Chapter 13

Carbon Footprint as a Tool to Limit Greenhouse Gas Emissions

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Additional information is available at the end of the chapter

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Abstract

The Carbon Footprint is the amount of greenhouse gases (GHG) produced during the life cycle of a product, a process, or a service (expressed in equivalent tons of carbon dioxide per functional unit of analyzed product/process/service). The patterns of fossil fuel combustion, carbon capture and sequestration, and conventional and unconventional fossil fuel production, but also the emissions linked with consumer behavior, can be analyzed considering their carbon footprint. In this chapter the carbon footprint tool is introduced, linking it to fossil energy systems and renewable energy systems, as well as the main products on the market, to provide information on which technology should be promoted to reduce GHG emissions.

Keywords: Carbon Footprint, ISO 14067, GHG, Life Cycle Assessment

1. Introduction

Carbon footprint, as an indicator of the impact of the emissions of GHG of products and services, is interesting for enterprises, consumers, and politicians [1]. Investors control the carbon footprint of their products as it is an indicator of their investment risk. Purchasing managers are interested in the carbon footprint of the goods that they are dealing with, and the market is beginning to offer consumers carbon-labeled products. These are the reasons for the popularity of product carbon footprint. It is defined as the mass of cumulated CO_2 emissions that can be measured through a supply chain or through the life cycle of a product [2]. The average per capita carbon footprint of continents and of the most important nations is reported in Table 1 (data are expressed in equivalent tons of carbon dioxide per capita per year). Also the contribution of different sectors is reported (expressed in percentage).

	Country footprint [tCO2e/p]	Construction (%)	Shelter (%)	Food (%)	Clothing (%)	Manufactured products (%)	Mobility (%)	Service (%)	Trade (%)
Europe	13	9	21	16	3	12	21	17	6
USA	29	7	25	8	3	12	21	16	8
Canada	20	8	18	8	2	9	30	18	6
South America	5	6	8	36	3	8	22	13	5
Russian Federation	10	9	40	15	1	3	16	17	1
Asia	7	11	14	24	4	11	19	16	4
Africa	2	6	13	40	2	6	10	22	3
Australia and New Zealand	16	8	18	18	3	9	19	16	13

Table 1. Carbon footprint of continents and most important nations [3]

Carbon footprint is most appropriately calculated using life-cycle assessment or input-output analysis [3,4]. In this sense it is based on the ISO 14040 [4] and ISO 14043 [5] norms, on life cycle assessment (LCA). Specific norms for carbon footprint of enterprises and products are ISO 14064 (part 1,2, and 3) [6-8], ISO 14067 [9], and PAS 2500 [10]. Carbon footprint calculation process is shown in Figure 1.

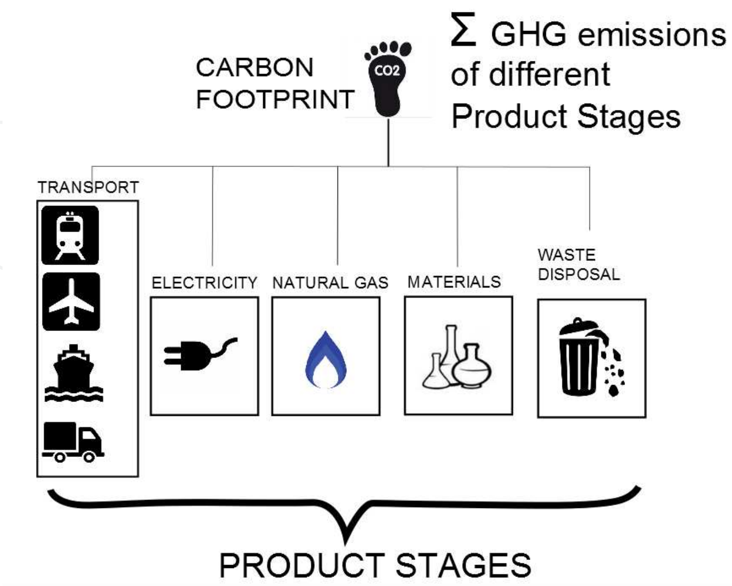

Figure 1. Carbon footprint calculation

Main emissions due to the most important processes are added through the whole life cycle. Carbon footprint of a purchased good or service can be calculated using Equation 1 [11].

$$PCF=S1+S2+S3+S4+OE \tag{1}$$

Where:

- S1 is the sum across purchased goods and services;
- S2 is the sum of emissions due to material inputs;
- S3 is the sum of emissions due to transport of material inputs;
- S4 is the sum of emissions due to waste outputs;
- OE stands for other emissions emitted in provision of the good or service.

In order to calculate carbon footprint, it is very important to consider the boundaries of the process: which emissions should be considered in calculation of the footprint? This problem can be solved by considering three definitions: Scope 1, Scope 2, and Scope 3.

Scope 1 indicates direct emissions, for example, on-site emissions; Scope 2 indicates emissions embodied in the purchased energy; and Scope 3 indicates all the emissions not covered under Scope 2, such as those associated with transport of goods and waste disposal [12].

Another important aspect is the functional unit, which is defined as a measure of the function of the studied system, and it provides a reference to which the inputs and outputs can be related. This enables the comparison of two essential different systems.

2. Carbon footprint of renewable energy systems

2.1. Carbon footprint of transport fuels

The carbon footprint of transport fuels has been analyzed in several studies starting from 1990. One of the most important is the study realized by Sheehan et al. [13] at National Renewable Energy Laboratory of the United States.This is an LCA study that includes the impact of CO_2 emissions. Most important operations belonging to the petroleum diesel product system include crude oil extraction, its transport to an oil refinery, crude oil refining to diesel fuel, its transportation to the user, and its use in a bus engine.

In addition to energy and environmental outputs in each step, energy and environmental inputs from raw materials use are also included. Generally, life cycle flows include all raw materials used for extraction. Likewise, life cycle flows from intermediate energy sources such as electricity, back to the extraction of coal, oil, natural gas, limestone, and other primary resources should be included.

Life cycle presents a typical allocation case because the refining process is a multiple product process and the other sub-products obtained during diesel production are shown in Figure 2, together with the definition of the most important processes involved in the refining step.

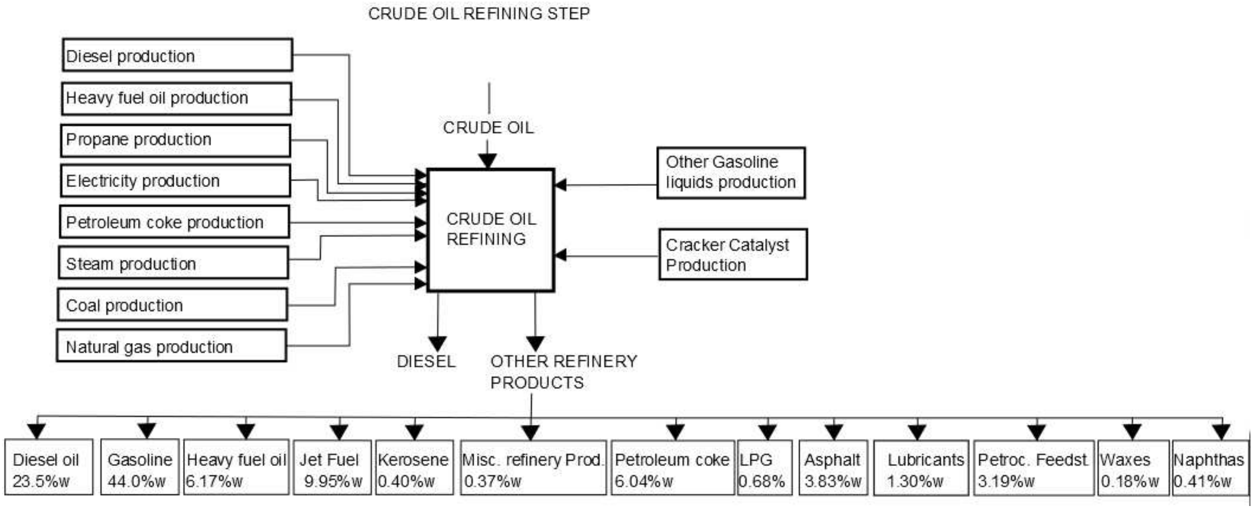

Figure 2. Crude oil refining step [13]

The final results show that diesel production and use account for a total emission of CO_2 of 633 gCO_2eq/bhp-h. The processes that contribute most to the release of CO_2 emissions are refining (which is responsible for 10% of the emissions) and petroleum combustion in the engine (which is responsible for 87% of the emissions).

2.2. Carbon footprint of electricity generation through fossil fuels

The electricity supply sector is responsible for over 7,700 million tonnes of CO_2 emissions annually (2,100 Mt C/yr); being 37.5% of total CO_2 emissions [14]. The annual carbon emissions, associated with electricity generation, is projected to surpass the 4,000 Mt C level by 2020 [15]. Past and projected electricity production from fossil fuels is shown in Table 2 and also CO_2 emissions per kWh.

	1995	2000	2010	2020
Coal	4,949	5,758	7,795	10,296
Natural Gas	1,932	2,664	5,063	8,243
Oil	1,315	1,422	1,663	1,941
Average GHG emissions (g CO_2/kWh)	158	157	151	147

Table 2. Past and projected global production from the electricity generating sector (TWh/yr) and average CO_2 emissions per kWh [14]

The efficiencies of modern thermal power stations using the steam cycle can exceed 40% based on lower heating value, although the average efficiency of the installed stock worldwide is closer to 30%. Recently, efficiencies of 48.5% have been reported and, with further development, by 2020, they could reach 55% at costs only slightly higher than current technology.

Physical carbon sequestration is more useful with the emissions of large point sources of CO_2 such as power plants. It can be captured either before combustion, in an IGCC or in a reforming process (transforming steam to methane), or after combustion from the flue gas stream using amine solvents, for example. The volume percentage of CO_2 in exhaust flue gases is between 4% (for gas turbines) and 14% (for a pulverized coal-fired plant), which means that large volumes of gas have to be treated using efficient solvents, and this will result in high-energy consumption because of solvent regeneration. These techniques will achieve an efficiency of 80–90% in carbon capture. Other carbon capture techniques include cryogenics, membranes, and adsorption. After the CO_2 has been captured, it is pressurized, typically up to 100 bar, before transportation to storage areas. CO_2 capture and compression imply a decrease on the thermal efficiency of a power plant, which has been estimated to be equal to 8–13%. The cost of CO_2 capture in power plants comprises between $30 and 50/t CO_2 of emissions; while the cost of CO_2 transportation is influenced by the distance and the capacity of the pipeline and ranges between $1 and 3/t CO_2 per 100 km. The cost of underground storage, which excludes the costs due to compression and transport, is estimated to range between $1 and 2/t CO_2 stored. With the development of new technologies, for example the development of new solvents and system components, the costs of carbon capture and storage would decrease.

2.3. Carbon footprint of residential heating systems based on fossil fuels

Glaeser and Kahn [16] evaluated the emissions released by American households for heating purposes. The two primary heating sources for households are fuel oil and natural gas. On the one hand in the United States, the use of fuel oil is pretty rare, with the exception of the Northeast, and it is used as a source of home heating in few metropolitan areas; on the other hand, natural gas is the most common home heating source; and in some areas electricity is also used. Natural gas consumption is driven primarily by climate.

For fuel oil and natural gas, there are conversion factors that enable to move from energy use to CO_2 emissions. In the case of fuel oil, the factor is 22.38 lb of CO_2 per gallon.

It can be considered that about 20,000 kWh/yr are required to heat a typical house in developed countries. If hard coal, oil, natural gas, and LPG are used, the annual total CO_2 emissions are 8,280 kg CO_2/yr, 6,280 kgCO_2/yr, 4,540 kg CO_2/yr, and 5,180 kg CO_2/yr, respectively [17]. These data agree with those reported by Johnson [18], which are shown in Figure 3.

2.4. Life cycle carbon footprint of shale gas

Recent advances in drilling and fracking technologies have made the access to huge deposits of natural gas in shale deposits technically and economically feasible. These are located across the United States and elsewhere [19,20], and thus shale gas production has grown about 48% per year from 2006 to 2010 in the United States. This fact will influence the American and the world energy outlooks for the near future, together with the variation in the oil price [21]. The

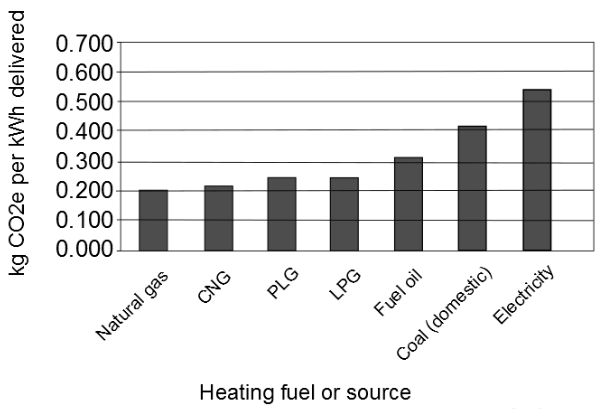

Figure 3. Carbon footprint of different heating fuels [18]

growth of the shale gas industry has brought important benefits, such as significant job growth, decoupling gas and oil prices, providing an alternative to the more polluting use of oil in transportation and of coal in power generation [22,23]. The carbon footprint of shale gas can be calculated evaluating or measuring the direct CO_2 emissions from its final use and evaluating indirect CO_2 emissions produced from fossil fuels used to extract, develop, and transport it. Also methane fugitive emissions and emissions from venting have to be considered. Literature studies have shown that the indirect CO_2 emissions throughout shale oil life cycle are relatively small than that of the direct combustion of the fuel. In fact indirect emissions range between 1 and 1.5 g CO_2/MJ−1 [24], whereas direct emissions range between 13-15 g CO_2/MJ [25,26]. Indirect emissions from shale gas are comparable with those due to conventional gas production [26].

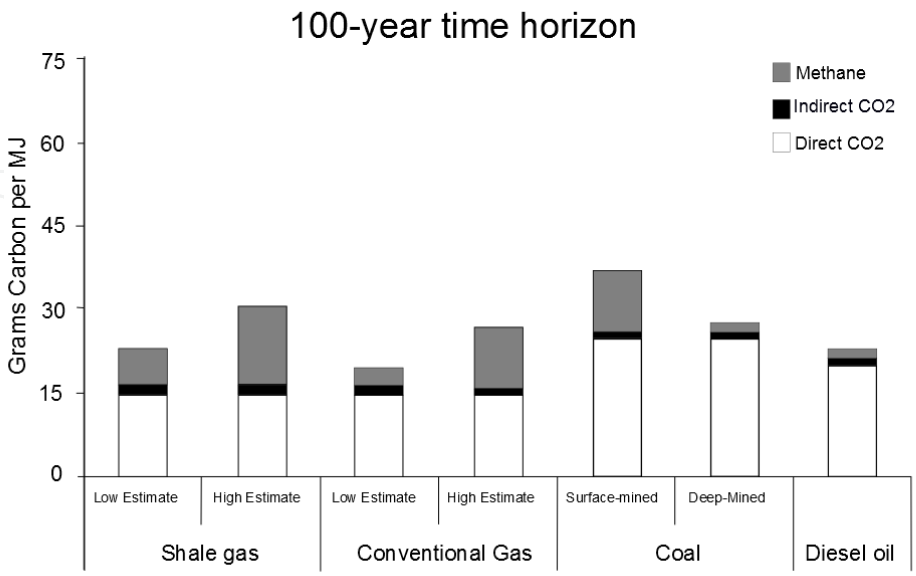

Figure 4. Comparison of GHG emissions from shale gas and conventional natural gas with low and high estimates of fugitive methane emissions, surface-mined coal, deep-mined coal, and diesel oil; time horizon equal to 100 years [27]

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From the most important studies available in literature, it can be inferred that both carbon footprints of shale gas and of conventional gas are dominated by direct CO_2 emissions and fugitive methane emissions. In Figure 4 direct emissions of CO_2 during combustion of shale gas, conventional gas, coal, and diesel oil are represented with white bars, whereas indirect emissions occurring during the development and the use of the energy sources are represented in black bars, and fugitive emissions of methane are represented with grey bars. All the emissions have been normalized to the quantity of energy released during combustion.

3. Carbon footprint of renewable energy systems

3.1. Carbon footprint of transport biofuels (biodiesel, bioethanol, biomethane)

The GHG emissions released during biodiesel life cycle are about 40–65% of those released during conventional diesel life cycle. For bioethanol technologies, the GHG emissions are deeply influenced by the technology. Emissions of the whole life cycle of bioethanol produced from corn can be about 80–90% of those of competitor fossil fuels. For bioethanol produced from sugar cane, a reduction of 75-80% in fossil fuels emissions can be achieved. Important factors that influence the final results are the amounts and type of fossil fuels used in the life cycle as energy carriers to produce, transport, and process the feedstock. Also non-CO_2 emissions, generated during the cultivation phase, such as N_2O, have to be considered. Besides, the efficiency in the conversion process is important too, together with the degree to which biomass is used to provide the energy required by the process, and feedstock yields during the cultivation phase. The mass and energy balances are also influenced by the capacity of the bioenergy plant and the scale of the project. In the case of large-scale projects, there will be important land use changes that can influence carbon stocks in the soil. Table 3 shows GHG emissions per kilometer travelled.

Transportation Fuel	GHG Emissions (gCO_2-eq./km)
Bioethanol from sugar cane	50-75
Bioethanol from other crops (corn, sugar beet, wheat)	100-195
Biogas	25-100
Biodiesel (rapeseed, soy, sunflower)	80-140
Fischer Tropsch diesel from biomass	15-55
Bioethanol from lignocellulose	25-50
Gasoline	210-220
Diesel	185-220
Natural gas	155-185

Table 3. GHG emissions per kilometer travelled using renewable fuels and fossil fuels [28]

3.2. Carbon footprint of electricity generation through renewable energy

The carbon footprint of electricity generation through RES (Renewable Energy Systems) are described in this section. Hydro-electricity is described first, and then wind power, followed by bioenergy systems and solar energy.

Hydro-electricity is the most developed renewable resource worldwide, even if it has to face social and environmental barriers [29]. In fact societal preferences are difficult to predict, while hydro-sites are often difficult to reach, which results in high transmission and capital investment costs. These are difficult to be accepted by private power companies. The global economic hydropower potential ranges between 7000 and 9000 TWh per year. Particularly rural communities without electricity appear to be convenient for small (<10 MWe), mini- (<1 MWe), and micro- (<100 kWe) scale hydro schemes. They have low environmental impacts, and generation costs are around 6–12 c/kWh. Emissions of GHG linked with hydro-electricity operation are due to flooding of land upstream of a dam that can imply a loss of biological carbon stocks and can produce methane emissions due to vegetation decomposition.

Wind power is a technology that has been developed recently. It has an intermittent flow and produces about 4% of total global electricity. In 2013 the production capacity reached 282,000 MWe, which implies a huge development, respect from year 2000 [30]. Denmark is producing about 40% of its total electricity consumption from wind power, and it's one of the main exporters of wind turbine technology. Many wind turbines will be sited off-shore. On the one hand in this way future demand can be met, the advantage is to increase the rated output to more than 3 MWe, to decrease costs linked with operation and maintenance, to have more reliable plants; on the other hand the cost of investment for wind turbines is decreasing, while the installed capacity increases. So wind power is becoming competitive with other sources of energy in highly windy areas. The costs of electricity generation in this case range between 3 and 5 c/kWh. The investment costs will fall from $1000 to $635/kWe and operating costs will decrease to about 0.01 c/kWh - 0.005 c/kWh [31].

Bioenergy can be produced from agricultural and forestry residues, animal effluents, the organic fraction of municipal solid wastes, and dedicated energy crops. Since biomass is widely spread in the territory, it is an interesting source of energy for rural and mountain areas. The challenge is to optimize the production of biomass, collection and logistics, optimize its conversion to energy and delivery to the end user, to provide a service that is economically competitive with that obtainable using other fossil fuels. Residual biomasses, such as bagasse, rice husks, straw, olive husk, bark, and sawdust often have a corresponding cost for disposal. Therefore, biomass-to-energy conversion, in the case of residues, can have good economic performance, especially in rural areas, where there is abundance of them. Denmark produces about 40% of the electricity it consumes through cogeneration plants, using wood waste and straw. Also biogas is produced from animal breeding effluents. Energy crops are less promising in the short term due to their higher production costs in terms of $/GJ of available energy. Also the competition for land use with food crops is becoming an issue. Biomass as a fuel is more reactive than coal if it is used in gasification process, which promotes the use of biomass in IGCC systems, that are approaching to commercial realization. Besides if coupled with carbon capture, biomass integrated gasification combined cycle can be a carbon-negative technology, because CO_2 is absorbed during biomass cultivation and production, and it is not released in the IGCC plant, due to carbon capture. On the one hand, capital investment for a biomass gasification–combined cycle plant, working with an high pressure reactor, is decreasing from $2000/kWe to $1100/kWe by 2020; on the other hand operating costs (fuel supply included) will decline from 3.98 to 3.12 c/kWh [31]. Actually operation costs for a traditional plat working with boiler plus steam turbine are about 5.50 c/kWh.

The cost of solar photovoltaic (PV) is slowly decreasing from $5,000/kWe to $4,000/kWe installed. The increase in the installed capacity corresponds to an increase in scale-up of manufacturing plants and the use of mass production techniques that are the main reasons for costs reduction. Also operating costs are quite high, being about 20–40 c/kWh. Promising new applications for solar PV are represented by grid connected buildings and by large installations (up to 1 MWe), which are pushing innovation in inverters and net metering systems. Other important markets for photovoltaic power systems are off-grid applications for rural areas, especially in developing countries where there is a need for electrification projects. The worldwide installed PV capacity is estimated to be about 178 GWe in 2014, while it will reach about 400 GWe in 2020. Conversion efficiencies of silicon cells are continuously improving. The efficiency of commercial monocrystalline modules is about 13–17%, whereas the efficiency of multicrystalline module is about 12–14%. Literature studies show that a single factory of 400 MWe capacity (obtainable with 5 million panels) can reduce production costs of 75%, due to economies of scale [32]. Neij [33] calculated that a $100 billion investment in manufacturing capacity would be needed in order to reach an acceptable generating level of 5 c/kWh (excluding back-up supply or storage costs). Capital costs for concentrated solar will fall from $4000/kWe to $2500/kWe by 2030 (Table 4) [34].

Technology	PF + fgd, NO_x, etc.	IGCC and super-critical	CCGT	PF + fgd + CO_2 capture	CCGT +CO_2 capture	Nuclear	Hydro	Wind Turbines	Biomass IGCC	PV and Solar thermal
Energy source	Coal	Coal	Gas	Coal	Gas	Uranium	Water	Wind	Biofuel	Solar
Emissions (gC/kWh)	229	190-198	103-122	40	17	0	0	0	0	0
Reduction potential to 2020 (MtC/yr)	Baseline	55	103	5-50	N.A.	191	37	128	77	20
Cost of C reduction ($/t C avoided)	Baseline	-10-40	0-156	159	71-165	-38-135	-31-127	-82-135	-92-117	175-1400

PF, pulverised fuel; fgd, flue gas desulphurization; IGCC, integrated gasification combined cycle

Table 4. Cost estimates of alternative mitigation technologies in the power generation sector compared to baseline pulverized coal-fired power plant and natural gas Combined Cycle with Gas Turbine (CCGT) power stations and the potential reductions in CO_2 emissions to 2020 [14]

3.3. Carbon footprint of residential heating systems based on renewable energy

Heat production and hot water supply to buildings are essential and important worldwide. The problem is how to produce them in a sustainable way, replacing fossil fuels. Today, it is intensively being discussed how to do so in the best way in future energy systems in which the combustion of fossil fuel should be reduced or completely avoided. One way could be through the promotion of low energy buildings in which the consumption of energy can be reduced or even removed (through the use for example of solar thermal heating systems). Another way could be the one to use excess heat produced from the industrial sector, waste incineration, power stations based on large-scale exploitation of geothermal energy, solar thermal energy, and heat pumps powered by excess wind energy. In these cases, a district heating network becomes essential. Table 5 shows the comparison of GHG emissions for different household.

Heat Source	GHG Emissions (gCO_2-eq./MJ)
Biomass (i.e., wood chips, pellets)	520
Geothermal	15
Solar thermal	1030
Coal	110150
Oil	90120
Natural gas	7085
Electricity from natural gas (space heating)	180210
Electricity from oil (space heating)	265295
Electricity from coal (space heating)	290320

Table 5. GHG emissions per unit output in the heating sector (taken from [28])

The development of district heating systems is linked with the development of other systems such as combined heat and power systems, which generate waste heat, together with power. These increase the fuel use efficiency [35]. Also heat pumps should be introduced in residential heating systems [18]. In some countries like Norway, district heating system's GHG emissions have been compared with those of individual heating systems and it has been found that the first have lower CO_2 emissions.

4. Carbon footprint of products

4.1. Carbon footprint in the food industry

Food industry sector is one of the major contributors to climate change [36]. In Sweden, it has been estimated that about 25% of GHG emissions from the private sector are due to the

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consumption of food [37]. In the European Union, food industry contribution to GHG emissions is estimated to be about 31% [36,38]. GHG emissions in the transport sector are mainly due to CO_2; while in agriculture most emitted GHG are methane (CH_4) and nitrous oxide (N_2O). The CO_2 emitted from land use change represents also an important source of emissions of the food production system. Starting from the publication of the Fourth Assessment Report of the IPCC in 2007 [39], the calculation of food carbon footprint has become more and more popular. Food carbon footprint is calculated by companies also for marketing purposes [40-42]. Also research efforts in the calculation of carbon footprint of food and in the estimate of its uncertainty have increased in recent years [43-46] (see Figure 5). Challenges in calculating the carbon footprint of food products can be linked with the functional unit, system boundaries and allocation, land use change, carbon sequestration in soils, uncertainties, and variation.

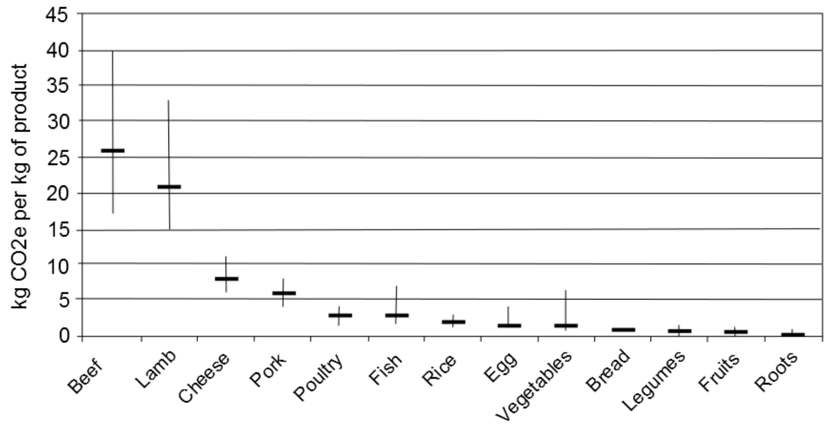

Figure 5. Carbon footprint of different types of food products at retail. Average values estimated to be representative for food products sold on the Swedish market. Error bars show ranges of values found in the literature. Emissions from land use change and carbon stock changes in soils are not included [47]

Besides marketing purposes, carbon footprint is calculated in the food sector also with the aim at reducing its value, producing more sustainable food. The main ways to reduce the product carbon footprint of food are as follows: by reducing emissions of CO_2 due to energy use in agriculture (for example improving energy efficiency and using renewable energy sources) and reducing CH_4 emissions from enteric fermentation and N_2O emissions from fertilizer nitrification in soil. CH_4 emissions can be reduced to some extent by altering the diet fed to ruminants [48], but the risk of pollution swapping is great [49,50]. N_2O emissions from soils can be reduced by optimizing nitrogen use and promoting N_2O inhibitors.

Another way to reduce GHG emissions in the food sector is changing the consumption patterns [51-54]; for example, switching from diets based on meat to diets in which proteins are also supplied by vegetables.

Being on-farm emissions (from cultivation and animals breeding) the most important source of GHG in food life cycle, numerous studies have tried to reduce them. Ahlgren [55] has used LCA to evaluate the use of biofuels in tractors and the substitution of mineral nitrogen fertilizers. This implied that 3–6% of a farm's available land was needed to produce the required biomass (to produce biofuels and fertilizer).

Another issue is represented by dairy production and the carbon footprint of milk [56,50]. An important area of research is the production of animal feed for the different diets used in livestock production [57-58].

4.2. Carbon footprint in the textile industry

Many enterprises in the textile and clothing industry are involved in product carbon footprint calculation. They range from fiber manufacturers (e.g., Lenzing, Advansa, Dupont) to producers of flooring material (e.g., InterfaceFlor, Desso, Heugaveld), to fashion brands (united in the Sustainable Apparel Coalition), to other organizations (European Commission and the Dutch branch organization Modint). They are using LCA to calculate the environmental impacts of textile-related products. Also educational textile and fashion institutes (e.g., the Amsterdam Fashion Institute) are promoting life cycle thinking, picking up the signals from companies and other organizations. A literature survey [59] shows that Collins and Aumônier [60] compiled a LCI (Life Cycle Inventory) on textile products upon references dating from 1978 to 1999. Another research executed by Kalliala and Talvenmaa [61] reports, for example, spinning energy, which is derived from a study out of 1997. In-depth investigation on weaving led to the research of Koç and Çinçik [62]. In the recent work of Shen [63], non-renewable energy use for the production processes of different fabrics is given, based upon a report from 1997 [64].

Walser et al. [65] have published a LCA study using inventory data for polyester (PET) textile production. The authors also noticed that the data in the Ecoinvent database [66] on cotton and bast fibers do not specify the yarn size, which has an important influence on energy use.

Figure 6 presents the carbon footprint of cotton textiles and of synthetic textiles. In the case of cotton, different yarn thickness are taken into account. They are expressed on decitex (abbreviated dtex). In the case of synthetic textiles, only yarn thickness of 70 dtex is taken into account.

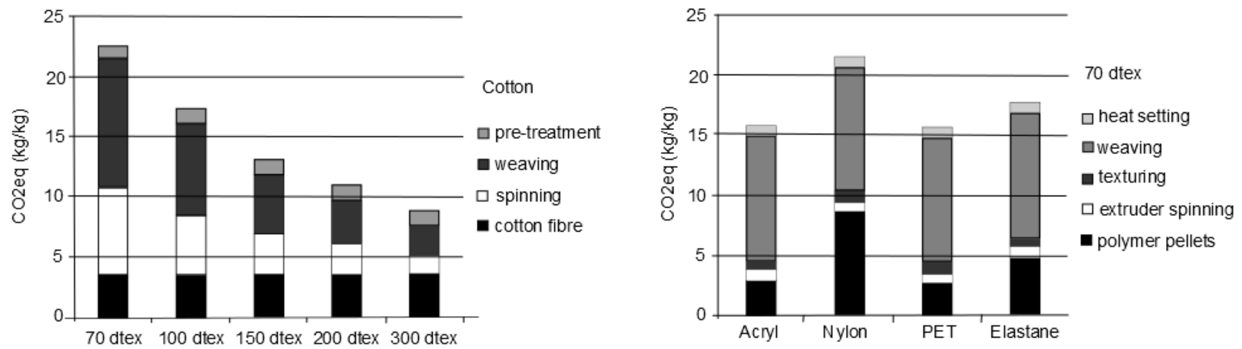

Figure 6. Carbon footprint of cotton textiles with yarn thickness comprised between 70 and 300 dtex (left) and synthetic textiles - acryl, nylon, PET, elastane-, with yarn thickness of 70 dtex (right) [59]

4.3. Carbon footprint in the cement industry

The cement industry is one of the sectors that contributes most to climate change, accounting for roughly 5% of the total CO_2 emissions worldwide [67]. Therefore reducing these emissions is a primary goal in order to comply with the objectives laid down in the Kyoto protocol to combat climate change. Currently, the cement industry, belonging to the WBSCD (World Business Council for Sustainable Development), has launched the Cement Sustainable Initiative program to meet the challenges of sustainable development. The carbon footprint is the most promising tool to evaluate the impact of carbon emissions of different products and can be an indicator to be used for eco-labeling. Several efforts have been made to develop it [68]. The study of Cagiao et al. [69] is based on the MC3 approach, also called organization-product-based-life-cycle assessment (OP-LCA). Given its top-down approach, this methodology first allows the organization's footprint to be calculated and then distributing it among the products that it manufactures. Some of the advantages are as follows:

a. It is a single methodology to be used both for organizations and products.

b. It uses all the financial accounts as input data.

c. The information flows automatically through the value chain.

d. The scope is always the same for all the analyses.

e. It is simple and easy-to-understand and adaptable.

f. Both the carbon footprint and the ecological footprint of the organization can be obtained [70-72].

The study of Cagiao et al. [69] was carried out with three potential scenarios in mind: case A pertaining to a conventional integral plant; case B which refers to a grinding plant; and case C, an integral plant which has been subject to the best available technical improvements. All the plants have the same productivity of 1,000,000 t/year. A summary of main results is proposed in Table 6.

Process	Emissions	Case
Carbon footprint of cement industry	1,003,555.2 tCO_2/year	Case A
	907,384.2 tCO2/year	Case B
	790,278.3 tCO2/year	Case C
Carbon footprint of one ton of cement	1.00 tCO2/tcement	Case A
	0.91 tCO2/tcement	Case B
	0.79 tCO2/tcement	Case C
Main parts of the carbon footprint produced	Direct emissions (75.33%) and wastes (17.98%)	Case A
	Materials (75.07%) and services (14.60%)	Case B
	Direct emissions (77.06%) and wastes (15.18%)	Case C
Reduction of total footprint by using BATs	213,276.9 tCO2/year (21.25% of initial carbon footprint)	

Table 6. Carbon footprint of cement production [69]

5. Product Carbon Footprint (PCF) case study

Fantozzi et al. [73] presents the study of the carbon footprint of a typical food product in Central Italy: truffle sauce. This is a mixture of vegetable oil and truffle in proportions of 33% and 67% respectively and minor components and spices (garlic, salt, pepper, etc.). Both truffles and olives are cultivated and harvested in a farm in Umbria (Italy). Olives are crushed in a mill that is situated few kilometers from the farm. Once it has been produced, the extra virgin oil, together with the truffle, is transported to another facility to produce bottled truffle sauce. The carbon footprint calculation is based on ISO 14076 technical standard. Product Category Rules (PCR) have been developed (see Table 7).

Stage	Rule	Description
Scope and functional unit	Scope	Calculate PCF of truffle sauce (expressed in kgCO_2eq/kg product)
	System boundary	Cultivation, transformation, packaging, and waste disposal are taken into account, while consumption is neglected
	Allocation	Allocation based on system expansion has to be preferred to allocation based on mass and economic value
Product definition	Truffle sauce	Truffle sauce is a mixture of vegetable oil and truffle in proportions of 33% and 67% respectively and minor components and spices (garlic, salt, pepper, etc.) that were not considered in the analysis
	LC stages	Cultivation; Milling; Truffle production; Transport; Sauce production
PCF calculation	Software	Simapro software was used to design process tree, and calculate PCF, based on the impact method GWP 100 years. Cut-off on processes impact is set to 1% to ease results view
	Data uncertainty	Data uncertainty was measured based on used instruments precision and on the uncertainty of Simapro datasets
Results communication	Label	A carbon footprint label was designed for the package

Table 7. Product Category Rules of truffle sauce [73]

The cut-off threshold on life cycle processes is about 1%. This decision is due to the need to simplify the process tree diagram. All the calculations are referred to the growing season 2011/2012.

The boundaries of the system analyzed are shown in Figure 7. Truffle sauce life cycle has been divided in the following product stages:

- cultivation;
- truffle production;
- truffle sauce production;
- packaging.

This is a clear example of a cradle-to-grave study, so GHG fluxes comprise also disposal of the packaging. The consumption phase is not considered in the study. The functional unit is 1 kg of truffle sauce.

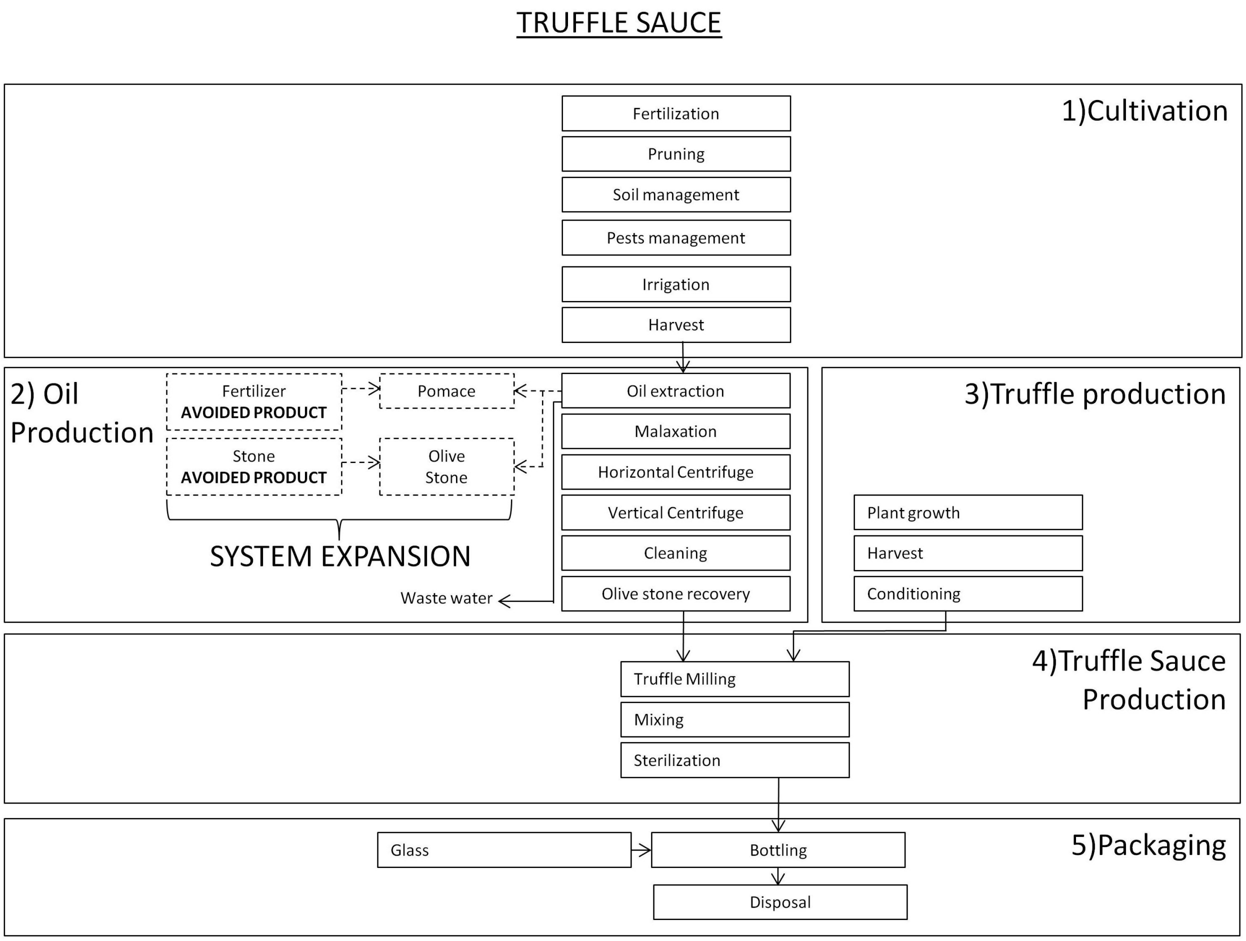

Figure 7. System boundaries [73]

Results of the analysis are proposed in Table 8. Cultivation gives an important contribution to the final impact of truffle sauce, while truffle production has a reduced impact, because it is a very extensive production. Olive trees cultivation uses fertilizers, diesel fuel for field operations, electricity for the olives harvest, herbicides and pesticides.

Life Cycle Stage	Contribution (kg CO_2eq/kg product)
1) Cultivation	0.94
2) Milling	0.28
3) Truffle production	0.09
4) Sauce production	0.06
5) Packaging production & disposal	0.77
6) Transport	0.03
7) Avoided emissionsAvoided fuel - Avoided fertilizer	0.18 0.02
Total	1.93

Table 8. Carbon footprint of truffle sauce [73]

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References

[1] Lash, J.; Wellington, F. Competitive advantage on a warming planet. Harv. Bus. Rev. 2007, 85 (3), 94–104.

[2] Hammond, G. Time to give due weight to the carbon footprint issue. Nature. 2007, 445 (7125), 256–256.

[3] Hertwich, E.; Peters, G. Carbon footprint of nations: A global, trade-linked analysis. Environ. Sci. Technol. 2009, 43, 6414–6420.

[4] ISO. ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework. International Organization for Standardization, Geneva, Switzerland, 2006a.

[5] ISO. ISO 14044: Environmental Management - Life Cycle Assessment - Requirements and Guidelines. International Organization for Standardization, Geneva, Switzerland, 2006b.

[6] ISO. ISO 14064-1: Greenhouse Gases - Part 1: Specification with Guidance at the Organization Level for Quantification and Reporting of Greenhouse Gas Emissions and

Removals. International Organization for Standardization, Geneva, Switzerland, 2006c.

[7] ISO. ISO 14064-2: Greenhouse Gases - Part 2: Specification with Guidance at the Project Level for Quantification, Monitoring and Reporting of greenhouse Gas Emission Reductions or Removal Enhancements. International Organization for Standardization, Geneva, Switzerland, 2006d.

[8] ISO. ISO 14064-3: Greenhouse Gases - Part 3: Specification with Guidance for the Validation and Verification of Greenhouse Gas Assertions. International Organization for Standardization, Geneva, Switzerland, 2006e.

[9] ISO. ISO/TS 14067: Greenhouse Gases e Carbon Footprint of Products e Requirements and Guidelines for Quantification and Communication. International Organization for Standardization, Geneva, Switzerland, 2013.

[10] BSI. PAS 2050:2011 Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services. British Standards Institution, London, 2011.

[11] Technical Guidance for calculating scope 3 emissions, World Resources Institute & World Business Council for Sustainable Development, 2013.

[12] Muthu, S.S. Assessment of Carbon Footprint in Different Industrial Sectors, Volume 1, Springer, 2014, ISBN 978-981-4560-40-5.

[13] Sheehan, J.; Camobreco, V.; Duffield, J.; Graboski, M.; Shapouri, H. Life cycle inventory of biodiesel and petroleum diesel in use in an urban bus. A report prepared for US Department of Agriculture and US Department of Energy, NREL/SR-580-24089 UC Category 1503, 1998.

[14] Sims, R.E.H.; Rogner, H.H.; Gregory K. Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. Energy Policy 2003, 31, 1315–1326.

[15] IEA. World Energy Outlook—1998 Update. International Energy Agency Report, IEA/OECD, Paris, France,1998.

[16] Glaeser, E L.; Kahn, M.E. The greenness of cities: Carbon dioxide emissions and urban development. J. Urban Econ. 2010,67, 404–418.

[17] http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,163182&_dad=portal&_schema=PORTAL.

[18] Johnson, E.P. Air-source heat pump carbon footprints: HFC impacts and comparison to other heat sources. Energy Policy. 2011,39, 1369–1381.

[19] IEA).I. E. A. World Energy Outlook 2011: Are We Entering a Golden Age of Gas?; International Energy Agency: Paris, 2011

[20] EIA. In Review of Emerging Resources: US Shale Gas and Shale Oil Plays. EIA, Ed.; Washington, DC, 2011, 4.

[21] EIA. Annual Energy Outlook 2011; US Energy Information Administration: Washington, DC, 2011.

[22] Deutch, J. The natural gas revolution and its consequences. Foreign Affairs 2011, 90 (1), 82-93.

[23] Thomas, C.K. The economic impact of shale gas extraction: A review of existing studies. Ecol. Econ. 2011, 70 (7), 1243-1249.

[24] Santoro, R.; Howarth, R.W.; Ingraffea, T. Life cycle greenhouse gas emissions inventory of Marcellus shale gas. Technical Report of the Agriculture, Energy, & Environment Program, Cornell University, Ithaca, NY, 2011. To be archived and made available on-line.

[25] Hayhoe, K.; Kheshgi, H.S.; Jain, A.K.; Wuebbles, D.J. Substitution of natural gas for coal: Climatic effects of utility sector emissions. Clim. Change. 2002, 54, 107–139.

[26] Wood, R.; Gilbert, P.; Sharmina, M.; Anderson, K.; Fottitt, A.; Glynn, S.; Nicholls, F. Shale Gas: A Provisional Assessment of Climate Change and Environmental Impacts. Tyndall Center, University of Manchester, Manchester, England, 2011. http://www.tyndall.ac.uk/sites/default/files/tyndallcoop_shale_gas_report_final.pdf.

[27] Howarth, R.W.; Santoro, R.; Ingraffea, A. Methane and the greenhouse-gas footprint of natural gas from shale formations. Clim. Change, 2011, 106, 679–690. DOI 10.1007/s10584-011-0061-5.

[28] Cherubini, F.; Bird, N.D.; Cowie, A.; Jungmeier, G.; Schlamadinger, B.; Woess-Gallasch, S. Energy- and Greenhouse Gas-based LCA of Biofuel and Bioenergy Systems: Key Issues, Ranges and Recommendations. Resou. Conser. Recy. 2009, 53, 434–447.

[29] Ackermann, T.; Garner, K.; Gardiner, A. Wind power generation in weak grids—economic optimisation and power quality simulation. Proceedings of the World Renewable Energy Congress, Perth, Australia, Murdoch University, 1999. pp. 527–532, ISBN 0-86905-695-6.

[30] EWEA Wind Energy—The Facts European Wind Energy Association. Report Prepared for the Directorate-General XVII Energy, European Commission, 1999.

[31] EPRI/DOE Renewable Energy Technology Characterizations. Electric Power Research Institute and US Department of Energy, Report EPRI TR-109496,December, 1997.

[32] KPMG. Solar Energy—From Perennial Promise to Competitive Alternative. Project Number 562. KPMG Bureau voor Economische Argumentatie,. Hoofddorp, Netherlands, 1999, p. 61.

[33] Neij, L. Use of experience curves to analyze the prospects for diffusion and adoption of renewable energy technology. Energy Policy, 1997, 23, 1099–1107.

[34] AGO, Australian Greenhouse Office. Renewable Energy Showcase Projects. Australian Greenhouse Office, Canberra, 1998. www.greenhouse.gov.au/renewable/renew3.html.

[35] Lund, H.; Moller, B.; Mathiesen, B.V.; Dyrelund, A. The role of district heating in future renewable energy systems. Energy 2010, 35, 1381–1390.

[36] EC. Environmental Impact of Products (EIPRO): Analysis of the Life Cycle Environmental Impacts Related to the Total Final Consumption of the EU 25. European Commission Technical Report EUR 22284 EN, 2006.

[37] SEPA. Konsumtionens klimatpåverkan (The Climate Impact of Consumption). Report No 5903. Swedish Environmental Protection Agency, Stockholm, 2008.

[38] Garnett, T. Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? Food Pol.2011, 36, 23–32.

[39] IPCC. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 2007.

[40] Tesco. Product carbon footprint summary. 2012. http://www.tescoplc.com/assets/files/cms/ Tesco_Product_Carbon_Footprints_ Summary(1).pdf. Accessed 22 May 2013.

[41] Lantmännen. Klimatdeklarationer. (Climate Declarations). 2013. http://lantmannen.se/omlantmannen/press–media/publikationer/klimatdeklarationer/. Accessed 16 May 2013.

[42] MAX. Klimatdeklaration (Climate Declaration). 2013. http://max.se/sv/Maten/Klimatdeklaration/. Accessed 22 May 2013.

[43] Roy, P.; Nei, D.; Orikasa, T. et al. A review of life cycle assessment (LCA) on some food products. J. Food Eng. 2009, 90, 1–10.

[44] de Vries, M.; de Boer, I.J.M. Comparing environmental impacts for livestock products: A review of life cycle assessments. Livestock Sci. 2010, 128, 1–11.

[45] Nijdam, D.; Rood, T.; Westhoek, H. The price of protein: review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. Food Pol. 2012, 37, 760–770.

[46] Röös, E.; Sundberg, C.; Tidåker, P.; Strid, I.; Hansson, P.-A. Can carbon footprint serve as an indicator of the environmental impact of meat production? Ecol. Ind. 2013, 24, 573–581.

[47] Röös, E. Mat-klimat-listan Version 1.0 (The Food-Climate-List Version 1.0) Report 2012:040. Department of Energy and Technology, Swedish University of Agricultural Sciences, Uppsala, 2012.

[48] Beauchemin, K.; Kreuzer, M.; O'Mara,C.; McAllister, T. Nutritional management for enteric methane abatement: A review. Aust. J. Exp. Agri. 2008, 48, 21–27.

[49] Shibata, M.; Terada, F. Factors affecting methane production and mitigation in ruminants. Anim. Sci. J. 2010, 81, 2–10.

[50] Flysjö, A. Greenhouse Gas Emissions in Milk and Dairy Product Chains—Improving the Carbon Footprint of Dairy Products. Dissertation, Aarhus University, 2012.

[51] Beddington, J.; Asaduzzaman, M.; Fernandez, A.; et al. Achieving Food Security in the Face of Climate Change: Summary for Policy Makers from the Commission on Sustainable Agriculture and Climate Change. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, 2011.

[52] Foley, J.; Ramankutty, N.; Brauman, K.A.; et al. Solutions for a cultivated planet. Nature 2011, 478, 337–342.

[53] Foresight. The Future of Food and Farming. Executive Summary. The Government Office for Science, London, 2011.

[54] SBA. Ett klimatvänligt jordbruk 2050 (Climate Friendly Agriculture 2050). Report 2050:35. Swedish Board of Agriculture, Jönköping, 2012.

[55] Ahlgren, S. Crop Production Without Fossil Fuel. Production Systems for Tractor Fuel and Mineral Nitrogen Based on Biomass. Dissertation, Swedish University of Agricultural Sciences, 2009.

[56] Thomassen, M.; Dalgaard, R.; Heijungs, R.; de Boer, I. Attributional and consequential LCA of milk production. Int. J. LCA 2008, 13, 339–349.

[57] Strid, E.I.; Elmquist, H.; Stern, S.; Nybrant, T. Environmental systems analysis of pig production. The impact of feed choice. Int. J. LCA 2005, 10, 143–154.

[58] Pelletier, N.; Pirog, R.; Rasmussen, R. Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. Agri. Syst. 2010, 103, 380–389.

[59] van der Velden, N.M.; Patel, M.K.; Vogtländer, J.G. LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. Int. J. LCA 2014, 19, 331–356. DOI 10.1007/s11367-013-0626-9.

[60] Collins, M.; Aumônier, S. Streamlined Life Cycle Assessment of Two Marks & Spencer Plc Apparel Products. Environmental Resources Management, Oxford, 2002.

[61] Kalliala, E.; Talvenmaa, P. Environmental profile of textile wet processing in Finland. J. Clean. Prod. 1999, 8, 143–154.

[62] Koç, E.; Çinçik, E. Analysis of energy consumption in woven fabric production. Fibres Text East Eur. 2010, 18 (79), 14–20.

[63] Shen, L. Bio-based and Recycled Polymers for Cleaner Production— An Assessment of Plastics and Fibres. Ph.D. Thesis, Department of Science, Technology and Society (STS)/Copernicus Institute, Utrecht University, 2011.

[64] Laursen, S.E.; Hansen, J.; et al. Environmental Assessment of Textiles. Environmental Project No. 369, Danish Environmental Protection Agency, 1997.

[65] Walser, T.; Demou, E.; Lang, D.J.; Hellweg, S. Prospective environmental life cycle assessment of nanosilver T-shirts. Environ. Sci. Technol. 2011, 45 (10), 4570–4578.

[66] Ecoinvent. Database Ecoinvent Version v2.2. The Swiss Centre for Life Cycle Inventories, 2010.

[67] Humphreys, K.; Mahasenan, M. Towards a Sustainable Cement Industry – Substudy 8: Climate Change. World Business Council for Sustainable Development: Cement Sustainability Initiative, 2002.

[68] Schneider, H.Y.; Samaniego, J. La huella del carbono en la producción, distribución y consumo de bienes y servicios. Naciones Unidas, CEPAL, Santiago de Chile, 2009, 46 pp.

[69] Cagiao, J.; Gómez, B.; Doménech, J.L.; Gutiérrez Mainar, S.; Gutiérrez Lanza, H. Calculation of the corporate carbon footprint of the cement industry by the application of MC3 methodology. Ecol. Indic. 2011, 11, 1526–1540.

[70] Doménech, J.L. La huella ecológica empresarial: el caso del puerto de Gijón. In: Actas de él VII Congreso Nacional de Medio Ambiente, 22–26 Noviembre, Madrid, 2004.

[71] Doménech, J.L. Huella ecológica y desarrollo sostenible. In: AENOR Ediciones, Madrid, 2007.

[72] Carballo Penela, A.; García-Negro, M.C.; Doménech, J.E. A methodological proposal for the corporate carbon footprint: an application to a wine producer company in Galicia (Spain). Sust. J. 2009, 1, 302–318.

[73] Fantozzi, F.; Bartocci, P.; D'Alessandro, B.; Testarmata, F.; Fantozzi P. Carbon footprint of truffle sauce in central Italy by direct measurement of energy consumption of different olive harvesting techniques. J. Clean. Prod. 2015, 87, 188-196.