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Halving energy demand from buildings: the impact of low consuming practices

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Abstract

Limiting global warming below 1.5°C requires rapid decarbonization of energy systems. Reductions of energy demand have an important role to play in a sustainable energy transition. Here we explore to what extent the emergence of low consuming energy practices, encompassing new behaviors and the adoption of more efficient technologies, can contribute to lowering energy demand and thereby to reducing CO2 emissions.

To this end, we design three detailed energy consumption profiles which could be adopted by individuals in current and future wealthy regions. To which extent do higher setpoint temperatures for air conditioners or the penetration of efficient showerheads reduce the aggregate energy demand? We investigate the potential of new practices at the global level for 2050 and 2100.

The adoption of new, energy saving practices could reduce global buildings' energy demand by up to 45% in 2050 and 59% in 2100 compared to a scenario following current trends. This strong reduction is primarily accounted for by changes in hot water usage, insulation of buildings and purchasing habits of space conditioning equipment. New behaviors and efficient technologies could make a significant long-term contribution to reducing buildings' energy demand, and thus facilitate achieving stringent climate change mitigation while limiting the adverse sustainability impacts from the energy supply system.

Keywords

Lifestyle changes, Behavioral changes, Energy consumption, Practices, Buildings' energy demand

Declarations of interest

The authors declare that there is no conflict of interests.

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1 Introduction

Limiting global warming below 1.5°C poses a great challenge to socio-economic structures across the world. On the one hand, geophysical studies revealed a proportional relationship between cumulative CO2 emissions and temperature increases (Matthews et al. 2009), which means that staying below 1.5°C global warming requires cumulated emissions to remain within a tight carbon budget (Rogelj et al. 2016). Carbon neutrality must therefore be reached by mid-century (Rogelj et al. 2015). On the other hand, the pace of emission reductions necessary for remaining below 2°C, and *a fortiori* below 1.5°C global warming, resembles only few examples in history (Riahi et al. 2015) and is unprecedented on a global scale.

Energy consumption in buildings accounted for one fifth of total CO2 emissions in 2010 (Lucon et al. 2014). These emissions resulted from both direct emissions released by on-site combustion of fossil fuels and biomass, as well as from indirect emissions attributed to electricity consumption in buildings and district heating. Reducing energy demand in buildings therefore constitutes an important strategy to decrease GHG emissions.

Many studies appraised the global potential for reduction of the energy consumed in buildings. Overall, they found this potential to be substantial (Lucon et al. 2014). However, these studies usually assessed the potential as a result of technological changes, leaving aside the impact of behavioral changes (*e.g* Chaturvedi et al. 2014; Teske et al. 2015; IEA 2016). Some other studies investigated the energy demand reduction potential following changes in lifestyles, while excluding technological changes. Thereby, these studies implied a dichotomy between technological and behavioral solutions (*e.g.* van Sluisveld et al. 2016; Ven et al. 2017).

However, this dichotomy between technological solutions and behavioral solutions to climate change overlooks the co-evolution of technologies and behaviors identified in several social theory frameworks. For instance, Steg and Vlek (2009), in a review of psychological studies focusing on the determinants of individual behavior, delineate three factors determining environmental behavior : individual motivations, habitual behavior, and contextual factors. The latter covers factors including physical infrastructure, technologies available on the markets and the characteristics of the technologies. Taking a more macro perspective, the socio-technical regime concept (Smith 2007; Geels et al. 2017) underlines that technical arrangements are embedded with links of social nature and that new technologies cannot advance without changes in purchase practices, daily uses, skills, etc. Drawing on these theories, but giving more weight to the individual perspective, Stephenson et al. (2010) conceived the Energy Cultures framework which encompasses the different dimensions of energy behaviors. In its terms, consumer energy behavior can be understood through the interactions between cognitive norms, material culture (technologies) and energy practices (activities, processes). Each dimension interacts with the others to shape the energy consuming behavior. For instance, the presence of an insulation layer on the external walls of a building will influence how much people heat, in which rooms, etc. Each dimension is influenced by different factors: education influences cognitive norms; energy prices affect energy practices, etc. By shifting one of these dimensions, it is possible to influence behaviors. The theory of practices (*e.g.* Shove and Walker 2010) constitutes another perspective on energy behaviors which insists on the inter-connectedness of many elements playing on the adoption and evolution of practices. Within this theoretical framework, Gram-Hanssen (2014) proposes to classify elements holding practices together within four categories: embodied habits, institutional knowledge, engagement (the meaning to people following practices) and technologies. There is therefore a widespread agreement across these various theories that technologies and behaviors are interdependent. For our purpose, this means that energy demand reduction potentials should consider technological and behavioral aspects alike.

Some analyses exploring the potential for reduction of energy demand already considered technological and behavioral approaches together. Taking an individual perspective, Dietz et al. (2009) considered all interventions US households could take to reduce their emissions, and therefore their energy demand, covering changes in technology purchase patterns as well as usage patterns. According to them, residential emissions could decrease by 20% within ten years if their measures were implemented. Anable et al. (2011) started from the assumption that behaviors change over time and that deep cuts in energy demand will require changes at the social level, implying new norms and conventions. From this premise, they imagine scenarios where people, motivated by concerns about energy use and environmental issues, change their consumption patterns as well as their technological choices. They find that the UK energy demand could decrease by 50% until 2050. More recently, Grubler et al. (2018) designed a low energy demand scenario at the global level. Despite the growing income and population in developing countries, their scenario also envisions a halving of buildings' energy demand until 2050,

In this paper, we investigate more closely the potential of new practices for the global buildings' energy demand. We design three individual energy consumption profiles which could prevail for individuals in current and future advanced economies. These profiles describe how people shower, heat or cool their dwellings and offices, insulate their buildings, etc. We hence focus on the question of how people consume energy, and not on the question of which factors drive them to change practices—like the influence of energy prices for instance. Two of these profiles display low consumption energy practices. With the Energy Demand Generator model (EDGE) — a bottom-up energy demand model projecting buildings' energy demand at the global scale for five energy services (Levesque et al. 2018) —, we can then appraise the impact of these contrasted energy practices on buildings' energy demand in 2050 and 2100.

We start with a description of the EDGE model. In the subsequent section, we present the scenarios for space heating, space cooling, water heating, cooking and appliances and light. We then turn to the results from the EDGE model, compare them with scenarios from other studies, before concluding.

2 Methodology

2.1 Description of the EDGE model

The Energy Demand GEnerator (EDGE) is an bottom-up energy demand model which currently focuses on the buildings sector (Levesque et al. 2018). It projects buildings' energy demand at the useful and final energy levels, distinguishing between five energy services and several energy carrier categories for European countries and ten other regions[1] covering the global demand. EDGE assumes

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[1] Africa, China, India, Japan, Middle East, South East Asia, Russia, the United States, Other OECD, Other non-OECD.

that consumption levels of energy services in developing countries, as these countries grow economically, will gradually converge to levels that developed countries currently have at similar per-capita income levels — adjusted for climate conditions. In developed countries, it assumes electric demand from appliances and lighting to increase with income levels, while space heating, space cooling, water heating and cooking are assumed to reach a saturation level. The model has been developed to cover a wide array of socio-economic trajectories. Socio-economic and behavioral assumptions are introduced through exogenous economic, population and climate projections but also through model parameters. EDGE is therefore able to provide a detailed representation of practices in buildings. All relevant equations in the model are explained in Levesque et al. (2018) and replicated in the Appendix.

2.2 Future scenarios for energy-consuming practices

In this section, we detail three scenarios for future energy consuming practices in buildings: a reference scenario (“Reference”), a low energy demand scenario (“Low”), and a very low energy demand scenario (“Very Low”). Energy practices in buildings cover a wide range of activities from taking a shower to the use of computers in a service company. For each scenario, we design a profile of energy practices, *i.e.* a combination of behaviors and technologies, and assess the repercussions at the global level for the consumption of energy in buildings. Each profile combines energy behaviors already existing in the sheer diversity of current consumption patterns (Lucon et al. 2014), and the adoption of technologies which either already exist, or whose development in the future is plausible.

We make assumptions about the energy consumed by these practices at the saturation level[2], *i.e.* when energy consumption is assumed not to rise anymore with increasing income. For instance, the temperature level maintained within built environment must revolve around values which are comfortable from a physiologic perspective. Once economic development allows for the achievement of a comfortable level, the indoor temperature is unlikely to correlate with further economic development. According to the dynamics of the EDGE model, the energy demand level in developing countries will converge towards this level as they catch up economically.

In addition to these assumptions, future energy demand will heavily depend on future population trends and income per capita projections. We use the demographic and economic projections from the SSP2—“Middle of the Road” — scenario (Dellink et al. 2017; KC and Lutz 2017), which assumes a continuation of historical patterns and was developed within the Shared Socio-economic Pathways framework (O’Neill et al. 2017). We assume that in all three scenarios, these projections will remain identical, *i.e.* we assume that changes in practices at the saturation level have no impact on the population and economic growth trajectories.

In the following, we will present our assumptions for space conditioning, water heating and appliances and lighting. We do not make any assumption for cooking practices at the saturation level as we assume there is only little room to change these practices in developed countries and because cooking represents only a small share of the demand in these regions —unlike in developing countries. However, cooking demand in developing countries will still converge towards developed countries’ patterns.

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[2] Except for appliances and lighting, where no saturation level is assumed in the model.

Our assumptions concentrate on the demand for useful energy. Except for space conditioning, we do no separate assumption for the final-to-useful energy efficiencies since there is only little room to improve these in developed countries. For space conditioning though, the efficiency of heat pumps and of air conditioning remains far from its theoretical optimum. There is therefore still room for large efficiency improvements, and we address this with our scenario assumptions.

2.2.1 Space conditioning

2.2.1.1 Indoor temperature

Indoor temperature is one of the most important drivers of the demand for heating and cooling. In the model EDGE however, indoor temperatures do not directly enter as model parameters, but rather indirectly via the computation of heating and cooling degree days (HDD and CDD, respectively). This computation requires a balance point to which outdoor temperatures are compared to derive the Degree Days. We will therefore derive the balance points for the Degree Days from our assumptions on comfortable indoor temperatures, internal heat gains and heterogeneity among people.

Comfortable indoor temperature

Thermal comfort is a key determinant of the satisfaction with the indoor environment. Two main models exist to account for the level of comfort corresponding with a given indoor temperature. The PMV model (Fanger 1970) explains thermal comfort as the result of heat transfers between the body and its environment. It takes six factors into account: the level of activity of the human body, clothing, air temperature, mean radiant temperature, air velocity and humidity. The model has been extended to better predict the comfort sensation reported by survey subjects by introducing a psychological parameter (Fanger and Toftum 2002).

On the other hand, Nicol and Humphreys (2002) take another approach and start from the observation that predictions from the PMV model, which are based on experiments in climate chambers, were not always successful in predicting comfort sensation in field studies. The authors assume a feedback between the climate and the adaptive behavior of individuals which explains why the range of comfortable temperatures might be large and vary across seasons and building set-ups. In particular, people might change their clothing, adjust the ventilation and shading of the building, depending on the climatic context. One important element influencing the range of comfortable temperatures is the ability to control the indoor temperature. Buildings with adaptive systems might therefore allow for a larger range of comfortable indoor temperatures. So, the extent to which adaptive strategies can broaden the range of comfortable temperatures depends on the heating and cooling systems in place, as well as whether or not the temperatures indoor tend to vary a lot across seasons (Rijal et al. 2017). Changing habits concerning desired indoor temperatures therefore necessitates technological systems which encourage indoor temperature variability while offering some controls to adapt. As an illustration, in a study assessing the thermal comfort in buildings complying with the *Setsuden* campaign in Japan, which required setting the temperature control to 28°C, the authors found that the design of buildings, which were built to run with air conditioning, was a limiting factor for the adoption of adaptive practices such as natural ventilation (Indraganti et al. 2013).

The incidence of temperature on thermal comfort, both in the PMV and in the adaptive model, is measured through reported comfort sensation by experiment subjects. However, the influence of indoor temperature may also be felt through the change in economic productivity (Hsiang 2010) or mental alertness (Tham and Willem 2010). This aspect is especially important as it used in studies assessing the future economic cost of global warming (Burke et al. 2015). Office managers might be more concerned by the influence of indoor temperatures on productivity than on the reported thermal comfort, as it directly affects firms' profits. Summarizing results from ergonomic studies on the relationship between indoor temperatures and performance loss, Hsiang (2010) finds that productivity starts declining above temperatures of 25-26°C.

Against this background, we consider that the future built environment, allowing for the adoption of adaptive strategies, will allow people to feel comfortable within a range of 19°C-26°C. This range slightly exceeds the 6°K interval reported in Rijal et al.(2017), but it is consistent with the range of comfortable temperatures between 17°C and 30°C given in Yang et al.(2014). It is also consistent with the temperature limit above which economic productivity declines. We chose our median estimates for indoor temperature within this range. Energy conserving practices will tend to be closer to the lower bound in the heating season and closer to the upper bound in the cooling season.

Internal Heat Gains

The discussion above pertains to the temperature people wish to have indoor. However, even without space conditioning, indoor and outdoor temperatures differ due to, among others, internal heat gains (IHG). IHG result from the metabolic activity of buildings' occupants, from the heat released during cooking and activities consuming hot water, from appliances as well as lighting. In countries where the climate would not, in principle, require demand for mechanical cooling, internal heat gains might justify the installation of air conditioning systems (Walker et al. 2014). IHG lead to higher indoor temperatures, depending upon the thermal insulation of the envelope. The better the insulation, the higher the temperature gains stemming from IHG. For the sake of simplicity, we assume IHG to contribute to a temperature increase of 3°C within buildings. Integrating the contributions of the different energy services and occupancy into the computation could be the focus of further research in the future. By adopting a static approach, and considering the growing demand for appliances and light projected in EDGE (Levesque et al. 2018), we might underestimate the impact of internal gains on indoor temperatures (Elsland et al. 2014), therefore overestimating space heating energy demand, and underestimating space cooling energy demand.

Heterogeneity

The functions representing energy demand for space conditioning in EDGE imply that in case the number of degree days is zero, the demand will also be zero. While this makes sense for the median behavior we have designed with the indoor temperatures and the IHG, the heterogeneity in behaviors makes this implausible. There will still be some heating (cooling) demand when the median behavior reaches its HDD (CDD) threshold because some people will have a higher (lower) preferred temperature. In order to account to some extent for the heterogeneity in the population, we shift the temperature balance point by 2°C.

HDD	Heating Season Indoor Temperature (°C)	Corresponding Outside Temperature (°C)	Threshold HDD after heterogeneity (°C)
Reference	22	19	21
Low	20	17	19
Very Low	19	16	18
CDD	Cooling Season Indoor Temperature (°C)	Corresponding Outside Temperature (°C)	Threshold CDD after heterogeneity (°C)
Reference	23	20	18
Low	25	22	20
Very Low	26	23	21

Internal Heat Gains (°C)	3
Heterogeneity (°C)	2

Table 1 Assumptions for the indoor temperature and Degree Days thresholds

2.2.1.2 Insulation of buildings

There are several channels through which the insulation of buildings could co-evolve with practices. First beyond its impact on indoor temperatures, insulation influences other aspects determining thermal comfort. Second, very efficient materials currently under development offer new properties and application opportunities beyond their mere thermal characteristics. These in turn could lead to new building designs and practices.

First, beyond its impact on energy requirements to meet a certain indoor temperature, insulation can have a positive impact on thermal comfort. As stated above, thermal comfort, according to the PMV theory, depends upon six factors including mean radiant temperature and air velocity. While insulation allows achieving higher indoor temperatures at a given level of energy consumption, it also allows improving other factors: the radiant temperature of surrounding surfaces and the air speed and turbulence. The insulation level of windows is especially influential in that respect as windows are currently the building components leading to the highest thermal losses, and the temperature difference between windows and the indoor temperature is therefore the largest. This temperature difference causes large radiant temperature exchanges as well as drafts, both leading to sensations of discomfort (Huizenga et al. 2006). Improved insulation can therefore increase the acceptance for reduced indoor temperatures. This is consistent with our assumption of lower indoor temperatures and an important mechanism for the Passive House concept, which aims at providing comfortable, low indoor temperatures (Passive Houses 2007; Cuce and Riffat 2015).

Second, very efficient materials under development might offer other properties which could shape new practices for buildings' developers and occupants. Traditional insulation materials such as mineral wool, expanded and extruded polystyrene reach thermal conductivity properties in the range of 0.03-0.04 W/(mK). Therefore, achieving low U-values for the building envelope necessitates thick insulation to compensate the high conductivity of concrete or bricks walls (Jelle 2011). State-of-the-art technologies including in particular vacuum insulation panels (VIP) and aerogels display thermal conductivities three to ten times lower than traditional materials and could therefore save a great amount of space to achieve similar or better levels of insulation. This property, combined with high costs for floor area in urbanized centers, makes highly isolating materials an attractive technology in expensive cities (Jelle 2011). The strong urbanization forecasted for the future could therefore offer a market opportunity for highly performant insulation material. Other properties such as the acoustic performance of building envelopes might lead people to increase the level of insulation. Aerogels perform well in this regard (Cuce et al. 2014; Schiavoni et al. 2016). Aerogels, in addition, may be opaque, translucent or transparent, possibly reconfiguring how insulation materials may be used.

Similarly to insulation building material, new technologies in windows offer prospects of large improvements in the U-values of windows. The estimates for current windows lie between 2 and 3.5 W/(m^2K) and new technologies ranging from triple glazing to aerogels reach U-values closer to 0.5 W/(m^2K).

In EDGE, U-value estimates are based on estimates for the European building stock. Estimates for other regions are derived by adjusting for climatic conditions and income levels in other regions. Because of this, we make our assumptions for the different scenarios based on assumptions for the European building stock.

We assume 2100 U-values for the whole building stock to decrease to 0.85 W/(m^2K) in the reference scenario, compared to 1.60 W/(m^2K) in 2015. As the average U-value of European buildings built between 2000-2010 is 0.85 (European Commission 2017), this is a conservative assumption, implying no further tightening of efficiency standards, but simply bringing old buildings to the current standard. In the Low and Very low demand scenarios, we assume tightened standards, driving U-values down to 0.45 W/(m^2K) in the Low demand scenario and 0.26 W/(m^2K) in the Very low demand scenario. Following the current trends, we therefore assume that the heat transfer coefficient of the envelope decreases by half in the reference scenario. The Low demand scenario shows a 72% decrease compared with the 2015 estimate and the Very low demand scenario shows a 84% decrease. More details on the assumptions can be found in the Appendix.

2.2.1.3 Efficiency of Heating and Cooling

Of all the technologies converting final energy to useful energy, heat pumps and air conditioning systems are probably the ones whose future might be most influential for energy demand. These technologies, unlike many others in buildings, remain far from their theoretical maximum[3]. Even on current markets in developed countries the efficiencies of air conditioners show a very broad range. Typical ranges spread from a SEER[4] (W/W) of 3 to a SEER of 8 (IEA 2018). Best available technologies reach a SEER up to 12, while market averages evolve around a SEER of 4.

Similarly to the scenarios from the IEA (2018), we assume that the efficiency of air conditioning systems will continue growing in the future. Starting from an historical value close to 3.7 for developed countries, we assume that the SEER will grow to 6 in Reference, 8 in Low and 10 in Very low. Thereby, we do not make assumptions beyond what currently best available technologies may deliver. Minimum energy efficiency standards and R&D investments could raise the efficiency of the air conditioners stock while maintaining prices of equipment affordable. There are already some examples of such policies: for instance in South East Asia, the ASEAN SHINE initiative aims at harmonizing air conditioner standards in ASEAN member countries, and at raising the efficiency of air conditioners available on the market (IEA 2017a).

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[3] As an example, the theoretical thermodynamic maximum for the coefficient of performance (COP, a performance index closely related to the Seasonal energy efficiency ratio (SEER)) of an air conditioner is 22.7, considering an indoor temperature of 22°C and an outdoor temperature of 35°C (22 +273.15)/(35-22)

[4] The Seasonal energy efficiency ratio (SEER) measures the ratio between the output cooling capacity and the electricity input, taking the seasonal range of outdoor temperatures into account. Here , as in IEA (2018), we use the definition of SEER in metric units (W/W).

For heat pumps, we assume a similar development for the SEER values as for the air conditioning systems. For the penetration of heat pumps, we assume that it will reach 30% of the *electric* heating demand in the Reference scenario, 50% in the Low Demand scenario, and 70% in the Very Low demand scenario.

2.2.1.4 Floor space demand

In EDGE, floor space demand increases with income per capita and decreases with population density. Future projections follow historical patterns and continue increasing with economic income without saturation. However, the increase of floor space demand in reaction to an income increment weakens at higher income levels and over time.

Other trajectories which would cut the tie between economic wealth and floor space demand are however possible. People might prefer living in cities with short distances between workplaces, dwellings, and recreational places, thus favoring compact cities, at the expense of large dwellings. More people might share their flats or houses so that the number of persons per dwelling increases. Urban policies such as zoning policies could help managing the expansion of cities and regulate their densities, reducing the floor space area per capita. In the Low demand scenario, we introduce a cap on the residential and commercial area per capita at the current level of demand from the United States (approximately 70 m^2/cap for the residential demand and 23 m^2/cap for commercial area). In the Very Low Demand scenario, the cap corresponds to Japanese levels (approximately 45 m^2/cap and 15 m^2/cap for residential and commercial, respectively).

2.2.2 Water Heating

Hot water is mostly needed for personal hygiene and washing clothes. In the United states, about half of the hot water was dedicated to washing clothes, 40% for personal hygiene and 3% for washing dishes (Inskeep and Attari 2014). There also exists a demand for hot water in public and commercial buildings—*e.g.* in hotels, laundry, restaurants, hospitals— but we were not able to find estimates for the consumption in these buildings. The discussion will therefore focus on residential uses.

Hot water usage can be lowered in many ways: people can spend less time under the shower, avoid taking baths, use low-flow shower heads, or they can shower with lower temperatures, etc. Efficiency standards for the white appliances market could also encourage the penetration of efficient models. In the next paragraphs we review our assumptions for each energy service. All assumptions are further detailed in the Appendix.

2.2.2.1 Personal hygiene

Currently in the United States, people spend an approximate 8 minutes per day under the shower and shower once a day (Inskeep and Attari 2014). As personal hygiene habits have varied in the past (Hand et al. 2005), we could assume that the saturation level could continue to change in the future. We assume that the saturation level in the reference case will remain at the level assumed for 2015. In addition we assume showerheads' flow rates of 9.5 L/min which is equivalent to the 2.5 g/min standard in the United States, and a temperature elevation from 15°C to 40°C. In the other scenarios, people are assumed to dedicate less time to showering. They shower once a day for five minutes in the Low Demand scenario, and four minutes every other day in the Very Low Demand scenario. They also adopt very efficient showerheads (7.6 L/min and 2.8 L/min). By comparison, the current WaterSense label in the United States requires showerheads' flow rates to fall below 7.6 L/min (2 g/min) while most efficient products rated by WaterSense reach as low as 3.8 L/min (1 g/min).

Most efficient products rated by the Australian Water Efficient Labels and Standards consume as low as 5 L/min. Newly developed products consume as little as 2.8 L/min.

The water demand for showering at the saturation level drops from 76 L/day/cap in the reference scenario, to 38 L/day/cap in the Low Demand scenario and 5.7 L/day/cap in the Very Low Demand scenario.

2.2.2.2 Clothes washing

Next to showering and bathing, cleanliness of clothes is one of the activities consuming the most hot water. In the reference case, we assume each individual to launch two wash cycles a week. Each cycle consumes 87 L (23 g/cycle) — the current consumption for a standard machine in the USA (Energy Star 2018) — and raises the water temperature from 15°C to an assumed 70°C. In the Low Demand scenario, people tend to wear clothes several times before washing them and halve the number of cycles per week to one. The water consumption within a cycle drops to 50 L (13 g/cycle), the consumption of Energy Star appliances, and the temperature to 40°C instead of 70°C. In the Very Low demand scenario, the water consumption decreases to 40 L per cycle, the value of efficient clothes washers on today's German market. The temperature of cycles is assumed to be 30°C.

The water demand in each scenario is 25 L/cap/day, 7 L/cap/day and 5.7 L/cap/day in the reference, Low Demand and Very Low Demand scenarios, respectively.

2.2.2.3 Dishwashers and faucets usage

Dishwashers and faucets usage are other sources of hot water consumption, though they are not as important as the first two services.

We assume that people will use dishwasher to wash their dishes at the saturation level. The efficiency of dishwasher varies greatly on today's markets. Habits can also play a role in reducing the demand of hot water. Avoiding rinsing dishes before placing them in the dishwasher or starting a wash cycle only for full loads help reducing hot water consumption. Here we assume that the number of wash cycles per capita will decline from the reference scenario to the Low Demand and Very Low demand scenarios. The efficiency of dishwasher is also expected to increase and the temperature used to wash dishes to decrease. Usage of faucets cover water demand for washing hands, for cooking, to clean vegetables, wash dishes not washable in the dishwasher, shaving, tooth brushing. The aggregate demand for hot water from faucets and dishwashers is estimated to be 10, 5 and 3 L/cap/day for the reference, Low Demand and Very Low demand scenarios.

2.2.2.4 Total demand for hot water

Adding up across all individual services, the demand for hot water is assumed to saturate at 111, 50 and 14 L/cap/day in the three scenarios. However, we only considered residential uses in the preceding paragraphs. As stated above, we were not able to find relevant data for the hot water consumption in other types of buildings including hotels, restaurants, laundry, etc. We make the arbitrary assumption that in regions reaching saturation of the demand, non-residential buildings use 5% of the residential demand. So, the demand for hot water in buildings is assumed to be 116, 52 and 15 L/cap/day. Considering the temperature elevation of water assumed for each service and scenario, these amounts of hot water correspond to energy demands of approximately 16, 5 and 1 MJ/cap/day. Thus, the low consumption lifestyles scenario uses as little as 13% of the reference demand level.

2.2.3 Appliances and Lighting

There are large heterogeneities in energy demand for appliances across regions, even between developed countries. According to our estimates adapted from IEA statistics (IEA 2015, 2017b, c), the 2015 demand for lighting and appliances in buildings was 1850 kWh/cap/yr in Europe, 2650 kWh/cap/yr in Japan, and 5200 kWh/cap/yr in the United States, while income levels per capita in Europe and Japan were comparable and were 25% lower than in the United States. These differences can be explained by varying ownership rates, penetration levels of new appliances, usage of appliances, energy wastage patterns, efficiency levels of appliances, and to the varying importance of the service sector in the economy.

Energy consumption for appliances and lighting can be reduced through many channels, as past policies and empirical studies have demonstrated. Information policies have proven a sound way of decreasing electricity consumption (Delmas et al. 2013), though feedback on consumption must be repeated over time to sustain limited power consumption reductions (Allcott and Rogers 2014). The framing of information messages can greatly alter the impact of information campaigns. For instance, information about monetary losses from overconsumption can lead to a licensing effect: consumers feel entitled to consume as they pay for it and may increase their consumption if they feel that consumption does not cost much (Delmas et al. 2013). By contrast, delivering information on environmental benefits from saving energy can yield higher savings (Asensio and Delmas 2015). All these feedback policies however need accurate information on electricity consumption, which necessitates the deployment of (smart) metering devices.

Stand-by electricity consumption from appliances can represent a significant share of residential electricity consumption — 11% in Europe (de Almeida et al. 2011) —, though it does not deliver energy services. The *One-watt Initiative* launched by the IEA at the turn of the century helped reducing stand-by power consumption of many appliances. The recent development of networked appliances poses new challenges for both appliances stand-by consumption and data centers. Similar efforts as for the stand-by consumption of traditional appliances could deliver large energy demand reductions (IEA 2013a).

Furthermore, market regulations and labelling policies can do a lot to change consumers' purchasing patterns. As shown by Grubb et al. (2014), mandatory efficiency labels quickly transformed appliances markets in the past. In the case of refrigerators in the Europe, the EU labeling policy, complemented with rebate and information programs, drove the market share of most efficient appliances from 5 to almost 60% within a decade. Other examples, including the *Top runner* program in Japan, the *Energy Star* program in the US or the *Energy Rating* in Australia raised the energy efficiency of appliances in the past (IEA 2013b).

The representation of appliances and lighting in EDGE is too synthetic to relate energy demand to concrete practices. However, the success of former policies to raise the penetration of efficient appliances and lighting fixtures suggests that new purchasing habits and market reforms can continue encouraging a shift towards low consumption patterns.

In the reference scenario of the EDGE model, the assumed income dependency of appliances and lighting converges towards a Japanese development with a demand of approximately 2650 kWh/cap/yr for an income level of US$35000. In the Very Low Demand scenario, we assume that income-dependent demand converges to a European trajectory —approximately

1850 kWh/cap/yr for the same income level — and assume a 30% decrease compared to the reference. The Low Demand scenario assumption lies in-between both cases and assumes a 15% decrease.

2.2.4 Timing

We assume that most of these changes will be effective by 2050. For the insulation and space conditioning equipment, we assume the full reduction will be achieved only by 2100, due to the inertia of the building stock.

3 Results

In this section, we assess the impact of the different energy consuming profiles on buildings' energy consumption. We first present the scenario results for final energy demand at the global level. Second, we attribute the differences observed across scenarios to individual changes in practices in order to evaluate which changes seem the most influential. Thirdly, we compare the impact of changes in practices with projections from other exercises.

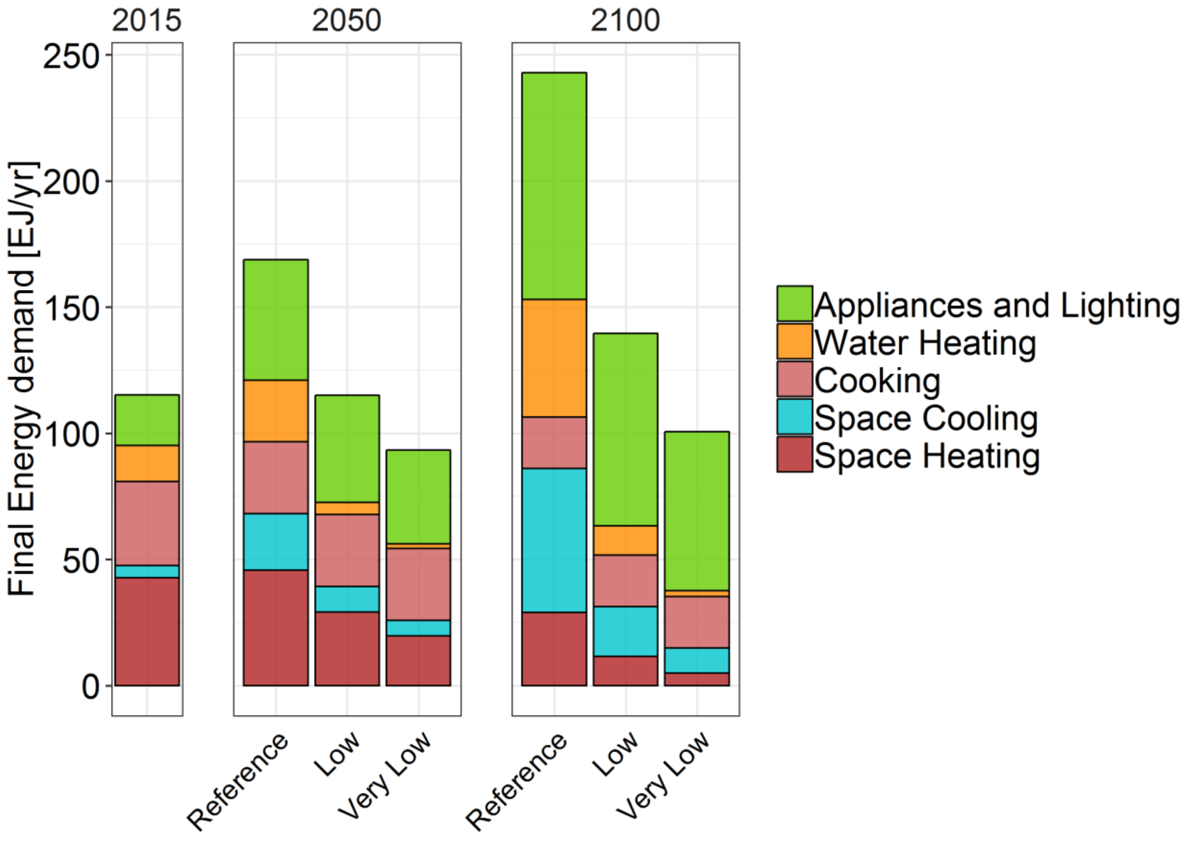

Figure 1: Final energy demand by end-uses for historical values as well as for the three practices scenarios.

Error! Reference source not found. displays the final energy demand in all three scenarios for 2015, 2050 and 2100. In 2015, the global demand amounted to 115 Ej/yr. The largest share of the demand was dedicated to space heating (37%). Cooking was another important service (29%), due to the widespread use of inefficient traditional biomass in developing countries. In 2050, the reference scenario shows a strong increase in the aggregate demand (+ 47%) spurred by a growth in appliances and lighting consumption, space cooling and water heating. In 2100, this pattern is accentuated with a doubling of the demand compared to 2015 (+111%), explained mostly by appliances and lighting (90 EJ/yr against 20 EJ/yr), space cooling (57 EJ/yr against 5 EJ/yr) and water heating (47 EJ/yr against 14 EJ/yr). The importance of the main energy services in 2015, space heating and cooking, strongly declines in the long term (12% and 8%, respectively).

Changes in practices assumed in the Low and Very Low energy demand scenarios transform the picture observed in the reference case. First, the increase in energy demand is much milder compared to 2015. The demand stagnates or decline between 2015 and 2050, while it rises modestly or declines up to 2100 (+21% for the Low scenario, and -13% for the Very Low scenario). Compared with the reference scenario, it means that changes in practices imply a decrease in energy demand of 32% and 45% in 2050, and 43% and 59% in 2100, for the Low and Very Low scenario, respectively. The impact of changes in practices on energy demand is therefore substantial.

Second, we evaluate the contribution of each change in practices. Even though these changes might be interdependent, especially the indoor temperature and the degree of insulation, we attribute the reduction in energy demand to individual dimensions of the practices. The decomposition follows the methodology presented in Sun and Ang (2000) and further explained in the Appendix. Figure 2 shows that the majority of the reduction in demand can be accounted for by space conditioning measures, mostly the improvement of the building envelope and by the adoption of efficient heat pumps and air conditioners. Another important part of the reduction in energy demand can be explained by water conservation measures and habits. Floor space demand reductions contribute only moderately compared with changed practices in indoor temperature and appliances and lighting.

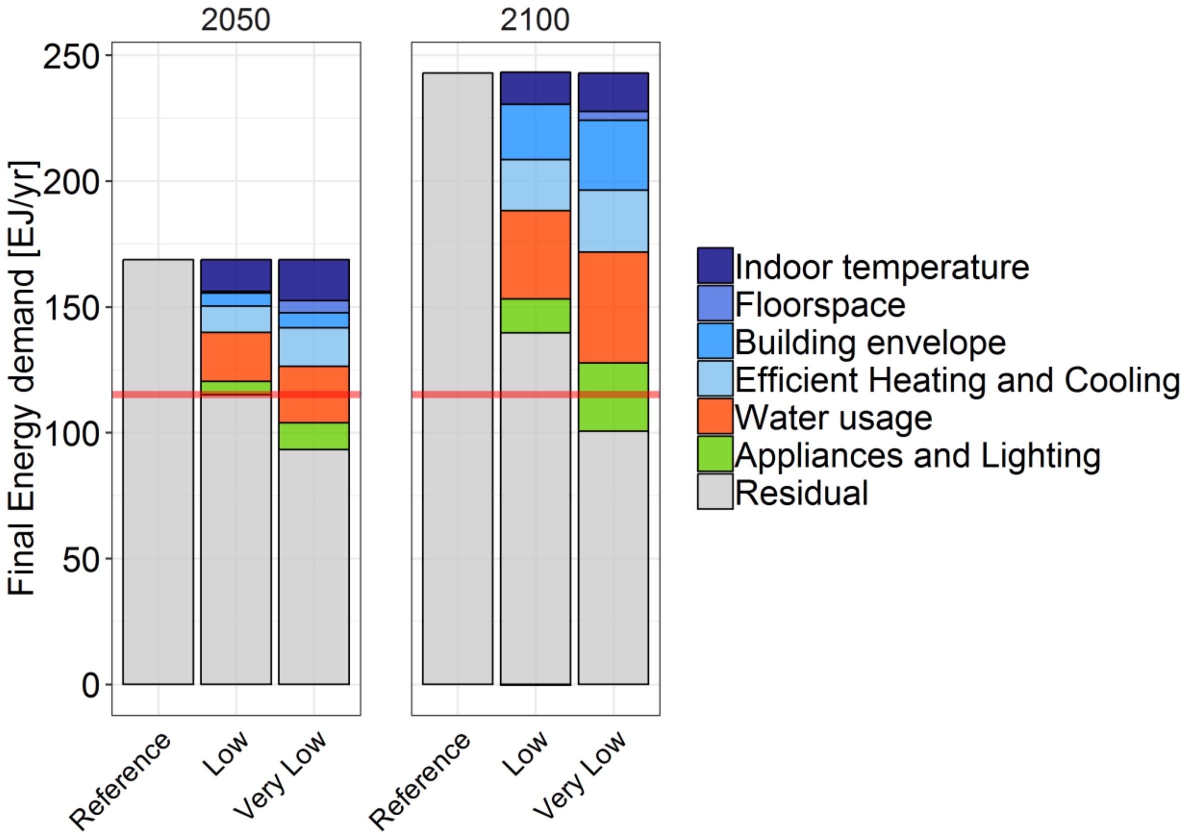

Figure 2 Contribution of individual aspects of changes in practices to decrease in energy demand compared to the reference scenario. The grey bar shows the final energy demand in each scenario. The red line gives the 2015 demand.

Thirdly, we compare the EDGE scenarios with other scenarios available in the literature. Figure 3 shows the reference and policy scenarios from the Integrated Assessment Model (IAM) REMIND (ADVANCE 2016; Luderer et al. 2018), the Energy Technology Perspectives (ETP, IEA 2017c), the IAM MESSAGE (Grubler et al. 2018) and the Greenpeace [R]evolution report (Teske et al. 2015). The Very Low scenario from EDGE slightly exceeds the reductions from the ETP B2DS scenario as well as from the Greenpeace [R]evolution scenario (-19% vs -7% and -8%). However it remains far from the reduction observed in the MESSAGE LED scenario (-43%), which is explained by differences in the demand for thermal needs (space conditioning, water heating, cooking), much lower in the LED scenario.

By construction EDGE and REMIND share a similar reference trajectory (see Appendix for more details). However the level of energy demand in the REMIND 1.5°C scenario is much higher than in both EDGE low consumption scenarios. This applies to 2050 (- 24% vs -31% and -45%), but is even more pronounced in 2100 (-15% vs -42% and -58%).

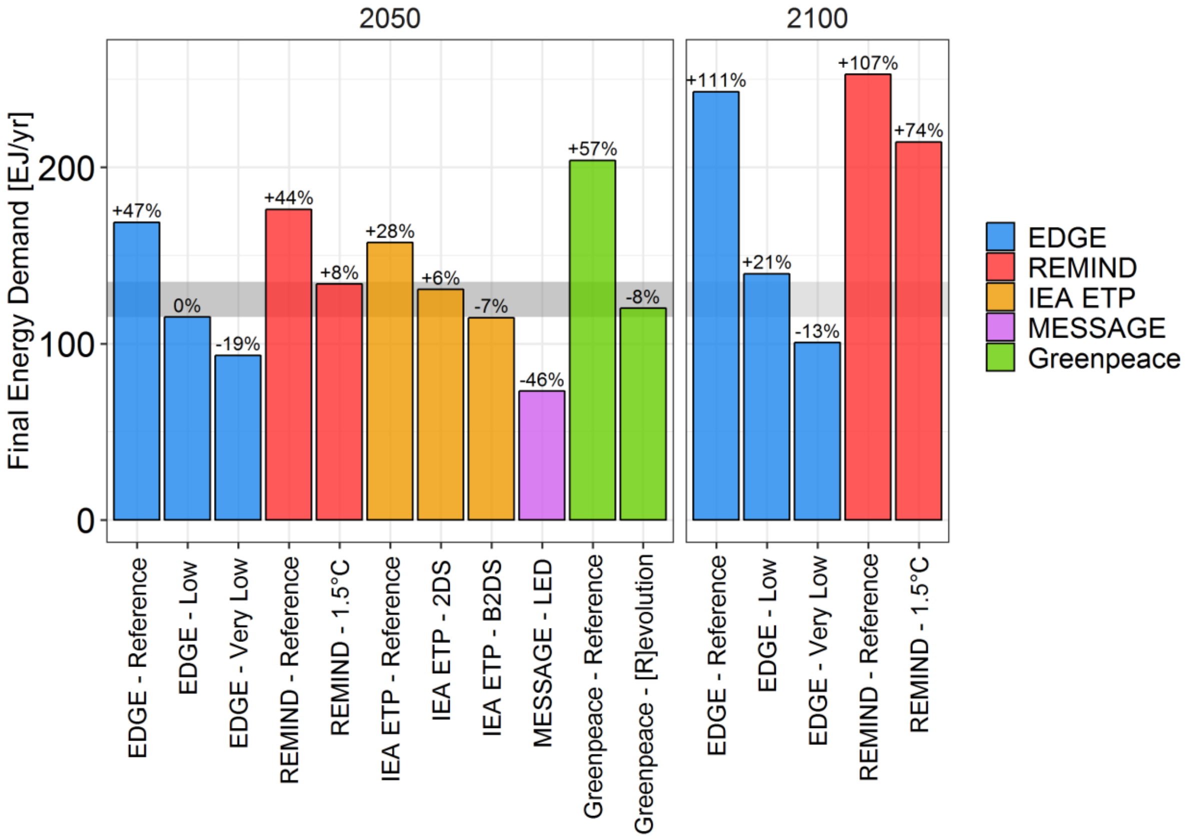

Figure 3 Buildings‘ final energy demand in 2050 and 2100 in various scenarios. The grey shaded area represents the range of historical values in the different models (2015 in EDGE and REMIND, 2014 in IEA ETP, 2020 in MESSAGE, 2012 for Greenpeace). The figures on top of the bars show the difference compared to the last historical value for each model. The REMIND reference scenario has been calibrated to approximately match the EDGE reference scenario. IEA ETP is taken from the IEA (2017c). The reference scenario refers to the Reference Technology Scenario, the 2DS to the 2°C Scenario and the B2DS to the Beyond 2°C Scenario. The LED scenario is taken from Grubler et al (2018) while the Greenpeace scenarios come from Teske et al. (2015).

4 Discussion

The adoption of new behaviors and technologies in buildings could have a large impact on energy demand. By 2100, it could lead to a reduction in final energy of 59%. This energy savings potential could leave energy demand in buildings below its 2015 value and avoid the doubling that is projected in the reference scenario as a consequence of socio-economic developments.

The reduction in energy demand are most importantly driven by changes in water consuming activities, new practices in the insulation of buildings, the penetration of efficient heat pumps and air conditioners. The adoption of behaviors reducing the time spent under the shower with water saving showerheads, the penetration of efficient washing machines and their reduced use could lead hot water consumption to decrease from 116 L/day/cap in the reference to a mere 15 L/day/cap. In Europe, the thermal conductivity of buildings constructed after 2000 greatly outperforms the average of the buildings’ stock, reflecting new practices in the construction sector. If this trend continues and similarly happens in other regions, with the adoption of new insulation materials, the quality of buildings’ envelopes could improve a great deal in the future. The average efficiency of air conditioners purchased today is by large below the state-of-the-art models available. Minimum

Energy Performance standards or labelling policies, by encouraging the uptake of efficient equipment could make a dent in energy demand.

Low consuming practices can achieve energy demand reductions which are much larger than in the REMIND 1.5°C scenario. The REMIND 1.5°C scenario ensures the energy system is consistent with a 1.5°C climate target at the lowest cost for the energy system. The moderate demand response in REMIND comes from the fact that energy prices only slightly increase in the 1.5°C scenario compared to the reference scenario (+ 25% in 2100). This means on the one hand, that achieving the 1.5°C target could be compatible with only moderate changes in energy practices; on the other hand, that changes in practices can alleviate the pressure on the energy supply to meet stringent climate targets and can lower the requirement to use the hotly debated carbon dioxide removal technologies (Smith et al. 2015; Vuuren et al. 2018; Grubler et al. 2018).

5 Conclusion

In this article, we explore the impact that the adoption of low consuming practices by individuals could have on the aggregate buildings' energy demand. Energy practices englobe both new technological choices and new behaviors in the use of these technologies. The practices considered here range from showering habits and technologies to the choice of indoor temperatures. We design three distinct consumption profiles and assess the outcome for global buildings' energy demand by 2050 and 2100.

We find that the adoption of low consuming practices can lead to energy demand reductions as large as 59% in 2100, which means that energy consumption from activities in buildings would decrease by 13% compared to the 2015 level, instead of rising by 111%. The decrease in energy demand is driven by new practices for hot water usage, insulation and by the increased use of efficient air conditioners and heat pumps. The lower floor space demand contributes only to a lesser extent.

The comparison with the REMIND 1.5°C scenario showed that moderate changes in practices might be compatible with a 1.5°C trajectory. But low consuming practices could greatly decrease the pressure on the energy supply system and reduce the adverse effects from a full decarbonization of energy supply.

6 References

ADVANCE (2016) Reference card - REMIND - ADVANCE. http://themasites.pbl.nl/models/advance/index.php/Reference_card_-_REMIND. Accessed 23 Oct 2017

Allcott H, Rogers T (2014) The short-run and long-run effects of behavioral interventions: Experimental evidence from energy conservation. The American Economic Review 104:3003–3037

Anable J, Brand C, Eyre N, et al (2011) Lifestyle and energy consumption. UKERC Report

Asensio OI, Delmas MA (2015) Nonprice incentives and energy conservation. Proceedings of the National Academy of Sciences of the United States of America 112:E510–E515. doi: 10.1073/pnas.1401880112

Burke M, Hsiang SM, Miguel E (2015) Global non-linear effect of temperature on economic production. Nature 527:235–239. doi: 10.1038/nature15725

Chaturvedi V, Eom J, Clarke LE, Shukla PR (2014) Long term building energy demand for India: Disaggregating end use energy services in an integrated assessment modeling framework. Energy Policy 64:226–242

Cuce E, Cuce PM, Wood CJ, Riffat SB (2014) Toward aerogel based thermal superinsulation in buildings: A comprehensive review. Renewable and Sustainable Energy Reviews 34:273–299. doi: 10.1016/j.rser.2014.03.017

Cuce E, Riffat SB (2015) A state-of-the-art review on innovative glazing technologies. Renewable and Sustainable Energy Reviews 41:695–714. doi: 10.1016/j.rser.2014.08.084

de Almeida A, Fonseca P, Schlomann B, Feilberg N (2011) Characterization of the household electricity consumption in the EU, potential energy savings and specific policy recommendations. Energy and Buildings 43:1884–1894. doi: 10.1016/j.enbuild.2011.03.027

Dellink R, Chateau J, Lanzi E, Magné B (2017) Long-term economic growth projections in the Shared Socioeconomic Pathways. Global Environmental Change 42:200–214. doi: 10.1016/j.gloenvcha.2015.06.004

Delmas MA, Fischlein M, Asensio OI (2013) Information strategies and energy conservation behavior: A meta-analysis of experimental studies from 1975 to 2012. Energy Policy 61:729–739. doi: 10.1016/j.enpol.2013.05.109

Dietz T, Gardner GT, Gilligan J, et al (2009) Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. Proceedings of the National Academy of Sciences 106:18452–18456

Elsland R, Peksen I, Wietschel M (2014) Are Internal Heat Gains Underestimated in Thermal Performance Evaluation of Buildings? Energy Procedia 62:32–41. doi: 10.1016/j.egypro.2014.12.364

Energy Star (2018) Clothes Washers. https://www.energystar.gov/products/appliances/clothes_washers. Accessed 13 Mar 2018

European Commission (2017) EU Buildings Database - Energy - European Commission. http://ec.europa.eu/energy/en/eu-buildings-database

Fanger PO (1970) Thermal comfort. Analysis and applications in environmental engineering. Thermal comfort Analysis and applications in environmental engineering

Fanger PO, Toftum J (2002) Extension of the PMV model to non-air-conditioned buildings in warm climates. Energy and buildings 34:533–536

Geels FW, Sovacool BK, Schwanen T, Sorrell S (2017) Sociotechnical transitions for deep decarbonization. Science 357:1242–1244. doi: 10.1126/science.aao3760

Gram-Hanssen K (2014) New needs for better understanding of household's energy consumption–behaviour, lifestyle or practices? Architectural Engineering and Design Management 10:91–107

Grubb M, Hourcade J-C, Neuhoff K (2014) Planetary economics. Routledge London

Grubler A, Wilson C, Bento N, et al (2018) A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nature Energy 3:515–527. doi: 10.1038/s41560-018-0172-6

Hand M, Shove E, Southerton D (2005) Explaining showering: A discussion of the material, conventional, and temporal dimensions of practice. Sociological Research Online 10:1–13

Hsiang SM (2010) Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. Proceedings of the National Academy of sciences 107:15367–15372

Huizenga C, Zhang H, Mattelaer P, et al (2006) Window performance for human thermal comfort

IEA (2016) Energy Technology Perspectives 2016. Organisation for Economic Co-operation and Development, Paris

IEA (2018) The Future of Cooling. International Energy Agency, Paris

IEA (2017a) Energy Efficiency Market Report 2017. International Energy Agency, Paris, France

IEA (2015) World Energy Outlook 2015. International Energy Agency, Paris, France

IEA (2017b) World energy balances. In: IEA World Energy Statistics and Balances. https://doi.org/10.1787/data-00512-en. Accessed 3 Jul 2018

IEA (2017c) Energy Technology Perspectives 2017: Catalyzing Energy Technology Transformations. International Energy Agency, Paris

IEA (2013a) January: Powering down to save energy need not be a turn-off. http://www.iea.org/newsroom/news/2013/january/powering-down-to-save-energy-need-not-be-a-turn-off.html. Accessed 29 Oct 2017

IEA (2013b) Transition to Sustainable Buildings: Strategies and Opportunities to 2050. International Energy Agency, Paris

Indraganti M, Ooka R, Rijal HB (2013) Thermal comfort in offices in summer: findings from a field study under the 'setsuden'conditions in Tokyo, Japan. Building and Environment 61:114–132

Inskeep BD, Attari SZ (2014) The water short list: The most effective actions US households can take to curb water use. Environment: Science and policy for sustainable development 56:4–15

Jelle BP (2011) Traditional, state-of-the-art and future thermal building insulation materials and solutions – Properties, requirements and possibilities. Energy and Buildings 43:2549–2563. doi: 10.1016/j.enbuild.2011.05.015

KC S, Lutz W (2017) The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Global Environmental Change 42:181–192. doi: 10.1016/j.gloenvcha.2014.06.004

Levesque A, Pietzcker RC, Baumstark L, et al (2018) How much energy will buildings consume in 2100? A global perspective within a scenario framework. Energy 148:514–527. doi: 10.1016/j.energy.2018.01.139

Lucon O, Ürge-Vorsatz D, Zain Ahmed A, et al (2014) Buildings. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Luderer G, Vrontisi Z, Bertram C, et al (2018) Residual fossil CO2 emissions in 1.5–2 °C pathways. Nature Climate Change 8:626–633. doi: 10.1038/s41558-018-0198-6

Matthews HD, Gillett NP, Stott PA, Zickfeld K (2009) The proportionality of global warming to cumulative carbon emissions. Nature 459:829–832. doi: 10.1038/nature08047

Nicol JF, Humphreys MA (2002) Adaptive thermal comfort and sustainable thermal standards for buildings. Energy and buildings 34:563–572

O'Neill BC, Kriegler E, Ebi KL, et al (2017) The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change 42:169–180. doi: 10.1016/j.gloenvcha.2015.01.004

Passive Houses (2007) Information on Passive Houses. http://passiv.de/former_conferences/Passive_House_E/passivehouse.html. Accessed 7 Mar 2018

Riahi K, Kriegler E, Johnson N, et al (2015) Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. Technological Forecasting and Social Change 90:8–23. doi: 10.1016/j.techfore.2013.09.016

Rijal HB, Humphreys MA, Nicol JF (2017) Towards an adaptive model for thermal comfort in Japanese offices. Building Research & Information 45:717–729

Rogelj J, Luderer G, Pietzcker RC, et al (2015) Energy system transformations for limiting end-of-century warming to below 1.5 °C. Nature Clim Change 5:519–527. doi: 10.1038/nclimate2572

Rogelj J, Schaeffer M, Friedlingstein P, et al (2016) Differences between carbon budget estimates unravelled. Nature Climate Change 6:245–252. doi: 10.1038/nclimate2868

Schiavoni S, D′Alessandro F, Bianchi F, Asdrubali F (2016) Insulation materials for the building sector: A review and comparative analysis. Renewable and Sustainable Energy Reviews 62:988–1011. doi: 10.1016/j.rser.2016.05.045

Shove E, Walker G (2010) Governing transitions in the sustainability of everyday life. Research policy 39:471–476

Smith A (2007) Translating sustainabilities between green niches and socio-technical regimes. Technology analysis & strategic management 19:427–450

Smith P, Davis SJ, Creutzig F, et al (2015) Biophysical and economic limits to negative CO2 emissions. Nature Climate Change 6:42–50. doi: 10.1038/nclimate2870

Steg L, Vlek C (2009) Encouraging pro-environmental behaviour: An integrative review and research agenda. Journal of environmental psychology 29:309–317

Stephenson J, Barton B, Carrington G, et al (2010) Energy cultures: A framework for understanding energy behaviours. Energy Policy 38:6120–6129. doi: 10.1016/j.enpol.2010.05.069

Sun JW, Ang BW (2000) Some properties of an exact energy decomposition model. Energy 25:1177–1188. doi: 10.1016/S0360-5442(00)00038-4

Teske S, Sawyer S, Schäfer O, et al (2015) Energy [r] evolution-a sustainable world energy outlook 2015. Greenpeace International and SolarPowerEurope and Global Wind Energy Council

Tham KW, Willem HC (2010) Room air temperature affects occupants’ physiology, perceptions and mental alertness. Building and Environment 45:40–44. doi: 10.1016/j.buildenv.2009.04.002

van Sluisveld MAE, Martínez SH, Daioglou V, van Vuuren DP (2016) Exploring the implications of lifestyle change in 2°C mitigation scenarios using the IMAGE integrated assessment model. Technological Forecasting and Social Change 102:309–319. doi: 10.1016/j.techfore.2015.08.013

Ven D-J van de, González-Eguino M, Arto I (2017) The potential of behavioural change for climate change mitigation: a case study for the European Union. Mitig Adapt Strateg Glob Change 1–34. doi: 10.1007/s11027-017-9763-y

Vuuren DP van, Stehfest E, Gernaat DEHJ, et al (2018) Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. Nature Climate Change 1. doi: 10.1038/s41558-018-0119-8

Walker G, Shove E, Brown S (2014) How does air conditioning become ‘needed’? A case study of routes, rationales and dynamics. Energy Research & Social Science 4:1–9

Yang L, Yan H, Lam JC (2014) Thermal comfort and building energy consumption implications – A review. Applied Energy 115:164–173. doi: 10.1016/j.apenergy.2013.10.062

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Appendix

1. Energy practices assumptions and EDGE modelling

In the following we detail the EDGE functions representing the consumption of energy services and we explain the assumptions made for the different energy practices.

1.1. Space conditioning

Space conditioning comprises both space heating and space cooling demands. In EDGE, space heating (SH) is a function of floor space (F), the quality of the buildings' envelope ($Uvalue$), and the Heating Degree Days (HDD). The parameter δ is a constant:

$$\frac{SH}{F \times Uvalue} = \delta \times HDD \tag{1}$$

Space Conditioning (SC) is a function of floor space (F), the quality of the buildings' envelope ($Uvalue$), income (I) and the Cooling Degree Days (CDD). The relation to CDD is non-linear since for a low amount of CDD, the penetration of cooling equipment will be low ($ClimateMaximum(CDD)$).

$$\frac{SC}{F \times Uvalue} = CDD \times ClimateMaximum(CDD) \times \frac{\phi_1}{1 + exp\left[\frac{\phi_2 - I}{\phi_3}\right]} \tag{2}$$

$$ClimateMaximum(CDD) = 1 - 0.949 \times e^{-0.00187 \times CDD} \tag{3}$$

1.1.1. Indoor temperature

HDD	Heating Season Indoor Temperature (°C)	Corresponding Outside Temperature (°C)	Threshold HDD after heterogeneity (°C)
Reference	22	19	22
Low	21	18	21
Very Low	20	17	20
CDD	Cooling Season Indoor Temperature (°C)	Corresponding Outside Temperature (°C)	Threshold CDD after heterogeneity (°C)
Reference	24	21	18
Low	25	22	19
Very Low	26	23	20

Internal Heat Gains (°C)	3
Heterogeneity (°C)	3

Table 2 Assumptions underlying the Degree Days thresholds

1.1.2. Insulation of buildings

Scenario	Building's component	Thermal conductivity of wall (W/mK)	Thickness of wall (m)	R wall (Km2/W)	Thermal conductivity of insulation (W/mK)	Thickness of insulation (m)	R insulation (Km2/W)	Rall (Km2/W)	Uall (W/Km2)	U-value (W/Km2)	Source
Current	Walls	1.70	0.40	0.24	0.04	0.02	0.66	0.89	1.12	**1.12**	EU Buildings Database Average
	Windows									**3.25**	EU Buildings Database Average
	Envelope									**1.60**	EU Buildings Database Average
Reference	Walls	1.70	0.40	0.24	0.04	0.07	1.99	2.22	0.45	**0.45**	EU Buildings Database 2000-2010
	Windows									**2.00**	EU Buildings Database 2000-2010
	Envelope									**0.85**	EU Buildings Database 2000-2010
Low	Walls	1.20	0.40	0.33	0.02	0.05	2.50	2.83	0.35	0.35	
	Windows									0.80	
	Envelope									0.45	
Very Low	Walls	1.00	0.40	0.40	0.01	0.05	5.00	5.40	0.19	0.19	
	Windows									0.50	
	Envelope									0.26	

Table 3 Assumptions on the U-values of buildings

Our estimates of U-values are based on the EU Buildings Database (European Commission 2017), where the U-values for different building components are given for EU countries and buildings of different vintages. As we were not able to gather similar data for other regions, we drew on the relationship between U-values and climate conditions in Europe to estimate U-values in other regions. In addition, U-values were adjusted upwards for countries with low income levels. While this methodology lets room for much uncertainty, we consider it is a reasonable first approximation. For more details on the methodology, please refer to Levesque et al.(2018).

The aggregate U-value for the envelope is estimated in the database as the mean of the U-values of all building components, implicitly assuming that each component represents a similar share of the outside surface. In that sense, the U-values in the EDGE model, following the estimates from the database, correspond more to an index than to the exact average U-value of the buildings stock.

For the current and reference practices, we take U-value estimates from the database for the whole building stock and for the stock built between 2000 and 2010, respectively (red figures in the table). Next, in order to estimate the impact of the thermal conductivity of the different materials, we depict physical properties of a wall which is consistent with the U-value estimate from the database. The consistency is obtained by adjusting the thickness of the insulation layer. To represent the future development in the U-values, we considered the potential improvements in insulation materials (Jelle 2011; Cuce et al. 2014; Schiavoni et al. 2016) and in windows (Jelle et al. 2012; Cuce and Riffat 2015) and how it compares to the current averages and latest practice. To compute the envelope U- value, we weighted the window value with approximately 0.25 and the wall value with 0.75, which are consistent with current data. In EDGE, we then lower the U-value estimates by the ratio between the current practice (1.60) and the scenario estimates.

1.1.3. Floor space demand

In EDGE, floor space demand is adjusted iteratively from one period to another. The demand for floor space per capita in period *t* and scenario *s* ($F_{t,s}$) depends upon the value in the former period ($F_{t-1,s}$), as well as in the change in income per capita $\left(\frac{I_{t,s}}{I_{t-1,s}}\right)$ and in the density $\left(\frac{D_{t,s}}{D_{t-1,s}}\right)$:

$$F_{t,s} = F_{t-1,s}\left(\frac{I_{t,s}}{I_{t-1,s}}\right)^{\beta_{t,s}}\left(\frac{D_{t,s}}{D_{t-1,s}}\right)^{\gamma} \tag{4}$$

In the low demand scenarios, we assume that the per capita demand for floor space cannot exceed a certain level, as summarized in Table 4.

Floor space	Saturation at current regional level	Residential	Commercial
Reference	None		
Low	USA	70	25
Very Low	Japan	45	16

Table 4 Assumption on floor space demand

1.2. Water Heating

Shower	Showers/day/cap	Shower length (min)	Showerhead (g/min)	Showerhead (L/min)	Hot water (L)	Target Temperature	Base Temperature	Useful energy (kJ/day)	Useful energy (GJ/yr)
Reference	1.0	8.0	2.5	9.5	75.7	40.0	15.0	7926.7	2.9
Low	1.0	5.0	2.0	7.6	37.9	38.0	15.0	3646.3	1.3
Very Low	0.5	4.0	0.8	2.8	5.7	38.0	15.0	546.9	0.2

Clothes Washing	Cycles per week/cap	Cycles per day	Water per cycle (g)	Water per cycle (L)	Hot water (L)	Target Temperature	Base Temperature	Useful energy (kJ/day)	Useful energy (GJ/yr)
Reference	2.0	0.3	23.0	87.1	24.9	70.0	15.0	5729.8	2.1
Low	1.0	0.1	13.0	49.2	7.0	40.0	15.0	736.0	0.3
Very Low	1.0	0.1	10.6	40.0	5.7	30.0	15.0	359.0	0.1

Dishwasher	Cycles per week/cap	Cycles per day	Water per cycle (g)	Water per cycle (L)	Hot water (L)	Target Temperature	Base Temperature	Useful energy (kJ/day)	Useful energy (GJ/yr)
Reference	1.5	0.2	5.3	20.0	4.3	60.0	15.0	807.7	0.3
Low	1.3	0.2	4.0	15.0	2.7	40.0	15.0	280.4	0.1
Very Low	1.0	0.1	2.6	10.0	1.4	40.0	15.0	149.6	0.1

Faucet	Minutes per day	Share hot water	Tap flow (g)	Tap flow (L)	Hot water (L)	Target Temperature	Base Temperature	Useful energy (kJ/day)	Useful energy (GJ/yr)
Reference	5.0	0.1	3.2	12.0	6.0	40.0	15.0	628.2	0.2
Low	4.0	0.1	1.3	5.0	2.0	38.0	15.0	192.6	0.1
Very Low	3.0	0.1	1.3	5.0	1.5	38.0	15.0	144.5	0.1

Sum Residential	Hot water (L)	Useful energy (kJ/day)	Useful energy (GJ/yr)
Reference	110.9	15092.4	5.5
Low	49.6	4855.4	1.8
Very Low	14.3	1200.0	0.4

Mark-up non-residential (restaurants, hotels, laundry) 0.05

Sum Buildings	Hot water (L)	Useful energy (kJ/day)	Useful energy (GJ/yr)
Reference	116.4	15847.0	5.8
Low	52.0	5098.2	1.9
Very Low	15.0	1260.0	0.5

Gallons to Liters	Specific heat (kJ/kg°C)	kJ to GJ
3.785	4.188	0.000001

Table 5 Assumption on the per capita consumption of hot water

In EDGE, the demand for water heating depends upon income (I), and follows a Gompertz function which approaches the asymptote ϕ_1 for high income values. Table 5 gives the detail of the assumptions made for the asymptote ϕ_1. For instance, in the reference scenario, this value is set to 5.8 GJ/yr.

$$WH = \frac{\phi_1}{1 + exp\left[\frac{\phi_2 - I}{\phi_3}\right]} \tag{5}$$

1.3. Appliances and Lighting

The demand for appliances and lighting in EDGE is represented synthetically to represent historical patterns. Fouquet (2014) showed that the income elasticity of energy demand decreased over time—and therefore decreased with income— in the United Kingdom. The elasticities fell below unity but remained above zero in the long term. This means that while a 1% increase in income will, in the long term, generate an increase in the energy demand for each service, the increase will be less than 1%. We implement these insights in our modelling by applying a function displaying declining income elasticity.

$$\sigma_{income} = \phi_1 + \frac{\beta}{\sqrt{I}} \tag{6}$$

With σ_{income} the income elasticity, ϕ_1 the lower bound of the elasticity below unity, I the income per capital and β a parameter influencing the speed of convergence towards the lower bound. By integrating (6) and multiplying by the factor α, we obtain:

$$AL = \alpha \times exp\left(\phi_2 + \phi_1 \times log(I) + \frac{\gamma}{\sqrt{I}}\right), \quad with\ \gamma = -2\beta \tag{7}$$

In the low demand scenario, α decreases by 15% from 1 to 0.85. In the very low demand scenario, α reaches 0.7.

2. Decomposition methodology

In Figure 2 from the main article, we disentangle the influence of new energy practices to explain the change in energy consumption. Some of the new practices though are interdependent and we cannot directly identify the effect of single practices on energy demand. For instance, the effect of lower indoor temperature will vary according to the width of the insulation layer on buildings' walls. In order to estimate the impact of individual practices on buildings energy demand, we therefore need to apply a decomposition technique. Here we rely on the methodology proposed by Sun and Ang (2000). They show that the variation of the variable *V* between the scenarios *S* and *T* can be decomposed into effects (x_i) attributable to each factor (X_i) (equations (8)and (9)). The effects x_i are computed as a sum of the basic variations of the X_i factor and of the evenly distributed interactions between factor variations (10).

$$V = X_1 X_2 \dots X_n \tag{8}$$

$$\Delta V = V^S - V^T = x_1 + x_2 + \cdots + x_n \tag{9}$$

$$x_i = \frac{V^S}{X_i^S}\Delta X_i + \frac{1}{2}\sum_{j\neq i}^{n}\frac{V^S}{X_i^S X_j^S}\Delta X_i \Delta X_j + \frac{1}{3}\sum_{j\neq i\neq \gamma}^{n}\frac{V^S}{X_i^S X_j^S X_\gamma^S}\Delta X_i \Delta X_j \Delta X_\gamma + \cdots + \frac{\Delta X_1 \Delta X_2 \ldots \Delta X_n}{n} \tag{10}$$

To apply this methodology to our scenarios, we first need to define energy service demand as a product similar to equation (8). Equations (11) and (12) give the formulas for space heating and space cooling. As we do not decompose the changes in water heating consumption and appliances and lighting, we do not need to create specific formulas for these energy services.

$$FE_{SH} = Factor_{SH} \times HDD \times Floorspace \times Uvalue \times Intensity_{SH} \tag{11}$$

$$FE_{SC} = Factor_{SC} \times CDD_{coef} \times Floorspace \times Uvalue \times Intensity_{SC} \tag{12}$$

Where:

$$Factor_{SH} = \frac{UE_{SH}}{Floorspace \times HDD \times Uvalue} \tag{13}$$

$$Factor_{SC} = \frac{UE_{SH}}{Floorspace \times CDD_{coef} \times Uvalue} \tag{14}$$

$$Intensity_X = \frac{FE_X}{UE_X} \tag{15}$$

$$CDD_{coef} = CDD \times \ ClimateMaximum(CDD) \tag{16}$$

The effects attributed to the changes in $Factor_{SH}$ and in $Factor_{SC}$ are shared equally between the other variables explaining the variations in energy demand. The effects from HDD and CDD_{coef} are lumped together in the “Indoor temperature” category.

3. REMIND scenarios

In Figure 3 from the main article, we display the results from two REMIND scenarios. In the following, we detail how EDGE and REMIND scenarios are linked, and how the 1.5°C scenario was set up.

3.1. Description of the REMIND model and comparison with EDGE

REMIND (Luderer et al. 2015; ADVANCE 2016) is an integrated energy-economy general equilibrium model with a detailed representation of the energy supply system and a synthetic representation of energy demand sectors. REMIND computes GHG emissions from the energy system, the agricultural and land-use sectors, and takes exogenous F-Gases emissions into account. Crucial path-dependencies of the energy supply system are introduced in the model through investment dynamics for individual conversion and distribution technologies, learning-by-doing cost curves, or constraints on ramp-up rates of innovative technologies. These path-dependencies are highly relevant for a realistic analysis of stringent climate targets, which require rapid transformations of energy systems to limit emissions. The demand for energy is represented for three sectors — buildings, industry and transport. Energy demand reductions can be achieved in climate policy scenarios through macro-economic substitution of capital for energy *via* a constant elasticity of substitution function. The demand can also shift from fossil fuels to electricity or low-carbon energy carriers, depending upon the relative energy prices. The model is linked to a reduced climate model, so that it is well suited for the investigation of energy demand and supply pathways consistent with specific climate targets (Luderer et al. 2013).

Due to the necessity of limiting computational needs, and as a heritage of its focus on supply side issues, REMIND's representation of energy demand is kept to a synthetic formulation. The question of how exactly people change their purchasing and consuming habits in a mitigation scenario compared to a reference scenario thus cannot be addressed directly with this tool. However, REMIND does provide information on the aggregate buildings energy demand response to climate policy, and due to the integration of most GHG emitting sectors and their interactions, it can ensure that the buildings energy demand pathway is consistent with a given climate target. The energy demand reductions result from the model cost optimization which strikes the balance between changes in energy supply side technologies and demand reductions to deliver an emission pathway consistent with a given climate target.

EDGE by contrast does not display the interactions with other emitting sectors, the costs of mitigation and is not capable of providing explicit consistency between an energy demand pathways and climate targets. But EDGE can use the information of how long people take shower, which temperature they have in their offices, how much they insulate their buildings. It is therefore in a position to describe practices and how changes in practices translate into aggregate energy demand.

Both models hence offer different perspectives on the future of buildings energy demand. Here, we combine both approaches and enhance the comparability of both models through the calibration of the REMIND baseline to the EDGE reference scenario.

3.2. Calibration of the REMIND baseline scenario

To allow for meaningful comparisons between both models' scenarios, we calibrate the REMIND baseline scenario so that its final energy demand pathways correspond to the EDGE reference scenario. We calibrate REMIND in an iterative process by adjusting efficiency parameters of the energy demand functions in REMIND until the final energy demand closely resembles the EDGE projections. It should be noted that buildings' energy demand in REMIND covers one minor sector in addition to the ones covered in EDGE[5] and therefore does not fully match the EDGE projections.

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[5] While EDGE only accounts for residential and commercial energy demand, REMIND also covers energy demand which could not be attributed to residential, commercial, industrial, transportation or non-energy uses (ONONSPEC in the IEA Energy Balances). This energy demand category is however small compared to the two residential and commercial uses.

The energy demand functions in REMIND take the form of a nested CES function. Each level of the CES nest has the following form.

$$V_o = \left(\sum_{(o,i)} \xi_i (\theta_i V_i)^{\rho_o} \right)^{\frac{1}{\rho_o}} \tag{17}$$

Where V_o is the output, V_i one of the inputs, ξ_i the output share of V_i, θ_i an efficiency parameter, ρ_o a parameter related to the elasticity of substitution σ_o.

$$\rho_o = 1 - \frac{1}{\sigma_o} \tag{18}$$

At the lowest level of the nested CES function, the inputs V_i represent energy carriers provided by the Energy System Module (ESM) of REMIND. The difficulty to produce these energy carriers is reflected in the energy prices derived from the ESM. The calibration consists in adapting the efficiency parameters ξ_i and θ_i such that, for the energy prices provided by the ESM, exogenous demand quantities $\overline{V_i}$ are optimal. These exogenous demand quantities are provided by the EDGE model.

The calibration has to fulfill two constraints. The first one is a technological constraint. According to the Euler's rule, the output of a homogenous function of degree one equals the sum of inputs weighted by their derivatives. The second constraint is economic: the ratio of derivatives must equal the ratio of prices, which we here simplify by equalizing prices and derivatives. From this we can compute the intermediary products in the nested CES function from the exogenous demand pathways $\overline{V_i}$ and from the exogenous prices $\overline{p_i}$, derived from the ESM (19).

$$V_o = \sum_{(o,i)} \overline{p_i} \overline{V_i} \tag{19}$$

We then equalize the prices and the derivatives by adjusting ξ_i and θ_i. The couple $(\xi_i, \theta_i) = \left(\frac{\overline{p_i} V_i}{V_o}, \frac{V_o}{V_i} \right)$ solves the equality between the prices and the derivatives.

By adjusting the quantities V_o (which become the inputs V_i at the above level of the CES nest) iteratively over the levels of the CES nest, and the parameters ξ_i and θ_i, we ensure that the quantities $\overline{V_i}$ at the bottom level of the CES nest are optimal for the $\overline{p_i}$ prices. At the top level of the CES nest, which combines labor, capital and energy services to produce GDP, we adjust the price of labor to make sure that the exogenous GDP trajectory is met while respecting equation (19).

However, the prices taken at first from the ESM may not correspond to the production of the EDGE quantities. To make sure that the prices from the ESM correspond to the exogenous energy demand quantities, we run REMIND with the efficiencies computed above and derive the new ESM prices from this run. We then compute new efficiencies based on the new prices and the EDGE projections, and run REMIND again. After several iterations, prices converge, so that the efficiencies computed do correspond to the EDGE projections and that the REMIND run yields the EDGE final energy projections.

3.3. REMIND Reference and 1.5°C scenarios

One of the main insights from climate research is the proportionality between cumulated emissions of carbon dioxide and global temperature increases (Matthews et al. 2009). This implies that to limit the global temperature increase to a certain target with a given likelihood, only a limited budget of

CO2 can be emitted. While the exact relation between specific amounts of carbon budgets and climate targets is still debated (Rogelj et al. 2016; Millar et al. 2017), we here follow the approach by Luderer et al. (2018) and assume a cumulated 2011-2100 budget of 400 Gt CO2 to achieve a 66% likelihood of staying below 1.5°C warming. Until 2020, policies are projected to follow the Nationally Determined Contributions pledged ahead of the Paris Agreement. From 2025, the model is free to compute the cost-minimizing trajectory consistent with the carbon budget.

4. References

ADVANCE (2016) Reference card - REMIND - ADVANCE. http://themasites.pbl.nl/models/advance/index.php/Reference_card_-_REMIND. Accessed 23 Oct 2017

Cuce E, Cuce PM, Wood CJ, Riffat SB (2014) Toward aerogel based thermal superinsulation in buildings: A comprehensive review. Renewable and Sustainable Energy Reviews 34:273–299. doi: 10.1016/j.rser.2014.03.017

Cuce E, Riffat SB (2015) A state-of-the-art review on innovative glazing technologies. Renewable and Sustainable Energy Reviews 41:695–714. doi: 10.1016/j.rser.2014.08.084

Fouquet R (2014) Long-Run Demand for Energy Services: Income and Price Elasticities over Two Hundred Years. Rev Environ Econ Policy 8:186–207. doi: 10.1093/reep/reu002

Jelle BP (2011) Traditional, state-of-the-art and future thermal building insulation materials and solutions – Properties, requirements and possibilities. Energy and Buildings 43:2549–2563. doi: 10.1016/j.enbuild.2011.05.015

Jelle BP, Hynd A, Gustavsen A, et al (2012) Fenestration of today and tomorrow: A state-of-the-art review and future research opportunities. Solar Energy Materials and Solar Cells 96:1–28

Levesque A, Pietzcker RC, Baumstark L, et al (2018) How much energy will buildings consume in 2100? A global perspective within a scenario framework. Energy 148:514–527. doi: 10.1016/j.energy.2018.01.139

Luderer G, Leimbach M, Bauer N, et al (2015) Description of the REMIND Model (Version 1.6). Social Science Research Network, Rochester, NY

Luderer G, Pietzcker RC, Bertram C, et al (2013) Economic mitigation challenges: how further delay closes the door for achieving climate targets. Environ Res Lett 8:034033. doi: 10.1088/1748-9326/8/3/034033

Luderer G, Vrontisi Z, Bertram C, et al (2018) Residual fossil CO2 emissions in 1.5–2 °C pathways. Nature Climate Change 8:626–633. doi: 10.1038/s41558-018-0198-6

Matthews HD, Gillett NP, Stott PA, Zickfeld K (2009) The proportionality of global warming to cumulative carbon emissions. Nature 459:829–832. doi: 10.1038/nature08047

Millar RJ, Fuglestvedt JS, Friedlingstein P, et al (2017) Emission budgets and pathways consistent with limiting warming to 1.5 °C. Nature Geoscience ngeo3031. doi: 10.1038/ngeo3031

Rogelj J, Schaeffer M, Friedlingstein P, et al (2016) Differences between carbon budget estimates unravelled. Nature Climate Change 6:245–252. doi: 10.1038/nclimate2868

Schiavoni S, D′Alessandro F, Bianchi F, Asdrubali F (2016) Insulation materials for the building sector: A review and comparative analysis. Renewable and Sustainable Energy Reviews 62:988–1011. doi: 10.1016/j.rser.2016.05.045

Sun JW, Ang BW (2000) Some properties of an exact energy decomposition model. Energy 25:1177–1188. doi: 10.1016/S0360-5442(00)00038-4