NTNU
Norwegian University of
Science and Technology

The Rebound Effect of a Shift to a Green Lifestyle

Eivind Lekve Bjelle

Master in Industrial Ecology
Submission date: June 2016
Supervisor: Richard Wood, EPT
Co-supervisor: Kjartan Steen-Olsen, EPT

Norwegian University of Science and Technology
Department of Energy and Process Engineering

NTNU
Norwegian University
of Science and Technology

Department of Energy
and Process Engineering

EPT-M-2016-14

MASTER THESIS

for

Student
Eivind Lekve Bjelle

Spring 2016

The rebound effect of a shift to a green lifestyle

Tilbakeslagseffekten ved eit skifte til ein grøn livsstil

Background and objective

To avoid serious climate change, countries have agreed that we need to limit global temperature rise to 2°C above pre-industrial levels. In order to achieve this, considerable changes must take place, both on the producer and consumer side. Most empirical research shows growth in consumption outpacing reductions due to technology. Hence reducing the carbon footprint of households is vital in order to avoid climate change, and studies propose that a shift to a green lifestyle is an important action in order to reach the temperature target. Such a shift would require the consumers to change their consumption pattern in areas such as personal transport, food consumption, residential heating and other goods and services. A shift to a green lifestyle could in the case of reduced consumption, be accompanied by a cost reduction for the consumer. When the consumer re-spends the saved money, a rebound effect arises as a reduction in the greenhouse gas emissions saved from the shift to a green lifestyle. The size of the rebound effect depends on which goods and services the consumer purchases. In some cases, it could lead to a higher carbon footprint than before the shift to a green lifestyle.

While there is much focus on reducing the carbon footprint of households, the rebound effect receives little attention. The student will consider the actions demanded by Norwegian households in order to reduce their carbon footprint to a level where the 2°C is achievable. A range of scenarios can be created for the change to a green lifestyle and for re-spending of the money saved. The student will also examine different approaches for calculating how consumers spend additional income, including average and marginal spending patterns. In order to calculate the total abatement actions needed by household to reach the 2°C, while also including the rebound effects, the student can use linear programming approaches to explore scenarios for green consumption.

The following tasks are to be considered:

1. Perform a literature review of the rebound effect in carbon footprints studies.
2. Examine the carbon footprint of Norwegian households and extract policy information on behavioural changes needed to reach the 2°C target – so called "green lifestyle" policies.
3. Explain methods to calculate carbon footprints, and explore alternate methods of re-spending of expenditure savings.
4. Calculate the reduced expenditures of a shift to a green lifestyle and the rebound effect

5. Use linear programming to calculate the abatement actions needed to reach the 2°C target, when also including the rebound effect.

-- " --

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 13. January 2016

Olav Bolland
Department Head

Richard Wood
Academic Supervisor

Research Advisor:

Preface

This thesis concludes my master studies in Industrial Ecology at the department of Energy and Process Engineering (EPT) at the Norwegian University of Science and Technology (NTNU).

With an academic background from economics, what sparked my interest at the Industrial Ecology studies was the connection between economic growth and sustainable development. I wanted to examine the connection further, and found this possibility in the input-output analysis course at NTNU.

The work of my specialization project in fall 2015 increased my interest in the subject and inspired me to research it further. The goal of this thesis has been to examine the importance of consumption side measures in achieving the 2°C of global warming and to highlight the importance of the rebound effect.

First, I would like to thank my supervisors Richard Wood and Kjartan Steen-Olsen for excellent guidance, valuable input and fruitful discussions at our weekly meetings the last year. Their academic input have been particularly important throughout the semester. Thanks to my parents who have provided me with moral support and good advice in the writing process. I am very grateful to my girlfriend who has shown patience and encouraged me throughout the process. A final appreciation goes my classmates in the Industrial Ecology program. Thank you for two great years and for sharing long days and nights in our study room towards the end of the last semester.

Abstract

Reaching the 2°C target of global warming, requires a 40-70% reduction in anthropogenic greenhouse gas emissions. Norwegian policy makers have implemented a term called “The Green Shift” that involves a transition into products and services associated with a substantial reduction in negative consequences for the climate. The focus is primarily on the role of the government, business, and technology improvements to achieve the needed reduction. However, studies show that this might not be enough, which calls for changes on the consumption side.

Households can contribute by adapting a green lifestyle comprising of a set of actions associated with cost reductions and reductions in greenhouse gas emissions. Rather than decreasing overall consumption, the assumption is total re-spending of the money saved from implementing the set of actions to avoid contributing to potential recession. This re-spending leads to additional greenhouse gas emissions, offsetting some of the reductions achieved in the first stage, a phenomenon known as the rebound effect. Although there is much focus on reducing the carbon footprint of households, the rebound effect receives less attention.

Cost changes and reductions in greenhouse gas emissions build on findings in the literature. Data from the Norwegian consumer expenditure survey serves as the basis for developing scenarios of re-spending. Calculations on rebound effects involve the use of input-output analysis, using EXIOBASE2, a multi-regional environmentally extended Input Output database. Optimization by linear programming approaches examine the needed changes by households to reach different emission reduction targets.

Implementing the green lifestyle without re-spending shows a 58% decrease in an average Norwegian household’s carbon footprint. When including re-spending, the reduction drops to 24-35% depending on the pattern of re-spending. The analysis shows that the key to reducing household carbon footprints to the requirements within the 2°C target of global warming is to curb the rebound effect. The linear programming results suggest that through implementing a pattern of re-spending restricted to specific goods and services, households can achieve up to a 50% reduction in carbon footprint with the lifestyle changes suggested. Increased focus on household behavioral changes combined with production side measures can provide the key to achieving the 2°C target of global warming.

Samandrag

Det trengs ein reduksjon på 40-70% i utslepp av menneskeskapte drivhusgassar for å nå 2-gradersmålet for global oppvarming. Norske myndigheiter har eit mål kalla "Det Grøne Skiftet" som inneber ein overgang til produkt og tenester som gir betydeleg reduksjon i negative konsekvensar for klima og miljø, enn det som er tilfelle i dag. I det grøne skiftet er det lagt vekt på at næringsliv, styresmakter og teknologiutvikling skal sørga for dei naudsynte reduksjonane. Fleire studie har vist at dette ikkje er nok, noko som fordrar til forandringar på konsumentsida.

Hushalda kan medverka ved å tileigna seg ein grøn livsstil samansett av ulike handlingar som reduserer både kostnadar og drivhusgassutslepp. Ved å forbruka pengane som vert spart på å utføra desse handlingane, kan hushalda halda det totale forbruket konstant for å framleis bidra til økonomisk vekst. Dette forbruket fører til nye drivhusgassutslepp, som utliknar noko av reduksjonen frå det første stadiet. Denne utlikninga vert kalla tilbakeslageffekten. Sjølv om det er mykje fokus på å redusera karbonfotavtrykket til hushalda, har ikkje tilbakeslageffekten fått same merksemd.

Kostnadsforandringar og reduksjon i drivhusgassutslepp frå dei ulike handlingane byggjer på litteratursøk, medan ulike forbruksmønsterscenario er basert på tal frå den norske forbruksundersøkinga. Talfesting av tilbakeslagseffektar er gjort ved bruk av input-output analyse og den multiregionale miljøutvida input-output databasen EXIOBASE2. Dei naudsynte forandringane som hushalda må gjennomføra for å nå ulike utsleppsmål vert utforska ved bruk av lineær programmering.

Resultata viser at eit gjennomsnittleg norsk hushald kan oppnå 58 prosent reduksjon i karbonfotavtrykket sitt. Når pengane som er spart vert forbrukt, går reduksjonen ned til 24-35 prosent, avhengig av forbruksmønster. Analysen viser at nøkkelen til å krympa hushalda sitt karbonfotavtrykk til nivåa innanfor 2-gradersmålet er å redusera tilbakeslagseffekten. Resultata frå den lineære programmeringa tyder på at gjennom å avgrensa forbruket av dei pengane som vert spart ved å innføra den grøne livsstilen, til spesifikke produkt og tenester, kan hushalda oppnå opp til 50% reduksjon i karbonfotavtrykk. Eit auka fokus på åtferdsforandringar i hushalda kombinert med tiltak på produksjonssida kan vera nøkkelen for å nå 2-gradersmålet for global oppvarming.

Table of Contents

List of figures

List of tables

Abbreviations

AFOLU	Agriculture, Forestry, and Other Land Use
CaCO3	Calcium carbonate
CaO	Calcium oxide
CGE	Computable General Equilibrium
CH4	Methane
CO2-eq	Carbon dioxide equivalents
EEBT	Emissions embodied in bilateral trade
EEIO	Environmentally extended input-output analysis
EF	Ecological Footprint
GHG	Greenhouse gas
GWP	Global Warming Potential
IOA	Input-Output Analysis
IPCC	Intergovernmental Panel on Climate Change
kWh	Kilowatt hour
LCA	Life Cycle Assessment
MDF	Medium-density fiberboard
MJ	Megajoule
MRIO	Multi-regional input-output
N2O	Nitrous Oxide
OECD	Organization for Economic Cooperation and Development
Pkm	Passenger-kilometer
PET	Polyethylene terephthalate
PPM	Parts per million

TMB Travel Money Budget

WTM World Trade Model

1 Introduction

1.1 Motivation

The need for a radical shift in behavior has probably never been larger than now, with the world facing the threat of global warming. Some models show a potential increase in average global temperature by the year 2100 of 4-5°C compared to the period 1986-2005 (Pachauri et al., 2014). According to the fifth IPCC report on global warming (Pachauri et al., 2014), a continued emission of greenhouse gases, leading to further global warming, will increase the likelihood of severe and irreversible impacts for people and ecosystems. Mitigating climate change requires substantial and sustained reductions greenhouse gas emissions.

Most agree on the importance of reduce anthropogenic GHG emission. The discussion rather centers on how we should do this and who has the largest responsibility of making changes. Two of the central ideas are that producers are responsible or that consumers are responsible. However, both parties have vital roles in reducing GHG emissions. Producers contribute through technology or efficiency improvement, while consumers contribute through behavioral changes.

The main difference of accounting for responsibility of emissions is that production-based national emission inventories account for domestic production including exports, while consumption based inventories subtract exports, but include imports (Peters, 2008). Accordingly, the difference between the two lies in the emissions embodied in international trade (Kanemoto et al., 2011). The production-based approach has previously been the most used, but in recent years, the consumption-based approach has gained popularity (Peters, 2008). Countries with emission-intensive exporting industries have emphasized the bias in producers being responsible for emission intensive exported good. Instead, they argue that importers of these goods should be held responsible (Kanemoto et al., 2011).

The consumption-based approach stems from the Ecological Footprint (EF) methodology (Rees, 1992). Rees (1992) used cities as an example to show that although we think of cities as geographically discrete places, the total area of land required to sustain an urban region is typically an order of magnitude larger than that within the city borders. Consequently, one should not look at the city as a separate entity, but rather examine the impact it has on the rest of the world. This idea is similar on a micro level, replacing cities with consumers. If the consumer of a final product is responsible for the entire ecological impact of the process that generated that product, we should charge the consumer for the total emissions related to the process (Bastianoni et al., 2004). Holding the consumer responsible for emissions along the production chain of goods and services is today considered desirable from an environmental perspective (Peters, 2008). Two different approaches exist within the consumer responsibility framework. The emissions embodied in bilateral trade (EEBT) approach considers total trade flows by using domestic emission intensities, while the multi-regional input–output analysis (MRIO) approach considers trade only into final consumption with global emission intensities (Peters, 2008, Kanemoto et al., 2011). The consumption-based approach is however not without challenges, such as implementation problems due to wide system boundaries (Peters, 2008).

Many researchers have pointed out the need for a shared responsibility of emissions between producers and consumers (Lenzen et al., 2007, Peters, 2008, Bastianoni et al., 2004, Munksgaard and Pedersen, 2001). These papers suggests different methods of sharing the responsibility. Peters (2008) weight the responsibility, while Munksgaard and Pedersen (2001) make a GHG emission trade balance. Others attempt to separate the responsibility of production processes by consistently delineating supply chains into mutually exclusive and collectively exhaustive responsibilities to be shared by all actors in an economy (Lenzen et al., 2007) or by assigning emissions to countries in proportion to the embodied GHG emissions needed along the chain (Bastianoni et al., 2004). The main challenge of these approaches is to avoid double counting of emissions.

A central question is how producers and consumers should act in order to influence each other to make environmentally beneficial choices. Assuming that consumers drive production through demanding goods and services, they have power through choosing which goods and services to buy. Environmentally conscious consumers have the incentive to buy products associated with low GHG emissions. Thus, they influence producers through demanding these products.

Goodall (2010) highlights the importance of consumers making active environmental choices. He suggests that businesses are not free to act in environmentally responsible ways unless their customers change their requirements, since producers who independently take environmental choices will lose in the competitive market, given that the environmental act comes with a cost for the business. Hence, consumers must actively demand that businesses make eco-friendly choices by changing their behavior or consumption pattern.

On the other hand, producers can be motivated to influence consumers. An example of this is if producers face a tax on GHG emissions in the production of goods and services. This creates an incentive for the producers to lower GHG emissions in production and consequently they influence consumers through making the product available on the market.

Holding exclusively the consumer or producer responsible for emissions seems to tell only part of the story. Shared responsibility approaches offer useful insight of assigning responsibility to different actors. If such approaches are not used, one should see the consumption- and production approach as complementary rather than replacements for each other. Several studies show that relying on either efficiency improvements or behavioral changes from consumers will not be enough to reach the reduction in emissions required to meet the 2°C target of global warming (Dietz et al., 2009, Goodall, 2010, Intergovernmental Panel on Climate Change, 2015, Swart et al., 2003, Alcott, 2008). When it comes to assigning responsibility, although the producer responsibility deserves attention, a majority of studies and policymakers do seem to favor the consumer responsibility viewpoint. This requires more environmentally aware consumers, with higher knowledge of the environmental performance of the activities they take part in.

There is an apparent contradiction between economic systems relying on growth to progress and the mitigation of climate change. From the perspective of governments, economic growth is essential, and they strive to find solutions that combine economic growth with climate change mitigation. Some reports have shown that such a development is possible. Through technological innovation and investments in efficient low-emission solutions it is possible to achieve higher employment, higher business profits and economic growth (The New Climate Economy, 2014, as cited in Klima- og miljødepartementet, 2014). However, there is no guaranty that economic growth is associated with a positive development for the climate and the environment. Arrow et al. (1995) argue that it is the content of economic growth; the composition of inputs and outputs that determine the environmental development associated with the growth. Some studies have attempted to show that an increase in GDP per capita can be associated with a reduction in environmental degradation, maybe the most famous being the Environmental Kuznets Curve, that proposes that the environmental impact indicator is an inverted U-shaped function of income per capita (Stern, 2004, Grossman and Krueger, 1991).

However, the robustness of this model has been heavily criticized (Stern, 2004, Stern et al., 1996).

Turning the question around, some research focus on the influence of climate change on economic growth. The findings suggest that ignoring climate change eventually will damage economic growth (Stern, 2007) and that poor countries will experience the largest damage on their growth reducing agricultural output, industrial output and aggregate investment as well as political instability (Dell et al., 2008)

Even though there is an increasing focus on the need for altering our lifestyle to reduce global warming, we are still not seeing the changes required. In Norway, the government and policymakers have introduced a term named the Green Shift (Ministry of Climate and Environment, 2014). The idea is that within a 30-50 year period, the society is to restructure in a way in which growth and development will take place within nature's tolerance limits. The focus is on a transition to products and services that mitigate climate change and negative environmental consequences. One of the primary goals is significant emission reductions in the transport sector, with the entire sector being fossil free in 2050. To achieve these goals, the Norwegian government will use policy instruments such as taxes on high emitting vehicles.

Generally, there is a large focus on the important role of the government, technological development, innovation, industries and businesses to achieve the Green Shift. The role of the individual consumer, on the other hand, receives less attention.

The consumer can implement two different types of action to achieve GHG emission reductions. The first is to reduce overall consumption; with the global population expected to increase in several decades to come, it seems unlikely that we can continue the increase in consumption of goods and services that we now are experiencing. Many researchers find that a decrease in material consumption is an important step for mitigating climate change (Garnaut, 2008, Stern, 2007). Furthermore, studies show that the growth in material consumption is not associated with an increase in happiness (Clark et al., 2008, DeLeire and Kalil, 2010, Alcott, 2008). Jackson (2005) found the existence of what he called a "double dividend", a win-win situation where we live better by consuming less and at the same time reduce our impact on the environment. The second choice is to alter the pattern of consumption. This involves moving consumption away from goods and services associated with high GHG emissions to goods and services associated with lower GHG emissions. Such a restructuring in, rather than a decrease in household consumption, will change the economic structure, but economic growth is still possible. Examples of changed consumption that will substantially lower the carbon footprint of individuals or households is to move consumption away from air transport and consumption of cattle and sheep (Goodall, 2010, Gardner and Stern, 2008, Garnaut, 2008).

Some studies suggest that consumers lack information on which choices they should make to curb climate change. Young et al. (2010) report that there is an “attitude-behavior gap”, where 30% of consumers state that they are very concerned about environmental issues, but they are struggling to translate this into purchases. Providing information on specific actions consumers can implement, how effective they are in reducing GHG emissions and the cost for the consumer of implementing each action, can provide information for the consumer as well as contextualize how different actions contribute to their carbon footprint. Studies find that ranked lists of actions and the benefits they produce, are effective and avoid the problem of consumers mistaking which mitigating actions are most beneficial (Gardner and Stern, 2008)

Implementing a set of behavioral actions to reduce GHG emissions typically comes with a cost reduction for the consumer or the household. Following the idea that total expenditure levels remain unchanged, the household re-spends this money. Re-spending the saved money on goods and services will emit additional GHG emissions. These re-added emissions produce a rebound effect, where some or all of the emissions saved from implementing actions in the first stage are lost due to the re-spending on goods and services.

Many studies have shown that the rebound effect is present and in some cases considerable (Binswanger, 2001, Hertwich, 2005, Alfredsson, 2004, Druckman et al., 2011, Greening et al., 2000, Thomas and Azevedo, 2013a). However, discussions of sustainable development often neglect the rebound effect (Binswanger, 2001, Hertwich, 2005, Alcott, 2008). A simple example illustrates the importance of the rebound effect. Suppose a household intending to lower their carbon footprint implements measures such as eating less meat, driving less and reducing household heating and cooling, and saves a certain amount of money from these measures. In the next stage, the households decides to spend that money on travelling by plane to a remote destination on holiday. Chances are that the GHG emissions generated by this travelling fully offsets the GHG emissions initially saved from the measures intended to lower their carbon footprint. If households lack information or knowledge about the rebound effect, attempts at reducing their carbon footprint can instead lead to an increase in GHG emissions.

1.2 Scope

There is a large focus on the role of corporations and governments to achieve the GHG emission reductions required to meet the 2°C target of global warming. However, research has shown that businesses and efficiency improvements alone is not enough to curb climate change. This calls for active changes on a household level. By quantifying GHG emission reductions and cost changes of a set of actions that households might implement, the idea is to inspire households to pursue a reduction in their carbon footprint and to feel a part of contributing to reducing global warming.

Since reducing overall consumption is a measure that potentially has negative influences on the economic system through stagnating economic growth, the premise of this thesis is rather a restructuring of household consumption. The starting point of the analysis is that households gain the knowledge on how they can lower their carbon footprint and want to implement a set of actions that reduce GHG emissions. When households implement these measures, it leads to a change in the pattern of consumption. In the first stage, when implementing these measures, the households are likely to obtain a lower cost compared to before implementing the measures. This cost reduction is equivalent to an increase in the household’s disposable income. In the second stage, the households re-spend this additional income, giving rise to the rebound effect. As the rebound effect in a worst case scenario can lead to higher GHG emissions than before implementing the actions, it is essential that households carefully consider how they re-spend the money saved in the first stage. Scenarios of re-spending money according to different spending patterns serves as a basis for analyzing the extent of the rebound effect and a discussion of how households should re-spend additional income. Under the assumption that overall household expenditure stays the same, a certain degree of offsetting of the GHG emission savings from implementing the actions alone is inevitable. This highlights the importance of households should gaining knowledge on the dynamics of the rebound effect. The final step of the analysis is to investigate whether the average Norwegian household can reduce their carbon footprint to the requirement of the 2°C target of global warming. Hence, I ask the following research questions:

- What can Norwegian households do to reduce their carbon footprint?

- How do Norwegian households re-spend the saved money from implementing the actions?
- How large is the rebound effect of this re-spending?
- How can households reduce the rebound effect?
- Can households reach the GHG emission reduction required to meet the 2°C target of global warming?

1.3 Thesis Structure

The thesis follows a format of six sections, including the current introduction.

Part 2 is a literature review consisting of the 2°C target for global warming, the current state of the Norwegian carbon footprint in a global setting, and the rebound effect. The literature review continues with a focus on the needed reduction in GHG emissions required by Norwegian households and actions that households can implement to reach this target. The section rounds off with an examination of different approaches to calculating spending patterns.

The methods section in part 3 includes the approaches used to calculate GHG emissions and cost reductions associated with each action, an analytical derivation of the input-output analysis framework and the rebound effect framework. The methods section also involves several adjustments made in order to fit the data to EXIOBASE2. Next follows the methodology for calculating different spending patterns and conversions needed to fit the calculations of the actions to the EXIOBASE2 database. Next follows two approaches using linear programming to finding the changes needed in order to reach different emission reduction targets. The first approach involves changing the spending pattern, while the other approach is to change the number of actions.

The results in part 4 include calculations on cost reduction and GHG emission reductions from implementing the actions, results from three scenarios of spending patterns, rebound effect results, before rounding off the section with results from the linear programming. Part 5 presents a more thorough discussion of the results, while part 6 includes concluding remarks on the implications of the results.

2 Literature and Background

2.1 The 2°C Target of Global Warming

According to the IPCC, it is now 95 percent certain that humans are the main cause of current global warming (Pachauri et al., 2014). The world seems to agree to a goal of stabilizing temperature increase to below 2°C relative to pre-industrial levels. To achieve this goal, we must substantially reduce the emission of anthropogenic GHG, with the most important being CO2, contributing to about 65% of the total (Pachauri et al., 2014).

Since CO2 is a greenhouse gas that stays in the atmosphere for a long period, many studies operate with cumulative CO2 emissions when discussing the 2°C target. More specifically, researchers discuss how much CO2 we can emit if we are to stay below a 2°C rise in global average temperature compared to pre-industrial levels. The CO2 concentration in the atmosphere is measured in parts per million (ppm), and the development in this parameter is closely related to global temperature change (Jansen, 2013). For pre-industrial times, most estimates of the CO2-consentration are in the range of 260-280 ppm (Wigley, 1983). However, especially since the 1960s this number has increased more rapidly than ever before (Figure 2.1).

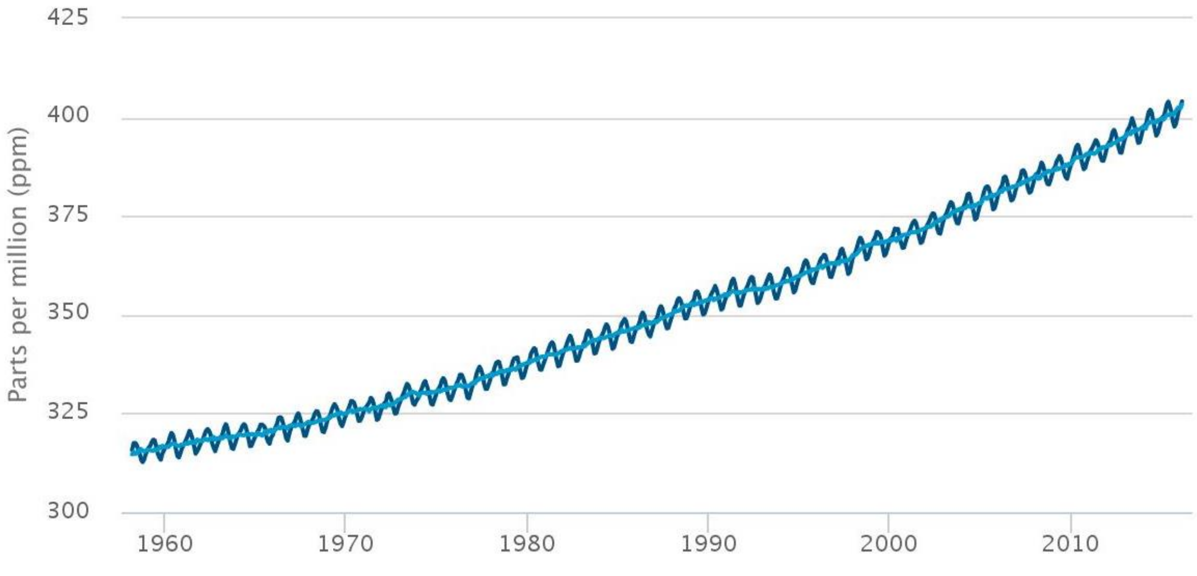


Figure 2.1: Development in CO2 concentration in the atmosphere since 1960, measured at the Mauna Loa Observatory, Hawaii

(Scripps Institution of Oceanography, 2016, as cited in Energi og Klima, 2016)

To achieve the 2^0C target, the CO2-concentration in the atmosphere needs to decline. The Organisation For Economic Co-operation and Development (2012) suggests that at a concentration of 450 ppm, there is a 50% chance of stabilizing the climate change at 2°C above pre-industrial levels, while baseline projections suggest an atmospheric concentration of 685 ppm CO_2-eq by 2050. Some studies suggest that we have to lower the CO_2 concentration even more, suggesting that a 2°C rise in global average temperature would have disastrous consequences, and that we should instead aim for a 1°C rise in global average temperature (Hansen et al., 2013). To achieve this, the concentration would need to be as low as 350 ppm. This involves a considerable decline in the concentration of just above 400 ppm that we face today.

The question remains as to how much CO_2 we can emit in the future, assuming the cumulative nature of CO_2 in the atmosphere. Energi og Klima (2016) suggest that we already have emitted about ¾ of the CO_2 in a 2°C target scenario. Peters et al. (2015) suggest that to have a 66% or larger chance of holding global warming to less than 2°C, total cumulative CO_2 emissions must remain below 3670 $GtCO_2$, from 1870 until well into the future. In 2014, the total remaining CO_2 quota was 903 $GtCO_2$ (with projections for 2015 suggesting a remaining quota of 865 Gt CO_2) (Figure 2.2). The calculated global emissions in 2014 was 35.9 Gt CO_2. Le Quéré et al. (2015) find that at current emission rates, the remaining quota will last around 20 years.

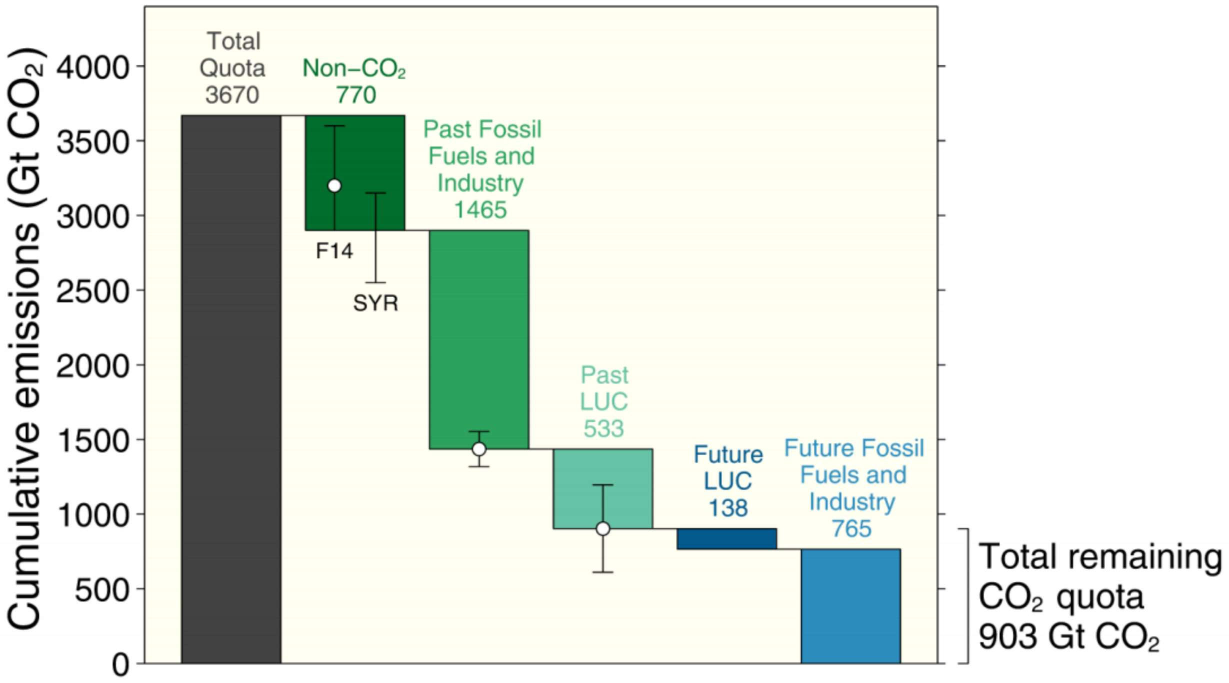


Figure 2.2: The remaining carbon quota for 66% chance to reach the 2°C target.

LUC=Land use Change

(Peters et al., 2015, Le Quéré et al., 2015)

It is evident that we need changes in anthropogenic emission patterns immediately.

The fifth IPCC report suggested that in order to reach the 2°C target for climate change, we would have to reduce our emissions from 48Gt (10^9 tons) CO2-eq in 2010 to 17 to 23 Gt CO2-eq. This corresponds to a decrease of 52-65% (Collins et al., 2013).

van Sluisveld et al. (2016) find that many studies so far have focused on technical solutions, such as renewable, carbon capture and energy efficiency technologies, to meet the 2°C climate target. However, the studies show that it becomes increasingly more difficult to obtain the 2°C climate target through technical solutions alone. They argue that we must include non-economical and non-technological drivers of energy system transformations if we are to reach the 2°C target. This highlights the need for lifestyle changes on an individual or household level. However, behavioral changes should be in addition to other measures, such as technological and economic measures.

Lifestyle changes come with various costs and effort needed. According to Steg (2008) people are more likely to carry out environmentally friendly behavioral changes with low cost and low efforts than changes associated with high costs and efforts. However, in order to reach the 2°C target, more costly measures requiring more effort, could be required as well.

A reason for the need for drastic changes in lifestyle is that the needed GHG emission reductions from households is substantial. Consumption by households constitute a large part of the anthropogenic GHG emissions when taking a life cycle perspective. The IPCC Fifth Assessment Report suggests that globally, if we are to reach the 2°C target, we must reduce the anthropogenic GHG emissions by 40-70% in 2050, and emissions levels near zero or below in 2100, compared to 2010 emission levels (Pachauri et al., 2014). It is reasonable to assume that households should aim for such emission reductions.

2.2 Carbon Footprint

Many researchers have discussed the true meaning of the term “carbon footprint” (Weidema et al., 2008, Wiedmann and Minx, 2008, Wright et al., 2011). It seems that the discussion revolves around whether the carbon footprint only should include CO2 emissions or other GHGs, such as CH4 and N2O as well. Many do seem to include several GHGs and use the unit CO2 equivalents, ending up with an indicator close to the Global Warming Potential indicator (GWP) used in life cycle assessment (LCA). Additionally, using the CO2-eq per monetary unit has the advantage of including information on emissions caused by the changes in consumption related to the money saved or extra money spent (Weidema et al., 2008).

Many studies have calculated the carbon footprint of households, some for households in a specific country (Goodall, 2010, Jones and Kammen, 2011, Steen-Olsen et al., Accepted for publication, Druckman and Jackson, 2009, Weber and Matthews, 2008), while others compare the carbon footprint of different countries (Hertwich and Peters, 2009, Ivanova et al., 2015). Hertwich and Peters (2009) break down the carbon footprint into consumption groups for several countries, which makes it possible to compare the composition of carbon footprints of different countries. In general, food consumption constitute a larger share of the per capita carbon footprint of developing countries, than in developed countries. In developed countries, mobility, trade and manufactured products make up a larger share of the per capita footprint than in developing countries (Figure 2.3).

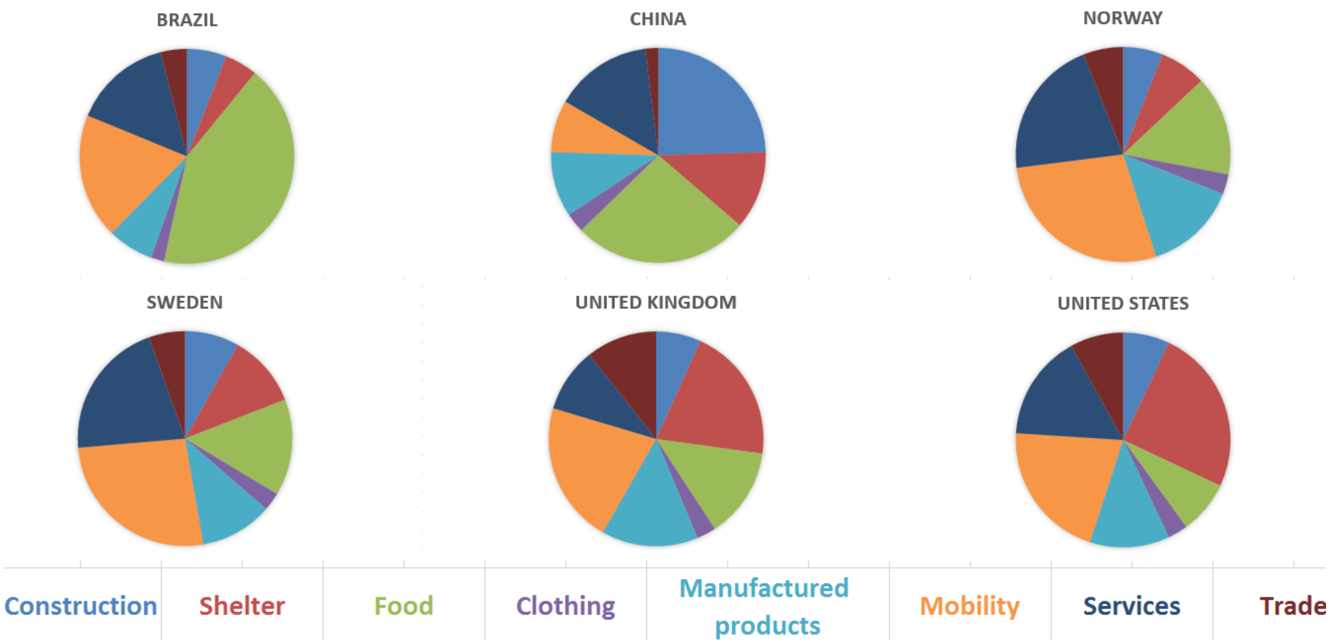


Figure 2.3: Relative share of per capita GHG footprint by consumption category for selected countries

(Hertwich and Peters, 2009) and author's own work

The following section examines closer how different consumption sectors contribute to carbon footprints, with a specific focus on Norway.

2.2.1 Current State of the Norwegian Carbon Footprint

The carbon footprint of a Norwegian person was according to Carbon Footprint of Nations (2010) 10.1 tons CO2-eq in 2010. The study takes a consumption approach, meaning that the final consumer is responsible for all GHG emissions associated with producing the good or service consumed. In this study, the carbon footprint of Norwegians had been stable around 15 tons CO2-eq per capita from 1990 until 2007, before suddenly falling to numbers around 10 tons CO2-eq per capita from 2007 to 2010. This sudden jump in emissions is unlikely, and probably more related to the calculation methods rather than a drastic reduction in emissions. They expect the margin of error of their calculations to be under 20%.

Many researchers agree that taking a consumption-based approach is the fairest way to account for emission responsibility. One of the primary reasons for this is that considerable portions of a household's carbon footprint can stem from indirect emissions embodied in imported goods and services. A recent study shows that as much as 43% of per capita emissions in Norway were indirect emissions embedded in imported goods consumed in Norway (Narbel and Isaksen, 2014). Another reason in favor of choosing consumption-based emission accounting is that of avoiding carbon leakage. If the norm is that nations only account for emissions within their own borders, then those that wish to curb their carbon footprint can move carbon intensive production to other countries to lower their own footprint (Weber and Peters, 2009, Stern, 2007, Baiocchi and Minx, 2010).

Also taking a consumption approach, Steen-Olsen et al. (Accepted for publication) found the carbon footprint of Norwegian households to be 22.3 tons CO2-eq per household in 2012. The household size in this study was 2.12 persons, giving per capita emissions of 10.5 tons CO2-eq. By examining the development in the carbon footprint of Norwegian households in the period 1999-2012, they found that the carbon footprint had increased by 26% in the period. This development does not correspond well with the numbers presented in Carbon Footprint of Nations (2010), however, both studies find similar carbon footprints for the most recent years.

The Millennium Development Goals Indicators (2015) found the Carbon footprint of Norway to be 9.2 tons CO2 per capita in 2011, however, they only include CO2, and not the other greenhouse gases that contribute to global warming, such as Methane (CH4) and Nitrous Oxide (N2O). According to the Emission Database for Global Atmospheric Research (EDGAR) (2000), 72% of anthropogenic greenhouse gas emissions are CO2, while CH4 accounts for 18% and N2O for 9%. While Hertwich and Peters (2009) found that 27.8% of global GHGs were non-CO2.

Assuming about 28% non CO2-emissions, we end up with 11.8 tons CO2-eq per capita in Norway, given that they account for the different emission intensities of the gases (Millennium Development Goals Indicators, 2015). This number is slightly higher than those found in Steen-Olsen et al. (Accepted for publication) and Carbon Footprint of Nations (2010).

Using an environmentally extended MRIO (EE-MRIO) model with an input-output table representing the flow of goods and services throughout the global economy for the reference year 2007, Ivanova et al. (2015) found the per capita carbon footprint of Norway to be 10.3 tons CO2-eq with consumption-based emission accounting. Furthermore, they found that household consumption contributed to over 60% of global GHG emissions, highlighting the importance of behavioral changes in households.

Le Quéré et al. (2015) presents The Global Carbon Budget accounting for anthropogenic CO2 emissions and their redistribution among the atmosphere, ocean, and terrestrial biosphere. As a part of this project, they account for consumption-based emissions by countries, enabling a comparison of CO2 emissions per capita of different countries, as well as how the emissions have changed over time from 1990 to 2013. This source only accounts for CO2 emissions, not the other GHG associated with a global warming potential (Updated from: Peters et al. (2011), For an explanation of issues around consumption emissions, see: Peters et al. (2012) Consumption emissions are computed as in Peters et al. (2011) using 'territorial emissions UNFCCC' as reference).

An interesting discussing is how the per capita carbon footprint of Norway compares to that of other countries. According to Ivanova et al. (2015), the global average is 3.4 tons CO2-eq per capita. This means that the Norwegian carbon footprint is over three times higher than the global average. The United States and Luxembourg are on top of Ivanova et al. (2015)'s list with 18.6 and 18.5 tons CO2-eq respectively. When ranking the countries included in the study from highest to lowest per capita emissions, the Norwegian footprint is number 17 out of 43. However, they mostly include industrialized countries in the list, which generally have a higher footprint than the global average. On one hand, these countries are more relevant to compare to Norway, but on the other hand, it can show a skewed picture when leaving out the developing countries.

The Millennium Development Goals Indicators (2015) have a list of carbon footprint per capita for all countries in the world. Even though they only include CO2 emissions, there is reason to believe that a list of CO2-eq will be similar. Qatar and Trinidad & Tobago are the countries with the highest emissions with 40.1 and 37.8 tons CO2 per capita respectively. In the other end of the list, we have Lesotho and Mali with 0.01 and 0.04 tons CO2 per capita respectively. When ranking the emissions from highest to lowest, Norway comes out as number 23 out of 210 countries. This shows a discouraging, but probably less biased picture of the Norwegian carbon footprint compared to the rest of the world.

Even though the Norwegian per capita carbon footprint is high, compared to the world average, it might be unfair to compare it to all the countries in the world. This is because Norway is a developed country with high living standards that we are yet to see in many developing countries. However, many developing countries will see their living standards improving in the following years. Comparing the per capita carbon footprint of Norway to more similar countries, could be more reasonable. Figure 2.4 shows a comparison of the per capita carbon footprint of Norway to some of the similar Nordic countries, other European countries, the United States, as well as China and Brazil (the two latter representing developing countries). The underlying data comes from four different sources (Carbon Footprint of Nations, 2010, Millennium Development Goals Indicators, 2015, Ivanova et al., 2015, Peters et al., 2012). We notice that the other Nordic countries have footprints quite close to Norway, Sweden a bit lower and Finland higher. Compared to the other European countries in the list, the per capita Norwegian carbon footprint seems to be somewhere in the middle, with the UK, Switzerland and Germany a bit higher, and France, Spain and Russia somewhat lower. The US has the highest per capita footprint of the selected countries in all three data sources, while Brazilians and the Chinese are well below the footprint of Norwegians.

The trends in the data sources seem to be that Carbon Footprint of Nations (2010) and Global Carbon Budget (Peters et al., 2012) show the highest footprint, while Ivanova et al. (2015) report slightly lower numbers, except for Norway and the United Kingdom. Millennium Development Goals Indicators (2015) have generally lower numbers, except for Russia, China and Brazil. One can expect the number of this study to be lower, as it only includes CO2 emissions. However, Global Carbon Budget (Peters et al., 2012) also include only CO2 emissions, but generally report higher numbers. The discrepancy between the two could come from different year of data collection. Another explanation for the discrepancy could be a difference in the methods used. Global Carbon Budget do report consumption-based emissions accounting, while the Millennium Development Goals Indicators (2015) does not report the emission accounting approach.

One would expect correlations between CO2 emissions per capita and CO2-eq emissions per capita. Where this is not the case (Russia, Brazil and China), it could be explained by the year of data collection. Ivanova et al. (2015) is based on data from 2007, Carbon Footprint of Nations (2010) is based on 2010 data, Millennium Development Goals Indicators (2015) is based on data from 2011 and the Global Carbon Budget are from 2013. The higher number of Russia, Brazil and China in Millennium Development Goals Indicators (2015) and Global Carbon Budget (Peters et al., 2012) could be explained by the rapid development in these countries the latest years.

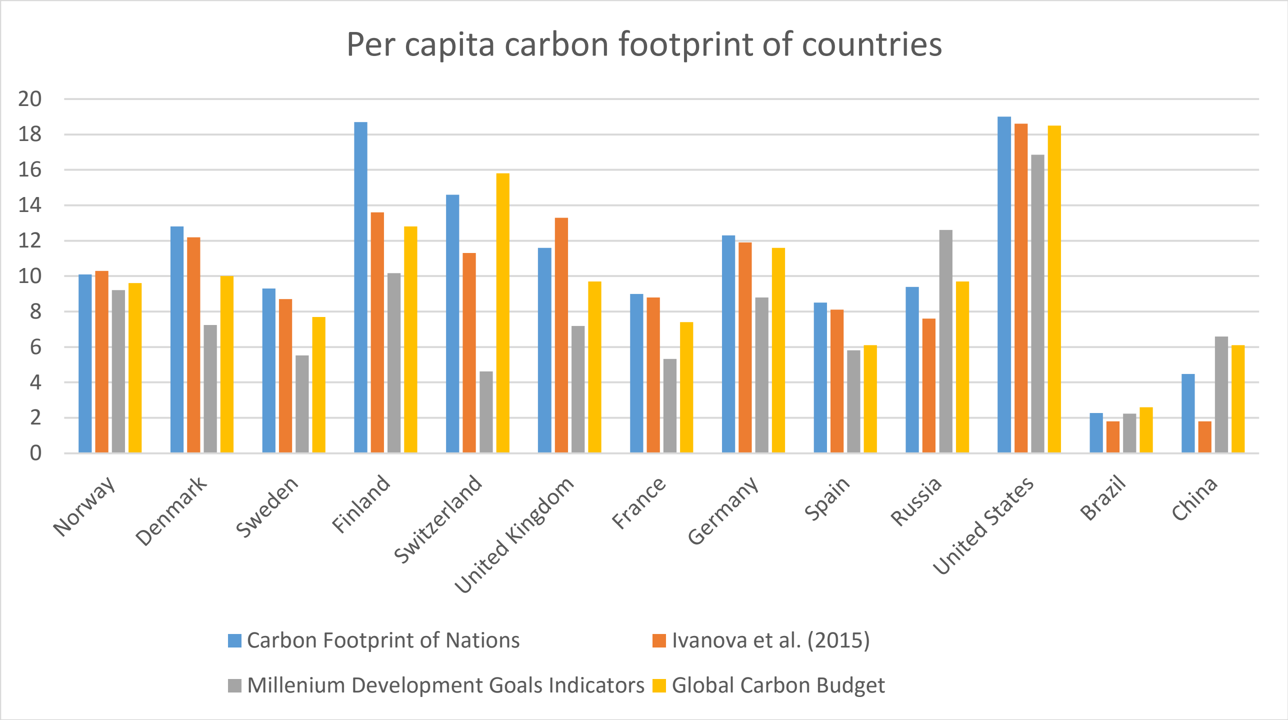


Figure 2.4: Per capita carbon footprint of countries

(Carbon Footprint of Nations, 2010, Millennium Development Goals Indicators, 2015, Ivanova et al., 2015, Peters et al., 2012)

The four data sources also provide information on how the per capita Norwegian carbon footprint has developed over time. Carbon Footprint of Nations (2010), Global Carbon Budget (Peters et al., 2012) and Millennium Development Goals Indicators (2015) provide data on carbon footprints back to 1990. Additionally, Steen-Olsen et al. (Accepted for publication) made estimations on the per capita carbon footprint of Norway, based on Norwegian consumption of goods and services from 1999 to 2012.

The sources show quite different results in development (Figure 2.5). In Global Carbon Budget (Peters et al., 2012), we observe a decline in CO2 emissions in the period 1998-2000, followed by an increase up until 2007. In the years after 2007, the emissions decrease again, but at a relatively slow rate. Carbon Footprint of Nations (2010) found a sharp decrease in the footprint in the years after 2006, followed by an increase in 2010. Millennium Development Goals Indicators (2015) and Steen-Olsen et al. (Accepted for publication) found the per capita carbon footprint was slightly increasing in the whole period of study, with the exception of a decrease in 2011 in Millennium Development Goals Indicators (2015).

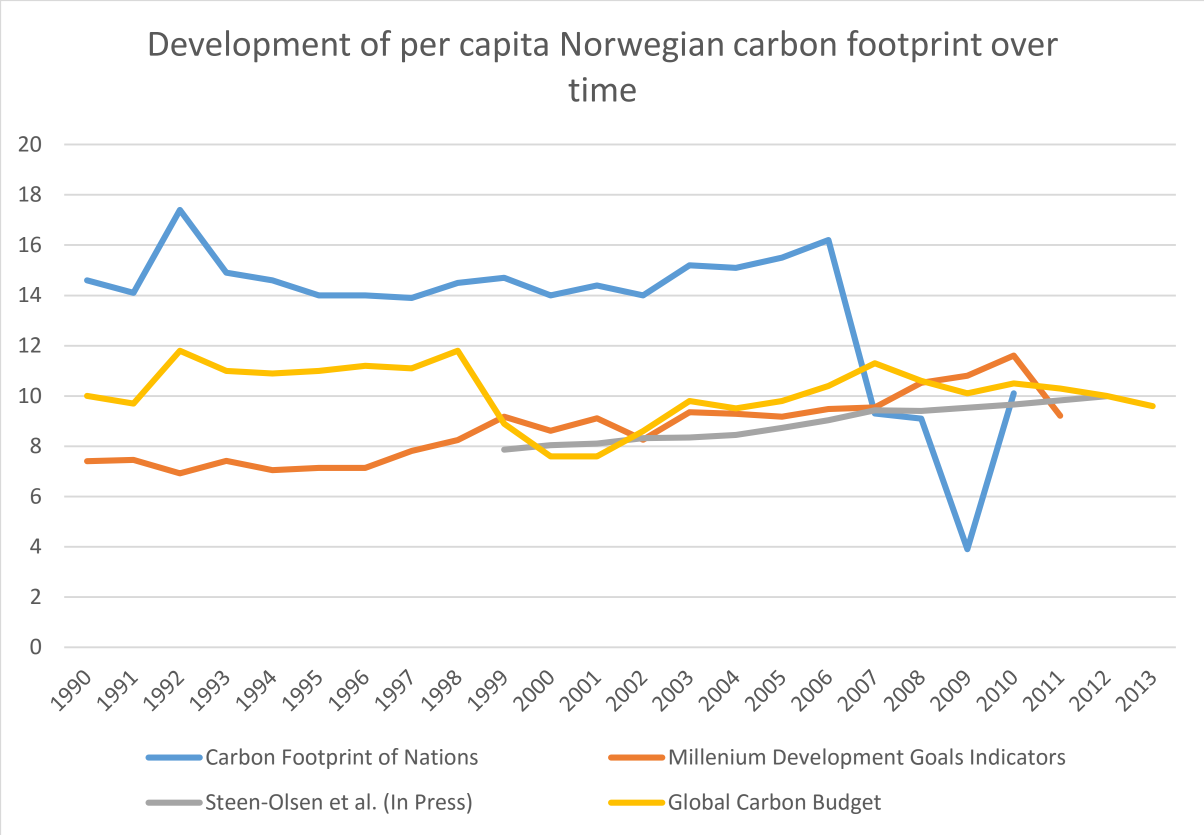


Figure 2.5: Development of per capita Norwegian carbon footprint over time

(Carbon Footprint of Nations, 2010, Millennium Development Goals Indicators, 2015, Steen-Olsen et al., Accepted for publication)

To identify what drives the per capita Norwegian carbon footprint requires a closer look at the goods and services purchased by Norwegian households. Data on detailed purchases of goods and services is provided by The Norwegian Consumer Survey from 2012 (Statistics Norway, 2013). This survey uses the COICOP classification of goods and services (United Nations Statistics Division, 2016). By using multipliers that give information on greenhouse gas emissions per monetary unit along with detailed data from the Consumer Survey, it is possible to find detailed information on emissions from specific goods and services. EXIOBASE2, a Multi-Regional Environmentally Extended Supply and Use/Input Output database (Tukker et al., 2013, Wood et al., 2015) provide the multipliers. The product classifications in EXIOBASE2 are similar, but not equal to those found in the COICOP classification, which calls for some adjustments in order to synchronize the multipliers to the product groups. It is important to mention that when synchronizing the two, there is some underreporting in the Norwegian Consumer Survey. Specifically, about 8% of the total carbon footprint and about 15% of household spending are unaccounted for in the survey (Steen-Olsen et al., Accepted for publication).

Several interesting points come up when combining data from the Consumer expenditure survey with the EXIOBASE2 database. Firstly, the list of top 10 goods and services that have the highest emissions in CO2-eq per NOK spent (Figure 2.6) show the largest multipliers in 0734, passenger transport by sea and inland waterway and 0722, Fuels and lubricants for personal transport equipment. Interestingly, passenger transport by air is number five on the list with a multiplier about four times lower than that for passenger transport by sea. This result seems surprising; however, the multiplier only reflects the emissions per NOK spent by the consumer, suggesting that price differences in the two transport modes can be the cause of the large difference between the multipliers.

The top 10 product categories in which Norwegian households spend most money (Figure 2.7) show that out of total spending Norwegians spend the most money on 0421 rentals of owner-occupiers, (renting a home) and 0711 Motor Cars.

The top 10 product categories that contribute to the largest carbon footprint (Figure 2.8) show that 0722 Fuels and lubricants for personal transport equipment (19%) and 0711 Motor Cars (8%) have the largest relative impacts. We also notice that consumption of Materials for the maintenance and repair of the dwelling (7%) Garments (3%), Meat (2%), Package Holidays (2%) also contribute to a large portion of the total footprint. Electricity, which accounts for about 3% of the total household spending, is not in the list of top 10 groups contributing to the largest carbon footprint. In fact, it only accounts for about 0.8% of the total carbon footprint. This is likely due to the low-emitting hydropower technology that dominates the electricity production in Norway.

These results make it possible to suggest areas in which Norwegians should alter their consumption habits in order to reduce their carbon footprint.

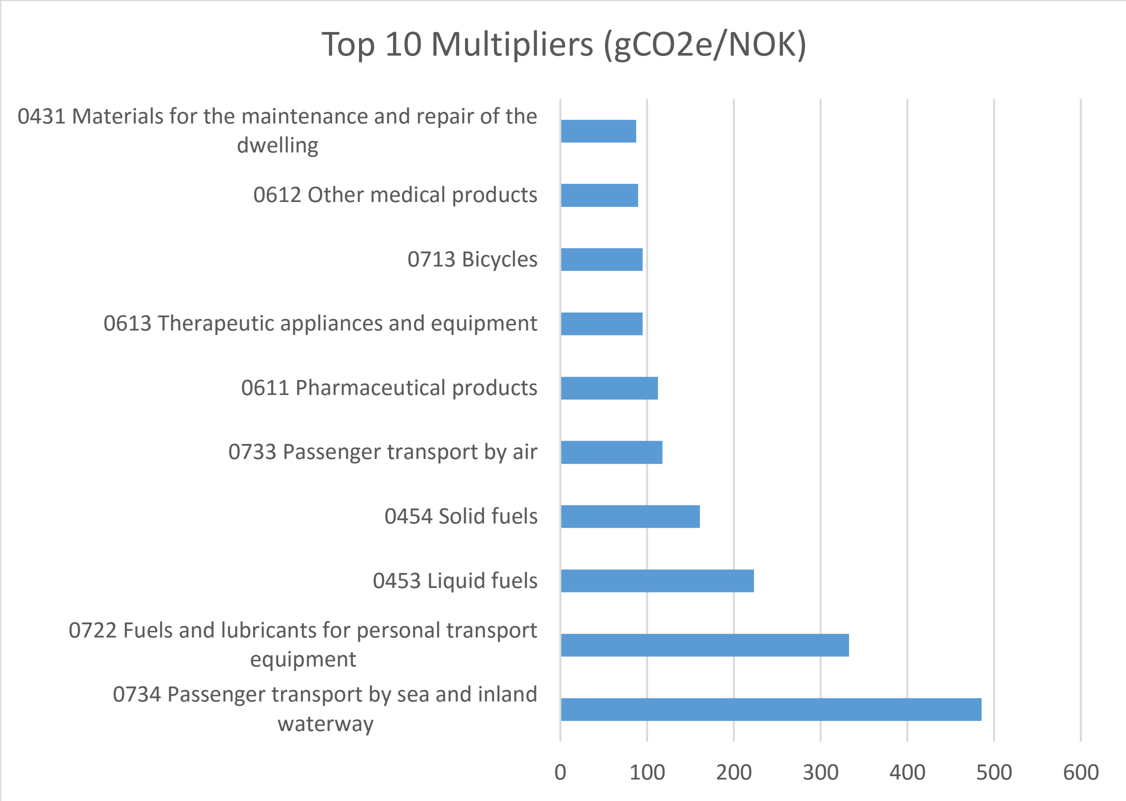


Figure 2.6: Top 10 Multipliers (gCO2e/NOK) in COICOP level 3 classification

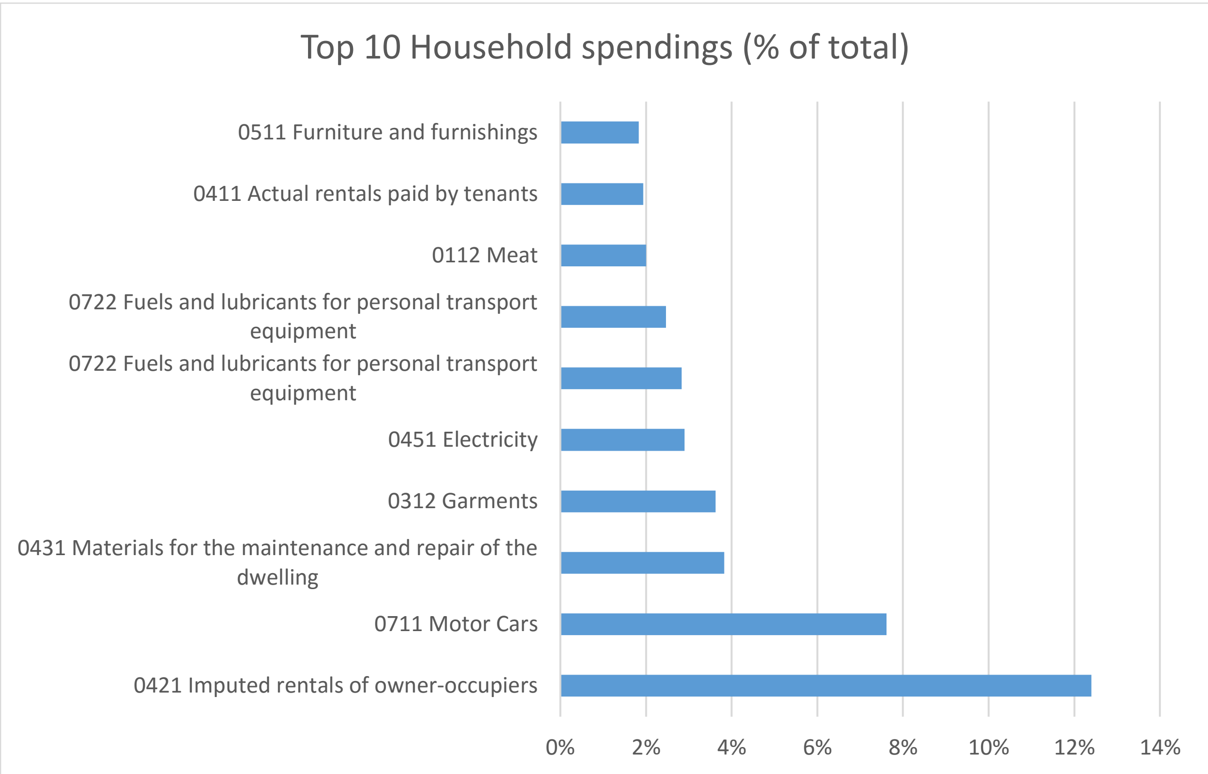


Figure 2.7: Top 10 household spending (% of total) in COICOP level 3 classification

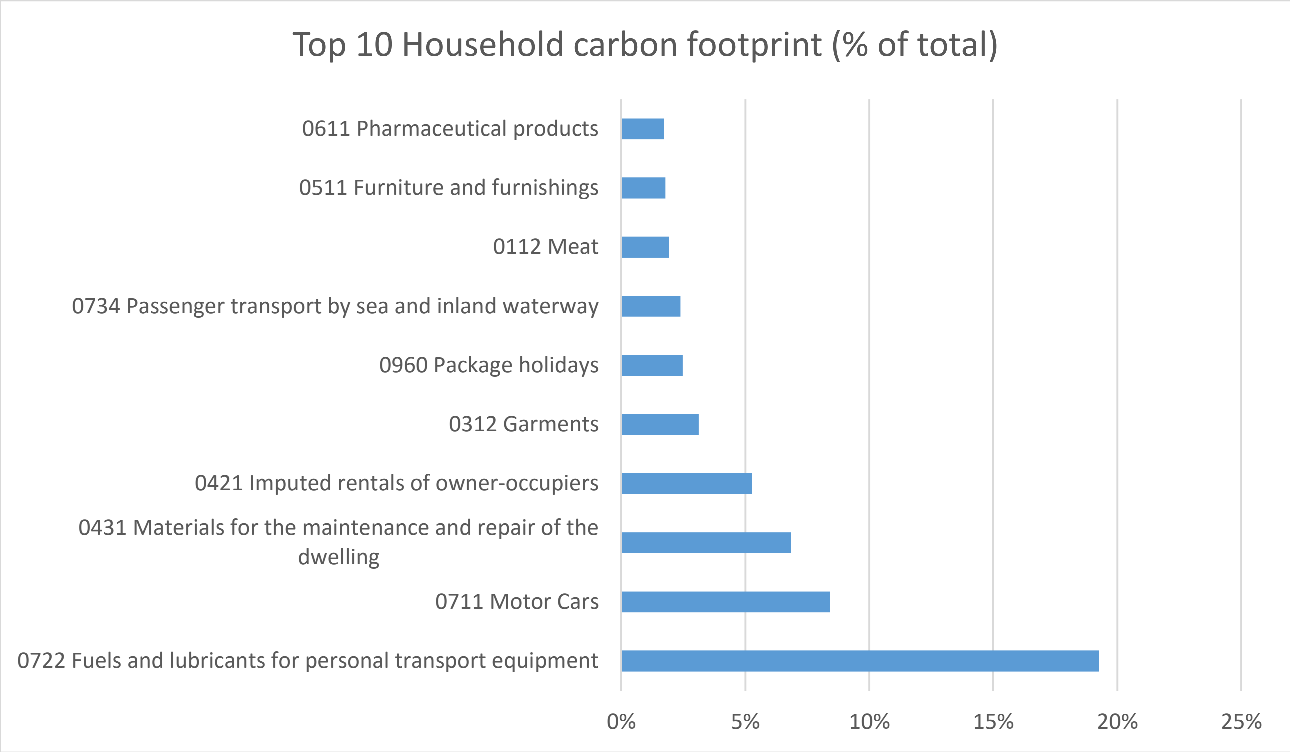


Figure 2.8: Top 10 household carbon footprint (percent of total) in COICOP level 3 classification

2.2.2 Consumption sectors

The consumption groups contributing to the largest shares of total Norwegian carbon footprint is transport (35%), Shelter (18%) and Food (10%) (Figure 2.9) according to a recent study (Steen-Olsen et al., Accepted for publication). The following section provides information on how the different components of the Norwegian carbon footprint compares to the global data, what is included in each sector and the most important drivers contributing to consumption in each sector.

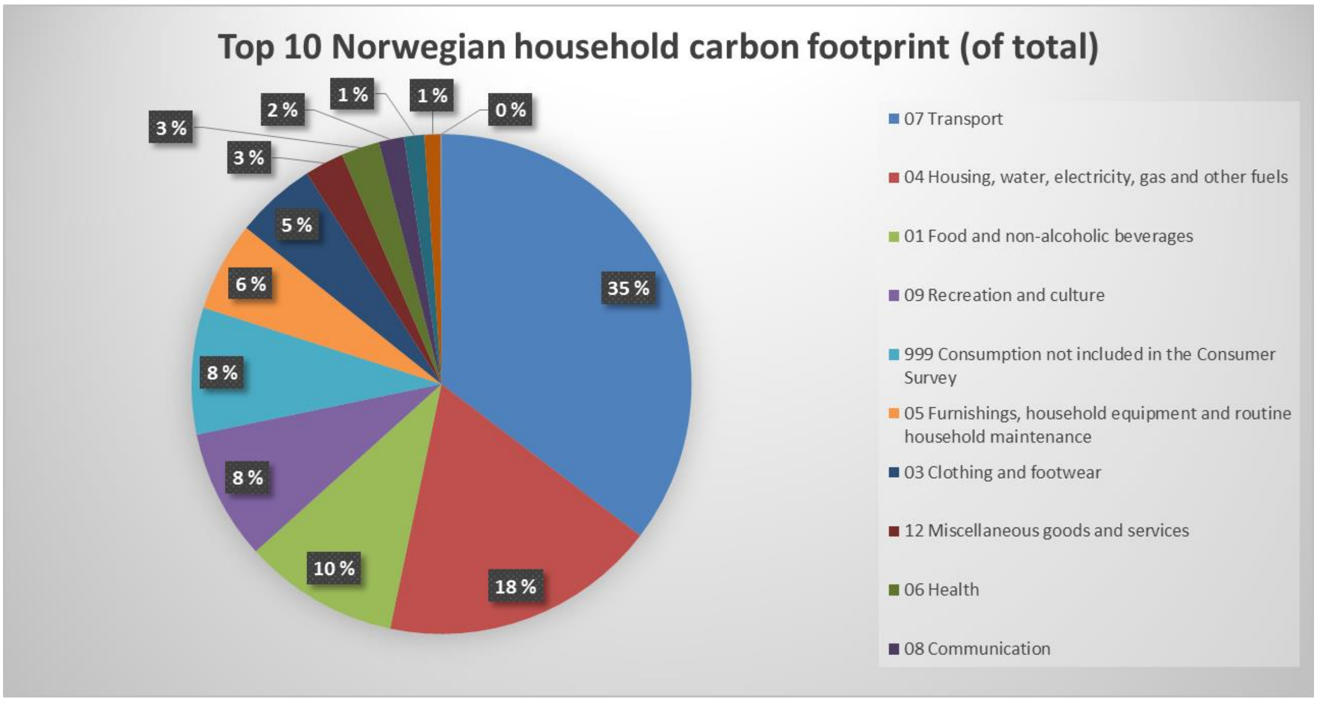


Figure 2.9: Top 10 household carbon footprint in percent of total, COICOP Level 1 classification (Steen-Olsen et al., Accepted for publication) and author's own work

2.2.2.1 Transport

Globally, the transport sector produced 7.0 GtCO2-eq of direct GHG emissions in 2010, and was responsible for 23% of total energy-related CO2 emissions (6.7 GtCO2) (Intergovernmental Panel on Climate Change, 2015). Of total direct GHG emissions (not including indirect emissions from production of fuels, vehicle manufacturing, infrastructure construction etc.), road transport contributed to 72%, Shipping to 9%, international aviation to 7% and domestic aviation to 4% (Figure 2.10).

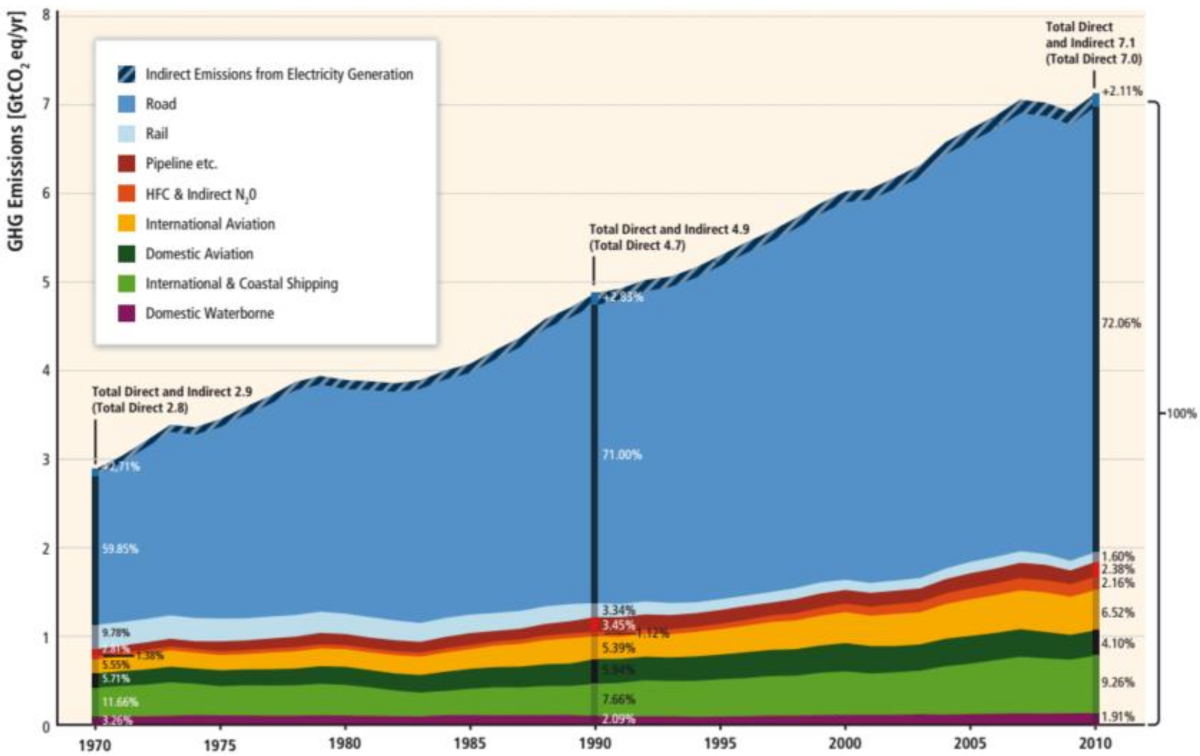


Figure 2.10: Direct GHG emissions of the transport sector by transport mode (Intergovernmental Panel on Climate Change, 2015)

In Norway, transport contribute to 35% (or 3.6 tons CO2-eq per person) of the total household carbon footprint (Steen-Olsen et al., Accepted for publication) (Figure 2.9), this is by far the largest footprint of the consumption groups included in the COICOP Level 1 classification.

Studies report that transport in other countries make up a somewhat smaller share of the household carbon footprint. Goodall (2010) finds that of total UK household carbon footprint, about 18% comes from transport use, while Druckman and Jackson (2009) found this number to be between 17% and 18% in 2004. Jones and Kammen (2011) suggests a higher number of 32% of the US household carbon footprint coming from transport, while Weber and Matthews (2008) found this to be 27% for US households. Tukker and Jansen (2006) reviewed studies that looked at contribution to different energy-related impact indicators per COICOP Level 1 category. In the reviewed studies they found that transport contributed to 15-36% of total impacts, with a study by Peters and Hertwich (2006) from Norway representing the highest of transport out of the total. Another study by Hertwich and Peters (2009) confirms that Norway has a particular high proportion of total per capita carbon footprint coming from the transport sector. Numerous factors could explain these results, such as affluence, scattered settlements and long distances between cities.

Calculating the carbon footprint coming from transport related consumption in households includes all upstream emissions associated with the purchase of vehicles, operation of personal transport equipment (fuels, maintenance, parking etc.) and transport services (passenger transport by railway, road, sea, air etc.) (United Nations Statistics Division, 2016).

The Intergovernmental Panel on Climate Change (2015) found several drivers that affect transport trends. One of the most important is the travel time budget. This is often assumed to be fixed, and is tied to both travel costs and time costs. When deciding speed of travel modes in urban areas, the assumption of fixed travel time budget is important to consider, as it involves people traveling larger distances when increasing the speed of a travel mode. Another important driver is costs and prices. Declining transport costs as a share of increasing personal expenditure is the major driver of increased transport demand in OECD countries in the last century, and more recently in non-OECD countries. A third driver for increased transport demand are social and cultural factors, such as population growth and changes in demographics. Economic structural change can lead to more and longer commutes and the development of large shopping centers located out of the city center leads to increased travel distances.

van Sluisveld et al. (2016) also focused on the importance of the travel time budget and the travel money budget. The Travel Money Budget gives information on the proportion of income people allocate to travelling. In their calculations on lifestyle changes to reach the 2°C target, they capped the Travel Money Budget to 7%, which is the lowest reported for a developed region (Japan). Furthermore, they increased the Travel Time Budget to allow for preference of slower transport modes, such as train and bicycle.

On a household level, Goodall (2010) highlights the importance of not buying a new car unless the old car is not working anymore. By not scrapping the old car, it will stay on the road and generate emissions as long as the household uses it as a second car. He suggests that such a second car accounts for almost 1 ton of CO2 yearly in the use-phase for the remainder of its lifetime.

Goodall (2010) argues that cutting out air travel is the single most efficient action to curtail GHG emissions from household consumption. He found that a year worth of gas consumption for a person in the UK contributed to the similar amount of GHG emissions as a one-way plane ticket to New York. He also found that one year of car use for a person in the UK had approximately the same emissions as two return flights between the UK and Athens. Many airlines only provide the CO2 emissions of their travels, but according to many researchers, the impact of other pollutants such as water vapor and oxides of nitrogen, along with contrails and the consequent cirrus cloud that help retain the sun's heat in the atmosphere, actually could double or triple the global warming impact of carbon dioxide alone (Goodall, 2010).

2.2.2.2 Shelter

According to the IPCC report of 2014, buildings accounted for 32% of total global energy use, with 24% for residential buildings and 8% for commercial buildings. Buildings account for 19% of energy-related GHG emissions, with approximately 12% coming from residential buildings.

Steen-Olsen et al. (Accepted for publication) found that emissions from housing contributed to 18% of the carbon footprint of Norwegian households. It thus seems as the residential sector makes up a larger portion of the total Norwegian carbon footprint than the global average. The cold Norwegian climate is likely an important reason for the residential sector making up a larger portion of the total in Norway than globally.

Energy use and GHG emissions in the residential building sector normally involves accounting for space heating and cooling, water heating, cooking, appliances and lighting. Of the global final energy consumption of residential buildings, space heating accounted for 32%, cooking 29% and water heating 24%, together 85% of the total (Figure 2.11).

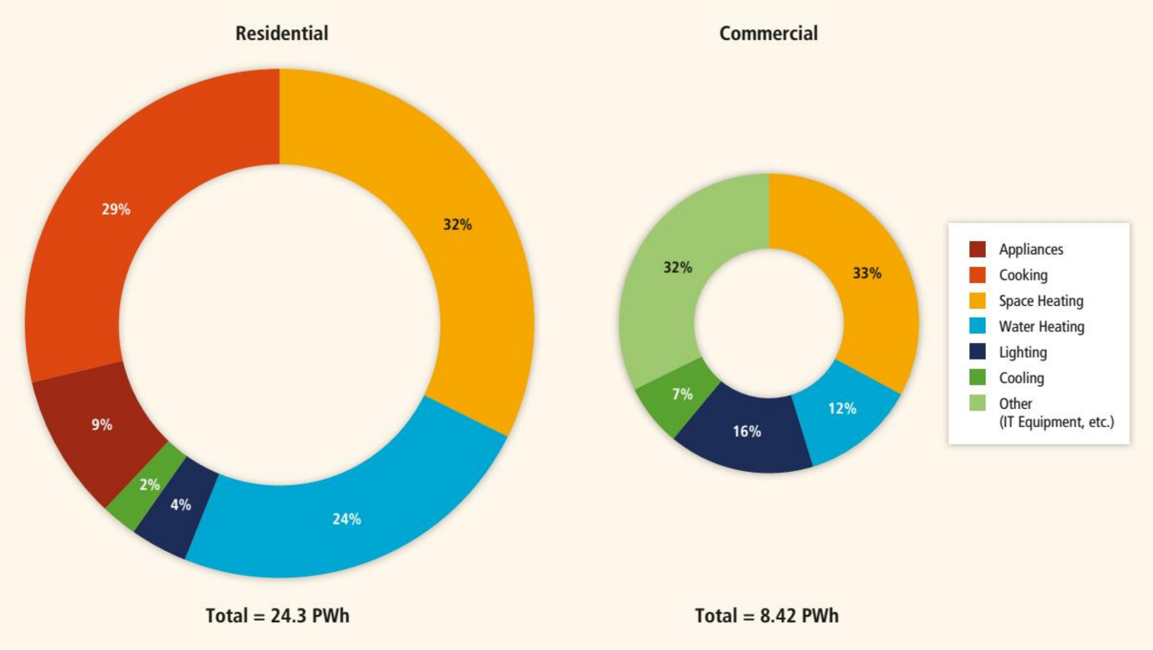


Figure 2.11: World building final energy consumption by end-use in 2010 (Intergovernmental Panel on Climate Change, 2015)

In Norway, as much as 66% of household energy use is for Space heating, while only 12% for heating water. The remaining 22% is for appliances, lighting, cooking and other equipment (Figure 2.12) (Bergesen et al., 2012).

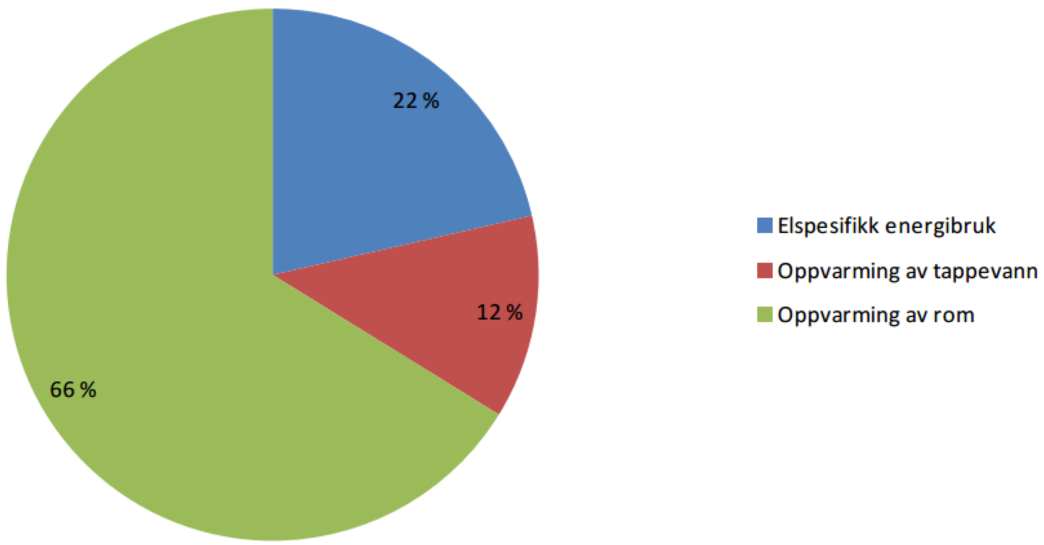


Figure 2.12: End-use of energy in Norwegian households

(Bergesen et al., 2012)

Over 60% of the emissions from residential buildings were indirect, meaning that they stem from electricity use in buildings (Intergovernmental Panel on Climate Change, 2015). Because of this high share of indirect emissions, values strongly depend on emission factors in electricity production. As much as 1.3 billion people on the earth lacked access to electricity in 2010, and 3 billion relied on highly polluting and unhealthy traditional solid fuels for household cooking and heating. The development in building related emissions is highly influenced by how these energy services will be provided (Intergovernmental Panel on Climate Change, 2015). Furthermore, the IPCC lists migration to cities, decreasing household size, increasing levels of wealth and lifestyle changes, increase in personal living space, the increased numbers and use of appliances and equipment as factors that will increase energy use in- and emissions from buildings.

van Sluisveld et al. (2016) points out the increasing number of appliances in households as an important driver for increasing carbon footprint in the residential sector. The increasing number of appliances comes with other unwanted side effects. In 2009, Standby power was responsible for approximately 1% of global carbon dioxide emissions (Goodall, 2010), or 3-

13% of residential electricity use (van Sluisveld et al., 2016), although this number is probably decreasing because of more energy-efficient appliances entering the market.

2.2.2.3 Food

According to Steen-Olsen et al. (Accepted for publication), food and non-alcoholic beverages contributed to about 10% of the total carbon footprint of Norwegian households. In a COICOP Level 1 classification, food consumption has the third largest footprint, only beaten by Transport (35%) and Housing (18%). When including restaurants, alcoholic beverages, tobacco and narcotics, as well as the underreporting in the Consumer Survey, the total food consumption is responsible for about 13% of the total Norwegian household carbon footprint (Figure 2.9).

The Intergovernmental Panel on Climate Change (2015) suggests that the AFOLU (Agriculture, Forestry, and Other Land Use) sector is responsible for about 24% of anthropogenic GHG emissions mainly from deforestation and agricultural emissions from livestock, soil and nutrient management. About half of these emissions come from agricultural production.

Other studies find similar figures. Goodall (2010) found that indirect emissions from food consumption in the UK in 2010 accounted for 15% of the carbon footprints of UK households, while Stehfest et al. (2009) suggested that the livestock sector alone accounted for 18% of global GHG emissions.

When calculating GHG emissions related to food consumption, all upstream emissions in the food production chain are included. Processes that contribute to emissions are fertilizer use, enteric fermentation, manure management and manufacturing among others.

Goodall (2010) identified the contribution of GHG emissions by different processes in the food production. The most significant contribution came from:

- Fertilizer use generating nitrous oxide (21%)
- Methane from animals and slurry (15%)
- Landfill gas from rotting food: methane and CO2 (10%)
- Food and drink manufacturing and processing (8%)

The Intergovernmental Panel on Climate Change (2015) found that the largest GHG emissions globally in the AFOLU sector come from:

- Land Use change and Forestry

- Drained Peat and Peat Fires
- Enteric Fermentation
- Manure on Pasture
- Synthetic Fertilizers

GHG emission intensities of different food products can give insight to understand the importance of diet choices on the emissions from our food consumption. On the worst end of the scale, there is cattle meat that produce about 5.5 kg CO2-eq per kg consumed, in a life-cycle perspective. On the other end, there is cereals producing well under 0.5 kg CO2-eq per kg consumed (Figure 2.13) (Intergovernmental Panel on Climate Change, 2015).

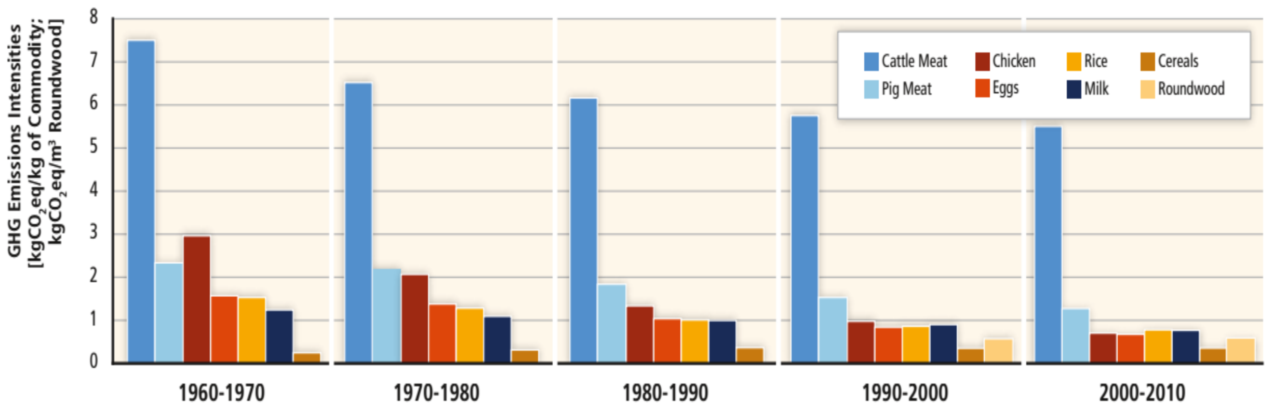


Figure 2.13: GHG emissions intensities of selected major AFOLU commodities for decades 1960s–2000

(Intergovernmental Panel on Climate Change, 2015)

Even though livestock contribute to a substantially larger carbon footprint than many other food products, some argue that food production from livestock in intensive systems or on overstressed grasslands are the main problem, and that sustainable food production systems produce far less methane (Goodall, 2010).

The packaging of food products potentially makes up a large share of the total carbon footprint associated with that food product. Goodall (2010) suggest that the energy costs to make the packaging used for food are about two-thirds of the energy value of the food itself. A study by Hospido et al. (2005) confirms this, suggesting that over 40% of total GWP of a glass bottle of beer is attributed to its packaging elements. When it comes to type of packaging material, Goodall (2010) argues that plastic packaging can outperform cardboard and paper packaging, because plastic is light, embodies relatively little energy and does not rot.

2.2.2.4 Clothing

According to Steen-Olsen et al. (Accepted for publication), emissions from clothing and footwear purchases contributed to over 5% (or about 1.1 ton CO2-eq) of the carbon footprint of Norwegian households.

Generally, in other nations, clothing purchases seem to make up a somewhat lower percentage of the total carbon footprint than in Norway (Hertwich and Peters, 2009). A UK study for example reports that clothing makes up about 2% of the total direct carbon footprint of UK households (Gracey and Moon, 2012)

The GHG emissions associated with consumption of clothing might be less obvious to the consumer, because the emissions are mostly indirect. In fact, according to Goodall (2010), clothing along with paper consumption, follow food as the most important of our personal purchases in terms of their climate change impact.

The clothing lifecycle, as defined by Gracey and Moon (2012), is split into three stages (Figure 2.14).

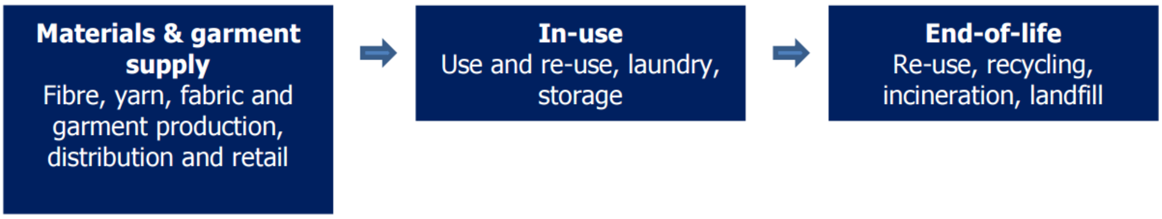


Figure 2.14: Overview of the clothing lifecycle

(Gracey and Moon, 2012)

The consumer is responsible for all upstream emissions associated with the processes in Figure 2.14, although some studies might account for the carbon footprint from the use phase, such as laundry and storage, in the shelter consumption group.

Thomas et al. (2012) studied the carbon footprint of clothing and the contribution of upstream processes to the footprint. They found that fabric production contributed to 33% of the total footprint of a typical garment, followed by yarn production, fiber production and washing in the use phase.

Concerning the fabric of clothing, studies seem to report different impact results, depending on the choice of indicators. Goodall (2010) found wool to be the worst fabric in terms of global warming potential (GWP), generating 80-90 kg CO2-eq per kg of clothing, while cotton and viscose only produced 30-40 kg CO2-eq per kg of clothing. Muthu et al. (2012) evaluated ten chosen fibers based on two indexes, the Environmental Impact Index and the Ecological Sustainability Index. They found the environmental impact to be the smallest for organic cotton and the largest for acrylics and polypropylene. Wool was the fiber that generated the sixth largest environmental impact.

2.2.2.5 Furnishings and Refurbishments

In EXIOBASE2, with different product classifications than COICOP, *Manufactured products: Household interior* made up 3.7% of the carbon footprint of Norwegian households. In a COICOP level 1 classifications, Furnishings, household equipment and routine household maintenance contributed to 5.8% of the carbon footprint (Figure 2.9) and 4.8% of total expenditure of Norwegian households in 2012 (Steen-Olsen et al., Accepted for publication). It represented the fifth largest carbon footprint of the consumption groups in the COICOP level 1 classification. Since relative share of carbon footprint is larger than the relative expenditure share, it means that the multiplier is large for this consumption group. In fact, Furnishings, household equipment and routine household maintenance has the second largest multiplier of 52.8 gCO2-eq/NOK. Only transport is higher, with a multiplier of 96.8 gCO2-eq/NOK. Examining the product group in more detail reveals that in the COICOP Level 3 classification, furniture and furnishings alone accounts for 1.8% of the total Norwegian carbon footprint (Steen-Olsen et al., Accepted for publication).

According to González-García et al. (2011) the furniture industry is an assembling industry, which employs several raw materials to manufacture its products. These products include wood, metals, plastics, textile, leather or glass.

The high carbon footprint in this consumption group is likely a result of high number of furnishing products per household combined with buying new products and scrapping old ones at a high rate.

2.2.2.6 Paper

In EXIOBASE2, paper and paper products account for 0.5% of total carbon footprint of Norwegian households. When including paper treatment and paper waste treatment, this number increases to 0.9%. In a COICOP Level 4 classification, when adding together emissions from consumption of books, papers and magazines and paper products, it adds up to 0.5% of household carbon footprint. Other studies suggest paper consumption contributing to about 1 % of total household carbon footprint (Goodall, 2010). According to the

Intergovernmental Panel on Climate Change (2015), the pulp and paper sector contributed to 0.2 Gt direct energy- and process related CO2 emissions in 2010. They also provide CO2 emission intensities of paper and pulp production, with both direct and indirect intensities of about 0.5 tons CO2/ton paper, with total emissions amounting to about 1.1 tons CO2/ton paper.

According to Globalis (2016), the paper consumption in Norway in 2005 was about 170 kg per person. The global average in 2013 was 57 kg per person. North America, the EU, Japan and Oceania have consumption between 150-250 kg paper per person, while at the other end of the scale, Africa has a consumption of under 10 kg paper per person.

The processes included in paper production are extraction of biomass, chemical or mechanical pulping, paper production, printing, recovered pulping, waste paper energy extraction, landfilling and incineration and transport (Laurijssen et al., 2010, Moberg et al., 2010). When accounting for the carbon footprint of paper consumption, all the GHG emissions from these processes are included.

According to Dias et al. (2007) and Moberg et al. (2010), the processes contributing to the largest GWP are paper production, printing and distribution and final disposal in a decreasing order, with about 50% of the total GWP generated in the paper production.

2.2.2.7 Other Sectors

Several other consumption groups contribute to household carbon footprint through indirect emissions from purchases. Maybe the most prominent not yet discussed, are cement and concrete (Figure 2.15) and plastic.

Cement and concrete production contributes to a substantial amount of CO2 emissions. The estimates suggest that this sector contributes to 5-7% of global CO2 emissions, generating 900 kg CO2 per ton of cement produced. In Norway, the cement consumption per capita is about 1/3 tons per year (SETIS, 2010).

Plastic waste generation per inhabitant in the EU-28 was about 30 kg in 2012 (Eurostat, 2015). Dormer et al. (2013) found that the carbon footprint of 1 kg of PET trays was 1.54 kg CO2-eq.

Studies do focus on reducing plastic waste, such as plastic bags and plastic bottles. Some of the actions suggested are reusing plastic bags and producing durable plastic products to reduce the demand for primary energy and process energy (van Sluisveld et al., 2016).

Regarding plastic waste recycling, van Sluisveld et al. (2016) suggest that 30% of post-consumer plastic waste are mechanically recycled, while the rest undergoes a chemical recycling process.

Cement and concrete as well as plastic waste are indirect sources of emissions, but studies usually incorporate the carbon footprint in the products that use plastic, concrete or cement. Hence, when calculating household actions to mitigate carbon footprint of plastic waste and cement consumption, there is a risk of double counting.

Another curiosity is cell phones, which according to Goodall (2010) contain about 25 kg of embedded GHG per piece. Only half of the emissions arise from the electronics. The high embedded GHGs relative to the weight of a typical cell phone are according to Goodall (2010) a result of the components and the phone being shipped long distances during the manufacturing and sales process. Hence, he argues that phones and other small electronic devices are of the few products other than fresh food for which transport emissions really make a difference. As a result, leaving the cell phone charger in the wall socket and the use-phase emissions matters little compared to the frequency of replacing the phone. He estimates that a person who changes phone every year contributes to 38 kg CO2-eq. Besides the phone production, running the network (29% of total) and leaving the charger in the socket (6% of total) contributes most to the carbon footprint.

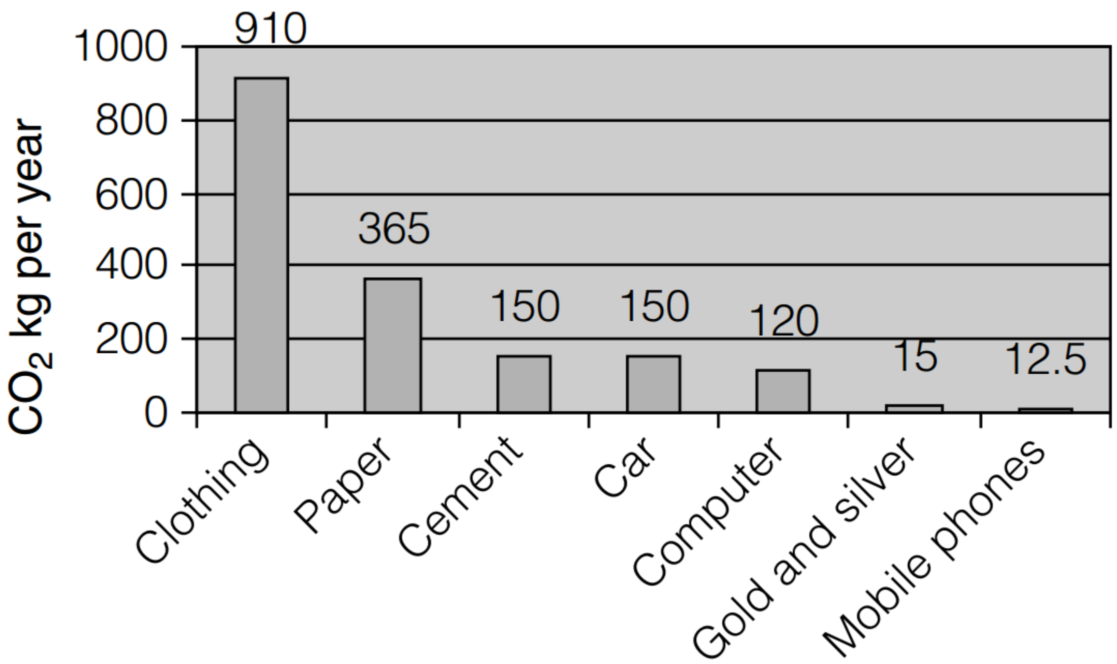


Figure 2.15: Indirect sources of emissions from an individual's purchases (Goodall, 2010)

Cement production includes three main process: raw material preparation, clinker production and clinker grinding and blending (Benhelal et al., 2013).

In accounting for the carbon footprint of plastic production, Dormer et al. (2013) includes the following processes:

- Raw material inputs
- Manufacturing processes
- End-of-life
- Secondary packaging
- Transportation

According to Benhelal et al. (2013) the two main sources of CO2 emissions in cement production are:

- Combustion of large amounts of mainly fossil fuels
- Decomposition of $CaCO_3$ to CaO and CO_2 as initial chemical reaction

In plastic production, Dormer et al. (2013) found the largest carbon footprints in the raw material inputs (45% of total) and the manufacturing processes (38% of total).

2.3 Measures for Reducing the Norwegian Carbon Footprint

The IPCC suggests that we need to reduce the anthropogenic GHG emissions by 40-70% in order to reach the 2ºC target of global warming. Considering a Norwegian per capita carbon footprint of 10-11 tCO2-eq/year, we can calculate the needed absolute reduction. This amounts to a 4-7.7 tCO2-eq reduction per capita, or a 8.6-16.6 tCO2-eq reduction per household when considering the average Norwegian household of 2.15 persons in 2014 (Statistics Norway, 2014b). The production side will provide some of the reductions through technology and efficiency improvements, given that overall consumption levels stay the same. However, as pointed out in the introduction, studies suggest that changes on the production side will not be enough to reach the 2°C target of global warming. There are complex interactions between the consumption and production side as, changes one side will have implications to the other side discussed in the introduction, and changes on both sides will be necessary. Given these complex interactions. The scope of this thesis is to examine the potential contribution of households, but these changes will influence the production side through e.g. changes in demand. These macroeconomic effects need careful considerations, but are outside the scope of this thesis.

If we are to achieve reductions on the consumption side, households need to change their consumption pattern in a range of goods and services. Some studies have attempted to calculate the possible reduction in carbon footprint through implementing a green lifestyle. Goodall (2012) found a 75% reduction in UK household emissions through implementing a wide range of measures. Gardner and Stern (2008) found energy savings in the range of 30-58% doing a similar U.S. based study. Druckman and Jackson (2010) created a reduced consumption scenario that resulted in 37% lower GHG emissions in UK emissions. However, none of these studies included rebound effects. Some studies of complete lifestyle changes include rebound effects, such as Druckman et al. (2011) who found an emission reduction of 2.3 tons CO2-eq per household by implementing three specific actions with rebound effects of 12-34% depending on re-spending. Alfredsson (2004) finds a reduction of 3.0 tons CO2 per household by adopting a “green” consumption and a rebound effect of 14% using a marginal spending pattern. While Murray (2013) find a reduction of 1.9 tons CO2-eq per household, with rebound effects of 9-12% assuming marginal re-spending.

Gardner and Stern (2008) claim that a desire to reduce carbon emissions, combined with knowledge of the financial and environmental benefits of mitigating actions, is insufficient. A person, they claim, must also know which actions will produce the benefits. Furthermore, they state that people often mistake which mitigating actions are most beneficial, and that the most readily information on sources of behavioral advice are not helpful. Following this logic, a ranking of behavioral advice that curb climate change would be beneficial.

The approach used by Gardner and Stern (2008) is to produce a list of energy conservation potential for 27 behavioral actions, both curtailment actions and actions that increase the efficiency, either through buying new equipment or through modifying existing equipment. An important finding is that efficiency-improving actions generally save more energy and carbon emissions than curtailment actions. Furthermore, they also find it is often sufficient to perform efficiency-improving actions only once, such as purchasing a more fuel-efficient car, while many curtailment actions need continuing effort, such as car-pooling to work. On the other hand, efficiency-boosting actions often come with a financial cost, while curtailment actions can even lead to financial savings.

The following section provides a literature review of the GHG emission reduction potential of different actions households can implement. The goal is to identify which actions are the most effective and to identify important parameters that contribute to GHG emissions. Furthermore, a goal of this section is to examine the changes required by the household to achieve the potential benefits.

2.3.1 Transport

The Intergovernmental Panel on Climate Change (2015) lists the most important actions in order to reduce GHG emissions from passenger and freight transport:

- Avoiding journeys when possible
- Modal shift to lower-carbon transport systems
- Lowering the energy intensity (MJ/passenger km or MJ/ton km)
- Reducing carbon intensity of fuels (CO2eq/MJ)

These categories involve sub-actions that are not possible on an individual level, such as increasing investment in public transport and restructuring freight logistics systems. However, many of the actions are possible on an individual level. These include internet shopping, walking and cycling, using public transportation or buying low-emitting vehicles.

The Norwegian Environment Agency suggests along with the IPCC that households can take the following actions to help reduce emissions of greenhouse gases (Miljødirektoratet, 2015).

- Less driving

- More bicycling and walking
- Avoid unnecessary travels
- More public transport
- More effective use of transport modes
- Reduce emissions from transport fuels

A common suggestion for reducing household's carbon footprint in personal transportation is cutting out all car trips under 3 km, and do these either by bicycling or walking instead. However, the environmental benefits might not be as large as we would hope. Goodall (2010) found that even though these trips account for a total of about one quarter of all journeys in the UK, they only represent 3.5% of the total distance each person drives each year.

2.3.2 Shelter

The Norwegian Environment Agency (Miljødirektoratet, 2015) suggested that buildings accounted for 18% of total GHG emissions globally. To reduce the impact they say that the most important actions households can take are to build more energy efficient houses, rehabilitate old houses and reduce the energy use for residential heating.

For appliances, the Intergovernmental Panel on Climate Change (2015) suggests that each individual equipment has an energy savings potential of about 40-50%. Recycling of appliances such as computers and cell phones is an important measure, as it makes use of the resources of the waste. Recycling instead of landfilling of appliances will not only reduce the emissions from production of precious metals and minerals, but will also reduce the extraction of these limited resources from the earth (Miljødirektoratet, 2015)

Goodall (2010) mention several household actions that can reduce GHG emissions from buildings. For house heating, these include installing a more efficient boiler, reducing internal winter temperature, and installing better insulation. A common suggestion for reducing GHG emissions related to household heating and cooling is increasing indoor temperature by 1°C when cooling is needed and decreasing it by 1°C when heating is needed (van Sluisveld et al., 2016). Goodall (2010) suggests a reduction potential of about 20% for emissions associated with home heating and cooling. A further 8% GHG emission reduction is achievable by measures in water heating, such as installing a more efficient boiler, replacing the showerhead and taking less hot and shorter showers. By reducing the use of lighting and installing energy-efficient lightbulbs, a further 5% reduction is achievable. Finally, by replacing old appliances with more efficient ones, a 12% additional GHG emission reduction is possible.

As mentioned in the introduction, calculations of GHG emissions include all upstream emissions in the production phase of goods and services. The share of the total energy use outside the use-phase depends on many factors, such as the lifetime of the product, the energy use in operation of the product, the materials used in production, the location of producing and using the product and transportation to the store among others. There are also large variations between products, when it comes to the share of energy use in the use phase. According to Gonzalez et al. (2012) use-phase emissions out of the total is about 99% for lighting products, about 90% for major appliances and in the range of 20-60% for electronic devices. A crude assumption is that for all the products in average, 90% of emissions occur in the use-phase.

Assuming that the household uses electricity as energy source and that emissions from electricity production is close to the Nordic electricity mix of 0.117 kg CO2-eq/kWh (ENOVA, 2013), we can calculate the reduced emission, based on the energy use reductions above. According to Statistics Norway (2014a), the average Norwegian household used 20 230 kWh of energy in 2012.

2.3.3 Food

Miljødirektoratet (2015) reports that the amount of food waste in Norway is substantial. They find that food waste is the type of waste with the largest increase in Norway, and that 2/3 of the food thrown away is edible. Based on this, they recommend Norwegian households to buy less food and throw away food waste. According to them, by reducing food waste, we can reduce total global GHG emissions by 1-12%.

Goodall (2010) found that a reduction of 68-85% compared to current GHG emissions related to food consumption was possible, depending on how radical of a change the consumer makes. He found the following actions to be the most important to curb household GHG emissions in the food sector:

- Switch to organic food
- Buy local food
- Eat less meat and dairy
- Buy minimally packaged food
- Avoid processed food
- Compost all organic materials

- Avoid supermarkets

Stehfest et al. (2009) found that a change in diet alone could result in GHG emission savings of 34-64% compared to the ‘business-as-usual’ scenario. A switch to a healthy diet would for example save 36% GHG emissions.

The Intergovernmental Panel on Climate Change (2015) suggests that changes in diet towards plant-based and less GHG intensive food can result in yearly global GHG emission savings of 0.7-7.3 GtCO2-eq by 2050. Reducing food losses and waste in the supply chain from harvest to consumption can reduce yearly GHG emissions by 0.6-6.0 GtCO2-eq.

Many studies focus on the need for replacing meat consumption and other animal food products with plant-based products. Miljødirektoratet (2015) suggest that making this replacement, while at the same time maintaining the amount and quality of proteins, we can reduce total global GHG emissions by 1-14%.

Other studies focus on a full switch to vegan or vegetarian diets. Grabs (2015) found a 20% reduction in GHG emissions from food consumption for households when switching to a vegetarian diet. A similar UK study found GHG emissions reductions of 18-30% for a switch to different types of vegetarian and vegan diets (Berners-Lee et al., 2012).

Some studies include the cost changes to the household of changing diet. A recent Swedish study suggested a 16% reduction in food expenditures from food consumption for households when switching to a vegetarian diet (Grabs, 2015). Alfredsson (2004) finds similar numbers with a cost reduction of 15% for a change to a “green” diet. A similar study in the UK found cost reductions of 5-15% for a switch to different types of vegetarian and vegan diets (Berners-Lee et al., 2012).

With 20-25% of food purchased by Norwegian households going to waste (Matvett, 2014), we can assume a 20-25% reduction in food costs by eliminating food waste.

2.3.4 Clothing

Goodall (2010) comes with the following suggestions for reducing the household carbon footprint associated with clothing and textiles:

- Avoid wool because of methane emissions from sheep
- Buy fewer clothes, but with better quality
- Organic cotton only marginal reduces emissions
- Transport emissions are small for clothes

- Dry cleaning does is not an important source of emissions for clothes
- Avoid unnecessary tumble drying and ironing

Based on 10 measures, Thomas et al. (2012) estimate the carbon footprint reduction potential of clothing to be 21% (Table 2.1). In an optimistic future situation in the UK where significant reductions have occurred for each measure, they estimate that the reduction can increase to 71%.

Reduction measure	Baseline (t CO_2e)	Reduction (t CO_2e)	Reduction %
Eco-efficiency across supply chain (production, distribution and retail) – Central scenario - 5% reduction for all fibres across supply chain	38,175,293	1,563,219	-4.1%
Design for durability (and product lifetime optimisation) - Central scenario - 10% longer lifetime of clothing	38,175,293	2,941,203	-7.7%
Shift in market to higher proportion of synthetic fibres - Central scenario - replace 10% of cotton with 50:50 poly-cotton. (*Data exclude in-use savings*)	38,175,293	164,150	-0.4%
Clean clothing less – Central scenario - washes per year reduced by 10%	38,175,293	989,905	-2.6%
Wash at lower temperature – Central scenario - weighted average wash temperature of 39.3°C	38,175,293	549,604	-1.4%
Increase size of washing and drying loads – Central scenario - load increases to 3.7kg	38,175,293	531,538	-1.4%
Use the tumble dryer less - Central scenario – 30% reduction in tumble dryer use in summer	38,175,293	430,367	-1.1%
Dispose less – re-use more – Central scenario – 15.4% of clothing ultimately reused in the UK	38,175,293	272,063	-0.7%
Start closed loop recycling of synthetic fibres - Central scenario – 5% of all clothing is recycled (closed loop)	38,175,293	352,144	-0.9%
Dispose less - recycle more (open loop) - Central scenario – 38% of all clothing is recycled open loop	38,175,293	195,729	-0.5%
Cumulative reduction[50]		7,989,921	-20.9%

Table 2.1: Measures to reduce the carbon footprint of clothing (Thomas et al., 2012)

2.3.5 Furniture

Households that wish to lower the carbon footprint associated with furniture consumption, can either consider the materials used in the furniture (Mitchell and Stevens, 2009) or increase the lifetime of the products, either by keeping them for a longer time, reusing or refurbishing them or by buying or selling second-hand products (Castellani et al., 2015, González-García et al., 2011).

Linkosalmi et al. (2016) argues that the furniture industry has raised environmental performance of furniture materials and manufacturing as one of their main improvement focus areas. Mitchell and Stevens (2009) find that through using 20% recycled medium-density fiberboard (MDF) up to a 0.52 tons of CO2-eq savings is possible for each ton of finished MDF board produced.

2.3.6 Paper

The literature presents several calculations on GHG reductions from household measures to curtail paper consumption. Goodall (2010) argues that the two most important things to do is to buy fewer magazines and newspapers and minimizing the amount of cardboard coming into the home.

By using print management systems, studies have found a reduction of 25-32% in paper consumption (Canonico et al., 2009, Dempsey and Palilonis, 2012). Combining print management systems with double-sided printing, as mentioned in Dempsey and Palilonis (2012), would further reduce the paper consumption.

Klimahandling.no (2016) states that each Norwegian household receives 45 kg of unsolicited mail and advertising in their mail box each year. By eliminating this, a reduction in the carbon footprint is possible at no cost for the household. Salhofer et al. (2008) did the same calculation on unsolicited mail, and found the reduction potential to be 13.5kg/cap. A somewhat lower number than for Norway when considering the average Norwegian household size of 2.22 people in 2012. However, Salhofer et al. (2008) include households that already refuse unsolicited advertising, resulting in a lower figure than assuming that a specific household that receives unsolicited advertising and mail stops to do so.

According to Moberg et al. (2010), by switching from newspapers to e-papers, it is possible to reduce the carbon footprint from 20 kg CO2-eq/year per reader to 10.2 kg CO2-eq/year per reader.

Moberg et al. (2011) did a life cycle assessment of the global warming potential of a book versus an e-book and found the values to be 1.3 and 0.87 kg CO2-eq per piece respectively.

2.3.7 Plastic

Considering that the average Norwegian person produces 7 kg of plastic waste each year (Statistics Norway, 2015a), reducing this waste will shrink the carbon footprint of households. Many studies that calculate the carbon footprint of plastic waste focus on items such as plastic bags, plastic bottles and plastic packaging (Muthu et al., 2011, Botto et al., 2011, Dormer et al., 2013). Botto et al. (2011) found the carbon footprint of bottled water to be 250 times greater than that of tap water. Muthu et al. (2011) pointed to the importance of a higher percentage of reuse and recycling of shopping bags instead of landfilling in order to scale down the carbon footprint. They found that plastic bags had 3-4 times the carbon footprint of non-woven bags.

2.4 The Rebound Effect[1]

The rebound effect stems back to 1866 and the Jevons Paradox (Jevons, 1866). Through observations in the coal market, Jevons argued that technology improvements in production ultimately led to increased consumption of coal through economic mechanisms. These mechanisms start with a technological improvement, leading to increased efficiency in one sector of the economy that reduces the input of resources required in the production of a certain good. This makes the production of the good cheaper, and reduces the price of the good. A reduced price then leads to an increased demand of the good. Hence, the initial technology improvement results in increased consumption of the good. Particularly for goods and services associated with high GHG emissions per unit produced, this means that the hoped for reduction in emissions, as an effect of the technological improvement, are not as high as expected. This is known as the rebound effect (Jevons, 1866, Saunders, 1992).

As energy efficiency improvements came under increasing study, the concept developed much further in the 1990s. In 1992, Saunders (1992) created the Khazzoom-Brookes Postulate, based on Daniel Khazzoom’s and Leonard Brookes’ independently developed observations about increased energy efficiency paradoxically leading to increased energy consumption. Using neoclassical growth theory, Saunders proved that this was possible under

[1] This section is modified from the literature review of my master project (Fall 2015)

certain reasonable conditions. The postulate laid the foundation for several empirical studies and for constructing the problem of the rebound effect.

Today there is substantial research on the rebound effect in several sectors of the economy. The sectors receiving most attention by researchers are transportation services and electricity services such as space-heating and electric end-uses (Thomas and Azevedo, 2013b, Druckman et al., 2011, Font Vivanco et al., 2014, Chitnis and Sorrell, 2015, Brännlund et al., 2007, Briceno et al., 2005, Small and Van Dender, 2007, Spielmann et al., 2008). Some research also exist on the rebound effect of a change to a “green diet” (Grabs, 2015, Alfredsson, 2004). There can be many reasons why these particular sectors are the focus of study. One is that these goods and services account for a large share of the budget of households. Another is that it is relatively easy for consumers to alter their consumption patterns within these consumption sectors. For example, a switch from personal car transport to public transport, a switch to a “greener” diet or reducing the indoor thermostat down by 1 °C are all possible adjustments for most households. Maybe the most important reason for the focus on the mentioned sectors is the combination of high expenditure shares and high GHG intensity, meaning that these categories account for a large share of the total GHG emissions from households. Chitnis et al. (2014) found that the categories responsible for the highest share of total household GHG emissions were food and non-alcoholic beverages, electricity, vehicle fuels and other transport. If households wish to lower their GHG emissions, they should focus on such sectors of high GHG emission intensities combined with large expenditure shares.

Reducing the household GHG emissions will be play an important part in achieving sustainable development for future generations. Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development., 1987). Such development involves sustainability in both production and consumption. While sustainable production typically focuses on technical measures to increase efficiency in production, the focus of sustainable consumption is rather on behavioral measures that aim to either reduce or change consumption. However, Hertwich (2005) observed that many policy makers see the role of sustainable consumption as promoting new sustainable products. He points out that sustainable consumption is much more than this, and mentions the importance of secondary effects such as behavioral spillover effects, where one environmentally friendly behavior can lead to another secondary environmentally friendly effect across behavioral categories (Thøgersen and Ölander, 2003). Another aspect is the enabling effects of new product solutions for households. These effects can be critical for the environmental impacts and allows for collaboration between those working on sustainable production and consumption (Hertwich, 2005).

A projection by the International Energy Agency (IEA) illustrates the important link between sustainability in production and consumption and the rebound effect. They estimate that by 2030, one half of the lowest-cost GHG abatement options in Organization for Economic Cooperation and Development (OECD) countries will come from energy efficiency, largely in end use technologies (IEA, 2009, as cited in, Thomas and Azevedo, 2013b). If these energy efficiency improvements result in large rebound effects, it will negatively influence sustainable development. In other words, if consumers react to these efficiency improvements in production by increasing their consumption of the good or service, like in the case of the Jevons Paradox, the potential GHG abatement resulting from the efficiency improvement is partially or fully lost.

Policymakers and research funders do seem to draw the connection between sustainable consumption and the rebound effect (Hertwich, 2005) and studies of sustainable consumption do include the rebound effect through the analysis of household environmental impacts. Consumption data typically come from consumer expenditure surveys. An example of an analysis on sustainable consumption and the rebound effect is Goedkoop et al. (1999) who studied car sharing as a means towards sustainable consumption. They found that cars owned by individuals are only in use for one hour each day, so the potential for sharing was large. Sharing cars is associated with lower expenditures, so the rebound effect comes into play when people re-spend the saved money from implementing car sharing.

2.4.1 Types of rebound effects

Generally, we divide the rebound into three types of effects: direct, indirect and macroeconomic rebound effects (Greening et al., 2000, Sorrell and Dimitropoulos, 2008). The following section uses this classification, but also includes a discussion of other types of rebound effects.

Within the field of energy economics, the rebound effect has received much attention. They define the rebound effect as increased consumption of an energy service due to improvements in efficiency, making the service cheaper (Sorrell et al., 2009). An example of this is increased fuel efficiency in cars, where technology improvements enables the consumer to drive longer on the same amount of fuel and at the same cost, compared to before the efficiency improvement.

2.4.1.1 Direct

The direct rebound effect in the previous example arises from the change in driving distance after the efficiency improvement. If driving decreases after the technology improvement, there is a negative rebound effect. If driving increases, but there is still a total reduction in GHG emissions, we have a positive direct rebound effect. If driving increases to such an extent that the total GHG emissions increase, despite the efficiency improvement it is known as a “backfiring” effect (Brookes, 2000). Generally, we have a positive direct rebound effect when technological improvements or behavioral changes associated with a specific good or service lead to increased consumption of that good or service.

The size of the direct rebound effect varies greatly with the goods and services examined, depending on variables such as consumption sector, short-term versus long-term effects, income levels and region and year of study, (Thomas and Azevedo, 2013b, Binswanger, 2001, Sorrell et al., 2009, Small and Van Dender, 2007).

2.4.1.2 Indirect

The indirect rebound effect arises when decreased or changed consumption in one specific consumption sector, leads to increased consumption in one or several other consumption sectors. The effect is a measure of how GHG emissions from re-spending on other goods and services offsets GHG emissions saved from a changed consumption in one specific consumption sector.

The sources of indirect rebound effects are many. A lowered price of one good or service, can lead to increased consumption of another good (Gillingham et al., 2013). Technological improvements in one consumption sector, can lead to freed up income that the household spends on other goods and services. Households can also actively induce an indirect rebound effect by implementing actions or buying products that save money and GHG emissions, which they later use on other goods and services (Druckman et al., 2011).

As the sources of the effect vary, the methodology to calculate the indirect rebound effect also vary. Several studies within energy economics often take the approach of the indirect rebound effect stemming from a price change on one or several goods and services (Thomas and Azevedo, 2013a, Thiesen et al., 2008, Gillingham et al., 2013). In these type of studies, typically the price of energy drops, leading to marginal changes in spending on other goods and services (Thomas and Azevedo, 2013b).

Other studies that take the approach of the household actively implementing actions that save GHG emissions and money (Druckman et al., 2011, Alfredsson, 2004, Murray, 2013). These studies typically do not consider price changes. In such studies, the indirect rebound effect emerges because of supply chain emissions associated with the re-spending of the saved money on goods and services.

Some researchers have found an inverse relationship between the direct and the indirect rebound effect (Thomas and Azevedo, 2013b, Chan and Gillingham, 2015). This is rational, since a small direct rebound effect indicates less money spent on the good or service in question, and more money saved that later is spent on other goods and services, creating a larger indirect rebound effect (Economic Consulting Associates, 2014). Using the same logic, a large direct rebound effect would give a small indirect rebound effect. Because of this inverse relationship, the GHG intensity of the expenditure categories in which the saved money is re-spent, is crucial for the environmental performance of the expenditure choice. If the consumption category in which the household saves money has a low in GHG intensity, chances are, households re-spend the money in consumption categories with relatively higher GHG intensities, resulting in worse environmental performances.

How the saved money is re-spent also varies between income groups. Some studies find an inverse relationship between rebound effects and household income (Thomas and Azevedo, 2013b, Chitnis et al., 2014). Additionally, when comparing countries, studies find higher rebound effects in developing countries than developed ones, due to a high energy intensity of goods and services purchased in developed countries (Economic Consulting Associates, 2014). A reason for this, they find, is that inhabitants of developing countries are more likely to spend the extra money on energy intensive appliances that are already common household items in developed countries.

2.4.1.3 Macroeconomic

Macroeconomic rebound effects are a result of complex interaction between economic actors, both consumers and producers. Hertwich (2005) argues that an energy efficiency improvement must lead either to substantial economic growth or to substantial reductions of energy use. The question is how the effect of the improvement distributes throughout the economy.

Greening et al. (2000) and Barker et al. (2009) present two different macroeconomic effects using examples from energy economics:

- **Economy-wide effects:** An energy efficiency decreases the demand for fuel, lowering the fuel price. This price reduction again increases the demand for fuel. A fall in the real price of energy services reduces the price of goods in the economy, leading to a series of price and quantity adjustments, with energy-intensive goods and sectors gaining at the expense of less energy-intensive ones. Energy efficiency improvements may also increase economic growth, which increases energy consumption.
- **Transformational effects:** Arise from technology change that alter the consumer's preferences, as well as social institutions, and rearrange the organization of production.

Gillingham et al. (2013) mention two macroeconomic effects:

- **Price Effect:** Efficiency improvements in an economic sector in a country leads to a lower price of a good in that country, but also leads to a price reduction of the good globally. This could potentially lead to an increased consumption of the good globally.
- **Growth Effect:** Increased energy efficiency in one sector creates opportunities in other sectors that consume more energy. E.g. development of lighter materials for fuel-efficient cars also lead to better airplanes and increased aviation

It seems as the economy-wide effects in Greening et al. (2000) can essentially be broken down into the growth effect and price effect of Gillingham et al. (2013).

The macroeconomic effects are often hard to pin down (Gillingham et al., 2013) and because of many economic features influencing each other, it is difficult to draw unambiguous conclusions on these effects. These economic features include energy consumption induced by a lower market price for energy, changes in economic structure, economic competiveness, investment and disinvestment, and labor market changes resulting from energy efficiency investments (Thomas and Azevedo, 2013b). Because macroeconomic effects are difficult to pin down, Integrated Assessment models usually omit possible interactions between impacts in one sector and impacts in another. Instead, these models calculate the impact on a sector-by-sector basis, and then add them up to arrive at the overall economy-wide impact (Stern, 2007). Other models, such as some computable general equilibrium (CGE) models or the World Trade Model (WTM) can capture macroeconomic effects. Simpler forms of these models typically do so by setting up linear programming approaches on input output tables (Duchin, 2005).

2.4.1.4 Time

A sub-type of rebound effects that is often not included in rebound studies are time rebound effects. This is a rebound effect based on time efficiency in consumption. If consumers can consume a product or service in less time, they tends to demand more of it (Achachlouei and Hilty, 2014). An example of a time rebound effect from the transport sector is development of faster cars (combined with an assumed increase in speed limits), where consumers will spend less time driving to their destination. If the consumer ends up driving a longer total distance, we have a time rebound effect. Some research has shown evidence of this. An example is faster transport leading to people expanding their radius of action, but keeping their total travel time constant (Hertwich, 2005).

Although some studies recognize the time dimension (Reisch, 2001, Binswanger, 2001), there is a lack of empirical research on time use and the environmental impacts of consumption (Jalas, 2002).

2.4.1.5 Other

Some studies discuss other types of rebound effects, though these are rarely considered. Madjar and Ozawa (2006) propose, in addition to direct, indirect and macroeconomic effects, a differentiation between physical and psychological rebound effects. Indicators for psychological rebound effects include fulfillment of needs and enhancing happiness. They also propose an expansion of physical indicators based on the scarcity of resources, such as the mentioned time rebound effect, space or volume constraints, skills, information and energy. Hertwich (2005) also encourages a decomposition and expansion of rebound effects, and suggests that behavioral changes can have indirect effects not mediated through the price mechanisms, such as one type of environmentally friendly behavior having a spillover effect to other types of behavior. Another is technical changes enabling other emission-reducing technologies. He states that such behavioral rebound and spillover effects can be either positive or negative and are to a large degree not covered in research.

2.4.2 Rebound Mechanisms

Economic mechanisms that explain why consumers change their spending patterns are important in studies of rebound effects. Most of these economic mechanisms start with an energy efficiency improvement. Since the mechanisms are of an economic nature, the assumption in this section is that consumer only react to changes in prices of goods and services, rather than making active consumption decisions themselves.

2.4.2.1 The Price Elasticity of Demand

The definition of the price elasticity of demand is the percentage change in quantity demanded in response to a one percent change in price. In the economic literature, it is common to model the rebound effect as the price elasticity of demand. In fact, the concept of the rebound effect came about to describe the price elasticity of energy demand (Khazzoom, 1980, Binswanger, 2001). This notion of the rebound effects referred to the substitution effect between energy-related services. An example is an increase in the fuel efficiency of cars, leading to consumers preferring car use over other transport modes (Jalas, 2002).

2.4.2.2 Income- and Substitution Effects

The income elasticity of demand is the ratio of the percent change in demand to the percent change in income. The income effect particularly relates to the indirect rebound effect when an increased efficiency in a sector of the economy leads to saved money for the consumer. The income effect studies the change in consumption resulting from a change in real income. In economic theory, the distribution of additional income among goods and services depends on whether the good is an inferior, normal or luxury good. Inferior goods are associated with a negative income elasticity of demand, meaning that increased income leads to decreased demand of the good. A normal good has a positive income elasticity of demand less or equal to one, meaning that increased income is associated with increased demand of the good. Luxury goods have income elasticities greater than one, where a one percent increase in income leads to a demand increase greater than one percent.

A substitution effect arises when prices increase, and consequently consumers prefer luxury goods rather than inferior goods. Staying with the example of an increase in fuel efficiency, decreasing the cost of driving, the substitution effect comes into play when consumers substitute car use for other transport modes.

Figure 2.16 shows the difference between the income effect and the substitution effect. The initial situation is point A, where the consumer maximizes utility by consuming an amount of good X and an amount of good Y. The line BC1 gives the budget constraint. A price decrease in Y then shifts the budget constraint to BC2. The substitution effect is the move from A to B, where the consumer replaces some consumption of X for more consumption of Y. The income effect is the move from B to C. Because the consumer now has a higher disposable income, he/she can move to a higher indifference curve. We see that Y in this figure is an inferior good, as consumption of Y decreases when the income increases.

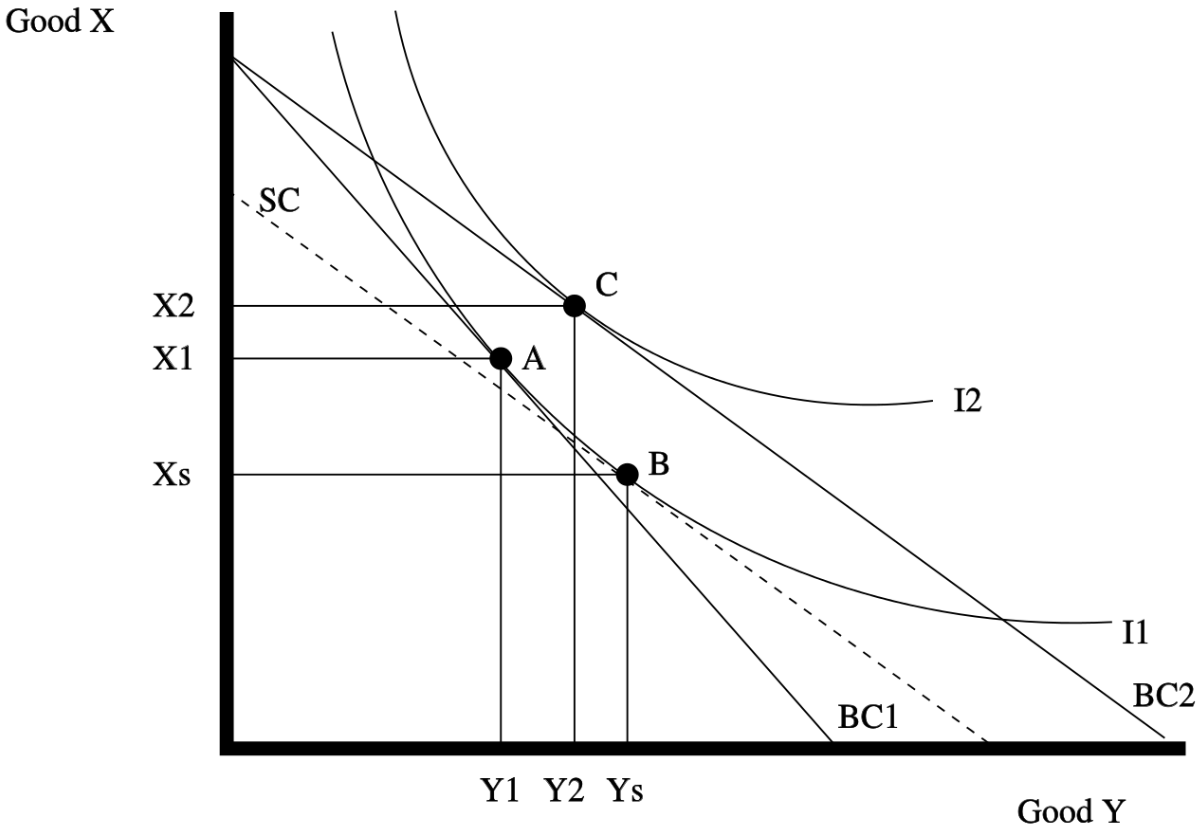


Figure 2.16 Substitution and income effects

(Jrincayc, 2008)

So how does this relate to the rebound effect? The income effect describes how additional income distributes among consumption categories, as these categories differ substantially in GHG intensities. The substitution effect relates to the rebound effect in how price changes lead to changed consumption of different goods. Thus, it is possible to manipulate consumer behavior through changing the price. An example of this is raising the price of fuel or making bus tickets cheaper.

Different measures to reduce GHG emission lead to different effects. Energy efficiency improvements such as a fuel efficiency increase, lead to both substitution and income effects. Behavioral changes, such as a switch to use of public transportation lead to income effects, as the price of the service remains the same (Chitnis et al., 2013).

In order to estimate the income and substitution effects, specific data is required. Both substitution and income effects require estimates of the GHG emission intensities and expenditure elasticity of different categories of goods and services. In addition, calculating the substitution effect, requires estimates of own-price and cross-price elasticities of different categories of goods and services. By using cross-sectional data on household expenditures, it is possible to estimate income effects, but not substitution effects because of small price variations within a specific year. On the other hand, by using time series or pooled cross-sectional (from multiple years) data on household expenditures, it is possible to estimate both income and substitution effects since prices vary significantly from year to year (Chitnis et al., 2013).

Some researchers have examined whether the rebound effect is mostly an income effect or price effect. Lovins (1988) argued that it is most likely an income effect rather than a price effect. Binswanger (2001) found that in a multi-services model, it is hard to make general statements about the rebound effect. The magnitude of the rebound effect depended on the assumptions about the substitutability between the services considered and the direction of the income effect. In a study on improving the household efficiency of home heating Dubin et al. (1986) argue that the rebound effect of 8-13% is primarily a price effect. The basis for analyses on the indirect rebound effects often is an increase in disposable income. Hence, it is likely that in such analyses, the effect is primarily an income effect.

2.4.2.3 Secondary Effect and Embodied Energy

Gavankar and Geyer (2010) identify two mechanisms relating to the indirect rebound effect. The secondary effect mechanisms, where energy consumption in goods and services increases because of an efficiency improvement in a different energy service. This effect typically arises because of an income- or substitution effect. The embodied energy mechanism involves the energy needed to achieve the enhancement in efficiency, such as in the case of a fuel-efficient car. This mechanism comes into play when replacing the existing product with the new product that includes the efficiency improvement.

The mechanisms behind the indirect rebound effect explain why consumers change their spending pattern and how these changes result in different types of rebound effects. However, the assumption of a passive role of the consumer only reacting to changes in prices of goods and services is not the approach in all studies on rebound effect. Instead, some studies assume that consumers actively wish to reduce their carbon footprint, and suggest a set of actions that changes behavior to achieve these reductions (Druckman et al., 2011, Briceno et al., 2005, Alfredsson, 2004, Chitnis et al., 2014, Murray, 2013, Grabs, 2015, Thiesen et al., 2008). Several of these articles are more relevant for the approach of this thesis.

2.4.3 Measuring Rebound Effects

In the rebound framework used in the literature, the actual energy- or GHG emission savings is equal to the expected savings minus the rebound effect (Figure 2.17). Despite the various use of methods, units and consumption sectors of focus in the literature, most researchers seem to use this framework.

Figure 2.17 Energy savings and the rebound effect

(Gavankar and Geyer, 2010)

However, there does not seem to be an agreed upon classification of the magnitude of the rebound effects. Hertwich (2005) suggests a classification of the rebound effect into three categories:

- **Weak rebound effect:** Efficiency measures are not as effective as expected
- **Strong rebound effect:** Most of the expected energy savings are not achieved
- **Backfire effect:** The efficiency measure leads to increased energy demand

A backfire effect would mean negative results in the equation (Figure 2.17). Studies present results of the rebound effect in percent, but a classification of the magnitude is not common. Hence, it is difficult to quantify Hertwich (2005)'s weak and strong rebound effects.

Many studies within the energy economics literature simultaneously measure the direct and indirect rebound effects by applying a system of demand models for goods, such as the Almost Ideal Demand System (AIDS) model (Thomas and Azevedo, 2013b, Deaton and Muellbauer, 1980). These models measure to which extent goods are complements and substitutes as well as the marginal changes in spending patterns as incomes rise and prices change, through measuring income and price elasticities. A weakness to this approach is that it does not account for time trends and changes in variables over time, such as technology development. Another important weakness to the approach is that it only accounts for Scope 1 emissions (combustion) and Scope 2 emissions (e.g. purchased electricity). It often does not account for Scope 3 emissions, which are supply-chain emissions associated with extracting materials, manufacturing, distributing and selling goods and services (Greenhouse gas protocol, 2012, Thomas and Azevedo, 2013b). Including Scope 3 emissions can alter the results substantially. In some cases, these are larger than total Scope 1 and Scope 2 emissions combined, which was the case when Cambridge University in 2012/2013 calculated the total carbon costs of their university as a whole (Cambridge University, 2014).

Rebound effect literature that include Scope 3 emissions typically do so by using environmentally extended input-output analysis (EEIO) or LCA (Druckman et al., 2011, Briceno et al., 2005, Hertwich, 2005, Lenzen and Dey, 2002, Alfredsson, 2004, Thomas and Azevedo, 2013a, Chitnis et al., 2014, Font Vivanco et al., 2014). Other papers combine LCA or IOA with different regressions methods (Nassen and Holmberg, 2009, Su, 2012). EEIO also combine modelling of all upstream emissions of a product with data on the monetary flows in the economy. By creating a database on a large number of products, EEIO can measure Scope 3 emissions across a range of different goods and services. Because it enables distributing re-spending across a variety of goods and services, EEIO is a valuable tool in rebound effect calculations.

It is possible to look at rebound effect from either a consumer or a producer perspective. Following Girod et al. (2011), classical economic theory sees the perspectives as connected since producers wish to maximize their output $Q(C, L, N)$, limited by C – capital, L – labor and N – natural resources, while consumers wish to maximize their utility U by consuming an amount of $x(i, t)$ all types of goods, $i = 1, \dots, i$ at time t. Different types of household resources $j = 1, \dots, j$ and the total amount of this resource $A_{res}(tot, j, t)$ restrain the household consumption. These resources include time, income, storage space or skills. We can see the connection between the producer and the consumer through monetary flows that go from the producer, through the labor market to the household, and through consumption, back to the producer. Households provide producers with labor, while producers provide consumers with goods and services.

The connection between consumers and producers is somewhat similar to a simplified version of the macroeconomic rebound effects discussed earlier because of the many stages of influencing each other. The following example involves only two actors, while for the macroeconomic effects there are numerous actors such as countries, industries and consumers.

A technological efficiency improvement in production enables the manufacturer to produce the same amount of goods or services with less input of labor, capital or natural resources. This reduction in input means a cost reduction for the producers, often accompanied with a reduction in emissions. However, since the producer wishes to maximize output, he increases production, making the most of the inputs. This increased production and associated increase in emissions is equivalent to a rebound effect on the supply side. However, the producer does not gain this increase in production unless the consumer increases demand. According to the theory of maximizing utility, if an increase in consumption of a product leads to increased utility, the consumer will increase demand. This increased demand is not possible without an increase in income for the consumer. The producer supplies the consumer with additional income through increased production input in form of labor, and possibly a decreased price of the product because of higher demand. Households spend the additional income on a variety of goods and services, resulting in a demand side rebound effect.

As it appears in classical economic theory, the rebound effects on supply and demand sides have a circular connection. Partly because of this circular connection and because of double counting, studies typically do not focus on rebound effects in production and consumption at the same time. Most studies on the field do take a demand side perspective. The approach of this thesis is taking a demand side perspective, but additionally, households change consumption based on a motivation to lower their carbon footprint, rather than based on price changes. In order to lower their carbon footprint, households need information on how their lifestyle contributes to GHG emissions and which actions they can take to lower these emissions.

2.5 Spending Patterns

A central question in the rebound literature is how people spend additional income. Two of the most common beliefs are the average and marginal spending pattern approaches. The first assumes that people spend additional income in proportion to their current consumption patterns, while the second assumes that consumption patterns change with increasing income. In addition to these two main approaches, I include a discussion of alternative approaches to calculating spending patterns.

2.5.1 Average

Calculating re-spending according to average consumption bundles means re-spending the money saved in the same proportion across goods and services as the current spending pattern. Another name for this approach is proportional re-spending. It is often used to examine the energy intensity of the economy using input-output tables (Gillingham et al., 2014). Using proportional re-spending of saved money is the chosen methodology in several studies of the rebound effect (Lenzen and Dey, 2002, Takase et al., 2005, Freire-González, 2011, Thomas and Azevedo, 2013a). However, many studies estimate the average spending patterns in addition to marginal spending pattern approaches to explore the difference between them (Thomas and Azevedo, 2013a, Freire-González, 2011, Thiesen et al., 2008).

2.5.2 Marginal

The central question when calculating marginal spending patterns is how individuals or households spend an incremental increase in disposable income. In the case of Norwegian households, the question is how they spend one additional NOK. In theory, the households would make a conscious decision of how they would allocate this small income increase across available goods and services. In practice, households would not distribute such small increases in disposable income across a wide range of goods and services, but for larger increases in income, a pattern different from the average spending pattern would most likely emerge. The approach to calculate how households spend additional money is to break down the population into different income groups and study how expenditures patterns differ between them (Hertwich, 2005). When moving from a lower income group to a higher one, it should tell us something about how households spend additional money.

Thiesen et al. (2008) take a marginal consumption pattern approach. By using data that come from Danish household consumer expenditure surveys, they examine marginal income changes and the resulting changes in consumption patterns. Hence, they find short-term changes in consumption patterns. They assume that the consumption pattern of the household changes towards the consumption pattern of the adjacent higher income group. However, they assume this for small income increases. It is possible that for small income increases and small time-steps, there is a certain inertia in spending pattern changes, meaning that people spend the extra money according to average, rather than marginal spending patterns. Thiesen et al. (2008) also find that the difference between average and marginal spending patterns is relatively small, and suggest using average consumption patterns as a first proxy to include marginal consumption. The paper also ignores the possibility of people saving up money for consumption on a specific product or service.

Gillingham et al. (2014) find two different approaches to estimating marginal spending patterns. One is to compare consumption patterns across income brackets using cross-sectional data, such as in Thiesen et al. (2008) (as cited in Gillingham et al., 2014). The other approach, used in Druckman et al. (2011) uses income elasticities that are based on how consumers change demand for goods and services over time as income rises. The latter approach relies on having data on expenditure elasticities on goods and services. An expenditure elasticity, also known as the income elasticity of demand, is a measure of the responsiveness of expenditure on, or the quantity demanded of, a good to a change in income, ceteris paribus (Browne et al., 2007).

The two approaches presented by Gillingham et al. (2014) to estimating marginal consumption are similar, but differs in the time perspective of gathering data. By examining income brackets using cross-sectional data, means comparing households with different income, while when using expenditure elasticities, the approach is to study how a household that experiences increasing income, changes its expenditure over a given period.

Font Vivanco et al. (2014) describes two ways of calculating marginal consumption, the income-shifting approach and the Engel curve approach. The income-shifting approach relates marginal liberated money with marginal changes from one income group to the adjacent higher income group. The different cross elasticities between consumption categories are implicitly considered. The Engel curve approach studies how expenditure on a given consumption category varies with household income. To separate the consumption decision from the decision of saving, income is assumed equal to total expenditure (Lewbel, 2008)

2.5.3 Other

Case-control studies evaluate expenditure patterns of groups who differ in their behavior in one specific sector of the economy (e.g. personal car vs. public transport), while controlling for income. This approach enables studying how specific groups of the population differ in their spending patterns. The approach is useful if the aim is to study specific scenarios, such as implementing a car-sharing scheme (Hertwich, 2005).

Kawajiri et al. (2015) performed an interesting study on estimating the rebound effect based on a questionnaire that asked the respondents first to estimate annual spending in 21 different groups of goods and services. Then they asked the respondents how much they thought they could save in a year by curtailing their spending on each item. Finally, in order to estimate the rebound effect, they asked the respondents to allocate all the savings from the second step across the 21 categories.

Instead of allocating expenditure on different goods and services, it is possible that households save money for a larger future investment, such as a car purchase or holiday. If households save enough money for such a cause, it would influence the spending pattern. The use of marginal or average spending patterns in this case could give inaccurate results. Still, the actual spending pattern would probably be closer to the marginal spending pattern, given that the future investment is associated with spending patterns of higher income groups.

In his study, Alfredsson (2004) found that when consumers adopt a “green” consumption pattern, for example a “green” diet, people re-spend the saved money in other consumption categories that have on average higher energy and CO2 intensities than the difference in intensity between the current and the “green” diet. The result is a backfiring effect of higher GHG emissions than in the original scenario. A reason for this may be a lack of knowledge about the rebound effect or the GHG emission intensity of consumption of different goods and services. If we instead assume that the household has knowledge about the carbon footprint and thus re-spend the money saved in a way that seeks to minimize the carbon footprint, we can say that the household adopts a “green” spending pattern. Not many studies have researched such re-spending, but Hertwich (2005) proposes a way of estimating spending patterns by case-control studies of comparing spending patterns of people who engage in a type of green consumption activity, to those who engage in an activity within that same consumption category that is considered less “green”. By comparing consumption patterns of people who consciously engage in green consumption in several different consumption categories, to those who do not, it might be possible to develop a green spending pattern.

2.5.4 Use in the Literature

There seems to be little agreement on the difference between marginal and average spending patterns or which of them to choose. Thomas and Azevedo (2013b) argue that the importance of the difference between them is empirically unclear. Hertwich (2005) suggests that the use of either marginal expenditure patterns or case-control studies might be a better choice than using the average spending pattern approach.

Goedkoop et al. (1999) state that marginal spending patterns are more important than average spending patterns. Thiesen et al. (2008) find that the difference is minimal between marginal and average spending patterns for global warming impacts. Nassen and Holmberg (2009), on the other hand, find that marginal expenditures are significantly different from average expenditures in the case of a change in real income. Thomas and Azevedo (2013a) and Freire-González (2011) and Thiesen et al. (2008) all find that marginal and average re-spending approaches both result in rebound effects in the same range, with a difference of only 1-4%.

Taylor and Houthakker (2009) (as cited in Thomas and Azevedo, 2013a) compare consumer's budget shares, which is equivalent to average spending patterns, with different methods on calculating marginal spending patterns (Table 2.2). They find that for some consumption categories, the difference when going from average to marginal consumption patterns is significant. The difference in budget-share is particularly large for food (5-7% decrease), transportation equipment (3-15% increase) and shelter (2-7% increase).

Category	2004 budget share	LES-normalized expenditure elasticity	IA-normalized expenditure elasticity	Marginal spending share (LES)	Marginal spending share (IA)
Food	8%	0.12	0.36	1%	3%
Shelter	15%	0.54	0.87	8%	13%
Appliances	3%	0.54	0.87	1%	2%
Electricity	2%	0.14	0.40	0.3%	1%
Natural gas	1%	0.14	0.40	0.2%	1%
Other utilities	4%	0.14	0.40	1%	2%
Gasoline	4%	2.3	1.3	9%	5%
Transportation equip.	11%	2.3	1.3	26%	14%
Public transit	0.2%	2.3	1.3	0.4%	0.2%
Air travel	1%	2.3	1.3	2%	1%
Health care	4%	0.27	0.52	1%	2%
Financial services	20%	0.27	1.3	22%	24%
Misc.	26%	1.1	1.2	29%	32%

Notes: LES = Linear Expenditure System, IA = Indirect Addilog System. Spending shares may not sum to 100% because of rounding truncation.

Table 2.2: Houthakker–Taylor expenditure elasticities used in rebound simulations

Taylor and Houthakker (2009) (as cited in Thomas and Azevedo, 2013a)

Girod et al. (2011) does a similar study showing that the share used for food decreases with increasing income, to point out the importance of marginal spending patterns. However, they also state that it is possible to show that average consumption is close to marginal consumption for smaller time steps (Stock, 1988). This aspect of the previously discussed inertia in changing pattern of consumption is important to consider.

The reasons behind the very different results in use of average versus marginal spending patterns could be many. One possibility is the variety of methods used in the studies above. Thomas and Azevedo (2013b) and Nassen and Holmberg (2009) use an EEIO framework, Thiesen et al. (2008) and Girod et al. (2011) use LCA, while Goedkoop et al. (1999) develop what they call a new analysis method, comparing cases by using four characterization axes (economic, ecological, identity/strategy and client acceptance). Numerous other possible answers to the different findings of the papers also exist, such as; data availability, differences in demographics or differences between income groups of the population studied. From the results found in Thomas and Azevedo (2013a) and Freire-González (2011) on comparing the rebound effect using different approaches to re-spending, it seems like although the difference between average and marginal spending patterns is present, it decreases when calculating re-spending in a rebound framework.

3 Methods

3.1 Household actions

The first part of the methods involves identifying 34 actions that save GHG emissions and changes cost for the households (Table 3.1). Later in the thesis, I refer to these actions by their corresponding number in Table 3.1. The units and the need for conversion of prices differ for some of the actions due to the use of different data sources. I adjust the units and prices at a later stage, before doing any calculations on re-spending or the rebound effects.

Action #	Household actions	Consumption sector	Conversion to 2007 prices needed?	Unit
1	Switch to Renault Zöe	Transport	yes	2.22/pkm
2	Switch to Tesla	Transport	yes	2.22/pkm
3	No trips by car under 3 km	Transport	yes	2.22/pkm
4	Only bus transport	Transport	yes	2.22/pkm
5	Car-pooling for work under 10 km	Transport	yes	2.22/pkm
6	Only train transport	Transport	yes	2.22/pkm
7	Walk instead of train (9.4 km)	Transport	yes	per year
8	Reduce business flights (one per month)	Transport	yes	per year
9	Eliminate long-distance flight for vacation	Transport	yes	per year
10	Reducing indoor temperature by 1°C	Residential	yes	per year
11	Space and water heating	Residential	yes	per year
12	Appliances and other	Residential	yes	per year
13	Grenn Diet	Food	no	per year
14	Eliminating food waste	Food	no	per year
15	Organic Green diet	Food	no	per year
16	Other measures (organic, local, composting)	Food	no	per year
17	Eco-efficiency across suply chain	Clothing	no	per year
18	Design for durability	Clothing	no	per year
19	Market shift to more synthetic fibres	Clothing	no	per year
20	Clean clothing less	Clothing	no	per year
21	Wash at lower temperature	Clothing	no	per year
22	Increase size of washing and drying loads	Clothing	no	per year
23	Use the tumble dryer less	Clothing	no	per year
24	Dispose less - reuse more	Clothing	no	per year
25	Start closed loop recycling of synthetic fibres	Clothing	no	per year
26	Dispose less - recycle more	Clothing	no	per year
27	Reduce clothing purchases by 20%	Clothing	no	per year
28	Average of changing 6 pieces of furniture	Furniture	yes	per year
29	Increase lifetime by 20%	Furniture	no	per year
30	Buy furniture with 20% recycled MDF	Furniture	no	per year
31	Eliminating unsolicited mail	Paper	yes	per year
32	Reduced printing	Paper	yes	per year
33	e-papers and e-books	Paper	yes	per year
34	Reducing plastic waste by 30%	Plastic	yes	per year

Table 3.1: Saving scenarios including units and need for price conversion

3.1.1 Transport

An average of 1.55 passengers per car (Transportøkonomisk Institutt, 2014) is the basis for the conversion of costs and GHG emissions from per vkm to per pkm. In order to have the units for GHG emission reductions and cost reduction on a per household basis, I multiply pkm by 2.22, which is the average Norwegian household size in 2012 (Statistics Norway, 2014b). As a result, the units in the transport scenarios involving car use, are (kg CO2-eq/pkm)*household size. The reason behind this choice is that the cost and GHG emission reductions in the scenarios of the other consumption sectors are on a per household basis.

The GHG emission savings and cost savings for all of the scenarios that are associated with daily travel by car or replacing car use with other transport modes are on a per pkm basis. The upper limit potential of each of the scenarios is the total pkm of car travel per person each year. In other words, a household cannot achieve larger GHG emission savings or cost reductions than the savings per pkm multiplied by the number of pkm travelled by car each year. Additionally, to avoid double counting, the sum of the pkm used in each scenario cannot exceed the total pkm traveled by car by each household. Table 3.2 presents the total kilometers traveled within each travel length per person per year

Total km traveled by car per person per year	Non-work related travel (km)	Work related travel (km)
<1 km	16	6
1-2.9 km	283	59
3-4.9 km	394	92
5-9.9 km	907	221
10-19.9 km	1411	491
>20km	6816	3220
Total	**9826**	**4088**

Table 3.2: Total daily travel by car per Norwegian person per year. Hjorthol et al. (2014) and author's won work

3.1.1.1 Switch from conventional gasoline vehicle to electric car

The starting point is an assumption that a household owns a conventional gasoline car, but now face a decision of buying a new car. The household can choose between buying a new gasoline car with similar emissions and costs per km driven. Alternatively, they can buy a new electric car. The models to choose is either a high-end electric vehicle, such as the Tesla model S, or a mid-range vehicle with good environmental performance, such as the Renault Zoe. I create two scenarios from the choices the household faces. The first comparing the costs and GHG emissions per passenger-kilometer (pkm) of choosing a Renault Zoe over a conventional gasoline car and the other comparing the Tesla Model S to the conventional gasoline vehicle. The estimated emissions per vkm for the conventional gasoline vehicle is 0.289 kg CO2-eq (Hawkins et al., 2012). This is life cycle emissions, which includes emissions from manufacturing, the use-phase and the end-of-life phase of the vehicle. Calculations on emissions from the two electric cars use the same methodology.

The Tesla Model S have estimated emissions of 0.165 kg CO2-eq/vkm. Manufacturing and end-of-life emissions here account for 0.123 kg CO2-eq/vkm (Nealer et al., 2015), while the remaining are emitted in the use-phase. Estimations of use-phase emissions have two components. Firstly, the estimated electricity use is 0.235 kWh/km (Blaker, 2015). Secondly, for electricity emissions, the estimate is 0.117 kg CO2-eq/kWh (ENOVA, 2013) using the Nordic electricity mix.

The estimated emissions for the Renault Zoe are 0.113 kg CO2-eq/kWh. Non-use-phase emissions account for 0.087 kg CO2-eq (Hawkins et al., 2012). The use-phase emission estimate bases on an estimated electricity use of 0.146 kWh/km (Renault, 2016) and electricity emissions of 0.117 kg CO2/kWh (ENOVA, 2013).

In calculating the costs of the different vehicles, I use the average cost per pkm. This is 4.25 NOK/vkm for the gasoline vehicle, 2.24 NOK/vkm for the Renault Zoe and 5.67 NOK/vkm for the Tesla Model S. All cost estimates come from Smartepenger (2016), which provides calculators for the cost structure of different types of vehicles based on variables such as the cost of purchasing the car, as well as different types of running costs and fixed costs. See Appendix B for more details.

3.1.1.2 Substitute car travel with other transport modes

Four of the household actions proposed involve substituting car travel for other modes of transport. These are:

- Walking instead of driving a car for all trips under 3 km
- Switch all daily car travel with bus transport
- Car-pooling for work travel by car under 10 km using a hybrid car

- Switch all daily car travel with train transport

The following methodology is common for the four scenarios. These scenarios all involve reducing car transport in favor of other transport modes, keeping the total pkm traveled per year constant. Assuming that the household still owns a car, but rather uses it less, the marginal price of car travel per vkm, rather than the average price is appropriate. The reasoning behind this is that household must pay the fixed costs, such as insurance and annual fees, regardless of reductions in the overall km traveled by car. Hence, the marginal cost per km leaves out fixed costs. In the original scenario, the household owns a conventional gasoline vehicle. Thus, the marginal cost of the car is 1.61 NOK/vkm (Appendix B). The emissions of the conventional gasoline car is 0.289 kg CO2-eq/vkm (Hawkins et al., 2012).

3.1.1.3 Walk instead of driving for trips under 3km

This action assumes that all trips that previously involved driving a car, instead are in the form of walking or bicycling. The assumption is that walking or bicycling as transport modes, are associated with no GHG emissions or costs for the household. Hence, the cost and GHG emission reductions are solely a result of reducing the pkm driven by car. The upper limit of this scenario is the total amount of pkm traveled by a person on trips under 3 km in a year, both for work related and non-work related travel (Table 3.2).

3.1.1.4 Substitute all daily car travel with bus transport

This action assumes that the household substitutes all daily travel by car with bus transport, but still owns a car. The cost per pkm of bus transport base on the total pkm traveled by car (Table 3.2), and the yearly cost of a public transport pass for an adult in Trondheim (ATB, 2015). GHG emissions of 0.029 kg CO2-eq/pkm for a long-haul bus are estimates from NSB (2015). The upper limit of this action is the total amount of pkm traveled by car in a year (Table 3.2).

3.1.1.5 Car-pooling for work travel by car under 10 km using a hybrid-electric car

Instead of using the household's own conventional gasoline car, the members of the household car-pool for work travel under 10 km using a hybrid-electric car. The number of people in the car is set to three, and the people in the car equally divide the costs and GHG emissions associated with the travel. Hence, by subtracting GHG emissions and costs per pkm of driving the gasoline vehicle with those in the car-pooling scenario, I obtain the GHG emission and cost reductions. Samaras and Meisterling (2008) provide the estimated life-cycle GHG emissions for the hybrid-electric car of 0.064 kg CO2-eq/vkm. Using the calculators at

Smartepenger (2015) the estimation for the marginal cost is 1.05 NOK/vkm for a hybrid-electric car. The upper limit for this action is the sum of all work-related travel under 10 pkm per person in a year (Table 3.2).

3.1.1.6 Substitute all daily car travel with train transport

The methods for calculating GHG emissions and cost reductions per pkm is the same as for the action that switches all daily car travel with bus transport. For train transport the GHG emissions are 0.025 kg CO2-eq/pkm, based on average emissions using an electric locomotive on the distance Trondheim-Oslo (NSB, 2015).

3.1.1.7 Actions involving other transport modes

The units of these actions are costs and GHG emissions saved per year since there is no double counting of scenarios, as is the case for the other transport action. Instead, the assumption is that the household currently undertakes a certain type of action. The cost and GHG emission savings then originate when the household makes changes to - or eliminates this action.

3.1.1.8 Walk Lerkendal - Trondheim S instead of taking the train (4.7 km each way)

The starting point here is that the all members of the household travel a daily return trip by train of 9.4 km every day of the year. The behavioral action is to walk or bicycle instead of using the train for this particular trip, while assuming no emissions or costs associated with bicycling or walking. The GHG emissions and costs of taking the train is the same as in the action of substituting all car travel with train transport.

3.1.1.9 One less return business flight per month (Trondheim – Oslo)

The first step of this action is an assumption of one business flight per month per household member at the equivalent distance of a return flight Trondheim (Værnes) – Oslo (Gardermoen). The calculations exclude costs and GHG emissions associated with the transport to and from the airports.

Data on average price for a return ticket on the distance comes from Denstadli and Rideng (2012), while the data on distance and CO2 emissions comes from ICAO (2015). This scenario only accounts for tailpipe CO2 emissions associated with air transport.

3.1.1.10 One less vacation to Bangkok, Thailand

The scenario is that instead of traveling to Bangkok, Thailand, the household spends their vacation at home. The data on distance and direct tailpipe CO2 emissions come from the same source as the action of reducing business flights (ICAO, 2015). The price estimate of 4500 NOK/person is the lowest price found for a return flight Oslo - Bangkok in January 2016. This price might be an underestimate compared to the average price paid for this distance.

3.1.2 Shelter

The calculations on potential GHG emission savings and cost reduction are on a yearly basis per household. An important assumption for these actions is that electricity is the only source of space heating by the household.

3.1.2.1 Reducing indoor temperature by 1°C

By reducing indoor temperature by 1°C in the seasons when indoor heating is needed, a cost reduction of 5% of the current heating costs is achievable (Akershus Enøk og Inneklima as, 1999, Vaillant, 2015, Novema Kulde, 2016). Since reducing indoor temperature only involves use-phase emissions, and will only reduce the electricity used by the household, we can also assume a 5% reduction in GHG emissions. The price of electricity is 0.727 NOK/kWh, which is the price of the third quarter in 2015 and includes the price of electricity, fees and grid rental (Statistics Norway, 2016). The GHG emission intensity is 0.117 kg CO2-eq/kWh of electricity (ENOVA, 2013). The yearly electricity use of the household is 20230 kWh (Statistics Norway, 2014a), while 78% of the total electricity use is for the purpose of space and water heating (Borge et al., 2004, Bergesen et al., 2012) (Figure 2.12).

3.1.2.2 Space and water heating

The calculations on possible GHG savings as well as associated cost reductions base on a retrofit of an existing building. As cited in the IPCC report, a review by Harvey (2013) showed that comprehensive retrofit packages for detached single-family homes achieved 50-75% reductions in total energy use. Such a retrofit would cost from 100-400 USD/m² (2010 prices). The average Norwegian household had in 2004 a size of around 120 m² (Andersen, 2005), so assuming a 65% reduction and costs of 350 USD/ m², the total cost would be 254,000 NOK using the USD to NOK conversion rate for 2010 (Norges Bank, 2016). Assuming a 40-year lifetime of the retrofits, the cost per year amounts to 6350 NOK. The second component of the yearly cost reduction arises from reduced use of energy. The electricity price, household electricity usage and the percentage of total energy use for space and water heating is the same as in the scenario of reducing indoor temperature by 1°C.

Yearly GHG emission savings for households bases on a 65% reduction in total residential energy use along with the data on the GHG intensity of the Nordic electricity mix, electricity use per household and electricity use for the purpose of space and water heating (Figure 2.12). Furthermore, according to Gonzalez et al. (2012) use-phase emissions out of the total is about 99% for lighting products, about 90% for major appliances and in the range of 20-60% for electronic devices. A crude assumption is that for all the products in average, 90% of emissions occur in the use-phase. This implies treating the remaining 10% as non-use-phase emissions and adding these to the use-phase emissions.

3.1.2.3 Appliances and other

The methodology for calculating GHG emission and cost reduction potential related to appliances and other residential measures, such as lighting is similar to that of space and water heating. The estimate from the Intergovernmental Panel on Climate Change (2015) is that each individual equipment has an energy savings potential of about 40-50% through measures such as recycling of appliances, increased energy efficiency and material use and increasing lifetime. Assuming that the average Norwegian household already has realized some of this potential, the estimation is that household can achieve a 30% energy savings in this area, at a one-time cost of 20 000 NOK. Assuming that these appliances in average have a lifetime of 10 years, it amounts to a yearly cost of 2 000 NOK. The parameters used for estimating reduced costs and GHG emissions are otherwise the same as for space and water heating. Notice that appliances and other measure account for the remaining 22% of the kWh use of households (Bergesen et al., 2012) (Figure 2.12). Furthermore, like for space and water heating, I assume that 10% of total emissions comes from non-use-phase sources (i.e. manufacturing and end-of-life).

3.1.3 Food

In order to estimate the GHG emission reductions, I use the original emissions found in EXIOBASE2 related to food consumption of Norwegian households. The original household spending data come from Steen-Olsen et al. (Accepted for publication) given in 2007 prices, which is the year of the data in EXIOBASE2. Absolute GHG emission and cost reductions for all actions in this consumption sector are based on these GHG emission and spending data.

3.1.3.1 Green diet

The literature reviewed suggests that a reduction of 40% of GHG emissions related to food consumption is achievable through a change in diet towards a healthier, less GHG intensive and more plant-based diet (Goodall, 2010, Stehfest et al., 2009, Berners-Lee et al., 2012, Intergovernmental Panel on Climate Change, 2015, Grabs, 2015). The cost reduction following such a change in diet is set to 15% (Grabs, 2015, Berners-Lee et al., 2012, Alfredsson, 2004).

3.1.3.2 Eliminating food waste

In Norway about 20-25% of food purchased by households is wasted (Matvett, 2014). This means that by eliminating food waste, we can assume a 20-25% reduction in food costs and GHG emissions.

3.1.3.3 Organic green diet

The assumption is that implementing an organic green diet increases food costs by 45% (Hvitved-Jacobsen, 2001, Consumerreports, 2015). However, the switch to a green diet offsets some of this cost increase. This cost decrease is set to 15% compared to original expenditure, based on the previous action of changing to a green diet.

The GHG emission reduction is the same as for the green diet plus a further 10% decrease compared to a conventional diet (Olesen et al., 2006).

3.1.3.4 Other measures (organic, local, composting)

This action is the combined benefits of several measures, such as eating local, composting and eating organic food. The GHG emission savings from this action is set to 15% compared to original emissions (Goodall, 2010). The assumed food cost increase is set to 20%.

3.1.4 Clothing

For the actions involving clothing consumption, the current GHG emissions come from EXIOBASE2, while the expenditure data come from Steen-Olsen et al. (Accepted for publication).

The calculations on GHG emission reduction potential and monetary savings base on the measures of Thomas et al. (2012) (Table 2.1), along with a 20% reduction in clothing purchases by households. Estimations of cost reductions are assumptions for each measure.

3.1.5 Furniture

The original estimates of GHG emissions associated with furniture comes from EXIOBASE2. The expenditures by Norwegian households on furniture come from Steen-Olsen et al. (2014). Furthermore, the expenditure data are from 2012, but adjusted to 2007 prices.

3.1.5.1 Changing six pieces of furniture

Calculations on investing in new and more environmentally friendly products comes from González-García et al. (2011) who evaluated the global warming reduction potential of different wooden products. I include six of these measures in the calculations of GHG emission reductions. Furthermore, assumptions on household cost reductions and the lifetime of the products come from stores selling similar products in Norway. The weighted average absolute emission reductions of the six measures found by González-García et al. (2011) and the assumed lifetime of the products are used as a proxy for the yearly GHG emission reduction potential. The assumed weighted average costs divided by the lifetime of the products make up the yearly cost reduction.

3.1.5.2 Increase lifetime of all furniture by 20%

Extending the lifetime of existing products is achieved either by keeping own products for a longer time, buying second-hand or selling the products instead of throwing them. Consequently, I reduce both the cost GHG emissions by 20% compared to the original data.

3.1.5.3 Buy furniture with 20% recycled medium-density fiberboard (MDF)

According to Mitchell and Stevens (2009) a 21% reduction in GHG emission for wood-based furniture is possible through using medium-density fiberboard. Furthermore, Linkosalmi et al. (2016) estimate that 60% of the materials in furniture is made of wood. Based on this, I assume a 12.6% reduction in GHG emissions. The use of medium-density fiberboard involves an assumed cost increase of 10% compared to the original scenario.

3.1.6 Paper

All calculations on GHG emission and cost reductions are bottom-up estimates. Hence, there is no need for original GHG emissions and household expenditures to make the calculations.

The emission intensity is set to 1.1 kg CO2-eq/kg paper (Intergovernmental Panel on Climate Change, 2015)

3.1.6.1 Eliminating unsolicited mail

Assuming that the household receives unsolicited mail, households achieve a reduction of 35 kg of paper by eliminating this (Klimahandling.no, 2016, Salhofer et al., 2008). Multiplied with the GHG intensity of paper, the saved GHG emissions are 38.5 kg CO2-eq. This action comes with no change in expenditures for the household since unsolicited mail is free of cost.

3.1.6.2 Reduced printing

By using print management systems combined with double-sided printing the household can obtain an estimated 30% reduction in paper consumption (Canonico et al., 2009, Dempsey and Palilonis, 2012). The cost per kg of paper is set to 20 NOK. An assumption of 50 kg printed-paper per households per year (printed at work and at home) leads to a cost reduction of 300 NOK and an emission reduction of 16.5 kg CO2-eq per household.

3.1.6.3 Reading e-papers and e-books instead of newspapers and books

This action involves an assumption of the household buying 10 books per year and a subscription to a newspaper. The assumption is that the price of books is the same as e-books, leading to no change in expenditures. The estimated cost of subscribing to an e-newspaper is 200 NOK lower than a regular newspaper per month. Consequently, the cost reduction is 2400 NOK per year.

Life cycle GHG emissions of an e-book is set to 0.43 kg CO2-eq lower than for a regular book (Moberg et al., 2011). For the switch to e-newspapers, a GHG emission reduction potential of 9.8 kg CO2-eq/year per reader is assumed (Moberg et al., 2010). A further assumption is that all members of the household reads the newspaper.

3.1.7 Plastic

3.1.7.1 Reducing plastic waste by 30%

According to Statistics Norway (2015a), the plastic waste per person in Norway is approximately 7 kg. The emission intensity is set to 3 kg CO2-eq/kg plastic (Winnipeg & Veolia Water, 2011). The price per kg plastic is set to 50 NOK.

3.2 Adjusting Actions

To calculate the actions on a per unit basis (Table 4.1) enables the household to choose a combination of the actions available for each unique activity (Appendix A). An alternative way of interpreting splitting up the actions implemented for each activity is that numerous households implement these actions, and that the numbers in the matrix that adjusts for double counting (Appendix A) resemble percentages of households implementing these actions.

Splitting up available actions for each activity is particularly relevant for some of the transport actions (number 1-6). One specific activity for these actions is non-related work-travel under 3 km. The household then has the option of which of the six available actions to implement for this specific activity. The household can choose combinations of actions to implement. For this specific activity, a natural choice for an environmentally aware household could be to walk all of these travels, and thus the matrix that adjusts for double counting will have the value 1 for this specific element, and 0 in the elements corresponding to all other available actions. The next step is to multiply the combination of actions chosen for each specific activity with the cost and GHG reductions per unit of the actions. By multiplying this with the number possible of each activity (Table 3.2 and Appendix A), I obtain the total cost and emission reduction structure of that particular combination of actions, while adjusting for double counting of actions. A specific suggestion of such combinations of actions (Appendix A) is the basis for further calculations. However, this matrix enables several scenarios of combinations of actions.

3.3 Marginal Spending Pattern

There are multiple approaches to calculating marginal spending patterns (Font Vivanco et al., 2014). One approach is to compare consumption patterns across income brackets using cross-sectional data like in Thiesen et al. (2008). Font Vivanco et al. (2014) calls this as the income-shifting approach. Statistics Norway (2013) provides detailed consumption patterns of households broken down into decile income brackets. By using this data, we can estimate how a Norwegian household will spend one additional NOK of income.

The Norwegian Consumer Survey classifies the deciles as follows:

- decile 1
- decile 2+3
- decile 4+5
- decile 6+7
- decile 8+9
- decile 10

The first step is to calculate the propensity to consume (MPC) given by:

$$\text{MPC}_{n,j} = \frac{\partial Q_i}{\partial I} = \frac{Q_{i_{n+1}} - Q_{i_n}}{I_{n+1} - I_n} \tag{1}$$

I is average income for the deciles, Q is demand for product group j, and n are decile groups 1 to 6. This gives us the marginal spending pattern, based on the different consumption from one group to the next (e.g. from decile 1 to decile 2+3)

Thus, I calculate the relative purchasing power of each of the categories of the deciles above:

$$RPP_n = \frac{APP_n}{\sum_{i=1}^{6} APP_i} \tag{2}$$

Where APP_n is the absolute purchasing power of decile group n, and RPP_n is the relative purchasing power of Decile n.

Finally, I calculate the marginal spending pattern according to the weighting of the relative purchasing power of the deciles:

$$MSP_j = \sum_{n=1}^{6} (MPC_{j,n} * RPP_n) \tag{3}$$

Where MSP_j is the marginal spending of product group j, $MPC_{n,j}$is the marginal propensity to consume product j in decile group n, and RPP_n the relative purchasing power of decile group n. When calculating the marginal consumption from one decile to the next, the average of the purchasing power of the two deciles is calculated. To avoid double counting when calculating marginal spending from one decile group to the next, all groups counted twice (all except decile 1 and decile 10), are weighted half.

3.4 Green Marginal Spending Pattern

The idea behind the green marginal spending pattern is that a household that wishes to lower its carbon footprint intentionally avoids re-spending money on goods and services that have high GHG emissions per NOK spent. This requires that households have information on the multipliers (CO2-eq/NOK) associated with the purchase of all goods and services. Elimination of goods and services base on the multipliers and the share of total consumption and includes the following product groups in the CREEA classification:

- #5 – Oil Seeds
- #21 – Cooking coal
- #43 – Products of meat cattle
- #49 - Processed rice

- #55 - Textiles (17)
- #67 – Motor Gasoline
- #71 - Kerosene
- #88 - N-fertilizer
- #94 - Biodiesels
- #117 - Fabricated metal products, except machinery and equipment (28)
- # 123 - Motor vehicles, trailers and semi-trailers (34)
- # 129 - Electricity by gas
- # 134 - Electricity by biomass and waste
- # 160 - Sea and coastal water transportation services
- #162 - Air transport services (62)
- # 183 - Food waste for treatment: biogasification and land application
- # 190 - Food waste for treatment: landfill
- # 194 - Textiles waste for treatment: landfill
- #56 - Wearing apparel; furs (18)
- #68 – Aviation Gasoline
- #72 - Gas/Diesel Oil
- #90 - Chemicals nec
- #95 - Other Liquid Biofuels
- # 118 - Machinery and equipment n.e.c. (29)
- #128 - Electricity by coal
- # 133 - Electricity by petroleum and other oil derivatives
- # 148 - Steam and hot water supply services
- #161 - Inland water transportation services
- #163 - Supporting and auxiliary transport services; travel agency services (63)
- #184 - Paper waste for treatment: biogasification and land application
- #191 - Paper for treatment: landfill

The next step is to reallocate the percentage shares of the deducted product groups to the remaining product groups in the following way:

$$a_{i_{GM}} = a_{i_M} + \left(\frac{a_{i_M}}{1 - \sum_{j=1}^{n} a_{j_M}}\right) * \sum_{j=1}^{n} a_{j_M} \tag{4}$$

$a_{i_{GM}} = Relative\ share\ of\ product\ i\ in\ the\ green\ marginal\ consumption\ vector$

$a_{i_M} = Relative\ share\ of\ product\ i\ in\ the\ marginal\ consumption\ vector$

$\sum_{j=1}^{n} = Sum\ of\ relative\ shares\ of\ deducted\ product\ groups\ j\ in\ the\ marginal\ consumption\ vector$

$n = Number\ of\ deducted\ product\ groups$

3.5 Derivation of the Input-Output Analysis Framework

Table 3.3 shows a simplified input-output table. The **Z-matrix** (industry x industry) is the total inter-industry flows matrix. The columns represent total input into each industry, while the rows show total output from each industry. The **V-vector/matrix** (value added x industry) is the total value added into the industries, and accounts for labor costs, profits, capital costs etc. The **y-vector** (industry x final demand) is the total final demand containing consumption of households and governments, private investment purchases and net exports. Finally, the **x-vector/matrix** (total output x industries) is the total output from the industries, given the final demand.

	Industries	**FD**	**Total Output**
Industries	Z	y	x
VA	$\overline{V}$		
Total Input	x		

Table 3.3: Simplified input-output table

Summing across the rows gives the total output **x**, given in equation (5).

$$\mathbf{Zi} + \mathbf{y} = \mathbf{x} \tag{5}$$

The **i-vector (**industries x 1) is a vector of ones: $\mathbf{i} = \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}$ and enables us to sum the **Z-matrix** into a vector. Equation (5) gives us the production balance (total input=total output)

The next step is to introduce the **A-matrix** (industries x industries) of intra-industry requirements. It gives us the requirements from each industry per unit produced by each of the industries. Thus, a_{ij} shows the requirement from industry i per unit produced by industry j.

$$\mathbf{A} = \begin{bmatrix} a_{11} & \cdots & a_{1j} \\ \vdots & \ddots & \vdots \\ a_{i1} & \cdots & a_{ij} \end{bmatrix}$$

Equation (6) shows the connection between the **A-matrix** and the **Z-Matrix.**

$$\mathbf{Z} = \mathbf{A}\hat{\mathbf{x}} \tag{6}$$

Here $\hat{\mathbf{x}}$ is the matrix $\hat{\boldsymbol{x}} = \begin{pmatrix} x_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & x_n \end{pmatrix}$ based on the **x-vector.**

Combining equations (5) and (6) we get a new production balance in equation (7):

$$\mathbf{x} = \mathbf{Ax} + \mathbf{y} \tag{7}$$

In (7) the left side is the production, while the right side is the demand. Where;

x = total output

Ax = intermediate output

y = final demand

By rearranging (7) and solving for total output, **x** we get:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-\mathbf{1}}\mathbf{y} \tag{8}$$

Where **I** (industries x industries) is the identity matrix:

Next, we use the definition of the Leontief Inverse:

$$(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{L} \tag{9}$$

By inserting (9) into (8) we get:

$$\mathbf{x} = \mathbf{Ly} \tag{10}$$

The **L-matrix** is the Leontief inverse and gives the requirements from each industry to produce the total output of each industry.

$$\mathbf{L} = \begin{bmatrix} l_{11} & \cdots & l_{1j} \\ \vdots & \ddots & \vdots \\ l_{i1} & \cdots & l_{ij} \end{bmatrix}$$

The number l_{ij} thus, is the output of industry i per unit final demand of industry j.

The next step is to include emissions in the calculations. We do this by including the **S-matrix** (stressors x industries) of stressors per economic output. This means that if i represents stressor category and j represents industry, $\mathbf{S}_{ij}$ would be the amount of stressor i associated with output of industry j. In matrix form this is:

$$\mathbf{S} = \begin{bmatrix} S_{11} & \cdots & S_{1j} \\ \vdots & \ddots & \vdots \\ S_{i1} & \cdots & S_{ij} \end{bmatrix}$$

We can now combine this with (10) to find the total impact associated with a final demand

$$\mathbf{F} = \mathbf{SLy} \qquad (11)$$

The **F-vector/matrix** has the dimensions (Stressors x Final demand) and gives us the total impact associated with a final demand.

Next, we define the multiplier **m** that shows the impact per unit expenditure.

$$\mathbf{m} = \mathbf{SL} \qquad (12)$$

I will use equation (12) in connection to the rebound framework later.

As mentioned, the **y-vector/matrix** typically consists of many different types of demand, such as household and government consumption or private investment purchases. This analysis only concerns the final demand of households, the **y-vector/matrix**, used in calculating the rebound effect.

3.6 Derivation of the Rebound Effect Framework

The rebound effect analysis involves the use of input-output analysis methodology. The data on Norwegian household consumption come from a multi-regional environmentally extended supply and use/Input Output database (MR EE SUT/IOT) called EXIOBASE2.

EXIOBASE *"was developed by harmonizing and detailing SUT for a large number of countries, estimating emissions and resource extractions by industry, linking the country EE SUT via trade to an MR EE SUT, and producing an MR EE IOT from this. The international input-output table that can be used for the analysis of the environmental impacts associated with the final consumption of product groups."* (EXIOBASE consortium, 2015)

The version used is the EXIOBASE2 with data from 2007 (Tukker et al., 2013, Wood et al., 2015). It includes information on

- 43 Countries, 5 RoW (Rest of the world) regions (and its 10% of the global GDP) base year 2007
- 200 products
- 163 industries
- 15 land use types
- Employment per three skill levels
- 48 types of raw materials
- 172 types of water uses

Two important adjustments were necessary in order to fit the calculations to the units in EXIOBASE2 (Wood et al., 2015, Tukker et al., 2013):

- Convert the savings into Euros using an exchange rate of €/NOK of 8.0165 (Wood et al., 2015, Tukker et al., 2013) and furthermore to Million Euros (10^6)
- Convert prices to the levels for 2007 used in EXIOBASE2 using the Norwegian consumer price index (Statistics Norway, 2015b) converting average prices for 2016 into average 2007 prices.

Calculating rebound effect involves re-spending the saved money from the set of actions according to the different scenarios of re-spending. The multipliers in EXIOBASE2 provides the needed data to calculate emissions associated with the re-spending.

The following analytical derivation of the rebound framework base on a study by Druckman et al. (2011).

The first step is to define the relative rebound effect as:

$$rebound\ effect = \frac{(potential\ savings - actual\ savings)}{Potential\ savings}.$$

Next, we define additional variables:

ΔH= Expected reduction in GHG emissions

ΔG= GHG emissions associated with the re-spending of saved money

ΔG offsets some of the initial anticipated GHG savings (ΔH). The actual emission reductions are $\Delta H - \Delta G$. Hence, the redefined rebound effect (RE) is:

$$RE = \frac{\Delta H - (\Delta H - \Delta G)}{\Delta H} = \frac{\Delta G}{\Delta H} \tag{13}$$

ΔH_i is the change in emissions between the original situation and after implementing the set of household actions. ΔH_i, ($i = 1\ to\ 34$) is determined exogenously by the 34 different actions that are implemented in order to reduce GHG emissions. Because of using this bottom-up approach, ΔH is determined outside of EXIOBASE2.

From (12) we have the multiplier that gives the emissions per monetary unit. However, the direct emissions from households $\boldsymbol{f\_hh}$ (such as emissions from a household driving a car) are not included in the multiplier. $\boldsymbol{f\_hh}$ is available in EXIOBASE2 as emissions by product consumed .We include the emissions per million € by defining a new multiplier pertaining to Norwegian households:

$$\mathbf{m}_{\text{NOR\_hh}} = \mathbf{f}_{\text{hh}} / \mathbf{y}_{\text{NOR\_hh}} \tag{14}$$

$\mathbf{y}_{\text{NOR\_hh}}$ obtained from EXIOBASE2 is the total Norwegian household final demand by products, and includes both domestically produced and imported goods consumed by households.

The next step is to redefine the multiplier to include $\mathbf{m}_{\text{NOR\_hh}}$:

$$\mathbf{m}_{\text{total}} = \mathbf{m}_{\text{NOR\_hh}} + \mathbf{m} \tag{15}$$

Re-spending of the saved money according to different scenarios are placed in a vector of re-spending $\boldsymbol{y^{re}}$

$$\mathbf{y^{re}} = \sum_{1}^{34} (\mathbf{y_{sav}} * \mathbf{B} * \mathbf{q}) * \mathbf{y^{sp}} \tag{16}$$

$\mathbf{y_{sav}}$ The vector of savings from the 34 actions not adjusted for double counting

B The matrix adjusting for double counting

q The vector that multiplies actions per unit by the total number of units

$\mathbf{y^{sp}}$ The spending pattern scenario

The re-added GHG emissions ΔG due to the re-spending of the saved money for actions i =1 to 34 and re-spending scenario j is:

$$\Delta G = \mathbf{m}_{\text{total}} * \mathbf{y}^{\mathbf{re}} \tag{17}$$

The final step is to insert for ΔG from (17) and ΔH from (13) to calculate the rebound effect

$$RE_{i\_j} = \frac{\Delta G_{i\_j}}{\Delta H_i} = \frac{\mathbf{m}_{\text{total}} * \mathbf{y}^{\mathbf{re}}}{\Delta H_i} \tag{18}$$

3.7 Conversion of Prices

EXIOBASE2 uses basic price as a basis for estimating GHG emissions and monetary flows. Because of exogenous calculations of GHG emission reductions and cost changes, when linking the household actions data with EXIOBASE2, it is necessary to convert to basic prices before calculating the emissions associated with re-spending the money. The link between what the households pay (purchaser's price) and basic price is:

$$BP = PP - tax - trdM - tspM \tag{19}$$

BP Basic price

PP Purchaser's price

tax Taxes on products

$trdM$ Trade Margins

$tspM$ Transport margins

When making the conversion to basic price, it is necessary to consider the responsibility of the households for the emissions in the different stages in (19). The conversion is based on calculations by Steen-Olsen et al. (Accepted for publication).

1. The taxes and margins are calculated as percent of total consumption in purchaser's price
2. The next step is to calculate the percentage distribution of margins among the margins sectors for trade margins and transport margins individually

3. Next, use the percentages of tax and margins out of total purchaser's price found in the first step to find the amount of taxes and margins baked into the Consumer Expenditure Survey data.
4. Finally, subtract both tax and margins, then add margins back into the margins sectors, using the distribution found in the second step

By performing these steps, the consumer is responsible for emissions associated with trade and transport margins, but not taxes, as they embody no emissions.

3.8 Linear Programming

Linear programming involves finding an optimal solution that minimizes or maximizes an objective function, subject to one or several linear constraints. These constraints can be limitations on materials or factor resources, such as capital or labor. Many MRIO studies within the input-output field use linear programming techniques. Examples are the World Trade Model that determines world prices, scarcity rents, and international trade flows based on comparative advantage in a world economy (Duchin, 2005) and the World Trade Model with Bilateral Trade (WTMBT), a linear program that minimizes global factor use to satisfy consumption requirements while respecting regional factor constraints (Duchin and Levine, 2015). Other approaches within the field include treating environmental standards analogous to capital and labor capacity constraints to determine the economic and environmental gains to free trade in products and emission permits (Ten Raa and Shestalova, 2015). An important limitation of linear programming is that the optimal solution often involves complete specialization, within studies of comparative advantage, this means that countries should specialize in production of very specific goods and services (Ten Raa and Shestalova, 2015, Duchin and Levine, 2015).

In comparison to this work, I am interested in seeing whether it is possible to look at linear programming from a consumption basis. Whilst earlier work looks at the possibilities for alternate technologies, or substitution at the industry level, in this analysis, the limit purely is to what households can do in terms of spending patterns. As such, I am interested in what mixture of spending will give us optimal environmental goals. Whilst clearly, the realization of an «optimal spending pattern» is subject to many constraints about basic versus discretionary spending, as well as localized requirements by household, the goal is to use linear programming to inform the scale and rate of possible change.

The analysis involves to alternative setups for optimization using linear programming. The first involves changing the number of actions, while the second approach is as mentioned in the previous paragraph to change the pattern of re-spending. For pragmatic purposes, I chose to base the analysis on the second approach rather than changing number of actions.

3.8.1 Changing Number of Actions

The first approach is to change the number of actions implemented in order to reach different emission reduction targets. By assigning behavioral cost values to each of the actions, the objective is to minimize the total behavioral cost of the set of actions. The starting point is the number of actions used in the calculations of the rebound effect (Table A.1). The linear program changes the values in elements of this matrix while keeping the sum of each column equal to zero. Furthermore, only the rows corresponding to the specific column (i.e. the actions corresponding to a specific activity) will have values over zero. The analytical setup is as follows:

Parameters and variables:

Name	Description	Unit	Size
f_nor_hh	Norwegian household emissions from EXIOBASE2	Kg CO2-eq	200 x 1
n_hh	Number of households in 2007 from Statistics Norway (SSB)	#	1 x 1
f_red_unit	Per unit GHG emission savings from implementing actions	Kg CO2-eq	34 x 1
m_tot_sectors	GHG emissions per expenditure of good/service	Kg CO2-eq/€*10^6	200 x 1
y_s	Cost reductions from actions not adjusted for double counting	€*10^6	34 x 1
y_nor_hh	Total expenditures of Norwegian households in 2007 from EXIOBASE2	€*10^6	200 x 1
y_marg_0	The marginal spending pattern calculated from the consumer expenditure survey	%	200 x 1
e1	A vector of ones used to sum vectors/matrices	n/a	1 x 34
e2	A vector of ones used to sum vectors/matrices	n/a	1 x 38

DC	The matrix that adjusts for double counting of actions (Table A.1)	n/a	34 x 38
q	The vector that multiplies each actions by the number of units possible of that action	n/a	1 x 38
bc	The vector of behavioral costs for the household on a scale from 1 to 10 for increasing costs	n/a	34 x 1
r	Index used for summations	n/a	34

Table 3.4: Parameters and variables for the linear programming changing number of actions

The **DC**-matrix is the one that will change values in the linear programming. This involves taking the **y_marg_new** vector as given by using **y_marg_0** as a proxy instead.

The equation for calculating the carbon footprint of the household is similar to the first approach:

$$f = f_{orig} - f_{red} - f_{re-add} \tag{20}$$

f Emissions per household after saving and re-spending

$f = \frac{\sum_1^{200}(\mathbf{f_{NOR_{hh}}})}{n\_hh}$ Original emissions per household from EXIOBASE2

$f_{red} = (\mathbf{f_{red_{unit}}}' * \mathbf{DC} * \boldsymbol{q}')$ Saved emissions from implementing actions

$f_{re-add} = ((\mathbf{m_{tot_{sectors}}} * \mathbf{y\_s}')' * \mathbf{y\_marg\_0}')' * (\mathbf{DC} * \mathbf{q}')$

Emissions re-added because of re-spending saved money from implementing actions

Constants:

$c1 = f_{orig}$ (1 x 1)

$\mathbf{c2} = \mathbf{f\_red\_unit}'$ (34 x 1)

$\mathbf{c3} = ((\mathbf{m_{tot_{sectors}}} * \mathbf{y\_s}')' * \mathbf{Y\_marg\_0}')'$ Emissions per unit of action according to the marginal spending pattern, not adjusted for double counting

(34 x 1)

Variables:

$\mathbf{x1} = (\mathbf{DC} * \mathbf{q}')$ (1 x 34)

$\mathbf{X2} = \mathbf{DC}$ (38 x 34)

The x matrix:

$\mathbf{X} = \begin{bmatrix} \mathbf{x1} \\ \boldsymbol{X2} \end{bmatrix}$ The solution obtained in linear programming (39 x 34)

Constraints:

Bounds:

$\mathbf{LB} = 0$ The lower bound for all elements in **X** is 0 (39 x 34)

$\mathbf{UB} = 1$ The upper bound is set to one for the row-elements corresponding to each column in **X2**. The bound is zero for the rest of the elements in **X2.** The upper bound in **x1** is equal to the largest sum of units possible for each action.

(34 x 38)

Linear inequalities:

$\mathbf{c2} * \mathbf{x1} + \mathbf{c3} * \mathbf{x1} \leq \big((1 - 0.05 * i) * c1\big) - c1$

The saved emissions plus the re-added emissions must be equal to or smaller than the emission reduction target (represented by $0.05 * i$. where $i = 1{:}\,20$.) multiplied with the initial emissions subtracted by the initial emissions. The emission reduction target increases in steps of 5% from 5% to 100%.

(1 x 1)

Linear equalities:

$\mathbf{e1} * \mathbf{X2} = \mathbf{e2}$ The sum of each column in **X2** must equal **e2**, which is equivalent to the sum of the actions connected to each unique activity adding up to 100% (1 x 38)

Objective function:

$Min\ z = \mathbf{bc}' * (\mathbf{x1})$ Minimize the sum of the behavioral costs of each action multiplied with the number of units implemented of each action

(1 x 1)

3.8.2 Changing Spending Pattern

The second approach to achieving GHG emission reductions is to change the pattern of re-spending on different goods and services, while holding total expenditure the same. Keeping expenditure levels unchanged involves a restructuring of households spending patterns, and if implemented on a large scale with large monetary savings for the household, it will require changes in the economy through shifting demand. However, it does not hinder economic growth that have potentially negative consequences for an economy.

In the setup of the linear program, the marginal spending pattern serves as a proxy for the spending pattern.

Parameters and variables:

Name	Description	Unit	Size
f_nor_hh	Norwegian household emissions from EXIOBASE2	Kg CO2-eq	200 x 1
n_hh	Number of households in 2007 from Statistics Norway (SSB)	#	1 x 1
f_red	GHG emission savings from implementing actions, adjusted for double counting	Kg CO2-eq	34 x 1
m_tot_sectors	GHG emissions per expenditure of good/service	Kg CO2-eq/€*10^6	200 x 1
y_sav	Cost reductions from actions adjusted for double counting	€*10^6	34 x 1
t_nor_hh	Expenditures of Norwegian households in 2007 from EXIOBASE2	€*10^6	200 x 1
y_marg_0	The marginal spending pattern calculated from the consumer expenditure survey	%	200 x 1
e	A vector of ones used to sum other vectors	n/a	200 x 1
y_marg_new	The new marginal spending vector that changes according to GHG emission reduction targets	%	200 x 1

r	Index used for summations	n/a	34

Table 3.5: Parameters and variables nomenclature used in the linear programming changing the re-spending

The first part involves changing **y_marg_0**, the vector that allocates re-spending across 200 product groups.

The starting point for the linear program is the formulation of the GHG emissions from the household:

$$f = f_{orig} - f_{red} - f_{re-add} \tag{21}$$

f Emissions per household after saving and re-spending

$f_{orig} = \frac{\sum_1^{200}(\mathbf{f_{NOR_{hh}}})}{n\_hh}$ Original emissions per household from EXIOBASE2

$f_{red} = \sum_{i=1}^{r}(\mathbf{f_{red}})$ Saved emissions from implementing actions

$$f_{re-add} = \sum_{i=1}^{r}(\mathbf{m_{tot_{sectors}}} * \mathbf{y_{sav}}') * \mathbf{y_{marg_{new}}}$$

Emissions re-added because of re-spending saved money from implementing actions

Constants:

$c1 = f_{orig}$ (1 x 1)

$c2 = f\_red$ (1 x 1)

$\mathbf{c3} = \sum_{i=1}^{r}(\mathbf{m_{tot_{sectors}}} * \mathbf{y_{sav}}')$ Total emissions per product group if re-spending all saved money in that specific product group (200 x 1)

Variables:

$\mathbf{x1} = \mathbf{y\_marg\_new}$

$\mathbf{x2} = \mathbf{y_{marg\_0}} - \mathbf{x1}$

The x vector:

$\mathbf{x} = \begin{bmatrix}\mathbf{x1} \\ \mathbf{x2}\end{bmatrix}$ The solution vector for the linear program (400 x 1)

Constraints:

Bounds:

$\mathbf{lb} = 0$ The lower bound for all elements in x is zero (400 x 1)

$\mathbf{ub} = 10$ The upper bound is set to 10, but to prevent re-spending in product groups of no initial spending according to y_marg_0, the upper bounds of these elements are zero. (400 x 1)

Linear inequalities:

$\mathbf{c3} * \mathbf{x1} \leq \big((1 - 0.05 * i) * c1\big) - c1 - c2$ The re-added emissions must be equal to or smaller than the emission reduction target represented by $0.05 * i$. where $i = 1{:}\,20$. The emission reduction target increases in steps of 5% from 5% to 100%. (1 x 1)

$-\mathbf{x2} - \mathbf{x1} \leq -\,\mathbf{y}_{\mathbf{marg_0}}$ This constraint helps convert all numbers in $x2$ to positive values, in order to be able to estimate the sum of the absolute change between **y_marg_0** and **y_marg_new**

(200 x 1)

$-\mathbf{x2} + \mathbf{x1} \leq \mathbf{y}_{\mathbf{marg_0}}$ This constraint helps convert all in $x2$ to positive values, in order to be able to estimate the sum of the absolute change between **y_marg_0** and **y_marg_new** (200 x 1)

Linear equalities:

$\mathbf{e}' * \mathbf{x1} = 1$ The sum of the elements must equal one, which is equivalent to 100%

(1 x 1)

Objective function:

$Min\ z = \boldsymbol{e} * (\mathbf{x2})$ Minimize the absolute sum of changes in each element from the marginal spending pattern to the ones found in the linear programming

(1 x 1)

4 Results

4.1 GHG Emission Reductions and Cost Changes

The results from calculating cost reductions and GHG emissions (Table 4.1) show that the actions within the transport, residential and food sectors achieve the largest GHG emission reductions. Households achieve the largest cost reductions by implementing Actions 1, 8 and 14, and more generally, we find the largest cost reductions in transport and food actions. Actions 2, 12, 15, 16, 18, 28 and 30 involve a cost increase for the households.

Action number	Household actions	Cost reductions (NOK 2016 prices)		GHG emission reductions (kg CO2-eq)
1	Switch to Renault Zöe	kr	32,885	3685
2	Switch to Tesla	kr	-23,233	2760
3	No trips by car under 3 km	kr	688	150
4	Only bus transport	kr	14,312	4863
5	Car-pooling for work under 10 km	kr	474	103
6	Only train transport	kr	14,312	4973
7	Walk instead of train (9.4 km)	kr	12,030	183
8	Reduce business flights (one per month)	kr	71,344	3112
9	Eliminate long-distance flight for vacation	kr	8,202	2629
10	Reducing indoor temperature by 1°C	kr	472	92
11	Space and water heating	kr	920	1333
12	Appliances and other	kr	-843	174
13	Grenn Diet	kr	11,853	1854
14	Eliminating food waste	kr	17,384	1020
15	Organic Green diet	kr	-23,706	2039
16	Other measures (organic, local, composting)	kr	-15,804	695
17	Eco-efficiency across suply chain	kr	-	57
18	Design for durability	kr	-1,649	107
19	Market shift to more synthetic fibres	kr	330	6
20	Clean clothing less	kr	660	36
21	Wash at lower temperature	kr	660	20
22	Increase size of washing and drying loads	kr	330	20
23	Use the tumble dryer less	kr	660	15
24	Dispose less - reuse more	kr	989	10
25	Start closed loop recycling of synthetic fibres	kr	-	13
26	Dispose less - recycle more	kr	-	7
27	Reduce clothing purchases by 20%	kr	6,597	279
28	Average of changing 6 pieces of furniture	kr	-3,070	96
29	Increase lifetime by 20%	kr	2,333	116
30	Buy furniture with 20% recycled MDF	kr	-1,166	73
31	Eliminating unsolicited mail	kr	-	39
32	Reduced printing	kr	246	17
33	e-papers and e-books	kr	1,970	26
34	Reducing plastic waste by 30%	kr	191	14

Table 4.1: Cost changes and GHG emission reductions per unit for each action

4.2 Spending Patterns

The marginal spending pattern calculations bases on the change in consumption pattern when moving to higher income deciles, as well as the relative purchasing power of deciles. When moving to higher income deciles we notice some general trends (Table 4.2). Firstly, the household's relative expenditure on clothing and footwear and recreation and culture increases. On the other hand, relative expenditure on health decreases. Relative consumption on other aggregated product groups seem to vary when moving upwards in income deciles. The product groups with largest variation when moving upwards in income deciles are transport, housing, water and electricity, gas and other fuels and food and non-alcoholic beverages.

Marginal Spending Pattern (weighted accoding to relative purchasing power) COICOP lvl 1					
	Deciles				
	1 to 2+3	2+3 to 4+5	4+5 to 6+7	6+7 to 8+9	8+9 to 10
01 Food and non-alcoholic beverages	7 %	17 %	17 %	11 %	6 %
02 Alcoholic beverages and tobacco	2 %	-1 %	2 %	2 %	1 %
03 Clothing and footwear	0 %	8 %	7 %	10 %	9 %
04 Housing, water, electricity, gas (...) ar	32 %	37 %	13 %	16 %	28 %
05 Furnishings, household equipment (...) ar	7 %	8 %	6 %	7 %	7 %
06 Health	4 %	1 %	0 %	0 %	1 %
07 Transport	40 %	11 %	26 %	28 %	21 %
08 Communication	-3 %	1 %	3 %	1 %	1 %
09 Recreation and culture	1 %	8 %	16 %	10 %	13 %
10 Education	-2 %	0 %	0 %	1 %	0 %
11 Restaurants and hotels	3 %	4 %	2 %	7 %	4 %
12 Miscellaneous goods and services	9 %	5 %	8 %	8 %	8 %
Relative purchasing power	11 %	15 %	19 %	24 %	32 %

Table 4.2: Marginal spending pattern calculations

The three scenarios of how households re-spend additional income (Table 4.3) show that the relative spending on housing, water, electricity, gas and other fuels is over 30% in the average scenario and under 10% in the green marginal scenario. Transport has the largest share of relative expenditures in the marginal scenario, with a sharp decrease in the green marginal scenario. Re-spending on clothing and footwear is only 1% in the green marginal scenario, compared to 8% in the marginal scenario. In the green marginal scenario, expenditure on housing, water, electricity gas and other fuels and transport to a large extent shift towards expenditure on food and non-alcoholic beverages and miscellaneous goods and services.

Spending patterns comparison (COICOP lvl 1)			
Product Groups	**Marginal**	**Average**	**Green Marginal**
01 Food and non-alcoholic beverages	11 %	12 %	18 %
02 Alcoholic beverages and tobacco	1 %	3 %	1 %
03 Clothing and footwear	8 %	5 %	1 %
04 Housing, water, electricity, gas (...)	24 %	31 %	9 %
05 Furnishings, household equipment (...)	7 %	6 %	11 %
06 Health	1 %	3 %	3 %
07 Transport	24 %	19 %	8 %
08 Communication	1 %	2 %	3 %
09 Recreation and culture	11 %	10 %	9 %
10 Education	0 %	0 %	0 %
11 Restaurants and hotels	4 %	4 %	6 %
12 Miscellaneous goods and services	8 %	6 %	30 %

Table 4.3: Spending Patterns comparison (COICOP level 1)

4.3 Rebound Effects

The results from the rebound calculations of the individual actions not adjusted for double counting (Table 4.4) show that re-spending money according to the green marginal spending pattern results in the smallest rebound, while re-spending according to the marginal spending pattern results in the largest rebound for all actions. However, for the actions associated with a negative cost reduction, the GHG emission reductions are largest when re-spending according to the marginal spending pattern, and smallest when re-spending according to the green marginal spending pattern.

The action resulting in the largest rebound effect of almost 600% is action 24 in the marginal re-spending scenario. We find the largest rebound effect in absolute value for action 8, resulting in a rebound of approximately 5 tons CO2-eq in the marginal re-spending scenario.

The action resulting in the lowest rebound effect is action 28 with a rebound effect of less than -200% in the marginal re-spending scenario. The smallest absolute rebound effect comes from implementing action number 2 resulting in additional savings of about 1.6 tons CO2-eq.

Action number	Household actions	Rebound effect %			Original GHG savings (kg CO2-eq)	GHG savings including rebound (kg CO2-eq)		
		Marginal	Average	Green marginal		Marginal	Average	Green Marginal
1	Switch to Renault Zöe	62 %	48 %	42 %	3685	1404	1922	2129
2	Switch to Tesla	-58 %	-45 %	-40 %	2760	4372	4006	3860
3	No trips by car under 3 km	32 %	25 %	22 %	150	103	114	118
4	Only bus transport	20 %	16 %	14 %	4863	3871	4096	4186
5	Car-pooling for work under 10 km	32 %	25 %	22 %	103	70	77	80
6	Only train transport	20 %	15 %	14 %	4973	3980	4206	4296
7	Walk instead of train (9.4 km)	456 %	353 %	311 %	183	-652	-462	-386
8	Reduce business flights (one per month)	159 %	123 %	108 %	3112	-1836	-713	-264
9	Eliminate long-distance flight for vacation	22 %	17 %	15 %	2629	2060	2189	2241
10	Reducing indoor temperature by 1°C	35 %	27 %	24 %	92	60	67	70
11	Space and water heating	5 %	4 %	3 %	1333	1270	1284	1290
12	Appliances and other	-34 %	-26 %	-23 %	174	232	219	213
13	Grenn Diet	38 %	29 %	26 %	1854	1157	1315	1378
14	Eliminating food waste	100 %	78 %	68 %	1020	-3	229	322
15	Organic Green diet	-68 %	-53 %	-47 %	2039	3434	3117	2991
16	Other measures (organic, local, composting)	-134 %	-103 %	-91 %	695	1625	1414	1330
17	Eco-efficiency across suply chain	0 %	0 %	0 %	57	57	57	57
18	Design for durability	-90 %	-70 %	-62 %	107	204	182	174
19	Market shift to more synthetic fibres	348 %	269 %	237 %	6	-14	-9	-8
20	Clean clothing less	107 %	83 %	73 %	36	-3	6	10
21	Wash at lower temperature	199 %	154 %	136 %	20	-19	-10	-7
22	Increase size of washing and drying loads	99 %	77 %	68 %	20	0	5	6
23	Use the tumble dryer less	253 %	196 %	173 %	15	-23	-15	-11
24	Dispose less - reuse more	597 %	461 %	407 %	10	-48	-35	-30
25	Start closed loop recycling of synthetic fibres	0 %	0 %	0 %	13	13	13	13
26	Dispose less - recycle more	0 %	0 %	0 %	7	7	7	7
27	Reduce clothing purchases by 20%	139 %	108 %	95 %	279	-109	-21	14
28	Average of changing 6 pieces of furniture	-223 %	-172 %	-152 %	96	308	260	241
29	Increase lifetime by 20%	119 %	92 %	81 %	116	-22	10	22
30	Buy furniture with 20% recycled MDF	-94 %	-73 %	-64 %	73	142	126	120
31	Eliminating unsolicited mail	0 %	0 %	0 %	39	39	39	39
32	Reduced printing	104 %	80 %	71 %	17	-1	3	5
33	e-papers and e-books	525 %	405 %	358 %	26	-111	-80	-67
34	Reducing plastic waste by 30%	95 %	73 %	65 %	14	1	4	5

Table 4.4: Rebound results and GHG emission savings including rebound

When adjusting for double counting of actions and aggregating the actions to consumption sectors (Table 4.5), the consumption group with the largest rebound is paper, while furniture has the lowest rebound. The largest rebound in absolute values is for the transport actions, when re-spending according to the marginal spending pattern. Over 8 tons of CO2-eq are lost from implementing the transport actions due to this pattern of re-spending. The lowest rebound in absolute value is for the furniture actions, resulting in additional savings of almost 150 kg CO2-eq.

When combining all actions, households can obtain a 58% reduction in their GHG emissions compared to the original carbon footprint of about 27.2 tons CO2-eq per household, without considering re-spending. Under the assumption of total household expenditure being constant, the reduction in GHG emissions drops to 24%, 32% and 35% for the marginal, average and green marginal re-spending scenarios respectively. In absolute values, this means a reduction of 6.4, 8.6 and 9.4 tons CO2-eq per household for the scenarios of re-spending.

	Rebound effect in %				GHG savings including rebound		
Household Actions	Marginal	Average	Green Marginal	Original GHG savings (kg CO2-eq)	Marginal	Average	Green Marginal
Transport	83 %	64 %	57 %	9847	1638	3501	4246
Residential	0 %	0 %	0 %	1383	1381	1381	1381
Food	16 %	13 %	11 %	3587	3006	3138	3191
Clothing	89 %	69 %	61 %	569	64	179	224
Furniture	-51 %	-39 %	-35 %	284	428	396	383
Paper	190 %	147 %	129 %	81	-73	-38	-24
Plastic	95 %	73 %	65 %	14	1	4	5
Total of all actions combined	**59 %**	**46 %**	**40 %**	**15766**	**6446**	**8561**	**9407**
Original carbon footprint of households (kg CO2-eq)				27170			
Reduction in carbon footprint				58 %	24 %	32 %	35 %

Table 4.5: Rebound results and GHG emission savings including rebound, per sector and adjusted for double counting

4.4 Linear Programming: Changing Pattern of Re-spending

The results from changing the consumption pattern of re-spending using linear programming (Figure 4.1) show that households can achieve up to a 50% reduction in GHG emissions by implementing the set of actions suggested in this paper while keeping total expenditure level unchanged. With smaller adjustments to their spending pattern, households can achieve a 25-30% reduction in GHG emissions compared to the reference of the marginal spending pattern. Re-spending on goods and services in the transport product group steadily declines as the reduction target increase. The clothing and footwear consumption group also shows a rapid decline in relative share of consumption, and is zero at about a 35% reduction target. Re-spending in consumption groups such as food and non-alcoholic beverages, furnishings, household equipment and routine household maintenance, housing, water, electricity, gas and other fuels and recreation and culture remain relatively unchanged with increasing reduction target. The only product groups seeing an increase in the relative share of re-spending all the way up to a 50% reduction target is miscellaneous goods and services. To achieve a 50% reduction, households must re-spend approximately 80% of the money on this particular product group.

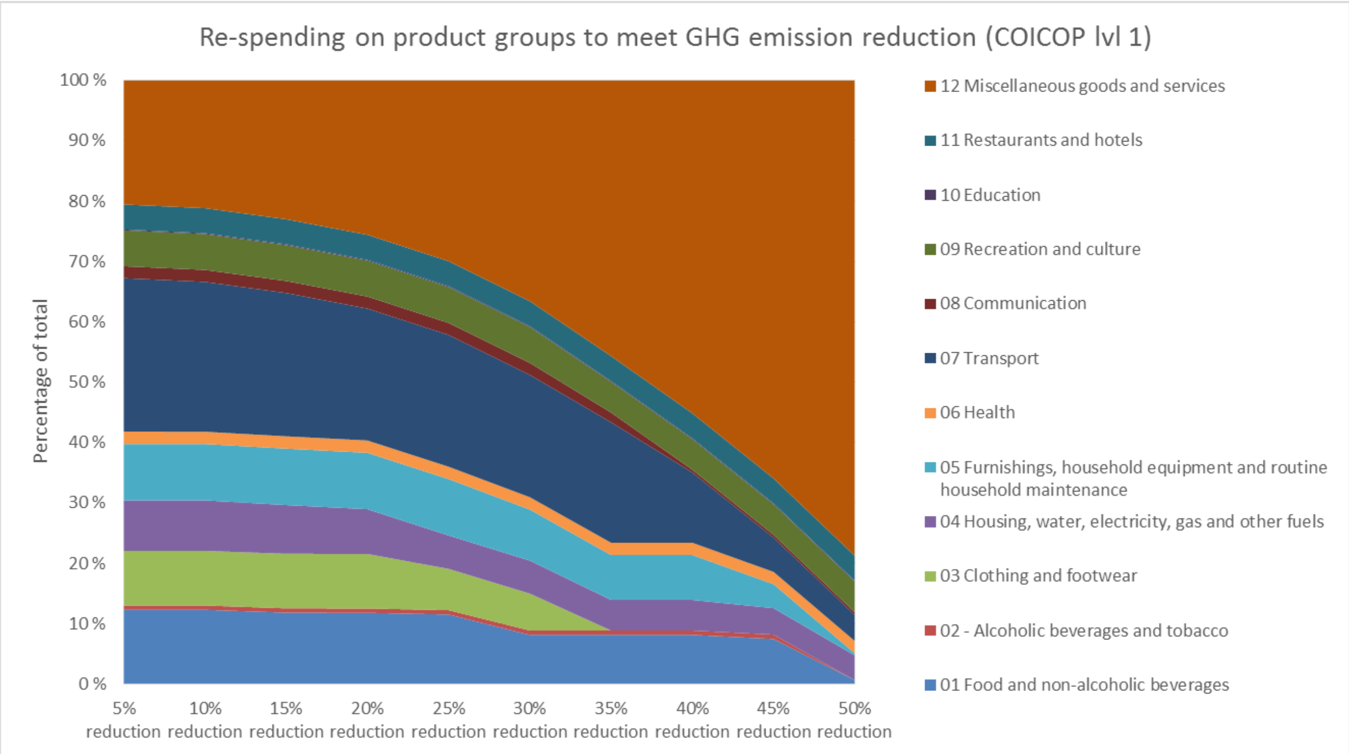


Figure 4.1: Linear programming: change in re-spending pattern needed to meet GHG emission reduction targets (COICOP level 1)

The objective of the linear program was to minimize the sum of the absolute changes in the spending pattern while achieving the GHG emission reductions (Figure 4.1). By comparing the marginal spending pattern with the different spending patterns needed to reach the GHG emission reduction targets for 200 goods and services, I obtain a measure of the changes needed to reach the different reduction targets. The measure used is the sum of the absolute value of changes in the consumption patterns (Figure 4.2). The sum is relatively low up until a 20-25% reduction in GHG emissions. For larger reductions, the sum increases rapidly. The graph shows resemblances to that of an exponential function.

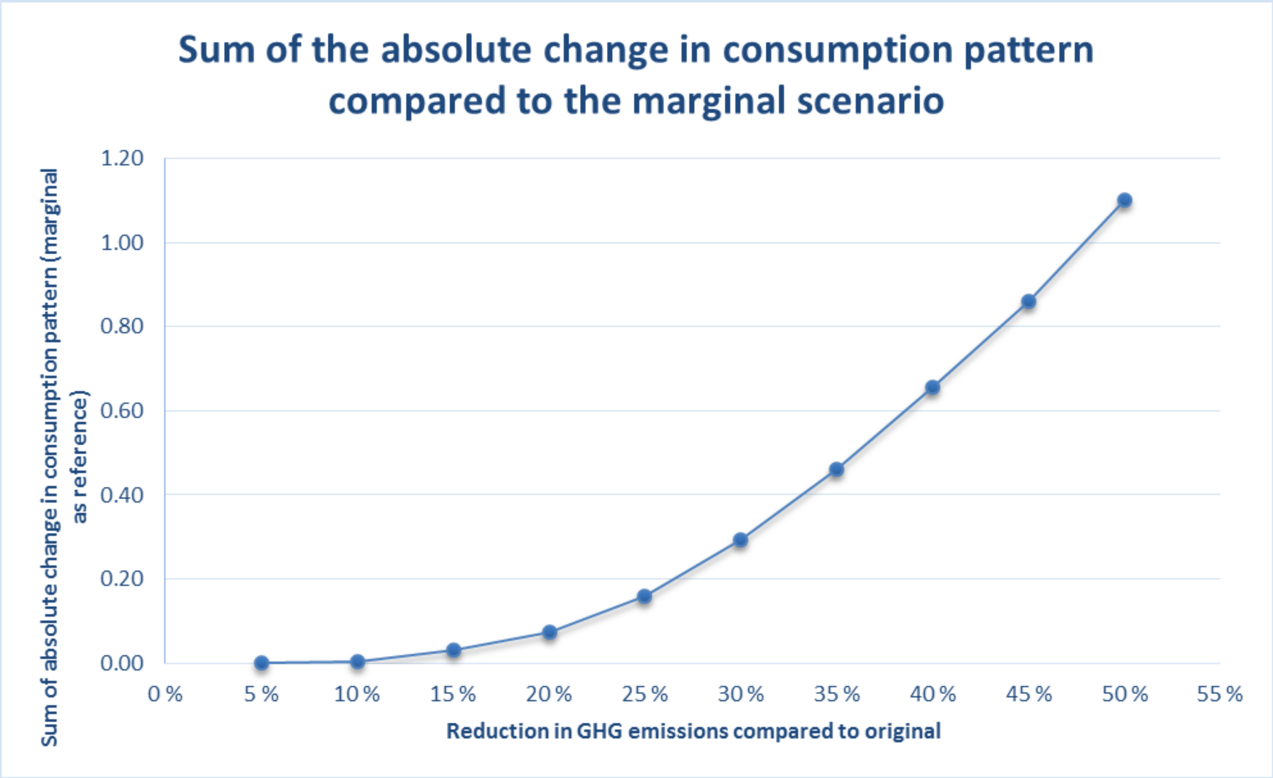


Figure 4.2: The sum of the absolute change in re-spending: Marginal versus emission reduction spending patterns

The relative re-spending on the 200 goods and services of the spending patterns change for the different reduction targets. The sum of the absolute change is measure of how much consumption changes overall based on the marginal spending pattern.

5 Discussion

5.1 Implications of Results

5.1.1 2°C Target of Global Warming

The results show that the reduction in carbon footprint from implementing the actions is 58%. When including rebound effects, the reduction drops to 24-35% (Table 4.5). Considering the needed reduction of 40-70% of anthropogenic GHG emissions in order to meet the 2°C target of global warming (Intergovernmental Panel on Climate Change, 2015), when including rebound, this set of actions do not achieve the needed reductions. However, when changing the re-spending in the linear programming, the reduction potential increased to 50%.

Another option to achieve further reductions is to change, add or eliminate actions. Changing actions can be done through optimizing the number of actions (Table A.1) using linear programming, while minimizing behavioral costs (section 3.8.1). Households likely achieve the largest GHG emission reductions by combining the two methods of optimizing the number of actions and the pattern of re-spending, given the constraint of equal total expenditure and not considering technological improvements. By relaxing these constraints, the household will reduce its carbon footprint further. The analysis excludes technological improvements, as the scope is to examine what households can achieve today. The constraint on total expenditure could be relaxed, but could have negative effects on economic growth as discussed in the introduction.

5.1.2 Rebound Effects

The calculations on rebound effects is in parts independent of the economic mechanisms discussed in the literature and background section. The reason for this is the assumption that the household takes a more active role in choosing which actions to implement, in contrast to much of the energy economics literature on rebound effects that assumes that households change their consumption based on price changes. The actions that households implement are independent of price changes, and instead the assumption is that the motivation is to reduce their carbon footprint.

The extent of the rebound effect ranges from 40 to 59% depending on the pattern of re-spending (Table 4.5). This is higher than results in the literature. Druckman et al. (2011) find rebound effects ranging from 12% to 34%. However, the 12% scenario involved a scenario of re-spending all saved money in the least GHG intensive category, which was “housing”. This is a stricter re-spending scenario than the green marginal spending scenario. Alfredsson (2004) find even lower GHG rebound effects of about 14% for an average re-spending scenario. Murray (2013) finds the rebound effect to be between 12% and 14% using a marginal spending pattern. However, most of these studies involve the household implementing only a handful of behavioral actions, meaning that the rebound results largely depend on the choice of actions.

The results of the individual actions suggested a large variation in rebound, ranging from (-) 223% to 597% (Table 4.4). However, because of the large number of actions, eliminating or adding an action will not affect the total rebound as much as if only implementing a handful of actions.

The rebound effect is primarily indirect because of changed expenditure on a specific good or service, leading to the household re-spending the money saved across all other goods and services according to scenarios of re-spending. This means that some of the re-spending results in a direct rebound effect as well. However, the results show the sum of the indirect and direct rebound effect. It is outside the scope of the thesis to disentangle the indirect and direct rebound effect, although possible by connecting each action to corresponding goods and services in the spending pattern. Then the direct rebound is the relative consumption share of the goods and services connected to the action, multiplied with their corresponding GHG intensity (Kg CO2-eq/unit of expenditure). Most of the literature present the combined effect, but some studies disentangle the indirect and direct effects (Thomas and Azevedo, 2013a, Chitnis et al., 2013).

Some of the results showed that the rebound effect of implementing actions or set of actions is negative (Table 4.4, Table 4.5). The source of these negative rebound effects is implementing one or several actions that induce a cost increase for the household. This is equivalent to a decrease in disposable income. Implementing these actions means that the household reduces consumption on other goods and services that was part of their spending pattern before implementing the actions. Hertwich (2005) mentions this type of rebound effect through spillover of environmental behavior, where environmentally aware households implement other types of beneficial behavior, such as spending additional income on more expensive organic food.

Implementing actions that come with a cost increase for the household does require a strong motivation to reduce the carbon footprint, and requires that households have freed up income to spend. However, the assumption is that the household implements the set of actions suggested, which in total comes with a cost reduction for the household. Thus, we should interpret the actions associated with cost increases as what Hertwich (2005) refers to as spillover effects.

5.1.3 Sufficiency and Efficiency Measures

The rebound literature often distinguish between rebound effects resulting from efficiency and sufficiency measures. Efficiency measures relate to energy efficiency improvements, such as purchasing a more fuel-efficient car, while sufficiency measures relate to behavioral changes that, assuming leaving environmental concern out of the utility function, lower utility or welfare. An example of a sufficiency measure is lowering indoor temperatures (Alcott, 2008, Chitnis et al., 2014). The set of actions proposed here involve both efficiency measures and sufficiency measures. Efficiency measures include buying an electric car, appliances, furniture and reading e-books and newspapers. Examples of sufficiency measures are reducing indoor temperature by 1°C, increasing lifetime of products, eliminating unsolicited mail or waste. What is not included are technological improvements not currently available to the consumer, but that will be available in the future. Possible exceptions to this are some of the actions within the clothing sector. Some of these require changes on the production side, such as; eco-efficiency across the supply chain (action 17) and start closed loop recycling of synthetic fibers (action 25).

Particularly sufficiency measures often involve a cost reduction for the household, and several papers assume saving some of the money from such measures (Figge et al., 2014, Chitnis et al., 2014, Druckman et al., 2011). One of the key assumptions in this thesis is re-spending all of the saved money, which could explain the higher rebound effect compared to that found in similar studies (Druckman et al., 2011, Alfredsson, 2004, Thomas and Azevedo, 2013a, Murray, 2013).

An important consequence of implementing sufficiency measures and altering re-spending patterns to minimize the rebound effect is that it will lead to a demand shift if implemented on a large scale. After establishing the rebound as part of mainstream discussion, this demand shift needs attention (Alcott, 2008).

5.1.4 Link to Production

The analysis only involves changes on the consumption side, apart from some of the actions in clothing consumption as mentioned above (chapter 5.1.3). As discussed in the literature section (chapter 2.3) there are complex interactions between the consumption and the production side, and ignoring the implications on the production side of households carrying out these actions would be inaccurate. Large-scale implementations of the suggested green lifestyle can even imply that consumers are able to drive production side changes e.g. by creating demand for products with higher recycled content, different fabrics of clothing or electric cars. By limiting the analysis to the consumption side, the idea is not to ignore the modifications on the production side, but rather that the household changes lead to production side changes that allow for further reductions in global GHG emissions. Mechanisms on the production side involve advertisement, increased research on technological improvements and producing goods and services with longer lifetime. These mechanisms are achievable through a large-scale consumer demand. Accordingly, by implementing the green lifestyle, the households can induce changes in production that further decrease emissions.

5.1.5 Total re-spending

An important assumption in the analysis is that of total re-spending, meaning that households do not save any of the money. This assumption is probably unrealistic, as households in reality most likely will put some of this money into savings. However, if households save a large portion of the savings, it could potentially have negative consequences from an economic point of view. In order to ensure economic growth, either consumption or investment levels must grow, or at least not drop. In the case of investment, the economic growth can continue. However, in the case of deferred or reduced overall consumption, it could have negative consequences. Deferred consumption can have negative short-term consequences if multiple households delay consumption simultaneously, while reduced consumption can in the worst-case lead to recession. Thus, assuming no re-spending is unrealistic in the case of multiple households implementing the set of actions.

Some studies have allowed for less than total re-spending, assuming some investments instead. Druckman et al. (2011) included investments in their study and found reduced rebound effects compared to a situation of no investments.

Assuming some investment or savings instead of total re-spending is probably a more realistic approach, but the implications if implemented on a large scale are uncertain, and could have negative consequences to economic growth. For these reasons, the assumption in this thesis is total re-spending of the saved money.

5.1.6 Spending Patterns

As shown in the literature review, studies on rebound effects do not seem to agree on which spending pattern is preferable. One finding is that the marginal spending pattern moves towards the average spending pattern for only incremental increases in income. However, assuming that the households implements the actions suggested, it amounts to a rather large cost decrease for the household. With the current scenario of set of actions, this cost decrease is approximately 150 000 NOK. Such a large cost decrease would justify that the household re-spends money according to marginal, rather than average spending patterns. On the other hand, assuming that the household implements the set of actions within a short time period, could mean that the average spending pattern is more realistic, as the literature review suggested an inertia in changing consumer behavior (Stock, 1988). Another aspect to consider is that of how conscious households are about their re-spending. It is reasonable to expect the household re-spending to change towards a green spending pattern as knowledge about the GHG intensity of goods and services increases. With this in mind, the green marginal spending pattern might be more realistic.

Anticipating how households will re-spend additional income is a demanding task that involves some uncertainty. However, considering which spending pattern to choose is important. Researchers should make this decision based on the methodology and assumptions of each specific study.

5.1.7 Linear programming

The linear programming results showed that re-spending shifted gradually towards product group 12: Miscellaneous goods and services in COICOP level 1 classification as the GHG emission reduction target increased (Figure 4.1). A closer look at this product group reveals that it contains goods and services within personal care and effects, social protection, insurance and financial services. A more detailed look on a 25-product level shows that business and financial services make up about 60-65% of the total re-spending for GHG emission reduction targets of 45-50% (Appendix D).

Whether the required re-spending are realistic to implement for the households is uncertain. The implementation likely gets less pragmatic as the reduction target increases. Up until a about a 30% reduction in GHG emission (Appendix D), the changes in the consumption pattern seem less dramatic. The consumption groups most affected at this reduction target is clothing and footwear, some type of manufactured products, mobility by land, water and air and some types of food. The interpretation of the decline in re-spending on these consumption groups is that they have a high GHG intensity per unit expenditure and thus are the most important to reduce spending on, in order to reduce rebound effects.

Examining the re-spending needed to achieve 40-50% reductions, we notice a sharp decline in vehicles and equipment and other manufactured products, an elimination of clothing and footwear, elimination of mobility by air and water, and a sharp increase in re-spending on business and financial services. Other consumption groups remain relatively unchanged, such as the shelter groups, most of the food groups and the other service groups. The interpretation of the relatively unchanged re-spending on these groups is that they contribute less to rebound effects through a low GHG intensity per unit of expenditure.

Generally, the trend is that households should focus their re-spending on all types of services, consumption related to shelter and certain types of food if they wish to achieve carbon footprint reductions within the requirements of the 2°C target. Households should eliminate re-spending on products related to fossil fuel use, such as mobility, and production processes demanding heavy use of resources, such as clothing and manufactured products.

The total savings of implementing the set of actions changes with different scenarios of number of actions implemented. With the current number of actions, the savings amount to about 150 000 NOK for the household, amounting to about 35% of the expenditures of the average Norwegian household in 2012 (Statistics Norway, 2013). This means that households still spend 65% of their money according to their existing spending pattern. Changing only 35% of expenditures according to the patterns suggested in the linear programming seems possible, but requires careful re-spending considerations by the household

The sum of the absolute changes in the marginal spending pattern and the spending patterns found for the emission reduction targets in the linear programming showed an exponential increase with increasing reduction targets (Figure 4.2). However, the unit of this figure might require some explanation. The spending patterns include 200 goods and services with relative shares of re-spending that sum to a 100%. This means that if re-spending on one of the goods and services changes by 1% (positive or negative) compared to the marginal spending pattern, this is equivalent to a 0.01 increase in the graph of Figure 4.2.

5.1.8 Carbon off-setting

Some studies include carbon offsetting as a means of reducing carbon footprint. This involves either buying an offset to compensate for actions associated with high GHG emissions, such as air travel, or actively offsetting your own actions through e.g. planting trees that store carbon (Goodall, 2010). However, studies have suggested that consumers who purchase carbon offsets for a particular good or service actually increase their consumption of this good or service (Harding and Rapson, 2013). Some studies also question the effectiveness of carbon offsets in actually contributing to lowered anthropogenic GHG emissions (Olsson et al., 2016, Mason and Plantinga, 2013).

The possibility of buying carbon offsets is excluded from the analysis, partly because of uncertainties in the effectiveness of carbon offsets and because it enables households of higher income levels to buy their way out of their GHG emissions.

5.2 Limitations and uncertainties

5.2.1 Assumptions and Implementations

Several of the proposed actions involve assumptions that have potential limitations. Additionally, some households might find the actual implementation of some of the actions to be challenging.

Action number 8 involves one return flight Trondheim – Oslo each month per person. This is clearly an overestimation of the average household's work related travels by airplane. Instead of considering only work related travel, one should interpret this as an illustrative example of how frequent flying domestically, both in the purpose of business and recreation, and international work related flying affects the carbon footprints of households. The flight distance used in this action is rather short, so if households conduct one or several long-distance flights within a year, it would sum up to the GHG emissions and costs associated with multiple return flights between Trondheim and Oslo. Work related travel by air transport is increasing in Norway, accounting for almost half of the total number of these travels (Denstadli and Rideng, 2012). Exact numbers combining distances and number of travels by air transport per person in Norway were scarce, but the findings in Denstadli and Rideng (2012) suggests that an average Norwegian person travels 0.4 trips by plane per month. Additionally, the transportation to and from the airports is not accounted for in the action. Taking these considerations into account, the overestimation of GHG emission and cost savings in action 8 is not as large as at the initial glance. However, some degree of overestimation is likely, since calculations depend upon the consumption of the average Norwegian household.

For actions 4 and 6, the assumptions of replacing all daily travels with bus and train transport respectively have potential limitations. Far from every Norwegian household has the opportunity to do all travels using these transport modes. One example of why this is difficult to implement is if households live in rural areas with low access to public transport. In the matrix that adjusts for double counting (Appendix A), I designate relatively low shares (10-30%) of each of the travel distances to these actions. The interpretation for this depends on whether one or several households implements the set of actions proposed. In the case of one household implementing the actions, the share designated to bus or train transport is in combination with the other transport actions, so that combining the actions available for the specific distance, covers the total km traveled within each distance. In the case of several households implementing the actions, the interpretation is that some households implement a larger share of the action than others do, but that the average of these are the values observed (Appendix A).

Some of the actions are difficult to implement for households because of considerations like infrastructure, urban versus rural area, access to appliances and products needed. This is particularly the case for the transport actions, as explained above. However, other actions such as the purchase of green or organic food and special types of furniture or materials might prove to be difficult for some households. However, since the analysis focuses on the average Norwegian household, most assumptions made and data used base on the consumption pattern of this household type. This means that the actual cost reductions and GHG emission savings will vary from household to household. Some households obtain lower reductions, if they for example already have implemented some of the actions (Gardner and Stern, 2008), while others will see a larger reduction potential, e.g. if they travel a longer distance per year than the average household.

The green marginal re-spending scenario bases on the marginal spending pattern. In order to reduce the GHG emissions, I eliminate re-spending on 31 of the highest emitting goods and services based on the emissions per monetary unit, and weight the eliminated consumption according to the relative consumption share of the remaining goods and services. This elimination process does not include considerations to the importance of the household of consuming these goods and services. In other words, I do not account for whether the individual household can implement the green consumption pattern or not. It is possible that some of the actions proposed will require that households spend more money on certain goods and services already excluded in the green marginal re-spending pattern. An example of this is that implementing a green diet could be inconsistent with eliminating re-spending on food products such as oil seeds. While buying an electric car might be incompatible with eliminating re-spending on electricity from sources such as coal, gas and biomass and waste, unless replaced with electricity from other sources. However, the re-spending scenarios do not exclude consumption on any goods and services entirely. They only assume that households spend the money saved from implementing the actions in a specific manner. The re-spending scenarios do not affect the rest of the household consumption.

5.2.2 Double-Counting

The idea behind the matrix that connects actions to specific activities (Appendix A) is to reduce double counting of GHG emission and cost reductions. This is the reason for the different units used for the actions (Table 4.1). For the transport actions involving daily travel (actions 1-6), the approach is to eliminate double counting through setting the limit to the total distance travelled within each distance range. As mentioned in the methods, it is possible to create many scenarios on the number of actions implemented. However, in the case of one household implementing the actions (as opposed to several households) including all of the actions would require the household to purchase a Tesla, a Renault Zoe and public transport passes, which would increase costs and alter the achieved GHG emission reductions. Buying a Tesla or a public transport pass without using them much could become more expensive than the costs per pkm suggested. Thus, the interpretation is rather that a certain percentage of households implement a specific action to fulfill a specific activity requirement. However, one household can choose several of the available actions for a specific activity, as long as only one of the actions involve a purchase, a household can e.g. choose to walk 60% of trips under 3 km and drive a Renault Zoe, the remaining 40%.

The methodology used in the transport scenarios involving daily travels should eliminate double counting. For some of the other actions however, double counting proved difficult to eliminate. Action number 14 (Table 3.1), eliminating food waste, is dependent upon the diet chosen, as it assumes reducing 22% of costs and GHG emissions associated with food purchases. However, the cost and GHG emission structure differs from diet to diet. This means that accounting for the different cost and GHG emission structures for the different diets would require different scenario for eliminating food waste for each of these. Instead of creating three different scenarios, I use the GHG emission and cost structure of the original scenario as a proxy. Considering the cost and GHG emission reductions of the other scenarios, eliminating food waste for the green diet (action 13), the cost and GHG emission reduction would be lower, while for the organic green diet (action 15), the cost reduction would be higher and the GHG emission reduction lower compared to the original scenario.

The potential double counting in action 30, buy furniture with 20% recycled MDF, follows a similar argument. It is dependent on action 28, average of changing 6 pieces of furniture, and action 29, increase lifetime of all products by 20% (e.g. through re-selling or longer lifetime). Both action 28 and 29 would change the original GHG emissions and cost structure that action 30 is based on. However, combining all three actions would result in larger GHG emission reductions and different costs than for each action alone. Thus, the actions are not disentangled, but for the current setup (Appendix A), the GHG emissions are most likely somewhat overestimated and the cost reductions underestimated since actions 28 to 30 all involve a cost increase.

The actions described above are the most obvious cases of double counting. However, smaller incidents of double counting are both likely and difficult to quantify. Examples of these are the actions involving appliance use in the clothing sector (actions 20-23) and action 12, appliances and other. Reducing the use of the washing machine and tumble dryer is somewhat dependent on the GHG emission and cost reduction potential found for action 12. The same is true for action 33, reading e-papers and e-books instead of newspapers and books. Action 33 increases appliance use, and thus depends on the calculations in action 12.

It is possible to make similar arguments for several of the actions in Table 3.1. However, finding exact estimates for GHG emission and cost reductions including double counting for all actions is challenging. Furthermore, the results would likely be uncertain because it requires controlling for a large number of variables. Although some instances of double counting occur in the calculations, the implications of this should not change the resulting GHG emission and cost reductions to a large degree.

5.2.3 Linear Programming

The methods presented two alternatives to optimization through linear programming. Changing the number of actions (Appendix A) while minimizing behavioral costs to the household is most likely the intuitive choice, as the households gain information on the amount of effort needed to reach the different reduction targets and which actions they should implement to achieve these targets. Appendix D shows a suggestion of assigning behavioral costs to each action with scores from one to ten, where ten represents the highest behavioral cost.

The other approach of changing the pattern of re-spending is more pragmatic, but might seem less intuitive to households, as changing the spending pattern of the money saved from implementing the actions requires the household to have information of the GHG intensity of goods and services. Furthermore, the objective of minimizing the absolute change in consumption pattern compared to the marginal is more abstract than minimizing behavioral costs.

The literature review suggested the need for information on which household actions are the most effective to reduce global warming (Gardner and Stern, 2008), which would be useful combined with information of the behavioral costs associated with implementing the actions. Hence, the choice of taking the more pragmatic approach of changing pattern of re-spending bases on the resources available.

Further research should focus on the behavioral costs associated with reaching GHG emission reduction targets and making explicit how different household actions contribute to reducing carbon footprint.

The conversion from purchaser price to basic price after the re-spending is formulated as a MATLAB function. The linear programming however, does not include the conversion from purchaser price to basic price. Excluding this conversion to basic price will influence the results. Since the price conversion involves subtracting trade and transport margins and taxes less subsidies, re-spending in purchaser price will likely overestimate the GHG emissions associated with re-spending. This overestimation is clear when comparing Table 4.5 and Figure 4.1. The marginal spending scenario shows a GHG emission reduction of 24% for the household (Table 4.5), while the linear programming shows that the spending pattern starts to change rapidly from a 20% reduction in GHG emissions (Figure 4.1). Since the linear programming uses the marginal spending scenario as the basis scenario, the change in the spending pattern in the linear programming should take place at a somewhat higher GHG emission reduction when converting to basic price. Thus, the results for the linear programming show an overestimation of the needed change in consumption pattern in order to reach the different GHG emission reduction targets.

5.2.4 Sensitivity Analysis

Calculating cost and GHG emission reductions of the actions involve using a large number of parameters. Numerous assumptions and the use of data with large deviations in the literature review, suggest the existence of some uncertainty in the parameters. A sensitivity analysis of the parameters would show how sensitive the results are to changes in parameters. A simple method is to change one parameter by a certain percentage and examine the effect on the result. Then repeat this procedure for all the parameters, commonly referred to as a one-at-a-time sensitivity analysis (Saltelli et al., 2000). A more complex method involves using Global sensitivity analysis. A sensitivity analysis is global when varying all input factors at the same time over the full range of possible values of the key parameters. This method can apportion the uncertainties in the results to different sources of uncertainty in the parameters or input of the model through e.g. the use of Monte Carlo filtering (Saltelli, 2004).

The large number of parameters used in the calculations means that a global sensitivity analysis is likely to be comprehensive. Still, it is reasonable to assume that the results are sensitive to changes in key parameters such as

- Household size
- Marginal and average cost per vkm for cars
- Emission factors for transport modes (kg CO2-eq/vkm)
- Passengers per car
- Lifetime of products

An example of a key parameter associated with a degree of uncertainty is the GHG intensity of the electricity mix. The assumption in the analysis is a GHG intensity of 0.117 kg CO2-eq/kWh, but the literature suggested a large variation in GHG intensity based on the electricity mix used, ranging from 0.02 kg CO2-eq/kWh for Norwegian Hydro Electricity to 0.819 kg CO2-eq/kWh for coal powered electricity (Schakenda and Askham Nyland, 2010, ENOVA, 2013).

It is important to reduce the uncertainties in such key parameters to the largest extent possible. A sensitivity analysis would identify such parameters and would improve the robustness of the results. However, the actual implementation of such an analysis is beyond the scope of this thesis.

6 Conclusion

This study provides insight to the important role of changes in household consumption to reaching the 2°C target of global warming. The literature review suggests that households lack information on how their consumption contributes to GHG emissions, and which actions they should take in order to reduce their carbon footprint. Thus, unlike similar studies that focus on a few behavioral actions, this analysis involves the average Norwegian household implementing a complete green lifestyle comprised of 34 specific behavioral actions. This requires a more active role of the household in achieving GHG emission reductions, than the approaches taken in other studies. The assumption of the household taking a more active role in reducing its carbon footprint however opens up other possibilities.

Implementing the suggested set of actions would require vast behavioral changes by the household. However, the gain could be a substantial cost decrease. Under the assumption that total expenditure level stays unchanged, how the household re-spends this money is crucial to the overall carbon footprint reduction.

In addition to the common average and marginal scenarios of re-spending, this analysis explores other approaches through implementing a green re-spending scenario as well as finding required re-spending to meet different reduction scenarios using linear programming. The scenarios of re-spending underline the importance of how the choice of goods and services modify the GHG emission reduction achieved. An initial reduction of 58% in household carbon footprint dropped to 24-35% when including rebound effects. Re-spending according to the marginal scenario led to the largest emissions while the green marginal scenario performed best. If households eliminate re-spending on the goods and services with high GHG intensities, they can lower the rebound effect. However, none of the three re-spending scenarios showed GHG emission reductions within the requirements of the 2°C target of global warming. To achieve this, the household must significantly alter their re-spending given the set off suggested actions. Through a strict pattern of re-spending, the linear programming results show carbon footprint reductions of up to 50% by curtailing re-spending on transport, clothing and footwear, and manufactured products such as appliances and vehicles. For emission reductions larger than 40%, re-spending largely shifts towards services associated with a low GHG intensity.

The scope of this thesis is to explore the importance of behavioral changes by households in reaching the 2°C target. This means excluding, but not ignoring the role of changes on the production side. An important implication of assuming an active role of the household is that the household choices can drive production changes. A large-scale implementation of the suggested green lifestyle would potentially lead to changes through sifting demand towards goods and services associated with lower GHG emissions. The production side can respond to this change in demand by production of environmentally better performing products leading to further emission reductions.

Fully or partially ignoring the rebound effect is equivalent to assuming decreased total expenditure. The results show that considerations involving the rebound effect is pivotal to the household reaching the reductions required. Furthermore, ignoring the rebound effect is potentially unrealistic as the overall consumption level decreases dramatically in a scenario of no re-spending.

When including rebound effects, the analysis shows that clearly the pattern of re-spending is very important. This calls for a larger focus on rebound effects in discussions on sustainable development.

Given the importance of the pattern of re-spending for households to achieve reductions in their carbon footprint, the linear programming shows that we can expect in the order of 25-30% reductions without massive changes in expenditure habits. Nevertheless, this requires much more investigation on the detailed structure of the spending pattern, and the balance between basic and discretionary expenditures.

To achieve further GHG emission reductions given the current set of actions, households must adopt specific patterns of re-spending restricted to certain goods and services. This requires both knowledge and sacrifices in consumption by the household.

This analysis shows that households implementing a green lifestyle can play an important part in mitigating global warming through reducing GHG emissions. Further research can expand upon the results from this thesis by investigating the willingness and behavioral costs of implementing different actions that reduce carbon footprint. Given the important role of re-spending and the rebound effect, it is essential to investigate which factors determine re-spending. Furthermore, studying the effect of investment instead of total re-spending can provide useful insight to ways of curtailing the rebound effect.

Changing household consumption on a large scale have implications to the economic structure, and to study the mechanisms of these economy-wide effects will help identify the consequences of a large-scale shift to a green lifestyle. Further studies on how lifestyle changes and production side changes can benefit from influencing each other to lower GHG emissions, will provide increased understanding on how we can reach the 2°C target of global warming.

References

ACHACHLOUEI, M. A. & HILTY, M. L. 2014. Modelling Rebound Effects in System Dynamics. *Proceedings of the 28th EnviroInfo 2014 Conference, Oldenburg, Germany*

AKERSHUS ENØK OG INNEKLIMA AS. 1999. *Enøkguiden* [Online]. Available: http://www.enok.no/enokguiden/02_1.html [Accessed 06.05.2016 2016].

ALCOTT, B. 2008. The sufficiency strategy: Would rich-world frugality lower environmental impact? *Ecological Economics,* 64**,** 770-786.

ALFREDSSON, E. C. 2004. "Green" consumption-no solution for climate change. *Energy,* 29**,** 513-524.

ANDERSEN, A. 2005. Enda romsligere for dem som bodde romslig fra før: bolig, omgivelser og miljø.

ARROW, K., BOLIN, B., COSTANZA, R. & DASGUPTA, P. 1995. Economic growth, carrying capacity, and the environment. *Science,* 268**,** 520.

ATB. 2015. *Billetter og priser* [Online]. ATB. Available: https://www.atb.no/priser/ [Accessed 19.11.2015.

BAIOCCHI, G. & MINX, J. C. 2010. Understanding changes in the UK's CO2 emissions: A global perspective. *Environmental Science & Technology,* 44**,** 1177-1184.

BARKER, T., DAGOUMAS, A. & RUBIN, J. 2009. The macroeconomic rebound effect and the world economy. *Energy Efficiency,* 2**,** 411-427.

BASTIANONI, S., PULSELLI, F. M. & TIEZZI, E. 2004. The problem of assigning responsibility for greenhouse gas emissions. *Ecological Economics,* 49**,** 253-257.

BENHELAL, E., ZAHEDI, G., SHAMSAEI, E. & BAHADORI, A. 2013. Global strategies and potentials to curb CO2 emissions in cement industry. *Journal of Cleaner Production,* 51**,** 142-161.

BERGESEN, B., GROTH, L. H., LANGSETH, B., MAGNUSSEN, I. H., SPILDE, D. & TOUTAIN, J. E. W. 2012. Energibruksrapporten 2012 - Energibruk i husholdninger. https://www.dibk.no/globalassets/energi/energibruksrapporten-2012.pdf.

BERNERS-LEE, M., HOOLOHAN, C., CAMMACK, H. & HEWITT, C. 2012. The relative greenhouse gas impacts of realistic dietary choices. *Energy Policy,* 43**,** 184-190.

BINSWANGER, M. 2001. Technological progress and sustainable development: what about the rebound effect? *Ecological Economics,* 36**,** 119-132.

BLAKER, M. 2015. *DEN SKITNE REALITETEN BAK ELBILENE* [Online]. NA.no Side3. Available: http://www.side3.no/motor/den-skitne-realiteten-bak-elbilene/8537423.html [Accessed 05.05.2016 2016].

BORGE, L., COLLETT, A., HALVORSEN, B., HAVSKJOLD, M., JACOBSEN, J., SCHESLIEN, U. & STOKKE, A. 2004. Differensiert el-avgift for husholdninger. *Norges offentlige utredninger (NOU).*

BOTTO, S., NICCOLUCCI, V., RUGANI, B., NICOLARDI, V., BASTIANONI, S. & GAGGI, C. 2011. Towards lower carbon footprint patterns of consumption: The case of drinking water in Italy. *Environmental Science & Policy,* 14**,** 388-395.

BRICENO, T., PETERS, G., SOLLI, C. & HERTWICH, E. 2005. Using life cycle approaches to evaluate sustainable consumption programs: car-sharing.

BROOKES, L. 2000. Energy efficiency fallacies revisited. *Energy Policy,* 28**,** 355-366.

BROWNE, M., ORTMANN, G. F. & HENDRIKS, S. 2007. Expenditure elasticities for rural households in the Embo ward, Umbumbulu, KwaZulu-Natal. *Agrekon,* 46**,** 566-583.

BRÄNNLUND, R., GHALWASH, T. & NORDSTRÖM, J. 2007. Increased energy efficiency and the rebound effect: Effects on consumption and emissions. *Energy Economics,* 29**,** 1-17.

CAMBRIDGE UNIVERSITY. 2014. *Scope 1, 2 and 3 emissions* [Online]. http://www.environment.admin.cam.ac.uk/what-are-we-doing/carbon/scope-1-2-and-3-emissions: Cambridge University. [Accessed 12.12.2015 2015].

CANONICO, S., SELLMAN, R. & PREIST, C. Reducing the greenhouse gas emissions of commercial print with digital technologies. Sustainable Systems and Technology, 2009. ISSST'09. IEEE International Symposium on, 2009. IEEE, 1-6.

CARBON FOOTPRINT OF NATIONS. 2010. *Carbon Footprint of Nations* [Online]. Available: http://carbonfootprintofnations.com/content/carbon_footprint_worldwide_1990_2010_/ [Accessed 27.02.2016 2016].
CASTELLANI, V., SALA, S. & MIRABELLA, N. 2015. Beyond the throwaway society: A life cycle-based assessment of the environmental benefit of reuse. *Integrated environmental assessment and management,* 11**,** 373-382.
CHAN, N. W. & GILLINGHAM, K. 2015. The Microeconomic Theory of the Rebound Effect and Its Welfare Implications. *Journal of the Association of Environmental and Resource Economists,* 2**,** 133-159.
CHITNIS, M. & SORRELL, S. 2015. Living up to expectations: Estimating direct and indirect rebound effects for UK households. *Energy Economics*.
CHITNIS, M., SORRELL, S., DRUCKMAN, A., FIRTH, S. K. & JACKSON, T. 2013. Turning lights into flights: Estimating direct and indirect rebound effects for UK households. *Energy Policy,* 55**,** 234-250.
CHITNIS, M., SORRELL, S., DRUCKMAN, A., FIRTH, S. K. & JACKSON, T. 2014. Who rebounds most? Estimating direct and indirect rebound effects for different UK socioeconomic groups. *Ecological Economics,* 106**,** 12-32.
CLARK, A. E., FRIJTERS, P. & SHIELDS, M. A. 2008. Relative income, happiness, and utility: An explanation for the Easterlin paradox and other puzzles. *Journal of Economic literature***,** 95-144.
COLLINS, M., KNUTTI, R., ARBLASTER, J., DUFRESNE, J.-L., FICHEFET, T., FRIEDLINGSTEIN, P., GAO, X., GUTOWSKI, W. J., JOHNS, T., KRINNER, G., SHONGWE, M., TEBALDI, C., WEAVER, A. J. & WEHNER, M. 2013. Long-term Climate Change: Projections, Commitments and Irreversibility. *In:* STOCKER, T. F., QIN, D., PLATTNER, G.-K., TIGNOR, M., ALLEN, S. K., BOSCHUNG, J., NAUELS, A., XIA, Y., BEX, V. & MIDGLEY, P. M. (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.
CONSUMERREPORTS. 2015. *The cost of organic food* [Online]. Available: http://www.consumerreports.org/cro/news/2015/03/cost-of-organic-food/index.htm [Accessed 07.05.2016 2016].
DEATON, A. & MUELLBAUER, J. 1980. An Almost Ideal Demand System. *The American Economic Review,* 70**,** 312-326.
DELEIRE, T. & KALIL, A. 2010. Does consumption buy happiness? Evidence from the United States. *International Review of Economics,* 57**,** 163-176.
DELL, M., JONES, B. F. & OLKEN, B. A. 2008. Climate change and economic growth: Evidence from the last half century. National Bureau of Economic Research.
DEMPSEY, M. E. & PALILONIS, A. 2012. Reuse, recycle… reduce: a greener library with print management. *Library Hi Tech,* 30**,** 408-417.
DENSTADLI, J., M. & RIDENG, A. 2012. Reisevaner på Fly 2011. *TØI Rapport.*
DIAS, A. C., ARROJA, L. & CAPELA, I. 2007. Life cycle assessment of printing and writing paper produced in Portugal. *The International Journal of Life Cycle Assessment,* 12**,** 521-528.
DIETZ, T., GARDNER, G. T., GILLIGAN, J., STERN, P. C. & VANDENBERGH, M. P. 2009. Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. *Proceedings of the National Academy of Sciences,* 106**,** 18452-18456.
DORMER, A., FINN, D. P., WARD, P. & CULLEN, J. 2013. Carbon footprint analysis in plastics manufacturing. *Journal of Cleaner Production,* 51**,** 133-141.
DRUCKMAN, A., CHITNIS, M., SORRELL, S. & JACKSON, T. 2011. Missing carbon reductions? Exploring rebound and backfire effects in UK households. *Energy Policy,* 39**,** 3572-3581.
DRUCKMAN, A. & JACKSON, T. 2009. The carbon footprint of UK households 1990–2004: A socio-economically disaggregated, quasi-multi-regional input–output model. *Ecological Economics,* 68**,** 2066-2077.

DRUCKMAN, A. & JACKSON, T. 2010. The bare necessities: How much household carbon do we really need? *Ecological Economics,* 69**,** 1794-1804.
DUBIN, J. A., MIEDEMA, A. K. & CHANDRAN, R. V. 1986. Price Effects of Energy-Efficient Technologies: A Study of Residential Demand for Heating and Cooling. *The RAND Journal of Economics,* 17**,** 310-325.
DUCHIN, F. 2005. A world trade model based on comparative advantage with m regions, n goods, and k factors. *Economic Systems Research,* 17**,** 141-162.
DUCHIN, F. & LEVINE, S. H. 2015. Rents in the era of resource scarcity: global payment flows under alternative scenarios. *Journal of Economic Structures,* 4**,** 1-17.
ECONOMIC CONSULTING ASSOCIATES 2014. Phase 1 final report: The rebound effect for developing countries. UK: Evidence on Demand.
EMISSION DATABASE FOR GLOBAL ATMOSPHERIC RESEARCH (EDGAR). 2000. *EDGAR 32FT2000* [Online]. PBL Netherlands Environmental Assessment Agency. Available: http://themasites.pbl.nl/tridion/en/themasites/edgar/emission_data/edgar_32ft2000/index-2.html [Accessed 27.02.2016 2016].
ENERGI OG KLIMA. 2016. *CO2 i atmosfæren* [Online]. Available: http://energiogklima.no/klimavakten/co2-i-atmosfaeren/ [Accessed 7.4.2016 2016].
ENOVA. 2013. *Klimarapportering* [Online]. ENOVA. Available: http://www.enova.no/innsikt/rapporter/resultatrapport-2013/5-rapportering-pa-energifondet-2012-og-2013/klimarapportering-/761/0/ [Accessed 10.3.2016 2016].
EUROSTAT. 2015. *Packaging waste statistics* [Online]. Eurostat. Available: http://ec.europa.eu/eurostat/statistics-explained/index.php/Packaging_waste_statistics [Accessed 11.4.2016 2016].
EXIOBASE CONSORTIUM. 2015. *Welcome to EXIOBASE* [Online]. Available: http://exiobase.eu/ [Accessed 14.12.2015 2015].
FIGGE, F., YOUNG, W. & BARKEMEYER, R. 2014. Sufficiency or efficiency to achieve lower resource consumption and emissions? The role of the rebound effect. *Journal of Cleaner Production,* 69**,** 216-224.
FONT VIVANCO, D., FREIRE-GONZÁLEZ, J., KEMP, R. & VAN DER VOET, E. 2014. The remarkable environmental rebound effect of electric cars: a microeconomic approach. *Environmental science & technology,* 48**,** 12063-12072.
FREIRE-GONZÁLEZ, J. 2011. Methods to empirically estimate direct and indirect rebound effect of energy-saving technological changes in households. *Ecological Modelling,* 223**,** 32-40.
GARDNER, G. T. & STERN, P. C. 2008. The Short List: The Most Effective Actions U.S. Households Can Take to Curb Climate Change. *Environment: Science and Policy for Sustainable Development,* 50**,** 12-25.
GARNAUT, R. 2008. The Garnaut climate change review. *Cambridge, Cambridge*.
GAVANKAR, S. & GEYER, R. 2010. The Rebound Effect :
State of the Debate and Implications for Energy Efficiency Research http://iee.ucsb.edu/files/pdf/Rebound%20Report%20for%20IEE-UCSB_0.pdf: Bren School of Environmental Science and Management.
GILLINGHAM, K., KOTCHEN, M. J., RAPSON, D. S. & WAGNER, G. 2013. The rebound effect is overplayed. *Nature,* 493**,** 475-476.
GILLINGHAM, K., RAPSON, D. & WAGNER, G. 2014. The Rebound Effect and Energy Efficiency Policy *FEEM Working Paper No. 107.2014*.
GIROD, B., DE HAAN, P. & SCHOLZ, R. 2011. Consumption-as-usual instead of ceteris paribus assumption for demand. *The International Journal of Life Cycle Assessment,* 16**,** 3-11.
GLOBALIS. 2016. *Papp- og papirforbruk Norge* [Online]. Globalis. Available: http://www.globalis.no/Land/Norge/(show)/indicators/(indicator)/3066 [Accessed 20.03.2016 2016].
GOEDKOOP, M. J., VAN HALEN, C. J. G., TE RIELE, H. R. M. & ROMMENS, P. J. M. 1999. Product Service systems,

Ecological and Economic Basics. Amersfoort, The Netherlands.
GONZÁLEZ-GARCÍA, S., GASOL, C. M., LOZANO, R. G., MOREIRA, M. T., GABARRELL, X., RIERADEVALL I PONS, J. & FEIJOO, G. 2011. Assessing the global warming potential of wooden products from the furniture sector to improve their ecodesign. *Science of The Total Environment,* 410–411**,** 16-25.
GONZALEZ, A., CHASE, A. & SOLUTIONS, E. 2012. What We Know and Don't Know about Embodied Energy and Greenhouse Gases for Electronics, Appliances, and Light Bulbs.
GOODALL, C. 2010. *How to live a low-carbon life : the individual's guide to tackling climate change,* London ; Washington, DC, Earthscan.
GOODALL, C. 2012. *How to live a low-carbon life: the individual's guide to stopping climate change*, Routledge.
GRABS, J. 2015. The rebound effects of switching to vegetarianism. A microeconomic analysis of Swedish consumption behavior. *Ecological Economics,* 116**,** 270-279.
GRACEY, F. & MOON, D. 2012. Valuing our clothes: the evidence base. WRAP.
GREENHOUSE GAS PROTOCOL. 2012. *FAQ* [Online]. Available: http://www.ghgprotocol.org/calculation-tools/faq [Accessed 14.12.2015 2015].
GREENING, L. A., GREENE, D. L. & DIFIGLIO, C. 2000. Energy efficiency and consumption - the rebound effect - a survey. *Energy Policy,* 28**,** 389-401.
GROSSMAN, G. M. & KRUEGER, A. B. 1991. Environmental impacts of a North American free trade agreement. National Bureau of Economic Research.
HANSEN, J., KHARECHA, P., SATO, M., MASSON-DELMOTTE, V., ACKERMAN, F., BEERLING, D. J., HEARTY, P. J., HOEGH-GULDBERG, O., HSU, S.-L. & PARMESAN, C. 2013. Assessing "dangerous climate change": required reduction of carbon emissions to protect young people, future generations and nature. *PloS one,* 8**,** e81648.
HARDING, M. & RAPSON, D. 2013. Do voluntary carbon offsets induce energy rebound? A conservationist's dilemma. Working Paper.
HARVEY, L. D. 2013. Recent advances in sustainable buildings: review of the energy and cost performance of the state-of-the-art best practices from around the world. *Annual review of environment and resources,* 38**,** 281-309.
HAWKINS, T. R., GAUSEN, O. M. & STRØMMAN, A. H. 2012. Environmental impacts of hybrid and electric vehicles—a review. *The International Journal of Life Cycle Assessment,* 17**,** 997-1014.
HERTWICH, E. G. 2005. Consumption and the rebound effect - An industrial ecology perspective. *Journal of Industrial Ecology,* 9**,** 85-98.
HERTWICH, E. G. & PETERS, G. P. 2009. Carbon footprint of nations: a global, trade-linked analysis. *Environ Sci Technol,* 43**,** 6414-20.
HJORTHOL, R., ENGEBRETSEN, Ø. & YTENG, T. P. 2014. Den nasjonale reisevaneundersøkelsen 2013/14 - nøkkelrapport. TØI Rapport.
HOSPIDO, A., MOREIRA, M. T. & FEIJOO, G. 2005. Environmental analysis of beer production. *International journal of agricultural resources, governance and ecology,* 4**,** 152-162.
HVITVED-JACOBSEN, K. 2001. *Pris på økologisk mat* [Online]. Dinside.no. Available: http://www.dinside.no/21841/pris-paa-okologisk-mat [Accessed 07.05.2016 2016].
ICAO. 2015. *Carbon Emissions Calculator* [Online]. International Civil Aviation Organization. Available: http://www.icao.int/environmental-protection/CarbonOffset/Pages/default.aspx [Accessed 19.11.2015.
IEA, I. E. A. 2009. *World Energy Outlook 2009 Edition,* http://www.worldenergyoutlook.org/weo2009/, International Energy Agency.
INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE 2015. *Climate Change 2014: Mitigation of Climate Change*, Cambridge University Press.
IVANOVA, D., STADLER, K., STEEN-OLSEN, K., WOOD, R., VITA, G., TUKKER, A. & HERTWICH, E. G. 2015. Environmental Impact Assessment of Household Consumption. *Journal of Industrial Ecology***,** n/a-n/a.

JACKSON, T. 2005. Live Better by Consuming Less?: Is There a “Double Dividend” in Sustainable Consumption? *Journal of Industrial Ecology,* 9**,** 19-36.

JALAS, M. 2002. A time use perspective on the materials intensity of consumption. *Ecological Economics,* 41**,** 109-123.

JANSEN, E. 2013. *400 ppm: Milepæl til besvær* [Online]. Energi og Klima. Available: http://energiogklima.no/kommentar/400-ppm-milepael-til-besvaer/ [Accessed 7.4.2016 2016].

JEVONS, W. S. 1866. *THE COAL QUESTION,* London,.

JONES, C. M. & KAMMEN, D. M. 2011. Quantifying carbon footprint reduction opportunities for U.S. households and communities. *Environ Sci Technol,* 45**,** 4088-95.

JRINCAYC. 2008. *Hicks Substitution effect* [Online]. https://en.wikipedia.org/wiki/File:Hicks_Substitution_effect.svg: Wikipedia. Available: https://en.wikipedia.org/wiki/File:Hicks_Substitution_effect.svg [Accessed 30.09.2015 2015].

KANEMOTO, K., LENZEN, M., PETERS, G. P., MORAN, D. D. & GESCHKE, A. 2011. Frameworks for comparing emissions associated with production, consumption, and international trade. *Environmental science & technology,* 46**,** 172-179.

KAWAJIRI, K., TABATA, T. & IHARA, T. 2015. Using a Rebound Matrix to Estimate Consumption Changes from Saving and its Environmental Impact in Japan. *Journal of Industrial Ecology,* 19**,** 564-574.

KHAZZOOM, J. D. 1980. Economic Implications of Mandated Efficiency in Standards for Household Appliances. *The Energy Journal,* 1**,** 21-40.

KLIMA- OG MILJØDEPARTEMENTET 2014. Klima + vekst = sant. Regjeringen.

KLIMAHANDLING.NO. 2016. *Si nei til uadressert reklame* [Online]. Available: http://klimahandling.no/si-nei-til-uadressert-reklame/ [Accessed 20.3.2016 2016].

LAURIJSSEN, J., MARSIDI, M., WESTENBROEK, A., WORRELL, E. & FAAIJ, A. 2010. Paper and biomass for energy?: The impact of paper recycling on energy and CO2 emissions. *Resources, Conservation and Recycling,* 54**,** 1208-1218.

LE QUÉRÉ, C., MORIARTY, R., ANDREW, R., CANADELL, J., SITCH, S., KORSBAKKEN, J., FRIEDLINGSTEIN, P., PETERS, G., ANDRES, R. & BODEN, T. 2015. Global Carbon Budget 2015. *Earth System Science Data,* 7**,** 349-396.

LENZEN, M. & DEY, C. J. 2002. Economic, energy and greenhouse emissions impacts of some consumer choice, technology and government outlay options. *Energy Economics,* 24**,** 377-403.

LENZEN, M., MURRAY, J., SACK, F. & WIEDMANN, T. 2007. Shared producer and consumer responsibility—Theory and practice. *Ecological Economics,* 61**,** 27-42.

LEWBEL, A. 2008. Engel curves. *The New Palgrave Dictionary of Economics,* 2.

LINKOSALMI, L., HUSGAFVEL, R., FOMKIN, A., JUNNIKKALA, H., WITIKKALA, T., KAIRI, M. & DAHL, O. 2016. Main factors influencing greenhouse gas emissions of wood-based furniture industry in Finland. *Journal of Cleaner Production,* 113**,** 596-605.

LOVINS, A. B. 1988. Energy Saving Resulting from the Adoption of More Efficient Appliances: Another View. *The Energy Journal,* 9**,** 155-162.

MADJAR, M. & OZAWA, T. 2006. Happiness and Sustainable Consumption: Psychological and physical rebound effects at work in a tool for sustainable design. *The International Journal of Life Cycle Assessment,* 11**,** 105-115.

MASON, C. F. & PLANTINGA, A. J. 2013. The additionality problem with offsets: Optimal contracts for carbon sequestration in forests. *Journal of Environmental Economics and Management,* 66**,** 1-14.

MATVETT 2014. Matvett og ForMat-prosjektet - Rapport fra virksomheten 2014. *ForMat-prosjektrapport.*

MILJØDIREKTORATET. 2015. *Togradersmålet* [Online]. Available: http://www.miljostatus.no/tema/klima/internasjonal-klimapolitikk/togradersmaalet/ [Accessed 29.01.2016.

MILLENNIUM DEVELOPMENT GOALS INDICATORS. 2015. *Carbon dioxide emissions (CO2), metric tons of CO2 per capita (CDIAC)* [Online]. United Nations Statistics Division. Available: http://mdgs.un.org/unsd/mdg/SeriesDetail.aspx?srid=751 [Accessed 27.2.2016 2016].
MINISTRY OF CLIMATE AND ENVIRONMENT. 2014. *Green shift – climate and environmentally friendly restructuring* [Online]. Regjeringen. Available: https://www.regjeringen.no/en/topics/climate-and-environment/climate/innsiktsartikler-klima/green-shift/id2076832/ [Accessed 09.04.2016 2016].
MITCHELL, A. & STEVENS, G. 2009. Life cycle assessment of closed loop MDF recycling: Microrelease Trial–Final Report. Wrap. ISBN.
MOBERG, Å., BORGGREN, C. & FINNVEDEN, G. 2011. Books from an environmental perspective—Part 2: e-books as an alternative to paper books. *The International Journal of Life Cycle Assessment,* 16**,** 238-246.
MOBERG, Å., JOHANSSON, M., FINNVEDEN, G. & JONSSON, A. 2010. Printed and tablet e-paper newspaper from an environmental perspective — A screening life cycle assessment. *Environmental Impact Assessment Review,* 30**,** 177-191.
MUNKSGAARD, J. & PEDERSEN, K. A. 2001. CO2 accounts for open economies: producer or consumer responsibility? *Energy Policy,* 29**,** 327-334.
MURRAY, C. K. 2013. What if consumers decided to all 'go green'? Environmental rebound effects from consumption decisions. *Energy Policy,* 54**,** 240-256.
MUTHU, S. S., LI, Y., HU, J. Y. & MOK, P. Y. 2011. Carbon footprint of shopping (grocery) bags in China, Hong Kong and India. *Atmospheric Environment,* 45**,** 469-475.
MUTHU, S. S., LI, Y., HU, J. Y. & MOK, P. Y. 2012. Quantification of environmental impact and ecological sustainability for textile fibres. *Ecological Indicators,* 13**,** 66-74.
NARBEL, P. A. & ISAKSEN, E. T. 2014. A carbon footprint proportional to expenditure-a case for Norway? *NHH Dept. of Business and Management Science Discussion Paper*.
NASSEN, J. & HOLMBERG, J. 2009. Quantifying the rebound effects of energy efficiency improvements and energy conserving behaviour in Sweden. *Energy Efficiency,* 2**,** 221-231.
NEALER, R., REICHMUTH, D. & ANAIR, D. 2015. Cleaner cars from cradle to grave: how electric cars beat gasoline cars on lifetime global warming emissions. *Union of Concerned Scientists Report*.
NORGES BANK. 2016. *VALUTAKURS FOR AMERIKANSKE DOLLAR (USD)* [Online]. Available: http://www.norges-bank.no/Statistikk/Valutakurser/valuta/USD/ [Accessed 10.03.2016 2016].
NOVEMA KULDE. 2016. *Driftsinstruks Besparelse ved varmepumper* [Online]. Available: http://novemakulde.no/05%5CINS%5Cinstr_enok.pdf [Accessed 06.05.2016 2016].
NSB. 2015. *Se hvordan tog, buss, bil og fly påvirker miljøet vårt* [Online]. NSB. Available: https://www.nsb.no/om-nsb/nsb-og-miljo/Milj%C3%B8kalkulator [Accessed 19.11.2015.
OLESEN, J. E., SCHELDE, K., WEISKE, A., WEISBJERG, M. R., ASMAN, W. A. H. & DJURHUUS, J. 2006. Modelling greenhouse gas emissions from European conventional and organic dairy farms. *Agriculture, Ecosystems & Environment,* 112**,** 207-220.
OLSSON, A., GRÖNKVIST, S., LIND, M. & YAN, J. 2016. The elephant in the room – A comparative study of uncertainties in carbon offsets. *Environmental Science & Policy,* 56**,** 32-38.
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT 2012. THE OECD ENVIRONMENTAL OUTLOOK TO 2050 - Key Findings on Climate Change.
PACHAURI, R. K., ALLEN, M., BARROS, V., BROOME, J., CRAMER, W., CHRIST, R., CHURCH, J., CLARKE, L., DAHE, Q. & DASGUPTA, P. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
PETERS, G., DAVIS, S. & ANDREW, R. 2012. A synthesis of carbon in international trade. *Biogeosciences,* 9.
PETERS, G. P. 2008. From production-based to consumption-based national emission inventories. *Ecological Economics,* 65**,** 13-23.

PETERS, G. P., ANDREW, R. M., SOLOMON, S. & FRIEDLINGSTEIN, P. 2015. Measuring a fair and ambitious climate agreement using cumulative emissions. *Environmental Research Letters,* 10**,** 105004.

PETERS, G. P. & HERTWICH, E. G. 2006. The Importance of Imports for Household Environmental Impacts. *Journal of Industrial Ecology,* 10**,** 89-109.

PETERS, G. P., MINX, J. C., WEBER, C. L. & EDENHOFER, O. 2011. Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences,* 108**,** 8903-8908.

REES, W. E. 1992. Ecological footprints and appropriated carrying capacity: what urban economics leaves out. *Environment and urbanization,* 4**,** 121-130.

REISCH, L. A. 2001. Time and wealth - The role of time and temporalities for sustainable patterns of consumption. *Time & Society,* 10**,** 367-385.

RENAULT. 2016. TECHNICAL SPECIFICATIONS RENAULT ZOE. Available: http://www.imprensa.renault.com.br/upload/produto/ficha-tecnica/zoe_2016-02-11_18-23-09.pdf [Accessed 05.5.2016 2016].

SALHOFER, S., OBERSTEINER, G., SCHNEIDER, F. & LEBERSORGER, S. 2008. Potentials for the prevention of municipal solid waste. *Waste management,* 28**,** 245-259.

SALTELLI, A. Global sensitivity analysis: an introduction. Proc. 4th International Conference on Sensitivity Analysis of Model Output (SAMO'04), 2004. 27-43.

SALTELLI, A., CHAN, K. & SCOTT, E. M. 2000. *Sensitivity analysis*, Wiley New York.

SAMARAS, C. & MEISTERLING, K. 2008. Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: implications for policy. *Environmental science & technology,* 42**,** 3170-3176.

SAUNDERS, H. D. 1992. The Khazzoom-Brookes Postulate and Neoclassical Growth. *The Energy Journal,* 13**,** 131-148.

SCHAKENDA, V. & ASKHAM NYLAND, C. 2010. CO2–emissions associated with different electricity mixes. *Ostfoldforskning. Publikasjoner. http://ostfoldforskning. no/uploads/dokumenter/publikasjoner/627. pdf (Page consultée le 2 novembre 2013)*.

SCRIPPS INSTITUTION OF OCEANOGRAPHY. 2016. *THE KEELING CURVE* [Online]. Available: https://scripps.ucsd.edu/programs/keelingcurve/ [Accessed 7.4.2016 2016].

SETIS. 2010. *Per capita cement consumption in selected countries* [Online]. European Commission. Available: https://setis.ec.europa.eu/setis-deliverables/info-graphics-library/capita-cement-consumption-selected-countries [Accessed 31.05.2016 2016].

SMALL, K. A. & VAN DENDER, K. 2007. Fuel efficiency and motor vehicle travel: The declining rebound effect. *Energy Journal,* 28**,** 25-51.

SMARTEPENGER. 2015. *Beregn årlige bilkostnader for bruktbil* [Online]. Smartepenger.no. Available: http://www.smartepenger.no/kalkulatorer/2164-beregn-arlige-bilkostnader-for-bruktbil [Accessed 19.11.2015.

SMARTEPENGER. 2016. *Kalkulatorer* [Online]. Smarte Penger. Available: http://www.smartepenger.no/kalkulatorer/ [Accessed 5.5.2016 2016].

SORRELL, S. & DIMITROPOULOS, J. 2008. The rebound effect: Microeconomic definitions, limitations and extensions. *Ecological Economics,* 65**,** 636-649.

SORRELL, S., DIMITROPOULOS, J. & SOMMERVILLE, M. 2009. Empirical estimates of the direct rebound effect: A review. *Energy Policy,* 37**,** 1356-1371.

SPIELMANN, M., DE HAAN, P. & SCHOLZ, R. W. 2008. Environmental rebound effects of high-speed transport technologies: a case study of climate change rebound effects of a future underground maglev train system. *Journal of Cleaner Production,* 16**,** 1388-1398.

STATISTICS NORWAY. 2013. *Forbruksundersøkelsen, 2012* [Online]. Statistisk Sentralbyrå. Available: https://www.ssb.no/inntekt-og-forbruk/statistikker/fbu [Accessed 8.3.2016 2016].

STATISTICS NORWAY. 2014a. *Energibruk i husholdningene, 2012* [Online]. SSB. Available: https://www.ssb.no/energi-og-industri/statistikker/husenergi [Accessed 20.3.2016 2016].

STATISTICS NORWAY. 2014b. *Familier og husholdninger, 1. januar 2014* [Online]. SSB. Available: https://www.ssb.no/befolkning/statistikker/familie/aar/2014-12-12 [Accessed 7.4.2016 2016].
STATISTICS NORWAY. 2015a. *Avfall frå hushalda, 2014* [Online]. Statistics Norway. Available: https://www.ssb.no/natur-og-miljo/statistikker/avfkomm/aar/2015-07-07#content [Accessed 06.06.2016 2016].
STATISTICS NORWAY. 2015b. *Konsumprisindeksen, oktober 2015* [Online]. Statistisk Sentralbyrå. Available: https://www.ssb.no/kpi [Accessed 19.11.2015.
STATISTICS NORWAY. 2016. *Elektrisitetspriser* [Online]. Statistics Norway. Available: https://www.ssb.no/statistikkbanken/selecttable/hovedtabellHjem.asp?KortNavnWeb=elkraftpris&CMSSubjectArea=energi-og-industri&checked=true [Accessed 6.5.2016 2016].
STEEN-OLSEN, K., OWEN, A., HERTWICH, E. G. & LENZEN, M. 2014. Effects of sector aggregation on CO2 multipliers in multiregional input–output analyses. *Economic Systems Research,* 26**,** 284-302.
STEEN-OLSEN, K., WOOD, R. & HERTWICH, E. G. Accepted for publication. The carbon footprint of Norwegian household consumption 1999-2012. Journal of Industrial Ecology.
STEG, L. 2008. Promoting household energy conservation. *Energy Policy,* 36**,** 4449-4453.
STEHFEST, E., BOUWMAN, L., VAN VUUREN, D. P., DEN ELZEN, M. G., EICKHOUT, B. & KABAT, P. 2009. Climate benefits of changing diet. *Climatic change,* 95**,** 83-102.
STERN, D. I. 2004. The Rise and Fall of the Environmental Kuznets Curve. *World Development,* 32**,** 1419-1439.
STERN, D. I., COMMON, M. S. & BARBIER, E. B. 1996. Economic growth and environmental degradation: The environmental Kuznets curve and sustainable development. *World Development,* 24**,** 1151-1160.
STERN, N. 2007. *The economics of climate change: the Stern review*, cambridge University press.
STOCK, J. H. 1988. A reexamination of Friedman's consumption puzzle. *Journal of Business & Economic Statistics,* 6**,** 401-407.
SU, Q. 2012. A quantile regression analysis of the rebound effect: Evidence from the 2009 National Household Transportation Survey in the United States. *Energy Policy,* 45**,** 368-377.
SWART, R., ROBINSON, J. & COHEN, S. 2003. Climate change and sustainable development: expanding the options. *Climate Policy,* 3**,** S19-S40.
TAKASE, K., KONDO, Y. & WASHIZU, A. 2005. An Analysis of Sustainable Consumption by the Waste Input-Output Model. *Journal of Industrial Ecology,* 9**,** 201-219.
TAYLOR, L. D. & HOUTHAKKER, H. S. 2009. *Consumer demand in the United States: Prices, income, and consumption behavior*, Springer Science & Business Media.
TEN RAA, T. & SHESTALOVA, V. 2015. Supply-Use Framework for International Environmental Policy Analysis. *Economic Systems Research,* 27**,** 77-94.
THE NEW CLIMATE ECONOMY 2014. BETTER GROWTH, BETTER CLIMATE - The New Climate Economy Report. The Global Comission on the Economy and Climate.
THIESEN, J., CHRISTENSEN, T., KRISTENSEN, T., ANDERSEN, R., BRUNOE, B., GREGERSEN, T., THRANE, M. & WEIDEMA, B. 2008. Rebound effects of price differences. *The International Journal of Life Cycle Assessment,* 13**,** 104-114.
THOMAS, B., FISHWICK, M., JOYCE, J. & VAN SANTEN, A. 2012. *A Carbon Footprint for UK Clothing and Opportunities for Savings* [Online]. WRAP. Available: http://www.wrap.org.uk/sites/files/wrap/Appendix%20IV%20-%20Carbon%20footprint%20report.pdf [Accessed 14.03.2016 2016].
THOMAS, B. A. & AZEVEDO, I. L. 2013a. Estimating direct and indirect rebound effects for U.S. households with input–output analysis. Part 2: Simulation. *Ecological Economics,* 86**,** 188-198.
THOMAS, B. A. & AZEVEDO, I. L. 2013b. Estimating direct and indirect rebound effects for US households with input-output analysis Part 1: Theoretical framework. *Ecological Economics,* 86**,** 199-210.

THØGERSEN, J. & ÖLANDER, F. 2003. Spillover of environment-friendly consumer behaviour. *Journal of Environmental Psychology,* 23**,** 225-236.

TRANSPORTØKONOMISK INSTITUTT 2014. Reisevaneundersøkelsen 2013/14 - Bilhold og bilbruk - faktaark.

TUKKER, A., DE KONING, A., WOOD, R., HAWKINS, T., LUTTER, S., ACOSTA, J., RUEDA CANTUCHE, J. M., BOUWMEESTER, M., OOSTERHAVEN, J., DROSDOWSKI, T. & KUENEN, J. 2013. EXIOPOL - DEVELOPMENT AND ILLUSTRATIVE ANALYSES OF A DETAILED GLOBAL MR EE SUT/IOT. *Economic Systems Research,* 25**,** 50-70.

TUKKER, A. & JANSEN, B. 2006. Environmental Impacts of Products: A Detailed Review of Studies. *Journal of Industrial Ecology,* 10**,** 159-182.

UNITED NATIONS STATISTICS DIVISION. 2016. *Detailed structure and explanatory notes: COICOP (Classification of Individual Consumption According to Purpose)* [Online]. Available: http://unstats.un.org/unsd/cr/registry/regcst.asp?Cl=5 [Accessed 08.03.2016 2016].

VAILLANT. 2015. *Energisparetips* [Online]. Available: https://www.vaillant.no/privatkunder/service-support/energisparetips/index.no_no.html [Accessed 06.05.2016 2016].

VAN SLUISVELD, M. A. E., MARTÍNEZ, S. H., DAIOGLOU, V. & VAN VUUREN, D. P. 2016. Exploring the implications of lifestyle change in 2 °C mitigation scenarios using the IMAGE integrated assessment model. *Technological Forecasting and Social Change,* 102**,** 309-319.

WEBER, C. L. & MATTHEWS, H. S. 2008. Quantifying the global and distributional aspects of American household carbon footprint. *Ecological Economics,* 66**,** 379-391.

WEBER, C. L. & PETERS, G. P. 2009. Climate change policy and international trade: Policy considerations in the US. *Energy Policy,* 37**,** 432-440.

WEIDEMA, B. P., THRANE, M., CHRISTENSEN, P., SCHMIDT, J. & LØKKE, S. 2008. Carbon footprint. *Journal of Industrial Ecology,* 12**,** 3-6.

WIEDMANN, T. & MINX, J. 2008. A definition of 'carbon footprint'. *Ecological economics research trends,* 1**,** 1-11.

WIGLEY, T. 1983. The pre-industrial carbon dioxide level. *Climatic Change,* 5**,** 315-320.

WINNIPEG & VEOLIA WATER 2011. WINNIPEG SEWAGE TREATMENT PROGRAM - SOUTH END PLANT

WOOD, R., STADLER, K., BULAVSKAYA, T., LUTTER, S., GILJUM, S., DE KONING, A., KUENEN, J., SCHÜTZ, H., ACOSTA-FERNÁNDEZ, J., USUBIAGA, A., SIMAS, M., IVANOVA, O., WEINZETTEL, J., SCHMIDT, J. H., MERCIAI, S. & TUKKER, A. 2015. Global sustainability accounting-developing EXIOBASE for multi-regional footprint analysis. *Sustainability (Switzerland),* 7**,** 138-163.

WORLD COMMISSION ON ENVIRONMENT AND DEVELOPMENT. 1987. *Our common future,* Oxford ; New York, Oxford University Press.

WRIGHT, L. A., KEMP, S. & WILLIAMS, I. 2011. 'Carbon footprinting': towards a universally accepted definition. *Carbon management,* 2**,** 61-72.

YOUNG, W., HWANG, K., MCDONALD, S. & OATES, C. J. 2010. Sustainable consumption: green consumer behaviour when purchasing products. *Sustainable development,* 18**,** 20-31.

Appendix A Adjustment matrices

	Daily km driven by car for all travels (non-work related)						Km driven by car for work related travel																															
Actions	<1 km	1-2.9 km	3-4.9 km	5-9.9 km	10-19.9 km	>20 km	<1 km	1-2.9 km	3-4.9 km	5-9.9 km	10-19.9 km	>20 km	Walk Lerkendal - Trondheim S instead of taking the train (4.7 km each way)	One less return business flight Trondheim - Oslo per month (video-conference instead)	One less vacation to Bangkok, Thailand	Space and water heating	Appliances and other	Diet	Eliminating food waste	Other measures (organic, local, composting)	Eco-efficiency across suply chain	Design for durability	Market shift to higher proportion of synthetic fibres	Clean clothing less	Wash at lower temperature	Increase size of washing and drying loads	Use the tumble dryer less	Dispose less - reuse more	Start closed loop recycling of synthetic fibres	Dispose less - recycle more	Reduce clothing purchases by 20%	Average of changing 6 pieces of furniture	Increase lifetime of all products by 20% (e.g. through re-selling or longer lifetime)	Buy furniture with 20% recycled MDF (medium-density fibreboard)	Eliminating unsolicited mail	Reduced printing (printing management system, two-sided printing)	Reading e-papers and e-books instead of newspapers and books	Reducing plastic waste by 30%
Switch from standard gasoline vehicle to best-performing electric vehicle (Renault Zoe)	0	0	0.5	1	0.6	0.63					1	1																										
Switch from standard gasoline vehicle to Tesla	0	0	0	0	0	0.02					0	0																										
No trips by car under 3 km	0.8	0.8																																				
Switch all daily car travel with bus transport	0.1	0.1	0.3	0	0.2	0.2	0	0	0	0	0	0																										
Car-pooling for work travel by car under 10 km using a hybrid car	0.1	0.1	0.2	0	0.2	0.15	0	0	0	0	0	0																										
Switch all daily car travel with with train transport							1	1	1	1	0	0																										
Walk Lerkendal - Trondheim S instead of taking the train (4.7 km each way)													1																									
One less return business flight Trondheim - Oslo per month (video-conference instead)														1																								
One less vacation to Bangkok, Thailand															1																							
Reducing indoor temperature by 1°C																0.1																						
Space and water heating																0.9																						
Appliances and other																	1																					
Grenn Diet																		0.9																				
Eliminating food waste																			1																			
Organic Green diet																		0.1																				
Other measures (organic, local, composting)																				1																		
Eco-efficiency across suply chain																					1																	
Design for durability																						1																
Market shift to higher proportion of synthetic fibres																							1															
Clean clothing less																								1														
Wash at lower temperature																									1													
Increase size of washing and drying loads																										1												
Use the tumble dryer less																											1											
Dispose less - reuse more																												1										
Start closed loop recycling of synthetic fibres																													1									
Dispose less - recycle more																														1								
Reduce clothing purchases by 20%																															1							
Average of changing 6 pieces of furniture																																1						
Increase lifetime of all products by 20% (e.g. through re-selling or longer lifetime)																																	1					
Buy furniture with 20% recycled MDF (medium-density fibreboard)																																		1				
Eliminating unsolicited mail																																			1			
Reduced printing (printing management system, two-sided printing)																																				1		
Reading e-papers and e-books instead of newspapers and books																																					1	
Reducing plastic waste by 30%																																						1
Total Number possible	16	283	394	907	1411	6816	6	59	92	221	491	3220	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table A.1: Matrix adjusted for double counting

	Daily km driven by car for all travels (non-work related)						Km driven by car for work related travel																																	
Actions	<1 km	1-2.9 km	3-4.9 km	5-9.9 km	10-19.9 km	>20 km	<1 km	1-2.9 km	3-4.9 km	5-9.9 km	10-19.9 km	>20 km	Walk Lerkendal - Trondheim S instead of taking the train (4.7 km each way)	One less return business flight Trondheim - Oslo per month (video-conference instead)	One less vacation to Bangkok, Thailand	Reducing indoor temperature by 1°C	Space and water heating	Appliances and other	Grenn Diet	Organic green diet	Eliminating food waste	Other measures (organic, local, composting)	Eco-efficiency across suply chain	Design for durability	Market shift to higher proportion of synthetic fibres	Clean clothing less	Wash at lower temperature	Increase size of washing and drying loads	Use the tumble dryer less	Dispose less - reuse more	Start closed loop recycling of synthetic fibres	Dispose less - recycle more	Reduce clothing purchases by 20%	Average of changing 6 pieces of furniture	Increase lifetime of all products by 20% (e.g. through re-selling or longer lifetime)	Buy furniture with 20% recycled MDF (medium-density fibreboard)	Eliminating unsolicited mail	Reduced printing (printing management system, two-sided printing)	Reading e-papers and e-books instead of newspapers and books	Reducing plastic waste by 30%
Switch from standard gasoline vehicle to best-performing electric vehicle (Renault Zoe)	1	1	1	1	1	1	1	1	1	1	1	1																												
Switch from standard gasoline vehicle to Tesla	1	1	1	1	1	1	1	1	1	1	1	1																												
No trips by car under 3 km	1	1					1	1																																
Switch all daily car travel with bus transport	1	1	1	1	1	1	1	1	1	1	1	1																												
Car-pooling for work travel by car under 10 km using a hybrid car							1	1	1	1																														
Switch all daily car travel with with train transport	1	1	1	1	1	1	1	1	1	1	1	1																												
Walk Lerkendal - Trondheim S instead of taking the train (4.7 km each way)													1																											
One less return business flight Trondheim - Oslo per month (video-conference instead)														1																										
One less vacation to Bangkok, Thailand															1																									
Reducing indoor temperature by 1°C																1																								
Space and water heating																	1																							
Appliances and other																		1																						
Grenn Diet																			1																					
Eliminating food waste																				1																				
Organic Green diet																					1																			
Other measures (organic, local, composting)																						1																		
Eco-efficiency across suply chain																							1																	
Design for durability																								1																
Market shift to higher proportion of synthetic fibres																									1															
Clean clothing less																										1														
Wash at lower temperature																											1													
Increase size of washing and drying loads																												1												
Use the tumble dryer less																													1											
Dispose less - reuse more																														1										
Start closed loop recycling of synthetic fibres																															1									
Dispose less - recycle more																																1								
Reduce clothing purchases by 20%																																	1							
Average of changing 6 pieces of furniture																																		1						
Increase lifetime of all products by 20% (e.g. through re-selling or longer lifetime)																																			1					
Buy furniture with 20% recycled MDF (medium-density fibreboard)																																				1				
Eliminating unsolicited mail																																					1			
Reduced printing (printing management system, two-sided printing)																																						1		
Reading e-papers and e-books instead of newspapers and books																																							1	
Reducing plastic waste by 30%																																								1

Table A.2: Matrix not adjusted for double counting

Appendix B Cost calculations for vehicles

Bilens pris	250 000	
Antall år du skal eie bilen	6 ▾	

Kostnadsforutsetninger:	**Automatisk**	**Dine tall**
Normal kjørelengde for bilklassen, km per år	14 000	
Din kjørelengde - km per år	14 000	16 939
Drivstoff-forbruk - liter per mil	0,70	0,7
Drivstoffpris - kr per liter	13,00	13
Rentekostnad (snitt lån og egenkapital)	4,00%	6%
Årsavgift	3 135	3 135
Forsikringskostnad - gjennomsnitt per år	7 441	6 000
Dekk-kostnader - gjennomsnitt per år	1 794	1 500
Vask, rekvisita og lignende - gjennomsnitt per år	1 147	10 000
Servicekostnad - gjennomsnitt per år	3 014	3 000
Reparasjonskostnad - gjennomsnitt per år	4 517	1 500
Verdifall 1.år (av kjøpspris)	20,0%	20%
Verdifall 2. år (av bruktverdi)	14,0%	14%
Verdifall 3. år (av bruktverdi)	13,0%	13%
Verdifall 4. år (av bruktverdi)	12,0%	12%
Verdifall 5. år (av bruktverdi)	11,0%	11%
Verdifall 6. år (av bruktverdi)	10,0%	10%

Totale kostnader:		
Antall år du eier bilen	6	
Kostnadspost	**Totalt**	**Per år**
Verdifall	146 192	24 365
Rentekostnad (etter skatt)	42 424	7 071
Drivstoff	92 487	15 414
Årsavgift	18 810	3 135
Forsikringskostnader	36 000	6 000
Dekk-kostnader	9 000	1 500
Vask, rekvisita og lignende	60 000	10 000
Servicekostnad	18 000	3 000
Reparasjonskostnad	9 000	1 500
Totalkostnad	431 913	71 985
Gjennomsnittskostnad per kjørte kilometer	4,25	
Gjennomsnittskostnad per dag	197	
Marginalkostnad for én ekstra kjørt kilometer (år 1)	1,61	
Marginalkostnad for bare drivstoff	0,91	

Figure B.1: Cost calculations for standard gasoline vehicle

(Smartepenger, 2016)

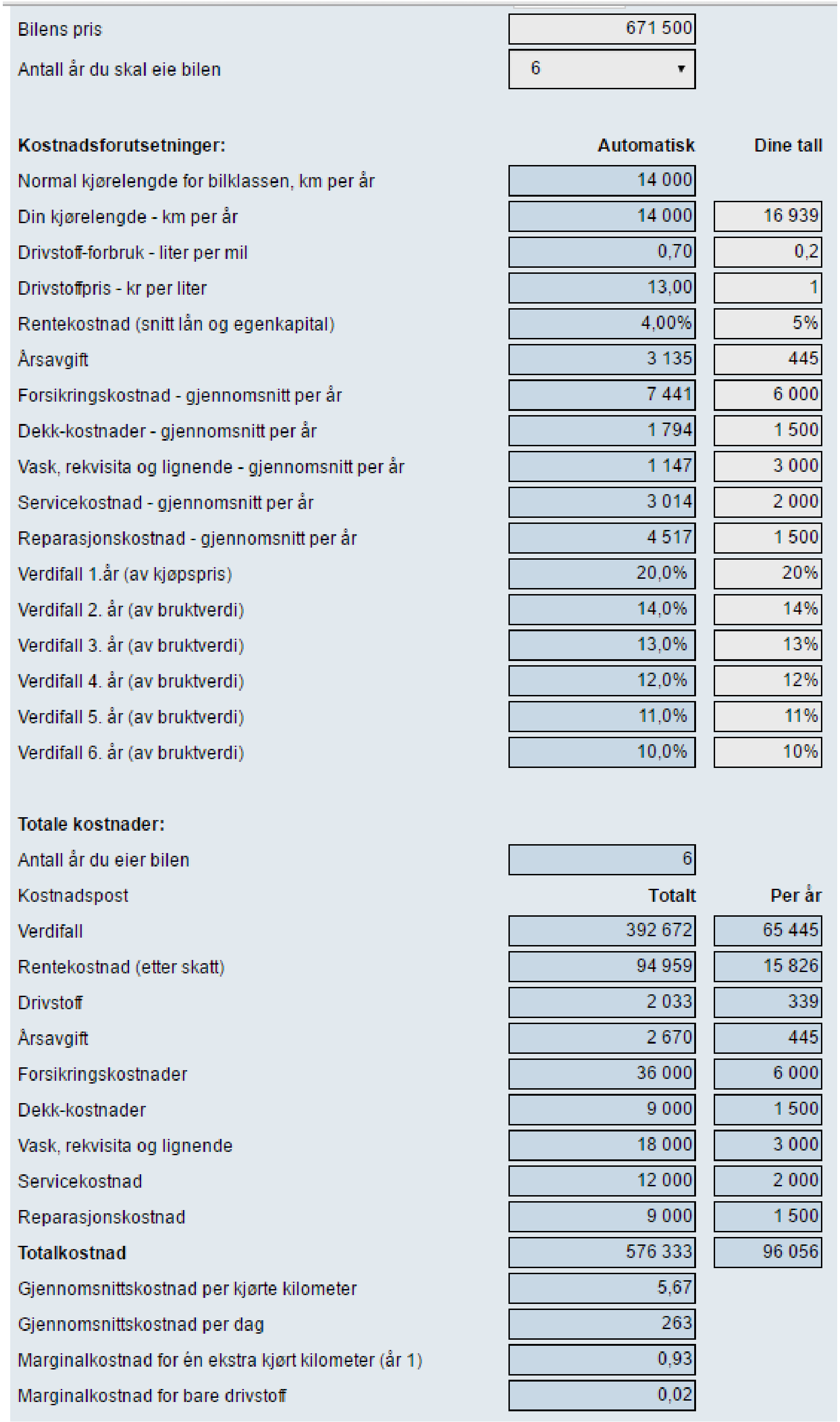
Bilens pris	192 000	
Antall år du skal eie bilen	6	

Kostnadsforutsetninger:	Automatisk	Dine tall
Normal kjørelengde for bilklassen, km per år	14 000	
Din kjørelengde - km per år	14 000	16 939
Drivstoff-forbruk - liter per mil	0,70	0,2
Drivstoffpris - kr per liter	13,00	1
Rentekostnad (snitt lån og egenkapital)	4,00%	5%
Årsavgift	3 135	445
Forsikringskostnad - gjennomsnitt per år	7 441	6 000
Dekk-kostnader - gjennomsnitt per år	1 794	1 500
Vask, rekvisita og lignende - gjennomsnitt per år	1 147	3 000
Servicekostnad - gjennomsnitt per år	3 014	2 000
Reparasjonskostnad - gjennomsnitt per år	4 517	1 500
Verdifall 1.år (av kjøpspris)	20,0%	20%
Verdifall 2. år (av bruktverdi)	14,0%	14%
Verdifall 3. år (av bruktverdi)	13,0%	13%
Verdifall 4. år (av bruktverdi)	12,0%	12%
Verdifall 5. år (av bruktverdi)	11,0%	11%
Verdifall 6. år (av bruktverdi)	10,0%	10%

Totale kostnader:		
Antall år du eier bilen	6	
Kostnadspost	**Totalt**	**Per år**
Verdifall	112 275	18 713
Rentekostnad (etter skatt)	27 151	4 525
Drivstoff	2 033	339
Årsavgift	2 670	445
Forsikringskostnader	36 000	6 000
Dekk-kostnader	9 000	1 500
Vask, rekvisita og lignende	18 000	3 000
Servicekostnad	12 000	2 000
Reparasjonskostnad	9 000	1 500
Totalkostnad	228 129	38 022
Gjennomsnittskostnad per kjørte kilometer	2,24	
Gjennomsnittskostnad per dag	104	
Marginalkostnad for én ekstra kjørt kilometer (år 1)	0,69	
Marginalkostnad for bare drivstoff	0,02	

Figure B.2: Cost calculations for Renault Zoe

(Smartepenger, 2016)



Bilens pris	671 500	
Antall år du skal eie bilen	6	
Kostnadsforutsetninger:	**Automatisk**	**Dine tall**
Normal kjørelengde for bilklassen, km per år	14 000	
Din kjørelengde - km per år	14 000	16 939
Drivstoff-forbruk - liter per mil	0,70	0,2
Drivstoffpris - kr per liter	13,00	1
Rentekostnad (snitt lån og egenkapital)	4,00%	5%
Årsavgift	3 135	445
Forsikringskostnad - gjennomsnitt per år	7 441	6 000
Dekk-kostnader - gjennomsnitt per år	1 794	1 500
Vask, rekvisita og lignende - gjennomsnitt per år	1 147	3 000
Servicekostnad - gjennomsnitt per år	3 014	2 000
Reparasjonskostnad - gjennomsnitt per år	4 517	1 500
Verdifall 1.år (av kjøpspris)	20,0%	20%
Verdifall 2. år (av bruktverdi)	14,0%	14%
Verdifall 3. år (av bruktverdi)	13,0%	13%
Verdifall 4. år (av bruktverdi)	12,0%	12%
Verdifall 5. år (av bruktverdi)	11,0%	11%
Verdifall 6. år (av bruktverdi)	10,0%	10%
Totale kostnader:		
Antall år du eier bilen	6	
Kostnadspost	**Totalt**	**Per år**
Verdifall	392 672	65 445
Rentekostnad (etter skatt)	94 959	15 826
Drivstoff	2 033	339
Årsavgift	2 670	445
Forsikringskostnader	36 000	6 000
Dekk-kostnader	9 000	1 500
Vask, rekvisita og lignende	18 000	3 000
Servicekostnad	12 000	2 000
Reparasjonskostnad	9 000	1 500
Totalkostnad	576 333	96 056
Gjennomsnittskostnad per kjørte kilometer	5,67	
Gjennomsnittskostnad per dag	263	
Marginalkostnad for én ekstra kjørt kilometer (år 1)	0,93	
Marginalkostnad for bare drivstoff	0,02	

Figure B.3: Cost calculations for Tesla (Smartepenger, 2016)

Appendix C Formulation of linear programming

Linear programming setup:

$$\min_{\mathbf{x}} z^t\mathbf{x}\ such\ that = \begin{cases} \mathbf{A} * \mathbf{x} \quad \leq \mathbf{b}, \\ \mathbf{Aeq} * \mathbf{x} \geq \mathbf{beq}, \\ \mathbf{lb} \leq \mathbf{x} \leq \mathbf{ub} \end{cases}$$

$\mathbf{A} = \begin{bmatrix} \mathbf{c3} & 0 \ldots 0 \\ -\mathbf{I}(200) & -\mathbf{I}(200) \\ \mathbf{I}(200) & -\mathbf{I}(200) \end{bmatrix}$	The coefficient matrix for the linear inequalities	(401 x 400)
Where $\mathbf{I}(200)$	is the identity matrix	(200 x 200)

$$\mathbf{b} = \begin{bmatrix} \big((1 - 0.05 * i) * c1\big) - c1 - c2 \\ -\mathbf{y}_{\mathbf{marg_0}} \\ \mathbf{y}_{\mathbf{marg_0}} \end{bmatrix}$$

|	The solution vector for the linear inequalities	(401 x 1)
$\mathbf{aeq} = [\mathbf{e}' \quad 0 \quad \ldots \quad 0]$	The coefficient vector for the linear equality	(1 x 400)
$beq = [1]$	The solution vector for the linear equality	(1 x 1)
$\mathbf{z} = [0 \quad \ldots \quad 0 \quad \mathbf{e}']$	The solution vector for the objective function	(1 x 400)
$\mathbf{lb} = zeros(400,1)$	Vector of lower bounds	
$\mathbf{ub} = ones(400,1) * 10;$	Vector of higher bounds	

$\mathbf{ub}\big(repmat\big(\mathbf{y}_{\mathbf{marg_0}}\big), 2,1\big) == 0) = 0;$ Set re-spending to zero for goods and services of no initial re-spending

For-loop to find x for each emission cap:

$for\ i = 1{:}\,20$

$\mathbf{b}(1,1) = \big((1 - 0.05 * i) * c1\big) - c1 + c2$

$\big[\mathbf{x}\big(:, (i+1)\big), zval(i+1)\big] = linprog(\mathbf{z}, \mathbf{A}, \mathbf{b}, \mathbf{aeq}, beq, \mathbf{lb}, \mathbf{ub});$

end

Where:

$zval$	Returns the value of the objective function for each emission cap (for each 5% reduction in emissions)
x	Returns the *x-vector* for each emission cap (for each 5% reduction in emissions

Appendix D Linear programming results

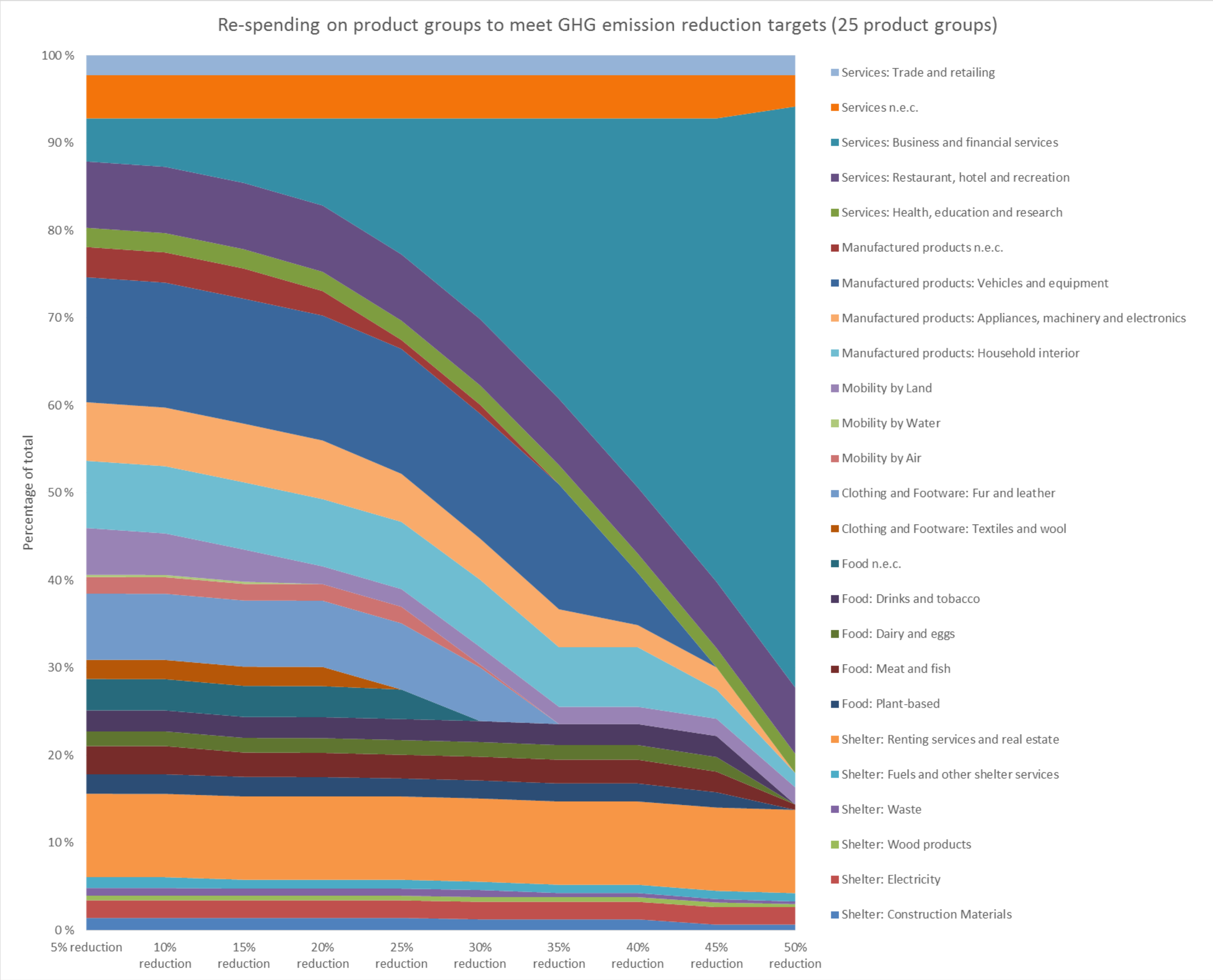


Table D.1: Detailed linear programming results for 25 product groups

Household actions	Behavioral Cost of implementing action (1-10)
Switch from standard gasoline vehicle to best-performing electric vehicle (Renault Zoe)	4
Switch from standard gasoline vehicle to Tesla	4
No trips by car under 3 km	5
Switch all daily car travel with bus transport	9
Car-pooling for work travel by car under 10 km using a hybrid car	9
Switch all daily car travel with with train transport	5
Walk Lerkendal - Trondheim S instead of taking the train (4.7 km each way)	6
One less return business flight Trondheim - Oslo per month (video-conference instead)	4
One less vacation to Bangkok, Thailand	7
Reducing indoor temperature by 1°C	3
Space and water heating	8
Appliances and other	7
Grenn Diet	8
Eliminating food waste	9
Organic Green diet	7
Other measures (organic, local, composting)	7
Eco-efficiency across suply chain	1
Design for durability	1
Market shift to higher proportion of synthetic fibres	2
Clean clothing less	5
Wash at lower temperature	2
Increase size of washing and drying loads	4
Use the tumble dryer less	5
Dispose less - reuse more	5
Start closed loop recycling of synthetic fibres	5
Dispose less - recycle more	3
Reduce clothing purchases by 20%	4
Average of changing 6 pieces of furniture	6
Increase lifetime of all products by 20% (e.g. through re-selling or longer lifetime)	5
Buy furniture with 20% recycled MDF (medium-density fibreboard)	3
Eliminating unsolicited mail	1
Reduced printing (printing management system, two-sided printing)	2
Reading e-papers and e-books instead of newspapers and books	5
Reducing plastic waste by 30%	5

Table D.2: Behavioral cost of implementing actions