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Climate change mitigation potential of Norwegian households and the rebound effect

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ABSTRACT

An increasing number of studies show that efficiency improvements alone will not be sufficient to attain the substantial emission reductions needed to mitigate global warming to a target of 2 °C. Consumption side changes are likely to be needed to achieve sufficient emission reductions. The United Nations emphasize the importance of developed countries taking the lead in lowering emissions to achieve the sustainable development goals. This paper assess to what extent Norwegian households can lower their carbon footprint consistent with territorial emission reductions towards the 2 °C target of global warming through implementing a set of behavioral actions. We evaluate the efficacy of the set of actions both initially and after considering rebound effects. A multiregional environmentally extended input-output database is linked with the Norwegian consumer expenditure survey to analyze both average and marginal expenditure per unit of increased income. Further, linear programming is applied to examine the changes needed by households to reach different emission reduction targets. We find that households implementing the full set of actions without re-spending can obtain a 58% decrease in their carbon footprint. When accounting for the effect of re-spending, this reduction drops to 24–35%, which is not within the requirements of the 2 °C target. The optimization analysis suggests households can achieve reductions up to 45% by restricting re-spending to specific goods and services. This indicates that curbing the rebound effect is key to achieving real reductions in household carbon footprints. We show that changing consumption patterns can significantly contribute to lowering anthropogenic greenhouse gas emissions without compromising the level of economic activity.

1. Introduction

The Intergovernmental Panel on Climate Change report of 2014 states that a 40–70% reduction in anthropogenic GHG emissions between 2010 and 2050 are needed to limit global warming to 2 °C above pre-industrial levels (Pachauri et al., 2014). The recent Paris Agreement calls for signatories to pursue efforts towards the even more ambitious goal of 1.5 °C to significantly reduce the risks and impacts of climate change. Recent studies show that it is becoming increasingly difficult to attain these goals through technical solutions alone (van Sluisveld et al., 2016). Historically, technological improvements have not outweighed the growth in impacts due to increased consumption (Wood, 2009). This underlines the need for a broader set of mitigation options, including on the consumption side (Davis and Caldeira, 2010).

A key challenge to limiting anthropogenic GHG emissions is to combine eco-efficiency on the production side with consumer efficiency on the consumption side (Throne-Holst et al., 2007). The 12. Sustainable development goal of the United Nations "ensure sustainable consumption and production patterns" makes the link explicit (United Nations, 2015). Optimal benefits are historically not achieved because the environmental gains from cleaner production (efficiency improvements and innovations) are offset by demand side aspects such as population growth and increased consumption and standards of living (Clark, 2007). Little agreement on strategies to approach sustainable consumption, such as focusing on eco-efficiency versus sufficiency measures and greening of markets versus awareness raising have further delayed progress in sustainable development (Mont and Plepys, 2008). Strategies to realize this potential includes "reasonable" consumption through changing consumption patterns complemented by "reasonable" production strategies (Kronenberg, 2007) and interfering more with consumer choices and markets, instead of a pure focus on greening

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Abbreviations

APP	Absolute purchasing power
CF	Carbon footprint
COICOP	Classification of Individual Consumption According to Purpose
GHG	Greenhouse gas
GWP	Global warming potential
ICEV	Internal combustion engine vehicle
IPCC	Intergovernmental Panel on Climate Change
MDF	Medium-density fiberboard
MPC	Marginal propensity to consume
MRIO	Multiregional input-output
NOK	Norwegian krone
pkm	Passenger-kilometer
RPP	Relative purchasing power
SCP	Sustainable consumption and production

production and products (Tukker et al., 2008).

Consumers have two options to reduce consumption-driven greenhouse gas (GHG) emissions. The first is to reduce overall consumption, which several studies find to be an important step in climate change mitigation (Garnaut, 2008; Ivanova et al., 2016; Stern, 2007), but which often has negative effects on economic growth (Silva Simas et al., 2017). The second option is to shift the pattern of consumption towards goods and services that are less GHG emission intensive (Throne-Holst et al., 2007). Some studies find that the contribution to climate mitigation of such changes in consumption patterns can be significant. Gardner and Stern (2008) found energy savings in the range of 30–58% studying the impacts of lifestyle change. Druckman and Jackson (2010) report 37% lower GHG emissions in a reduced consumption scenario, while Alfredsson (2004) found a 30% reduction in CO_2 by adopting a “green” consumption pattern.

However, it is often not realistic to consider lifestyle changes without regarding impacts on the household budget. If households for example reduce their car travel to lower their environmental impact, this will both reduce costs and GHG emissions. However, rebounds occur when consumers *re-spend*[1] this saved money from driving less on a vacation by airplane to a faraway destination. This produces additional GHG emissions that offset the initial emission reductions. This mechanism is known as the rebound effect, first described by Jevons (1866) and later by Saunders (1992) and the Khazzoom-Brookes Postulate which states that increased energy efficiency leads to increased energy consumption. The rebound effect has been seen in practice in car-free households in Vienna (Ornetzeder et al., 2008).

Rebound effects can arise either from efficiency improvements that make a good or service cheaper or from changing the pattern of consumption leading to lower costs, known as sufficiency strategies. There are three main types of rebound effects; direct (re-spending on the same good or service as the one where money is saved), indirect (re-spending on other goods and services) and various macroeconomic effects (how the effect of the efficiency improvement or changed consumption distributes throughout the economy) (Greening et al., 2000).

Since Jevons (1866), researchers have known that efficiency improvements are subject to rebound effects. However, recent studies have shown that sufficiency strategies also are subject to rebound effects (Figge et al., 2014). In the discussions of a transition to a circular economy, overcoming rebound effects of efficiency and sufficiency strategies is pointed out as a key challenge (Ghisellini et al., 2016). If rebound effects are not overcome, the last resort is to reduce economic activity on the macro level (Figge et al., 2014).

Previous rebound effect studies often analyze the impacts of one or a few behavioral actions, rather than lifestyle changes. Grabs (2015) found GHG emission rebound effects of 49% from changing to a vegetarian diet. Briceno et al. (2005) found indirect rebound effects of 42–49% from car-sharing schemes. Chitnis et al. (2013) found direct and indirect rebound effects in the range of 5–15% from energy efficiency improvements by UK households. Font Vivanco et al. (2014) found rebound effects in the range of 3–5% when changing from a conventional car to a plug-in hybrid electric passenger car. Chitnis and Sorrell (2015) found combined direct and indirect rebound effects of energy efficiency improvements by UK households to be 41%, 48% and 78% for measures involving domestic gas use, electricity use and vehicle fuel use respectively.

Studies on rebound effects from complete lifestyle changes are less common. Chitnis et al. (2014) found combined direct and indirect rebound effects of 15–35% for different combinations of household actions. Rebound effects were lowest for measures affecting domestic energy use and largest for reducing food waste. Druckman et al. (2011) found combined indirect and direct rebound effects from three efficiency measures to be 34%, which dropped to 12% when restricting re-spending to goods and services with low GHG intensities. Alfredsson (2004) found CO_2 rebound effects of 238% for “green” food consumption, 12% for “green” travel and 19% for “green” housing. An overall “green” consumption pattern resulted in 14% rebound using a “green” re-spending scenario. Murray (2013) found effects in the range of 9–12% for combined sufficiency measures concerning vehicle fuel and household electricity.

This paper investigates consumption side changes as a complementary strategy to efforts to decarbonize the production side to achieve sufficient emission reductions. We assess to what extent households can contribute to CF (carbon footprint) reductions on the scale of what is needed to keep to the 2 °C target of global warming. The 2 °C target is translated to a required per-capita emissions reduction of 40% for Norway (Norwegian Ministry of Climate and Environment, 2015). An equivalent per-capita reduction from the consumption side is then taken (to cover the fact that a large proportion of Norway's CF is embodied in imports). A set of actions is suggested that reduce GHG emissions in line with this target. Only consumption side changes are considered here, whereas (as discussed above), these will need to complement production side changes. We build on existing work as well as novel linear programming approaches to develop a framework to investigate rebound effects of different scenarios of fully re-spending the savings (Section 2). We explore differences between average and marginal spending patterns, as well as a constrained “green” spending pattern. We then calculate the possible reduction in household CF when including rebound effects and relate results to methodological choices of the analysis (Sections 3 and 4), before concluding and assessing the implications of the results in the final section.

2. Methods

2.1. Norwegian carbon footprints

The CF is calculated using the input-output framework developed by Wassily Leontief in the 1930s (Leontief, 1936). A basic

[1] Full *re-spending* in this paper relates to first implementing a behavior that saves money, and then spending an equivalent amount of money on one or several alternative goods or services.

input-output model consists of a system of linear equations, where each equation describes the distribution of an industry's product throughout the economy. It considers flows of products from industrial sectors (producers) to other sectors (consumers), and thus describes the composition of inputs required by a particular industry to produce its output (Miller and Blair, 2009). For a derivation of the input-output framework, see S2. The framework has been applied extensively to looking at CFs of domestic consumers (Wood and Dey, 2009).

Total (direct + indirect) emissions per unit of expenditure, called emission multipliers, were obtained using the multiregional environmentally extended input-output database EXIOBASEv2, which includes information on 48 regions and 200 products for the reference year 2007 (Wood et al., 2015). The database provides high detail on greenhouse gas emission intensive products (Wood et al., 2014). All major forms of greenhouse gas emissions (CO_2, CH_4, N_2O and SF_6 using IPCC emission factors (Solomon et al., 2007)) are included. EXIOBASE provides emission estimates for each sector in each region as well as for direct emissions by households. The number of Norwegian households was obtained from Statistics Norway (2014).

In this work we further utilize spending pattern data by consumer group from the Norwegian Consumer Expenditure Survey of 2012 (Statistics Norway, 2013). Both handling of under-reporting and conversion of the data from COICOP (Classification of Individual Consumption According to Purpose) classification to the EXIOBASEv2 classification and pricing was dealt with using the framework of Steen-Olsen et al. (2016).

2.2. Cost and emission savings of household actions

After screening the Norwegian household CF, we assess the GHG reduction potential and the direct economic impacts of 34 household actions. The base scenario is the average Norwegian household's current pattern of consumption. A literature survey is used to obtain the needed data on each action in sufficient detail. GHG emissions and direct economic impacts of the actions are calculated by comparing a current type of consumption behavior to an environmentally better performing alternative, before scaling up to yearly savings per household. Where the literature presents relative savings from actions, absolute savings are calculated based on the current average consumption in EXIOBASEv2. The 34 actions are distributed among seven sectors of household consumption: transport, shelter, food, clothing, furniture, paper and plastic (see S1 for detailed calculations and data sources). Consumer price indices and exchange rate data (Statistics Norway, 2015) are used to convert to 2007 costs in Norwegian *kroner*[2] (NOK), and further to basic prices for later connection to the input-output modelling in the rebound framework (S2 and Section 2.4).

2.3. Adjusting for double counting

Since some of the actions cover the same household activities, the degree to which actions overlap must be evaluated to determine the cumulative effects of implementing several actions simultaneously. This potential double counting is accounted for by introducing an actions-activity matrix (S3). In this matrix, we for example distribute travels within a specific distance range among six transport modes to cover the total yearly distance traveled. Net savings in emissions and costs are multiplied by the number of units available for each activity to obtain the total cost and emission reduction structure of that combination of actions. The actions-activity matrix serves as the basis for further calculations, but it enables several other scenarios.

2.4. Rebound effect framework

The rebound effect framework builds on the assessment of the Norwegian household footprint, but integrates the household actions and the rebound effects. We look purely at Norwegian consumption irrespective of region of origin by aggregating across exporting regions and dividing by product level expenditure to give weighted emission multipliers per unit demand for the 200 products detailed in EXIOBASE (see S2 in supporting information).

The relative environmental rebound effect (Druckman et al., 2011) is defined as:

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

A redefinition of this is:
Δh = Expected reduction in GHG emissions.
Δg = GHG emissions associated with re-spending.
This gives the actual emission reduction: $\Delta h - \Delta g$.
The rebound effect (re) is then

$$\mathrm{re} = \frac{\Delta h - (\Delta h - \Delta g)}{\Delta h} = \frac{\Delta g}{\Delta h} \tag{1}$$

where Δh is determined based on literature findings (S1 and Section 2.2).

For Δg direct emissions from households (f_{hh}) are added to the weighted multiregional emission multipliers for Norwegian consumption from EXIOBASEv2 (see S2 in supporting information) to give emission multipliers m_{tot} that include both direct and indirect emissions per unit of expenditure.

Full re-spending of the saved money according to different scenarios (y_{re}) is then:

$$y_{re} = \sum_{1}^{34} (y_{sav} * B * q) * y_{sp} \tag{2}$$

y_{sav} is the direct financial savings from the 34 actions not adjusted for double counting.B is the matrix adjusting for double counting.q is the vector of total number of units per action.y_{sp} is the scenario of re-spending.

Re-added GHG emissions (Δg) due to re-spending are then given as:

$$\Delta g = m_{tot} * y_{re} \tag{3}$$

Finally, Δg from Eq. (3) is inserted into Eq. (1) to calculate the rebound effect

$$\mathrm{re} = \frac{\Delta g}{\Delta h} = \frac{m_{tot} * y_{re}}{\Delta h} \tag{4}$$

2.5. Spending patterns

After finding rebound effects using the framework above, the next step is to look into the development of the re-spending scenarios (y_{re}) to assess the impact of re-spending on rebound effects. We examine three scenarios: average, marginal and green re-spending. While the average and marginal approaches are common in the literature, the green scenario is developed for this study.

[2] In 2007, 1 € was equivalent to around 8.02 NOK.

2.5.1. Average

The average spending pattern is the shares of total consumption for each product group converted to the EXIOBASE classification. All savings are re-spent across products in the same proportions as the current average household expenditure.

2.5.2. Marginal

In the marginal scenario, it is assumed that households change their spending pattern towards that of higher income groups as income increases.

There are multiple approaches to calculating marginal spending patterns (Font Vivanco et al., 2014). Our approach builds on Thiesen et al. (2008) who comparted consumption patterns across income brackets using cross-sectional data. We obtain detailed data on household consumption patterns (COICOP Level 2 classification) broken down into six income brackets consisting of income deciles 1, 2-3, 4-5, 6-7, 8-9, and 10 (Statistics Norway, 2013). This is used to calculate a weighted average distribution of an incremental increase in income.

The marginal propensity to consume (MPC) from one income group to the adjacent one is found as:

$$\mathrm{MPC}_{n,i} = \frac{\partial \mathrm{Q}_i}{\partial \mathrm{i}} = \frac{\mathrm{Q}_{i_{n+1}} - \mathrm{Q}_{i_n}}{\mathrm{i}_{n+1} - \mathrm{i}_n} \tag{5}$$

In Eq. (5), i_n is the average income of income group n, while Q_i is demand for product group i. This gives the marginal propensity to consume product i when moving from income group n to income group $n+1$.

Next, the relative purchasing power of each of the six income groups is calculated:

$$\mathrm{rpp}_n = \frac{\mathrm{app}_n}{\sum_{i=1}^{6} \mathrm{app}_i} \tag{6}$$

app_n is the absolute purchasing power of income group n.rpp_n is the relative purchasing power of income group n.

The weighted relative purchasing power (rppw_n) when moving from one income group to the adjacent one is then:

$$\mathrm{rppw}_n = 0.5{*}\mathrm{rpp}_n + 0.5{*}\mathrm{rpp}_{n+1} \tag{7}$$

Eq. (7) is used for all income groups, except the lowest and highest which are assigned a weighting factor of one as these income groups are counted only once.

Finally, the marginal spending pattern is given as:

$$\mathrm{msp}_i = \sum_{i=1}^{5} (\mathrm{MPC}_{n,i}{*}\mathrm{rppw}_n) \tag{8}$$

where msp_i is the marginal spending on product group i.

2.5.3. Green

We further develop the green spending pattern based on the marginal spending pattern. The idea is that environmentally aware households avoid re-spending on goods and services with high emission multipliers. Selected goods and services eliminated from additional spending in this pattern have a combination of large GHG intensity and a large share of total consumption (selected commodities in S4). Shares of the deducted product groups are reallocated to the remaining groups as:

$$\mathrm{a}_{i_G} = \mathrm{a}_{i_M} + \left(\frac{\mathrm{a}_{i_M}}{1 - \sum_{j=1}^{d} \mathrm{a}_{j_M}}\right) {*} \sum_{j=1}^{d} \mathrm{a}_{j_M} \tag{9}$$

a_{i_G} is the relative share of product i in the green consumption vector. a_{i_M} is the relative share of product i in the marginal consumption vector. a_{j_M} is the relative share of product j (deducted product) in the marginal consumption vector. d *is the* number of deducted product groups.

2.6. Optimizing pattern of re-spending

We introduce optimization methods in the analysis to investigate the potential of altering the pattern of re-spending. This enables studying the degree to which households must adapt their re-spending to achieve different reductions in their CF. Linear programming finds 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. Several multiregional input-output (MRIO) studies within the input-output field use linear programming techniques, but usually employed for choice of technology. Examples are the World Trade Model that determines world prices, scarcity rents, and international trade flows based on comparative advantage in a world economy, described in Duchin (2005) and further developed to include bilateral trade in Hammer Strømman and Duchin (2006). The World Trade Model with Bilateral Trade builds on the logic of comparative advantage (Duchin and Levine, 2015). This often leads to complete specialization in production as the optimal solution, which is considered an important limitation of linear programming (Ten Raa and Shestalova, 2015).

In comparison to that work, we are interested in seeing whether it is possible to look at linear programming from a consumption basis. Whilst earlier works study possibilities for alternate technologies, or substitution at the industry level, this analysis is purely limited to what households can do in terms of spending patterns. As such, we are interested in what mixture of spending will yield optimal environmental effects. Whilst the realization of an «optimal spending pattern» is subject to many constraints about basic versus discretionary spending, as well as localized requirements by households, the goal is to use linear programming to inform the scale and rate of possible change. In the setup of the linear program (S6.1), we start with the marginal re-spending scenario as a default and then impose stepwise restrictions on the minimum overall CF savings tolerated. The objective function is set to minimize the change in re-spending compared to the default.

3. Results

To identify areas of large potential reductions in the CF of the average Norwegian household, we look into updating the work of Steen-Olsen et al. (2016) who ranked the goods and services according to largest consumption share, GHG emissions, and emission multipliers. Consumption data is from the Norwegian Consumer Survey of 2012 (Statistics Norway, 2013), while emission multipliers and GHG emissions are calculated by Steen-Olsen et al. (2016).

Several of the consumption groups with the highest emission multipliers include fuel or passenger transport consumption. A combination of high emission multiplier and large share of total consumption results in a large CF. However, some consumption with relative high expenditure shares have lower than expected CFs. An example is electricity that accounts for 3% of total spending, but is not included in the top 10 CF groups. This is likely due to a low

Table 1
Top 10 products groups by emission multipliers, total spending and carbon footprint for Norwegian household consumption.

Top 10 emission multipliers COICOP level 3 (2007)	
Product Group	Top 10 emission multipliers (gCO_{2}-eq/NOK)
0734 Passenger transport by sea and inland waterway	486
0722 Fuels and lubricants for personal transport equipment	333
0453 Liquid fuels	223
0454 Solid fuels	161
0733 Passenger transport by air	118
0611 Pharmaceutical products	113
0613 Therapeutic appliances and equipment	95
0713 Bicycles	95
0612 Other medical products	90
0431 Materials for the maintenance and repair of the dwelling	87
Top 10 household spending COICOP level 3 (2007)	
Product Group	**Percent of total**
0421 Imputed rentals of owner-occupiers	12%
0711 Motor Cars	8%
0431 Materials for the maintenance and repair of the dwelling	4%
0312 Garments	4%
0451 Electricity	3%
0722 Fuels and lubricants for personal transport equipment	3%
1111 Restaurants, cafés and the like	2%
0112 Meat	2%
0411 Actual rentals paid by tenants	2%
0511 Furniture and furnishings	2%
Top 10 CF COICOP level 3 (2007)	
Product Group	**Percent of total**
0722 Fuels and lubricants for personal transport equipment	19%
0711 Motor Cars	8%
0431 Materials for the maintenance and repair of the dwelling	7%
0421 Imputed rentals of owner-occupiers	5%
0312 Garments	3%
0960 Package holidays	2%
0734 Passenger transport by sea and inland waterway	2%
0112 Meat	2%
0511 Furniture and furnishings	2%
0611 Pharmaceutical products	2%

emission multiplier, since electricity consumed in Norway is largely hydropower-based.

3.1. Household actions

Table 2 shows the 34 actions chosen to reduce the household CF, as well as corresponding GHG emission and cost savings potential from implementing each action individually (for calculations see S1). In Table 2 savings are shown for actions individually, disregarding potential double counting issues.

Comparing Table 2 with Table 1, several interesting trends appear. Large CF reductions for the transport actions are as expected based on large consumption shares and large emission multipliers for transport related consumption. Food and shelter actions also result in large CF reductions, but the reduction potential of shelter actions is more a result of large share of total expenditure than that of the food actions. Garments have in Table 1 the fifth highest CF. However, most of the clothing actions do not contribute to large CF reductions, indicating that the CF of garments is a result of a high household budget share. Reducing business flights (one per month) results in the largest cost reduction, however it ranks fourth in largest GHG emission savings.

3.2. Spending patterns

Comparing the three approaches to calculating spending patterns (Table 3) indicates how Norwegian households spend money when income rises (average to marginal) and how households who which to lower their CF could spend their money (marginal/average to green).

The decrease in spending on particularly shelter (category 04) and the increase in transport (category 07) from the average to the marginal scenario indicates a low and a high income elasticity of demand respectively for these consumption groups. The large shares on miscellaneous goods and services and food in the green scenario are due to constraining re-expenditure on products within the other more environmentally impacting categories. The miscellaneous goods and services category contains amongst others insurance, financial services, personal care and social protection (United Nations Statistics Division, 2016).

3.3. Rebound effects for individual actions

The GHG emission savings including rebound effect in absolute values (Table 2) are given as $((1 - \% \, re)*original \; GHG \; savings)$. The green spending pattern achieves the best results in reducing GHG emissions when including rebound. Actions with negative rebound effects are a result of a cost increase of implementing the action. Hertwich (2005) calls this a spillover of environmental behavior, where environmentally aware households implement other types of beneficial behavior, such as spending additional income on more expensive organic food. Actions that backfire (over 100% rebound) do so because of a high ratio of saved expenditures to reduced emissions. However, these in general have low initial GHG emission savings, resulting in small effects in absolute terms.

The set of actions includes both demand shifts (e.g. buying an

Table 2
Household actions with according GHG emission and financial savings from implementing each action individually including rebound effects of different spending pattern scenarios (discussed in Section 3.3).

Household Actions	Savings in NOK (2007 Prices)	GHG savings (kg CO_2-eq)	Rebound Effects		
			Marginal	Average	Green
Switch to budget electric car	32,885	3685	62%	48%	42%
Switch to top of the line electric car	−23,233	2760	−58%	−45%	−40%
No trips by car under 3 km	688	150	32%	25%	22%
Only bus transport	14,312	4863	20%	16%	14%
Car-pooling for work under 10 km	474	103	32%	25%	22%
Only train transport	14,312	4973	20%	15%	14%
Walk instead of train (9.4 km)	12,030	183	456%	353%	311%
Reduce business flights (one per month)	71,344	3112	159%	123%	108%
Eliminate long-distance flight for vacation	8202	2629	22%	17%	15%
Reducing indoor temperature by 1 °C	472	92	35%	27%	24%
Space and water heating	920	1333	5%	4%	3%
Appliances and other	−843	174	−34%	−26%	−23%
Green Diet	11,853	1854	38%	29%	26%
Eliminating food waste	17,384	1020	100%	78%	68%
Organic Green diet	−23,706	2039	−68%	−53%	−47%
Other measures (organic, local, composting)	−15,804	695	−134%	−103%	−91%
Eco-efficiency across supply chain	0	57	0%	0%	0%
Design for durability	−1649	107	−90%	−70%	−62%
Market shift to more synthetic fibers	330	6	348%	269%	237%
Clean clothing less	660	36	107%	83%	73%
Wash at lower temperature	660	20	199%	154%	136%
Increase size of washing and drying loads	330	20	99%	77%	68%
Use the tumble dryer less	660	15	253%	196%	173%
Dispose less - reuse more	989	10	597%	461%	407%
Start closed loop recycling of synthetic fibers	0	13	0%	0%	0%
Dispose less - recycle more	0	7	0%	0%	0%
Reduce clothing purchases by 20%	6597	279	139%	108%	95%
Average of changing 6 pieces of furniture	−3070	96	−223%	−172%	−152%
Increase lifetime by 20%	2333	116	119%	92%	81%
Buy furniture with 20% recycled MDF	−1166	73	−94%	−73%	−64%
Eliminating unsolicited mail	0	39	0%	0%	0%
Reduced printing	246	17	104%	80%	71%
e-papers and e-books	1970	26	525%	405%	358%
Reducing plastic waste by 30%	191	14	95%	73%	65%

Table 3
Comparing spending patterns (COICOP Level 1 classification).

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

electric car) and reduced consumption (e.g. reducing indoor temperature by 1 °C). The aim is to exclude technological improvements not currently available to the consumer. Possible exceptions to this are some actions within the clothing sector that require changes on the production side, such as eco-efficiency across the supply chain.

3.4. Cumulative rebound effects

Relative and absolute CF reductions for the three re-spending scenarios are found using the actions-activity matrix that adjusts for double counting (Table 4).

Transport, shelter and food actions result in the largest CF reductions. Implementing the combined transport actions have large rebound in all re-spending scenarios because of large financial cost reductions. There is no rebound of the combined shelter actions, since financial costs add to close to zero. CF reductions of the furniture actions are enhanced since these come with a cost increase.

The decrease in CF reduction from before re-spending (58%) to after re-spending (24–35%) underlines the importance of including rebound effects. The goal of reducing anthropogenic GHG

Table 4
Sectoral and total rebound results and GHG emission savings including rebound adjusted for double counting.

Household Actions	Original GHG savings (kg CO_2-eq)	Rebound effect in percent		
		Marginal	Average	Green
Transport	9847	83%	64%	57%
Shelter	1383	0%	0%	0%
Food	3587	16%	13%	11%
Clothing	569	89%	69%	61%
Furniture	284	−51%	−39%	−35%
Paper	81	190%	147%	129%
Plastic	14	95%	73%	65%
Total of all actions combined	**15,766**	**59%**	**46%**	**40%**
Original CF of households	**27,170**			
Reduction in CF	**58%**	**24%**	**32%**	**35%**

emissions by 40% (10.9 tons CO_2-eq per household) is not achieved with this set of actions when including rebound effects. However, households can achieve further reductions through changing, adding or eliminating actions. Such scenarios can be explored by using optimization approaches.

3.5. Optimization of re-spending

In the final part of the assessment, we use linear programming to explore how the rebound effect can be reduced through changes in re-spending patterns. We impose stepwise restrictions on the minimum overall CF savings tolerated, starting from the default marginal re-spending pattern (24% overall CF reduction) and moving towards the theoretical maximum (58% reduction, equal to no re-spending) (Fig. 1). The objective is to achieve specific emission reductions while minimizing the change in the consumption pattern. Whilst linear programming approaches give only indicative results, as determined by the extent of the constraints applied, they do allow for visualizing the scale of change required.

The results show that households can achieve up to 35–45% CF reductions with moderate changes in their pattern of re-spending. Strict re-spending on goods and services with low GHG intensities for reductions above 35–45% makes the practical implementation of this re-spending questionable. This is seen by the rapid increase in the change in pattern of consumption for reduction targets over 40% (S6.4). The total financial savings is about 150,000 NOK, or about 35% of total expenditures (Statistics Norway, 2013). Although requiring careful re-spending considerations, changing only 35% of total expenditure seems feasible.

The increased re-spending on “Housing, water, electricity, gas, and other fuels” for large CF reductions is different from the green spending pattern (Table 3) that showed an increase in consumption on “Miscellaneous goods and services” and a decrease in “Housing, water, electricity, gas, and other fuels”. However, since the linear program's objective is to minimize change in consumption compared to the marginal scenario, consumption will not simply move towards consumption groups with the lowest emission multipliers. Instead, it will choose consumption groups with a combination of large consumption shares and low emission multipliers. A disaggregation into 25 consumption groups reveals a heavy move towards “Shelter: Electricity” for larger CF reductions (S6.3), which could be considered an anomaly for Norway in the international context because of the low-carbon electricity mix. The emission multiplier of electricity by hydro is actually the fourth lowest of all 200 product groups for final consumption expenditure by Norwegian households in EXIOBASEv2 (S7). A second analysis available in the SI, that excludes the impact of margins on different products, instead shows a shift to services rather than electricity (S6.5). The message is the same however – there are radical shifts in consumption patterns at around 40% reduction.

4. Discussion

Most of the scenarios in this paper show CF reductions that are not within the minimum 40% reduction in anthropogenic GHG emissions needed to stay within the 2 °C target of global warming. Only scenarios of moderate to large changes in household consumption show CF reductions above this. However, the potential reductions are larger when including future efficiency improvements in production and optimal collaboration between producers, consumers and policy makers. It is also important to consider that the household CF tells only part of the story on the demand side. Similar large reductions in emissions related to government and capital consumption are also required.

4.1. Re-spending

Further CF reductions can be achieved by relaxing the constraint of total re-expenditure and including technological improvements. Considering less than total re-spending could have negative effects on economic growth through deferred or reduced overall consumption. Deferred consumption have potential negative short-term consequences, while reduced overall consumption can of course, lead to recession or “de-growth”. The implications of this is not considered in the scope of this work.

The green re-spending scenario does not consider whether the goods and services eliminated from re-spending are basic or discretionary. Purchasing an electric car might for example 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 affects only 35% of total household expenditure.

4.2. Rebound effects

The large number of actions should indicate that the rebound effects of 40–59% are less sensitive to changing, eliminating, or adding actions. These results are, however, generally higher than those found in other similar studies. Druckman et al. (2011) found effects of 12–34%. However, in the 12% scenario all re-spending was in the least GHG intensive category. This is a stricter re-spending than the green re-spending scenario. Of other similar studies, Alfredsson (2004) found rebound effects of 14% for an average re-spending scenario, Murray (2013) found effects of 12–14% for a marginal re-spending scenario, while Chitnis et al. (2014) found effects of 15% from combined efficiency measures and 35% from

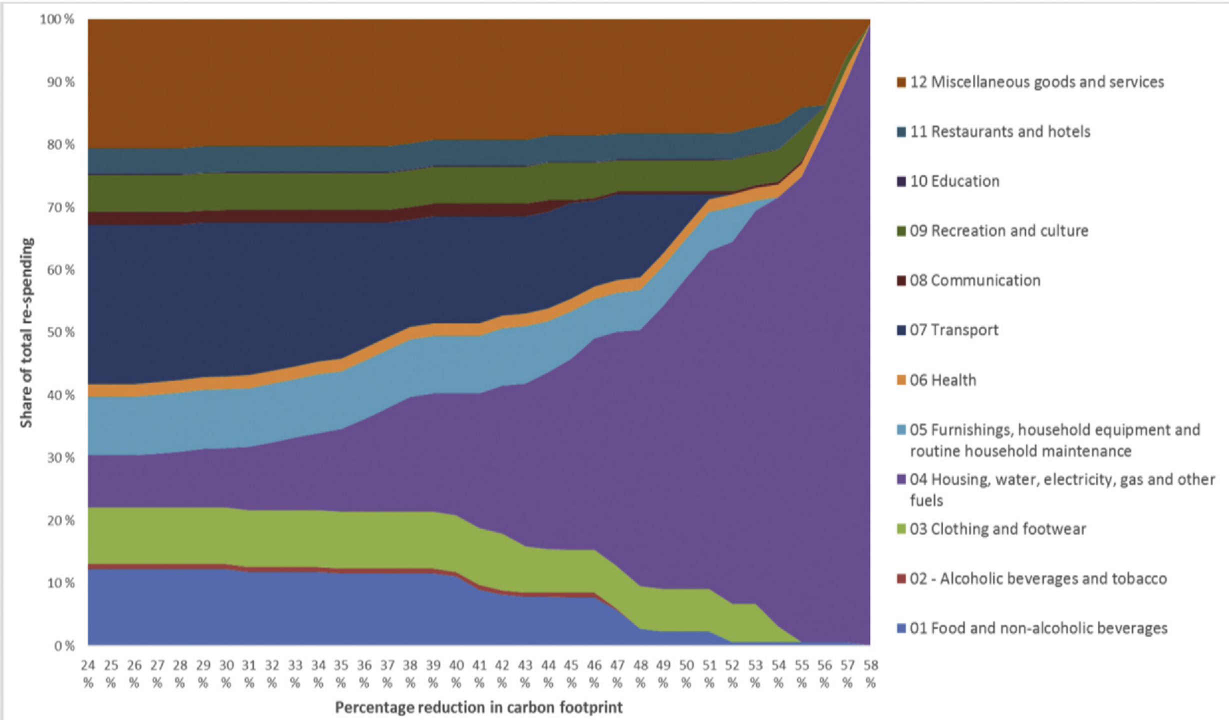

Fig. 1. Pattern of re-spending for different CF reduction targets (COICOP level 1).

combined sufficiency measures. However, in these three studies households implement only a handful of actions, making rebound results dependent on the choice of actions. Our results are however comparable to those in Freire-González (2011) with rebound effects of 56–65%, but that study only looks at rebound effects from energy efficiency improvements in the use of energy in the household.

Rebound effects are primarily indirect as the scenarios include re-spending across most goods and services. However, as re-spending on the same good or service as that of the behavioral action is included, a small portion of the total is direct rebound. Disaggregating types of rebound effects is outside the scope of this study.

Considering the validity of the different re-spending scenarios is important. The large cost decrease of 150,000 NOK from the current lifestyle change, justifies the use of the marginal pattern of re-spending. If households continue on a similar consumption pattern as before the lifestyle change, the average re-spending could be a good choice. However, assuming that households take CF considerations into their choice of re-spending, the green re-spending scenario is plausible.

Large-scale implementation of the suggested lifestyle change can drive production side changes through shifting demand. This potential demand-shift needs attention (Alcott, 2008). The idea behind restricting the analysis to consumption side changes is not to ignore the modifications on the production side, but rather to allow household changes to drive production side changes that generate further GHG emission reductions.

4.3. Optimization

Electricity by hydro had an unrealistically large share of re-spending found in the optimization results. The focus should rather be to re-spend saved money on goods and services that are both fulfilling and have low emission multipliers. Consumption groups that could provide both environmental and personal benefits include education services, printed matter, and recorded media, as well as recreational, cultural, and sporting services.

Under the assumption of stable or even increased consumption levels, households should focus their re-spending on higher quality goods and services, such as organic food or durable electronic products to curb the rebound effect as these goods have low emission multipliers.

4.4. Limitations and uncertainties

Practical difficulties in implementing the suggested lifestyle change because of considerations like infrastructure, urban versus rural area and access to appliances and products (e.g. organic food or special types of furniture) are likely. This is particularly relevant for actions requiring access to specific transport modes. As such, the current setup fits a scenario of multiple households implementing the actions, as relatively low shares are assigned to bus and train transport for the travel distances.

One return business flight per month per person at a first glance seems overestimated. However, it should rather be interpreted as an example of how frequent flying affects the household CF. The flight distance used for this action is rather short, so one or several long-distance flights within a year are comparable to the GHG emissions and costs associated with multiple return business flights. In Norway, air transport now accounts for almost half of all work related travels (Denstadli and Rideng, 2012). Exact data on air transport per person in Norway were scarce, but Denstadli and Rideng (2012) suggest Norwegians travel 0.4 trips per person by plane per month.

The optimization approach is highly stylistic in changing the pattern of re-spending to reduce the household CF, and does not consider household intuition of the GHG intensities of goods and services. The objective of minimizing absolute change in consumption pattern compared to the marginal scenario is quite abstract. Further research could focus on measures that are more intuitive, such as the behavioral costs associated with achieving GHG emission reduction targets.

The purpose of the actions-activity matrix is to account for double counting; however, complete elimination is unlikely. Double counting related to the transport actions involving daily travel is accounted for by setting a limit to the total distance travelled within each distance range. Other actions are however, more entangled. Eliminating food waste for example depends on the diet choice. Here, the original scenario is used as a reference, but the food waste will depend on the choice of diet. Buying furniture with 20% recycled MDF (medium-density fiberboard) follows a similar argument as it depends on the type and lifetime of the furniture. Some actions in the clothing sector, and reading e-newspapers and e-books are linked to the mitigation potential of “appliances and others”. However, we believe that these instances of double counting should not change the results significantly.

5. Conclusion

This study examines the potential CF reduction of changing household consumption. We propose an ambitious lifestyle change consisting of 34 behavioral actions and investigate to what extent the average Norwegian household can achieve sufficient reductions in their CF in line with a 2 °C target of global warming, and what impact rebound effects will have. Implementing the lifestyle change would imply considerable behavioral changes, but most of these also equate to substantial financial savings. Under the assumption that total expenditure levels stay unchanged, how households re-spend these savings is crucial to the overall CF reduction. The analysis includes the common average and marginal scenarios of re-spending, implementing a green re-spending scenario, as well as finding required re-spending to meet different reduction scenarios using linear programming. An initial reduction of 58% in household CF dropped to 24–35% for the re-spending scenarios when including rebound effects. To lower the rebound effect, households should eliminate re-spending on goods and services with high GHG intensities. Given the importance of the pattern of re-spending, the linear programming approach shows that CF reductions of 35–45% can be achievable without massive changes in expenditure habits. Particularly, households should curtail re-spending on goods and services associated with fossil fuel use, such as mobility, and production processes demanding heavy use of resources, such as clothing and certain manufactured products. For emission reductions within the 40% official reduction target of the Norwegian government by 2030, re-spending must largely shift towards services associated with a low GHG intensity.

If we are to limit global warming to the 2 °C target, action is needed now rather than later. We should not rely entirely on future technology improvements to do the job, but complement them with changes on the consumption side. To acquire sufficient CF reductions before re-spending, changes are not limited to consumption of products associated with high GHG intensity per unit of expenditure. Since the ratio of the average GHG intensity associated with the lifestyle change compared to that of the re-spending determines the rebound effect, a comprehensive consumption change will necessarily result in larger absolute rebound than small changes. The rebound results in this study are therefore large compared to other similar studies.

Ignoring the rebound effect is equivalent to assuming decreased total expenditure, which could severely compromise economic activity. This calls for a larger focus on rebound effects and factors that determine re-spending in discussions on sustainable development and the transition to a circular economy.

Further research on the willingness and behavioral costs of implementing different actions that reduce CF could provide understanding of the best ways to reduce CF on the consumption side. Studying the effect of investment instead of total re-spending can give useful insight to ways of curtailing the rebound effect.

Large-scale implementation of the set of actions can drive production changes through shifting demand towards goods and services associated with low GHG intensities. The production side can respond to this demand shift by production of environmentally better performing products, leading to further emission reductions. Further studies on how lifestyle changes and production side changes can benefit from influencing each other to lower GHG emissions will offer increased understanding on how to achieve the emission reductions needed to reach the 2 °C target of global warming.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2017.10.089.

References

Alcott, B., 2008. The sufficiency strategy: would rich-world frugality lower environmental impact? Ecol. Econ. 64, 770–786.
Alfredsson, E.C., 2004. "Green" consumption-no solution for climate change. Energy 29, 513–524.
Briceno, T., Peters, G., Solli, C., Hertwich, E., 2005. Using Life Cycle Approaches to Evaluate Sustainable Consumption Programs: Car-sharing.
Chitnis, M., Sorrell, S., 2015. Living up to expectations: estimating direct and indirect rebound effects for UK households. Energy Econ. 52, 100–116.
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. Ecol. Econ. 106, 12–32.
Clark, G., 2007. Evolution of the global sustainable consumption and production policy and the United Nations Environment Programme's (UNEP) supporting activities. J. Clean. Prod. 15, 492–498.
Davis, S.J., Caldeira, K., 2010. Consumption-based accounting of CO_2 emissions. Proc. Natl. Acad. Sci. U. S. A. 107, 5687–5692.
Denstadli, J.M., Rideng, A., 2012. Reisevaner På Fly 2011. TØI Rapport.
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., 2010. The bare necessities: how much household carbon do we really need? Ecol. Econ. 69, 1794–1804.
Duchin, F., 2005. A world trade model based on comparative advantage with m regions, n goods, and k factors. Econ. Syst. Res. 17, 141–162.
Duchin, F., Levine, S.H., 2015. Rents in the era of resource scarcity: global payment flows under alternative scenarios. J. Econ. Struct. 4, 1–17.
Figge, F., Young, W., Barkemeyer, R., 2014. Sufficiency or efficiency to achieve lower resource consumption and emissions? The role of the rebound effect. J. Clean. Prod. 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. Environ. Sci. Technol. 48, 12063–12072.
Freire-González, J., 2011. Methods to empirically estimate direct and indirect rebound effect of energy-saving technological changes in households. Ecol. Model. 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. Environ. Sci. Policy Sustain. Dev. 50, 12–25.
Garnaut, R., 2008. The Garnaut Climate Change Review.
Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32.
Grabs, J., 2015. The rebound effects of switching to vegetarianism. A microeconomic analysis of Swedish consumption behavior. Ecol. Econ. 116, 270–279.

Greening, L.A., Greene, D.L., Difiglio, C., 2000. Energy efficiency and consumption - the rebound effect - a survey. Energy Policy 28, 389–401.
Hammer Strømman, A., Duchin, F., 2006. A world trade model with bilateral trade based on comparative advantage. Econ. Syst. Res. 18, 281–297.
Hertwich, E.G., 2005. Consumption and the rebound effect - an industrial ecology perspective. J. Ind. Ecol. 9, 85–98.
Ivanova, D., Stadler, K., Steen-Olsen, K., Wood, R., Vita, G., Tukker, A., Hertwich, E.G., 2016. Environmental impact assessment of household consumption. J. Ind. Ecol. 20, 526–536.
Jevons, W.S., 1866. The Coal Question: an Enquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal-mines. Macmillan.
Kronenberg, J., 2007. Making consumption “reasonable”. J. Clean. Prod. 15, 557–566.
Leontief, W.W., 1936. Quantitative input and output relations in the economic systems of the United States. Rev. Econ. Stat. 105–125.
Miller, R.E., Blair, P.D., 2009. Input-output Analysis: Foundations and Extensions. Cambridge University Press.
Mont, O., Plepys, A., 2008. Sustainable consumption progress: should we be proud or alarmed? J. Clean. Prod. 16, 531–537.
Murray, C.K., 2013. What if consumers decided to all ‘go green’? Environmental rebound effects from consumption decisions. Energy Policy 54, 240–256.
Norwegian Ministry of Climate and Environment, 2015. New Emission Commitment for Norway for 2030 – towards Joint Fulfilment with the EU. Meld. St. 13 (2014–2015). Report to the Storting (white paper).
Ornetzeder, M., Hertwich, E.G., Hubacek, K., Korytarova, K., Haas, W., 2008. The environmental effect of car-free housing: a case in Vienna. Ecol. Econ. 65, 516–530.
Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., 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, IPCC.
Saunders, H.D., 1992. The Khazzoom-Brookes postulate and neoclassical growth. Energy J. 13, 131–148.
Silva Simas, M., Pauliuk, S., Wood, R., Hertwich, E.G., Stadler, K., 2017. Correlation between production and consumption-based environmental indicators. The link to affluence and the effect on ranking environmental performance of countries. Ecol. Indic. 76, 317–323.
Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M., Miller, H., 2007. Climate Change 2007: the Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
Statistics Norway, 2013. Forbruksundersøkelsen, 2012 [Online]. Statistics Norway. Available from: www.ssb.no/inntekt-og-forbruk/statistikker/fbu. (Accessed 8 March 2016).
Statistics Norway, 2014. Familier Og Husholdninger, 1. Januar 2014 [Online]. SSB. Available from: www.ssb.no/befolkning/statistikker/familie/aar/2014-12-12. (Accessed 7 April 2016).
Statistics Norway, 2015. Avfall Frå Hushalda, 2014 [Online]. Statistics Norway. Available from: www.ssb.no/natur-og-miljo/statistikker/avfkomm/aar/2015-07-07#content. (Accessed 6 June 2016).
Steen-Olsen, K., Wood, R., Hertwich, E.G., 2016. The carbon footprint of Norwegian household consumption 1999–2012. J. Ind. Ecol. 20, 582–592.
Stern, N.H., 2007. The Economics of Climate Change: the Stern Review. Cambridge University Press.
Ten Raa, T., Shestalova, V., 2015. Supply-use framework for international environmental policy analysis. Econ. Syst. Res. 27, 77–94.
Thiesen, J., Christensen, T., Kristensen, T., Andersen, R., Brunoe, B., Gregersen, T., Thrane, M., Weidema, B., 2008. Rebound effects of price differences. Int. J. Life Cycle Assess. 13, 104–114.
Throne-Holst, H., Stø, E., Strandbakken, P., 2007. The role of consumption and consumers in zero emission strategies. J. Clean. Prod. 15, 1328–1336.
Tukker, A., Emmert, S., Charter, M., Vezzoli, C., Sto, E., Munch Andersen, M., Geerken, T., Tischner, U., Lahlou, S., 2008. Fostering change to sustainable consumption and production: an evidence based view. J. Clean. Prod. 16, 1218–1225.
United Nations, 2015. Goal 12: Ensure Sustainable Consumption and Production Patterns [Online]. Available from: www.un.org/sustainabledevelopment/sustainable-consumption-production/. (Accessed 2 August 2017).
United Nations Statistics Division, 2016. Detailed Structure and Explanatory Notes: COICOP (Classification of Individual Consumption According to Purpose) [Online]. Available from: http://unstats.un.org/unsd/cr/registry/regcst.asp?Cl=5. (Accessed 8 March 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. Technol. Forecast. Soc. Change 102, 309–319.
Wood, R., 2009. Structural decomposition analysis of Australia's greenhouse gas emissions. Energy Policy 37, 4943–4948.
Wood, R., Dey, C., 2009. Australias carbon footprint. Econ. Syst. Res. 21, 243–266.
Wood, R., Hawkins, T.R., Hertwich, E.G., Tukker, A., 2014. Harmonising national input—output tables for consumption-based accounting — experiences from EXIOPOL. Econ. Syst. Res. 26, 387–409.
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. Sustain. Switz. 7, 138–163.