land use change and forestry (LULUCF) in Denmark have not been included. This is because it does not make sense to include national land use change in an analytic IO-model for only one country because the real drivers of deforestation are all demand for land while the major deforestation takes only place in a few countries (outside Denmark).

The emissions from imported products in the original FORWAST model are 83.6 million tonne CO_2-eq. As mentioned, the modelling of imported products in the original FORWAST model has been modified in the current study. When taking into account that the energy mix is different in EU27 and in rest of the world (RoW), the emissions related to imported products in Denmark becomes 87.2 million tonne CO_2-eq.

The total emissions from Danish economy can then be calculated as Danish emissions at 94.4 million tonne CO_2-eq. plus emissions from imported products at 87.2 million tonne CO_2-eq., i.e. we have total emissions at 182 million tonne CO_2-eq. In order to arrive at the emissions related to Danish consumption, we need to subtract the emissions associated with the production of exported products. These emissions are 112 million tonne CO_2-eq. Hence, the emissions related to Danish consumption can be calculated as 182 million tonne CO_2-eq. minus 112 million tonne CO_2-eq. equal to 70 million tonne CO_2-eq.

We now also want to add the contribution from land use induced land use change emissions. These emissions are 9.9 million tonne CO_2-eq. So when including the contribution from iLUC, the emissions from Danish consumption arrives at 80 million tonne CO_2-eq.

In order to arrive at the final estimate of the carbon footprint of Danish consumption, we only need to add the special contribution to global warming potential from operation of aircrafts at high altitudes. This adds another 1.2 million tonne CO_2-eq. Hence, the final estimate of the carbon footprint of Danish consumption is ~81 million tonne CO_2-eq.

The description/calculation described above is illustrated in **Figure 0.3**.

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[9] This includes emissions from Danish ships, aircrafts, lorries etc. which are fueled/bunkered abroad.

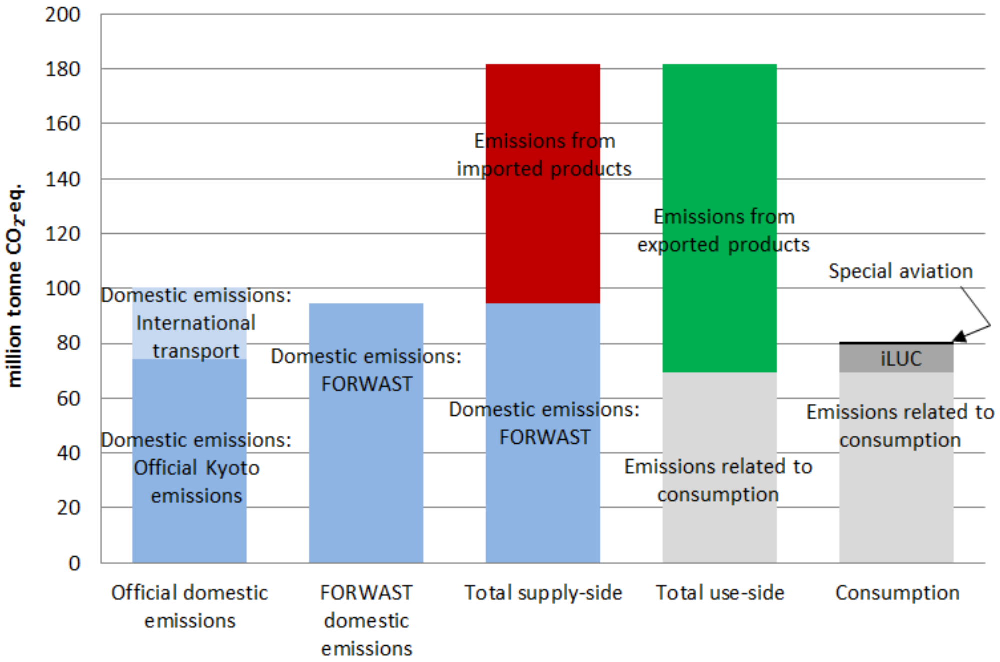

Figure 0.3: Denmark 2003. Stepwise description of how to come from traditional territory emission accounts to the final estimate of the consumption based emissions. Each result column represents a step as described in the text above the figure. The starting point is the column to the left, and the final result can be read in the column to the right.

Figure 0.3 describes the procedural steps in going from the official Kyoto results to the final consumption based results. **Table 0.1** below summarizes the effect of the three modifications made to the original FORWAST model.

Table 0.1: Effects on the results of the three modification steps of the original FORWAST model.

	Original version	**Modification 1:** modified import	**Modification 1+2** modified import, and inclusion of iLUC	**Modification 1+2+3** modified import, inclusion of iLUC, and special GWP from aviation
Modifications of the original FORWAST model				
Year	2003	2003	2003	2003
Imports data	EU27	**EU27 + RoW**	**EU27 + RoW**	**EU27 + RoW**
Inclusion of iLUC	no	no	**yes**	**yes**
Inclusion of additional GWP from aviation	no	no	no	**yes**
Results	million tonne CO_2-eq.	million tonne CO_2-eq.	million tonne CO_2-eq.	million tonne CO_2-eq.
Supply side				
DK domestic emissions	94.4	94.4	94.4	96.8
DK imports	83.6	87.2	111	112
Use side				
DK Consumption	68.2	69.5	79.3	80.5
DK exports	110	112	126	128
Total supply = total use	**178**	**182**	**206**	**209**

The last column in **Table 0.1** represents the final results for Danish economy. These results are illustrated visually in the figure below which shows GHG-emissions using different analytical perspectives. The special contributions from indirect land use changes and aviation are specified in the 'breakdown' of emissions to the left in the figure. It appears that all iLUC is placed as import. This means that all land use changes and intensification takes place outside Denmark. Note that it does not mean that only imported products are associated with iLUC; iLUC is caused by any demand for productive land – also land in Denmark.

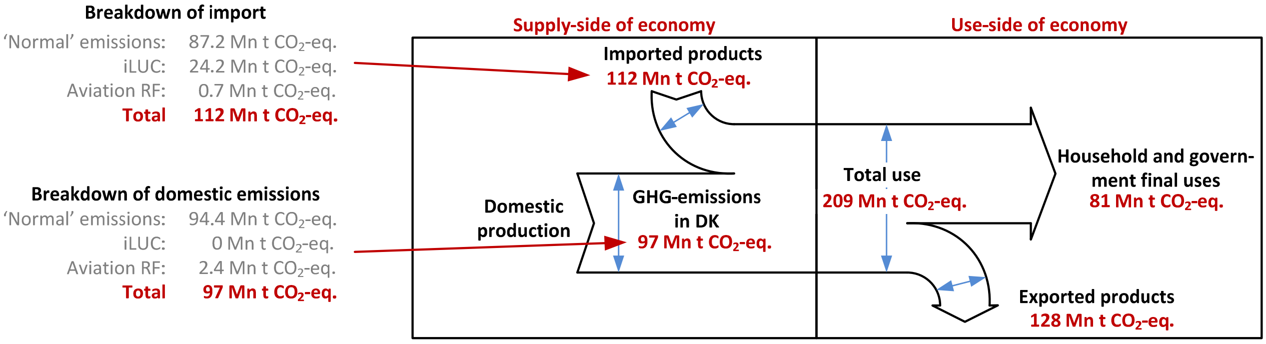

Figure 0.4: Denmark 2003. Illustration of the GHG-emissions relating to Danish economy for the different perspectives of the analysis. The contributions from iLUC and special radiative forcing from aviation are shown in the breakdown of import and domestic emissions to the left.

Compared to the reviewed other studies of GHG-emissions related to Danish economy in **Figure 0.2**, the calculated emissions are higher than those of the FORWAST 2003 and Exiobase v1 2000; similar to those of the GTAP 2001 study, and lower than the results in the DK IO 1999 and Concito 2008 studies.

Around 58% of the emissions related to Danish consumption occur in Denmark. The most important purchased products in terms of GHG-emissions are: electricity/heat, direct emissions from combustion of fuels (mainly transport, fuels), and real estate services, i.e. housing. It also appears that social services such as health and social work, public service and security and education are among purchases that cause significant emissions.

In terms of land use (occupation of land measured in hectare years), Danish consumption is associated with the occupation of more than 1.6 times Denmark's area. This occupied area refers to the land that is kept productive (plant, animal and wood production and built-up land) in order to produce all the products consumed by the Danish citizens.

Export

The GHG-emissions associated with the production of exported products in Denmark are 128 million tonne CO_2-eq. The exported products with the highest GHG-emissions are ship transport, meat products (pork), and electricity.

Import

The total GHG-emissions related to import are 112 million tonne CO_2-eq. The single most important emitters of GHG-emissions in the product system related to Danish import are: electricity/heat production in RoW, transport by ship in EU27, and transformation of forest to cropland.

Domestic emissions

Domestic emissions are what are typically reported as official national emissions. According to the model calculations, the domestic emissions are 97 million tonne CO_2-eq. (including emissions from international bunkering). The single most important emitters of GHG-emissions in Denmark are: electricity/heat production, transport by ship, and direct emissions by households/government (i.e. mainly from car driving and to a lesser extent individual heating).

iLUC uncertainties

The GHG-emissions from iLUC have shown to be of particular importance, i.e. around 12% of the emissions from Danish consumption. The iLUC model applies a marginal approach where the ILUC results represent the emissions compared to a situation where Danish consumption did not exist. For illustrative purposes, a simplified average approach has also been used (see sensitivity analysis 4 in **Figure 0.5** below). This approach simply divides the global LULUCF emissions (as is without considering any temporal issues) by the global areas of land in use. It can easily be demonstrated that this approach is lacking a cause-effect relationship; if the global LULUCF emissions were negative, i.e. in a situation with reforestation, then increased consumption of land using products would lead to more negative emissions/more reforestation which is obviously not true.

The modelling of iLUC emissions is associated with uncertainties regarding:

- identifying the share between how much a change in demand for land is met by land transformation (deforestation) and intensification of land already in use
- dealing with temporal issues relating to land transformation/deforestation
- carbon stocks in transformed land (carbon stock before and after transformation)
- identification of the means and emissions associated with intensification

The uncertainties regarding the identification of the means and emissions associated with intensification are regarded as the most significant. Therefore a number of sensitivity analyses are carried out focussing on this. Below in **Figure 0.5**, sensitivity analysis 1, 2 and 3 analyses different aspects of the above mentioned uncertainties relating to intensification.

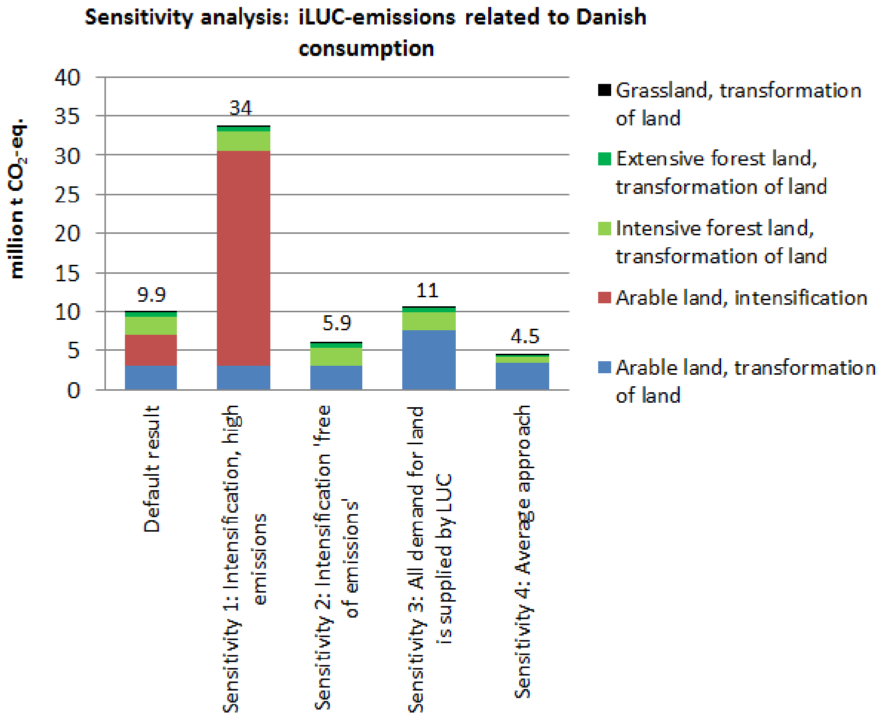

Figure 0.5: Results of sensitivity analysis evaluating the effect from different iLUC assumptions. The results show the iLUC GHG-emissions related to Danish consumption. Unit: million tonne CO_2-eq.

It appears from the iLUC sensitivity analyses that the default modelling assumption leads to results within the range of the sensitivity analyses. The differences in the results of the sensitivity analyses indicate that the iLUC emissions are associated with significant uncertainties.

List of abbreviations and terms

Abbreviations

C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq.	Carbon dioxide equivalents (generally measured as GWP100)
CF	Carbon footprint
dLUC	Direct land use changes
EUR	Euro
f	Final demand vector
GHG	Greenhouse gas
GTAP	Global Trade Analysis Project
GWP100	Global warming potential for a time horizon of 100 years
iLUC	Indirect land use changes
IO	Input-output
IPCC	Intergovernmental Panel on Climate Change
kt	Thousand tonne (kilo tonne))
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LULUCF	Land use, land use change, and forestry
MEUR	Million euro
N_2O	Dinitrogen oxide (also sometimes called nitrous oxide)
NAMEA	National accounting matrices including environmental accounts
U	Use table
UNFCCC	United Nations Framework Convention on Climate Change
V’	Supply table

Commonly used terms

Final demand vector (**f**)

Functional unit

Input-output table: the meaning of this is identical to ‘technology matrix’ and ‘direct requirement table’

Supply table (**V’**)

Technology matrix: the meaning of this is identical to ‘direct requirement table’ or ‘input-output table’

Use table (**U**)

Countries/regions

DK	Denmark
EU27	European Union (27 member countries)
GLO	Global/the World
ROW	Rest of the world

1 Introduction

1.1 Background and purpose

In order to improve the knowledge of Denmark's "carbon footprint", the Danish Energy Agency (DEA) has commissioned a study on the national consumption-related greenhouse gas (GHG) emissions. Besides providing new results, this study does also provide a critical review of previous studies. The focus of the review is highlighting methodological differences and any other aspects causing differences in the results obtained.

The main goal of this project is to provide the best possible estimate of Denmark's consumption-related "carbon footprint". By carbon footprint is meant GHG-emissions, expressed as carbon dioxide equivalents (CO_2-eq.). Consumption-related is defined as GHG-emissions from the Danish economy including imports, while emissions associated with exports are excluded. In this respect, the limitations of the traditional geographical approach to account for national emissions are addressed by taking into account the full life cycle of imported products to Danish economy. Data on production, imports, and exports of goods and services are obtained from environmentally-extended input-output (IO) tables.

An additional goal of the project is to provide an overview of the products and services imported to and exported from Denmark, and their embedded GHG-emissions.

A detailed description of the data and methods used in the calculations is provided. This involves clear descriptions of choices and assumptions made to determine the GHG intensity of products and services produced in Denmark and in other countries. In addition to the GHG-emissions typically included in official national emission reports and common input-output models, the current study also includes contributions from land use induced land use changes and special radiative forcing from operation of aircrafts at high altitudes.

This document reports the project and its results, and has been carried out by 2.-0 LCA consultants from October to December 2013.

1.2 Carbon footprint (CF)

The concept 'carbon footprint (CF)' emerged and became a buzzword in the last half of the first decade of the 2000s (Weidema et al. 2008). The concept is very similar to the global warming potential (GWP) impact category in life cycle assessment. In 2013, a technical specification (ISO/TS 14067) on carbon footprint was published. The requirements on methods are almost fully identical to ISO 14040 and 14044 on life cycle assessment.

In ISO/TS 14067 (2013, p 1) a carbon footprint of a product is defined as "*sum of greenhouse gas emissions … and removals … in a product system …, expressed as* CO_2 *equivalents … and based on a life cycle assessment … using the single impact category … of climate change*".

Expressing climate change as a single impact category measured in CO_2 equivalents means that all GHG-emissions associated with a product are turned into one indicator. In ISO/TS 14067, this indicator is calculated using the so-called global warming potential (GWP), where different emissions' radiative forcing during a 100 year time horizon is expressed relative to the radiative forcing of CO_2 in the same time horizon. This means that the contribution to climate change from different greenhouse gasses can be expressed in CO_2 equivalents. Of the so-called long-lived greenhouse gasses[10] CO_2, CH_4 and N_2O accounts for approximately 96% of the GWP100 from global emissions in 2000 (IPCC 2007, p 2006). The last 4% comes from several halocarbons such as CFCs, SF_6, PFCs, HFCs, and HCFCs.

Table 1.1: Global warming potentials for the three major greenhouse gasses (IPCC 2007, p 212).

GHG-emission	Global warming potential (GWP100)
Carbon dioxide (CO_2)	1 kg CO_2-eq./kg
Methane (CH_4)	25 kg CO_2-eq./kg
Nitrous oxide (N_2O)	298 kg CO_2-eq./kg

In the current study biogenic emissions have generally been excluded, i.e. contributions to GWP from CO_2-uptake from plant growth (negative GWP) as well as CO_2-emissions from decay or combustion of plant material are not included. However, there is one exception; emissions from land use changes are included despite these emissions have biogenic origin. The GWP from land use changes/deforestation is modelled in a special way taking into account the effect from temporal issues. This is further described in **section 3.5**.

The life cycle assessment approach referred to in ISO/TS 14067 means that all GHG-emissions in the life cycle of the product under study are accounted for. This implies that emissions from raw material extraction, processing, transport, use and end-of-life of the product are included in the inventory.

Results of carbon footprints and life cycle assessments are always shown relative to a so-called functional unit. The functional unit is a "*quantified performance of a product system for use as a reference unit*" (ISO 14040), i.e. a specification of what all emissions and results are related to. For products, a distinction between functional units which includes 'cradle to grave' and 'cradle to gate' emissions is often used. The latter does not include the use and disposal stage while this is included in 'cradle to grave' studies. For life cycle studies at the societal level the 'cradle to grave' perspective is typically used for studies focusing on consumption, while studies on export typically only focus on emissions related to the production of products to the point where they are exported (i.e. the 'gate' in a 'cradle to gate' study).

Carbon footprints and LCAs are not necessarily limited to focusing on products, but the same concept can be applied to assess life cycle emissions at other levels as well, see **Table 1.2**.

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[10] CO_2, CH_4, N_2O, and halocarbons (IPCC 2007).

Table 1.2: Different application levels of carbon footprint (or life cycle assessment).

Level	Focus/functional unit
Product or service	Focusses on the emissions throughout a product's or service's life cycle.
Organisation	Focusses on the emissions related to typically one year of operation of a company. This includes directly emitted emissions from the company (typically from combustion of fuels), emissions related to purchased electricity and hot water/steam, and other upstream emissions related to the production and distribution of purchased goods and services by the company. Most often downstream effects from products supplied by the company are not included.
Project, programme or policy	This focus is closely related to environmental impact assessments (EIA) of projects and strategic environmental assessments (SEA) of programmes and policies. The main difference is that carbon footprints include all upstream (and sometimes downstream) implications of the project, programme and policy, where the typical focus is EIA and SEA is primarily on direct effects and not so much on entire product systems.
Society	A society can be e.g. a municipality, nation, regional or the whole world. The focus is on the life cycle emissions related to consumption by the society's citizens, the production by the society's industries as well as life cycle emissions related to imported and exported products.

The current study belongs to carbon footprint studies applied to the societal level in **Table 1.2**.

2 Review of existing carbon footprint studies for Denmark

This section gives an overview of previous studies addressing the topic of greenhouse gas (GHG) emissions associated to the Danish economy. Some studies are entirely devoted to Denmark, whereas others have a wider international scope, with Denmark being one of countries included.

The included studies in this review are:

1. Danish input-output model for 1999 (Weidema et al. 2005)
2. EUROSTAT study on greenhouse gas emissions embodied in trade for 2005 (Rørmose et al. 2009)
3. Greenhouse gas emissions from the Danish economy for 2007 (Gravgård et al. 2009)
4. Carbon footprint of nations (GTAP) for 2000 (Hertwich and Peters 2009)
5. Concito study of GHG-emissions from Danish consumption for 2008 (Chrintz 2010)
6. FORWAST project: Danish and EU27 input-output model for 2003 (Schmidt et al. 2010, Schmidt 2010a&b, and Hermansen et al. (2010)
7. Exiobase v1 (Koning et al. 2011 and www.exiobase.eu)

2.1 About the review

The purpose of the review is to obtain results on Denmark's carbon footprint from existing studies and to identify the reasons behind differences in results. When reviewing the existing studies, the GHG-emissions from the different perspectives in **Figure 2.1** are sought identified (despite not available in all studies).

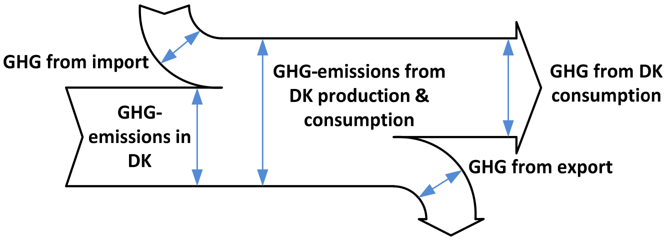

Figure 2.1: Different perspectives for analysing and accounting emissions related to national carbon footprints.

In order to identify the differences in results from the different studies a number of characteristics of the studies are recorded. Based on among others Chrintz and Schmidt (2012), the following characteristics have been identified as the most influential on national carbon footprints:

- Year
- Included GHG-emissions (for GWP100)
- Modelling of import to Denmark
- International bunkers, i.e. emissions from fuel bunkered abroad by Danish ships and aircrafts
- Land use changes addressed
- Increased radiative forcing from aircraft operation

2.2 Danish input-output model for 1999

This first model was the result of the project "Prioritisation within the integrated product policy", commissioned by the Danish Environmental Protection Agency in the years 2003-4 (Weidema et al. 2005). The main objective of the project was first to establish a detailed and well-documented method for prioritising product areas and product groups where Danish measures would provide most environmental improvement.

The method was based on environmentally-extended IO-tables, also known as NAMEAs (National accounting matrices including environmental accounts). The study included 138 product groups and it was not limited to GHG-emissions only, but to the wider set of impact categories typically included in life cycle assessment (LCA), in this case to those included in the Danish EDIP method (Hauschild and Wenzel 1998). To enable a more complete environmental assessment of product groups, the coverage of the official Danish NAMEA was extended with more environmental exchanges. In particular, the aim was to include all exchanges that contributed more than 1.5% to the normalisation reference for Denmark provided by the EDIP method.

To reflect the way each industry reacts on changes in supply and demand, all industries were systematically analysed for long-term production constraints. Based on this, several adjustments were made for the product prioritisation to take into account these constraints. This mainly affected agriculture, the dairy and meat industries, electricity production and the recycling industries.

In terms of GHG-emissions, the study included carbon dioxide (CO_2), methane (CH_4) and dinitrogen monoxide (N_2O), obtained from the Danish NAMEA, although methane and N_2O emissions were complemented based on Nielsen et al. (2003).

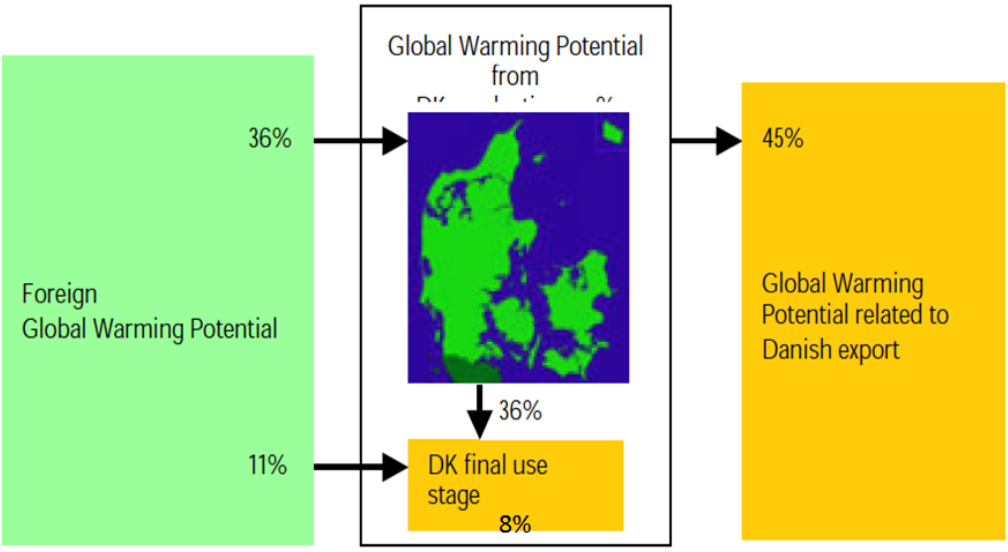

Figure 2.2. The GHG-emissions related to Danish production and consumption, in percentage of the total, where Danish activities amount to 53%. The emissions related to Danish consumption are 55% of the total whereas the remaining 45% is related to exports (Weidema et al. 2005, p 35).

The total environmental impact caused by Danish production and consumption (total domestic and foreign emissions) in year 1999 was of 183 million tonnes of CO_2-eq, or 34.4 tonnes CO_2-eq. per person (Weidema et al. 2005, p 135). Additional to the direct emissions from Danish production and final use, this includes emissions caused abroad by production of products imported to Danish industries and final use, but excludes impacts caused by re-exported products, as well as impacts caused abroad by consumption of products produced in Denmark. When only Danish activities are included, as defined by the national accounting principles (Plovsing & Dalgaard 1997), the GHG-emissions amount to 97.3 million tonnes CO_2-eq, or 18.3 tonnes CO_2-eq. per person.

From a production perspective, the main activities (those with a contribution above 2% of the national total) are transport by ship (14%), electricity (17.4%), pork and pork products (3.8%), cattle and dairy products (3.8%), dwellings (2.9%), wholesale trade (2.6%) and refined petroleum products (2.3%).

The total environmental impact caused by Danish consumption (final uses) in year 1999 was 55% of the 183 = 101 million tonnes of CO_2-eq, or 18.9 tonnes CO_2-eq. per person (Weidema et al. 2005, p 35,135).

From a consumption perspective, the main contributions come from dwellings and heating (7.7%), car purchase and driving (6%), tourist expenditures abroad (3.7%), and clothing purchase and washing (2.1%) (Weidema et al 2005, p 36).

Table 2.1: Summary of the review of 'Danish input-output model for 1999'.

Danish input-output model for 1999		
Characteristics of the study		
Year		1999
Included GHG-emissions (for GWP100)		CO_2, CH_4, N_2O
Modelling of import to Denmark		US IO-model for 1998 Trade linking modelling
International bunkers		Included
Land use changes addressed		No
Increased radiative forcing from aircraft operation		No
Results		
GHG-emissions	**Supply side**	
	DK domestic emissions	97 million tonnes CO_2-eq.
	DK imports	86 million tonnes CO_2-eq.
	Use side	
	DK Consumption	101 million tonnes CO_2-eq.
	DK exports	82 million tonnes CO_2-eq.
	Total Production & consumption	**183 million tonnes CO_2-eq.**

2.3 Eurostat study on greenhouse gas emissions embodied in trade

In this study (Rørmose et al. 2009) the main emphasis was put on the calculation of the emissions embodied in imports. In previous studies the latter had been calculated applying the assumption that all imports had given rise to an amount of emissions that are exactly the same as it would have been if the imported products had been produced in Denmark. This is a very convenient assumption, but also one that is not very likely to hold in the real world.

In order to build the IO-model for 2005, three main sets of data were required:

- Imports by industry and country: this was obtained from National trade statistics, including 130 products and services.
- Emission intensities or emissions by output: emission intensities related to the imports from member states of the European Union were obtained from Eurostat, whereas emission intensities related to imports from other countries were based on information provided by the German

research center Gesellschaft für Strukturforschung mbH, as well as information obtained from the World Resource Institute.
- IO data and models for the countries involved in the calculations: IO-tables were obtained from Eurostat, at the 60 products/sectors level. For importing countries outside of Europe it was decided to choose an EU member state as a surrogate. For example, China was modelled as the Czech Republic and the USA as Germany.

As for the GHG-emissions included in the study, only CO_2 is considered.

In terms of data collection, the project was concerned with the following steps:
- To calculate and distribute the direct Danish import in a 60 products by 50 countries and rest of the world (ROW) matrix.
- To collect emission intensities for all of these 51 countries at the A60 level.
- To collect IO-tables for as many of these countries at the 60 industry or 60 product level as possible and calculate inverted matrices of intermediate domestic and imported deliveries.

On the basis of these data three different approaches to calculate emissions embodied in imports were applied:
- The first approach (A) was to apply the Danish emission intensity as well as the Danish IO-table. This is similar to applying the aforementioned assumption that emissions are the same as if the imported products had been produced in Denmark. This was done only for reference.
- The second approach (B) was to introduce country-specific emission intensities.
- The third approach (C) replaces the Danish IO-model with country-specific models.

It should be noted that the imports are modelled substantially different from the other studies in this review; whereas the other studies include emission estimates for all imported products, the Eurostat study excludes all imports that are directly or indirectly used for the production of exports. E.g. if a Danish window frame manufacturer imports aluminium as a raw material, and then exports the window frames, then the imported aluminium is not included. Therefore, the emissions embodied in trade in the Eurostat study are significantly lower than in the other studies.

Table 2.2: Summary of the review of 'EUROSTAT study on greenhouse gas emissions embodied in trade'.

EUROSTAT study on greenhouse gas emissions embodied in trade		
Characteristics of the study		
Year		2005
Included GHG-emissions (for GWP100)		CO_2
Modelling of import to Denmark		A) DK IO-model for 2005 B) Emission intensities C) Country specific IO-models for 2005 Not trade linking modelling
International bunkers		Not mentioned – probably not included
Land use changes addressed		No
Increased radiative forcing from aircraft operation		No
Results		
GHG-emissions	**Supply side**	
	DK domestic emissions	
	DK imports	A) 13 million tonne CO_2 B) 21 million tonne CO_2 C) 25 million tonne CO_2
	Total Production & consumption	n.a.
	Use side	
	DK Consumption	n.a.
	DK exports	A,B and C) 20 million tonne CO_2
	Total supply = total use	**n.a.**

The (A) results for import in first column of **Table 2.2** shows that CO_2 emissions embodied in import were 13 million tonnes when modelling import by assuming that the impact is the same as if it was produced in Denmark (modelling with the DK IO-model). The step of applying country-specific (B-results) emission intensities instead of just using the Danish makes embodied GHG-emissions in imports increased the CO_2 embodied in trade by 62% (from 13 million tonnes to 21 million tonnes). Going a step further by using country specific IO-models (C-results), another 3.3 million tonnes CO_2 are added to the imports. As a consequence the Danish CO_2 balance with the rest of the world changes from surplus to a 4.2 million tonnes deficit. This points to the fact that the Danish industry is more efficient in their use of intermediate input in general than many other countries.

2.4 Greenhouse gas emissions from the Danish economy for 2007

The work by Gravgård et al. (2009) is based on Statistics Denmark's Environmental Accounts for Denmark, and aims to describe the emissions of GHG caused by Danish economic activities. This includes emissions of the GHG included under de Kyoto Protocol. The publication describes the extent of emissions from the industries and the households. Furthermore, the publication contains analytical results on the relationship between the structural characteristics of the Danish economy and the emissions of GHG.

By using the principles of the so-called Environmental Accounts, Statistics Denmark's Environmental Accounts for Denmark takes into account all the economic activities underlying the Gross Domestic Product (GDP) as described by the Danish National Accounts. Using these principles, total Danish emissions of GHG were 130 million tonnes CO_2-eq. in 2007. This is equivalent to 24 tonnes per Dane. 89% of the GHG impact comes from CO_2, N_2O contributes 6%, CH_4 accounts for 4%, while emissions from halocarbons constitute 1% of the total.

The above figures can be compared with the Danish GHG-emissions calculated following the Intergovernmental Panel on Climate Change (IPCC) definition. These amount to 66 million tonnes CO_2-eq. in

2007, or 12 tonnes per Dane. Thus, in 2007 total CO_2 emissions from Danish economic activities were more than twice as large as the emissions accounted for in the principles laid down by the IPCC and the Kyoto Protocol. This is due to the following reasons:

- The Kyoto Protocol does not include emissions from international transport carried out by Danish companies, including shipping between international ports.
- The calculations by Gravgård et al. (2009) include emissions from the burning of biomass, which is an important source of primary energy in Denmark. Under the IPCC rules, biogenic CO_2 is considered climate-neutral.

According to Gravgård et al. (2009) industries have contributed 90% to the total Danish emissions, with households making up the remaining 10%.

Gravgård et al. (2009) also found that from 1990 to 2007, total emissions of CO_2 from Danish economic activities increased by 62% from 72 million tonnes to 117 million tonnes. This increase was caused mainly by an increase in Danish shipping activities. In 2007, the emissions caused by Danish sea transport in international waters accounted for more than 40% of the total CO_2 emissions.

Table 2.3: Summary of the review of 'Greenhouse gas emissions from the Danish economy for 2007'.

Greenhouse gas emissions from the Danish economy for 2007		
Characteristics of the study		
Year		2007
Included GHG-emissions (for GWP100)		CO_2 (also biogenic), CH_4, N_2O and halocarbons
Modelling of import to Denmark		Not included, the study only focus on direct emissions in DK
International bunkers		Yes
Land use changes addressed		No
Increased radiative forcing from aircraft operation		No
Results		
GHG-emissions	**Supply side**	
	DK domestic emissions	n.a.
	DK imports	n.a.
	Use side	
	DK Consumption	n.a.
	DK exports	n.a.
	Total supply = total use	**130 million tonne CO_2-eq.**

2.5 Carbon footprint of nations (GTAP) for 2001

Hertwich and Peters (2009) provided an analysis of carbon footprint of nations using a global multiregional IO-model based on the Global Trade Analysis Project (GTAP) database for the reference year 2001 (Dimaranana 2006). The GTAP database contains the IO-tables and bilateral trade statistics for 57 sectors and 87 regions. The GTAP regions cover 72 individual countries and 15 aggregated regions. The aggregated regions represent geographically similar countries where no IO data was collected, for example, the "rest of Oceania" includes all of the countries in Oceania not including Australia and New Zealand, and the IO-table is estimated as a weighted average of Australia and New Zealand. The study addressed final consumption by households, governments, and for investments, following the conventions of national accounts.

In this analysis, the carbon footprint is defined as the emissions of CO_2, CH_4, N_2O, and fluoride emitted in the production of goods and services used for final consumption, and GHG-emissions occurring during the consumption activities themselves, akin to the tier 3 carbon footprint in the Greenhouse Gas Protocol

(Matthews et al. 2008) and the climate footprint (Wiedmann and Minx 2008). The different GHG-emissions are weighted together using GWP100 as in the Kyoto Protocol.

It must be highlighted that the sources and sinks of land use, land use change, and forestry (LULUCF) were not included due to the difficulty in allocating them to particular economic activities. In many countries LULUCF is the dominant source of emissions, thus care should be taken to note that the results from this study only consider the emissions of fossil fuels and process emissions.

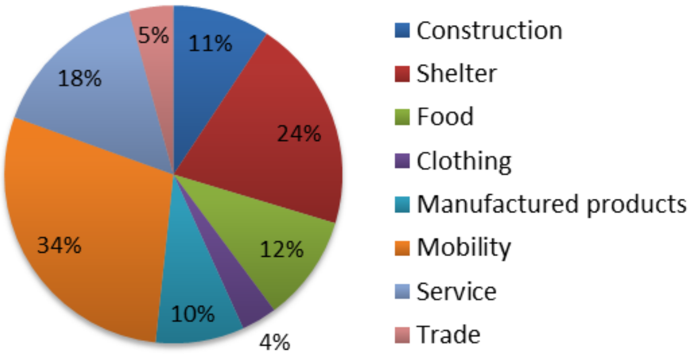

Figure 2.3. Split of GHG-emissions in Denmark in 2001 (Hertwich and Peters 2009).

The results of the study were provided at country level, with Denmark showing in 2001 a carbon footprint of 81 million tonnes CO_2-eq, or 15.2 tonnes CO_2-eq. per person. Figure 2.3 shows how this footprint is shared by different sectors of the economy. It can be seen that mobility and housing are the main contributors to the Danish carbon footprint, followed by the service sector.

Table 2.4: Summary of the review of 'Carbon footprint of nations (GTAP) for 2001'.

Carbon footprint of nations (GTAP) for 2001		
Characteristics of the study		
Year		2001
Included GHG-emissions (for GWP100)		CO_2, CH_4, N_2O, and fluoride
Modelling of import to Denmark		Country specific IO-models for 2001 Trade linking modelling
International bunkers		Yes
Land use changes addressed		No
Increased radiative forcing from aircraft operation		No
Results		
GHG-emissions	**Supply side**	
	DK domestic emissions	n.a.
	DK imports	n.a.
	Use side	
	DK Consumption	81 million tonne CO_2-eq.
	DK exports	n.a.
	Total supply = total use	**n.a.**

2.6 Concito study of GHG-emissions from Danish consumption for 2008

Concito is a Danish green think tank. In 2010 they published a study which quantified the GHG-emissions related to Danish consumption. Concito did not present a dedicated model, but instead they based their quantification of GHG-emissions related to Danish consumption on a number of studies (of which most are included in the current literature review; see **section 2.2** and **2.5**). The GHG-emissions obtained from various studies are adjusted to represent data for 2008 by accounting for economic growth and elasticity for GHG-emissions and by adding estimated emissions from land use changes and from radiative forcing from aircraft operation.

Table 2.5: Summary of the review of 'Concito study of GHG-emissions from Danish consumption for 2008'.

Concito study of GHG-emissions from Danish consumption for 2008		
Characteristics of the study		
Year		2008
Included GHG-emissions (for GWP100)		CO_2, CH_4, N_2O (not explicitly specified)
Modelling of import to Denmark		Different approaches obtained from existing studies
International bunkers		Yes
Land use changes addressed		Yes
Increased radiative forcing from aircraft operation		Yes
Results		
GHG-emissions	**Supply side**	
	DK domestic emissions	n.a.
	DK imports	n.a.
	Use side	
	DK Consumption	99-115 million tonne CO_2-eq.
	DK exports	n.a.
	Total supply = total use	**n.a.**

2.7 FORWAST

The FORWAST project is an EU FP6 project that was finalised in 2010. As part of the project environmentally extended IO-models were developed for all EU27 countries. This was aggregated to an EU27 IO-model. As part of the project, there was special focus on Denmark; therefore the Danish IO-model was trade linked with the EU27 model. Hence, the GHG-emissions embodied in import to Denmark were modelled as if they were produced in EU27.

Further, in the FORWAST project not only all monetary transactions in economy were modelled, but also, as a mirror of the monetary economy, physical tables in mass units were created. This also included the establishment of mass balances for each industry in each country which enabled for calculating the waste flows. Waste flows can principally be calculated as inputs to economy (resources) minus outputs (emissions). This calculation was further detailed by tracking the fate of each input of each product to each industry. The creation of physical tables, created a number of new features for the use and quality for IO-modelling:

- **Consistency checks:** When having IO-models in monetary units only, there is no check of how well the modelled inputs and outputs of products of each industry reflects the real world. E.g. when just using the pure monetary tables, it was discovered that many feedstocks/raw materials in manufacturing industries were missing. Further, the introduction of physical data also allowed for differentiation of prices over industries and to match with other detailed data on e.g. energy use and raw material input per unit of output for the different industries.
- **National waste accounts:** can be calculated
- **National mass flow accounts:** can be calculated

Table 2.6: Summary of the review of FORWAST. The emissions are calculated using the FORWAST DK and EU27 2003 IO-database in the LCA software SimaPro.

FORWAST		
Characteristics of the study		
Year		2003
Included GHG-emissions (for GWP100)		CO_2, CH_4, N_2O
Modelling of import to Denmark		EU27 Trade linking modelling
International bunkers		Yes
Land use changes addressed		No
Increased radiative forcing from aircraft operation		No
Results		
GHG-emissions	**Supply side**	
	DK domestic emissions	94.4 million tonne CO_2-eq.
	DK imports	83.5 million tonne CO2-eq.
	Use side	
	DK Consumption	68.2 million tonne CO_2-eq.
	DK exports	110 million tonne CO_2-eq.
	Total supply = total use	**178 million tonne CO_2-eq.**

2.8 Exiobase

The project EXIOPOL was funded by the European Commission, comprising 38 universities and centres of research from Europe, China and India. The top-down approach developed in EXIOPOL considered the following questions:

- What are the external costs of global economic production?
- What are the impacts embodied in European imports?
- What are the dynamic impacts of policy interventions in the following areas: buildings, mobility, and food?

These questions were answered with the help of the EXIOBASE database (Koning et al. 2011 and http://www.exiobase.eu), which constituted the main deliverable of this project. EXIOBASE is a detailed, transparent, harmonised, global Multi-Regional Environmentally Extended Input-Output Table with externalities, called EXIOBASE, with the following characteristics:

- Covering 43 countries (95% of the global economy) and the Rest of World (combining the remaining 150+ countries).
- Full trade matrices with insights on which product from which country is exported to which industry sector in another country.
- Distinguishing 129 industry sectors and products.
- Covering 30 emitted substances and 80 resources by industry.
- Extensions aggregated to compile indicators such as GWP, Acidification, Total material requirement, and external costs. The latter were calculated by assessing the external costs of a kg per gas emission of a specific substance by a specific industry in a specific country, considering population density, rural or urban location, and stack height related to the emission.

Besides creating the database itself, EXIOPOL also carried out some forecasting of future environmental impacts based on scenarios affecting buildings, transport, food and agriculture. These scenarios served to determine the extent to which certain environmental policies could reduce impacts on areas such as GHG-emissions, water use and land use.

The results of an analysis of the Exiobase data for Denmark are shown in **Table 2.7**.

Table 2.7: Summary of the review of Exiobase v1. The database was imported into and calculations were made in the LCA software SimaPro.

Exiobase		
Characteristics of the study		
Year		2000
Included GHG-emissions (for GWP100)		CO_2, CH_4, N_2O
Modelling of import to Denmark		43 countries + rest-of-world (RoW) Trade linking modelling
International bunkers		Yes
Land use changes addressed		No
Increased radiative forcing from aircraft operation		No
Results		
GHG-emissions	**Supply side**	
	DK domestic emissions	81.8 million tonne CO_2-eq.
	DK imports	55.8 million tonne CO_2-eq.
	Use side	
	DK Consumption	72.4 million tonne CO_2-eq.
	DK exports	65.2 million tonne CO_2-eq.
	Total supply = total use	**138 million tonne CO_2-eq.**

2.9 Summary of the review

To the best of our knowledge, seven studies/projects/databases have addressed the topic of GHG-emissions of the Danish economy, mostly through an IO approach. The geographical scope of these studies varies, though. Some of them had the purpose of looking at Denmark specifically, whereas others had a wider scope, such as Europe, or even the world, and Denmark was among the countries within the scope. From a time perspective, the studies cover the period from 1999 to 2008, however a consistent time series for Danish GHG-emissions cannot be derived, not only because there are some years not covered in this period, but most importantly, because of the lack of methodological harmonization between studies. We comment below on these differences in methodology, as well as on the differences in final results shown by these studies.

In terms of GHG-emissions covered, most studies include the main ones, namely CO_2, CH_4 and N_2O. Some of them additionally cover other substances, such as halocarbons, although this is judged to lead to minor differences in outcome, given that the latter typically involve a relatively minor contribution expressed in CO_2-eq. emissions. Only the Eurostat study didn’t look at several GHGs, focusing only on CO_2. Most studies also address emissions from ships and aircraft abroad, only with the exception of the Eurostat study. This can make a difference in the final results, given that these are important sources of emissions for Denmark. With regard to aircraft, the review shows that none of the studies take into account the specific impact of emissions at high altitude. This is not surprising, as there is no standard approach for this. For further discussion on aviation emissions the reader is referred to **section 3.6**.

One of the main areas where studies differ is the way emissions from imports are considered. The approaches range from not considering these emissions at all, which is the case in the DK IO2007 study (Gravgård et al. 2009), to inclusion with different levels of resolution, the lowest being the assumption that imports have the same GHG efficiency as Danish production, and the highest being the consideration of country-specific efficiencies. The Eurostat study (Rørmose et al. 2009) models import substantially different from the other studies; whereas the other studies include emission estimates for all imported products, the Eurostat study has excluded all imports that are directly or indirectly used for the production of exports. Therefore, the emissions embodied in trade in the Eurostat study are significantly lower than in the other studies.

Another source of potential disagreement in results is whether or not LULUCF is included. The only study to address this explicitly is the Concito study. The study by Gravgård et al. (2009) included biogenic CO_2 emissions from biomass burning, which are to some extent linked to LULUCF, but emissions related to LULUCF abroad, associated with Danish imports, were not included. The latter are judged to be of much higher magnitude than those occurring within the Danish borders.

Figure 2.5 shows graphically the results from the seven reviewed studies, in million tonnes CO_2-eq. The graph attempts to show all the contributions from the supply as well as the use side, however this is not possible for all studies, since not all of them provide figures at this level. Only three studies, namely the Danish study from 1999, FORWAST and EXIOBASE provide a total production plus consumption figure.

For DK domestic emissions, the studies show results between 80 and 130 million tonne CO_2-eq. Some of these differences are obviously related to the reference year. However, the Exiobase seems to have lower domestic emissions (~8 million tonne CO2-eq.) than the official reported figures by Statistics Denmark (2013c), and the other studies also show some deviations: compare **Figure 2.4** (official reported GHG-emissions) and **Figure 2.5** (summary of the literature review). The high emissions in the DK IO2007 (Gravgård et al. 2009) can be explained by the fact that this study also includes biogenic CO_2, which is not included in the other studies.

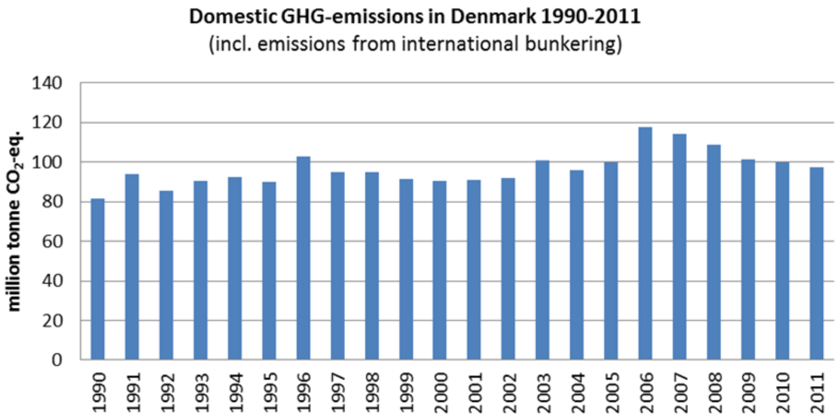

Figure 2.4. Official domestic GHG-emissions as reported by Statistics Denmark (2013c). The emissions from international bunkering are included. Biogenic CO_2 is not included.

For imports and exports, the Eurostat study show significantly lower results than the other studies (as explained above). The DK IO1999 and the FORWAST studies show similar results, while Exiobase show significantly lower (>20 million tonne CO_2-eq. lower) results. Despite the fact that trade is modelled by using other data, it is not clear why Exiobase show lower emissions related to import. It may be because of differences in the modelling of re-export (included versus not included).

For DK consumption, the DK IO1999 study and the Concito study show similar results at around 100 million tonne CO_2-eq. The other studies (GTAP, FORWAST and Exiobase) show consumption based emissions at 68-81 million tonne CO_2-eq.

For total supply = total use, Exiobase shows the lowest value, of 138 million tonnes, whereas the DK IO1999 study and FORWAST provide similar figures of around 180 million tonnes. These studies are in good agreement from the supply side (domestic emissions and imports), while the match from the use side (consumption and exports) is not as good.

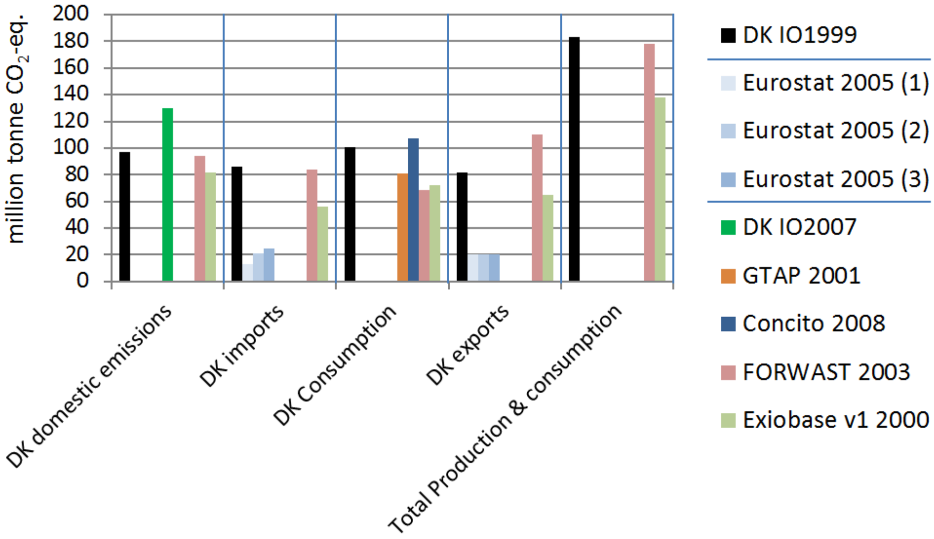

Figure 2.5. Summary of the results on GHG-emissions related to Danish economy based on the review of existing studies/models.

In general the review shows that, unsurprisingly, heterogeneous results are obtained by different studies, due to different underlying methods and assumptions. It should be noted that the concept of environmentally-extended input output tables is relatively new[11], and it is expected that as the interest in this approach increases, harmonization among studies will, too.

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[11] According to Suh eds. (2009), the efforts to couple LCA and input-output analysis emerged in the early 1990s.

3 Description of the methods to estimate the carbon footprint of Denmark

In this chapter the general methods for calculating the carbon footprint of a nation are described. The chapter is introduced by a general description of how carbon footprint can be calculated, and the similarities with life cycle assessment are described. Having established and described the general method for calculating carbon footprints of nations, it is described how the models are created in order to give a complete and accurate picture of the carbon footprint. Further, it is described how results representing different perspectives of a nation's carbon footprint can be derived and interpreted with the model.

3.1 General description of the input-output method

The geographical system boundary approach and its limitations

The most common way nation's GHG-emissions are presented is following the 'Guidelines for National GHG Inventories' (IPCC 2006) for national emissions inventories under the Kyoto Protocol. The latest Danish inventory report is published in Nielsen et al. (2013). The national emissions inventories under the Kyoto Protocol follow a geographical system boundary. This means that, in principle, all emissions that are taking place within the Danish territory are included while everything else is excluded; this is illustrated by the red circle in **Figure 3.1**.

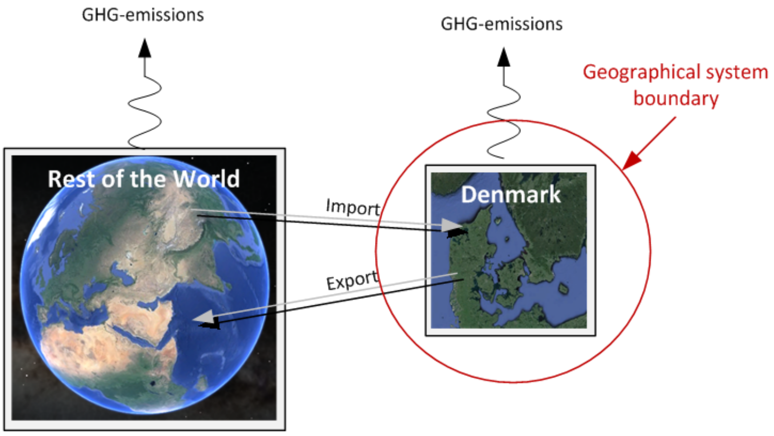


Figure 3.1. System boundary (geographical) of emission inventories following the guidelines for national emissions inventories under the Kyoto Protocol. (Map pictures are obtained from Google earth 2013).

Table 3.1 provides an overview of the official Danish national emission inventories from 1990 to 2011. The emissions are shown as (1) the reported emissions to UNFCCC (Kyoto emissions), plus (2) emissions from bunkering, i.e. emissions from Danish operated ships, aircrafts and vehicles abroad, equals (3) total GHG-emissions emitted by Danish industries and households.

Table 3.1: Overview of total national CO_2-emissions from Denmark as of the official emissions inventories. Emissions are obtained from Statistics Denmark (2013a) and given in million tonne. The GWP (CO2-eq.) is calculated using the characterisation factors in **Table 1.1**. The contribution from international transport (bunkering) is specified separately.

Year	**GHG-emissions (million tonne)**												
	1990	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
(1) GHG-emissions on Danish territory (the Kyoto accounting)													
CO_2 (fossil)	52.9	53.7	55.5	55.2	60.2	54.8	51.1	59.1	54.3	50.9	48.5	48.8	43.9
CH_4	0.29	0.28	0.28	0.28	0.28	0.27	0.27	0.27	0.27	0.27	0.26	0.27	0.26
N_2O	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
CO_2-eq. (GWP100)	**69.4**	**68.4**	**70.0**	**69.4**	**74.1**	**68.3**	**63.9**	**71.7**	**67.1**	**63.7**	**60.8**	**61.2**	**56.2**
(2) Danish GHG-emissions abroad (international transport)													
CO_2 (fossil)	12.0	21.6	20.7	22.2	26.0	27.2	35.3	45.0	46.2	44.1	39.9	37.8	40.3
CH_4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2-eq. (GWP100)	**12.2**	**22.0**	**21.0**	**22.6**	**26.5**	**27.7**	**36.0**	**45.8**	**47.0**	**44.9**	**40.7**	**38.6**	**41.1**
(3) = (1)+(2) Total GHG-emissions emitted by Danish industries and households													
CO_2 (fossil)	64.8	75.3	76.2	77.4	86.2	82.0	86.4	104.1	100.5	94.9	88.4	86.6	84.2
CH_4	0.29	0.28	0.29	0.28	0.28	0.27	0.27	0.27	0.27	0.27	0.26	0.27	0.26
N_2O	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
CO_2-eq. (GWP100)	**81.6**	**90.4**	**91.1**	**92.0**	**100.6**	**96.0**	**99.9**	**117.6**	**114.2**	**108.6**	**101.5**	**99.7**	**97.3**

A disadvantage of the geographical approach as shown in **Figure 3.1** and **Table 3.1** is that the implications of international trade are not accounted for. This implies that a country that imports emission-intensive products and exports non-intensive products/services will appear as a 'clean' country, while the countries that produce and export the emission-intensive products will appear as 'dirty'. Some unintended consequences of this are:

- the consumption of goods in a country can remain unchanged while the emissions may go up or down because of changes in the trade with more or less emission-intensive products.
- if countries outsource emission-intensive production, this will appear as reductions in national emissions. But in reality, the consequence may be that the overall emissions increase if the exporting country has lower production costs (more products per monetary unit) and/or less clean technologies.
- if the production and consumption remains unchanged, but the producers and consumers start to import cleaner products, this will not have an effect on the national emissions.

The problems related to the geographical system boundary can be, even more clearly, illustrated by a simple example of aluminium production in **Figure 3.2**.

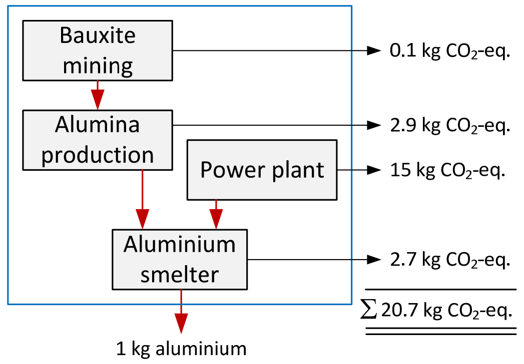


Figure 3.2. Simplified product system for aluminium production with indication of GHG-emissions from the involved industrial activities. The CF figures for aluminium production are obtained from Schmidt and Thrane (2009).

If a country uses aluminium, it affects the whole product chain from bauxite mining to aluminium smelter. If a country hosts an aluminium smelter (i.e. the system boundary is set around the aluminium smelter), but imports the alumina raw material and the required electricity, then the emissions related to aluminium will be relatively small. It is clear that this approach does not include all affected sources of emissions related to aluminium consumption.

Hence a carbon footprint approach based on a geographical system boundary may lead to generation of misleading information on the environmental performance of a country's activities as well as on the effect of mitigation actions. The solution on the problem is to include all life cycle emissions of all consumed products – also the imported ones. This is further described in the next section.

The product-oriented system boundary approach

The product-oriented system boundary includes all sources of emissions related to the production, consumption and disposal of a product – irrespectively of where in the world these sources are located. This principle is also often referred to as the life cycle perspective which is used in life cycle assessment (LCA) (ISO 14040/44).

The life cycle perspective is illustrated in **Figure 3.2**, which shows a simplified product system for aluminium (notice that the use and disposal stages are not shown). In order to describe that the life cycle perspective can be applied for all products at the national and global scale, the aluminium case is used. In **Figure 3.3**, the description of the product system of aluminium is further detailed by also specifying the so-called intermediate flows (bauxite, alumina and electricity) between the involved industrial activities.

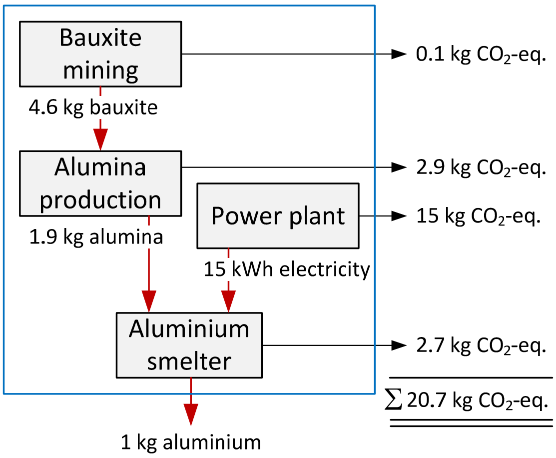


Figure 3.3. Simplified product system for aluminium production with indication of intermediate flows between industrial processes and GHG-emissions from the involved activities. The data are obtained from Schmidt and Thrane (2009).

The product system in **Figure 3.3** can also be presented using table representation, see **Table 3.2**. The format of the table is based on the so-called supply-use framework (Eurostat 2008), where each column represents a box (=industry) in **Figure 3.3** and each row represents a flow (=product) in **Figure 3.3**. The final use column (**f**) is introduced just to have a place to indicate that the final output of the system is 1 kg aluminium. The upper-part of the table is called the supply table (**V'**), and it shows the supplies of products from industries. The middle part is called the use table (**U**), and it shows the use of products, and the bottom-part is called the extension table (**B**), and it shows emissions from each industry (and sometimes also other elementary exchanges such as resource inputs, land use, value added etc.). It can now be observed that **Table 3.2** show the same information as **Figure 3.3**. So the same information for life cycle modelling can be represented in ordinary LCA flow charts as well as using table representation.

Table 3.2: Product system for aluminium as of **Figure 3.3** presented by table representation (supply-use framework).

Products		**Industry**					
Supply	Unit	Bauxite mining	Alumina production	Power plant	Aluminium smelter		Total
Bauxite	kg	4.6					4.6
Alumina	kg		1.9	V'			1.9
Electricity	kWh			15			15
Aluminium	kg				1		1
Use		Bauxite mining	Alumina production	Power plant	Aluminium smelter	**Final use**	Total
Bauxite	kg		4.6				4.6
Alumina	kg			U	1.9	f	1.9
Electricity	kWh				15		15
Aluminium	kg					1	1
Emissions		Bauxite mining	Alumina production	Power plant	Aluminium smelter	**Final use**	Total
CO_2	kg	0.1	2.9	15	2.7		20.7

B

Based on the supply-use table with environmental extension as in **Table 3.2**, the life cycle emissions can be calculated using a number of mathematical operations. The first step of these operations is to create a so-called 'technology matrix' or 'direct requirement table'[12], here denoted **A**. The example in **Table 3.2** is simple because none of the industries supply by-products. In this simple case, the technology matrix can be created by normalising (i.e. dividing) all values in each column with the supply of the industry. If some of the activities are associated with by-products, i.e. off-diagonal values in **Table 3.2**, then it must be decided how to model the by-products. This can in principle be done either by substitution (i.e. by-products substitute alternative production) or by allocation (multiple-output activities are partitioned into single output activities). There are standard procedures for how to handle this in LCA (Weidema et al. 2009; Weidema et al. 2013) and in input-output (IO) analysis (Suh et al. 2010; Eurostat 2008), and this subject will not be described further in the current report[13].

An technology matrix (**A**) show the inputs of products to an activity per unit of output of the activity. Each column in the IO-table represents an activity, while the rows represent flows. It is the numbers embraced in the red square in **Table 3.3** that is referred to as the IO-table (**A**), and the emissions are referred to as an environmental extension (**B**). In **Table 3.3** the technology matrix derived from the supply-use table in **Table 3.2** is shown.

---

[12] The technology matrix/direct requirement table are also sometimes referred to as the input-output (IO) table.

[13] The FORWAST-model which is the model that will be used as the main model in the current study uses the so-called by-product technology assumption. This corresponds to substitution in life cycle inventory modelling (Suh et al. 2010), which is the recommended approach in LCA (ISO 14044, clause 4.3.4). The by-product technology assumption leads to exactly the same results as the so-called commodity technology assumption (Suh et al. 2010), which is the recommended approach in Eurostat (2008).

Table 3.3: Technology matrix (**A**) for the activities involved in the product system of aluminium. The technology matrix is created using the information in the supply-use table in **Table 3.2**.

Products		**Industry**			
Supply		Bauxite mining	Alumina production	Power plant	Aluminium smelter
Unit		kg	kg	kWh	kg
Reference product		1	1	1	1
Use	**unit**		**A**		
Bauxite	kg		2.4		
Alumina	kg				1.9
Electricity	kWh				15.0
Aluminium	kg				
Emissions	**unit**		**B**		
CO_2	kg	0.022	1.5	1.0	2.7

Having an IO-table (**A**), the production volume of each activity to deliver a specified output, e.g. 1 kg aluminium can be calculated as shown in **Equation 3.1** (Heijungs and Suh 2002).

Equation 3.1

$$\mathbf{s} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f}$$

where:

I is the identity matrix (square table with ones on the diagonal, and zeros in the remaining entries)

f is the vector specifying the considered product output, and

s specify the so-called 'scaling factors', which is the production volume of each activity

The meaning of **Equation 3.1** is illustrated by calculating the scaling factors for the activities in the IO-table in **Table 3.3** when demanding 1 kg aluminium; see **Equation 3.2**:

Equation 3.2

$$\mathbf{s} = \left(\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} 0 & 2.4 & 0 & 0 \\ 0 & 0 & 0 & 1.9 \\ 0 & 0 & 0 & 15 \\ 0 & 0 & 0 & 0 \end{bmatrix}\right)^{-1} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 4.6 \\ 1.9 \\ 15 \\ 1.0 \end{bmatrix}$$

Looking at the calculated scaling factors (**s**) in **Equation 3.2**, it appears that the scaling factors are identical with the actual production volumes as in **Table 3.2** – and also the product flows as in **Figure 3.3**.

Having calculated the scaling factors (**s**) related to 1 kg aluminium, and having the environmental extension (**B**) of the IO-table, specifying the emissions per unit of output per activity, the life cycle emissions (**G**) can be calculated as shown in **Equation 3.3** (Heijungs and Suh 2002).

Equation 3.3

$$\mathbf{g} = \mathbf{Bs} = \mathbf{B}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{f}$$

where:

g is the vector of resulting emissions, and

B is the extension matrix having dimension emissions by industries, and

The meaning of **Equation 3.3** is illustrated by calculating the resulting CO_2 emissions for the activities in the IO-table in **Table 3.3** when demanding 1 kg aluminium; see **Equation 3.4**:

Equation 3.4

$$\mathbf{g} = [0.022 \quad 1.5 \quad 1.0 \quad 2.7] \begin{bmatrix} 4.6 \\ 1.9 \\ 15 \\ 1.0 \end{bmatrix} = 20.7$$

It appears from **Equation 3.4**: that the calculated life cycle emissions are exactly the same as demonstrated in **Table 3.2** and **Figure 3.3**.

In this section, it has been demonstrated how a traditional product life cycle can be represented using the supply-use and input-output framework, and how the exactly the same life cycle emissions can be derived from the two different representations of the system. Hence, the principles of life cycle assessment and input-output modelling are very similar, which is the main message in this section. In the next section, the principles of the simple product system of only one product (aluminium) are scaled up to represent a life cycle assessment or an input-output analysis of societal total consumption.

From single product to an economy-wide total product system

Let us now we expand the number of industries and products in **Table 3.2**, to represent the entire economy of a country, and use monetary units (e.g. EUR) for the transactions of products instead of physical (kg and kWh). This is illustrated in **Table 3.4**. Compared to **Table 3.2**, it should be noted that the final use is now the total consumption in Denmark, and not only 1 kg of a specific product. Further, a new row has been added below the use table, i.e. the value added table; here illustrated as just one row including operating surplus, compensation of employees and taxes. The value added table is needed in order to account for all economic inputs to industries.

Balance at the industry level: It can be seen that the total outputs from industries (totals row below supply table) is in balance with the total inputs to industries (totals row below)

Balance at the product level: The sum of domestically produced products and imported products is called the total supply of products. This information can be seen in the totals column to the right of the supply table. It appears that the total supply is balanced with the total use, which is the sum of products used by Danish industry, final uses (households and government) and export. The total use can be seen in the column to the right of the use table.

It should be noted that the supply-use table as shown in **Table 3.4** does not contain all the information to calculate the true life cycle emissions. This is because the framework does not contain information on product systems related to imported products.

Table 3.4: The Danish economy in 2003 presented by table representation (supply-use framework). All product flows are in units of million euro (MEUR2003) and emissions are in units of thousand tonne (kt). Data are obtained from deliverable 3.2 of the EU FP6 project FORWAST: http://forwast.brgm.fr/

Products		Industry				Trade		Final uses	Total
Supply	Unit	Agriculture & food	Materials & machinery	Energy and water	Services	Imports	Exports	Final use	Total
Agriculture & food	MEUR	8,653	306	0	0	1,877			**10,837**
Materials & machinery	MEUR	8	69,545	0	294	48,440			**118,287**
Energy and water	MEUR	0	9	5,573	685	151			**6,418**
Services	MEUR	0	322	15	226,807	16,378			**243,523**
Total output from industries	**MEUR**	**8,662**	**70,183**	**5,588**	**227,785**				
Use									
Agriculture & food	MEUR	1,247	6,024	58	480		1,980	1,048	**10,837**
Materials & machinery	MEUR	1,956	24,672	1,345	17,656		48,488	24,170	**118,287**
Energy and water	MEUR	179	899	368	1,429		914	2,628	**6,418**
Services	MEUR	1,828	11,821	926	71,547		28,971	128,429	**243,523**
Value added									
Operating surplus, compensation of employees, taxes	MEUR	3,451	26,767	2,891	136,673				
Total inputs to industries	**MEUR**	**8,662**	**70,183**	**5,588**	**227,785**				
Emissions	Unit	Agriculture & food	Materials & machinery	Energy and water	Services			Final use	Total
CO_2 (fossil)	kt	2,604	9,841	28,412	34,422			9,853	85,132
CH_4	kt	131	5	16	176			9	338
N_2O	kt	20.4	3.1	0.4	2.2			1.1	27.2

As for the aluminium-specific simplified product system in **Table 3.2**, an IO-table can be derived from the supply-use table in **Table 3.4**[14]. This is shown in **Table 3.5**.

Table 3.5: Technology matrix (**A**) for the activities involved in Danish economy-wide product system. The technology matrix is created using the information in the supply-use table in **Table 3.4**.

Products		Industry				
Supply		Agriculture & food	Materials & machinery		Energy and water	Services
Unit		MEUR	MEUR		MEUR	MEUR
Reference product		1	1		1	1
Use	unit					
Agriculture & food	MEUR	0.144	0.082		0.010	0.002
Materials & machinery	MEUR	0.225	0.355		0.241	0.077
Energy and water	MEUR	0.021	0.013	**A**	0.066	0.003
Services	MEUR	0.211	0.165		0.163	0.315
Value added						
Operating surplus, compensation of employees, taxes	MEUR	0.399	0.385		0.519	0.603
Emissions	unit					
CO_2 (fossil)	kt	0.301	0.142		5.098	0.152
CH_4	kt	0.015	0.000	**B**	0.003	0.001
N_2O	kt	0.002	0.000		0.000	0.000

---

[14] The IO-table has been created using the so-called by-product technology assumption. This implies that all by-products (off-diagonals in the supply table V') have been moved down into the use table (U) with a negative sign before the columns have been normalized by the supply. This procedure is further described in Suh et al. (2010).

As in the case for aluminium, the life cycle emissions associated with a specified functional unit (e.g. total Danish consumption + export) can now be calculated using **Equation 3.3**. It should be noted that since some fuels are also burned in the households and governments activities (final use column in **Table 3.4**), the associated emissions $\mathbf{g}_{\mathbf{final}}$ also need to be added. The emissions are calculated in **Equation 3.5**. Note that emissions are shown in units of thousand tonne (kt).

Equation 3.5

$$\mathbf{g} = \mathbf{B}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} + \mathbf{g}_{\mathbf{final}} \rightarrow$$

$$\begin{bmatrix} \mathbf{CO_{2,fossil}} \\ \mathbf{CH_4} \\ \mathbf{N_2O} \end{bmatrix} = \begin{bmatrix} 112{,}343 \\ 555 \\ 58 \end{bmatrix} + \begin{bmatrix} 9{,}853 \\ 9 \\ 1 \end{bmatrix} = \begin{bmatrix} \mathbf{122,195} \\ \mathbf{564} \\ \mathbf{59} \end{bmatrix}$$

Comparing the life cycle emissions associated with the output of the Danish economy (consumption + export) in **Equation 3.5** with the total emissions in the environmental extension table in **Table 3.4**, it can be seen that the calculated emissions are higher. This is because the emissions in **Table 3.4** do not include contributions from imported products. In **Equation 3.5** the emissions related to imported products are calculated using the so-called closed-economy assumption, where it is assumed that all imported products are produced in the same way as domestically produced products. This is obviously not a very accurate assumption. Especially for a small country as Denmark which relies on very high import shares for a number of products, such as e.g. cars and electronic products, the domestic industries are not a good representation of the foreign industries that produce the imported products.

Therefore, in order to have more accurate production data, the Danish IO-model has to be linked with IO-models for the countries from which Denmark imports products. This is further described in **section 3.3**.

3.2 Which results can be derived from the model: consumption, production and imports

In the previous section, the general method of input-output modelling has been described. In the current section, it is described which results can be calculated using the model.

As described in the previous section, the structure and principles of an IO-model are very similar to ordinary life cycle assessment models. In fact an IO-model is comparable with an ordinary life cycle inventory database. When using the model for analysing various environmentally related issues, the products under study are defined by the final demand vector (**f**) as in **Equation 3.3** and **Equation 3.5**. Using life cycle assessment terminology, the final demand vector is identical to the functional unit of the study.

In principle, an IO-model can be used for calculating the life cycle emissions for any functional unit, i.e. it can be for one unit of individual products or it can be the sum of several products representing the total consumption, export, import etc. at the societal level. Some examples of different final demand vectors and associated scope of the analysis are illustrated in **Figure 3.4**.

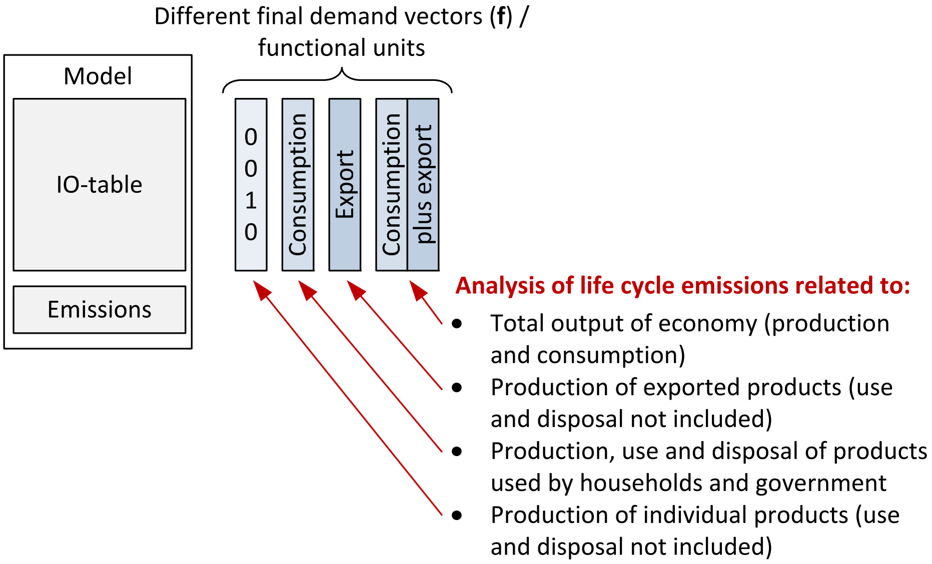


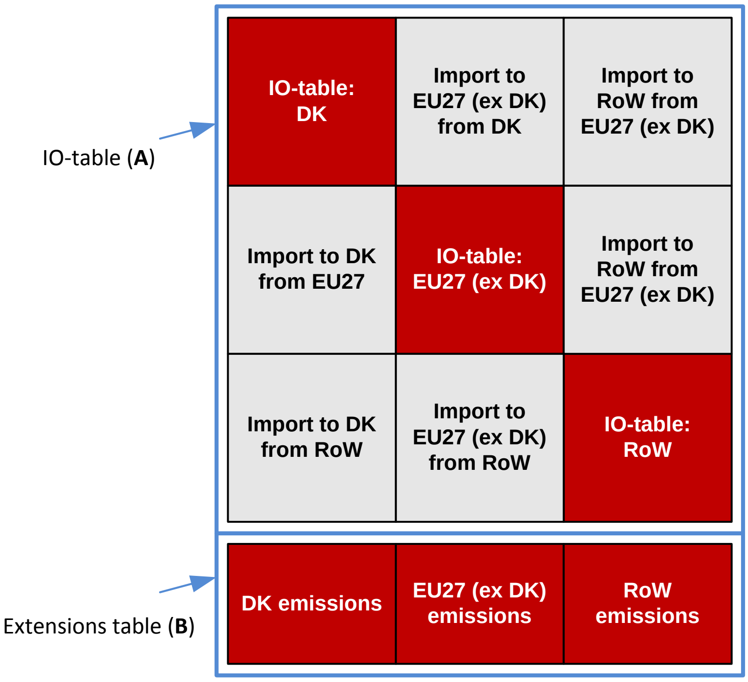
Figure 3.4: Illustration of different final demand vectors and the associated focuses of the analysis.

In addition to the listed focusses of the analysis in **Figure 3.4**, the life cycle emissions associated with imported products are also often calculated. This can be done by adding up emissions which are not emitted in Denmark. The model illustrated in **Figure 3.4** does not distinguish between different countries. This issue is further described in **section 3.3**.

3.3 Modelling of international trade

The presented example in **Table 3.5** and **Equation 3.5** used a simple assumption regarding imported products; namely that all imported products are produced in the same way (with same emissions) as domestically produced products. This is obviously not a very accurate assumption. Especially for a small country as Denmark which relies on very high import shares for a number of products, such as e.g. cars and electronic products, the domestic industries are not a good representation of the foreign industries that produce the imported products.

The solution on this problem is to create so-called trade-linked multi-regional IO-models. These models link several national IO-tables so that imported products are modelled using data from the exporting countries. A simple trade-linked IO-model with three linked countries/regions is illustrated in **Figure 3.5**.



IO-table: DK	Import to EU27 (ex DK) from DK	Import to RoW from EU27 (ex DK)
Import to DK from EU27	IO-table: EU27 (ex DK)	Import to RoW from EU27 (ex DK)
Import to DK from RoW	Import to EU27 (ex DK) from RoW	IO-table: RoW
DK emissions	EU27 (ex DK) emissions	RoW emissions

Figure 3.5: Illustration of trade-linked multi-regional IO-table. The IO-table links three countries/regions: Denmark, EU27 (ex DK) and rest-of-the-world (RoW). The red boxes represent domestic product transactions (IO-table) and emissions (extensions table), while the grey boxes represent the trade with products.

An example of a multi-regional IO-model is the Exiobase database, which cover 43 countries (95% of the global economy) and the Rest of the World (combining the remaining 150+ countries). The database uses year 2000 as base year. More information on the database can be found here: http://www.exiobase.eu/

3.4 Modelling of international transport

When Danish owned ships, aircrafts and vehicles are refuelled abroad, the associated emissions are sometimes not included in the extensions table. The emissions are often referred to as emissions from bunkering. The reason for this exclusion is that these emissions are not regulated under the Kyoto Protocol, and consequently, they shall not be included in national emission inventories completed within the UNFCCC framework. Since the emission inventories used for IO-models are often exactly the inventories completed within the UNFCCC framework, it is often seen that the emissions from bunkering are not included in IO-models.

Since Denmark has a very large shipping sector (including Maersk Line), emissions from bunkering are in particular relevant for Danish emission inventories. According Statistics Denmark (2013a), the non-Kyoto emissions accounted for as much as 41% in 2011 (See **Table 3.6**).

Table 3.6: Overview of total national CO_2-emissions from Denmark, with specification of emissions from international bunkering from Danish operated ships, aircrafts, vehicles and other (transport and trade across borders). Emissions are given in thousand tonne, kt, and data are obtained from Statistics Denmark (2013a).

Year	**CO_2-emissions (kt)**					
	on Danish territory (Kyoto inventory)	from Danish operated ships abroad	from Danish operated aircrafts abroad	from Danish operated vehicles abroad	Other: transport and trade across national borders	**Total**
1990	57,515	9,176	272	0	2,514	69,477
1995	66,657	10,947	426	0	1,850	79,880
2000	60,637	19,068	514	0	2,028	82,247
2005	61,856	32,343	1,620	484	870	97,173
2010	63,712	34,140	1,205	1,798	696	101,551
2011	58,382	37,097	1,090	1,324	826	98,719

If the emissions from bunkering are not included in the environmental extension of an IO-model, the emissions per unit of supply from the ship, air and road transport will be underestimated. Therefore, it is important that these emissions are included in the environmental extension.

In IO-tables, transport inputs to each industry activity are included as:

- directly purchased transport services by the companies in the industry activities
- indirectly purchased transport services when products are purchased from retail/wholesale where transport is included in the paid price (this is further described in Schmidt et al. 2010, p 20-23)

All transport services in economy are either directly purchased by industries or allocated to purchased products by the industries. Hence, IO-models generally include average transport services for all product transactions. However, transport of a specific product is modelled as average transport for this product, regardless if the product is imported to Denmark from China or if it is domestically produced.

3.5 Inclusion of indirect land use changes (iLUC)

According to Le Quéré et al. (2012), around 9% of global carbon emissions in 2010 originated from deforestation. Often, these emissions are not addressed in life cycle assessment (LCA) because the causal link between the use of land and deforestation is not well described and because there is a missing consensus on how to establish this link. Further, several studies suggest that effects from intensification of cropland may be caused by changes in demand for land.

In the current study an advanced cause-effect based iLUC model is applied. The iLUC model is developed by **2.-0 LCA consultants** in a project supported by a range of industries (e.g. Unilever, DuPont, TetraPak, Arla Foods, DONG Energy, United Plantations), universities (e.g. Swedish University of Agriculture Sciences, Aalborg University, Aarhus University and Copenhagen University) and other research related organisations (e.g. The Sustainability Consortium, the ecoinvent LCA database, Round Table on Sustainable Palm Oil (RSPO) and the Japanese National Agricultural Research Center) plus several others. More information on the iLUC-project can be found here: http://www.lca-net.com/projects/ilucmodel/. Currently, a series of scientific articles describing the model is in preparation. Published descriptions of the model can be found in Schmidt et al. (2012b) and Schmidt and Brandão (2013).

The iLUC model has several key characteristics that make it superior to many of the other models:

- the model can be implemented in a supply-use and input-output framework
- is applicable to all crops (also forest, range, build etc.) in all regions in the world
- it overcomes the allocation/amortisation of transformation impacts
- it is based on modelling assumptions that follow cause-effect relationships and standard modelling consistent with any other LCA-processes

It is acknowledged that the iLUC model referred to above is one among many other models and that there currently is no consensus in the LCA community how to model iLUC. Therefore, the contributions to results from iLUC are reported separately. Furthermore, when interpreting and using results care should be taken and uncertainties should be considered.

Global deforestation and how to ascribe it to its drivers

The underlying assumption of the iLUC model is that land use changes (LUC) are caused by changes in demand for land. If there were no changes in the demand for land, then there would be no land use changes. The challenge is then to create a causal link between the demand for land and land use changes. In the following, this link is established via a market for land.

Before establishing the link between demand for land and LUC, we must first define what is meant by land. Land can be perceived as a capital input. In biomass producing activities (such as crop cultivation, forestry and pasture) land is a required capital input in order to be able to produce biomass. A parallel to this is that biomass producing needs inputs of tractors in order to be able to produce biomass. Inputs of land to a land using activity can be measured as hectare years (ha yr), i.e. occupation of a given area during a given period of time. However, when using land for biomass production the land's productivity will be very different depending on the location of the land occupation; 1 ha yr field in Denmark will be associated with lower potential yields than 1 ha yr in the wet tropics. Therefore, land is measured as productivity weighted hectare years (pw ha yr). The productivity weighting factor is based on the potential net primary production, NPP_0 (Haberl et al. 2007a,b), and it is calculated as the NPP_0 at the location of interest divided by the global average NPP_0 of the relevant land market, e.g. 6110 kg C/ha yr for market for arable land (markets are explained later in the section).

The fact that land use changes are referred to as indirect is not much different from the tractor example above. In fact the use of tractors could also be referred to as 'indirect tractor production'. The term 'indirect' just indicate that the tractor is not produced in the same activity as the one that is using the tractor. In the same manner, some land use changes (LUC) are not taking place in the same activities as the ones that use land.

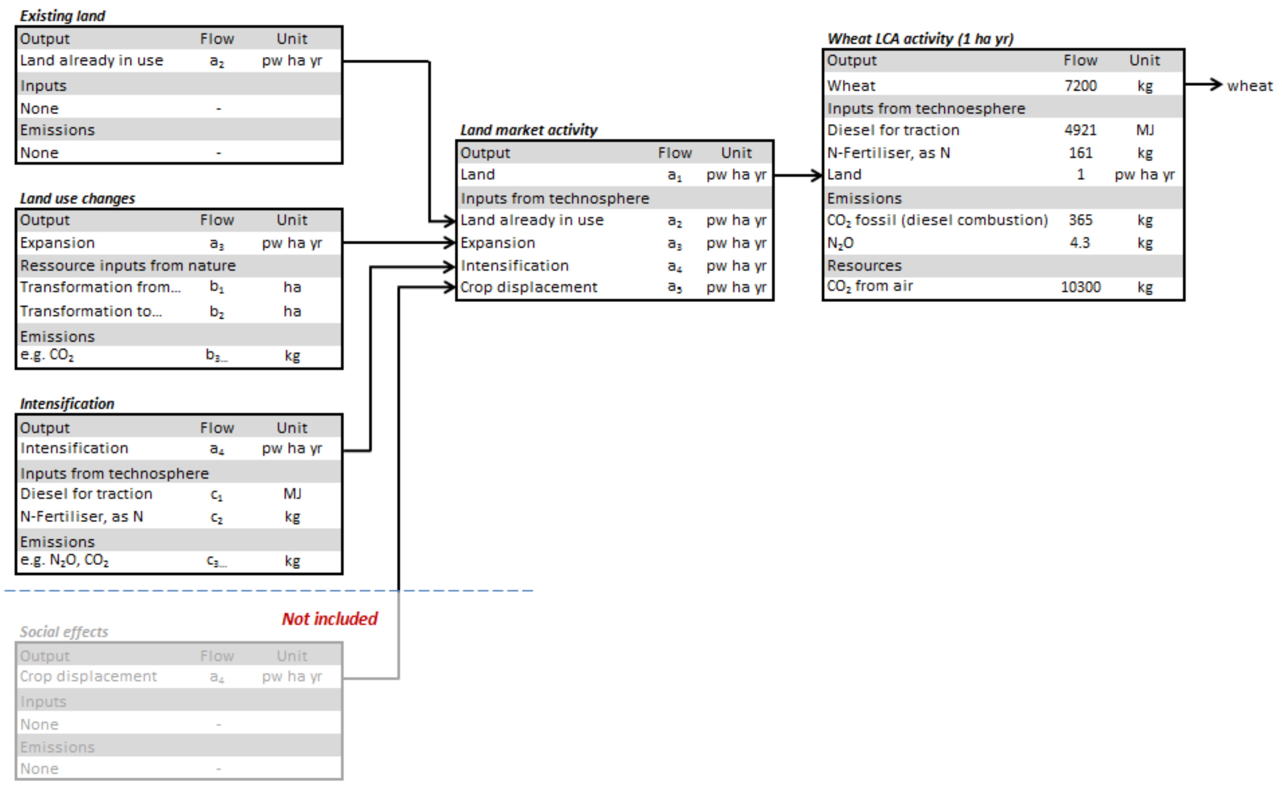
The point to be taken from above is that land (or rather 'biomass production capacity') is something that is used and produced as all other products. The only thing that is special for the product 'land' is that it is produced in another way than other products. A large part of the land that is used in a specific year is land that was already in use the previous year. So we can say that there is a high 'recycling rate' of land. But it can also be observed from land statistics that not all land that is used in a specific year is land that was already in use the previous year. Every year, the area of productive land is increasing, and this new land is 'produced' by transforming some land that was not in use (often natural forest) into land in use (often agricultural land or managed forests). It can also be observed that land already in use is becoming more productive every year due to increased inputs (fertilisers, pesticides, water) and changes in management. This so-called intensification of land already in use can be seen as another source of biomass production capacity than the land transformation source.

Hence, we have identified three sources of land-equivalents in terms of biomass production capacity:

- Use of land which is already in use ('recycling' of land)
- Transformation of land not in use into land in use
- Intensification of land already in use

There is a potential fourth source of land is 'crop displacement', i.e. when more land to meet a specific demand is met by a reduction in land use by other activities. The effects associated with 'crop displacement' will be changes in prices land based commodities (crops etc.) which can lead to social impacts. However, since LCA and IO-models are typically used for generating decision support in the long term, the default assumption is that price effects are removed by competition and 'Crop displacement' effects have therefore been assumed to be zero in the current study.

Since there is more than one supplier of land, we can introduce a market activity; market for land. The principle is illustrated in **Figure 3.6**.



Existing land

Output	Flow	Unit
Land already in use	a_2	pw ha yr
Inputs		
None	-	
Emissions		
None	-	

Land use changes

Output	Flow	Unit
Expansion	a_3	pw ha yr
Ressource inputs from nature		
Transformation from…	b_1	ha
Transformation to…	b_2	ha
Emissions		
e.g. CO_2	$b_{3…}$	kg

Intensification

Output	Flow	Unit
Intensification	a_4	pw ha yr
Inputs from technosphere		
Diesel for traction	c_1	MJ
N-Fertiliser, as N	c_2	kg
Emissions		
e.g. N_2O, CO_2	$c_{3…}$	kg

Land market activity

Output	Flow	Unit
Land	a_1	pw ha yr
Inputs from technosphere		
Land already in use	a_2	pw ha yr
Expansion	a_3	pw ha yr
Intensification	a_4	pw ha yr
Crop displacement	a_5	pw ha yr

Wheat LCA activity (1 ha yr)

Output	Flow	Unit
Wheat	7200	kg
Inputs from technoesphere		
Diesel for traction	4921	MJ
N-Fertiliser, as N	161	kg
Land	1	pw ha yr
Emissions		
CO_2 fossil (diesel combustion)	365	kg
N_2O	4.3	kg
Resources		
CO_2 from air	10300	kg

Not included

Social effects

Output	Flow	Unit
Crop displacement	a_4	pw ha yr
Inputs		
None	-	
Emissions		
None	-	

Figure 3.6: Illustration of land using activity (wheat cultivation) which has input of land from the market for arable land. The land market activity has inputs of the different sources/suppliers of land. It is indicated that 'crop displacement' is not included.

Markets for land

The market for land is regarded as being global, i.e. the demand for 1 pw ha yr in Denmark will have same iLUC effects as 1 pw ha yr in e.g. Malaysia. Although land as such cannot be moved, the production of crops (and other biomass) can, and the resulting products are traded on global markets.

Currently, five different markets for land in the iLUC model are considered. These five markets cover all land in the world. The markets are described in **Table 3.7**.

Table 3.7: Five different markets for land in the iLUC model.

Market for land	Description
Arable land	Fit for arable cropping (both annual and perennial crops), for intensive or extensive forestry, and pasture.
Intensive forest land	Fit for intensive forestry but unfit for arable cropping because e.g. the soil is too rocky. Forest crops grown on intensive forestland may be managed as intensively or extensively. Intensive forestland may also be used for other uses, e.g. livestock grazing and extensive forestry.
Extensive forest land	Not fit for more intensive forestry (e.g. clear cutting and reforestation, species control etc.) because e.g. it is too hilly, too remote, or it is very infertile making intensive forestry uneconomic. Forests grown on extensive forestland are typically harvested after natural regrowth with mixed species.
Grassland	Too dry for forestry and arable cropping. Grassland is most often used for grazing.
Barren land	Not fit for biomass production.

Land use changes – marginal versus average approach

According to **Figure 3.6**, the market for arable land has inputs from three different suppliers of land. One of the supplies of land, 'land already in use' is special in the sense that this supply is not capable responding to changes in demand for land (because it is already in use). If there were no changes in the demand for land, all land would be supplied by this supply with no impacts.

The iLUC model includes in principle all land use changes; all transformations and all intensification taking place. Hence, the mix of the different supplies of land is given by the relative differences in the inputs to the market for land. The total global area of arable land is much larger than the annual increase of arable land (achieved by land transformation) and the land equivalents achieved by intensification.

An average approach to the modelling of iLUC would include all inputs to the market for land, while a marginal approach would only include inputs from suppliers which are capable changing their supply. Hence, the marginal approach would not include land already in use, and the market for land would only have inputs of land from transformation and intensification.

Since, land already in use is not associated with any impacts, an average approach will lead to significant lower results than a marginal approach. But which approach is the right one to use? Since the question we are trying to answer with the current study is something like: "what is the impact from Danish consumption". Inherently, this needs to be compared with a situation where the consumption would not take place. Hence, the marginal approach will provide the most logical answer.

Incorporating transactions of land in the IO-framework

In the technology matrices (input-output tables), the agricultural activities have inputs of tractors. Hence, when analysing the life cycle emissions of crop production, the emissions from the production of tractors are included. But currently, there is no row in the IO-table that specifies the use of land. Nor is there a column specifying the supply of land. Hence, in order to be able to model indirect land use changes explicitly, additional rows and columns are inserted in the IO-model. **Figure 3.7** illustrates how a market for land and three associated suppliers of land can be incorporated in the IO-framework. In the figure, it is indicated where land using industries have inputs of land (from the market for land), where the land market activity has inputs of land from suppliers of land (land already in use, transformation and intensification), and where the iLUC emissions take place, i.e. in the transformation and intensification activities.

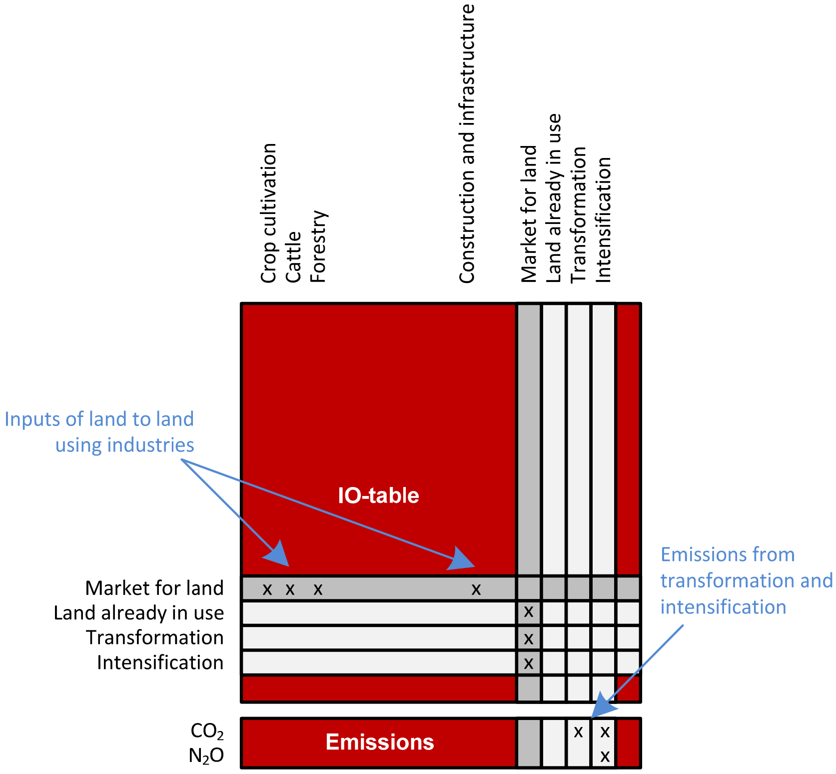


Figure 3.7: Illustration of how a market for land and four suppliers of land are incorporated in the IO-framework. The illustration here only shows one market for land and associated suppliers of land.

Modelling the GWP implications of deforestation – timing issues for emissions

The following section is based on Schmidt and Brandão (2013). When the occupation of land causes deforestation, a critical point is often to decide the period of time over which the deforestation emissions should be allocated or 'amortised', which essentially cannot be done in an objective way. Our model instead models the actual acceleration of deforestation and emissions, and therefore does not need the arbitrary amortisation assumptions. If only expansion is considered, occupation of 1 ha in 1 year will cause 1 ha deforestation. After the duration of 1 yr, the land is released to the market for land, i.e. to other crops, which can then be grown without deforestation. Hence, the occupation of 1 ha-yr is modelled as 1 ha deforestation in year 0 and -1 ha deforestation in year 1. This is illustrated in **Figure 3.8**. In order to model the GHG effects of this temporary acceleration of deforestation, the timing issue in addressed in the calculation of the global warming potential. This is described in the following.

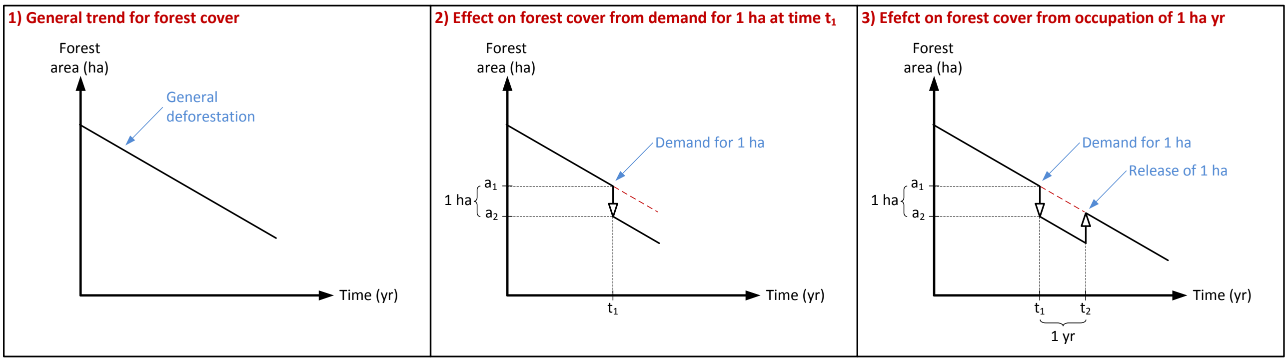


Figure 3.8: Stepwise description of how the occupation of 1 ha in 1 year from t_1 to t_2 affects the global forest cover over time.

The IPCC Global Warming Potential (GWP) (IPCC 2007, p 210) is normally used for expressing the relative importance of different GHG-emissions. Most often (or always) this is done relative to CO_2. The GWP of 1 kg of a GHG emission is calculated as the cumulative radiative forcing over a given period of time (time horizon) relative to the cumulative radiative forcing of 1 kg CO_2 during the same period of time. The formula is given in **Equation 3.6** (IPCC 2007, p 210). The GWP is influenced by the decay rate of the considered GHG-emissions and the radiative forcing of the emission.

Equation 3.6

$$GWP_i = \frac{\int_0^{TH} RF_i(t)dt}{\int_0^{TH} RF_{CO_2}(t)dt}$$

where:

GWP_i is the global warming potential for substance *i*
TH is the applied time horizon
RF_i is the radiative forcing for substance *i*
RF_{CO2} is the radiative forcing for CO_2

When applying a time horizon of 100 years, it can be calculated that 1 kg methane has an equivalent cumulative radiative forcing to 25 kg CO_2 because it has a greater radiative efficiency (despite its shorter residence time in the atmosphere). In order to make this calculation, it is necessary to know how CO_2 is removed from the atmosphere as a function of time. CO_2 is removed from the atmosphere by plants (through photosynthesis) and the oceans. **Figure 3.9** shows the fraction of a pulse emission of CO_2 remaining in the atmosphere as a function of time. According to this equation, of an emission of 1 kg of $CO_{2,}$ 0.5 kg will remain in the atmosphere after 30 years.

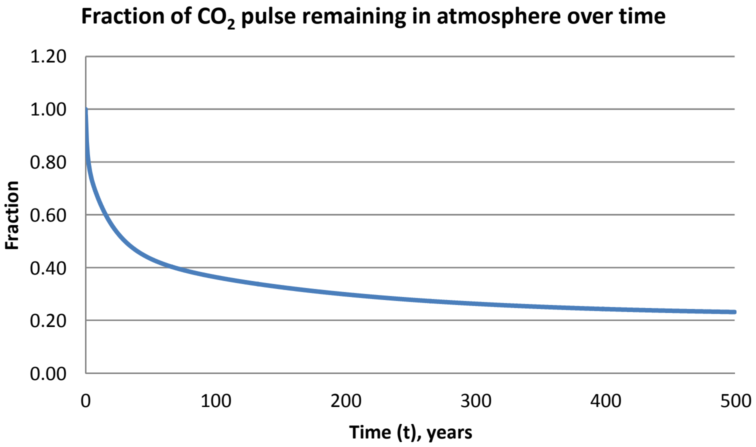


Figure 3.9: Fraction of a CO_2 pulse present in the atmosphere as a function of time. The fraction is calculated using the Bern carbon cycle, see **Equation 3.7**.

The Bern carbon cycle is used to describe the fraction of a pulse emission of CO_2 that remains in the atmosphere over time. The Bern carbon cycle is shown in **Equation 3.7**: (IPCC 2007, table 2.14)

Equation 3.7

$$Fraction(t) = 0.217 + 0.259 \cdot e^{-t/172.9} + 0.338 \cdot e^{-t/18.51} + 0.186 \cdot e^{-t/1.186}$$

When modelling deforestation in the current study, the GWP approach is expanded to also account for different timing of emissions. **Equation 3.8** applies this to a difference in timing Δt (relative to a reference time t=0) for a substance *i*. **Equation 3.9** shows this applied to CO_2.

Equation 3.8

$$GWP_{i,\Delta t} = \frac{\int_{\Delta t}^{TH} RF_{i,\Delta t}(t-\Delta t)dt}{\int_{0}^{TH} RF_{CO_2,t=0}(t)dt}$$

where:

$GWP_{i,\Delta t}$ is the global warming potential for substance *i* emitted at time Δt relative to t = 0
TH is the applied time horizon
$RF_{i,\Delta t}$ is the radiative forcing for substance *i*, emitted at time Δt relative to t = 0
$RF_{CO2,t=0}$ is the radiative forcing for CO_2 emitted at time t = 0

Equation 3.9

$$GWP_{CO2,\Delta t} = \frac{\int_{\Delta t}^{100} CO_{2,fraction}(t-\Delta t)dt}{\int_{0}^{100} CO_{2,fraction}(t)dt}$$

$$= \frac{\int_{\Delta t}^{100} 0.217 + 0.259 \cdot e^{-(t-\Delta t)/172.9} + 0.338 \cdot e^{-(t-\Delta t)/18.51} + 0.186 \cdot e^{-(t-\Delta t)/1.186} dt}{\int_{0}^{100} 0.217 + 0.259 \cdot e^{-t/172.9} + 0.338 \cdot e^{-t/18.51} + 0.186 \cdot e^{-t/1.186} dt}$$

The principle of **Equation 3.9** is illustrated in **Figure 3.10**.

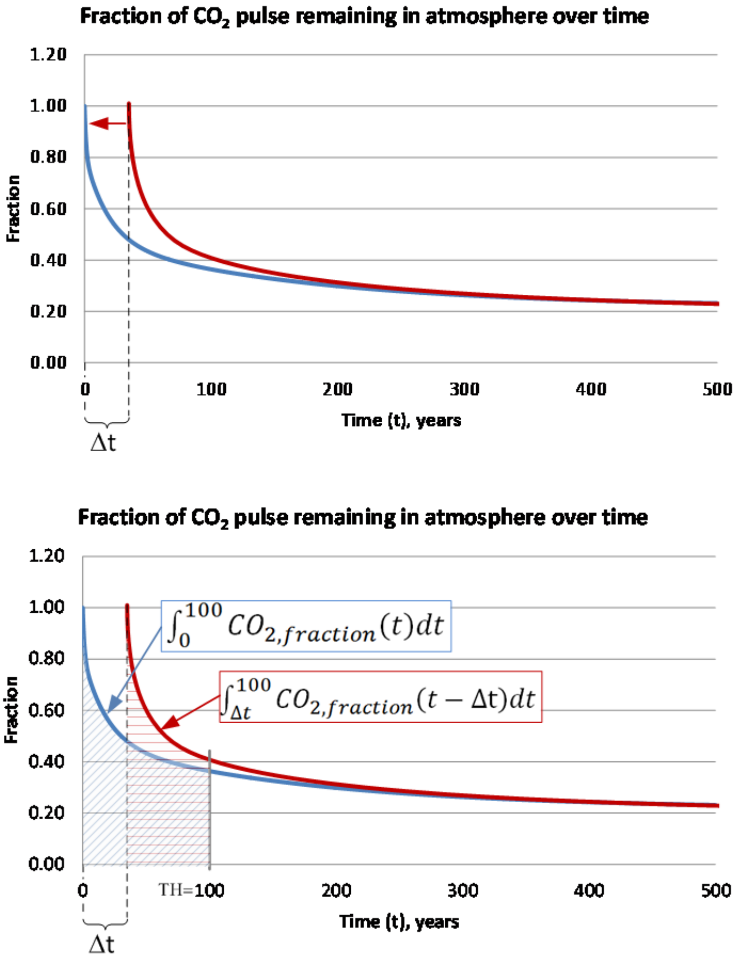


Figure 3.10: ***Top:*** **Effect of emitting a CO_2 pulse at time Δt is illustrated as moving the CO_2 decay curve to the right.** ***Bottom:*** **The denominator in Equation 3.9** is illustrated as the blue shaded area (CO_2 emitted at time 0), and the nominator is illustrated as the red shaded area (CO_2 emitted at time Δt).

By inserting **Equation 3.7** in **Equation 3.9** for CO_2 with Δt = 1 year and TH = 100 years, it can be calculated that:

Equation 3.10

$$GWP_{CO2,\Delta t=0} = 1$$
$$GWP_{CO2,\Delta t=1} = 0.9924$$

This means that emitting 1 kg CO_2 in year 1 has the same GWP100 effect as emitting 0.9924 kg CO_2-eq. in year 0. It also means that speeding up 1 kg CO_2 emission by one year has the following effect: 1 kg CO_2 minus 0.9924 kg CO_2-eq. = 0.00761 kg CO_2-eq.

The iLUC model - quantified

In the following the concepts described above a supplemented with number, so that the model can be used to quantify iLUC emissions. The iLUC model includes two types of 'industries' supplying land to the market for land. Each of the two types of industries has specific suppliers:

1. Transformation of land not in use
    - Transformation From secondary forest To cropland
    - Transformation From primary forest To intensive forest
    - Transformation From secondary forest To intensive forest
    - Transformation From primary forest To extensive forest
    - Transformation From grassland To pasture
2. Intensification of land already in us
    - Intensification, arable land
    - Intensification, pasture

The inputs from the different suppliers above to each of the markets for land are shown in **Table 3.8**.

Table 3.8: Overview of the inputs to the different markets for land. All flows represent annual flows of a representative year between 2000 and 2010. Note that intensification is measured in units of million ha equivalents; this refer to the amount of land released by annual intensification. (Schmidt et al 2012 and Schmidt and Brandão 2013)

Input of land to the land markets	Unit	Market for arable land	Market for intensive forest land	Market for extensive forest land	Market for grassland	Market for barren land
Transformation of land						
From secondary forest To cropland	Mha	13.0				0
From primary forest To intensive forest	Mha		0.38			0
From secondary forest To intensive forest	Mha		3.37			0
From primary forest To extensive forest	Mha			3.86		0
From grassland To pasture	Mha				4.59	0
Intensification	Mha yr eq.	24.7			38.7	**0**

The calculated emissions per transformed hectare of land for the different transformation activities are shown in **Table 3.9**. The CO_2 emissions are based on data on carbon stocks in different land use categories in IPCC (2006). The CO_2-eq. from accelerated CO_2 emissions are calculated by multiplying the CO_2 emissions by the time-GWP-weighting factor in the section '**Modelling the GWP implications of deforestation – timing issues for emissions**'.

Table 3.9: Overview of the emissions from the land transformation activities.

Transformation	From	secondary forest	primary forest	secondary forest	primary forest	natural grassland
	To	cropland	intensive forest	intensive forest	extensive forest	pasture
Product output						
Reference flow	ha	1	1	1	1	1
Emissions						
CO_2	t	272	354	178	176	77
Accelerated CO_2, as CO_2-eq. (GWP100)	t	2.07	2.70	1.35	1.34	0.59

The inputs to the intensification activity is calculated as the total annual increase in N-fertiliser divided by the total annual land equivalents obtained from intensification, i.e. the 24.7 Mha in **Table 3.8**. The total annual increase in N-fertiliser is calculated based on time series of N-fertiliser production obtained from IFA (2013). The global average annual increase in N-fertiliser production from 2000 to 2009 was 2.33 million tonne N. The associated N_2O-emission is calculated based on IPCC (2006) for a weighted average of maize, rice and what which are the most important crops regarding intensification globally.

Table 3.10: Overview of the transactions of the intensification activities.

Intensification	From	Intensification of arable land	Intensification of grassland
Product output			
Reference flow	ha yr	1	1
Fertiliser inputs			
N-fertiliser, as N	t	0.094	0
Emissions			
N_2O	t	0.0021	0

In **Table 3.11** the GHG-emissions from iLUC for occupation of one hectare in one year (1 ha yr) in different regions of the world are shown.

Table 3.11: GHG-emissions from iLUC related to the occupation of one hectare arable land in one year (1 ha yr) in different regions of the world.

Country/region	Indicator for potential productivity (NPP_0 measured as t C ha^{-1})	Relative indicator for potential productivity (pw ha yr)	GHG-emissions from iLUC per occupation of 1 ha yr
World average arable land	6.1	1.0	1.7
Denmark (DK)	7.0	1.1	1.9
Brazil (BR), Cerrado region	9.0	1.5	2.5
Europe (EU27), Central	7.0	1.1	1.9
Malaysia (MY)	11.0	1.8	3.0
India (IN), Southern India	7.0	1.1	1.9
Indonesia (ID)	13.0	2.1	3.5
Ukraine (UA)	5.0	0.8	1.4

3.6 Inclusion of increased radiative forcing from aviation

There are specific effects of emissions in high altitude, which lead to a higher contribution of aviation to the problem of climate change than just the emission of CO_2 from burning fuels. For subsonic aviation, these non-CO_2 effects include (Lee et al. 2010):

- Emissions of NO_x result in the formation of tropospheric ozone (O_3) with a positive radiative forcing (warming).
- Emissions of NO_x result in the destruction of ambient methane (CH_4), with a negative radiative forcing (cooling), which is accompanied by a parallel, decadal loss of tropospheric O_3.
- Emissions of sulphate (SO_4) particles result in a negative radiative forcing (cooling).
- Emissions of soot particles result in a positive radiative forcing (warming).
- The formation of persistent linear contrails in the wake of an aircraft result in both positive and negative radiative forcing effects but overall, cause a positive one (warming).
- The formation of contrail-cirrus clouds from spreading contrails similarly to line shaped-contrails results in both positive and negative radiative forcing effects but overall, is considered to cause a positive one (warming).
- A sub-component of aviation-induced cirrus (AIC) is a mechanism whereby soot particles seed cirrus clouds. This effect may result in either positive or negative radiative forcing effects (warming/cooling) but is rather uncertain over the sign and proven existence of the effect.

The first assessment of the climatic impact of the emissions from aviation was done by the IPCC (Penner et al. 2000), using radiative forcing as a metric, see **Figure 3.11**. This assessment found that in 1992 the total radiative forcing caused by aviation emissions (excluding cirrus formation) was 2.5 times that of CO_2 emissions alone. This so-called radiative forcing index (RFI) has been used as a multiplication factor to calculate the overall carbon footprint of aviation emissions, however this approach is plainly wrong (Forster et al. 2007), given that the RFI is based on radiative forcing only, whereas the GWPs used in the Kyoto Protocol and in carbon footprinting take into account the lifespan of substances in the atmosphere. Currently there are no clear recommendations by the IPCC on how to deal with this subject, and as shown by the review carried out by Jungbluth (2012), in LCA, carbon footprinting, emission trading, etc., practitioners have either omitted aviation's non-CO_2 effects altogether, or they have applied a RFI ranging from 2 to 2.7-2.8, sometimes to the total CO_2 emissions, sometimes only to those occurring in the stratosphere.

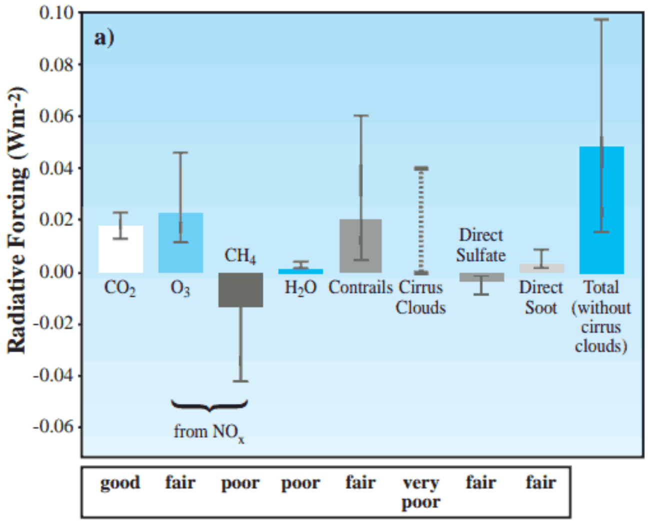


Figure 3.11: Radiative forcing from aircraft in 1992 (Penner et al. 1992).

The lack of recommendations by the IPCC in this area is related to the fact that the scientific understanding of these environmental processes is not yet good enough (Forster et al. 2007). Many of the non-CO_2 emissions from aviation correspond to short-lived substances, not currently covered by the Kyoto protocol. As opposed to emissions of e.g. CO_2, the climatic impact of short-lived substances depends on where and when the emissions are introduced into the atmosphere. For aircraft emissions it is not only important to know the location in the globe where the emission takes place, but also the altitude (Fuglestvedt et al. 2010). For these reasons, Penner et al. (2000) considered that the GWP metric was not suited at all to assess this kind of emissions and preferred to use radiative forcing instead.

In spite of the methodological limitations, GWP values for different time horizons have been provided for the different emitted substances (see Fuglestvedt et al. 2010), and these have been applied in peer-reviewed research (Borken-Kleefeld et al. 2013, Lee et al. 2010). In this study we have decided to apply the GWP100 values to aviation emissions as proposed by Lee et al. (2010), including those for NOx, water vapour, contrails and AIC. No GWP100 values have been applied to sulphate and black carbon, due to the fact that in practice their contribution to CO_2-eq. emissions is very low in a 100-year perspective.

Table 3.12: GWP100 values considered for non-CO_2 aviation emissions.

GHG	**GWP100 (kg CO_2-eq/kg GHG)**	**Comments**
N-NO_x	71	Very high uncertainty. Values range from -2.1 to 71.
H_2O	0.14	High uncertainty. This factor is applied to the total amount of water emitted in the exhaust gases.
Contrails	0.21	High uncertainty. This factor is applied to the total amount of CO_2 emitted in the exhaust gases.
Aviation-induced cirrus (AIC)	0.63	Very high uncertainty. This factor is applied to the total amount of CO_2 emitted in the exhaust gases.

It must be highlighted that NO_x produces a radiative forcing not only when emitted at high altitudes, but also at ground level, where it produces a cooling effect. Thus for consistency a (negative) GWP100 value for NO_x emitted at ground level could be considered, and applied to emissions sources other than aircraft. According to Wild et al. (2001) global NO_x emissions (on a N basis) have a GWP100 of -11 kg CO_2-eq/kg. In practice though this contribution in terms of CO_2-eq. is negligible[15] when compared to that from conventional long-lived GHG-emissions over a 100-year time horizon, and for this reason it has not been considered in the study.

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[15] As an example, an average European car (ecoinvent dataset 'operation, passenger car, RER') has a tailpipe emission of 0.19 kg CO_2/km, whereas the NO_x emission is of 0.00053 kg/km. Assuming a N fraction of 39% in the NO_x (i.e. 50% NO and 50% NO_2) and applying a GWP100 of -11 kg CO_2/kg N-NO_X, the NO_x correspond to 0.0025 kg CO_2-eq, that is a contribution three orders of magnitude smaller than the CO_2 actually emitted.

4 Description of data to estimate Denmark's carbon footprint

In this chapter the data used for the calculation of Denmark's carbon footprint are described. The starting point is to define some key criteria for choosing an existing elaborated IO-model for Denmark and then to choose one. This is described in **section 4.1**. The following sections describe the methods and data sources that have been used for creating the model, and some key figures on Danish economy are extracted from the model.

4.1 Model chosen

Within the scope of the current study, it is not desirable to create a new and recent environmentally extended trade-linked IO-model for Denmark. The creation of such models is very time consuming, and currently there is ongoing work on creating such models (e.g. the EU FP7 projects; CREEA and DESIRE). Hence, the creation of a new model would be redundant to existing ongoing work. As described in **chapter 2** there are existing models for Denmark.

When choosing a model for the current study, the following criteria have been used:

- **Year:** The model should be as recent as possible
- **Level of detail:** The model should have a high level of detail, i.e. number of different industries and products, in order to enable for meaningful analysis
- **Physical units:** In additional to monetary transactions, the model should also include physical flows (mass and energy) enabling for:
    - making sanity checks (does the model fits with the physical reality, e.g. compliance with physical statistics?)
    - analysing impacts per monetary unit (GHG-emissions/EUR product) as well as per physical unit (GHG-emissions/kg product)
    - analysing the impacts related to different management options of waste flows
- **Modeling of imports:** The model needs to be trade-linked with relevant exporting countries

Based on the literature review in **chapter 2** a number of candidates of models have been identified. In **Table 4.1**, these models are evaluated using the listed criteria above. Based on the review, the FORWAST model has been chosen as the model for the current study. It should be noted, that various modifications of the FORWAST model are introduced in order to arrive at a more accurate and recent result; this is described in **chapter 5**.

Table 4.1: GWP100 values considered for non-CO_2 aviation emissions.

IO-model	Year	Level of detail	Physical units	Modelling of imports
Evaluation				
Weidema et al. (2005) (**section 2.2**)	1999	138 sectors/ products	No	Import modelled as USA (1998)
Gravgård et al. (2009) (**section 2.4**)	2007	130 sectors/ products	energy accounts	Import modelled as DK production (closed economy assumption)
Hertwich and Peters (2009) (**section 2.5**)	2001	57 sectors/ products	No	Trade-linked: 87 regions
FORWAST (**section 2.7**)	2003	132 sectors /products	Mass (balanced on product and industry level) Energy (balanced on product level)	Import modelled as EU27
Exiobase (**section 2.8**)	2000	132 sectors /products	No	Trade-linked: 44 regions
Chosen model				
FORWAST (**section 2.7**)	2003	132 sectors /products	Mass (balanced on product and industry level) Energy (balanced on product level)	Import modelled as EU27

4.2 Methods and data sources for emissions: The FORWAST model

A brief introduction to the FORWAST model is provided in **section 2.7**. The methodology on how the model has been created is described in Schmidt et al. (2010). A detailed description of all data for Denmark can be found in Hafner et al. (2010, chapter 4). Documentation of data for all other EU27 countries can be found in Hafner et al. (2010) and Rejman-Burzyńska et al. (2010). The elaborated core data sets used for the creation of the model are available as country specific excel files here: http://forwast.brgm.fr/results_deliver.asp (deliverables 3.2 and 4.2).

The data and methods of the FORWAST model are briefly summarised below. It should be noted that the description below refers to the creation of the original FORWAST model. In the current study, a number of modifications of the original FORWAST model have been carried out; this is described in **chapter 5**.

Original supply-use table from statistical agencies: The starting point of the creation of the Danish supply-use table was a detailed supply-use table (~2000 products by 134 industries) provided by Statistics Denmark. This was turned into square tables (134 products by 134 industries).

Modifications of the original supply-use tables from statistical agencies: In order to have a better level of detail and to be able to model different physical flows including various waste flows, some of the products/industries were disaggregated (subdivided). E.g. basic steel production was divided into the following two industries production of virgin steel and recycling of steel scrap. The disaggregation operations were based on data from detailed life cycle inventories (among other). Further, in order to harmonise the level of detail with the supply-use tables for other EU27 countries, some of the products/industries in the Danish tables were aggregated (merged).

Emissions: Domestic emissions from Danish industries and households were obtained from the national emission inventories as provided by Statistics Denmark (2013a). Those emissions inventories include emissions from bunkering. In addition to the emissions provided from national emission inventories, biogenic CO_2 uptake and emissions from crop cultivation, forestry, and animal and human respiration were also included. Hence, the inventory uses a true balanced approach for all CO_2 emissions.

Physical flows: A main focus of the FORWAST project was to estimate waste flows (calculated from mass balances of resource inputs, product transactions and emissions outputs) and to analyse the environmental implications of different waste management strategies. Hence, the monetary supply-use tables were supplemented by physical accounts in mass units (physical mirror image of all monetary transactions). Further, the resource inputs to economy were also included in the extension tables. The procedure for accounting for physical flows and how to incorporate physical waste flows as transactions within the supply-use tables is described in detail in Schmidt et al. (2010). Further, an updated description is available in Schmidt et al. (2012a).

The final IO-model: The final IO-model is a so-called hybrid model because:

- it is based on economic data from the national account as well as process-specific data from life cycle inventories (used for the disaggregation), and
- the transactions in the model are in different units; flows of products which have a physical mass are accounted in dry matter mass, flows of electricity/heat/steam are accounted in energy units, and other flows of mainly service products are accounted in monetary unit.

4.3 Key figures on Danish economy extracted from the FORWAST data sets

The FORWAST data set which is the basis of the Danish environmentally extended IO-table used in the current study contains a lot of information on the structure of Danish production, consumption and trade. Some key characteristics are extracted from the data set and presented here in this section. Data on monetary and physical (dry matter mass) transactions of products are extracted from the data set. The data set obviously also contains key information on Danish emissions as of the national emissions account. However, these data/results are presented in the results chapters (**chapter 6**) and not here.

Products and services produced and consumed in Denmark

The total supply of Danish industries was 312,000 MEUR in 2003. The most important of these products are listed in **Table 4.2**.

Table 4.2: Danish **production** of products in 2003 as of the FORWAST data set.

Monetary domestic supply			**Physical domestic supply**		
Products	**MEUR2003**	**Share**	**Products**	**Million tonne (DM)**	**Share**
Health and social work	24,065	7.7%	Sand, gravel and stone from quarry	57.7	38.7%
Real estate services	22,763	7.3%	Crude petroleum and natural gas	23.8	15.9%
Wholesale trade	21,529	6.9%	Concrete, asphalt and other mineral products	13.1	8.8%
Business services n.e.c.	16,032	5.1%	Grain crops	10.4	7.0%
Public service and security	15,747	5.0%	Refined petroleum products and fuels	8.6	5.7%
Transport by ship	12,537	4.0%	Gas	6.1	4.1%
Education services	12,537	4.0%	Animal feeds	3.9	2.6%
Retail trade and repair services	10,081	3.2%	Cement, virgin	2.7	1.8%
Financial intermediation	9,362	3.0%	Crops n.e.c.	1.7	1.1%
Buildings, non-residential	8,924	2.9%	Meat and fish products	1.5	1.0%
Land transport; transport via pipelines	8,511	2.7%	Clay and soil from quarry	1.2	0.8%
Chemicals n.e.c.	7,719	2.5%	Chemicals n.e.c.	1.2	0.8%
Post and telecommunication	7,635	2.4%	Pigs	1.0	0.7%
Buildings, residential	7,392	2.4%	Wood products, except furniture	1.0	0.7%
Computer and related services	7,384	2.4%	Paper and paper products	0.9	0.6%
Machinery and equipment n.e.c.	7,158	2.3%	Furniture; other manufactured goods n.e.c.	0.9	0.6%
Meat and fish products	6,212	2.0%	Forest products	0.9	0.6%
Infrastructure, excluding buildings	6,026	1.9%	Pulp, virgin	0.9	0.6%
Recreational and cultural services	5,580	1.8%	Bricks	0.8	0.6%
Hotels and restaurants	5,467	1.8%	Machinery and equipment n.e.c.	0.8	0.5%
Other	89,558	29%	Other	10.0	7%
Total*	**312,218**	**100%**	**Total***	**149.3**	**100%**

*Note that the numbers are not additive as such since the output of one industry is often used as an input to another.

The Danish households and government (i.e. public uses financed via taxes) used 156,000 MEUR in 2003. The most important uses are listed in **Table 4.3**. Notice that **Table 4.3** presents final uses in units of MEUR as well as million tonne (dry matter).

Table 4.3: Danish **final consumption** (households and government) of products in 2003 as of the FORWAST data set.

Monetary final use		
Products	**MEUR2003**	**Share**
Health and social work	23,649	15.1%
Real estate services	17,216	11.0%
Public service and security	14,172	9.1%
Education services	11,558	7.4%
Retail trade and repair services	9,183	5.9%
Buildings, non-residential	6,387	4.1%
Wholesale trade	5,898	3.8%
Buildings, residential	5,290	3.4%
Infrastructure, excluding buildings	4,320	2.8%
Financial intermediation	4,221	2.7%
Recreational and cultural services	3,668	2.3%
Hotels and restaurants	3,619	2.3%
Machinery and equipment n.e.c.	3,612	2.3%
Trade and repair of motor vehicles; service stations	3,364	2.2%
Computer and related services	3,271	2.1%
Electricity, steam and hot water	2,100	1.3%
Insurance and pension funding	2,015	1.3%
Motor vehicles and trailers	1,985	1.3%
Membership organisations	1,952	1.2%
Transport equipment n.e.c.	1,898	1.2%
Other	26,895	17%
Total	**156,275**	**100%**

Physical final use		
Products	**Million tonne (DM)**	**Share**
Refined petroleum products and fuels	2.2	22.1%
Sand, gravel and stone from quarry	2.1	21.0%
Gas	1.2	11.4%
Machinery and equipment n.e.c.	0.5	5.1%
Crops n.e.c.	0.5	4.9%
Forest products	0.5	4.8%
Furniture; other manufactured goods n.e.c.	0.5	4.5%
Animal feeds	0.4	4.4%
Food preparations n.e.c.	0.3	2.9%
Grain crops	0.2	2.3%
Flour	0.2	1.8%
Meat and fish products	0.2	1.6%
Wood products, except furniture	0.1	1.4%
Chemicals n.e.c.	0.1	1.2%
Beverages	0.1	1.2%
Fabricated metal products, except machinery	0.1	1.0%
Dairy products	0.1	1.0%
Fruits and vegetables, processed	0.1	0.9%
Electrical machinery n.e.c.	0.1	0.8%
Coal, lignite, peat	0.1	0.7%
Other	0.5	5%
Total	**10.1**	**100%**

Imports and exports to Denmark

In 2003, the total Danish import and export were 67,000 million EUR and 80,000 million euro respectively. The most important imported and exported products are listed in **Table 4.4** and **Table 4.5**.

Table 4.4: Danish **import** of products in 2003 as of the FORWAST data set.

Monetary import		
Products	**MEUR2003**	**Share**
Transport by ship	8,584	12.8%
Machinery and equipment n.e.c.	4,929	7.4%
Chemicals n.e.c.	4,527	6.8%
Motor vehicles and trailers	3,266	4.9%
Radio, television and communication equipment	3,018	4.5%
Office machinery and computers	2,507	3.8%
Refined petroleum products and fuels	2,193	3.3%
Wearing apparel and furs	2,123	3.2%
Electrical machinery n.e.c.	1,982	3.0%
Furniture; other manufactured goods n.e.c.	1,828	2.7%
Transport equipment n.e.c.	1,804	2.7%
Meat and fish products	1,742	2.6%
Rubber and plastic products	1,635	2.4%
Fabricated metal products, except machinery	1,527	2.3%
Paper and paper products	1,368	2.0%
Textiles	1,347	2.0%
Instruments, medical, precision, optical, clocks	1,312	2.0%
Business services n.e.c.	1,186	1.8%
Wood products, except furniture	1,157	1.7%
Computer and related services	1,147	1.7%
Other	17,664	25%
Total	**66,846**	**100%**

Physical import		
Products	**Million tonne (DM)**	**Share**
Refined petroleum products and fuels	13.0	26.2%
Coal, lignite, peat	7.3	14.6%
Crude petroleum and natural gas	3.5	7.0%
Sand, gravel and stone from quarry	3.4	6.9%
Wood products, except furniture	1.9	3.9%
Iron basic, virgin	1.8	3.6%
Crops n.e.c.	1.7	3.3%
Animal feeds	1.6	3.2%
Chemicals n.e.c.	1.5	3.0%
Paper and paper products	1.3	2.7%
Grain crops	1.1	2.1%
Minerals from mine n.e.c.	0.9	1.9%
Fertiliser, N	0.9	1.7%
Plastics basic, virgin	0.8	1.6%
Concrete, asphalt and other mineral products	0.7	1.4%
Machinery and equipment n.e.c.	0.7	1.4%
Iron, after first processing	0.6	1.3%
Rubber and plastic products	0.6	1.3%
Fabricated metal products, except machinery	0.6	1.2%
Flour	0.6	1.1%
Other	5.2	11%
Total	**49.8**	**100%**

Table 4.5: Danish **export** of products in 2003 as of the FORWAST data set.

Monetary export		
Products	**MEUR2003**	**Share**
Transport by ship	11,581	14.4%
Wholesale trade	8,281	10.3%
Chemicals n.e.c.	7,306	9.1%
Machinery and equipment n.e.c.	5,595	7.0%
Meat and fish products	4,984	6.2%
Furniture; other manufactured goods n.e.c.	2,597	3.2%
Crude petroleum and natural gas	2,541	3.2%
Electrical machinery n.e.c.	2,455	3.1%
Radio, television and communication equipment	2,316	2.9%
Land transport; transport via pipelines	1,954	2.4%
Instruments, medical, precision, optical, clocks	1,950	2.4%
Motor vehicles and trailers	1,626	2.0%
Dairy products	1,592	2.0%
Rubber and plastic products	1,572	2.0%
Wearing apparel and furs	1,547	1.9%
Air transport	1,354	1.7%
Fabricated metal products, except machinery	1,326	1.7%
Food preparations n.e.c.	1,326	1.7%
Business services n.e.c.	1,309	1.6%
Computer and related services	1,270	1.6%
Other	15,874	20%
Total	**80,353**	**100%**

Physical export		
Products	**Million tonne (DM)**	**Share**
Crude petroleum and natural gas	13.0	36.3%
Refined petroleum products and fuels	4.2	11.6%
Gas	2.6	7.1%
Grain crops	2.3	6.4%
Sand, gravel and stone from quarry	1.5	4.2%
Cement, virgin	1.3	3.6%
Meat and fish products	1.1	3.0%
Iron basic, virgin	0.9	2.4%
Chemicals n.e.c.	0.8	2.3%
Furniture; other manufactured goods n.e.c.	0.7	1.9%
Concrete, asphalt and other mineral products	0.7	1.9%
Machinery and equipment n.e.c.	0.6	1.8%
Minerals from mine n.e.c.	0.6	1.6%
Fertiliser, N	0.5	1.4%
Rubber and plastic products	0.4	1.2%
Paper and paper products	0.4	1.1%
Animal feeds	0.4	1.0%
Fabricated metal products, except machinery	0.4	1.0%
Vegetable and animal oils and fats	0.3	0.9%
Sugar	0.3	0.9%
Other	3.0	8%
Total	**35.8**	**100%**

5 Modifications of the selected model

The chosen model, i.e. FORWAST, to calculate and analyse the Danish carbon footprint has some limitations in terms of accuracy and completeness. The most important limitations with respect to the scope of the current study are assessed to be:

- The model represents the Danish economy in 2003, i.e. the data in the model are ten years old.
- Import is modelled as if everything was imported from average EU27 production, i.e. with prices and technology level not too far from Danish conditions compared to other important exporting countries to Denmark such as China and India.
- Indirect land use changes are not included
- Additional global warming potential from aviation is not included

In the following sections, it is described how elements of the FORWAST model are adjusted to address the listed limitations above.

5.1 Original FORWAST model: Danish production& consumption 2003

The original non-modified FORWAST model yields the GHG-emissions related to Danish economy in 2003 as shown in **Table 5.1** (which is identical to **Table 2.6**).

Table 5.1: GHG-emissions related to Danish economy by using the original FORWAST IO-model. The emissions are calculated using the FORWAST DK and EU27 2003 IO-database in the LCA software SimaPro.

FORWAST		
Original FORWAST model		
Year		2003
Imports data		EU27
Inclusion of iLUC		no
Inclusion of additional GWP from aviation		no
Results	million tonne CO_2-eq.	tonne CO_2-eq./pers.
Supply side		
DK domestic emissions	94.4	17.5
DK imports	83.6	15.5
Use side		
DK Consumption	68.2	12.7
DK exports	110	20.4
Total supply = total use	**178**	**33.1**

5.2 Addressing the fact that the input data do not reflect recent time

The GHG-emissions related to Danish economy changes over time, and therefore data for 2003 may deviate from current emission levels of today (2013). The composition of the societal total environmental impact can be expressed by the so-called IPAT equation (Chertow 2001):

Equation 5.1

$$\mathbf{I}\ (\mathbf{impact}) = \mathbf{P}(\mathbf{poulation}) \times \mathbf{A}\ (\mathbf{affluence}) \times \mathbf{T}\ (\mathbf{technology})$$

where:

- **I** is the impact
- **P** is the number of citizens (unit = persons)
- **A** is the consumption per person (unit = consumption / person)
- **T** is a technology factor representing the environmental efficiency of the production of consumed goods (unit = impact / unit of consumption)

It appears that the unit of I (impact) is the same as of PxAxT. In an IO-model context the total consumption (PxA) can be expressed by the overall economic activity of which GDP can be used as an indicator. The technology factor (T) then expresses consumption mixes and technological development such as improved energy efficiencies, more environmental friendly raw materials, and various emission abatements. Only real time-series of IO-models (or parts of them) can capture the technology component referred to above. Since time-series of IO-tables, which are compatible with the FORWAST model, are not available, it is regarded as being out of scope of the current study to estimate the change in GHG-emissions from 2003 to a more recent date caused by changes in consumption mixes and technological development. Therefore, a more simplistic approach is applied by focussing on developments in GDP and national GHG-emissions (national system boundary), see **Figure 5.1**.

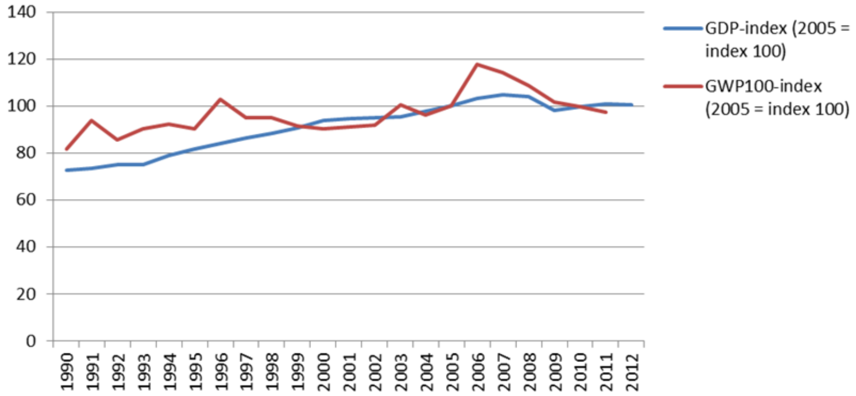

Figure 5.1: Development in GDP and national GHG-emissions (GWP100) from 1990 to 2011/12. 2005 = Index 100 (Statistics Denmark 2013a,b). GDP is recorded in fixed prices (2005).

It appears from **Figure 5.1** that GDP has not changed very much from 2003 (the base year of the FORWAST model) to 2012. The index in 2003 is 95 while it is 100 in 2012, i.e. an increase at 5%. In the same period of time a decrease in national GHG-emissions from index 101 to 97 can be observed, i.e. a decrease at 4%.

Hence, the data indicate that emissions have decreased both in absolute terms and in relative terms (per GDP) from 2003 to 2011/12.

However, this reduction could be due to the fact that the import share of products has increased. In 2012 the domestic production developed from 2470 billion DKK in 2003 to 2799 billion DKK in 2012 (fixed prices, 2005) (Statistics Denmark 2013c). In the same period the import developed from 570 billion DKK in 2003 to 808 billion DKK in 2012 (fixed prices, 2005). Hence, the overall average import share of the total supply of products in Denmark has increased from 570/(2470+570)=19% to 808/(2799+808)=22%. Consequently, the presumable net reduction in total GHG-emissions related to the Danish economy may either be smaller or not present.

It is not possible to establish whether the total life cycle GHG-emissions related to the Danish economy has changed from 2003 to today. The observed indicators go in different directions and the different contributing trends may level each other out. Therefore, given the present data, the best estimate of GHG-emission related to Danish economy today (2013) are in the same range as in 2003 which is the base year of the FORWAST IO-model.

5.3 Data for imported products

In the original version of the FORWAST model, all import to Denmark was modelled as if it was produced in EU27. The supply-use tables for Denamrk and for EU27 contain information on the origin of import divided on import intra EU and extra EU. It is thus possible to link all import from outside EU27 to an IO-model that can represent the rest of the world (RoW). Since there is no FORWAST-compatible IO-models available, a more simplified approached is introduced. RoW is modelled using a copy of the EU27 IO-model, but with a few adjustments. This includes a modification of the electricity supply sector, where the fuel mix (and associated emission) is adjusted to reflect some important trade partners of EU.

Adjusting flows related to electricity mix in rest-of-world

Since this simplified approach only provides a limited representativeness of the rest of the world, only little effort in identifying and modelling a correct fuel mix has been done. The applied fuel mix in RoW reflects the average of the fuel mix related to US and Chinese electricity production.

Table 5.2: Electricity mixes in OECD Europe, China and USA in 2003 (IEA 2013).

Source of electricity	OECD Europe	China	USA	Weighted average of China and USA
Nuclear	29%	2%	20%	14%
Hydro	14%	15%	7%	9%
Solar/wind/other	1%	0%	0%	0%
Coal	31%	79%	52%	61%
Oil	5%	3%	3%	3%
Gas	18%	0%	17%	11%
Biofuels and waste	2%	0%	2%	1%

Based on the weighted average electricity mix in **Table 5.2**, it is assumed that the electricity mix in RoW can be represented by 61% coal based electricity, 14% natural gas based electricity and 25% non-fuel based electricity. In order to calculate the new fuel inputs and CO_2 emissions of the RoW electricity sector, some key characteristics of the relevant fossil fuels are needed. This is presented in **Table 5.3**. It should be noted that only CO_2 emissions are modified, since CH_4 and N_2O emissions from electricity generation are relatively insignificant.

Table 5.3: Fuel to electricity efficiencies are estimated, calorific values and CO_2 emission factors are obtained from Nielsen et al. (2013). Data are applicable for 2003. The density of natural gas is 0.8 kg/Nm^3.

Source of electricity	Fuel to electricity efficiency	Lower heating value (MJ/kg)	CO_2 Emission factor (kg CO_2/MJ)
Coal	35%	25	0.095
Oil	35%	41	0.078
Gas	40%	50	0.057

Based on the information in **Table 5.2** and **Table 5.3**, the new fuel inputs and CO_2 emissions in the RoW electricity sector can be calculated. This is presented in **Table 5.4**. For comparison the fuel inputs and CO2 emissions are also shown for the original FORWAST data for the EU27 electricity sector as well as the calculated ones for the OECD Europe electricity sector. The two latter ones only deviate slightly, which indicates that the applied assumptions in the calculations seem robust. Some of the deviations are also due to the fact that the geographical boundaries of EU27 are not fully identical with the OECD Europe.

Table 5.4: Illustration of which fuel inputs and emissions that are modified in the FORWAST electricity sector to better represent the rest-of-world electricity sector. The column with 'OECD Europe electricity sector' (IEA 2013) is included for comparison with the FORWAST EU27 electricity sector.

Modification of electricity sector		FORWAST EU27 electricity sector	OECD Europe electricity sector	RoW electricity sector
Data source				
Data source		FORWAST data set	**Table 5.2** and **Table 5.3**	
Supply	**Unit**			
Electricity	kWh	1	1	1
Fuel inputs	**Unit**			
Coal	kg	0.132	0.126	0.249
Gas	kg	0.023	0.033	0.020
Oil	kg	0.009	0.012	0.008
Emissions	**Unit**			
CO_2	kg	0.401	0.430	0.650

Effects on results when modifying data for imports

In **Table 5.5**, the effects on results are shown, when modifying the imports data as described above.

Table 5.5: Effects on results when the imports from outside EU27 is modelled using the modified EU27 IO-model as representative for an IO-model for rest-of-world (RoW).

	Original FORWAST model	FORWAST with modified import
Modifications of the original FORWAST model		
Year	2003	2003
Imports data	EU27	**EU27 + RoW**
Inclusion of iLUC	no	no
Inclusion of additional GWP from aviation	no	no
Results	million tonne CO_2-eq.	million tonne CO_2-eq.
Supply side		
DK domestic emissions	94.4	94.4
DK imports	83.6	87.2
Use side		
DK Consumption	68.2	69.5
DK exports	110	112
Total supply = total use	**178**	**182**

Compared to the other studies in the literature review in **chapter 2**, the new figures for Danish import at 87 million tonne CO_2-eq. are slightly higher than the original FORWAST results at 84 million tonne CO_2-eq., very close to the DK IO 1999 study (Weidema et al. 2005) which show 86 million tonne CO_2-eq., and somehow higher than the Exiobase v1 result at 56 million tonne CO_2-eq.

5.4 Inclusion of indirect land use change

Indirect land use changes (iLUC) are modelled and quantified using the model described in **Chapter 3.5**. In order to operationalise the model in the IO-framework, land use in units of productivity weighted hectare years (pw ha yr) needs to be identified for all industries in DK, EU27 and in RoW. The land uses that need to be identified are the crosses in **Figure 3.7** which represent inputs of land to land using activities.
Further, it needs to be specified which markets for land are affected. The latter is sometimes challenging since the actual land cover (e.g. forest) may not be the same as the market for land. E.g. in Denmark, most of the forests are grown on land that can also be used for arable cropping. Hence, due to the definition of markets for land in **Table 3.7**, the affect market will be the market for arable land.

It has been assumed that the potential productivity of land in DK, EU27 and RoW is the same. The regions are too big to be suitable for giving meaningful estimates of differences in productivity.

Land use in DK, EU27 and rest of world

The starting point of linking the FORWAST IO-model with the iLUC model is to identify how much land is used, i.e. the flow that will eventually be used to link the two models.

The land areas in Denmark, EU27 and the world (which are the ones modelled in the modified version of the FORWAST model) are divided into land cover types using data from FAOSTAT (2013), see **Table 5.6**.

Table 5.6: Division of the total land area in Denmark, EU27 and the world into arable land, forest, permanent meadows and pastures, and other. Other includes built-up and related land, barren land, other wooded land, etc. Data are obtained from FAOSTAT (2013).

Land cover type in FAOSTAT	Denmark (1000 km^2)	EU27 (1000 km^2)	The world (1000 km^2)
Arable	22.7	1,222	15,222
Forest	5.1	1,533	40,706
Permanent meadows and pastures	3.8	674	33,867
Other	10.7	755	40,395
Total	**42.4**	**4,184**	**130,190**

The iLUC model; how are the land-producing "industries" created in the IO-model

The iLUC model includes two types of industries supplying land to the market for land (see more in **section 3.5**);

1. Transformation of land not in use
2. Intensification of land already in use

The 'transformation of land' activities only include emissions, and hence these activities do not have inputs of products from other industries in the FORWAST IO-model. But the intensification activities have inputs of fertiliser, which is supplied by the fertiliser industry in the FORWAST model. In the FORWAST model the unit of fertiliser flows is dry matter mass, while in the iLUC model, the unit is mass of fertiliser as nitrogen (N). It has been assumed that N-fertiliser has N-content of 35%. Hence, an input of 1 kg N in the iLUC model, corresponds to an input of 1/0.35 = 2.85 kg N-fertiliser in the FORWAST model.

Linking the land uses to markets for land in the iLUC model

Table 5.6 is the starting point of identifying how much land is used according to the different types of land markets in the iLUC model (**Table 3.7**). The first step here is to identify whether the land is used for productive purposes by humans (referred to as 'land in use') or not (referred to as 'land not in use'). The 'forest' and the 'other' categories cover both land in use and land not in use, while arable and permanent meadows and pastures are both land in use. More detailed data on forests have been obtained from FAO (2010), see **Table 5.7**. In this table, it has been roughly assumed that all primary forests are not in use, that 50% of 'other naturally regenerated forest' is in use, and all planted forests are in use.

Table 5.7: Distribution of forests into three characteristics as of FAO (2010).

Forest type	Denmark	EU27	The world
Characteristic as of FAO (2010)			
Primary forest	5%	3%	36%
Other naturally regenerated forest	21%	69%	57%
Planted forest	75%	28%	7%
Total	**100%**	**100%**	**100%**
Assumed use of forests			
Not in use => Primary forests and 50% of other naturally regenerated forests	15%	38%	64%
In use as extensively managed forest => 50% of other naturally regenerated forests	10%	35%	29%
In use as intensively managed forest => planted forests	75%	28%	7%
Total	**100%**	**100%**	**100%**

According to Ramankutty et al. (2006), 2-3% of the world's land area is build-up land. Based on this, it has been assumed that 2.5% of the total land areas in **Table 5.6** is build-up land. This is subtracted from the 'other' land cover type in **Table 5.6**. The remaining of the 'other' land has been assumed to be not in use.

Since the markets for land represent the land's suitability for different uses, the actual land use may not fit with the type of land market. E.g. most forests in Denmark are cultivated on land that is also suitable for arable cropping, i.e. the forests use land from the market for arable land. Data on land cover, land suitability and overlay of the two are not easy accessible, and the collection and processing of good quality of such data at the global scale are outside the scope of the current study. Instead, a more simplified approach has been used, where the overlapping of actual land uses with the markets for land have been estimated for Denmark, EU27 and for the world. These estimates are presented in **Table 5.8**.

Table 5.8: Estimated distribution of markets for land which are used by the different land covers. The "highest grade" of land is arable, and then the suitability for different biomass production purposes is decreasing when moving towards right.

	Land suitability:					
Land cover	**Arable**	**Intensive forestry**	**Extensive forestry**	**Grazing**	**Non-biomass**	**Total**
Denmark						
Arable	100%					**100%**
Forest	80%	20%				**100%**
Permanent meadows and pastures	80%	15%		5%		**100%**
Other	100%					**100%**
EU27						
Arable	100%					**100%**
Forest	50%	40%	10%			**100%**
Permanent meadows and pastures	25%	25%	25%	25%		**100%**
Other	80%	10%	5%	3%	2%	**100%**
The world						
Arable	100%					**100%**
Forest	50%	40%	10%			**100%**
Permanent meadows and pastures	10%	10%	10%	70%		**100%**
Other	80%	10%	5%	3%	2%	**100%**

For forest land cover not in use, it has been roughly estimated that this is on 60% land suitable for arable cropping, 15% land suitable for intensive forestry and 15% land suitable for extensive forestry. In the same manner, for other land cover not in use, it has been roughly estimated that this is on 50% land suitable for grazing and 50% land not suitable for biomass production. It should be noted that these assumptions do not affect any results – it is just to have a place to put the land not in use in **Table 5.9**. The numbers, though extremely uncertain estimates, can be interpreted as the remaining potential land for arable cropping, forestry and grazing.

Based on the information above, the total land areas of Denmark, EU27 and the world have been classified into land in use and land not in use, and to fit with the land markets in the iLUC model. This is shown in **Table 5.9**.

Table 5.9: Classification of land areas in Denmark, EU27 and the world into 'land in use' and 'land not in use'. Land in use is divided into arable, intensive forest, extensive forest, permanent meadows and pastures and build-up land. Land not in use is divided into forest and other. Unit 1000 km^2.

	Market for land:					
Land cover (1000 km^2)	Arable land	Intensive forest land	Extensive forest land	Grassland	Non-biomass land	**Total**
Denmark						
Land in use						
Arable	22.7					**22.7**
Intensive forest	3.1	0.8				**3.9**
Extensive forest	0.4	0.1				**0.5**
Permanent meadows and pastures	3.1	0.6		0.2		**3.8**
Build-up land	1.1					**1.1**
Land not in use						
Forest	0.5	0.2	0.2			**0.8**
Other				4.8	4.8	**9.6**
Total	**30.8**	**1.6**	**0.2**	**5.0**	**4.8**	**42.4**
EU27						
Land in use						
Arable	1,222					**1,222**
Intensive forest	573	459	115			**1,147**
Extensive forest	79	63	16			**158**
Permanent meadows and pastures	169	169	169	169		**674**
Build-up land	84	10	5.2	3.1	2.1	**105**
Land not in use						
Forest	137	46	46			**228**
Other				325	325	**650**
Total	**2,264**	**746**	**350**	**497**	**327**	**4,184**
The world						
Land in use						
Arable	15,222					**15,222**
Intensive forest	15,228	12,182	3,046			**30,455**
Extensive forest	2,095	1,676	419			**4,190**
Permanent meadows and pastures	3,387	3,387	3,387	23,707		**33,867**
Build-up land	2,604	325	163	98	65	**3,255**
Land not in use						
Forest	3,637	1,212	1,212			**6,061**
Other				18,570	18,570	**37,140**
Total	**42,172**	**18,783**	**8,226**	**42,374**	**18,635**	**130,190**

The next step is to allocate each of the 'land in use' land areas in **Table 5.9** to the industries in the FORWAST IO-model (see classification in '**Appendix A: Industry/product classification in the FORWAST IO-model**'). The sum of intensive and extensive forest is used by the forest industry.

Table 5.10: Allocation of 'land in use' land cover in **Table 5.9** on FORWAST industries. The allocation between grain crops and other crops is based on FAOSTAT (2013) and the other allocations are estimated.

			Country/region	
Land cover	**FORWAST industries**	**Denmark**	**EU27**	**The world**
Arable	Grain crops	89%	66%	57%
	Crops n.e.c.	11%	34%	43%
Intensive forest + Extensive forest	Forest products	100%	100%	100%
Permanent meadows and pastures	Bovine meat and milk	100%	100%	100%
	Poultry and animals n.e.c.	0%	0%	0%
Build-up land	Buildings, residential	33%	33%	33%
	Buildings, non-residential	33%	33%	33%
	Infrastructure, excluding buildings	33%	33%	33%

Based on the information **Table 5.9** and **Table 5.10**, the total land cover is allocated to FORWAST industries and linked to the five markets for land in the iLUC model. The land use inputs to each industry (in units of ha yr) are normalised by the total supply of the reference products of the industries (as of the supply tables of the FORWAST data sets; deliverable D3.2 and D4.2: http://forwast.brgm.fr/results_deliver.asp).

Effects on results when including the contribution from indirect land use changes

In **Table 5.11**, the effect on results is shown, when including the contribution from iLUC as described above.

Table 5.11: Effects on results when the contribution from indirect land use changes is included.

	Original version	**Modification 1:** modified import	**Modification 1+2** modified import, and inclusion of iLUC
Modifications of the original FORWAST model			
Year	2003	2003	2003
Imports data	EU27	**EU27 + RoW**	**EU27 + RoW**
Inclusion of iLUC	no	no	**yes**
Inclusion of additional GWP from aviation	no	no	no
Results	million tonne CO_2-eq.	million tonne CO_2-eq.	million tonne CO_2-eq.
Supply side			
DK domestic emissions	94.4	94.4	94.4
DK imports	83.6	87.2	111
Use side			
DK Consumption	68.2	69.5	79.3
DK exports	110	112	126
Total supply = total use	**178**	**182**	**206**

Sensitivity analysis and evaluation of the contribution from iLUC

The modelling of indirect land use changes is related to significant uncertainties. Therefore, this section focusses on looking into the underlying contributions to the overall iLUC result, and evaluates some of the uncertainties related to the applied model. Further comparisons with other modelling approaches are presented.

Table 5.12 presents the overall land use related to the Danish consumption in 2003. The area of Denmark is 42.4 km^2 (**Table 5.6**). Comparing this number with **Table 5.12**, it appears that Danish consumption is associated with the occupation of 1.6 times Denmark's area with managed land, i.e. productive agricultural or forest land or build-up land. More than half of the land is managed forest (57%) followed by cropland (31%), pasture (9%) and build-up land (3%). The majority of the land occupation takes place outside Denmark (41% in EU27 and 43% in RoW) while 16% takes place in Denmark. This does not mean that land is not occupied in Denmark, but rather that a large part of the land in Denmark is used to produce products that are exported. The total land occupation (related to all activities in Denmark) is presented in **Table 5.6**.

Table 5.12: Breakdown of the total land use related to Danish consumption. Unit: 1000 km^2 yr.

	Geography			
Land cover	**DK land use**	**EU27 land use**	**RoW land use**	**Total**
Cropland	4.41	7.60	8.43	**20.4**
Managed forest	3.22	16.90	17.46	**37.6**
Pasture	1.50	2.25	2.20	**6.0**
Build-up land	1.48	0.24	0.44	**2.2**
Total	**10.6**	**27.0**	**28.5**	**66.1**

The total contribution from of iLUC related GHG-emissions related to Danish consumption is 9.9 million tonne CO_2-eq. This number is broken down in **Table 5.13** in terms of markets for land, contributing main groups of activities (industries) and geographies where the land occupation takes place.

Table 5.13: Breakdown of the iLUC related contribution to GHG-emissions from Danish consumption. Million tonne CO_2-eq.

	Geography			
Land markets and land using activities	**DK land use**	**EU27 land use**	**RoW land use**	**Total**
Market for arable land				
Grazing animals	0.34	0.093	0.031	**0.46**
Crops	0.59	1.3	1.2	**3.0**
Forestry	0.42	1.4	1.4	**3.2**
Buildings and infrastructure	0.24	0.032	0.03	**0.31**
Total	**1.6**	**2.8**	**2.6**	**7.0**
Market for intensive forest land				
Grazing animals	0.034	0.084	0.033	**0.15**
Crops				**0**
Forestry	0.096	1.0	1.0	**2.1**
Buildings and infrastructure		0.0036	0.0066	**0.010**
Total	**0.13**	**1.1**	**1.1**	**2.3**
Market for extensive forest land				
Grazing animals		0.076	0.029	**0.11**
Crops				**0**
Forestry		0.23	0.23	**0.46**
Buildings and infrastructure		0.0016	0.0029	**0.0045**
Total	**0**	**0.30**	**0.27**	**0.57**
Grassland				
Grazing animals	0.00047	0.0035	0.0096	**0.014**
Crops				**0**
Forestry				**0**
Buildings and infrastructure		0.000046	0.000081	**0.00013**
Total	**0.00047**	**0.0036**	**0.010**	**0.014**
Total				
Total	**1.7**	**4.2**	**4.0**	**9.9**

Table 5.13 shows which activities (and where) that cause the total iLUC emissions at 9.9 million tonnes CO_2-eq. In **Figure 5.2** (baseline column) it is shown which activities in the iLUC model that contributes to the total emissions at 9.9 million tonnes CO_2-eq. It appears that the most significant contributors to iLUC emissions are intensification of cropland and transformation of land to arable.

Sensitivity analysis 1: In The default iLUC model, the global annual increase in fertiliser consumption is assumed to represent intensification, and that all other means of intensification are achieved without emissions (better management, irrigation, pesticides, improved seedling material/GMO, better soil preparation etc.). However, it can be argued that several of the other means of intensification than additional fertiliser application are exogenous, i.e. they are part of general technological development and they are not affected by changes in demand for land. Therefore, a sensitivity analysis has been carried out where all intensification is achieved by additional fertiliser, and the use of additional fertiliser has been identified through fertiliser-yield dose-response functions for the most important crops that are intensified, i.e. a weighted average of maize in USA, paddy rice in India and wheat in China (Schmidt et al 2012 and Schmidt and Brandão 2013). This leads to a significant higher use of fertilisers and associated emissions; around 6 times more.

Sensitivity analysis 2: Some biofuel studies assume that intensification is not associated with any emissions. Therefore, a sensitivity analysis is run assuming no emissions related to intensification.

Sensitivity analysis 3: Another sensitivity analysis where the only way new land can be created is by land transformation is also run (i.e. assuming no intensification).

Sensitivity analysis 4: The fourth sensitivity approach is a very simplistic average approach to iLUC (somehow similar to the one of Audsley et al. 2009). The approach calculates the iLUC GHG-emissions per hectare of occupied land as global LUC emissions (tonne CO_2) (obtained from **Table 3.8** and **Table 3.9**) divided by global land occupation (ha yr) (bottom line in **Table 5.9**). This is done for the same markets for land as in the baseline iLUC model. The average approach can be characterized by the fact that it is additional up to the global scale, i.e. if all global land occupation was included in the study, the LUC and associated LUC emissions would add up to global LUC emissions. However, it should be noted that this approach does not tell anything about what happens if there is more or less demand for land; the approach simply ascribe or allocate global LUC emissions to global land occupation. Further, the approach does not address any timing issues of LUC nor does it include intensification.

Table 5.14 shows the iLUC GHG-emissions per ha yr in the different sensitivity analysis, and **Figure 5.2** shows the resulting iLUC GHG-emissions in the sensitivity analysis for Danish consumption.

Table 5.14: iLUC GHG-emissions per global average hectare year (ha yr) in the baseline result and in sensitivity analysis. Unit: t CO_2-eq. /ha yr.

iLUC emissions in Sensitivity analysis	Baseline	1	2	3	4
GHG-emissions per global average ha yr ($t\ CO_2$-eq/ha yr)	**Default result**	**Intensification, high fertiliser/ emissions**	**Intensification without emissions**	**No intensification, only LUC**	**Average approach**
Market for arable land	1.67	7.30	0.717	1.82	0.839
Market for intensive forest land	1.49	1.49	1.49	2.70	0.391
Market for extensive forest land	1.34	1.34	1.34	1.34	0.825
Market for grassland	0.063	0.063	0.063	0.590	0.083
Market for barrren land	0	0	0	0	0

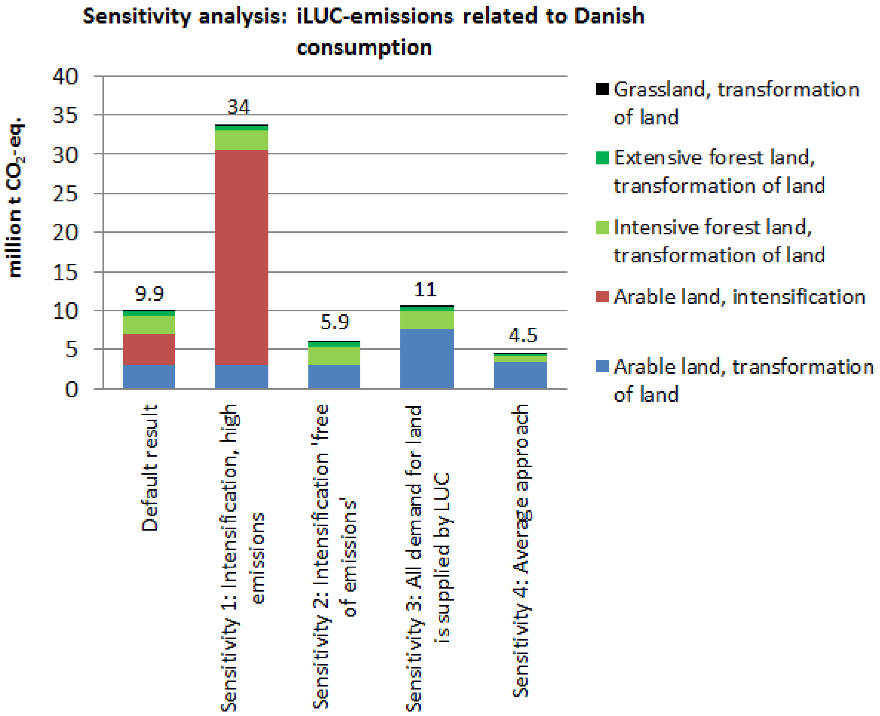

Figure 5.2: Results of sensitivity analysis evaluating the effect from different iLUC assumptions. The results show the iLUC GHG-emissions related to Danish consumption. Unit: million tonne CO_2-eq.

It appears from the results of the sensitivity analysis in **Figure 5.2** that the iLUC assumptions have potentially significant effect on the results. The baseline iLUC method gives a result close to the median of the compared iLUC assumptions. Around 40% of the emissions in the baseline iLUC method originate from intensification of cropland already in use, and around 30% originate from transformation of forest to arable land. Intensification emissions are modelled based on the proportion between the total annual land equivalents achieved by intensification (according to FAOSTAT) and the total annual increase in fertiliser use (and associated emissions when applied to land), i.e. an average approach where only emissions associated with additional fertiliser are included. Sensitivity analysis 1 and 2 show the effect of assuming intensification in the higher end and the lower end (no intensification emissions). The sensitivity analysis reveals that significant uncertainties are present. The default result represents an average approach to the modelling of intensification, which is regarded as the best estimate if better data on constraints on means of intensification and emissions associated with different means of intensification are not available. However, it should be noted that the default modelling of intensification assumes that other means of intensification than fertiliser are free of emissions which is clearly an underestimation. However, it can be expected that the emissions associated with changes in irrigation, seedling material, management, soil preparation etc. are relatively small.

The third sensitivity analysis is more realistic than sensitivity analysis 2 in the way that no demand for land is supplied out of no-where or 'free of emissions', since all demand for land is supplied by LUC. However, this sensitivity analysis clearly over-estimates the effect on LUC and underestimates the effects on intensification. The iLUC emissions in sensitivity analysis 3 are not very different from the emissions in the baseline iLUC method.

The fourth sensitivity analysis, which represents a simplistic average approach, shows the lowest iLUC emissions. Since this approach is based on current global deforestation rates (and associated emissions) and current global total land use, the model does not say anything about what are the impacts related to a change in demand for land. Hence, it is not recommended to use results based on the average approach.

Summarizing on iLUC, it can be concluded that the contribution is significant regardless of how it is modelled, and that the modelling is associated with significant uncertainties. The most significant uncertainties are identified as the ones associated with the modelling of intensification of land already in use. Further, the applied time horizon for the calculation of GWP from accelerated deforestation is important (Schmidt and Brandão 2013); shorter time horizons that the applied 100 years will significantly increase emissions associated to deforestation. However, this has not been investigated in the current study.

5.5 Inclusion of special global warming potential from aviation

As discussed in **section 3.6**, emissions from aircrafts involve specific contributions to climate change, due to the fact that these emissions take place at high altitude. In this section we attempt to estimate the CO_2-eq. from Danish aircraft emissions. Besides conventional long-lived GHGs, this estimate considers the additional effects on the climate of:

- Emissions from water vapour.
- Emissions from NO_x.
- Formation of condensation trails (contrails), that is, the thin clouds that form at the tail of an aircraft.
- Formation of cirrus clouds induced by the spread of contrails, which also influence the heat budget of the planet.

The GHG-emissions (as CO_2-eq.) associated with aircraft emissions have been calculated based on the average emissions from kerosene fuel combustion per unit of air transport service (obtained from the IO-model) and the GWP values for a 100-year time horizon, including the specific ones for aviation emissions previously presented in **section 3.6**.

Table 5.15 shows the characterisation factors for converting GHG-emissions into GWP100, and **Table 5.16** shows the data used and the resulting CO_2-eq. figure per EUR2003 of air transport service supplied by Danish and other European-operated aircrafts respectively.

Table 5.15: Global warming potentials for emissions from aviation.

Emission	GWP100 (kg CO_2-eq/kg)	Comment
CO_2	1	'Conventional' GWP100 from IPCC (2007).
CH_4	25	
N_2O	298	
NO_x-N	71	GWP100 from Lee et al. (2010). The factor refers to NO_x-N.
H_2O^a	0.14	GWP100 from Lee et al. (2010).
Contrails	0.21	GWP100 from Lee et al. (2010).
Aviation-induced cirrus	0.63	GWP100 from Lee et al. (2010).

Table 5.16: Emissions and the related GWP100 per EUR air transport service supplied. The GWP100s are calculated by multiplying the emissions by the GWP100 factors in **Table 5.15**.

Emission	**Danish operated aircrafts**		**Other European-operated aircrafts**	
	Emission (kg/EUR2003)	**GWP (kg CO_2-eq./EUR2003)**	**Emission (kg/EUR2003)**	**GWP (kg CO_2-eq./EUR2003)**
Emissions obtained from the FORWAST-model				
CO_2	1.07	1.07	1.11	1.11
CH_4	2.33E-05	0.00	3.10E-05	0.00
N_2O	3.73E-05	0.01	3.26E-05	0.01
NO_x	1.4E-03[c]	0.10	1.95E-03[c]	0.14
Calculated emissions				
H_2O[a]	0.420	0.06	0.44	0.06
Contrails (as CO_2) [b]	1.07[b]	0.22	1.11[b]	0.23
Aviation-induced cirrus (as CO_2) [b]	1.07[b]	0.67	1.11[b]	0.70
Total	-	**2.13**	-	**2.56**

[a] Lee et al. (2010): 0.393 kg water vapour per kg CO_2.

[b] Lee et al. (2010): the basis for calculating the impact of contrails and cirrus is the amount of CO_2 produced.

[c] As NO_x-N. Nitrogen dioxide contains 30% N by weight.

As it can be seen in the table above, the overall carbon footprint of aviation emissions is more than twice as much as the CO_2 emissions alone. For both Danish and European aircraft, most of this additional impact is related to contrails and the formation of cirrus. It must be borne in mind though that the level of scientific understanding of these atmospheric processes, and therefore their net impact on the climate, is far from being complete. Conventional GHG accounting is focused on long-lived substances such as CO_2 and N_2O, for which the concept of GWP was developed. However the specific effects of aviation emissions involve substances with a relatively short atmospheric life span, which makes the application of GWP concept challenging. It must also be borne in mind that just like with conventional GHGs, the magnitude of the impact depends on the choice of time horizon. As an example, the GWP of cirrus formation increases 3.5 times with respect to CO_2 when a 20-year horizon is chosen instead of the typical 100-year period used in carbon footprinting (Lee et al. 2010).

In spite of the current limitations to derive reliable GWPs for the substances emitted by aircraft, it is clear though that accounting only for the conventional GHGs (basically CO_2) constitutes an underestimate. The figures obtained in **Table 5.16** are not intended to accurately reflect the impact of aviation, but clearly show that this particular activity has a higher impact than conventional carbon footprinting would demonstrate.

Effects on results when including the contribution from special effects on GWP from aviation

In **Table 5.17**, the effect on results is shown, when including the special contribution to global warming potential from aviation.

Table 5.17: Effects on results when the special contribution from aviation induced GWP is included. This involves GWP from NO_x, H_2O, contrails and cirrus.

	Original version	**Modification 1:** modified import	**Modification 1+2** modified import, and inclusion of iLUC	**Modification 1+2+3** modified import, inclusion of iLUC, and special GWP from aviation
Modifications of the original FORWAST model				
Year	2003	2003	2003	2003
Imports data	EU27	**EU27 + RoW**	**EU27 + RoW**	**EU27 + RoW**
Inclusion of iLUC	no	no	**yes**	**yes**
Inclusion of additional GWP from aviation	no	no	no	**yes**
Results	million tonne CO_2-eq.	million tonne CO_2-eq.	million tonne CO_2-eq.	million tonne CO_2-eq.
Supply side				
DK domestic emissions	94.4	94.4	94.4	96.8
DK imports	83.6	87.2	111	112
Use side				
DK Consumption	68.2	69.5	79.3	80.5
DK exports	110	112	126	128
Total supply = total use	**178**	**182**	**206**	**209**

5.6 Summary of the modifications of the FORWAST IO-model

In this chapter the original FORWAST has been modified in order to have a more accurate result representing the GHG-emissions related to Danish economy. The following modifications have been made:

- **Time:** The model represents the Danish economy in 2003, i.e. the data in the model are ten years old.
  - ⇒ **Modifications:** None. It was assessed that given the present data and model, it was not possible to produce a more accurate result by adjusting the FORWAST model in a simplified way using rough indicators.
  - ⇒ **Effect:** None
- **Import** is modelled as if everything was imported from average EU27 production, i.e. with prices and technology level not too far from Danish conditions compared to other important exporting countries to Denmark such as China and India.
  - ⇒ **Modifications:** Imports to Denmark from EU27 and rest of the world were separated (as well as imports to EU27 were modelled specifically). Production outside EU27 is represented by a modified version of the FORWAST EU27 IO-model, where the electricity sector has been modified to better represent exporting countries to EU27. The applied electricity mix is a weighted average of USA and China.
  - ⇒ **Effect:** This modification increased the emissions related to Danish consumption by 1.9%
- **iLUC:** Indirect land use changes are not included
  - ⇒ **Modifications:** The FORWAST IO-model was consistently linked with a novel and cause-effect based iLUC model.
  - ⇒ **Effect:** This modification increased the emissions related to Danish consumption by 14%
- **GWP from aviation:** Additional global warming potential from aviation is not included
  - ⇒ **Modifications:** Special contributions to GWP from aviation were included as emissions in the 'air transport' sectors in Denmark, EU27 and RoW in the FORWAST IO-model.
  - ⇒ **Effect:** This modification increased the emissions related to Danish consumption by 1.5%

Overall, the modifications of the model increased the GHG-emissions related to Danish consumption with 18% of which the contribution from iLUC is the most important.

It should be noted that all the modifications of the FORWAST model are associated with uncertainties, especially the contribution from iLUC.

6 Results: Denmark's carbon footprint

This chapter presents the results of the calculations of Denmark's carbon footprint calculated with the model described in **chapters 3** to **5**.

6.1 GHG-emissions related to Danish consumption

Recalling the general descriptions of the input-output method for calculating life cycle emissions related to national economies, one focus of the analysis can be on the consumption perspective. The functional unit of such an analysis is the total consumption by households and government. This corresponds to all products supplied to the Danish market (domestic production plus import) minus exported products. The functional unit of the analysis of Danish consumption is illustrated in **Figure 6.1**.

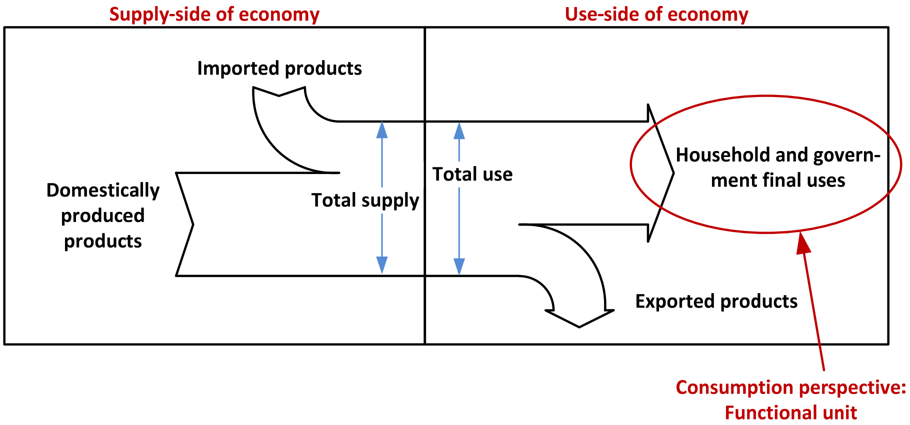

Figure 6.1: Illustration of the product flows in national economy and the functional unit of an analysis using the consumption perspective.

The total Danish final consumption is described in **Table 4.3**.

The GHG-emissions related to Danish consumption are calculated as 80.5 million tonnes CO_2-eq. In **Table 6.1** the results are shown relative to different key units; per capita, and per unit of GDP. Compared to the reviewed other studies of GHG-emissions related to Danish economy in **Figure 2.5**, the calculated emissions are higher than those of the FORWAST 2003 and Exiobase v1 2000; similar to those of the GTAP 2001 study, and lower than the results in the DK IO 1999 and Concito 2008 studies.

As land occupation has also been included in the FORWAST IO-model as an environmental extension (see **section 5.4**), the results in terms of land use (area occupied) can also be calculated; this is shown in the second results column in **Table 6.1**. In terms of land use, it appears that Danish consumption is associated with the occupation of more than 1.6 times Denmark's area (Denmark's area is described in **Table 5.6**). This occupied area refers to the land that is kept productive (plant, animal and wood production and build-up land) in order to produce all the products that end up in Danish consumption.

Table 6.1: GHG-emissions and land use related to Danish final consumption.

Unit of results	GHG-emissions	Unit	Land use	Unit
Absolute results				
Absolute results	80.5	million tonne CO_2-eq.	66.1	1000 km^2 yr
Relative results				
Per capita	15.0	tonne CO_2-eq./person	1.23	ha yr/person
Per GDP	0.0575	kg CO_2-eq./DKK2003	0.0472	m^2 yr/DKK2003

The absolute results in **Table 6.1** are broken down into different contributing factors in **Table 6.2**.

It appears from **Table 6.2** that around 56% of the emissions related to Danish consumption occur in Denmark. Similarly, 16% of the land use is in Denmark. The remaining land in Denmark is used for production of exported products or for non-productive purposes. Indirect land use changes account for 12% of the total emissions, and special radiation forcing from aviation accounts for 1.5%.

Table 6.2: GHG-emissions and land use related to Danish final consumption.

Contribution	**GHG-emissions** million tonne CO2-eq.	**Land use** 1000 km^2
DK production and import		
Domestic emissions/land use	45.3	10.6
Emissions/land use in EU27	12.1	27.0
Emissions/land use in RoW	12.0	28.5
Indirect land use changes		
Transformation of land	5.90	-
Intensification of land already in use	4.0	-
Aviation, special contribution		
Aviation GWP	1.24	-
Total		
Total	**80.5**	**66.1**

The most important products purchased directly by Danish households and government are illustrated in **Figure 6.2**. The direct emissions from households/government activities are included; the main source of emissions in this activity is emissions from combustion of transport fuels and also to a lesser extent individual heating.

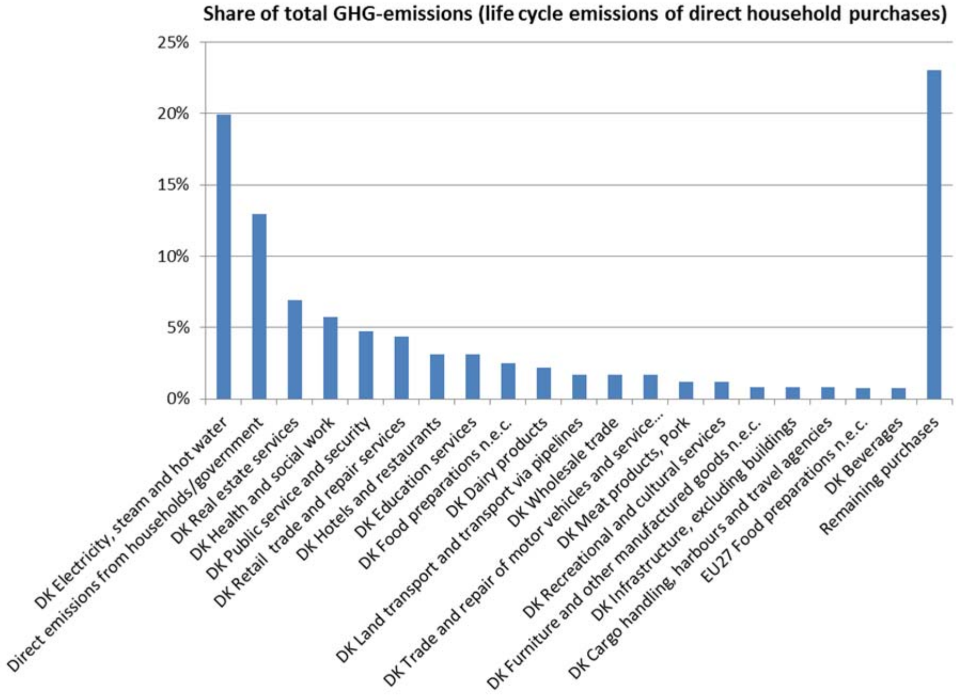

Figure 6.2: Illustration of the relative share of GHG-emissions from the most important direct purchases from Danish households and government.

It appears from **Figure 6.2** that the 20 purchases with the largest GHG-emissions (incl. direct household emissions) account for 77% of the total GHG-emissions at 80.5 million tonne CO_2-eq. The most important purchased products are: purchase of electricity/heat, direct emissions from combustion of fuels (mainly transport fuels), and real estate services, i.e. housing. It also appears that social services such as health and social work, public service and security and education are among purchases that cause significant emissions.

Another perspective of tracking the contributions to the total emissions at 80.5 million tonne CO_2-eq. is to identify from which activities the emissions occur. E.g. if an important purchase by households is real estate services, then the actual sources of the emissions are to be found upstream in the production processes of construction materials. This perspective of a contribution analysis is shown in **Figure 6.3**. It appears from **Figure 6.3** that the 20 most GHG-emitting activities in the product system relating to Danish consumption emit around 71% of the total emissions. The single most important emitters of GHG-emissions in the product system related to Danish consumption are: electricity/heat production, direct emissions from households, and transformation of secondary forest to cropland (part of iLUC).

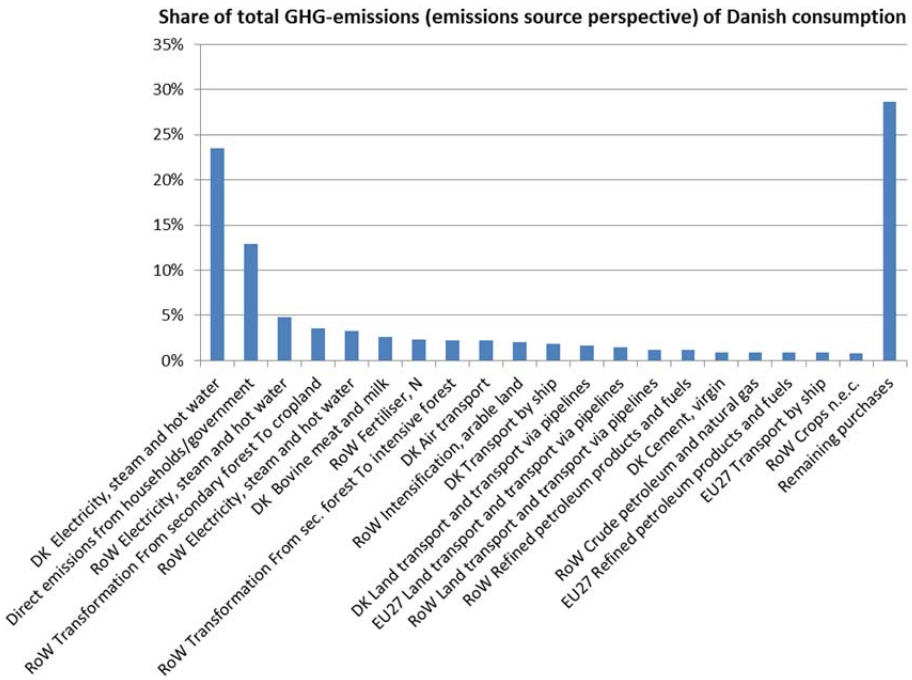

Figure 6.3: Illustration of the relative share of GHG-emissions from the 20 most GHG-emitting activities in the product system relating to Danish consumption.

6.2 GHG-emissions related to Danish export

This section describes the GHG-emissions associated with export. The functional unit of the analysis of Danish export is illustrated in **Figure 6.4**.

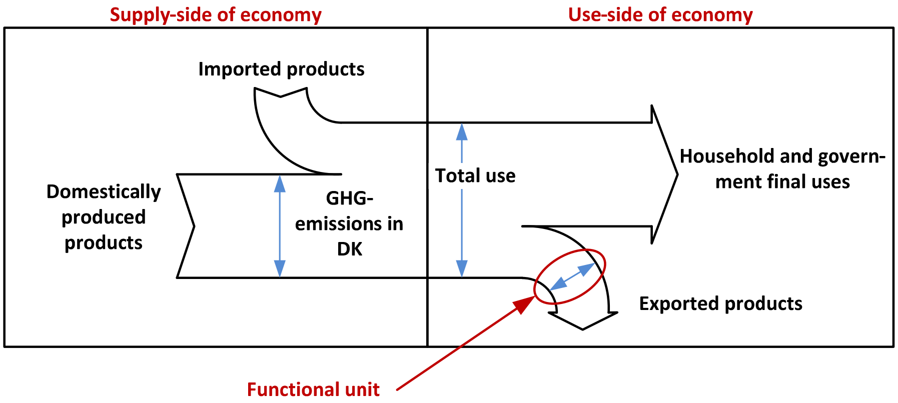

Figure 6.4: Illustration of the product flows in national economy and the functional unit of an analysis of Danish export.

The GHG-emissions from Danish export are 128 million tonne CO_2-eq. The 20 exported products with highest GHG-emissions are shown in **Figure 6.5**.

It appears from **Figure 6.5** that the 20 exported products with the largest GHG-emissions account for 45% of the total GHG-emissions at 128 million tonne CO_2-eq. The most important products are: ship transport, meat products (pork), and electricity.

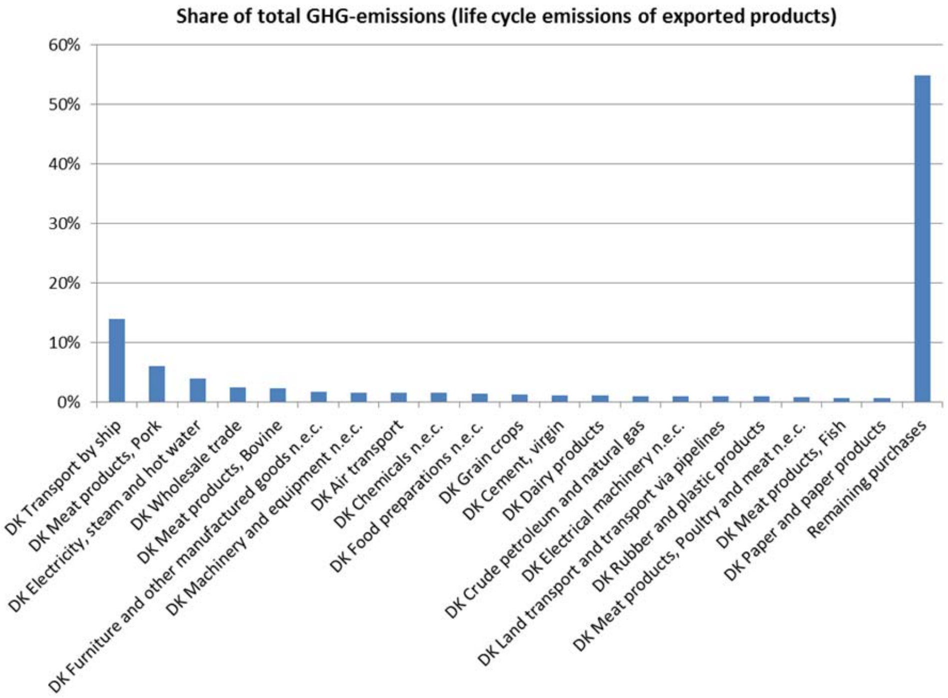

Figure 6.5: Illustration of the relative share of GHG-emissions from the 20 most GHG-emitting products which are exported from Denmark.

Another perspective of tracking the contributions to the total emissions from exported products at 128 million tonne CO_2-eq. is to identify from which activities the emissions occur. This perspective of a contribution analysis is shown in **Figure 6.6**. It appears from **Figure 6.6** that the 20 most GHG-emitting activities in the product system relating to Danish export emit around 55% of the total emissions. The single most important emitters of GHG-emissions in the product system related to Danish export are: transport by ship, electricity/heat production, and transformation of forest to cropland. It is remarkable, that some of the major emitters of GHG-emissions related to the production of products exported from Denmark are located outside Denmark.

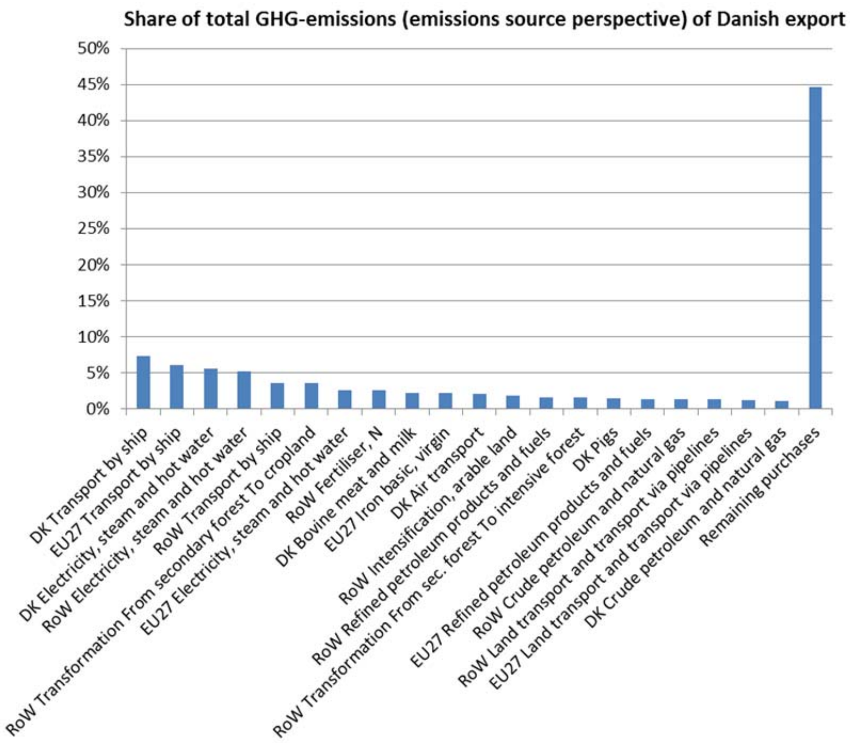

Figure 6.6: Illustration of the relative share of GHG-emissions from the 20 most GHG-emitting activities in the product system relating to Danish export.

6.3 GHG-emissions related to Danish import

In this section the GHG-emissions related to Danish import are analysed. The functional unit of the analysis of Danish import is illustrated in **Figure 6.7**.

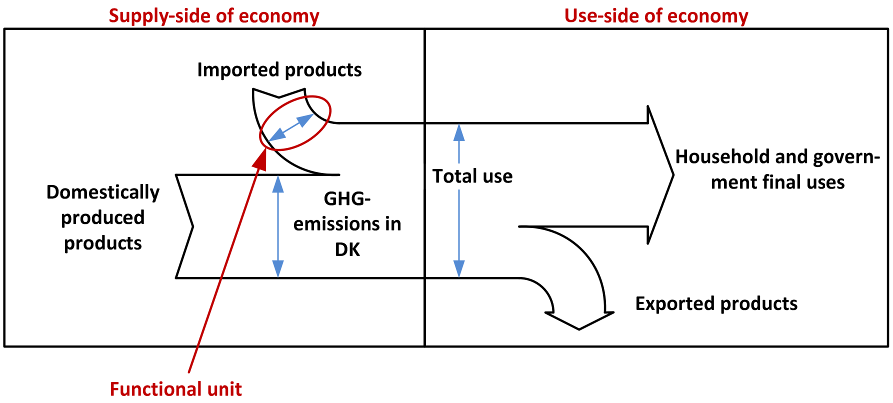

Figure 6.7: Illustration of the product flows in national economy and the functional unit of an analysis of Danish import.

The total GHG-emissions related to import are 112 million tonne CO_2-eq. The 20 largest GHG emitters in the product system of the imported products to Denmark are shown in **Figure 6.8**.

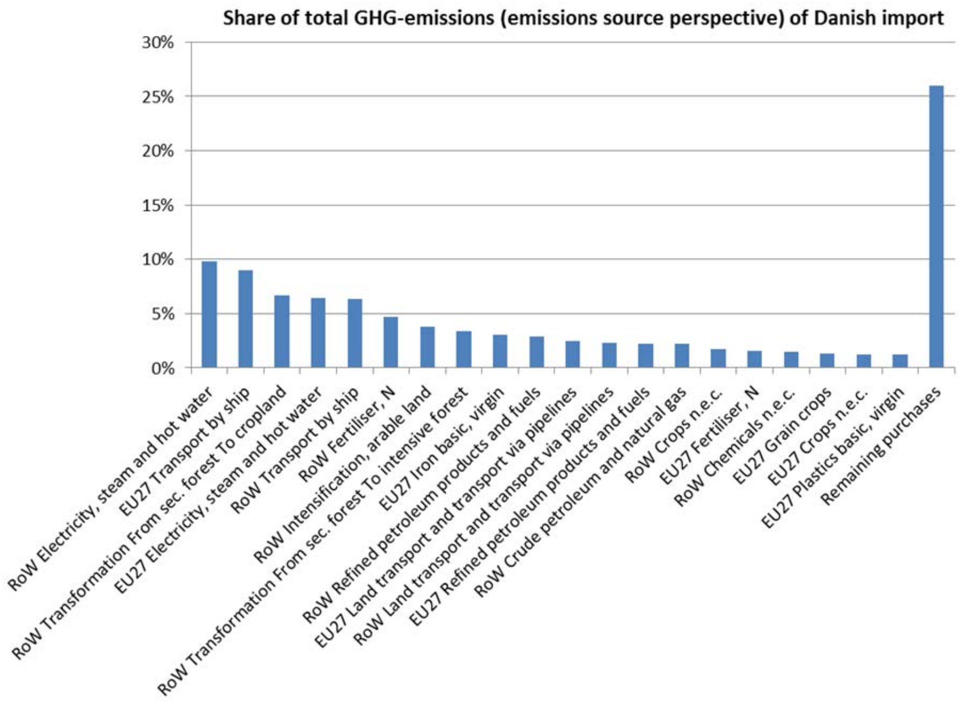

Figure 6.8: Illustration of the relative share of GHG-emissions from the 20 most GHG-emitting activities in the product system relating to Danish import.

It appears from **Figure 6.8** that the 20 most GHG-emitting activities in the product system relating to Danish import emit around 74% of the total emissions. The single most important emitters of GHG-emissions in the product system related to Danish import are: electricity/heat production in in RoW, transport by ship in EU27, and transformation of forest to cropland.

When evaluating the impacts related to import, it is relevant to know which products are imported, where they are produced, and what the impact per unit of product is. This will be investigated further in the following. However, it should be noted that such information is not contained in the FORWAST model, and therefore this has been analyzed using another model; Exiobase v1 (Koning et al. 2011 and http://www.exiobase.eu). As it appears from summary of the literature review in **section 2.9**, the emissions calculated with the Exiobase model seem to be lower than the other models. Therefore, the GHG-emissions presented in the following are not fully compatible with the other results.

In **section 4.3**, the economically and physically (mass) most important imported products to Denmark are listed. Based on this it has been chosen to focus more on the imported products with the highest economic value that also have a physical weight, i.e. import of service products is regarded as being less interesting. The following imported products have been selected for further investigation: machinery and equipment, chemicals, motor vehicles, radio/television etc., office machinery, wearing apparel/furs, electrical machinery, and furniture etc. **Figure 6.9** show the GHG-intensities (kg CO_2-eq./EUR2003) for the selected imported products for Denmark and for the most important exporting countries. The most importing exporting countries have been identified using the BACI trade database for 2007 (Gaulier and Zignago 2010).

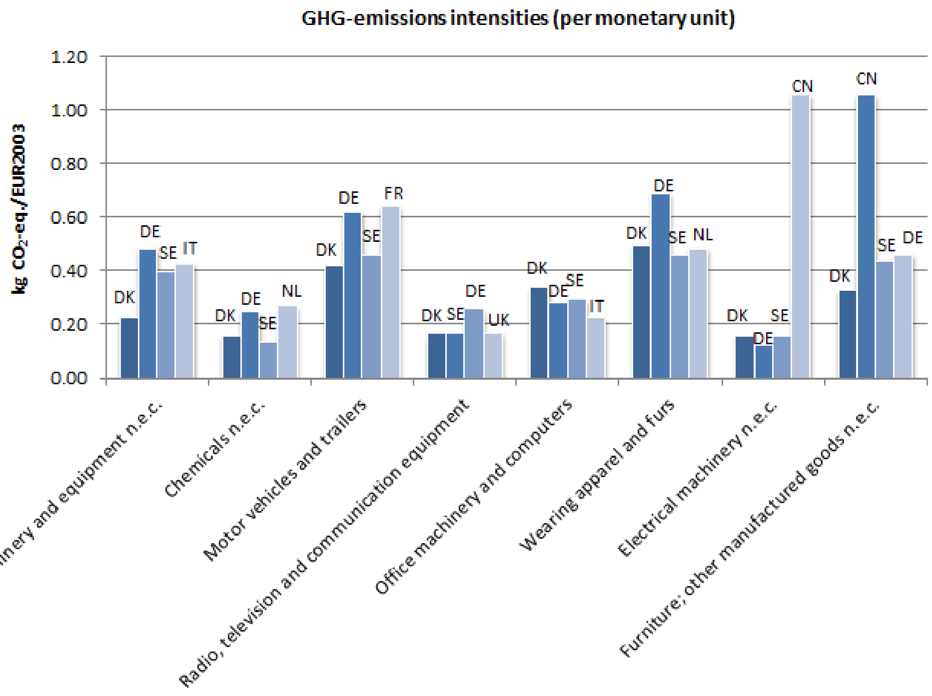

Figure 6.9: GHG-emission intensities (kg CO2-eq./EUR2003) for some of the most important imported products and the most important exporting countries. The data are extracted from Exiobase v1 (Koning et al. 2011 & http://www.exiobase.eu).

6.4 Direct GHG-emissions in Denmark

In this section, the GHG-emissions emitted from Danish industries and households are described, i.e. the emissions which are typically reported as official national emissions (see **section 3.1**). The functional unit of the analysis of Danish domestic emissions is illustrated in **Figure 6.10**.

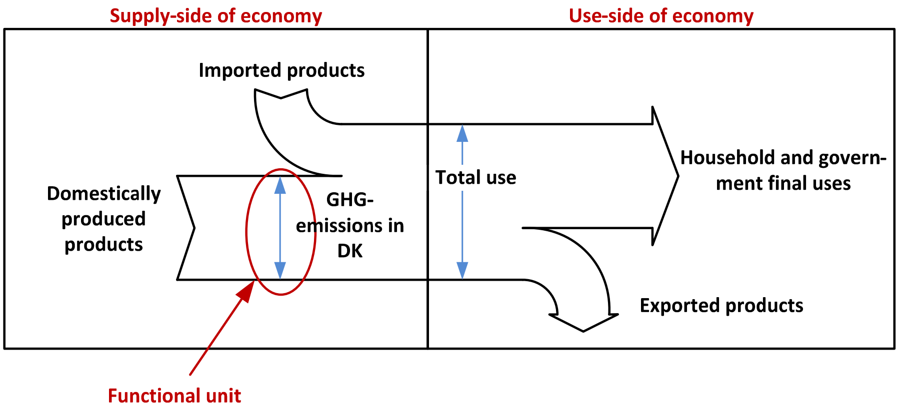

Figure 6.10: Illustration of the product flows in national economy and the functional unit of an analysis focussing on direct emissions occurring in Denmark.

According to the modified FORWAST model, the total domestic GHG-emissions are 97 million tonne CO_2-eq. (including emissions from international bunkering). The official reported Danish GHG-emissions for 2003 are 101 million tonne CO_2-eq. (Statistics Denmark 2013a). This relatively small deviation is caused by the special modelling of waste flows in the FORWAST model, which leads to small inconsistencies in the up-scaled economy based on model calculations compared to the original supply-use tables.

The 20 largest GHG-emitters (as industry groups) in Denmark are shown in **Figure 6.11**.

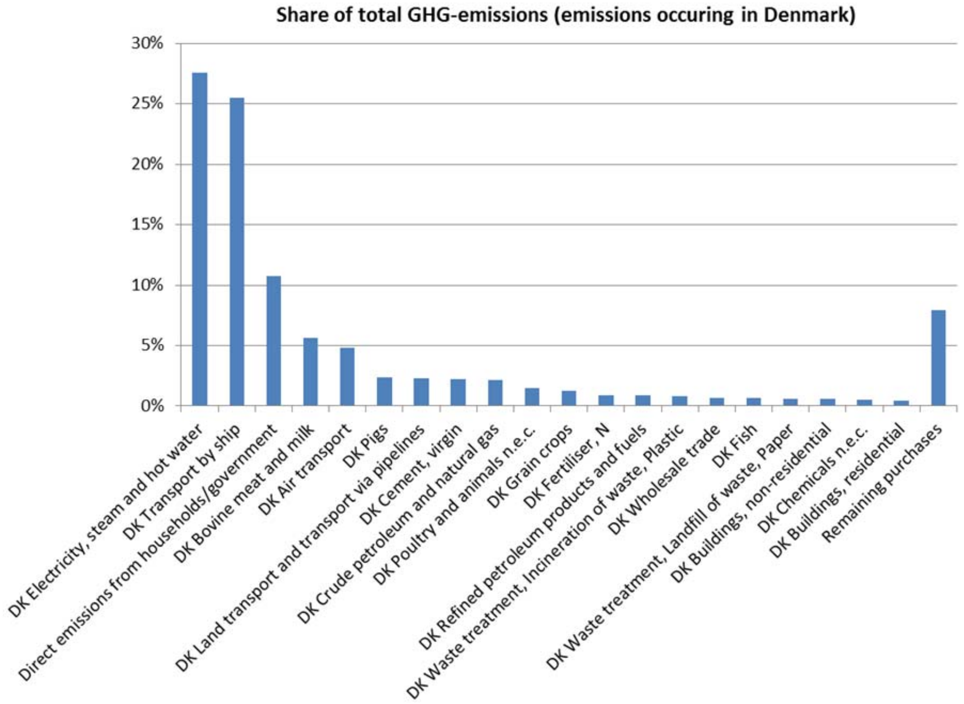

Figure 6.11: Illustration of the product flows in national economy and the functional unit of an analysis focussing on direct emissions occurring in Denmark.

It appears from **Figure 6.11** that the 20 largest GHG-emitters in Denmark emit around 92% of the total national emissions. The single most important emitters of GHG-emissions in Denmark are: electricity/heat production, transport by ship, and direct emissions by households/government (i.e. mainly from car driving and individual heating). One of the contributions in **Figure 6.11** is 'DK Waste treatment, Landfill of waste, Paper'. This contribution is a modelled outcome of the special waste module in FORWAST and it is not regarded as reflecting reality. The high amount of paper waste to landfill comes from reject from paper recyclers in Denmark where the treatment has been modelled as landfill with associated CH_4 emissions.

6.5 GHG-emissions from total supply = total use in Denmark

In **section 6.1**, the emissions related to Danish consumption are described. In the current section, the GHG-emissions related to all activities in Denmark are described, i.e. the domestic emissions plus emissions from imported products which equals emissions related to the production of all products which are used domestically in Denmark plus all exported products. This approach is also sometimes referred to as 'total production and consumption'. This approach is relevant to focus at in order to estimate the total emissions which can be governed by Denmark (consumers and producers). The functional unit of the analysis of Danish total supply = total use is illustrated in **Figure 6.12**.

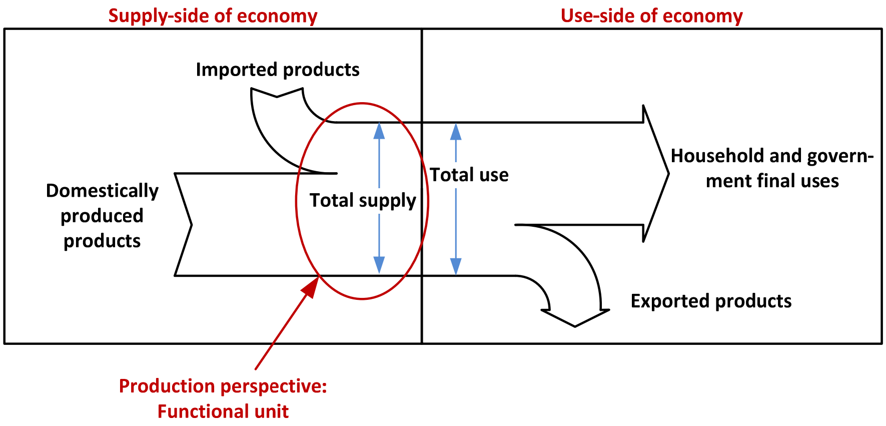

Figure 6.12: Illustration of the product flows in national economy and the functional unit of an analysis of the total supply = total use.

The results related to total supply = total use can be calculated by adding the emissions from the production of exported products (**section 6.2**) to the consumption related results (**section 6.1**).

The emissions from total supply = total use are 209 million tonne CO_2-eq. of which the Danish consumption accounts for 80.5 million tonne CO_2-eq. and the production of exported products accounts for 166 million tonne CO_2-eq.

7 Conclusion

The purpose of the current study is to improve the knowledge of Denmark's consumption based "carbon footprint". More specifically this includes increased knowledge of the different perspectives for which national emissions can be analyzed. Especially, the limitations of the traditional geographical approach to account for national emissions are addressed by taking into account the full life cycle of imported products to Danish economy.

Denmark's carbon footprint is studied by 1) reviewing existing studies focusing on Denmark's carbon footprint and 2) detailed model calculations using an existing model which is modified to obtain a higher degree of completeness and accuracy. The chosen model which is used for the detailed calculations is the FORWAST model, which is a Danish & European environmentally extended input-output model that was developed through an EU funded research project under the sixth framework programme. The original version of this model is associated with a number of limitations which are sought reduced by several modifications. These modifications include; improved modelling of imported products, inclusion of emissions from indirect land use changes (iLUC) and inclusion of special global warming potential from aviation. The applied iLUC model is comprehensively described and integrated with the FORWAST model.

7.1 Literature review

The literature review includes review of seven studies of the Danish carbon footprint. The review registered the reported Danish domestic emissions, emissions related to import, export, consumption and the totals, i.e. domestic emissions + emissions from imported products = emissions from consumption + export. The outcome of the literature study is summarized in **Figure 7.1**.

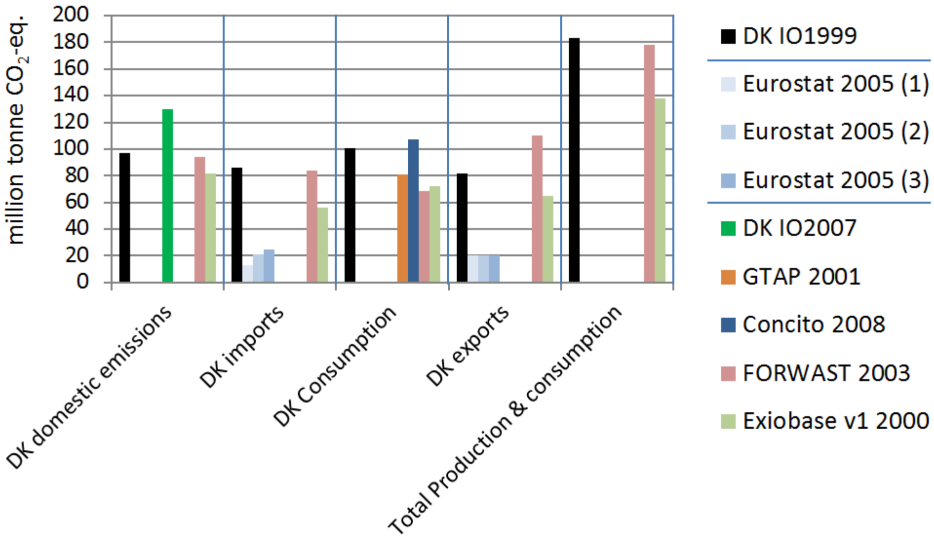

Figure 7.1. Summary of the results on GHG-emissions related to Danish economy based on the review of existing studies/models.

In general the review shows that, unsurprisingly, heterogeneous results are obtained by different studies, due to different underlying methods and assumptions. It should be noted that the concept of environmentally-extended input output tables is relatively new, and it is expected that as the interest in this approach increases, harmonization among studies will, too.

The causes of differences in results from the seven reviewed studies are identified as:

- Different baseline years. The studies cover the period from 1999 to 2008.
- Almost all studies included the same GHG-emissions; CO_2, N_2O and CH_4. However, some studies included biogenic CO_2 and other studies included other substances, such as halocarbons. The latter is judged to lead to minor differences in outcome.
- Import is modelled in different ways: The approaches range from not considering these emissions at all, which is the case in the DK IO2007 study (Gravgård et al. 2009), to inclusion with different levels of resolution, the lowest being the assumption that imports have the same GHG efficiency as Danish production, and the highest being the consideration of country-specific efficiencies. The Eurostat study (Rørmose et al. 2009) models import substantially different from the other studies; whereas the other studies include emission estimates for all imported products, the Eurostat study has excluded all imports that are directly or indirectly used for the production of exports. Therefore, the emissions embodied in trade in the Eurostat study are significantly lower than in the other studies.
- Another source of potential disagreement in results is whether or not LULUCF is included. The only study to address this explicitly is the Concito study.

7.2 Results from the detailed model calculations

The overall results for GHG-emissions relating to the different perspectives of the analysis are illustrated in **Figure 7.2**.

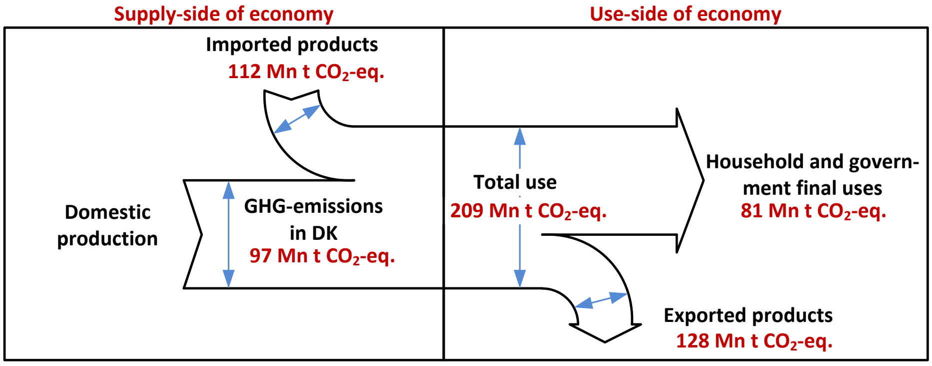

Figure 7.2. Illustration of the GHG-emissions relating to Danish economy for the different perspectives of the analysis.

Consumption perspective

The emissions from Danish consumption at 80.5 million tonne CO_2-eq. corresponds to 15.0 tonne CO_2-eq. per citizen in Denmark and 0.0575 kg CO_2-eq. per DKK[16] GDP. Of the absolute result at 80.5 million tonne CO_2-eq., 12% is related to indirect land use changes, and 1.2% is associated with the special radiative forcing from aviation. The remaining sources of emissions are the more traditional sources such as combustion of fossil fuels in various industries, cultivation and animal production emissions and other fugitive GHG-emissions. Of those more traditional sources, the most important ones are GHG-emissions from electricity/heat generation (in DK, RoW and EU27), direct emissions in households (passenger car

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[16] DKK2003 currency

transportation and to a lesser extent individual heating), bovine meat/milk production (DK), fertiliser production (RoW), and transport by air and ship.

Around 56% of the emissions related to Danish consumption occur in Denmark. Indirect land use changes (iLUC) contribute with 12% of the total GHG-emissions related to Danish consumption. This contribution is significant and it is associated with significant uncertainties. The major uncertainties related to iLUC are identified as 1) the share of a change in land that is supplied by intensification of land already in use and by land use changes respectively, and 2) the modelling and associated emissions related to intensification of land already in use. An uncertainty analysis of iLUC has been carried out, where different modelling assumptions were tested. This outcome of the sensitivity analysis showed that iLUC emissions were between 33.5 million tonne CO_2-eq. and 5 million tonne CO_2-eq. where the default result is somewhere in the middle.

In addition to the GHG-emissions related to Danish consumption, the land use (occupied area) was also calculated. The calculation showed that Danish consumption is related to the occupation of an area which corresponds to around 1.6 times Denmark's area. Around 57% of this area is managed forest, 31% is arable land (or land that is suitable for arable cropping), 9% is grassland and the remaining 3% is build-up land.

Export

The GHG-emissions associated with the production of exported products in Denmark are 128 million tonne CO_2-eq. The exported products with the highest GHG-emissions are ship transport, meat products (pork), and electricity.

Import

The total GHG-emissions related to import are 112 million tonne CO_2-eq. The single most important emitters of GHG-emissions in the product system related to Danish import are: electricity/heat production in in RoW, transport by ship in EU27, and transformation of forest to cropland.

Domestic emissions

Domestic emissions are what are typically reported as official national emissions. According to the model calculations, the domestic emissions are 97 million tonne CO_2-eq. (including emissions from international bunkering). The official reported Danish GHG-emissions for 2003 are 101 million tonne CO_2-eq.; the official reported national emissions are shown from 1990 to 2011 in **Figure 7.3**. The relatively small deviation between the model result and the official emissions is caused by the special modelling of waste flows in the FORWAST model, which leads to small inconsistencies in the up-scaled economy based on model calculations compared to the original supply-use tables.

The single most important emitters of GHG-emissions in Denmark are: electricity/heat production, transport by ship, and direct emissions by households/government (i.e. mainly from car driving and to a lesser extent individual heating).

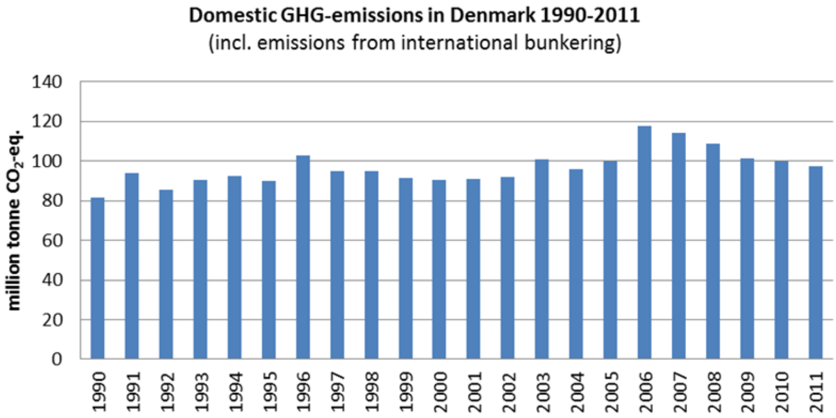

Figure 7.3. Official domestic GHG-emissions as reported by Statistics Denmark (2013c). The emissions from international bunkering are included. Biogenic CO_2 is not included.

Total supply = total use

The emissions associated with all activities in Denmark, i.e. the emissions from Danish consumption plus the production of exported products are 209 million tonne CO_2-eq.

7.3 Model outlook

The results in the current study have been calculated using a modified version of the FORWAST IO-model. Though, the features of the FORWAST model were assessed to be the best suited model, it is still associated with weaknesses. The major weaknesses of this model are:

- import is modelled using only an EU27 IO-table and a modified version of this EU27 table to represent the rest of the world (RoW)
- the model is relatively old, i.e. it represents 2003

Two currently ongoing EU seventh framework projects are worth mentioning in this respect. The first one is the CREEA project (http://creea.eu/) in which a similar hybrid IO-model as of the FORWAST is being created. The second project is the DESIRE project (http://fp7desire.eu/) in which time-series of the IO-model from the CREEA project are created. When the IO-models of the projects become available, it is expected that the calculation of the Danish carbon footprint can be made with a higher level of data quality and detail of the contribution analysis. Some of the features of the two projects are briefly described in the following. The CREEA project ends in April 2014, and the DESIRE project ends in February 2016. The CREEA IO-model will be published as the Exiobase v2 IO-model. It can be expected that the database will be made available through the Exiobase web-page: http://www.exiobase.eu/.

The advantages of the CREEA model are that the IO-model:

- uses the same mass flow analysis approach as of the FORWAST model (Schmidt et al. 2010; Schmidt et al. 2012a) allowing for several and relatively detailed waste modelling and mass balance checks
- is a multi-regional IO-model covering 43 countries and four rest of world (RoW regions), i.e. it has a true global scope
- represents a newer year than FORWAST, namely 2007,
- relies on data from a much more streamlined and consistent data collection procedure than FORWAST. Hence a higher data quality can be expected

The DESIRE IO-model can be expected to have the same scope as the CREEA model. Based on macro-economic historical data and future scenarios, time series will be built. This enables for having IO-models that represents any year, and to calculate detailed time series of carbon footprint results.

Since the CREEA and DESIRE models are based on monetary AND physical (mass and energy) supply-use tables, the hybrid models can be used for detailed analysis of production and trade in monetary as well as physical units (as in **chapter 4.3** of the current report). Further, since price information on all products are embodied in the model, GHG-intensities (kg CO_2-eq./EUR and kg CO_2-eq./kg) of all products in all countries can be calculated. The global scope of the models with 43 countries plus 4 RoW regions also allows for detailed analysis of where in the world Danish consumption causes impacts.

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Appendix A: Industry/product classification in the FORWAST IO-model

The table below specifies and describes the industry and product classification in the FORWAST hybrid IO-model. The names and classification of industries and products are identical. The name of an industry corresponds to its main product. The model for Denmark includes 137 industries/products and 10 household activities/consumption groups, i.e. in total 147 activities/products. The model includes four industry/product categories:

- Physical product, i.e. products which have a physical mass (dry matter) or electricity/heat (energy unit).
- Service products, i.e. products which are not physical products. These products are measured in monetary units.
- Waste treatment activities/services. The waste treatment service is the service to have som waste (or by-product) treated, e.g. recycling, incineration, landfill. Waste treatment services are measured in units of kg dry matter material for treatment.
- Household consumption groups, e.g. meals, communication, health care etc. The sum of the household activities is equal of the final demand of households and government.

In the table below, the type of activity/product, the unit of the main product of industries, and the NACE classification are specified. Further, the main by-products (if any) of the activities are specified.

No	Product type	Unit	Name	Main by-product of waste treatment services	NACE classification
1	Physical	Mass product	Bovine meat and milk		1.21
2	Physical	Mass product	Pigs		1.23
3	Physical	Mass product	Poultry and animals n.e.c.		01.24+01.25
4	Physical	Mass product	Grain crops		01.1(disaggr.)
5	Physical	Mass product	Sugar beets		01.1(disaggr.)
6	Physical	Mass product	Potatoes		01.1(disaggr.)
7	Physical	Mass product	Horticulture, orchards etc.		01.1(disaggr.)
8	Waste treatment	Mass waste	Manure treatment	Fertiliser, N and Fertiliser, other than N	1.21+1.23+01.24+01.25(disaggr)
9	Physical	Mass product	Forest products		2 (disaggr.)
10	Waste treatment	Mass waste	Recycling of waste wood	Forest products	2 (disaggr.)
11	Physical	Mass product	Fish		5
12	Physical	Mass product	Coal, lignite, peat		10
13	Physical	Mass product	Crude petroleum and natural gas		11
14	Physical	Mass product	Iron ores from mine		13.1
15	Physical	Mass product	Bauxite from mine		13.2(disaggr.)
16	Physical	Mass product	Copper from mine		13.2(disaggr.)
17	Physical	Mass product	Metals from mine n.e.c.		13.2(disaggr.)
18	Physical	Mass product	Sand, gravel and stone from quarry		14.1+14.21
19	Physical	Mass product	Clay and soil from quarry		14.22
20	Physical	Mass product	Minerals from mine n.e.c.		14.3+14.4+14.5
21	Physical	Mass product	Meat products; Pork		15.1+15.2(disaggr)
22	Physical	Mass product	Meat products; Bovine		15.1+15.2(disaggr)
23	Physical	Mass product	Meat products; Poultry and meat n.e.c.		15.1+15.2(disaggr)
24	Physical	Mass product	Meat products; Fish		15.1+15.2(disaggr)
25	Physical	Mass product	Dairy products		15.5
26	Physical	Mass product	Fruits and vegetables, processed		15.3
27	Physical	Mass product	Vegetable and animal oils and fats		15.4
28	Physical	Mass product	Flour		15.6
29	Physical	Mass product	Sugar		15.83
30	Physical	Mass product	Animal feeds		15.7
31	Physical	Mass product	Food preparations n.e.c.		15.8(ext.)
32	Physical	Mass product	Beverages		15.9
33	Physical	Mass product	Tobacco products		16
34	Physical	Mass product	Textiles		17
35	Physical	Mass product	Wearing apparel and furs		18
36	Physical	Mass product	Leather products, footwear		19
37	Physical	Mass product	Wood products, except furniture		20
38	Physical	Mass product	Pulp, virgin		21.11(disaggr.)
39	Waste treatment	Mass waste	Recycling of waste paper	Pulp, virgin	21.11(disaggr.)
40	Physical	Mass product	Paper and paper products		21.12+21.2
41	Physical	Mass product	Printed matter and recorded media		22
42	Physical	Mass product	Refined petroleum products and fuels		23 (disaggr.)
43	Waste treatment	Mass waste	Recycling of waste oil	Refined petroleum products and fuels	23 (disaggr.)
44	Physical	Mass product	Fertiliser, N		24.15(disaggr.)
45	Physical	Mass product	Fertiliser, other than N		24.15(disaggr.)
46	Physical	Mass product	Plastics basic, virgin		24.16(disaggr.)+24.17(disaggr.)
47	Waste treatment	Mass waste	Recycling of plastics basic	Plastics basic, virgin	24.16(disaggr.)+24.17(disaggr.)
48	Physical	Mass product	Chemicals n.e.c.		24(disaggr.)
49	Physical	Mass product	Rubber and plastic products		25
50	Physical	Mass product	Glass, mineral wool and ceramic goods, virgin		26.1(disaggr.)+26.2(disaggr.)

No	Product type	Unit	Name	Main by-product of waste treatment services	NACE classification
51	Waste treatment	Mass waste	Recycling of glass, mineral wool and ceramic goods	Glass, mineral wool and ceramic goods, virgin	26.1(disaggr.)+26.2(disaggr.)+26.3(disaggr.)
52	Physical	Mass product	Cement, virgin		26.5(disaggr.)
53	Waste treatment	Mass waste	Recycling of slags and ashes	Cement, virgin	26.5(disaggr.)
54	Physical	Mass product	Concrete, asphalt and other mineral products		26.6(disaggr.)+26.7(disaggr.)+26.8(disaggr.)
55	Waste treatment	Mass waste	Recycling of concrete, asphalt and other mineral products	Sand, gravel and stone from quarry	26.6(disaggr.)+26.7(disaggr.)+26.8(disaggr.)
56	Physical	Mass product	Bricks		26.3(disaggr.)+26.4
57	Waste treatment	Mass waste	Recycling of bricks	Bricks	26.3(disaggr.)+26.4
58	Physical	Mass product	Iron basic, virgin		27.1(disaggr.)
59	Waste treatment	Mass waste	Recycling of iron basic	Iron basic, virgin	27.1(disaggr.)
60	Physical	Mass product	Aluminium basic, virgin		27.42(disaggr.)
61	Waste treatment	Mass waste	Recycling of aluminium basic	Aluminium basic, virgin	27.42(disaggr.)
62	Physical	Mass product	Copper basic, virgin		27.44(disaggr.)
63	Waste treatment	Mass waste	Recycling of copper basic	Copper basic, virgin	27.44(disaggr.)
64	Physical	Mass product	Metals basic, n.e.c., virgin		27.4(disaggr.)
65	Waste treatment	Mass waste	Recycling of metals basic, n.e.c.	Metals basic, n.e.c., virgin	27.4(disaggr.)
66	Physical	Mass product	Iron, after first processing		27.2(disaggr.)+27.3(disaggr.)+27.5(disaggr.)
67	Physical	Mass product	Aluminium, after first processing		27.2(disaggr.)+27.3(disaggr.)+27.5(disaggr.)
68	Physical	Mass product	Copper, after first processing		27.2(disaggr.)+27.3(disaggr.)+27.5(disaggr.)
69	Physical	Mass product	Metals n.e.c., after first processing		27.2(disaggr.)+27.3(disaggr.)+27.5(disaggr.)
70	Physical	Mass product	Fabricated metal products, except machinery		28
71	Physical	Mass product	Machinery and equipment n.e.c.		29
72	Physical	Mass product	Office machinery and computers		30
73	Physical	Mass product	Electrical machinery n.e.c.		31
74	Physical	Mass product	Radio, television and communication equipment		32
75	Physical	Mass product	Instruments, medical, precision, optical, clocks		33
76	Service	Monetary value	Motor vehicles and trailers		34
77	Service	Monetary value	Transport equipment n.e.c.		35
78	Physical	Mass product	Furniture and other manufactured goods n.e.c.		36
79	Service	Monetary value	Recycling services		37
80	Physical	Energy unit	Electricity, steam and hot water		40(disaggr.)
81	Physical	Mass product	Gas		40(disaggr.)
82	Service	Monetary value	Water, fresh		41
83	Service	Monetary value	Buildings, residential		45.1(disaggr.)+45.21(disaggr.)+45.22+45.3+45.4+45.5(disaggr.)
84	Service	Monetary value	Buildings, non-residential		45.1(disaggr.)+45.21(disaggr.)+45.22+45.3+45.4+45.5(disaggr.)
85	Service	Monetary value	Infrastructure, excluding buildings		45.1(disaggr.)+45.21(disaggr.)+45.22+45.3+45.4+45.5(disaggr.)
86	Service	Monetary value	Trade and repair of motor vehicles and service stations		50
87	Service	Monetary value	Wholesale trade		51
88	Service	Monetary value	Retail trade and repair services		52
89	Service	Monetary value	Hotels and restaurants		55
90	Service	Monetary value	Land transport and transport via pipelines		60
91	Service	Monetary value	Transport by ship		61
92	Service	Monetary value	Air transport		62
93	Service	Monetary value	Cargo handling, harbours and travel agencies		63
94	Service	Monetary value	Post and telecommunication		64
95	Service	Monetary value	Financial intermediation		65
96	Service	Monetary value	Insurance and pension funding		66
97	Service	Monetary value	Services auxiliary to financial intermediation		67
98	Service	Monetary value	Real estate services		70
99	Service	Monetary value	Renting of machinery and equipment etc.		71
100	Service	Monetary value	Computer and related services		72

No	Product type	Unit	Name	Main by-product of waste treatment services	NACE classification
101	Service	Monetary value	Research and development		73
102	Service	Monetary value	Business services n.e.c.		74
103	Service	Monetary value	Public service and security		75
104	Service	Monetary value	Education services		80
105	Service	Monetary value	Health and social work		85
106	Waste treatment	Mass waste	Incineration of waste: Food	Electricity, steam and hot water	90(disaggr.)
107	Waste treatment	Mass waste	Incineration of waste: Paper	Electricity, steam and hot water	90(disaggr.)
108	Waste treatment	Mass waste	Incineration of waste: Plastic	Electricity, steam and hot water	90(disaggr.)
109	Waste treatment	Mass waste	Incineration of waste: Metals	none	90(disaggr.)
110	Waste treatment	Mass waste	Incineration of waste: Glass/inert	none	90(disaggr.)
111	Waste treatment	Mass waste	Incineration of waste: Textiles	Electricity, steam and hot water	90(disaggr.)
112	Waste treatment	Mass waste	Incineration of waste: Wood	Electricity, steam and hot water	90(disaggr.)
113	Waste treatment	Mass waste	Incineration of waste: Oil/Hazardous waste	none	90(disaggr.)
114	Waste treatment	Mass waste	Biogasification of food waste	Electricity, steam and hot water	90(disaggr.)
115	Waste treatment	Mass waste	Biogasification of paper	Electricity, steam and hot water	90(disaggr.)
116	Waste treatment	Mass waste	Biogasification of sewage slugde	Electricity, steam and hot water	90(disaggr.)
117	Waste treatment	Mass waste	Composting of food waste	none	90(disaggr.)
118	Waste treatment	Mass waste	Composting of paper and wood	none	90(disaggr.)
119	Waste treatment	Mass waste	Waste water treatment, food	none	90(disaggr.)
120	Waste treatment	Mass waste	Waste water treatment, other	none	90(disaggr.)
121	Waste treatment	Mass waste	Landfill of waste: Food	Electricity, steam and hot water	90(disaggr.)
122	Waste treatment	Mass waste	Landfill of waste: Paper	Electricity, steam and hot water	90(disaggr.)
123	Waste treatment	Mass waste	Landfill of waste: Plastic	none	90(disaggr.)
124	Waste treatment	Mass waste	Landfill of waste: Iron	none	90(disaggr.)
125	Waste treatment	Mass waste	Landfill of waste: Alu	none	90(disaggr.)
126	Waste treatment	Mass waste	Landfill of waste: Copper	none	90(disaggr.)
127	Waste treatment	Mass waste	Landfill of waste: Metals nec	none	90(disaggr.)
128	Waste treatment	Mass waste	Landfill of waste: Glass/inert	none	90(disaggr.)
129	Waste treatment	Mass waste	Landfill of waste: Mine waste	none	90(disaggr.)
130	Waste treatment	Mass waste	Landfill of waste: Textiles	Electricity, steam and hot water	90(disaggr.)
131	Waste treatment	Mass waste	Landfill of waste: Wood	Electricity, steam and hot water	90(disaggr.)
132	Waste treatment	Mass waste	Landfill of waste: Oil/Hazardous waste	none	90(disaggr.)
133	Waste treatment	Mass waste	Landfill of waste: Slag/ash	none	90(disaggr.)
134	Waste treatment	Mass waste	Land application of compost	Fertiliser, N and Fertiliser, other than N	90(disaggr.)
135	Service	Monetary value	Membership organisations		91
136	Service	Monetary value	Recreational and cultural services		92
137	Service	Monetary value	Services n.e.c.		93
138	Household	Monetary value	Household use: Clothing		n.a.
139	Household	Monetary value	Household use: Communication		n.a.
140	Household	Monetary value	Household use: Education		n.a.
141	Household	Monetary value	Household use: Health care		n.a.
142	Household	Monetary value	Household use: Housing		n.a.
143	Household	Monetary value	Household use: Hygiene		n.a.
144	Household	Monetary value	Household use: Leisure		n.a.
145	Household	Monetary value	Household use: Meals		n.a.
146	Household	Monetary value	Household use: Security		n.a.
147	Household	Monetary value	Household use: Social care		n.a.