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Exploring the implications of lifestyle change in 2 °C mitigation scenarios using the IMAGE integrated assessment model

Mariësse A.E. van Sluisveld [a,b,*], Sara Herreras Martínez [a], Vassilis Daioglou [a], Detlef P. van Vuuren [a,b]

[a] Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, NL-3584 CS Utrecht, The Netherlands
[b] PBL Netherlands Environment Assessment Agency, PO Box 303, 3720 BA Bilthoven, The Netherlands

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ABSTRACT

Most model studies focus on technical solutions in order to meet the 2 °C climate target, such as renewable, carbon capture and energy efficiency technologies. Such studies show that it becomes increasingly more difficult to attain the 2 °C target with carbon price driven technical solutions alone. This indicates the need to focus more on non-economic and non-technological drivers of energy system transformations, which are generally not explicitly included in long-term scenario studies. This study implements a set of lifestyle change measures for residential energy use, mobility and waste management in the integrated assessment model IMAGE. We analyze the implications of these lifestyle changes in a business-as-usual and 2 °C climate mitigation reference case. We find that lifestyle change measures included in this study mostly affect the end-use sectors. By 2050, the measures reduce CO_2 emissions in the residential sector by about 13% and in the transport sector by about 35% compared to baseline emissions. The indirect implications in the industry and energy supply sectors were found to be negligible. In mitigation scenarios the contribution of lifestyle measures is dampened in end-use sectors as they overlap with more technical measures. Yet, as they may create opportunities to mitigate in sectors without more radical changes in (1) the energy infrastructure and (2) on the short term, it leads to a more cost-efficient mitigation strategy. Further research in how behavior can be internalized into integrated assessment studies is recommendable.

1. Introduction

Scenario analysis shows that substantial emission reductions are required in order to limit global temperature increases to 2 °C. Most model studies introduce very ambitious changes in energy demand, supply and land use to meet a 2 °C climate target. Common policy recommendations include, for example, large-scale introduction of intermittent renewable power, negative emissions from bioenergy with carbon capture and storage (BECCS), the introduction of advanced technologies for energy efficiency and energy supply and increased material efficiency. Generally such model studies suggest that, under full participation of sectors and regions in climate policy, it is possible to implement these energy system transformations. In reality, however, implementation of climate policy will be limited by various barriers such as economic (e.g. vested interests and sunk investments), social (e.g. values and lifestyles, cognitive routines, alignment between social groups) and political factors (e.g. opposition to change from vested interests, uneven playing field) (Cagno et al., 2013; Geels, 2005; Hof et al., 2013; Staub-Kaminski et al., 2014). In the past, this has often led to a reformulation of policy ambitions. One example of this is the European Unions' Energy Efficiency Directive, which was amended in response to the lag in achieving its primary energy consumption reduction target of 20% by 2020 (EEA, 2013).

As a result, modeling studies have started to explore non-optimal situations (e.g. limitations in joint international commitments, instrumentation and availability of technologies) (Clarke et al., 2009; IEA, 2012; Rao et al., 2008; Stocker, 2013; Tol, 2009; van Vuuren et al., 2012). These studies show that in the case of delayed action or limited technology availability the 2 °C target could become unattainable.

Although assessment reports mention the notion of lifestyle change as an alternative way to reduce carbon emissions (Fisher et al., 2007; IPCC, 2014), very few studies have evaluated its potential or implications in global assessment modeling (Bernstein et al., 2007; Metz et al., 2007; Roy, 2012; Weber and Perrels, 2000). This means that while cost-optimal model scenarios are considered to be too optimistic in terms of timing of action, or technology availability, they might also be regarded as too conservative by leaving out a particular set of mitigation options. In that context, we assess alternative mitigation options by focusing on behavioral and lifestyle changes. The strength of global assessment modeling (also known as Integrated Assessment Modeling, IAM), compared to earlier studies emphasizing the contribution of

* Corresponding author at: PBL Netherlands Environment Assessment Agency, PO Box 303, 3720 BA Bilthoven, The Netherlands.
E-mail address: mariesse.vansluisveld@pbl.nl (M.A.E. van Sluisveld).

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lifestyle change, is that it allows analyzing the interactions of lifestyle changes with other, technical, measures.

Thus, the aim of this study is to explore the implications of lifestyle change in an Integrated Assessment Model (IAM)-based mitigation scenario and to highlight the strengths and limitations of energy demand modeling. An integrated assessment approach allows for the quantitative assessment of system impacts and the interaction between subsystems. To this respect we contribute to the aim by exploring the following research questions:

- How can lifestyle and lifestyle change be included in an integrated assessment model?
- How much could a set of lifestyle changes contribute to achieving 2 °C climate targets, given the interaction with other measures?

In Section 2 we will address the research boundaries and introduce a framework of lifestyle change measures. Section 3 discusses scenario results, followed by contextual limitations in Section 4. Section 5 presents the overall conclusions of the study.

2. Methods and materials

2.1. Modeling framework

In order to explore the potential and implications of behavioral and lifestyle change, we apply the Integrated Model to Assess the Global Environment (IMAGE) modeling framework (Stehfest et al., 2014). The IMAGE framework is an integrated assessment tool that is applied to study long term dynamics of global change in the energy and land system. The framework consists of various system-dynamic submodels, such as, among others, the energy model TIMER (Section 4.1 in Stehfest et al., 2014), coupled to the climate policy model FAIR(SiMCaP) (Section 8.1 in Stehfest et al., 2014) and the land use model IMAGE (Stehfest et al., 2014):

- Within the energy model TIMER, the annual demand and supply of different energy carriers is described for a set of 26 world regions. Changes in energy demand within the available sectors (industry, transport, residential, services, non-energy and other) are related to structural changes, autonomous and price-induced changes in energy intensity and price-based fuel substitution. Several submodules of TIMER simulate the various demand sectors in more detail, such as TRAVEL for passenger travel (Girod et al., 2013), REMG for household energy use (Daioglou et al., 2012) and NEDE for the non-energy (petrochemical) sector (Daioglou et al., 2013). The market share of energy carriers or technologies used is determined by a multinomial logit (MNL) function, accounting for differences in relative costs and preferences per option (Van Vuuren et al., 2011).
- The FAIR model calculates the difference between baseline and global emission pathways using a cost-optimal approach involving regional marginal abatement cost (MAC) curves and combined with the SiMCaP pathfinder module uses an iterative procedure to find multi-gas emission pathways that correspond to a predefined climate target (Van Vuuren et al., 2007).
- The land use model of IMAGE represents the use of land for food, timber and fuel productions in relation to alternative uses of land for natural ecosystems. The area that is required could be influenced on the one hand by changes in demand and on the other by different production systems (yields).

2.2. Lifestyle-change measures in integrated assessment modeling

Changes in lifestyle can be expressed in changes in energy demand either through more (1) physical efficiency boosting actions or (2) curtailment measures (Gardner and Stern, 2008; Gutowski et al., 2008; von Borgstede et al., 2013). In this study we zoom in on curtailment measures as people are found to be more likely to carry out environmentally friendly behavioral changes with low cost and low efforts than others (Steg, 2008). Moreover as energy efficiency improvement measures overlap with technological improvements already included in the model, we exclude these measures here.

Global Integrated Assessment Models (IAMs) generally do not explicitly model individual decision making. Instead, various proxies are employed to internalize some degree of behavioral variation. In the IMAGE framework the following elements represent some of the decision-making processes:

- Many decisions in the model are represented by (multinomial) logit functions that assign large market shares to attractive (low costs for the service) options and small or no market share to unattractive (expensive) options. This equation embeds decisive heterogeneity in the model. The market shares are determined by logit parameters simulating price sensitivity, hence imposing a certain price-elastic preference order.
- Related to the previous bullet, in evaluating the attractiveness of different options the multinomial logit equations not only include energy prices but also other factors representing consumer preferences or governmental policies in so-called 'preference' or 'premium' factors (De Vries et al., 2001). Preference factors seek to represent a wide variety of empirically unquantifiable (market) externalities;
- Regional diversity is accounted for through calibrating on differences in energy demand per region, e.g. refrigeration energy use is explicitly different in the USA than for other regions, whereas floor space per capita is significant lower in Japan (Daioglou et al., 2012);
- In some cases constants are applied that represent a certain exogenous trend within the model (e.g. fixed vehicle occupancy rates, discount rates, and lifetimes).

There are several ways to analyze the impact of behavioral change in the model. As explained further, we look at a set of identified lifestyle change measures. The impact of these measures can be included in IMAGE by changing the existing parameterization. This includes:

(1) Adjusting the (multinomial) logit parameters to change the preference order for specific choices (e.g. transport mode);
(2) Allowing regional energy demand parameters to converge to a top performing region;
(3) Capping parameters to a certain value (e.g. ownership rates can be fixed to (or abolished from) current day ownership rates).

2.3. Framework of lifestyle change measures

For the purpose of energy demand modeling we consider lifestyle change as an activity that is manifested in the housing and transport domains, including end-of-life considerations (Bedford et al., 2004; Daioglou et al., 2012; Girod et al., 2013; OECD, 2008). Below we describe the lifestyle change measures that have been selected from literature and how these are translated into the IMAGE integrated assessment framework.

2.3.1. Household domain

In the household domain, lifestyle measures can be identified with respect to space heating, water heating, appliance use and waste management.

2.3.1.1. Space heating

- Reducing demand for cooling and heating

The most common climatic indicator of the demand for heating and cooling services is the degree day (in °C/year). The degree day describes the number of degrees above or below a certain desired temperature over an entire year (which may vary for heating and for cooling) (Isaac and van Vuuren, 2009). We assume a behavioral change in which a user accepts a difference to the desired (room) temperature by adapting the base temperature of 18 °C by 1 °C downwards (for space heating) or 1 °C upwards (for space cooling).

- Capping household dimensions

For most developed countries, larger dwelling sizes (0.7% increase in energy demand per annum) and lower occupancy rates (0.5% increase in energy demand per annum) have tended to drive up energy demand for space heating, offsetting reductions achieved through efficiency gains (IEA, 2008). Hence, limiting home size has been suggested as a measure in literature (Dietz et al., 2009). To approach this lifestyle change, we assume that with increasing affluence, the increase of floor space per capita is limited to 2010 levels of a representative developed region (EU). This scenario also explicitly differentiates between urban and rural regions, of which the values are set at 40 m^2/cap for urban households and 50 m^2/cap for rural households (allowing regions with greater values to converge within a decade) (IEA, 2004). The measure can also be seen as a limitation to the heated and/or air conditioned surface area in homes.

2.3.1.2. Water heating

- Reduced use of heated water

Heating water uses about a third of the annual gas used for space heating in high-income areas (Goodall, 2010), and is mainly done for activities such as, among others, showering and cleaning. With an assumed average of 8 minutes a day to shower, we assume a reduction of shower time of 2 minutes to reduce the energy needed for heating water. We apply a correction factor in total energy demand for water heating based on an estimate calculated from literature. With an estimated water throughput of 15 L/min (Wright, 2011), a required temperature elevation of 50 °C, and a 0.0011 kWh/L energy consumption per degree of water heating (Goodall, 2010), on average, this could lead to a 25% energy reduction.

2.3.1.3. Appliance use

- Reduced rate of appliance ownership per household

In developed regions, large appliances such as refrigerators, freezers, washing machines, dishwashers and televisions account for about 50% of household electricity consumption in appliances (IEA, 2008). An important driver of appliance energy use is the rate of ownership. We limit maximum ownership rates for major domestic appliances and entertainment devices to the present maximum ownership rates, which would have increased over time otherwise. For tumble dryers we assume they are gradually phased out over the decade.

- Switch off standby mode

Between 3% and 13% of residential electricity use in high-income regions can be attributed to standby power consumption (de Almeida et al., 2011; EEA, 2005). Specifically office equipment (such as information and communication technologies) and entertainment devices (such as consumer appliances) have the largest share in standby energy demand (de Almeida et al., 2011). We assume an appliance standby energy use as listed in LBNL (Lawrence Berkeley National Laboratory, 2013), and deduct this from the total average energy consumption per appliance category as described in Daioglou et al. (2012).

- More efficient or smarter use of appliances

A number of energy-conscious behavior options can be considered for appliances, such as choosing different wash temperatures, maximizing washing load per cycle, switching off the oven or the hotplates before the end of a cooking period, locating 'cold' appliances wisely (e.g. not near an oven), cooling hot food before storing or thawing food in the refrigerator and keeping it filled up (or limit the use 'over-dimensioned' appliances) (Geppert and Stamminger, 2010; Lucon et al., 2014; Wood and Newborough, 2003). Due to varying reduction potentials in the various measures (see for an overview Geppert and Stamminger, 2010; Lucon et al., 2014), we assume the best available technology (BAT) energy consumption for technology functions as a proxy for possible reduced energy demand per appliance category (Goodall, 2010; Lawrence Berkeley National Laboratory, 2013).

2.3.1.4. Waste management

- Reduced demand for consumer plastic

Waste management is expected to be an increasing challenge, as the generation of municipal waste is projected to increase within the OECD regions (OECD, 2008). Reusing plastic bags or using durable plastic products rather than disposables could reduce the total volume of municipal waste. This measure is implemented by reducing the intensity of useful energy demand in the industry and non-energy sectors to represent reduced material processing. We reduce the energy intensity of demand for the ethylene sector with 15-20% to depict reduced energy demand for plastics production. This in turn reduces the demand of primary energy to be used as feedstock, but also process energy in the form of heat and electricity.

- Plastic waste recycling

In order to assess possibilities of material efficiency improvement throughout the lifecycle of non-energy products (such as recycling and incineration with electricity generation), we also account for possible routes of post-consumer plastic waste (PCW). It is assumed that 50% of plastic production can be collected as PCW and recycled. The volume of PCW undergoing mechanical recycling is capped at 30% in order to account for decreased material properties (downcycling), the remaining PCW undergoes chemical recycling processes.

2.3.2. Transport domain

In the transport domain, there are various lifestyle measures related to curtailment. Here, we discuss reduced vehicle use and a mode shift to public transport.

- Reduced vehicle use

As described in Schäfer and Victor (2000) and Schäfer et al. (2009), individuals reserve a fixed proportion of income for traveling (travel money budget, TMB), which increases with economic growth and analogous rising motorization rate (number of light duty vehicles per 1000 inhabitants). The TMB increases till saturation is reached at 10–15% in (high-income) motorized regions, as opposed to 3–5% in non-motorized (developing) regions. In order to dampen the increase of motorization (e.g. representing car sharing or carpooling), we cap the TMB to the reported value for Japan (7%) which is the lowest reported value in literature for a developed region.[1] We allow the model to adjust to this value over an interval of a decade. Moreover, to slow down the decrease in vehicle occupancy with rising income, we introduce an income elasticity of −5% for all transport modes (Girod et al., 2013).

- Mode shift to public transport

Despite limiting the available TMB, the continuous increase of income leads simultaneously to a higher preference for faster modes. To

[1] Driven by an exceptional large share of public high-speed transport in Japan, due to e.g. the *Shinkansen* high-speed railway (Schäfer and Victor, 2000).

reduce high-impact traveling we influence the mode split by differentiating non-monetary preferences per mode, in favor of the bicycle and railway transportation, similarly to Girod et al. (2013). Moreover, to correspond with the increase in the preference for slower modes, we allow an additional 0.5 minute per year on the traveling time budget (TTB).

Table 1 summarizes the measures that have been implemented in the IMAGE model framework. The introduced lifestyle changes include actual or estimated changes in energy demand as reported in literature. As some measures are only qualitative prescriptions (e.g. downsizing your home) we translate these into the model by using historical and regional best practices already included in the model. We also distinguish between measures that can take immediate effect and those that require an adjustment from the current situation.

2.4. Scenario design

For this study we introduce four different scenarios to analyze the implications of lifestyle change in a 2 °C scenario and an integrated assessment context (see Table 2).

1) The baseline scenario (*Baseline*) is a stylized scenario assuming business-as-usual without detailed assumptions on planned (regional) climate policy. Projections for GDP growth rates stem from the OECD Environmental Outlook (OECD, 2010) which describes an average annual global growth rate of 3.5% between 2010 and 2050. Population assumptions are based on the United Nations population prospects (UN, 2008), in which the global population reaches 9.55 billion at the end of the century. For this baseline, the IMAGE projections on energy consumption are similar to the projections of the IEA World Energy Outlook (IEA, 2011) showing a continuation of historical trends and the range found in literature as reviewed by van Vuuren et al. (2012).
2) A second scenario (*Baseline + lifestyle*) combines the baseline projection together with the lifestyle change measures as described in the framework, to assess the contribution of lifestyle change relative to the default settings.
3) The third scenario (*2 Degrees*) consists of a default, cost-optimal mitigation scenario as calculated by the model targeted to not exceed the 2 °C temperature increase, assuming no lifestyle changes.
4) Finally, the fourth scenario (*2 Degrees + lifestyle*) combines the same lifestyle assumptions as considered under the *Baseline + lifestyle* scenario with a climate mitigation target. This scenario can be interpreted in two ways:
   a) The first way is to introduce lifestyle change measures as additional to the existing cost-optimal mitigation scenario. The outcomes reflect the additional mitigation potential that can be achieved via lifestyle change next to an existing set of more large-scale infrastructure and technology-oriented measures. This translates into the model as a similar carbon tax (ctax) price path over time as in the default *2 Degrees* scenario.
   b) The second way is by allowing lifestyle change measures to exist in tandem with carbon price driven measures – in this situation a new cost — optimal optimum reflects the implications of lifestyle change on the required mitigation efforts. In the model this translates into a scenario meeting a similar concentration target (ppm) in 2100 as the default *2 Degrees* scenario.

Table 2
Scenario overview table.

Scenario	Subname	Description
Baseline (default)	–	The baseline scenario used throughout this study
Baseline + lifestyle	–	The baseline including all the lifestyle measures addressed in the lifestyle change framework
2 Degrees (default)	–	A cost-optimal mitigation scenario with primarily price-based mitigation measures that stay in line with a 450 ppm climate stabilization target in 2100.
2 Degrees + lifestyle	ctax	A mitigation scenario that includes lifestyle change measures next to price-based mitigation measures.
	ppm	A cost-optimal mitigation scenario allowing lifestyle change measures to exist in tandem with price-based mitigation measures.

To assess the implications of lifestyle change and to control for the various system interactions we mainly address the first interpretation in the forthcoming results.

This study focuses on the aggregated (global) level, with a temporal scale up to 2100 and zooms in onto four sectors (energy supply, industry, residential and transport). The energy supply sector accounts for power and heat generation and other energy conversions (e.g. refineries, synfuel production), resource extraction and energy transmission and distribution (e.g. gas pipelines). The industry sector includes heavy industry such as steal and cement production and petrochemicals. The residential and commercial sector includes both heating and cooling as well as appliance energy use. The transport sector includes freight and passenger travel and bunker fuels.

Table 1
Overview table of implementable lifestyle changes.

Domain	Measure	Implementation	Transition	Source
Transport	Reduced vehicle use	• Capping the travel money budget	Gradual	TIMER/IMAGE
		• Changing income elasticity to −5% to prevent lower passenger load per mode	Immediate	Girod et al. (2013)
	Mode shift to public transport	• Change of perceived price and increase of TTB by 0.5 min/year	Immediate	TIMER/IMAGE Girod et al. (2013)
Household	Reduced heating/cooling demand	• Change of base temperature by 1 °C, reducing the number of heating degree days or cooling degree days.	Immediate	TIMER/IMAGE Isaac and van Vuuren (2009)
	Reduced appliance ownership	• Reduced ownership levels for 'luxury goods' to zero (no tumble dryers, dish washers etc.)	Gradual	TIMER/IMAGE
		• Maximum ownership rates for other major domestic appliances are fixed to 2013 values.	Immediate	
	More efficient use of appliances	• BAT energy consumption estimates and make appliances converge to these new levels gradually over time.	Immediate	Goodall (2010)
	Switch off stand-by mode	• Reduce annual appliance energy consumption based on estimations of standby mode energy consumption per appliance	Immediate	Lawrence Berkeley National Laboratory (2013)
	Reduces water heating	• A correction factor in total energy demand for water heating (based on cutting down 2 min of shower time), based on an estimate in literature.	Immediate	Goodall (2010) Daioglou et al. (2012)
	Capping household dimensions	• Maximum floor space (m^2/cap) is fixed to a representative 2010 value, differentiating for rural (50 m^2/cap) and urban households (40 m^2/cap)	Immediate	TIMER/IMAGE IEA (2004)
	Reduced plastic consumption	• Reduce intensity of useful energy demand in ethylene production by 15–20%	Gradual	TIMER/IMAGE
	Plastic waste recycling	• Assuming active household plastic waste separation from general waste.	Immediate	TIMER/IMAGE
		• Assuming available infrastructure in which max. 20% is mechanically recycled and max 30% chemically recycled.	Immediate	Daioglou et al. (2013)

To assess the implications of lifestyle change measures on attaining the 2 °C objective the analysis focuses on CO_2 emission trajectories and secondary energy carriers. Among the energy carriers addressed, solid fuel denotes coal (incl. cokes and other commercial solid fuels), liquid fuel denotes oil as light liquid fuel (LLF) or heavy liquid fuel (HLF) and commercial liquid fuel from biomass, gaseous fuel denotes natural gas.

3. Results

3.1. Direct implications of lifestyle change

In the following paragraphs we will discuss the implications of the lifestyle change for each sector.

3.1.1. Residential

The residential and commercial sector has been responsible for about 32% of total global final energy use and 19% of energy-related greenhouse gas emissions in 2010 and is expected to double or triple its emissions by mid-century due to increasing life-standards in emerging regions. The largest part of greenhouse gas emissions are indirect CO_2 emissions from electricity use in buildings (Lucon et al., 2014), followed by emissions from direct energy use (with space heating and water heating as most energy consuming respectively) (Steg, 2006).

In the baseline scenario, emissions in the residential and commercial sector are projected to increase from less than 3 $GtCO_2$ today to 4 $GtCO_2$ by 2100 (See Fig. 1). We find that the set of lifestyle change measures can lead to a sustained emission reduction potential of about 13% over time (and as early as 2030, see Table 3). Under stringent 2 °C climate ambitions, the calculations show that the measures have become less effective if combined with technology-oriented and energy efficiency measures (showing even a decreasing additional effect over time).

3.1.2. Transport

The transport sector is often considered to be the most difficult and expensive sector to reduce greenhouse gas emissions (Schäfer and Victor, 2000). Conventional mitigation strategies focus on supply-side vehicle technology efficiency gains and fuel switching as the central theme for this sector. These measures create several challenges on the short term as most aspired technological changes are not yet commercially available and require major infrastructure changes and investments (Anable et al., 2012).

Table 3
Overview of emission reductions compared to baseline emissions for household related lifestyle change measures in the IMAGE model (in %).

	Reductions compared to *Baseline*		
	2030	2050	2100
Baseline + lifestyle	13%	16%	15%
2 Degrees	24%	50%	84%
2 Degrees + lifestyle (ctax)	34%	58%	87%

Lifestyle changes on the other hand could lead to an immediate shift from a predominant oil and bioenergy oriented to a more electricity-based transport sector (see Fig. 2). This is an effect of the mode shift from personal vehicles to public transport, which opens up opportunities to use renewable energy sources on the short term without substantial changes to the energy infrastructure. This change in transportation behavior has the potential to achieve an increasing emission reduction potential in the transport sector over time (see Table 4), with a sustained reduction potential of about 35% by 2050 compared to baseline emissions. However, similar to the residential sector, we find that under 2 °C ambitions the lifestyle change measures lead to a relatively smaller reduction potential than the reduction potential achieved under *Baseline* assumptions (creating only a 7 to 13 percentage point deviation from the default over time).

3.2. Indirect implications of lifestyle change

Although lifestyle measures are not implemented in the energy supply and industry sector directly, some of the measures regarding energy and material conservation will lead indirectly to impacts in these sectors.

3.2.1. Power sector

The energy supply sector is acknowledged to be the largest contributor to global anthropogenic greenhouse gas emissions, responsible for 35% in 2010. Although multiple options exist to reduce energy supply sector greenhouse gas emissions, the central theme in long-term mitigation scenarios is generally the development and deployment of low-carbon technologies (Clarke et al., 2014). Society can have an indirect impact on the power supply sector and the composition of fuel for power generation by changing their energy consumption — either through reducing energy demand or by increasing the use of electricity

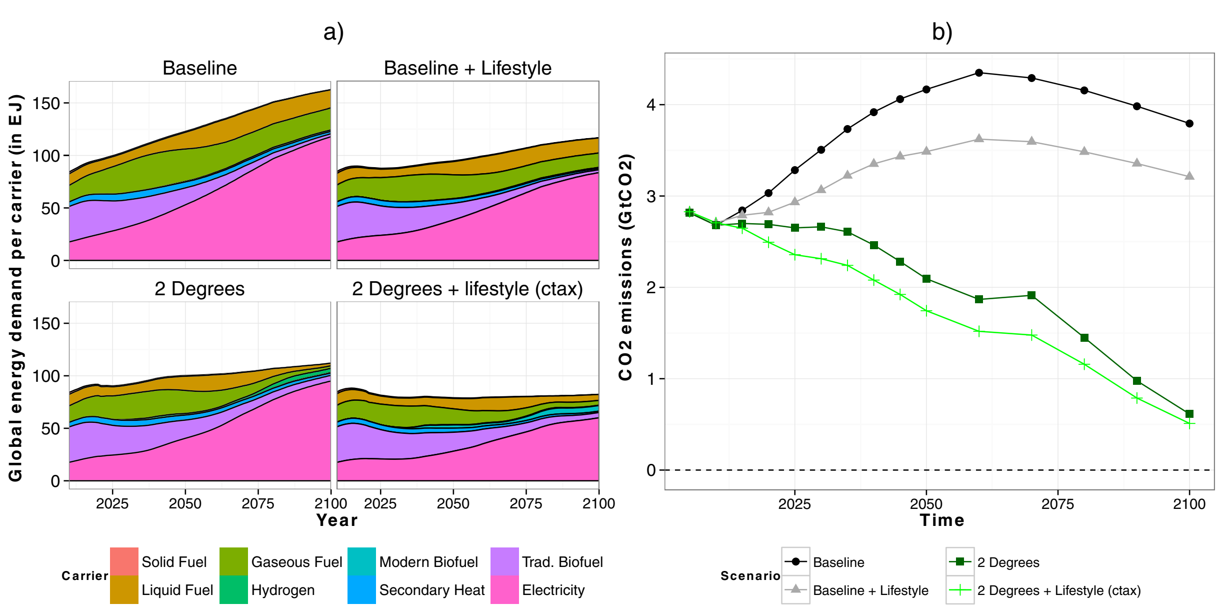

Fig. 1. Overview of the effect of lifestyle changes in the residential sector on the use of secondary energy carriers (panel a, in EJ) and CO_2 emission trajectories (panel b, in $GtCO_2$).

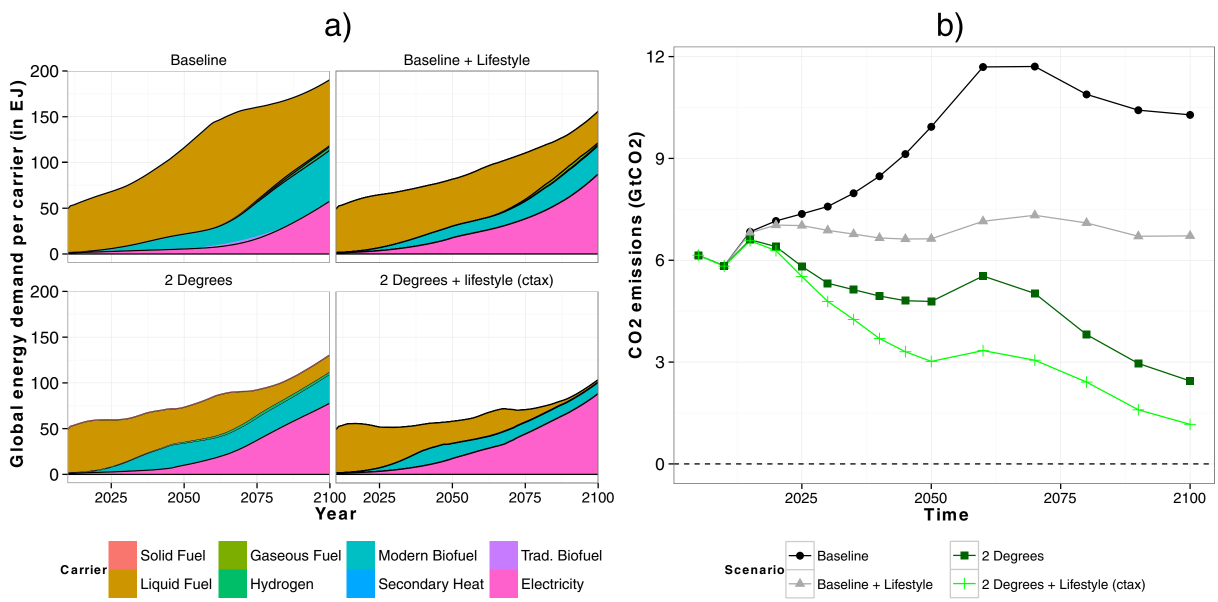

Fig. 2. Overview of the effect of lifestyle changes in the transport sector on the use of secondary energy carriers (panel a — limited to passenger travel in EJ) and CO_2 emission trajectories (panel b, in $GtCO_2$).

in the household and transport domains. We observe that the introduced lifestyle changes lead to changes in electricity demand in the residential and transport sector, but these do not have a significant impact on the fuel mix or emissions in the power sector (see Fig. 3). Overall a sustained emission reduction potential of about 3–5% is achieved by 2030. In a 2 °C context an additional 2 percentage point greater emission reduction potential can be achieved in the energy supply sector compared to the default 2 °C mitigation scenario.

3.2.2. Industry

Despite continued improvements in energy and process efficiency, industry related emissions are increasing and represent just over 30% of global greenhouse gas emissions in 2010 (Lucon et al., 2014). Lifestyle change measures can indirectly impact the producing industry through reducing material consumption (e.g. through curtailment and recycling and re-use). The effects of lifestyle change measures on the industry sector show to be limited in both the baseline as well as the *2 Degrees* scenario (see Fig. 3). This is partly an effect created by only implementing measures that explicitly target the petrochemical sector (such as plastic reuse and recycling), as well as an effect of limited feedback of the industry to other demand sectors and vice versa. Hence in this study we find that a lower demand for materials (mainly polymers) leads to emission reductions that have a near negligible effect in the total industry sector (increasing up to 4% by 2100) (see Fig. 4). Indirect effects of lifestyle changes in the transport sector and residential and commercial sectors are not further included in this estimate.

Overall, as underlined in the results, lifestyle changes do not impose large structural changes in the energy intensive sectors under both *Baseline* as *2 Degrees* assumptions. This implies that in order to decarbonize these sectors the mitigation efforts remain dependent on technology-oriented measures. Given how the added effect of lifestyle change measures become relatively smaller under *2 Degrees* assumptions, we deduct that this is an effect of a decarbonizing energy system. However, as society is decarbonizing its energy intensive sectors, the weight of meeting 2 °C ambitions will shift to sectors that are less easily decarbonized. Especially for those sectors, lifestyle changes will play a vital role in reducing carbon emissions more early on (like the transport sector).

Table 4
Overview of emission reductions compared to baseline emissions for the transport related lifestyle change measures in the IMAGE model (in %).

	Reductions compared to *Baseline*		
	2030	2050	2100
Baseline + lifestyle	9%	33%	35%
2 Degrees	30%	52%	76%
2 Degrees + lifestyle (ctax)	37%	70%	89%

3.3. Implications of lifestyle change on 2 °C mitigation

Limiting temperature increase by 2 °C with a high likelihood (>66%) is often linked with staying within a cumulative CO_2 emission budget of 1000 $GtCO_2$ over the 2011–2100 timeframe (Clarke et al., 2014). Under *Baseline* assumptions the cumulative emissions reach up to 5000 $GtCO_2$ in 2100. Lifestyle change measures show to have only a limited impact on the system as a whole — depicting a reduction potential of about 7% in total cumulative CO_2 emissions by 2100. Lifestyle change measures alone thus prove to be insufficient to stay in line with 2 °C ambitions (see Fig. 5).

Initially the impact of lifestyle change measures in a mitigation scenario on total CO_2 emissions appear to be analogous to the *Baseline*-equivalent. However, several vital differences can be observed. First of all, in order to not exceed the 1000 $GtCO_2$ carbon budget the energy system has to transform to a carbon neutral system which can be achieved no sooner than 2090 under cost-optimal assumptions. However, low effort and low cost lifestyle changes create additional emission reductions throughout the century leading to a total carbon budget of about 650 $GtCO_2$ in 2100 (or 27% less cumulative emissions than under default *2 Degrees*). This is an effect of achieving negative emissions already by 2060.

If we correct for this effect by preventing the carbon budget to go beyond what is in line with 2 °C (*2 Degree + lifestyle* (ppm)), we find that lifestyle change measures allow a greater cumulative emission profile over the first half of the century. This higher emission profile is a manifestation of reduced energy demand in society, which dampens the adoption rate of more biomass-based energy supply and carbon storage technologies to replace existing capital and to compensate for the increasing energy need on the short-term. In the second half of the century the *2 Degrees + lifestyle (ppm)* scenario follows a similar route as under default 2 °C settings, but due to reduced overall demand and an movement towards electric based transport, a greater volume of

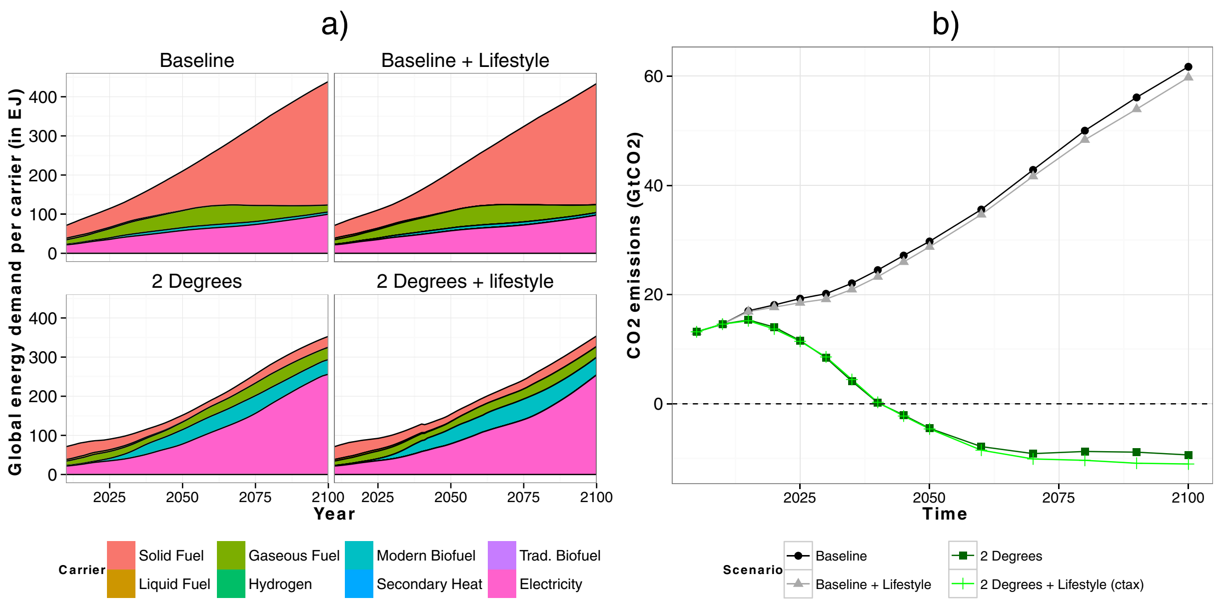

Fig. 3. Overview of the effect of lifestyle changes on the power sector on the use of secondary energy carriers (panel a — in EJ, 'Electricity' represents power generated by renewable sources) and emission trajectories (panel b, in $GtCO_2$).

biomass has become available to be utilized in the power sector. This leads eventually to deeper negative emissions at the end of the century.

Overall, by preemptively reducing energy demand and transitioning to electricity-driven end-use sectors, multiple opportunities are unlocked to mitigate in the more difficult to mitigate sectors. This is in particular reflected in the required carbon pricing and total mitigation costs to remain within a carbon budget of 1000 $GtCO_2$. As illustrated in Fig. 6, lifestyle change measures create a more cost-efficient mitigation scenario without additional radical changes in the energy infrastructure. This is represented by a carbon price value that is USD\$100/tCO_2 (or a sustained 15%) lower throughout the century under lifestyle assumptions than compared to the reference scenario. It is however important to underline that this effect is achieved by assuming that lifestyle changes can be realized without any costs for people or policies.

4. Discussion

4.1. Representation of lifestyle change in IAMs

In this study we have analyzed 10 different lifestyle change measures to reduce carbon emissions which are assumed to be of low cost and low effort in nature. Some caveats with respect to the analysis need to be accounted for:

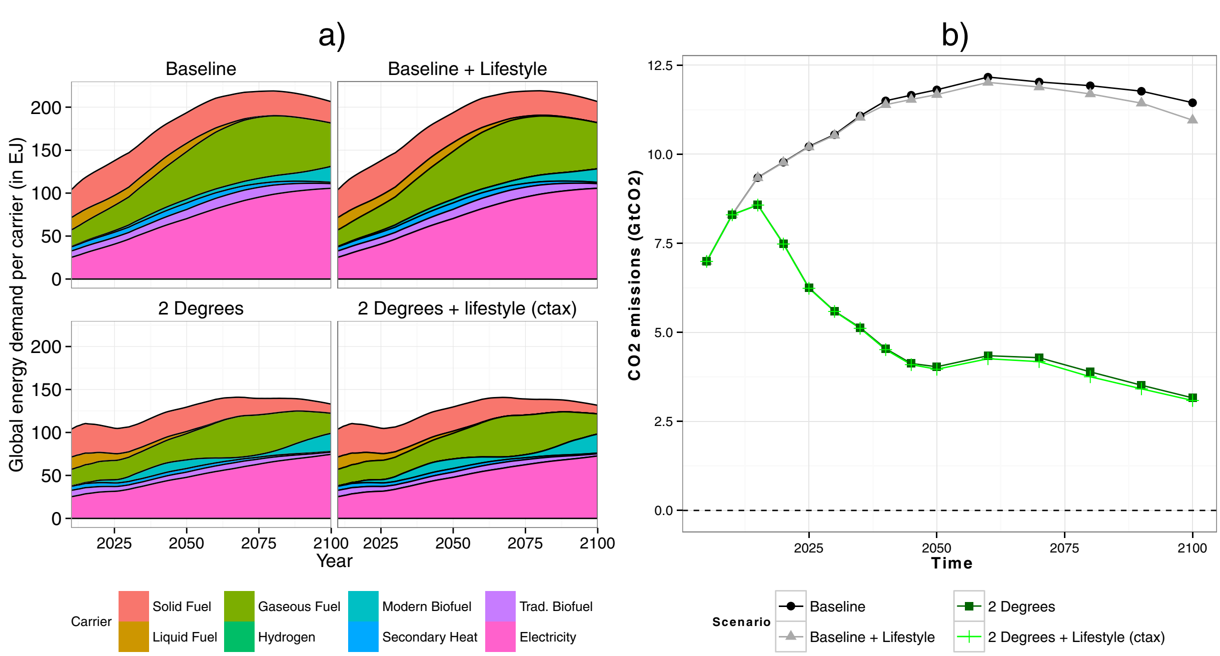

Fig. 4. Overview of the effect of lifestyle measures in the industry sector on the use of secondary energy carriers (panel a) and emission trajectories (panel b, in $GtCO_2$).

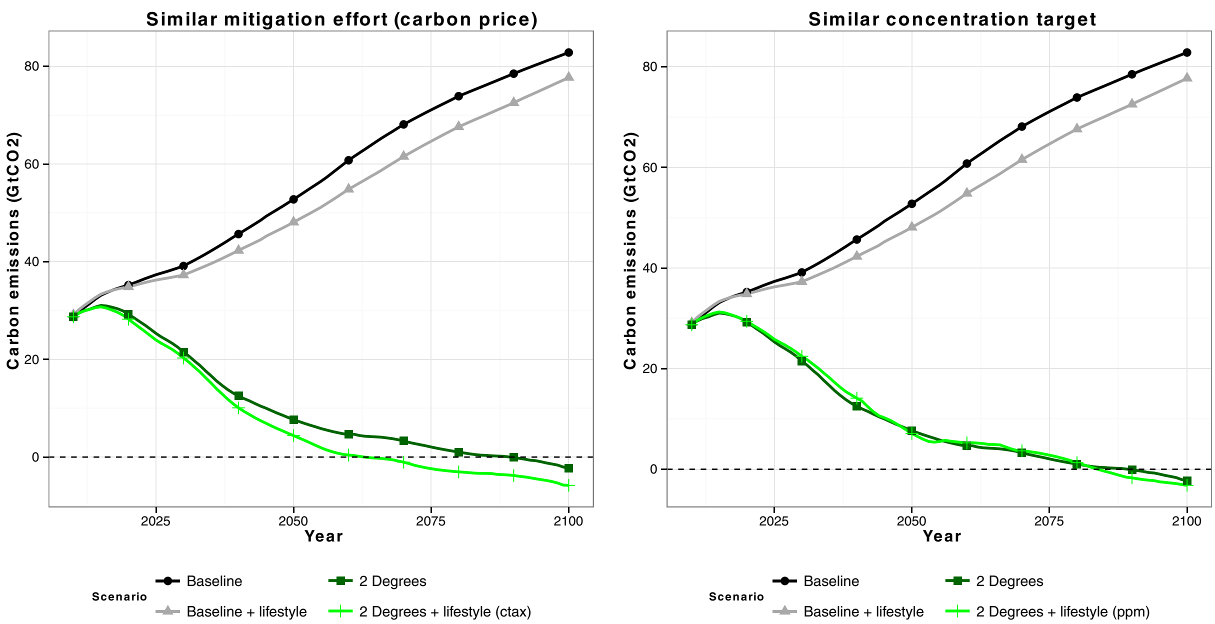

Fig. 5. CO_2 emission trajectories for similar carbon pricing (left, in $GtCO_2$) and similar climate target (right, in $GtCO_2$).

1) *Methodological limitations*: The measures studied in this study are to some degree an arbitrary selection from the existing literature. Some scholars argue that focusing on low cost and low effort lifestyle measures, if unranked in terms of energy reduction potential, is not effective (Gardner and Stern, 2008). In this study we focus more on curtailment measures which have a less quantifiable energy reduction potential than efficiency measures and could in this light be considered as less significant environmental behavior. However, as argued in Poortinga et al. (2003) people probably undertake energy saving actions that are based on more popular notions of pro-environmental behavior (such as very simple and homy measures) and thus the measures tested in this study can be considered of higher symbolic value. The results in this study also compare to reduction potentials as reported in literature for the short term (20% in both the residential (Dietz et al., 2009; Lucon et al., 2014) and transport sector (Sims et al., 2014). This is surprising, as these studies do not differentiate between efficiency and curtailment behavior as explicitly as this study and also assume more radical change in the energy infrastructure.

Moreover, this study assumes changes in behavior that can be induced without any costs for the individual or intervening policies. This is most likely not the case, particularly considering the wide variety of behavioral intervention options (which vary in their success) and their short-lived effects (Abrahamse et al., 2005). Future work could include the evaluation of the costs of policy interventions required to achieve behavioral change, specifically as cost factors appeal to integrated assessment modeling.

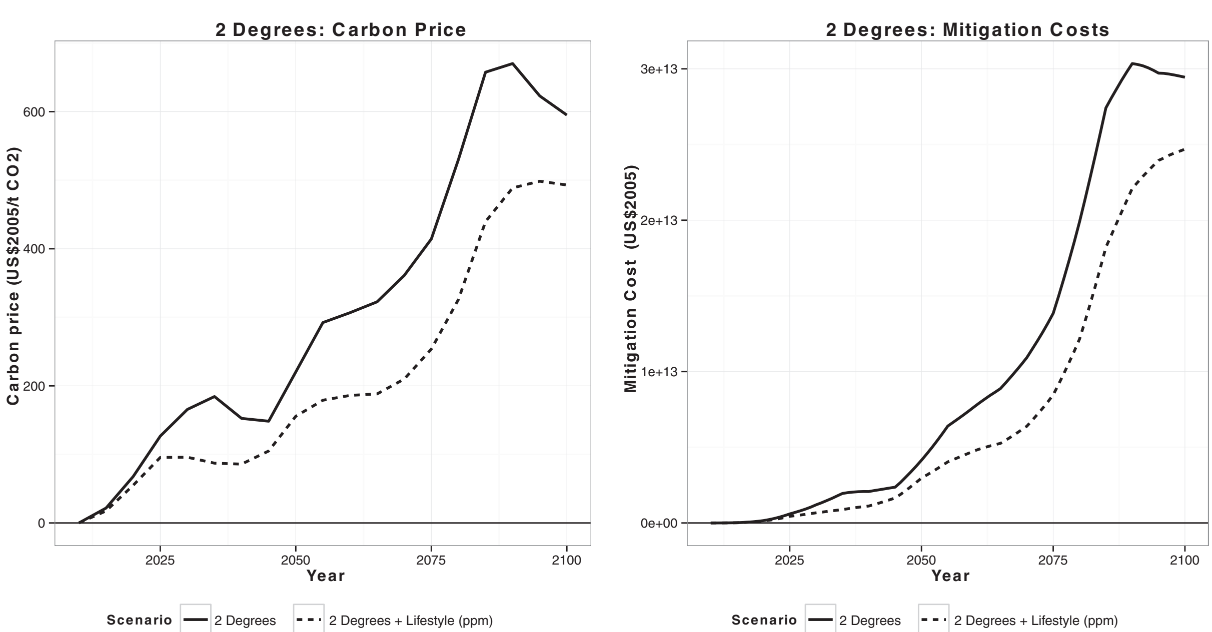

Fig. 6. Differences in required carbon tax projections (left, in US$2005) and total mitigation costs (right, in US$2005) for the *2 Degrees* and *2 Degrees + lifestyle scenario (ppm)*.

2) *Limited representation of lifestyle change in IAMs*: The way we have implemented most lifestyle change measures is by changing context-dependent variables. As socio-economic trends (such as low education, income, age, gender, employment status and attitudes) (OECD, 2008) and the interactions with lifestyle are not dynamically captured, one might argue that the study design is characterized by highly stylized assumptions.

An entry point to stepping away from ad-hoc implementation could be found in extending the influence of contextual factors next to the common carbon price driven responses or by creating further boundaries to optimization. Information needs to become available on the diversities and heterogeneities of behavior (e.g. preferences, agents, geographies, influence of past experiences) and included in the model. Further research could also focus on integrating other principles from techniques that model behavioral diversities more explicitly (e.g. agent-based modeling).

3) *Limitations in integrated assessment*: Generally energy models have a stylized representation of energy and material demand, which is mostly based on historically observed correlations between economic activity, energy or material intensity and energy or product demand. Although various interrelations are included in the IMAGE model, such as the interaction between energy demand for space heating, floor space, heating degree days and heating intensity ($kJ_{UE}/m^2/HDD$) (Daioglou et al., 2012; Isaac and van Vuuren, 2009), these are generally limited to the feedbacks between energy demand, energy resources and energy prices. The result of this is that feedbacks between various sectors are limited (i.e. impact of reduced vehicle use and reduced floorspace on the automobile and cement industries is not represented). Furthermore, as behavioral diversities are based on exogenous socio-economic parameters, the effect of reduced consumption on these is also poorly represented.

It should be noted that the purpose of this study is to qualitatively assess the possible implications of lifestyle change in mitigation scenarios rather than quantifying the available potential exactly. Therefore, we consider these caveats to be not important in the light of the conclusions.

4.2. Barriers and policies for lifestyle change measures

Several real-life challenges also exist which limit the potential and up-take of lifestyle change. There are several factors that play a role in real-world implementation of the measures discussed in this study.

1) *Ability to adopt*: The ability to adopt certain lifestyle changes is highly dependent on contextual factors, such as the availability of knowledge, the available infrastructure, cultural norms and economic factors (Steg, 2008). As described in Csutora (2012), Gatersleben et al. (2002) and Tabi (2013), the energy demand for heating and electricity seems to some degree more closely related to socio-economic and demographic factors (e.g. income, household size, family composition) than any other factor. Willing individuals might therefore have limited space to dissociate itself from environmentally indifferent behavior.
2) *Tailored approach*: Generally a combination of regulatory, economic and information-based instruments ("policy packages") are more effective than single policy instruments (Rohde et al., 2012; OECD, 2008; Abrahamse et al., 2005). Although information campaigns achieve only modest changes in behavior, they are in particular effective for low cost and low effort changes (Steg, 2008). The participation rate could be increased by combining information-based tools with regulatory policy instruments, such as obligating the collection of waste as well as capping the use of plastic per capita. The effectiveness of economic instruments is more dichotomous, as they can be push (making environmental unfavorable behavior more expensive and subsequently less attractive) or pull incentives (making environmental behavior less expensive). Pull measures are perceived as more voluntary (freedom of choice) and are therefore more accepted, yet may be less effective than push measures because these are noncommittal in nature (Steg, 2008).
3) *Continuous priming*: Measures to overcome habitual behaviors are aimed at increasing the level of awareness, which require tailored and repeated knowledge until the desired change is acquired or in line with current (energy saving) trends (Lindén et al., 2006). Maintaining these changes in behavior is specifically challenging, as is illustrated in a multitude of behavioral phenomena that describe the return to habitual behavior (such as the drawback effect (EEA, 2013) or various change undermining behaviors (such as observed with the so-called rebound effect (Madlener and Alcott, 2009), boomerang effect (Harding and Rapson, 2013) or moral licensing (Tiefenbeck et al., 2013)).
4) *Extent*: As people are more familiar with ways to reduce direct energy use than indirect energy use, incentives to reduce energy demand in households are perceived as more favorable. Direct energy use has the benefit of being more easily monitored on meters in and around the house, whereas for indirect energy use it is unclear how far the extent reaches (Steg, 2008). This in particular creates obstacles in implementing lifestyle changes in, for example, sustainable consumption for which also substantial reduction potential is reported (in particular for reduced meat consumption) (Stehfest et al., 2009).

Introducing and sustaining lifestyle change is thus not as straightforward as a (prescriptive) modeling approach may suggest. The design of a successful policy strategy requires knowledge of all these factors that determine and sustain changes in specific behaviors.

5. Conclusion

This study aimed to explore the implications of various low-cost and directly implementable lifestyle changes in a 2 °C mitigation context. By using the IMAGE integrated assessment framework we have compared four scenarios in terms of secondary energy demand, carbon emission reductions and their economic potential to their reference case. The main conclusions of this study are:

This study presents a relatively simple method for assessing lifestyle changes measures in IMAGE. Integrated assessment models generally do not explicitly model behavior. Within the IMAGE framework behavioral heterogeneity can be embedded through mechanisms causing a specific order of preference based on (non-) energy prices and by capping or fixing other energy demand drivers. In this study we introduced lifestyle measures by changing key model parameters in line with estimates in literature. This method provides a relatively simple method to assess the implications of lifestyle change measures in an integrated assessment context. However, as socio-economic trends and various interactions between sectors are not dynamically captured in the model, study designs like these are characterized by highly stylized assumptions. In order to conduct more proper behaviorally-realistic modeling, information needs to become available on the diversities and heterogeneities of behavior (e.g. preferences, agents, geographies, influence of past experiences) and included in the model.

Lifestyle changes are most effective in the end-use sectors, leading to a CO_2 emission reduction potential of about 15% in the residential and 35% in the transport sector compared to baseline emissions. The results show that lifestyle change can impact fuel demand and carbon emissions both directly and indirectly in the residential sector, mainly through changing (water) heating habits and by reducing appliance energy use. These lifestyle changes can lead to a reduction of residential emissions by about 13% compared to the baseline assumptions. Furthermore, structural changes in travel behavior could reduce CO_2 emissions in the transport sector by about 35% in 2050 compared to baseline emissions. In the power sector, as well as the industry sector, lifestyle changes generally have an indirect impact — leading to negligible changes in fuel composition and emission reductions.

The effects of lifestyle change measures in mitigation scenarios are analogous to baseline scenarios but the overall impact is reduced. The lifestyle change measures considered in this study are on their own insufficient to meet the 2 °C climate objective. Moreover, as these changes do not impose large structural changes in the energy intensive sectors under both *Baseline* as *2 Degrees* assumptions, a 2 °C mitigation strategy remains dependent on technology-oriented policy measures. However, in mitigation scenarios, the contribution of lifestyle measures are dampened in the end-use sectors as the effectiveness overlaps with more technology-oriented measures.

Lifestyle change measures create opportunities to mitigate in sectors without more radical changes in (1) the energy infrastructure and (2) on the short term. This leads to a more cost-efficient mitigation strategy. By preemptively reducing energy demand and transitioning to electricity-driven end-use sectors, multiple opportunities are unlocked to mitigate in the more difficult to mitigate sectors. Moreover, it allows for a more gradual energy transition as lifestyle changes allow for a greater cumulative emission profile over the first half of the century. This is in particular reflected in the required carbon pricing that is USD$100/t$CO_2$ (or a sustained 15%) lower throughout the century under lifestyle assumptions than compared to the reference.

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Mariësse A.E. van Sluisveld is researcher at PBL Netherlands Environmental Assessment Agency and Utrecht University, the Netherlands. Her current work focuses on alternative transition pathways that meet long-term climate policy targets. She holds a degree in Sustainable Development with a major in Energy and Resources.

Sara Herreras Martínez holds a degree in Energy Science and a degree in Chemistry. She worked as a researcher as part of the IMAGE modeling team at the University of Utrecht, the Netherlands. She has major interest on the role of developing countries on climate change mitigation. Previously she worked at the consultancy Climate Focus giving advice on climate policies and climate finance.

Vassilis Daioglou is a PhD candidate at Utrecht University, the Netherlands, and PBL Netherlands Environmental Assessment Agency. His current research focuses on assessing the long term possibilities of using bioenergy for carbon dioxide emission mitigation. His interests lie in developing and using models that investigate the relations between energy–economy–environment.

Detlef P. van Vuuren is professor of integrated assessment of global environmental change at Utrecht University, the Netherlands, and senior researcher at PBL Netherlands Environmental Assessment Agency. His work concentrates on scenario analysis of response strategies to global environmental change issues. Detlef van Vuuren has published over 180 peer-reviewed articles and has been an author on a large number of integrated assessment reports.