Masters thesis
Two years

Environmental sciences

A fossil-free Sweden in 2050 and the impact on Swedish emissions
A consumption-based scenarios approach

Chris Celis

Mittuniversitetet
MID SWEDEN UNIVERSITY

Campus Härnösand Universitetsbacken 1, SE-871 88. **Campus Sundsvall** Holmgatan 10, SE-851 70 Sundsvall.
Campus Östersund Kunskapens väg 8, SE-831 25 Östersund.
Phone: +46 (0)771 97 50 00, Fax: +46 (0)771 97 50 01.

MID SWEDEN UNIVERSITY
Ecotechnology and Sustainable Building Engineering

Examiner: Anders Jonsson, anders.jonsson@miun.se

Supervisor: Erik Grönlund, erik.gronlund@miun.se

Author: Chris Celis, chris.celis@gmail.com

Degree programme: International Masters Programme in Ecotechnology & Sustainable Development, 120 credits

Main field of study: Environmental sciences

Semester, year: VT, 2020

Abstract

Sweden has the goal to reduce greenhouse gas emissions without increasing emissions abroad. This study uses consumption-based emissions data from the PRINCE-project to show where emissions from Swedish consumption take place and how large the share of fossil fuel emissions is. Scenarios are made to compare the emission reductions from reducing the use of fossil fuels to the potential for emission reductions by changes in consumption patterns for three main consumption groups, food, buildings & construction, and transport. These three consumption groups represent 67 % of the Swedish consumption-based emissions. The results show that Sweden has limited though still significant impact on consumption-based emissions since most emissions take place outside Sweden. For the three main consumption groups, it is shown that changing consumption patterns has the same potential for reducing the emissions than completely ending the use of fossil fuels in Sweden. Large differences exist between the consumption groups. Ending the use of fossil fuels in Sweden would reduce emissions from food by 21 %, from buildings & construction by 50 % and from transport by 27 %. It can be concluded that if Sweden wants to lower their emissions from consumption, it is important to take measures at both national and international level. Focusing on both reducing fossil fuel use as well as changes in consumption patterns prove to be equally important and should be taken simultaneously to achieve the largest and fastest emissions reductions.

Keywords: Consumption-based emissions, Sweden, emission scenarios

Table of contents

1 Introduction 1
1.1 Sweden's climate and emission goals 1
1.2 Emissions accounting 2
1.2.1 Production-based emissions accounting 2
1.2.2 Consumption-based emissions accounting 3
1.2.3 Previous work 3
1.3 Purpose 4
1.4 Objectives 4
1.4.1 Scope 4
2 Materials and methods 4
2.1 Consumption-based emissions data 4
2.2 Consumption groups and consumer categories 5
2.3 Scenarios 6
2.3.1 Energy mix 6
2.3.2 Food consumption emission scenarios 6
2.3.3 Buildings & construction 8
2.3.4 Transport 10
2.3.5 Public services 11
2.3.6 Clothing 12
2.3.7 Steel, metal, and machinery activities 12
2.3.8 Petroleum, plastic, and chemical activities 12
2.3.9 Electronics, IT & communications, cultural, sports and religious activities 13
3 Results 13
3.1 Consumption-based greenhouse gas emissions per capita in Sweden 13
3.2 Share of fossil CO_2 in total GHG emissions from Swedish consumption 14
3.3 Food scenarios 16
3.4 Buildings & construction scenarios 17
3.5 Transport scenarios 18
3.6 Results other consumption groups 19

4 Discussion 20
4.1 Methods and scenarios 20
4.1.1 Consumption groups 20
4.1.2 Emissions data 20
4.1.3 Electricity mix and biofuels availability 21
4.1.4 Scenarios 23
4.2 Overall emissions 23
4.3 Food consumption 24
4.4 Buildings & construction activities 25
4.5 Transport activities 25
5 Conclusions 26
6 Future research 27
7 Literature list 28
Appendix 31

1 Introduction

It is estimated that anthropogenic effects, so far, caused around 1° - 1.1°C of global warming compared to pre-industrial levels (IPCC, 2018; UNEP, 2019). Across Europe, the temperature increase is almost 2°C since the second half of the 19th century. The last five year average global temperature, from 2014 to 2018, is the highest on record (ECMWF, 2019). At the current pace of 0.2°C per decade, it is likely that 1.5°C of global warming is reached between 2030 and 2052 (IPCC, 2018). In the Paris Agreement of 2015, the signing countries agreed to take appropriate actions to keep global warming below 2°C above pre-industrial levels and to pursue limiting global warming to 1.5°C. Based on the global temperature targets set out in the Paris Agreement, each country develops nationally determined contributions (NDCs) that embody the efforts to reduce national emissions and adapt to the impacts of climate change (UNFCCC, 2019).

1.1 Sweden's climate and emission goals

Next to the NDCs that Sweden commits itself to in the Paris Agreement, Sweden also has its own climate and emission targets. For this, the Swedish Government introduced the "environmental objectives system" that consists of three parts: the generational goal, the national environmental objectives, and the milestone targets. With its generational goal, set in 2010, Sweden sets the overall objective of environmental policy to *"hand over to the next generation a society in which the major environmental problems have been solved, without increasing environmental and health problems outside Sweden"* (Naturvårdsverket, 2018). With this, the Swedish Government intends to guide environmental actions taken on every level of society towards achieving a clean and healthy environment. It connects environmental efforts on recovery of ecosystems, conserving biodiversity and the natural and cultural environment, good human health, efficient material cycles free from dangerous substances, sustainable use of natural resources, efficient energy use, and patterns of consumption. The 16 national environmental quality objectives cover different areas such as unpolluted air and lakes free from eutrophication and acidification, to functioning forest and farmland ecosystems. For each of the 16 objectives, there are specifications regarding the desired environmental state. The climate change objective is defined as follows: *"In accordance with the UN Framework Convention on Climate Change, concentrations of greenhouse gases in the atmosphere must be stabilised at a level that will prevent dangerous anthropogenic interference with the climate system. This goal must be achieved in such a way and at such a pace that biological diversity is preserved, food production is assured, and other goals of sustainable development are not jeopardised. Sweden, together with other countries, must assume responsibility for achieving this global objective"* (Naturvårdsverket, 2018, p. 9). The third part of the environmental objectives system are the milestone targets. They identify the desired social changes and the steps that need to be taken to achieve the generational goals within the timeline that is set out. The milestone targets cover five areas: reduced climate impact, air pollution, biodiversity, dangerous substances, sustainable urban development, and waste. For reduced climate impact, the milestones are (Naturvårdsverket, 2019a, p. 1) (Naturvårdsverket, 2019c, p. 1):

- 40 % less emissions by 2020 compared to 1990 (activities outside EU ETS)
- 63 % less emissions by 2030, 70 % less emissions from domestic transport (excluding domestic aviation since it is in the EU ETS)
- 75 % less emissions by 2040
- 85 % less emissions by 2045, zero net emissions of GHGs
- Negative emissions after 2045

In 2017, Sweden has adopted a Climate Act and the Climate Policy Framework in their efforts to achieve the goal of reaching net-zero emissions by 2045 and net negative emissions after that. The Climate Policy Framework is meant to provide long term climate policy that is clear and coherent towards the market and other stakeholders. The Climate Policy Framework contains a Climate Act, climate targets and a climate policy council. The Climate Act states that the government's climate policies must be based on the climate targets and the government shall present a climate report in the yearly Budget Bill, make a climate policy action plan, every four years, that describes how the climate targets shall be achieved and assure the climate policy goals and budget policy goals work together. The climate policy council is an interdisciplinary expert body that oversees that the Government's policies are compatible with the national climate targets. The council makes a yearly progress report with the current emission trends and the work that has been done to address climate change (Naturvårdsverket, 2019a). Supplementary measures like increased carbon uptake in forests, verified emission reductions outside Swedish borders and carbon capture and storage based on biomass combustion (bio-CCS) can be used to achieve the national goal of net-zero emissions (Naturvårdsverket, 2019a). The currently decided and planned policy instruments are insufficient to achieve the reduced climate impact objective stated in the 16 environmental objectives (Naturvårdsverket, 2019b).

1.2 Emissions accounting

Keeping track of current emissions and the progress towards the goals that are set by the Swedish Government, the European Union or in agreements like the Paris Agreement, needs a well-structured and uniform emissions accounting system. This is also necessary for developing and implementing climate mitigation policies (Chen et al., 2018). There are two main types of national emissions accounting, production-based and consumption-based accounting, each has its own purpose, boundaries and accompanying strengths and weaknesses.

1.2.1 Production-based emissions accounting

Production-based, also called, territorial-based emissions accounting includes greenhouse gas (GHG) emissions and uptakes that take place within the national territory, including offshore areas over which the country has jurisdiction. Emissions from international shipping and air transport are not included in the national accounts, they are reported separately in reporting to the IPCC. Emissions from road transport and fishing activities are assigned to the country where the fuel was sold (IPCC, 2006). Production-based emissions accounting is used in the national inventories, international treaties and in reporting to the United Nations Framework Convention on Climate Change (UNFCCC). Reporting to the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories is also done using these according these emissions accounting principles. High income countries such as Sweden import more than thirty percent of all consumed products. This adds up to more than four tonnes of CO_2 per capita that is not accounted for when using production-based emissions accounting methods (Davis & Caldeira, 2010). In reporting under the Kyoto protocol, emissions from international aviation and international shipping also aren’t allocated to any country (Larsson, Kamb, Nässén, & Åkerman, 2018). Using the production-based emissions accounting method, Sweden could theoretically lower their emissions by importing more. Thereby moving emissions caused by consumption in Sweden to other countries. If emissions in one country grow because of production or consumption in another, it is called a spillover effect (Moran, Wood, & Rodrigues, 2017). These spillovers would be contrary to their goal of not increasing environmental and health problems outside Sweden. Keeping in mind that the technologies in developing countries are often less efficient and there is less regulation regarding emissions, the total emissions can be even higher because of this. This effect of displaced emissions is called carbon leakage (Franzen & Mader, 2018). Another effect is that national measures to curb emissions are not effective because the source of the emissions lies out of control of the Swedish Government. Referring to the emission reduction targets that Sweden has set for itself, including the condition of not causing extra emissions elsewhere in the world, it can be concluded that territorial- i.e. production-based emissions accounting is not sufficient (Moran et al., 2017).

1.2.2 Consumption-based emissions accounting

Consumption-based emissions accounting allocates the emissions to the geographic area where the goods and services are finally consumed. In consumption-based accounting, the emissions caused by the production of goods and services that originate in other countries are included in the emissions of the country where the final consumption takes place. Emissions embodied in products and services that are exported are subtracted. This accounting method visualizes the actual emissions that are caused by consumption in a geographic region, instead of merely accounting emissions occurring in that region. Consumption-based CO_2 emissions accounting includes the spillover effects of carbon intensive production moving, often to less regulated countries with more carbon intensive energy production (Franzen & Mader, 2018).

To establish efficient policies that steer the Swedish society towards zero net emissions without increasing emissions abroad, hidden emissions due to import must be included.

1.2.3 Previous work

The PRINCE project was organised, set up by the Swedish statistics bureau in collaboration with several Swedish and non-Swedish universities, to provide a framework for calculating the environmental impact due to Swedish consumption. This resulted in detailed emissions data, that is used in this study. The products and services, consumed in Sweden, that cause the largest emissions and the geographical spread of the emissions are identified in Fauré et. al (2019). Further work has been done by Fauré, Finnveden and Gunnarsson-Östling (2019), scenarios were created wherein Sweden achieves a low-carbon society in 2050.

1.3 Purpose

This report can support decisionmakers in developing long-term strategies for lowering GHG emissions from Swedish consumption. It can show which changes in consumption patterns achieve the highest emissions reductions.

1.4 Objectives

In this study, scenarios will be developed that show how ending the use of fossil fuels has an impact on Swedish consumption-based emissions, and this for all main consumption groups. The effects of ending the use of fossil fuels will also be compared to changes in consumption behaviour for three important consumption categories being food, buildings & construction, transport.

1.4.1 Scope

This study is limited to emissions from Swedish consumption and is based on emissions data of the years 2008 – 2014.

2 Materials and methods

2.1 Consumption-based emissions data

Swedish consumption-based emissions were extracted from the PRINCE database and are presented in result section 1 (3.1). The PRINCE model was constructed according a framework that was developed for the Swedish Environmental Protection Agency and the Swedish Agency for Marine and Water Management. It was developed to provide Policy-Relevant Indicators for National Consumption and Environment (PRINCE). PRINCE is a hybrid model that combines a global environmentally extended multi-regional input-output model (EE-MRIO) shown in Figure 1, with the detailed Swedish national environmental accounts. The Swedish Standard Industrial Classification (SNI), based on the industry standard classification system used by the European Union, NACE Rev.2, is primarily an activity classification system. Production units, such as companies and local units, are classified based on the type of activity carried out at the unit. A company or local unit can encompass several different types of activities (SNI codes). A list with the SNI codes can be found in 0. To model emissions caused by imported products, the financial import data is coupled to the Environmentally Extended Multi-Regional Input-Output (EE-MRIO) EXIOBASE. Multipliers describe the environmental impact of imported goods and services per product group and per country/region. The imported monetary value of each product group is then multiplied by the environmental impact or emissions per monetary value to become the total environmental impact/emissions for that imported product group.

Calculating emissions from Swedish consumption can be simplified to:

Domestic emissions = (emission intensity domestically produced goods * quantity used for domestic consumption) + direct household emissions

Environmental impact from imported products:

Emissions abroad due to SE consumption = emission intensity goods country X * quantity used for domestic consumption

Quantity of goods used for domestic consumption = total import - total export

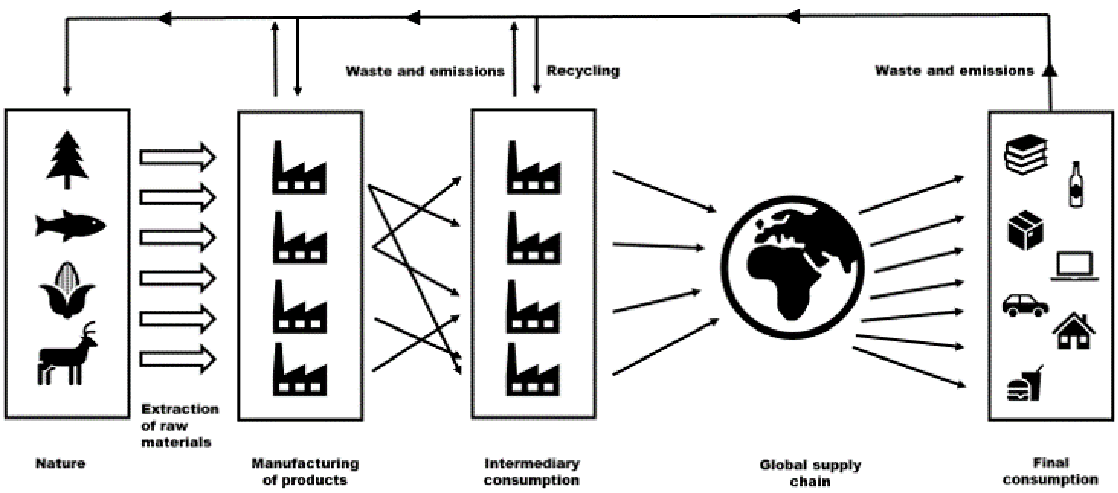


Figure 1: Schematic image of an environmentally-extended input-output model, reproduced based on (Steinbach et al., 2018)

2.2 Consumption groups and consumer categories

The PRINCE database uses the SNI product classification that comprises fifty different product categories. The SNI consumption categories were divided into consumption groups. Food, Buildings & construction, transport and clothing consumption were grouped according the classification used in (Fauré, Finnveden, et al., 2019). All other consumption groups are compiled at own discretion, according the name of the SNI code. The composition of the consumption groups can be found in Appendix C. The database contains data on three consumption categories: consumption by households, governments and by capital formation but in this study, no distinction is made between final consumer categories since this is of less importance when showing overall emissions scenarios.

To calculate the emissions per capita, the absolute emissions are divided by the corresponding population number of those years as found in the national statistics (SCB, 2019).

2.3 Scenarios

For each of the consumption groups there are three basic scenarios of which the impact on Swedish consumption-based emissions will be assessed. The three scenarios are: Sweden becomes fossil-free, Europe (EU includes Switzerland & Norway in this study) becomes fossil-free and the whole world becomes fossil free. For consumption of food, buildings & construction and transport more scenarios have been made. These are described in more detail in sections 2.3.2, 2.3.3 and 2.3.4. The results are presented in a cumulative manner. This means that the scenarios amplify each other instead of merely showing the effect of a single scenario.

2.3.1 Energy mix

Energy provided by fossil fuels will have to be replaced by energy from renewable sources. A mix of renewable energy technologies will be used, depending on the application and sector. The technologies that supply renewable electricity differ per region, depending on the availability (Figure 2). For Sweden, the wind power focused 100 % renewable electricity scenario from the Swedish Energy Agency (2019) is used to determine the electricity mix, except for the 8 % electricity from biomass in that scenario which is divided over the other renewable technologies . The electricity mixes for Europe and the rest of the world are based on scenarios made by Haller, Ludig, Bauer (2012), Solar power Europe and LUT University (2020), and Pleßmann, Blechinger (2016). The emission factors of each mix can be found in appendix A.

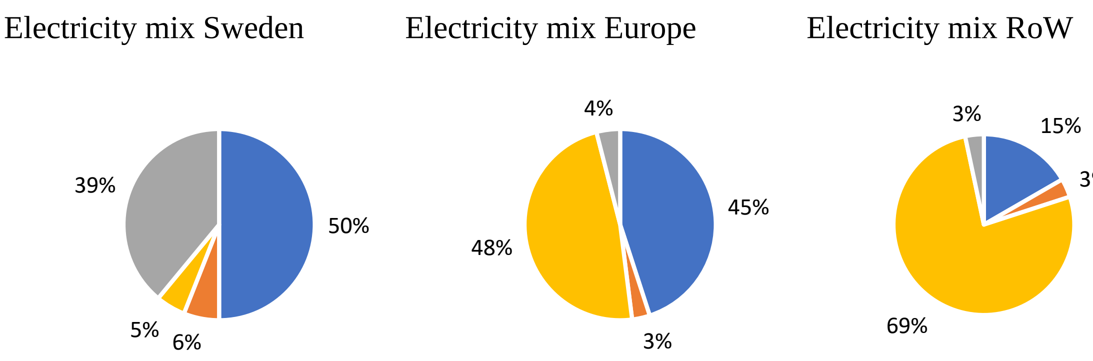


Figure 2: Electricity mix per region, in share of generated electricity

Solar PV Onshore wind Offshore wind Hydro

2.3.2 Food consumption emission scenarios

There are 5 food scenarios, each having several sub-scenarios. In all scenarios where fossil fuels are removed, fossil-based energy inputs are replaced by 50 % energy from renewable electricity and 50 % from biofuel. The emissions relating to renewable electricity are calculated according the region-specific emissions for electricity that are mentioned in the electricity scenarios. The scenarios with 50 lower consumption of animal products and the 100 % plant-based scenario lower the methane emissions by respectively 50 % and 100 %

assuming animal husbandry causes all methane emissions in Swedish and European agriculture (Milne et al., 2014). Methane emissions from agricultural products coming from outside Europe are lowered by respectively 40 % and 80 % because methane emissions from enteric fermentation are assumed to cause approximately 80 % of the methane emissions from agriculture worldwide, with the rest being caused by rice production (FAO, 2014). N_2O emissions are not taken into account in this study, but these are significant. The degree to which they are caused by animal husbandry is much lower since most of the N_2O emissions come from soils and heavily associated with the use of synthetic fertilizers and animal manure for soil fertilization (Smith et al., 2007). In the 32.5 % more efficient scenario it is assumed that a combination of reductions in food waste and higher yields together with improved efficiency in production methods will cause the production to lower by 32.5 %. To what extent the individual factors contribute to the efficiency gains is not decided. The combination scenario combines the 100 % plant-based and the 32.5 % higher efficiency scenarios, in each of the fossil fuel reduction scenarios.

Table 1: Food consumption scenarios. Fossil reduction scenarios and consumption pattern scenarios are

1a	Fossil fuel use as normal 50 % lower consumption of animal products	- Food consumption related methane emissions are removed o 50 % of methane emissions in SE and EU o 40 % of methane emissions in the rest of the world
1b	Fossil fuel use as normal 100 % plant-based diet	- Food consumption related methane emissions are removed o 100 % of methane emissions in SE and EU o 80 % of methane emissions in the rest of the world
1c	Fossil fuel use as normal 32.5% higher efficiency	- Overall emissions are lowered by 32.5 %
1d	Combination	- Scenarios 1b and 1c are combined
2a	Sweden is fossil free No dietary changes	- Swedish fossil CO_2 emissions from the food consumption group are removed - 50 % of the fossil fuel-derived energy use is replaced by the Swedish electricity mix and related emissions - 50 % of the fossil fuel-derived energy use is replaced by biofuel and related emissions
2b	Sweden is fossil free 50 % lower consumption of animal products	- Scenario 2a - Food consumption related methane emissions are removed o 50 % of methane emissions in SE and EU o 40 % of methane emissions in the rest of the world
2c	Sweden is fossil free 100 % plant-based diet	- Scenario 2a - Food consumption related methane emissions are removed o 100 % of methane emissions in SE and EU o 80 % of methane emissions in the rest of the world
2d	Sweden is fossil free 32.5 % higher efficiency	- Scenario 2a - Overall emissions are lowered by 32.5 %
2d	Combination	- Scenario 2a - 100 % plant-based - 32.5 % higher efficiency

3a	The EU is fossil free No dietary changes	- All fossil CO_2 emissions in Sweden and the EU, from the food consumption group are removed - 50 % of the fossil fuel-derived energy use is replaced by electricity mix and related emissions - 50 % of the fossil fuel-derived energy use is replaced by biofuel and related emissions
3b	The EU is fossil free 50 % lower consumption of animal products	- Scenario 3a - Food consumption related methane emissions are removed o 50 % of methane emissions in SE and EU o 40 % of methane emissions in the rest of the world
3c	The EU is fossil free 100 % plant-based diet	- Scenario 3a - Food consumption related methane emissions are removed o 100 % of methane emissions in SE and EU o 80 % of methane emissions in the rest of the world
3d	The EU is fossil free 32.5 % higher efficiency	- Scenario 3a - Overall emissions are lowered by 32.5 %
3d	Combination	- Scenario 3a - 100 % plant-based - 32.5 % higher efficiency
4a	World is fossil free No dietary changes	- All fossil CO_2 emissions related to food consumption in Sweden are removed - 50 % of the fossil- and biofuel-derived energy use is replaced by electricity mix and related emissions - 50 % of the fossil- and biofuel-derived energy use is replaced by biofuel and related emissions
4b	World is fossil free 50 % lower consumption of animal products	- Food consumption related methane emissions are removed o 50 % of methane emissions in SE and EU o 40 % of methane emissions in the rest of the world
4b	World is fossil free 100 % plant-based diet	- Scenario 4a - Food consumption related methane emissions are removed o 100 % of methane emissions in SE and EU o 80 % of methane emissions in the rest of the world
4c	World is fossil free 32.5 % higher efficiency	- Scenario 4a - Overall emissions are lowered by 32.5 %
4d	Combination	- Scenario 4a - 100 % plant-based - 32.5 % higher efficiency

2.3.3 Buildings & construction

The building & construction scenarios follow the same main structure where the separate and cumulative impact of consumption pattern changes and eliminating the use of fossil fuels in Sweden, the EU and the rest of the world is modelled. For each of the three scenarios an additional scenario is made to model the effect of reducing the use-phase energy demand of buildings by 50 percent, and one that models a reduction of the total energy demand (use-phase + emissions embodied in materials). This assumption is based on a continuation of efforts to further improve beyond the energy efficiency targets the EU has set for achieving 32.5 percent efficiency gains by the year 2030 (European Commission, 2018). Heat pumps can contribute to lower energy use for heating. Changes in building materials (e.g. wooden instead of concrete building frames) and innovation is assumed to provide lower emissions from materials (e.g. fossil free steel and cement) (European Commission, 2019b; Nässén, Hedenus, Karlsson, & Holmberg, 2012). It is assumed that all emissions are caused by energy. All fossil energy will be replaced by the scenario electricity mix of the region where the energy is used.

Table 2: Building & construction scenarios

1a	Fossil fuel use as normal 50 % lower energy need use phase buildings	- The energy use allocated to direct heating, electricity, gas, and heat is lowered by 50 % and replaced by SE electricity mix and related emissions
1b	Fossil fuel use as normal 50 % overall efficiency improvement (materials + use phase)	- 50 % of the fossil CO_2 and CO_2-eq methane emissions are removed, half of the fossil-based energy is replaced by electricity
2a	Sweden is fossil free	- All fossil CO_2 and CO_2-eq emissions from methane that take place in Sweden are removed - The energy use is completely replaced by electricity mix and related emissions
2b	Sweden is fossil free 50 % lower energy need use phase buildings	- Scenario 2a - The energy use allocated to direct heating, electricity, gas, and heat is lowered by 50 %
2c	Sweden is fossil free 50 % overall efficiency improvement (materials + use phase)	- Scenario 2a - Overall energy use is lowered by 50 %, this includes all energy used for the buildings and construction sector in Sweden
3a	The EU is fossil free	- All fossil CO_2 and CO_2-eq emissions from methane that take place in Sweden and the EU are removed - The energy use is completely replaced by electricity of the Sweden/EU mix and related emissions
3b	The EU is fossil free 50 % lower energy need use phase buildings	- Scenario 3a - The energy use allocated to direct heating, electricity, gas, and heat is lowered by 50 %
3c	50 % overall efficiency improvement (materials + use phase)	- Scenario 3a - Overall energy use is lowered by 50 %, this includes all energy used for buildings and construction sectors in Sweden.
4a	World is fossil free	- All fossil CO_2 and CO_2-eq emissions from methane are removed - The energy use is completely replaced by electricity of the Sweden/EU/RoW mix and related emissions
4b	World is fossil free	- Scenario 4a

	50 % lower energy need buildings	- The energy use allocated to direct heating, electricity, gas, and heat is lowered by 50 %
4c	50 % overall efficiency improvement (materials + use phase)	- Scenario 4a - Overall energy use is lowered by 50 %, this includes all energy used for buildings and construction sectors in Sweden

2.3.4 Transport

All road vehicles switch to battery-electric vehicles (BEV) in the transport scenarios. Transport over water and via air switch to biofuels. The three main scenarios eliminate the use of fossil fuels subsequently in Sweden, the EU, and the whole world. Two scenarios that show the impact of consumption behaviour changes on emissions are included: A reduction of road transport by 20 percent and completely stopping the use of domestic air transport. In both cases, the transport is moved to transport by train so that there is no reduction in the amount of transported goods and persons, only a switch in modes of transport.

Table 3: Transport scenarios

1a	Fossil fuel use as normal 20 % less road transport	- 20 % of all motorized road transport in Sweden is moved to transport by train
1b	Fossil fuel use as normal No domestic air travel	- All domestic air transport in Sweden is replaced by transport by train
2a	Sweden is fossil free	- All road transport switches to BEV - Water transport switches to biofuel - Air transport switches to biofuel
2b	Sweden is fossil free 20 % less road transport	- Scenario 2a - 20 % of all motorized road transport in Sweden is moved to transport by train
2c	Sweden is fossil free No domestic air travel	- Scenario 2a - All domestic air transport in Sweden is replaced by transport by train
3a	Europe is fossil free	- Scenario 2a - The European supply chain is electrified and runs on the EU scenario electricity mix
3b	Europe is fossil free 20 % less road transport in SE	- Scenario 3a - 20 % of all motorized road transport in Sweden is moved to transport by train
3c	Europe is fossil free No domestic air travel in SE	- Scenario 3a - All domestic air travel in Sweden is moved to transport by train
4a	World is fossil free	- Scenario 3a - The global supply chain is electrified and runs on the RoW scenario electricity mix

4b	World is fossil free 20 % less road transport in SE	- Scenario 4a - 20 % of all motorized road transport in Sweden is moved to transport by train
4c	World is fossil free No domestic air travel in SE	- Scenario 4a - All domestic air travel in Sweden is moved to transport by train

2.3.5 Public services

The public services group comprises educational, social care, health care and public services as well as defence activities. The main scenario structure is used where all fossil emissions related to the activities are removed and replaced by emissions related to producing the renewable electricity that is needed to replace the fossil energy. First for Sweden, then the rest of the European Union and as last the scenario where the whole world made the switch to renewable energy. An exception is made for the defence and public services where the fossil energy used in Sweden is replaced by biofuel-based energy and accompanying emissions. The reasoning behind this is that direct fuel use of the military is included in these emissions and that this might be difficult to replace by electricity.

Table 4: Public services scenarios

1.	Sweden is fossil free	- All activities except defence and public services are electrified, the energy delivered by fossil fuels is replaced by electricity from the Swedish electricity mix - Fossil energy used in Sweden, for defence and public services, is replaced by energy from biofuels
2.	Europe is fossil free	- All fossil fuel emissions that are emitted in the rest of Europe* because of the supply of goods for the public services group are removed - The fossil-based energy is replaced by electric energy with according emissions
3.	World is fossil free	- All fossil fuel emissions that are emitted because of the supply of goods for the public services group are removed - The fossil-based energy is replaced by electric energy with according emissions

2.3.6 Clothing

In the product group clothing, only manufacturing and processing of clothes and fabrics is included because trade activities like retail are included in other categories. The basic scenario structure is followed where Sweden, the EU and the rest of the world become fossil free.

Table 5: Clothing scenarios

1.	Sweden becomes fossil free	- All Swedish-based fossil emissions are removed - Fossil energy is replaced by electric energy and according emissions
2.	EU becomes fossil free	- All EU-based fossil emissions are removed - Fossil energy is replaced by electric energy and according emissions
3.	RoW becomes fossil free	- All RoW-based fossil emissions are removed - Fossil energy is replaced by electric energy and according emissions

2.3.7 Steel, metal, and machinery activities

All steel production and processing activities are assumed to be electrified. This is not yet possible at commercial scale though is expected to be commercialised by the year 2030 (European Commission, 2018).

2.3.8 Petroleum, plastic, and chemical activities

Since these categories only comprise the production of refined petroleum products, plastics, and chemical products it is assumed that these will still take place when fossil fuels are not used anymore but with non-fossil raw materials. For the scenarios, this means that all fossil emissions will be removed. The fossil energy input will be replaced by the renewable electricity mix and emissions relative to the region the emissions are taking place in.

Table 6: scenarios petroleum, plastic, and chemical products

1.	Sweden becomes fossil free	- All Swedish-based fossil emissions are removed - Fossil energy is replaced by electric energy and according emissions
2.	EU becomes fossil free	- All EU-based fossil emissions are removed - Fossil energy is replaced by electric energy and according emissions
3.	RoW becomes fossil free	- All RoW-based fossil emissions are removed - Fossil energy is replaced by electric energy and according emissions

2.3.9 Electronics, IT & communications, cultural, sports and religious activities

These consumption groups do not have any specific scenario characteristics. They all follow the basic three scenario modes with Sweden, the EU and the whole world becoming fossil free. All fossil energy inputs are assumed to be replaced by electricity.

3 Results

The baseline emissions, extracted from the PRINCE database are presented in section 3.1 and 3.2. In 3.1 the total emissions and the region of origin of the emissions are presented. Section 3.2 shows the 2008 – 2014 average share of fossil CO_2 in total greenhouse gas emissions, for the main consumption groups and per region of origin. In 3.3 to 3.6 the results of the modelling approach are presented.

3.1 Consumption-based greenhouse gas emissions per capita in Sweden

Yearly average per capita greenhouse gas emissions from Swedish consumption between 2008 and 2014 are 11.67 tonnes carbon dioxide equivalents. A noticeable dip in emissions found place in 2009 but emissions quickly returned to the same level in 2010, rising further to a peak of 13.06 t per capita in 2011. Since the peak in 2011, emissions have declined to 10.38 t per person in 2014. The fossil share of emissions is illustrated as the black line in Figure 3. Food accounts for 12% of emissions, buildings for 36%, transport 17%, clothing 2%, public services 8 % and all other categories together contribute 24 % on average. Over the years 2008 – 2014, the share of each category in relation to the total emissions is stable.

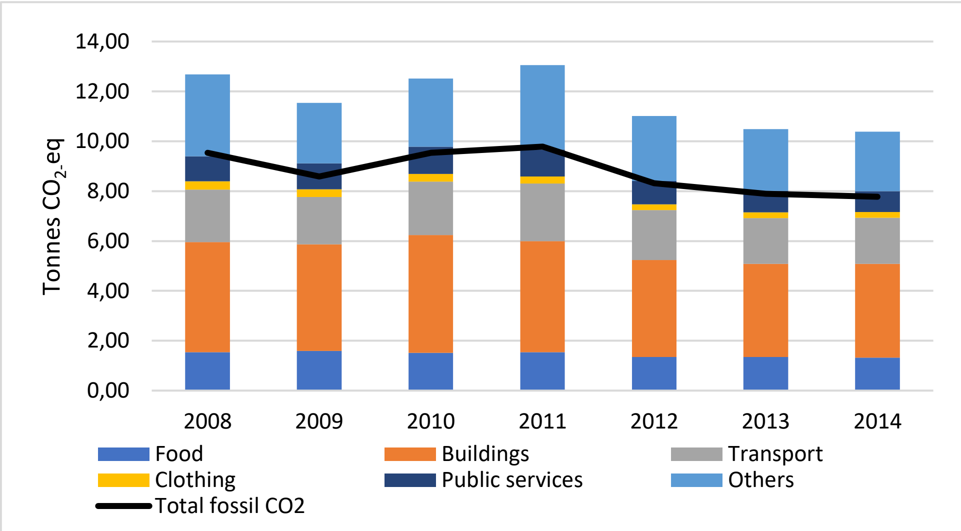


Figure 3: per capita GHG emissions from Swedish consumption [tonne Co2-eq per capita]

Only 35 % of the GHG emissions caused by Swedish consumption are actually emitted in Sweden, 22 % is emitted in the rest of Europe and 43 % of the emissions are produced in countries outside the European Union (**Fout! Verwijzingsbron niet gevonden.**). These ratios are stable within a ± 3 % range in the 2008 - 2014 time-period.

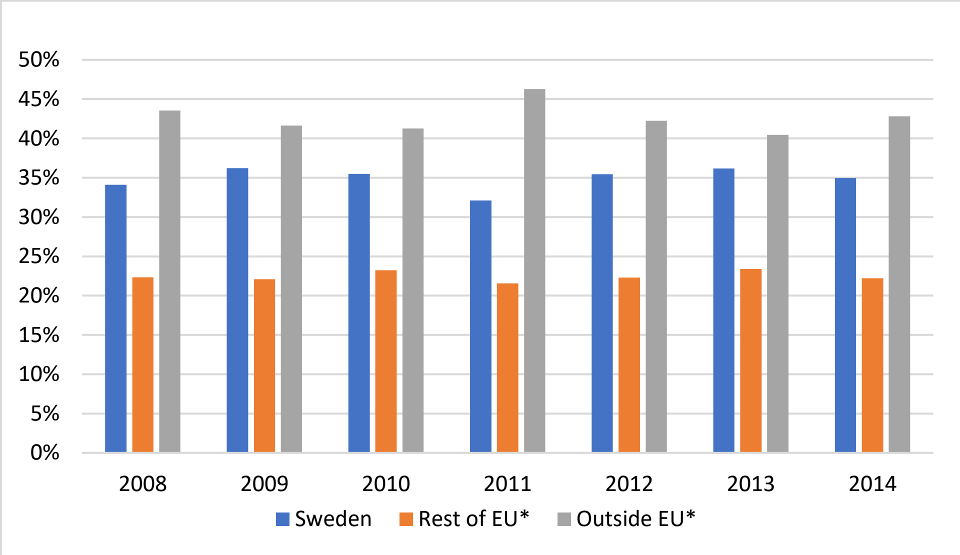


Figure 4: Origin of GHG emissions from Swedish consumption

3.2 Share of fossil CO_2 in total GHG emissions from Swedish consumption

The use of fossil fuels is the largest driver of GHG emissions in all consumption groups except food, illustrated in Figure 5.

Total annual greenhouse gas emissions from food consumption are 1.46 tonnes $CO_{2\text{-eq}}$ per capita, of which 39 % is emitted in Sweden, 31 percent in the rest of the European Union and 30 percent in the rest of the world. Emissions from food products cultivated in Sweden are one third fossil based while for products from the rest of the EU and the rest of the world this is 51 percent and 43 percent.

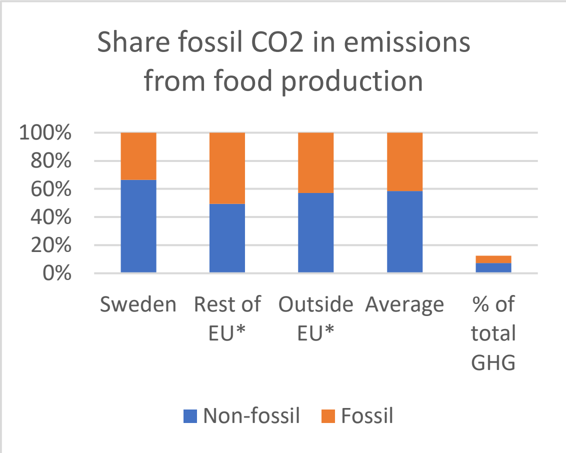
Housing and construction attributes 4.18 tonnes $CO_{2\text{-eq}}$ per capita, good for 36 percent of total annual GHG emissions. Eighty-four percent of GHG emissions come from fossil fuels with 25 percent from direct household fossil fuel use and 21 percent from construction and engineering activities. Fossil CO_2 emissions from electricity generation, gas and heat supply are responsible for 15 percent of the total emissions of this consumption group.

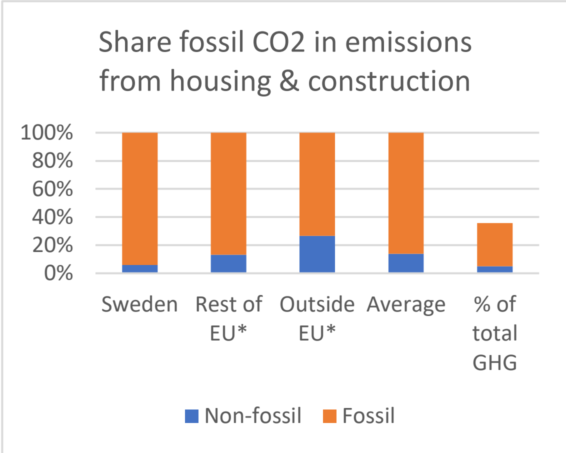
Seventeen percent of the yearly emitted GHGs, 2.02 tonnes per capita, are caused by transportation in Sweden. Of this, 30 percent is emitted in Sweden and 90 percent of that are direct CO_2 emissions from burning fossil fuels. Forty-one percent of the emissions are emitted outside Europe, whereof 70 percent has its origins in fossil fuels.

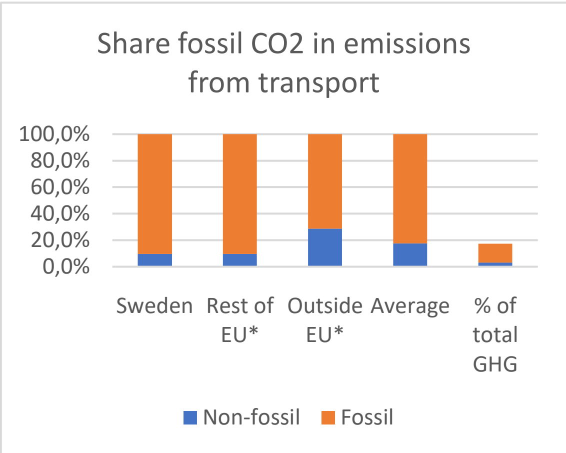
Per capita, clothing contributes 0.19 tonnes of $CO_{2\text{-eq}}$ GHG emissions of which 97 percent is fossil. Only 0.3 percent of the emissions related to clothing are taking place in Sweden, 20 percent in the rest of the EU and almost 80 percent outside the EU.

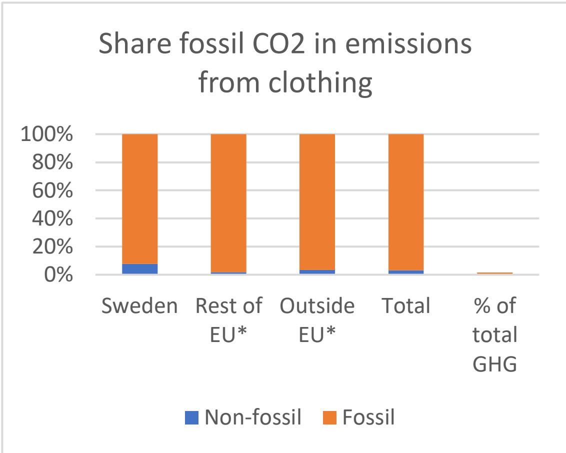
Public services are responsible for 8 percent of Swedish consumption-based emissions. An average of 75 percent of the emissions have fossil origins. About one fourth of the emissions are related to education services, one-third is healthcare related, almost thirty percent is by defence and governmental services and 15 percent is related to social work and social care.

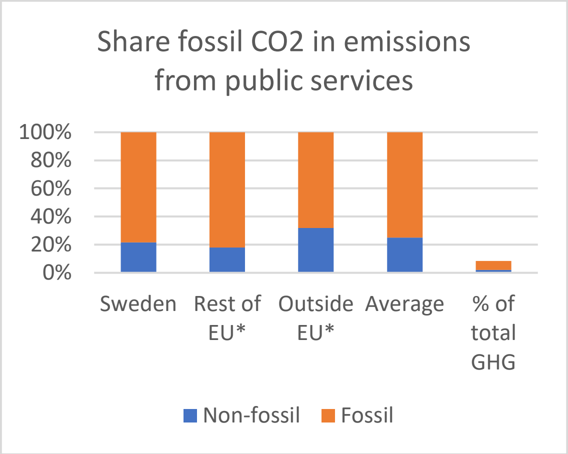
Other services account for 2.76 tonnes of $CO_{2\text{-eq}}$ GHG emissions, that is almost one quarter of the total emissions. Three quarters of this is of fossil origin. The main contributors in this group are refined petroleum products with 27 percent, electronic products and electrical equipment with 14 percent, chemical and pharmaceutical products as well as hospitality & food services with 7 percent each. Telecommunications IT services and media together account for 7 percent of this group. All the other categories individually account for less than one percent of total emissions.











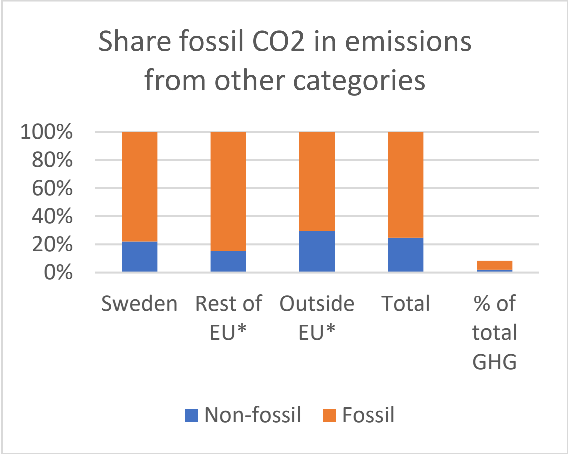


Figure 5: Share of fossil-based CO_2 emissions in total GHG emissions, and share of GHG emissions per consumption group relative to total emissions, for the main consumption groups

3.3 Food scenarios

Table 7 shows the effects of eliminating the use of fossil fuels and behavioural changes on total GHG emissions due to Swedish consumption of food products. Greenhouse gas emission reductions are almost similar in the scenarios with a 32.5 % more efficient food supply chain and a switch to a 100 % plant-based diet. Emissions would lower as much with each of these behavioural scenarios than they would when the use of fossil fuels in the food supply chain would be eliminated completely. The effect of behavioural changes remains very large, switching to a plant-based diet or increasing supply chain efficiency with 32.5 % would halve the emissions, even in the scenario where the world becomes fossil free. When the 100 % plant-based scenario is combined with 32.5 % efficiency gains in the supply chain, the emissions from food consumption would lower even more to 0.36 tons CO_{2eq} per capita per year.

Table 7: Results food scenarios [tonne CO_2-eq per capita]

Scenario	Fossil reductions	50% less animal products	100% plant-based diet	32,5% more efficient	Combination
Baseline emissions	1,46	1,46	1,46	1,46	1,46
Business as usual	1,46	1,23	0,99	0,98	0,67
Sweden fossil free	1,30	1,08	0,86	0,88	0,58
Europe fossil free	1,12	0,90	0,68	0,76	0,46
World fossil free	0,98	0,75	0,53	0,66	0,36

Table 8: Sensitivity analysis food scenarios: 50 % higher emissions from electricity [tonne CO_2-eq per capita]

Scenario	Fossil reductions	50% less animal products	100% plant-based diet	32,5% more efficient	Combination
Baseline emissions	1,46	1,46	1,46	1,46	1,46
Business as usual	1,46	1,23	0,99	0,98	0,67
Sweden fossil free	1,30	1,08	0,86	0,88	0,58
Europe fossil free	1,13	0,91	0,69	0,76	0,46
World fossil free	0,99	0,77	0,55	0,67	0,37

3.4 Buildings & construction scenarios

The results of lowering the use of fossil fuels as well as the effects of changing the energy needs in buildings and efficiency gains throughout the supply chain are displayed in

. Ending the use of fossil fuels in Sweden immediately halves the GHG emissions in the buildings & construction scenarios. Making buildings more energy efficient would also lower the yearly emissions by a quarter. If there would be fifty percent less energy use in the whole supply chain, materials and energy during use phase included, emissions would lower by 47 %. The impact of energy used during operation and energy used for the construction materials reduces to respectively 4 % and 31 % in the scenario of a fossil free world. From the sensitivity analysis in Table 10, it appears that the relative impact of an electricity system with a 50 % higher emission intensity per kWh results in an average difference of 2 % emissions over all scenarios. The relative impact of a 50 % increase in emissions from electricity is the highest in the scenario of a fossil free world without further changes in the energy requirements of buildings and materials.

Table 9: Results building & construction scenarios [tonne CO_2-eq per capita]

Scenario	Fossil reductions	<50 % energy use in buildings	<50 % overall energy use
Baseline emissions	4,17	4,17	4,17
Business as usual	4,17	3,15	2,21
Sweden fossil free	2,10	2,08	2,07
Europe fossil free	1,66	1,64	1,57
World fossil free	0,49	0,47	0,34

Table 10: Sensitivity analysis building & construction scenarios: 50 % higher emissions from electricity [tonne CO_2-eq per capita]

Scenario	Fossil reductions	<50 % energy use in buildings	<50 % overall energy use
Baseline emissions	4,17	4,17	4,17
Business as usual	4,17	3,18	2,21
Sweden fossil free	2,13	2,10	2,09
Europe fossil free	1,72	1,69	1,58
World fossil free	0,61	0,53	0,37

3.5 Transport scenarios

Sweden becoming fossil free, without other measures, lowers GHG emissions more than the 2 other scenarios, less road transport or no domestic flying would, without reducing the use of fossil fuels. Completely stepping away from fossil fuels would reduce emissions from transport by almost sevenfold, to 0.3 tonnes of carbon dioxide equivalent emissions per capita. If all scenarios are followed, the yearly greenhouse gas emissions would be reduced by 96 percent, to 0.08 tonnes per capita. Table 12 displays the scenarios with 50 % higher emissions from electricity use. The results show that the effect is small in relation to the total emission reductions, although the emissions in the scenario with no domestic air transport and a fossil free world double compared to the scenarios with standard emissions from electricity use.

Table 11: Results transport scenarios [tonne CO_2-eq per capita]

Scenario	Fossil reductions	<20% road transport	No domestic flying
Baseline emissions	2,02	2,02	2,02
Business as usual	2,02	1,96	1,81
Sweden fossil free	1,49	1,43	1,22
Europe fossil free	0,99	0,96	0,78
World fossil free	0,30	0,29	0,08

Table 12: Sensitivity analysis transport scenarios: 50 % higher emissions from electricity [tonne CO_2-eq per capita]

Scenario	Fossil reductions	<20% road transport	No domestic flying
Baseline emissions	2,02	2,02	2,02
Business as usual	2,02	1,96	1,81
Sweden fossil free	1,50	1,44	1,23
Europe fossil free	1,04	1,00	0,83
World fossil free	0,38	0,38	0,17

3.6 Results other consumption groups

For all other consumption groups, the three basic scenarios are modelled. Large differences can be seen between consumption groups.

Table 13: Consumption-based emissions from other consumption groups [tonne CO_2-eq per capita]

Consumption group	Baseline	Sweden fossil free	Sweden + Eu fossil free	World fossil free
Clothing	0,27	0,27	0,24	0,09
Public services	0,97	0,72	0,55	0,21
Steel products	0,51	0,50	0,36	0,10
Petroleum products	1,00	0,97	0,82	0,20
Electronics	0,38	0,38	0,28	0,07
Media, IT, communications	0,22	0,18	0,13	0,04
Financial & legal services	0,06	0,04	0,03	0,01
Culture, sport, religion	0,20	0,13	0,10	0,04
Other consumption	0,40	0,30	0,21	0,09
Total	**4,02**	**3,48**	**2,70**	**0,84**

Table 14: Sensitivity analysis other consumption groups scenarios: 50 % higher emissions from electricity [tonne CO_2-eq per capita]

Consumption group	**Baseline**	**Sweden fossil free**	**Sweden + Eu fossil free**	**World fossil free**
Clothing	0,27	0,27	0,24	0,09
Public services	0,97	0,72	0,56	0,25
Steel products	0,51	0,50	0,36	0,12
Petroleum products	1,00	0,97	0,83	0,26
Electronics	0,38	0,38	0,29	0,09
Media, IT, communications	0,22	0,18	0,13	0,05
Financial & legal services	0,06	0,04	0,03	0,01
Culture, sport, religion	0,20	0,13	0,10	0,04
Other consumption	0,40	0,30	0,22	0,11
Total	**4,02**	**3,49**	**2,76**	**1,01**

4 Discussion

4.1 Methods and scenarios

4.1.1 Consumption groups

The consumption groups (1.1.1.1.1.1.1C) are compiled from the 59 consumption categories and associated emissions found in the PRINCE database. The 59 consumption categories in PRINCE are already a simplified and less detailed version of the national economic activity classification that contains more than 1600 different economic activities. This means some detail is lost. This results in activities being assigned to consumption groups that could be assigned to other groups if the full detail were provided in PRINCE. In other cases, following the same consumption groups as Fauré et. al (2019) resulted in illogically assigned consumption categories, usually with low impact on emissions.

- Consumption category A02 – forestry products – is assigned to the food consumption group. This is probably because A02 contains wild food products from forests. Forestry activities are also included in A02, but PRINCE does not provide the detail to determine the share that emissions from forestry food products has compared to other forestry products. The share of the consumption category A02 in the consumption group food is only 3 % and is therefore seen as not important enough to influence the results in a significant manner.
- Consumption category C17 – paper – is assigned to consumption group buildings & constructions. This follows the classification of Fauré et. al (2019). No explanation is found to this reasoning. The share of C17 in total emissions of the buildings & construction group is 0.5% and is therefore negligible.
- Consumption category G45-47 – wholesale and retail – is assigned to the transport consumption group as in Fauré et. al (2019). G45-47 is a compilation of various wholesale and retail activities including the sale of vehicles and transport related activities but also wholesale and retail activities of various other consumption goods as foods, perfumes, etc. No further detail is found in PRINCE nor is there any documentation that allows for an assessment of to what extent the emissions that are found in PRINCE contain emissions from consumption categories other than transport. Consumption group G45-47 makes up 31 % of the total emissions of the transport consumption group. If transport related emissions are not most of the emissions in this category, the emissions for the transport consumption group could change significantly but no estimate can be made of to what extent.

4.1.2 Emissions data

The PRINCE database contains the results of the models that are run by the research group making the framework for Swedish consumption-based emissions accounting. It is not a model but a database, that means it has certain limitations. The emissions data is static, it is not a functioning model that is interactive with parameters that can be changed to model the effect of any changes. This has some effects on the results presented in this report. If emissions from products made in Sweden change, because Sweden becomes fossil-free, this normally effects the whole supply chain, yet these so-called feedback effects are not seen in the PRINCE data. An example clarifies: In PRINCE, the metal produced in Sweden would have a certain amount of emissions per ton that is produced, mainly caused by using fossil fuels like coal, cokes, etc. If the metal then gets produced in Sweden without fossil fuels (this would be scenario 1 in this report), this will result in much lower emissions per ton of produced steel. The steel gets exported and used to make cars in another country and imported back to Sweden in the finished cars. The cars that are imported into Sweden would have lower emissions associated to them because the steel that is used caused lower emissions. In the results presented in this report, these feedback effects are not shown because the emissions related to the import of products are static and do not change when something in the supply chain is changed. This results in higher emissions than would be in a fully functional MRIO model coupled to the detailed national accounts. Moran et. al (2017) found that the feedback effects in Sweden account for only 0.2 % of the emissions, therefore this is not seen as a problem in the results of the scenarios where Sweden lowers the use of fossil fuels. How large the effect is on the scenarios where the EU lowers the emissions is not clear. In the scenarios where the whole world lowers the emissions, the feedback effects are cancelled since all fossil-fuel emissions are removed.

The database was last updated in 2018, the years it covers are from 2008 – 2014. In a search for more recent data the Swedish Statistics Database was consulted. Since the national consumption-based emissions statistics are based on the PRINCE model, these should contain the same data, but this was not the case. After unsuccessful attempts to determine the cause of the differences, the SCB was contacted. The cause of the difference in emissions data turned out to be a recent update of the EXIOBASE database. EXIOBASE is used to model Swedish consumption-based emissions and the update resulted in a retroactive change of the emissions. The format the SCB publishes national consumption-based emissions in is not completely compatible and not as detailed as the PRINCE database. In the data retrievable from SCB there are no details on the region the emissions connected to import come from, it only shows the part that is Swedish and foreign. Newer data with the same level of detail was requested but could not be provided by the SCB. This means the “older” data in PRINCE had to be used since in the scenarios there is differentiation between Swedish, European, and non-European emissions. A comparison showed that the average emissions in PRINCE are 15 percent higher than the updated emissions published in the SCB database.

4.1.3 Electricity mix and biofuels availability

The electricity mix is an important factor in modelling the future emissions. Most of the future energy needs in the scenarios will be delivered in the form of electricity. The electricity mix chosen in the scenarios is based on as recent as possible reports that model a completely renewables-based electricity system. These reports incorporated technological and economic developments as well as the geographical boundaries the technologies are subjected to. The most probable technologies that are expected to provide the largest share of the electricity (wind and solar PV) have emission factors that differ a factor 3 but are both low compared to current technologies. The emission factors that are used are adopted from the IPCC (2014). During the transition to a 100 % renewable energy system these emission factors will get lower because the emissions related to the energy used to produce the energy technologies will be lower. This effect is not considered in this study. Nevertheless, a sensitivity analysis was included that accounts for a fifty percent higher emission factor from electricity. This was done to include the potential effects of using other technologies, with higher emission factors. Efficiency gains because of switching from fossil fuels to electricity are also not included in this study but could be as high as 10 to 40 % depending on the sector (European Commission, 2019b)(European Commission, 2018).

The electricity mix for Sweden that was derived from the Swedish Energy Agency scenario with a large share of wind power (Swedish Energy Agency, 2019) included eight percent electricity from biomass. In the one hundred percent renewable electricity scenarios for the Europe and the rest of the world taken from SolarPower Europe and LUT University (2020) and Ram et. al (2019) there was only a marginal share of biomass in the total primary energy supply. Electricity production from biomass is not included in any of the electricity mixes in this study because the discussion on how to deal with biomass emissions is ongoing. Although the IPCC considers it as renewable and thus, carbon neutral, other studies suggest using different accounting methods because the effect on global warming is not net zero. Cherubini et. al (2011) suggests using a method based on the actual global warming potential (GWP) using a newly designed GWP_{bio} index, that is dependent on the rotation period and atmospheric decay functions. Other authors suggest using lifecycle emissions that include emissions of the power plants' construction, operation, etc. Kadiyala et. al (2016) performed literature review on lifecycle emissions from various biomass types and found large differences between the different types of biomass and technologies. Because taking all these differences into consideration in this study would make it too complex for completion within the given timeframe it is assumed there is no use of biomass in any of the scenarios in this study. A sensitivity analysis was performed where the emission factor for electricity production from both wood chip biomass from Baltic forest (22 gCO_2/kWh) as well as Ireland willow (131 gCO_2/kWh) from Kadiyala et. al (2016) was used. This resulted in less than 1 % difference in total emissions when assuming an 8 % share of biomass in electricity production for each of the electricity mixes. The sensitivity analysis where emissions from electricity are increased by 50 % has a 3 to 4 times higher impact than including biomass in the electricity mix. Therefore, it is not seen as crucial to the outcome of this study to include biomass.

Electricity production with nuclear technologies are not used in the electricity mix because they are not representing any significant share (<1%) in the 2050 energy models that take into account the lifespan of currently operating reactors and the economic incentives of building new reactors (Ram et al., 2019; SolarPower Europe and LUT University, 2020). If through policy decisions there will be an expansion of nuclear capacities, this will however not influence the average emission factor of the electricity mix since according the IPCC the emission factor of electricity generated with nuclear technology is the same (12 gCO_2/kWh) as the emission factor of electricity from offshore wind and differs insignificantly from onshore wind technology, which has a large share in all of the electricity mixes.

No further research was performed on the availability of biofuels that are used to supply for fifty percent of the energy needs for agriculture, transport by water and domestic air transport. Since biofuels are currently used in most European countries as addition to diesel or in the form of bioethanol it is assumed there is enough capacity to fulfil the scenario needs.

4.1.4 Scenarios

The scenarios presented in this study are a projection of how the emissions would evolve if the scenario conditions are met. The chance or the degree to which these scenarios come true are completely depending on the political and societal evolutions. The fossil-free scenarios for Sweden and Europe are more likely to be achieved than the scenario where the whole world becomes fossil-free. Sweden has already communicated that it wants to lead in becoming fossil-free and is taking actions by involving all stakeholders in achieving this goal through its Sweden fossil-free initiative (Löfven, 2019). The EU has not stated the target of becoming completely fossil-free but currently agreed upon plus proposed measures would already result in fossil fuels accounting for ± 10 % of electricity production (European Commission, 2018). With the Green Deal, the intention is to further increase the EUs climate ambitions and become climate neutral by 2050, which implies deep reductions of the use of fossil fuels. When and if the rest of the world will end fossil-fuel use is highly uncertain, but a general evolution towards renewables is noticeable.

4.2 Overall emissions

The findings in this study show how reducing the use of fossil fuels in Sweden has an impact on Swedish consumption-based emissions. A comparison with other mitigation options like reducing road transport, air transport, dietary changes and energy efficiency improvements is made to provide perspective on the effects of these efforts. Unlike previous scenario efforts that rely on a fixed set of extensive behavioural and societal changes, as performed by Fauré, Finnveden and Gunnarson-Östling (2019), the scenarios in this report display the mitigation potential and synergetic effects of individual mitigation efforts. This report also provides an insight in what the effects of international mitigation actions will have on emissions from Swedish consumption.

This scenarios approach demonstrates what the effects of lowering the use of fossil fuels in Sweden, Europe, and the rest of the world, are on Swedish consumption-based emissions. If Sweden stops using fossil fuels, without taking any other measures, annual GHG emissions will lower from 11.67 tonnes $CO_{2\text{-eq}}$ to 8.36 tonnes $CO_{2\text{-eq}}$. This represents only 27 % of the total GHG emissions. When the whole of the EU phases out fossil fuels, emissions from Swedish consumption lower by 44 % and if the whole world stops using fossil fuels this would reduce Swedish emissions by 77 %. These results confirm the findings by Davis &

Caldeira (2010) that show high dependency on import and large spillover emissions in western-European countries. The sensitivity to changes in the technologies for electricity production are very low, 50 % higher emissions by electricity use result in only 1 % to 7 % higher emissions. Because of the uncertainties that are inherent to any scenario that covers such a large timespan, these differences are negligible. Since the PRINCE database does not function like a fully functional MRIO model, the effects of reduced emissions in one region do not cause reduced emissions in the regions that are connected through trade. This causes higher than realistic emissions in the scenarios where emissions are lowered due to fossil-fuel reductions or other measures. Moran et. al (2017) have found that these feedback effects are 0.2 % for Sweden, suggesting the effect is very small in the scenarios where emissions are reduced in Sweden. How large the feedback effects are in the scenarios where emissions are lowered in the whole EU region is not known.

4.3 Food consumption

Food consumption is responsible for 13 % of total GHG emissions, which is similar to the results from Schmidt et. al, (2019). The share of emissions caused by burning fossil fuels is lower than in the other categories which makes the switch to renewable energy less impactful than in other consumption groups. If Sweden switches from fossil fuels to the scenario mix of 50 % renewable electricity and 50 % biofuels, this only decreases the total emissions from food consumption by 11 %. The highest impact Sweden can have, is by reducing the consumption of animal products. Efficiency gains in food production can also contribute significantly to reducing emissions and especially reducing food waste is an effective measure since reducing demand has effects that go beyond Swedish borders. Forestry products is one of the consumption categories that are included in the food consumption group, because the consumption group is adopted from Fauré et. al, (2019). The reason is that wild food products coming from forests fall under this category. One could argue that not all forestry products are part of food consumption, but since the forestry products category only represents 3 % of the food consumption group it is not a significant problem.

The scenarios for food consumption rely on the assumption that all agriculture related methane emissions in Europe arise from animal husbandry. Methane emissions are responsible for about 40 % of total GHG emissions from agriculture Table 7. If animal husbandry is responsible for only a part of the methane emissions, this will have an impact on the results. The impact will not be large enough to change the general outcome of the results. Another assumption is that energy needs related to food production are replaced by electricity and biofuels, each 50-50. If this ratio changes it has effects on the emissions related to the scenarios. The impact of that is rather small since the energy needs in agriculture are relatively low compared to buildings & construction or transport. If the efficiency gains assumed in the scenarios are achieved or not is very much dependent on policy and societal incentives.

4.4 Buildings & construction activities

The largest decline in greenhouse gas emissions, by ending the use of fossil fuels, is found in the buildings and construction sector. This is also the consumption group Sweden has the highest impact on. When Sweden ends fossil fuels, without further measures, emissions lower by 50 %? From 4.17 tonnes $CO_{2\text{-}eq}$ per capita to 2.10 tonnes per capita, which represents 18 % of the yearly GHG gas emissions by Swedish consumption. Reducing the energy need in buildings can cause significant emissions reductions but there also is a risk for negative feedbacks because of the emissions from increased material use. Switching from fossil fuels to heat pumps for heating buildings can be a win-win since this has a direct impact on the use of fossil fuels and lowers the primary energy needs. A combination of lower energy use in buildings and lowering or changing the use of construction materials, from concrete to wood, has potential emissions savings that equal ending the use of fossil fuels. Which is similar to the results of an LCA performed by Nässén et. al, (2012). If the whole world ends using fossil fuels, the reduction of greenhouse gas emissions for buildings and construction can be reduced to almost 10 % of the current emissions. Without any other measures concerning energy efficiency or other material choices.

The European residential sector is currently on track for a 38 % reduction in primary energy demand in the residential sector by 2050 (compared to 2005), this is without extra measures (European Commission, 2018). This is not yet the 50 % used in the scenario. The Green Deal is expected to increase the ambitions further, making the 50 % used in the scenario more realistic. Regarding the total primary energy reduction of 50 % there are also promising signs that this can be achieved. Significant reductions are expected because of ongoing electrification. The EU Green Deal is aiming at supporting fossil free steel production by 2030 (European Commission, 2019a). Together with further emission reductions in cement production and increasing use of wood in construction, the probability of the scenario increases. Everything depends completely on political decisions taken in the 2020 to 2030 period, since it takes 25 years to transform an industrial sector and all the value chains (European Commission, 2019b).

4.5 Transport activities

By far the largest emissions reduction in transport that lies within Sweden's control is switching from fossil fuelled to all electric road transport. This can lower emissions by a quarter. The single most impactful measure is ending domestic air transport and switching that by transport via railways. When fossil fuels are removed from the whole transport supply chain, the emissions would be almost sevenfold lower, from 2.02 t $CO_{2\text{-}eq}$ to 0.3 t $CO_{2\text{-}eq}$ per capita. When combined with the other scenario measures, reducing road transport by 20 % and switching domestic air to train transport, transport emissions can be lowered by 96 %. The allocation of category G45 – G47 to the transport consumption group is adopted from Fauré et. al (2019). The SNI categories that are included in transport include category G45 – G47, which includes wholesale and retail trade, repair and sales of motor vehicles and motorcycles. This includes most retail activities, not only transport related retail. The

PRINCE database does not allow more detail, which means that the share of transport related emissions in the wholesale & retail category cannot be determined.

Sweden is banning the sale of new gasoline and diesel cars from 2030 onwards. The transition away from fossil fuels will start long before that because the market for these cars will be less favourable. Electricity driven vehicles already make up 50 % of the newly sold cars in Norway, and sales are growing in other countries. Battery costs are still falling rapidly, with yearly cost reductions of about 20 % (Bloomberg NEF, 2019). Which will soon make an electric car as expensive as a traditional combustion engine car. Battery technology is also expected to get better, with batteries getting lighter and more energy dense which enables even broader use like in long-range busses and trucks. Further electrification of railways is expected too but of minor importance since these emissions are already very low. Transport by water is said to switch to biofuels in this study but there are signs that a part of the shipping industry will switch to electricity too. This evolution is mainly expected in ferries, but they do account for a significant part of domestic shipping industry. Switching to electric drivetrains will decrease emissions compared to biofuels. The impact of water transport is only 3 %, which means any changes are insignificant in the total outcome. A large part of the emissions in transport are due to production and sales of motor vehicles and these will be getting lower together with other industries.

5 Conclusions

The use of fossil fuels causes 75 % of all Swedish consumption-based greenhouse-gas emissions in the period 2008 – 2014. By reducing the use of fossil fuels, Sweden has only limited impact on its own consumption-based emissions because most of the emissions due to consumption are taking place outside Sweden. Large cross-border effects can be realised by changes in consumption. If all scenarios that do not require reductions in fossil fuels are fulfilled, the potential emission reductions are slightly larger than when Sweden would stop using fossil fuels for the three main consumption groups. This would also help Sweden in achieving the goal of not increasing emissions abroad while reducing their own emissions. The results show that international cooperation is important for reducing the emissions.

There are large differences between consumption groups. Food has the lowest fossil share in emissions, with fossil fuel use accounting for 33 % of the emissions related to food consumption. The largest share is found in the buildings & construction, with fossil fuel use causing 88 % of the emissions. Scenarios show that changes in consumption patterns towards eating less meat and reducing food waste have a higher potential for reducing emissions than Sweden becoming fossil free. Making buildings 50 % more energy efficient has the potential to lower emissions from the consumption group buildings & construction by 25 %. The same emission reduction can be achieved by completely switching fossil fuel use for heating in residential buildings to heat pumps. In transport, the largest emission reductions can be made by reducing the use of fossil fuels in road transport as well as the supply chain. Moving road transport to transport by train, bicycle or foot reduces emissions immediately though the potential is limited since trains are bound to railways and stations while transport by foot or bicycle has a limited range.

6 Future research

Connecting emissions scenarios to the economic consequences to form the most cost-effective mitigation strategies could be very useful in policymaking and strategic planning. More in-depth analyses of the consumption-based emissions and designing a functional model that allows for running more detailed scenarios could be a particularly useful tool for researchers as well as policymakers or organisations.

7 Literature list

Bloomberg NEF. (2019). A Behind the Scenes Take on Lithium-ion Battery Prices. Retrieved June 7, 2020, from Electric Vehicle Outlook 2020 website: https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

Chen, Z. M., Ohshita, S., Lenzen, M., Wiedmann, T., Jiborn, M., Chen, B., … Liu, Z. (2018). Consumption-based greenhouse gas emissions accounting with capital stock change highlights dynamics of fast-developing countries. *Nature Communications*, *9*(1). https://doi.org/10.1038/s41467-018-05905-y

Cherubini, F., Peters, G. P., Berntsen, T., Strømman, A. H., & Hertwhich, E. (2011). CO2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. *GCB Bioenergy*, *3*(5), 413–426. https://doi.org/10.1111/j.1757-1707.2011.01102.x

Davis, S. J., & Caldeira, K. (2010). Consumption-based accounting of CO 2 emissions. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(12), 5687–5692. https://doi.org/10.1073/pnas.0906974107

ECMWF. (2019). European State of the Climate 2018. Retrieved February 6, 2020, from European State of the Climate 2018 website: https://climate.copernicus.eu/surface-temperature

European Commission. (2018). *In-depth analysis in support of the commission communication COM(2018) 773. A clean planet for all A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy*.

European Commission. (2019a). *Annex to the communication from the commission on the European Green Deal*. https://doi.org/10.2307/j.ctvd1c6zh.7

European Commission. (2019b). *European Green Deal Communication*. https://doi.org/10.2307/j.ctvd1c6zh.7

FAO. (2014). Agriculture , Forestry and Other Land Use Emissions by Sources and Removals by Sinks. In *ESS Working Paper No.2* (Vol. 2). Retrieved from http://www.fao.org/docrep/019/i3671e/i3671e.pdf

Fauré, E., Dawkins, E., Wood, R., Finnveden, G., Palm, V., Persson, L., & Schmidt, S. (2019). Environmental pressure from Swedish consumption – The largest contributing producer countries, products and services. *Journal of Cleaner Production*, *231*, 698–713. https://doi.org/10.1016/j.jclepro.2019.05.148

Fauré, E., Finnveden, G., & Gunnarson-Östling, U. (2019). Four low-carbon futures for a Swedish society beyond GDP growth. *Journal of Cleaner Production*, *236*, 13. https://doi.org/10.1016/j.jclepro.2019.07.070

Franzen, A., & Mader, S. (2018). Consumption-based versus production-based accounting of CO 2 emissions : Is there evidence for carbon leakage ? *Environmental Science and Policy*, *84*(March), 34–40. https://doi.org/10.1016/j.envsci.2018.02.009

Haller, M., Ludig, S., & Bauer, N. (2012). Decarbonization scenarios for the EU and MENA power system: Considering spatial distribution and short term dynamics of renewable generation. *Energy Policy*, *47*, 282–290. https://doi.org/10.1016/j.enpol.2012.04.069

IPCC. (2006). 2006 IPCC Guidelines for National Greenhouse Inventories – A primer, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Miwa K., Srivastava N. and Tanabe K. In *Iges*.

IPCC. (2014). *Technology-specific Cost and Performance Parameters*.

IPCC. (2018). Summary for Poliymakers. In *Global warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*. Retrieved from https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_High_Res.pdf

Kadiyala, A., Kommalapati, R., & Huque, Z. (2016). Evaluation of the life cycle greenhouse gas emissions from different biomass feedstock electricity generation systems. *Sustainability (Switzerland)*, *8*(11). https://doi.org/10.3390/su8111181

Larsson, J., Kamb, A., Nässén, J., & Åkerman, J. (2018). Measuring greenhouse gas emissions from international air travel of a country's residents methodological development and application for Sweden. *Environmental Impact Assessment Review*, *72*(May 2018), 137–144. https://doi.org/10.1016/j.eiar.2018.05.013

Löfven, S. (2019). Statement of Government Policy, 21 January 2019. Retrieved May 15, 2020, from Swedish Government website: https://www.government.se/speeches/20192/01/statement-of-government-policy-21-january-2019/

Milne, A. E., Glendining, M. J., Bellamy, P., Misselbrook, T., Gilhespy, S., Rivas Casado, M., … Whitmore, A. P. (2014). Analysis of uncertainties in the estimates of nitrous oxide and methane emissions in the UK's greenhouse gas inventory for agriculture. *Atmospheric Environment*, *82*, 94–105. https://doi.org/10.1016/j.atmosenv.2013.10.012

Moran, D., Wood, R., & Rodrigues, J. F. D. (2017). A Note on the Magnitude of the Feedback Effect in Environmentally Extended Multi-Region Input-Output Tables. *Journal of Industrial Ecology*, *22*(3), 532–539. https://doi.org/10.1111/jiec.12658

Nässén, J., Hedenus, F., Karlsson, S., & Holmberg, J. (2012). Concrete vs. wood in buildings - An energy system approach. *Bulding and Environment*, *51*, 361–369. https://doi.org/10.1016/j.buildenv.2011.11.011

Naturvårdsverket. (2018). *Swedens' environmental objectives - an introduction*. Retrieved from http://www.swedishepa.se/About-us/Publikationer/ISBN/8800/978-91-620-8820-0/

Naturvårdsverket. (2019a). Sweden's Climate Act and Climate Policy Framework - Swedish Environmental Protection Agency. Retrieved February 7, 2020, from http://www.swedishepa.se/Environmental-objectives-and-cooperation/Swedish-environmental-work/Work-areas/Climate/Climate-Act-and-Climate-policy-framework-/

Naturvårdsverket. (2019b). The national environmental quality objectives - reduced climate impact. Retrieved February 18, 2020, from http://www.swedishepa.se/Environmental-objectives-and-cooperation/Swedens-environmental-objectives/The-national-environmental-objectives/Reduced-Climate-Impact/

Naturvårdsverket. (2019c, August 20). Milestone targets - Swedish Environmental Protection Agency. Retrieved February 19, 2020, from http://www.swedishepa.se/Environmental-objectives-and-cooperation/Swedens-environmental-objectives/Milestone-targets/

Pleßmann, G., & Blechinger, P. (2016). *How to meet EU GHG emission reduction targets? A model based decarbonization pathway for Europe's electricity supply system until 2050*. https://doi.org/10.1016/j.esr.2016.11.003

Ram, M., Bogdanov, Dmitrii Aghahosseini, A., Gulagi, A., Oyewo, S. A., Child, M., Caldera, U., … Breyer, C. (2019). *Global Energy System based on 100% Renewable Energy* (p. 321). p. 321. Retrieved from http://energywatchgroup.org/new-study-global-energy-system-based-100-renewable-energy

SCB. (2019). *Swedish Population Statistics*. Retrieved from https://www.scb.se/en/finding-statistics/statistics-by-subject-area/population/population-composition/population-statistics/#_Keyfigures

Schmidt, S., Södersten, C. J., Wiebe, K., Simas, M., Palm, V., & Wood, R. (2019). Understanding GHG emissions from Swedish consumption - Current challenges in reaching the generational goal. *Journal of Cleaner Production*, *212*, 428–437. https://doi.org/10.1016/j.jclepro.2018.11.060

Smith, P., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., … Sirotenko, O. (2007). Agriculture In Climate Change 2007: Mitigation. *Cambridge University Press*, (4), 1–44. https://doi.org/10.2753/JES1097-203X330403

SolarPower Europe and LUT University. (2020). *100% Renewable Europe - How to make Europe's energy system climate-neutral before 2050*. Brussels.

Steinbach, N., Palm, V., Cederberg, C., Finnveden, G., Persson, L., Persson, M., … Trimmer, C. (2018). *Miljöpåverkan från svensk konsumtion - nya indikatorer för uppföljning*. Retrieved from http://www.naturvardsverket.se/Om-Naturvardsverket/Publikationer/ISBN/6800/978-91-620-6842-4/

Swedish Energy Agency. (2019). *100 procent förnybar el*.

UNEP. (2019). *Emissions Gap Report 2019*. Nairobi.

UNFCCC. (2019). Paris Agreement on Climate Change. *Reducing Greenhouse Gas Emissions and Improving Air Quality*, 11–22. https://doi.org/10.1201/9781351116589-2

Appendix

Appendix A.

Emission factors used in calculations

Table 15: Renewable electricity mix Sweden, EU, RoW. Based on (Ram et al., 2019; SolarPower Europe and LUT University, 2020; Swedish Energy Agency, 2019)

Region	Technology	Emissions (gCO_2-eq /kWh)	Average emissions (gCO_2-eq /kWh)
Sweden	50 % Onshore wind 6 % Offshore wind 5 % Solar PV 39 % Hydropower	11 12 41 24	17.63
Europe	45 %Onshore wind 3 % Offshore wind 48 % Solar PV 4 % Hydropower	11 12 41 24	25.95
Rest of the world	25 %Onshore wind 3 % Offshore wind 69 % Solar PV 3 % Hydropower	11 12 41 24	32.12

Biofuel	Calculation number
70 % less CO_2-eq /MJ than MJ gasoline	0,3
Energy & material efficiency	Calculation number
50% higher energy efficiency	50,0%
50% higher efficiency overall	50,0%

Appendix B.

SNI Swedish Standard Industrial Classification 2007

A AGRICULTURE, FORESTRY AND FISHING
01110 Growing of cereals (except rice), leguminous crops and oil seeds
01120 Growing of rice
01131 Growing of potatoes
01132 Growing of sugar beet
01133 Growing of vegetables in the open
01134 Growing of vegetables in greenhouses
01135 Growing of mushrooms etc.
01140 Growing of sugar cane
01150 Growing of tobacco
01160 Growing of fibre crops
01191 Growing of flowers and ornamental plants in greenhouses
01199 Growing of other non-perennial crops n.e.c.
01210 Growing of grapes
01220 Growing of tropical and subtropical fruits
01230 Growing of citrus fruits
01240 Growing of pome fruits and stone fruits
01250 Growing of other tree and bush fruits and nuts
01260 Growing of oleaginous fruits
01270 Growing of beverage crops
01280 Growing of spices, aromatic, drug and pharmaceutical crops
01290 Growing of other perennial crops
01301 Plant propagation in greenhouses
01302 Plant propagation in the open
01410 Milk production and raising of dairy cattle
01420 Raising of other cattle and buffaloes
01430 Raising of horses and other equines
01440 Raising of camels and camelids
01450 Raising of sheep and goats
01461 Raising of piglets
01462 Raising of swine for slaughter
01471 Egg production
01472 Raising of poultry
01491 Reindeer husbandry
01492 Breeding of pet animals
01499 Raising of other animals n.e.c.
01500 Mixed farming
01610 Support activities for crop production
01620 Support activities for animal production
01630 Post-harvest crop activities
01640 Seed processing for propagation
01700 Hunting, trapping and related service activities
02101 Forest management
02102 Silviculture
02109 Other forestry activities
02200 Logging
02300 Gathering of wild growing non-wood products
02401 Wood measurement
02409 Other support services to forestry
03111 Marine trawling
03119 Other marine fishing
03120 Freshwater fishing
03210 Marine aquaculture
03220 Freshwater aquaculture
B MINING AND QUARRYING
05100 Mining of hard coal
05200 Mining of lignite
06100 Extraction of crude petroleum
06200 Extraction of natural gas
07100 Mining of iron ores
07210 Mining of uranium and thorium ores
07290 Mining of other non-ferrous metal ores
08110 Quarrying of ornamental and building stone, limestone, gypsum, chalk and slate
08120 Operation of gravel and sand pits; mining of clays and kaolin
08910 Mining of chemical and fertiliser minerals
08920 Extraction of peat
08930 Extraction of salt
08990 Other mining and quarrying n.e.c.
09100 Support activities for petroleum and natural gas extraction
09900 Support activities for other mining and quarrying
C MANUFACTURING
10111 Livestock slaughtering
10112 Processing and preserving of meat in cuts
10120 Processing and preserving of poultry meat
10130 Production of meat and poultry meat products
10200 Processing and preserving of fish, crustaceans and molluscs
10310 Processing and preserving of potatoes
10320 Manufacture of fruit and vegetable juice
10390 Other processing and preserving of fruit and vegetables
10410 Manufacture of oils and fats
10420 Manufacture of margarine and similar edible fats
10511 Cheese production
10519 Other dairy production
10520 Manufacture of ice cream
10611 Production of flour
10612 Manufacture of breakfast cereals, blended flour mixes and other prepared grain mill products
10620 Manufacture of starches and starch products
10710 Manufacture of bread; manufacture of fresh pastry goods and cakes
10721 Manufacture of crispbread
10722 Manufacture of rusks, biscuits and preserved pastry goods and cakes
10730 Manufacture of macaroni, noodles, couscous and similar farinaceous products
10810 Manufacture of sugar
10821 Manufacture of sugar confectionery
10822 Manufacture of cocoa and chocolate confectionery
10830 Processing of tea and coffee
10840 Manufacture of condiments and seasonings
10850 Manufacture of prepared meals and dishes
10860 Manufacture of homogenised food preparations and dietetic food
10890 Manufacture of other food products n.e.c.
10910 Manufacture of prepared feeds for farm animals
10920 Manufacture of prepared pet foods
11010 Distilling, rectifying and blending of spirits
11020 Manufacture of wine from grape
11030 Manufacture of cider and other fruit wines
11040 Manufacture of other non-distilled fermented beverages
11050 Manufacture of beer
11060 Manufacture of malt
11070 Manufacture of soft drinks; production of mineral waters and other bottled waters
12000 Manufacture of tobacco products
13100 Preparation and spinning of textile fibres
13200 Weaving of textiles
13300 Finishing of textiles
13910 Manufacture of knitted and crocheted fabrics
13921 Manufacture of curtains, bed linen and other linen goods
13922 Manufacture of tarpaulins, tents, sails etc.
13930 Manufacture of carpets and rugs
13940 Manufacture of cordage, rope, twine and netting
13950 Manufacture of non-wovens and articles made from non-wovens, except apparel
13960 Manufacture of other technical and industrial textiles
13990 Manufacture of other textiles n.e.c.
14110 Manufacture of leather clothes
14120 Manufacture of workwear
14130 Manufacture of other outerwear
14140 Manufacture of underwear
14190 Manufacture of other wearing apparel and accessories
14200 Manufacture of articles of fur
14310 Manufacture of knitted and crocheted hosiery
14390 Manufacture of other knitted and crocheted apparel
15110 Tanning and dressing of leather; dressing and dyeing of fur
15120 Manufacture of luggage, handbags and the like, saddlery and harness
15200 Manufacture of footwear
16101 Sawmilling
16102 Planing of wood
16103 Impregnation of wood
16210 Manufacture of veneer sheets and wood-based panels
16220 Manufacture of assembled parquet floors
16231 Manufacture of prefabricated wooden buildings
16232 Manufacture of wooden doors
16233 Manufacture of wooden windows
16239 Manufacture of other builders' carpentry and joinery n.e.c.
16240 Manufacture of wooden containers
16291 Manufacture of wood fuels
16292 Manufacture of other products of wood
16293 Manufacture of articles of cork, straw and plaiting materials
17111 Manufacture of mechanical or semi-chemical pulp
17112 Manufacture of sulphate pulp
17113 Manufacture of sulphite pulp
17121 Manufacture of newsprint
17122 Manufacture of other printing paper
17123 Manufacture of kraft paper and paperboard
17129 Manufacture of other paper and paperboard
17211 Manufacture of corrugated paper and paperboard and corrugated board containers
17219 Manufacture of other containers of paper and paperboard
17220 Manufacture of household and sanitary goods and of toilet requisites

Appendix C.

Composition of consumption groups. Consumption group in bold with the SNI codes of the consumption categories under the consumption groups.

Buildings & construction	**Clothing**	**Financial & legal services**
C 17	C13-15	J62-63
C 31-32		K64
D 35	**Petroleum products**	K65
D 36-39	C 19	K66
F	C 20-21	M69-70
L68	C 22	
M71-72		**Public services**
Direct fuel	**Steel & metal products**	O84
	C 24	P85
Food	C25	Q86
A 01	C28	Q87-88
A02		
A03	**Electronics**	**Transport**
C10-12	C 26	C 29
	C 27	C 30
Culture, sports & religious services		G 45-47
R90-92	**IT & communications**	H 49
R93	J 58	H 50
S94	J59-60	H 51
	J61	H 52-53
		N 79