Technological Forecasting & Social Change 146 (2019) 253–266

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

journal homepage: www.elsevier.com/locate/techfore

Halving energy demand from buildings: The impact of low consumption practices

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ARTICLE INFO

Keywords:
Lifestyle changes
Behavioral changes
Energy consumption
Practices
Buildings' energy demand

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 the extent to which the emergence of low energy consuming practices, encompassing new behaviors and the adoption of more efficient technologies, could contribute to lowering energy demand and thereby to reducing CO_2 emissions.

To this end, we design three detailed energy consumption profiles which could be adopted by individuals in current and future wealthy regions. To what extent does the setting of air conditioners to higher temperatures or the widespread use 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 energy demand from buildings by up to 47% in 2050 and 61% 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 consumer choices in air conditioners and heat pumps. New behaviors and efficient technologies could make a significant long-term contribution to reducing buildings' energy demand, and thus facilitate the achieval of stringent climate change mitigation targets while limiting the adverse sustainability impacts from the energy supply system.

1. Introduction

Limiting global warming in line with the Paris Climate Agreement poses a great challenge to socio-economic structures across the world. On the one hand, geophysical studies revealed a proportional relationship between cumulative CO_2 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 23% of energy-related CO_2 emissions in 2014 (Rogelj et al., 2018). These emissions resulted from both direct emissions released by on-site combustion of fossil fuels and biomass (8%), as well as from indirect emissions attributed to electricity consumption in buildings and district heating (15%). 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; IEA, 2016; Teske et al., 2015). 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 last 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 (Geels et al., 2017; Smith, 2007) underlines that technical arrangements include a social dimension and that new technologies cannot advance without changes in

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https://doi.org/10.1016/j.techfore.2019.04.025
Received 31 July 2018; Received in revised form 25 March 2019; Accepted 24 April 2019

purchasing practices, daily rituals, professional skills, etc. Drawing upon 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 this framework, 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. 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 the people following such 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 the interventions that US households could take to reduce their emissions, and therefore their energy demand, covering changes in technology purchase patterns as well as usage habits. According to them, residential emissions could decrease by 20% within ten years if all these 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 global energy demand from buildings. We first present 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 then 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 homes 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 energy consuming practices. With the EDGE model, we can then appraise the impact of these contrasted energy practices on buildings' energy demand in 2050 and 2100, and compare with scenarios from other studies, before concluding.

2. Methods

2.1. Description of the EDGE model

The Energy Demand GEnerator (EDGE) is a 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 that consumption levels of energy services in developing countries will gradually converge to levels observed in developed countries for 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 present 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 business. For each scenario, we design a profile of energy practices (Fig. 1), 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.

Our assumptions concern primarily the level of consumption at high levels of income. The low demand scenarios therefore do not curb the service demand for low-income countries. Instead, they reduce the level of saturation for wealthy consumers. For instance, the demand for space cooling in developed countries will be lower in case people adopt more efficient air conditioners or accept higher indoor temperatures. At the same time, people in developing countries will increase their purchases of air conditioners as their income rises.

In addition to these assumptions, future energy demand will heavily depend on future population trends and per capita income 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 the five energy services depicted in EDGE: space cooling, space heating, water heating, appliances and lighting, and cooking.

Our assumptions concentrate on the demand for useful energy. Except in the case of heat pumps and air conditioners, we do not make a separate assumption for the final-to-useful energy efficiencies. We concentrate on heat pumps and air conditioners because their efficiencies remain far from their theoretical optimum. There is thus still room for large efficiency improvements, and we address this with our scenario assumptions.

2.2.1. Space heating and space cooling

2.2.1.1. Indoor temperature. Indoor temperature is one of the most important drivers of the demand for heating and cooling. In the

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

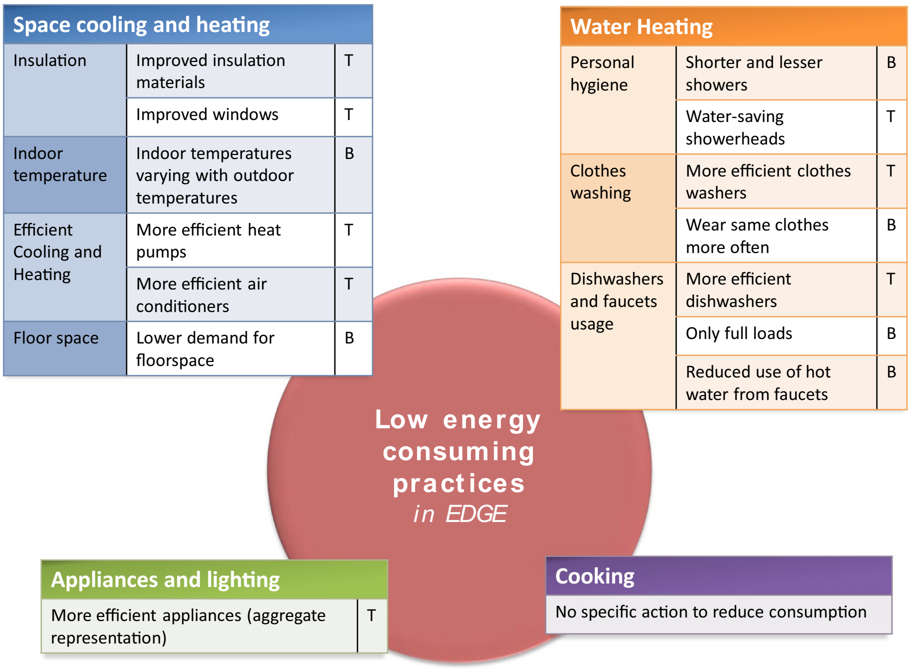

Fig. 1. Scenario assumptions for low energy consuming practices in EDGE. The right column of each table indicates whether the measure is predominantly behavioral (B) or technological (T).

Table 1
Assumptions for the indoor temperature and Degree Days thresholds.

HDD	Heating season indoor temperature (°C)	Corresponding outside temperature (°C)	Threshold HDD after heterogeneity (°C)
Reference	22	20	23
Low	20	18	21
Very Low	19	17	20
CDD	**Cooling season indoor temperature (°C)**	**Corresponding outside temperature (°C)**	**Threshold CDD after heterogeneity (°C)**
Reference	23	21	18
Low	25	23	20
Very Low	26	24	21
Internal heat gains (°C)			2
Heterogeneity (°C)			3

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. These assumptions are summarized in Table 1.

2.2.1.1.1. *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 climate and the 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 (Table 1). 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.

2.2.1.1.2. Internal heat gains. The discussion above pertains to the temperature people wish to have indoor. However, even without space heating or cooling, indoor and outdoor temperatures differ due to, among other factors, internal heat gains (IHGs). IHGs result from the metabolic activity of building occupants, from the heat released during cooking and activities which consume 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). IHGs lead to higher indoor temperatures, depending upon the thermal insulation of the envelope: The better the insulation, the higher the temperature gains stemming from IHGs. For the sake of simplicity, we assume IHGs to contribute to a temperature increase of 2 °C within buildings.[2] 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.

2.2.1.1.3. Heterogeneity. The functions representing energy demand for space heating and cooling in EDGE (see Appendix) 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 IHGs, the real-world heterogeneity in behaviors and perceived comfort temperatures 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 3 °C.

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 determinants of 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.

To further elaborate on the first effect, 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 improves 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 in the heating season and is an important mechanism for the Passive House concept, which aims at providing comfortable, low indoor temperatures (Cuce and Riffat, 2015; Passive Houses, 2007).

Regarding the second phenomenon, 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 building envelopes 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, could make highly isolating materials an attractive technology in expensive cities (Jelle, 2011). The strong urbanization forecasted for the future could therefore offer a niche 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 $W/(m^2 K)$ and new technologies ranging from triple glazing to aerogels reach U-values closer to 0.5 $W/(m^2 K)$ (Cuce and Riffat, 2015; Jelle et al., 2012).

In EDGE, the current estimates for buildings' U-values are based on the EU buildings batabase (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 much room for uncertainty, we consider it a reasonable approximation. For more details on the methodology, please refer to Levesque et al. (2018)

The assumptions for the current and Reference scenario properties of the buildings stock are summarized in Table 2a and Table 2b. For the

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[2] We compute the estimate of 2 °C by assuming a transmission loss of the building envelope of 1.6 $W/(m^2 \cdot °C)$, internal heat gains equal to 3 W/m^2—this is within the range of 1–5 W/m^2 found in (Elsland et al., 2014). We consider no ventilation losses and no solar heat gains, and we assume the ratio between external surface and indoor floor space to be one. These assumptions give us a temperature increase of 1.875 °C which we round to 2 °C.

Table 2a
Assumptions and data for the current and scenario walls characteristics. The underlined figures are directly taken from the EU buildings database.

Scenario & year	Building's component	Thermal conductivity of wall (W/mK)	Thickness of wall (m)	R wall (Km2/W)	Thermal conductivity of insulation (W/mK)	Average Thickness of insulation (m)	R insulation (Km2/W)	Rall (Km2/W)	Uall (W/m2)	U-value (W/Km2)
Current - 2010	Walls	1.70	0.40	0.24	0.04	0.02	0.66	0.89	1.12	1.12
Reference - 2100	Walls	1.70	0.40	0.24	0.04	0.07	1.99	2.22	0.45	0.45
Low - 2100	Walls	1.20	0.40	0.33	0.02	0.05	2.50	2.83	0.35	0.35
Very Low -2100	Walls	1.00	0.40	0.40	0.01	0.05	5.00	5.40	0.19	0.19

Table 2b
Buildings' components U-values. The underlined figures are directly taken from the EU buildings database. To compute the envelope U-value, we weighted the window value with approximately 0.25 and the wall value with 0.75, which is consistent with current data.

Scenario & year	Building's component	U-value (W/Km2)
Current - 2010	Walls	1.12
	Windows	3.25
	Envelope	1.60
Reference - 2100	Walls	0.45
	Windows	2.00
	Envelope	0.85
Low - 2100	Walls	0.35
	Windows	0.80
	Envelope	0.45
Very Low -2100	Walls	0.19
	Windows	0.50
	Envelope	0.26

current U-values, we take the estimate from the database for the whole buildings stock at 1.60 W/(m^2 K). In the Reference scenario, we assume that U-values for the whole building stock will decrease to 0.85 W/(m^2 K) by 2100. As this value corresponds to the average U-value of European buildings built between 2000 and 2010 (European Commission, 2017), this is a conservative assumption, implying no further tightening of efficiency standards, but simply bringing old buildings to the current standard.

For the Low and Very Low scenarios, we introduce assumptions based on the future development of insulation materials and windows. To do this, we first reconstruct exemplary buildings' characteristics—thermal conductivity of dry walls, of insulation material and insulation layer width—which are consistent with current estimates of the U-value of the aggregate buildings stock. The consistency is achieved through the adjustment of the average thickness of insulation (Table 2a). We then make our assumptions on the evolution of the individual characteristics and assess the impact of the buildings' stock aggregate U-values.

For the thermal conductivity of dry walls, we consider an evolution comparable to a shift from dense concrete (assumed at 1.7 W/mK) to brickwork walls (assumed at 1.2 W/mK). There would be much more efficient materials (e.g. insulating bricks have a thermal conductivity of 0.15 W/mK), but because this characteristic is unlikely to change for standing buildings, we chose a rather conservative assumption. The quality of insulation material also improves and the thermal conductivity of these materials decreases by 50% in the Low scenario and by 75% in the Very Low scenario compared to the Reference. These values correspond to the difference between standard materials, such as extruded polystyrene, and state-of-the-art technologies like aerogels (Cuce et al., 2014; Jelle, 2011; Schiavoni et al., 2016). The average thickness of insulation is assumed to decrease in the Low and Very Low scenarios compared the Reference scenario because high-performing insulation materials can achieve low U-values with thin layers and that thin layers are cheaper and more suitable in urban contexts. Similar improvements are assumed for windows with the spread of triple glazing or aerogels which can achieve U-values as low as 0.5 W/(m^2·K) (Table 2b) (Cuce and Riffat, 2015; Jelle et al., 2012). In the Low scenario, the U-value of windows improves by 60% compared to the Reference. This figure rises to 75% in the Very Low scenario. In order to compute the U-value estimate for the whole envelope based on the estimates for the walls and the windows, we weight the U-value from the wall with approximately three quarters and that of windows with one quarter, in line with the ratios observed in the current data.

Overall, our assumptions for the European building stock are that until 2100, the U-value for the whole envelope will decrease by 47% (0.85 W/(m^2 K)) in the Reference compared to 2015 (1.60 W/(m^2 K)), 72% (0.45 W/(m^2 K)) in the Low scenario and 84% (0.26 W/(m^2 K)) in the Very Low scenario. Because the historical U-values in the EDGE regions differ from the European values from Table 2b, we do not assume the average building envelopes in each region to achieve the absolute U-values stated above. Instead, the U-values are projected to decrease compared to their historical value by 47%, 72% and 84% in the Reference, Low and Very Low scenarios, respectively. The current regional U-values will decrease linearly between 2015 and 2100 to reach the full U-value reduction by 2100.

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 of 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).

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 and reduced living spaces. 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) (Table 3).

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 in the market of white appliances could also encourage the penetration of efficient models. In the next paragraphs we review our assumptions for each energy service. All assumptions are to be found in Table 4a and Table 4b.

2.2.2.1. Personal hygiene. Currently in the United States, people spend approximately 8 min 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 5 min in the Low Demand scenario, and 4 min 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 for washing clothes 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 for

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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) and not in BTU/h/W.

Table 3
Assumptions on floor space demand.

Floor space	Saturation at current regional level	Residential (m^2)	Commercial (m^2)
Reference	None	–	–
Low	USA	70	25
Very Low	Japan	45	16

Table 4b
Saturation level for hot water consumption and the related energy consumption.

	Hot water (L)		Useful energy (GJ/yr)	
Scenario	Total residential	Total buildings (+5%)	Total residential	Total buildings (+5%)
Reference	110.9	116.4	5.51	5.8
Low	49.6	52.0	1.77	1.9
Very Low	14.3	15.0	0.44	0.5

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 assumption based on our own judgement 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 Very Low 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, 2017c), 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 were comparable in Europe and Japan 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

Table 4a
Assumptions on the per capita consumption of hot water.

Shower	Showers/day/cap	Shower length (min)	Showerhead (L/min)	Hot water (L)	Target Temperature	Base Temperature	Useful energy (GJ/yr)
Reference	1.0	8.00	9.5	75.7	40	15	2.89
Low	1.0	5.00	7.6	37.9	38	15	1.33
Very Low	0.5	4.00	2.8	5.7	38	15	0.20
Clothes Washing	**Cycles per week/cap**	**Cycles per day**	**Water per cycle (L)**	**Hot water (L)**	**Target Temperature**	**Base Temperature**	**Useful energy (GJ/yr)**
Reference	2.0	0.29	87.1	24.9	70	15	2.09
Low	1.0	0.14	49.2	7.0	40	15	0.27
Very Low	1.0	0.14	40.0	5.7	30	15	0.13
Dishwasher	**Cycles per week/cap**	**Cycles per day**	**Water per cycle (L)**	**Hot water (L)**	**Target Temperature**	**Base Temperature**	**Useful energy (GJ/yr)**
Reference	1.5	0.21	20.0	4.3	60	15	0.29
Low	1.3	0.18	15.0	2.7	40	15	0.10
Very Low	1.0	0.14	10.0	1.4	40	15	0.05
Faucet	**Minutes per day**	**Share hot water**	**Tap flow (L)**	**Hot water (L)**	**Target Temperature**	**Base Temperature**	**Useful energy (GJ/yr)**
Reference	5.0	0.10	12.0	6.0	40	15	0.23
Low	4.0	0.10	5.0	2.0	38	15	0.07
Very Low	3.0	0.10	5.0	1.5	38	15	0.05

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, pp. 166–169), mandatory efficiency labels quickly transformed appliances markets in the past. In the case of refrigerators in the Europe, the EU labelling 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, pp. 225–231).

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, 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 we therefore 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. Cooking

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, most importantly through the shift from traditional to modern fuels.

2.2.5. Timing

We assume that all changes will be effective by 2050 and stay constant in the period from 2050 to 2100, except for insulation, heat pumps and air conditioning. For these, we assume the full reduction will be achieved only by 2100, due to the inertia of the building stock. The cap on floor space per capita is effective from 2020, but regions already exceeding the cap will decrease the demand gradually towards the maximum floor space demand.

3. Results

We first present the scenario results for final energy demand at the global level. Fig. 2 displays the final energy demand in all three scenarios for 2015, 2050 and 2100, disaggregated by energy services. In 2015, the global demand amounted to 115 EJ/yr. The largest share of demand was dedicated to space heating (34%). Cooking was another important service (26%), 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 (+62%) 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 (+126%), explained mostly by appliances and lighting (86 EJ/yr against 22 EJ/yr), space cooling (81 EJ/yr against 5 EJ/yr) and water heating (42 EJ/yr against 19 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). These trends are driven by the growth in population and income, especially in hot regions, where the potential for space cooling demand is large.

The changes in consumer practices assumed in the Low and Very Low energy demand scenarios paint a very different picture from the Reference case. First, the increase in energy demand is much milder compared to 2015. The demand in the Low (Very Low) scenario stagnates (declines) between 2015 and 2050, while it rises modestly (declines) by 2100 (+26% for the Low scenario, and −11% for the Very Low scenario). Compared to the Reference scenario, this implies that changes in practices can engender a decrease in energy demand of 33% and 44% by 2050, and 47% and 61% by 2100, for the Low and Very Low scenario, respectively. The impact of changes in practices on energy demand is therefore substantial.

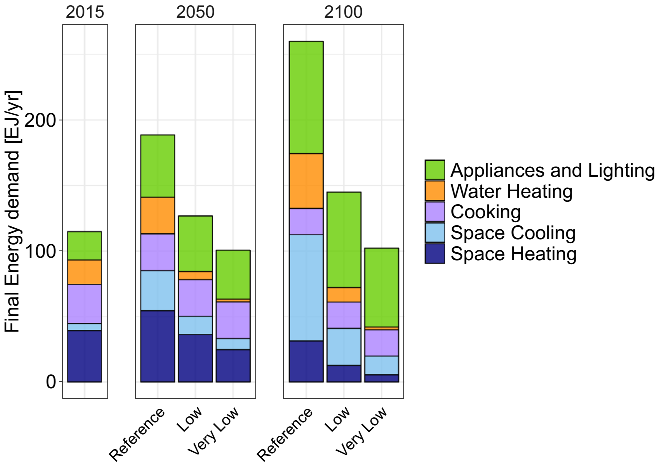

Fig. 2. Final energy demand by end-use shown for historical values (left) as well as for the three scenarios of future energy consumption practices in 2050 and 2100.

Second, we evaluate the contribution of each individual change in consumption patterns. Even though these changes might be interdependent, in particular the indoor temperature setting 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 is further explained in the Appendix. Fig. 3 displays the contribution of individual measures to the total energy demand reductions. It shows that the majority of the reduction in demand can be accounted for by space heating and cooling measures, mostly through improvement of the building envelope and 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 (WH). Floor space demand reductions contribute only moderately compared with changed practices in indoor temperature and appliances and lighting.

Thirdly, we compared the EDGE scenarios with other scenarios available in the literature. Fig. 4 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 (−12% 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 heating and cooling, water heating, cooking), much lower in the LED scenario.

By design, EDGE and REMIND share a similar reference trajectory (see Appendix for more details). However, the energy demand reductions in REMIND mitigation scenarios are assumed to be induced by carbon pricing only, without additional regulation or non-price-driven lifestyle changes towards energy saving practices. As a consequence, the energy demand in the REMIND 1.5 °C scenario is much higher than in both EDGE low consumption scenarios. This applies to 2050 (−23%

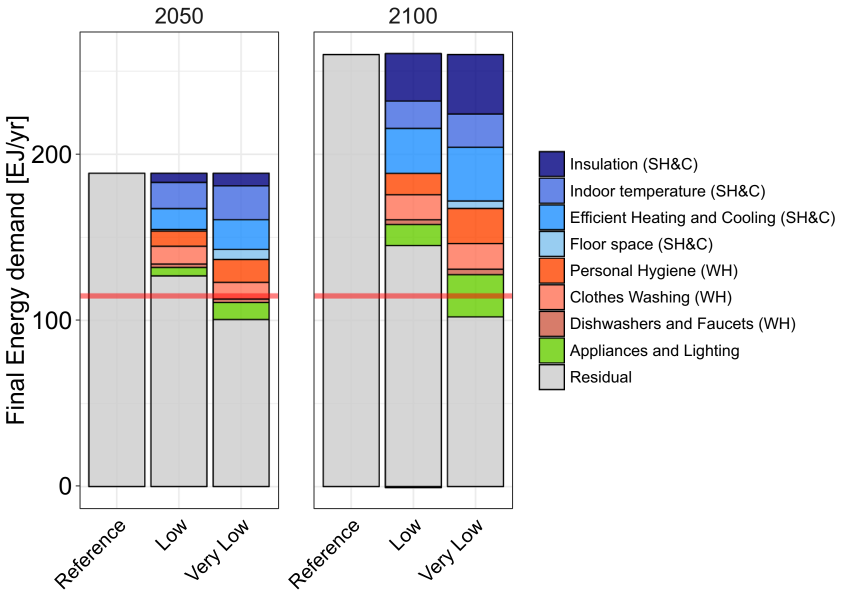

Fig. 3. Contribution of individual aspects of changes in practices to decrease in energy demand compared to the reference scenario. The grey bar shows the final energy demand in each scenario. The red line gives the 2015 demand. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

vs −33% and −47%), but is even more pronounced in 2100 (−14% vs −44% and −61%).

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 61% reduction in final energy demand from the sector. This potential for energy savings could leave energy demand in buildings below its 2015 value - a stark contrast to the doubling of consumption projected by the Reference scenario, owing to socio-economic developments.

The reduction in energy demand is driven most prominently by new practices in the insulation of buildings, the penetration of efficient heat pumps and air conditioners, and reductions in water consumption. In real-world practice, there is ample opportunity for improvement in all three of these factors. First, the thermal conductivity of buildings constructed after 2000 in Europe greatly outperforms the average of the continent's building stock, reflecting new practices in the construction sector. If this trend continues with other world regions following suit, and alongside the adoption of new insulation materials, the quality of building envelopes could improve a great deal in the future. Second, the average efficiency of air conditioners purchased today is, by and 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. Third, over 100 L of hot water per person per day could be saved compared to the Reference scenario via the adoption of water-saving showerheads combined with shorter showering habits, and the penetration of high efficiency washing machines combined with a reduction in their use frequency.

The purpose of this paper has been to illustrate the impact that deep shifts in energy practices could have on energy demand. It has not been concerned with the critical question of how exactly to achieve these changes, or more specifically the selection of policies which could foster them. A foreseeable first reflex of policy makers could be to distinguish between policies which address technology uptake and those that aim to change behaviors. However, as underlined by the social theory literature reviewed in the introduction, technologies and behaviors are

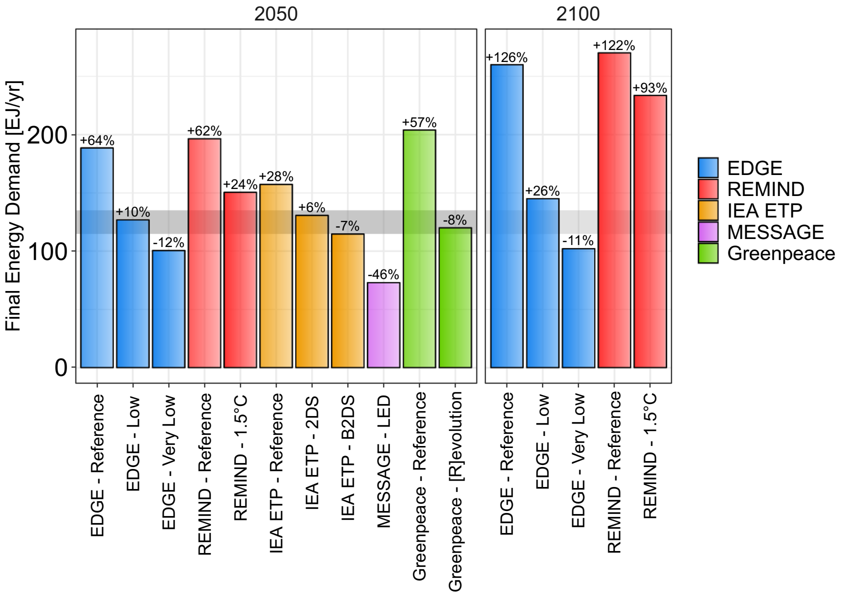

Fig. 4. Final energy demand from buildings in 2050 and 2100 in various scenarios. The grey shaded horizontal area represents the range of historical values in the different models (2015 in EDGE and REMIND, 2014 in IEA ETP, 2020 in MESSAGE, 2012 for Greenpeace). The percentages above the bars show the 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).

often inseparable. Changing one can influence the other. Technology-directed policies like standards could certainly deliver demand reductions when the link between technology and behavior is relatively weak, e.g. replacing an inefficient refrigerator might not change the way refrigerators are used (although some empirical studies show that refrigeration efficiency gains have been partially offset by increasing refrigerator size, see e.g. (Davis et al., 2014)). However, when the link between technology options and behavior is stronger—e.g. a water-saving shower head offers a different user experience, building standards might change investment patterns— pure technological policies are likely to have unforeseen effects which would need to be checked by other, probably more complex, policies.

Low consumption practices can achieve energy demand reductions which are much larger than 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 solely by means of carbon pricing. This means that, on one hand, the 1.5 °C target could even be achieved with only moderate changes in energy practices. On the other hand, such changes in practices could greatly reduce residual fossil CO_2 emissions, thus alleviating pressure on the energy supply to meet stringent climate targets and mitigating the necessity of controversial and potentially unsustainable carbon dioxide removal technologies (Bertram et al., 2018; Grubler et al., 2018; Smith et al., 2015; Vuuren et al., 2018).

5. Conclusion

In this article, we explore the impact that the adoption of low energy consuming practices by individuals could have on the aggregate energy demand from buildings. Energy practices encompass both new technological choices and new behaviors in the use of these technologies. The practices considered here range from showering habits to new air conditioning and heating technologies. We designed three distinct consumption profiles and assessed the outcome for global building sector energy demand by 2050 and 2100.

We find that the adoption of low consumption practices can save as much as 61% of the energy that would be consumed by 2100 in the reference scenario. In other words, energy consumption from activities in buildings at the end of the century would decrease by 11% compared to the 2015 level, instead of a 126% increase. 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.

A comparison of the present results with the REMIND 1.5 °C scenario showed that even moderate changes in practices might be compatible with a trajectory limiting global warming below 1.5 °C. But energy saving practices could greatly alleviate pressure on the energy supply system and reduce the adverse effects from a full decarbonization of energy supply.

This paper has shown that deep changes in energy practices would allow for considerable reductions in energy demand. However, it has not described a set of policies which would be able to deliver such changes. In particular, the complementarity of carbon pricing policies with other dedicated policies targeting the different dimensions of energy consumption practices would be an important topic for future research.

Declarations of interest

The authors declare that there is no conflict of interests.

Acknowledgement

This work was supported by the European Union's Horizon 2020 research and innovation program under grant agreement No 730403 (INNOPATHS).

Appendix A

A. EDGE equations

In the following we detail the EDGE functions representing the consumption of energy services.

Space heating and space cooling

In EDGE, space heating (*SH*) is a function of floor space (*F*), the quality of the building envelope (*Uvalue*), and the Heating Degree Days (*HDD*). The demand for space heating energy increases linearly with floor space and HDD, and decreases linearly with the quality of the building's insulation. The parameter δ is a constant which is estimated against past data:

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

Space Cooling (*SC*) is a function of floor space (*F*), the quality of the building envelope (*Uvalue*), income (*I*) and the Cooling Degree Days (*CDD*). The relation between space cooling demand and CDD is non-linear since for a low amount of CDD, the penetration of cooling equipment will be low (Eq. (3)). Thus, the ownership rate of air conditioners, implicit in the equation, increases both with the number of CDD (Climate Maximum) and with income. The relationship between income and the demand for space cooling per square meter follows an S-curve, meaning that it reaches saturation after a certain level of income is passed.

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

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

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 $\left(\frac{D_{t,s}}{D_{t-1,s}}\right)$:

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

Water heating

The demand for water heating depends upon income (I), and follows a Gompertz function which approaches the asymptote ϕ_1 for high income values. In the Reference scenario, the value of ϕ_1 is set to 5.8 GJ/yr.

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

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 Eq. (6) and multiplying by the factor α, we obtain:

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

B. Decomposition methodology

In Fig. 3, 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) (Eqs. (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 (Eq. (10)).

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

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

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

To apply this methodology to our scenarios, we first need to define energy service demand as a product similar to Eq. (8). Eqs. (11) and (12) give the formulas for space heating and space cooling. As we do not decompose the changes 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.

For the decomposition of the impact of water heating, we simply attribute the decrease in water heating to the individual measures based on their contribution to the reduction of demand in the scenario assumptions.

C. REMIND scenarios

In Fig. 4, 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.

Description of the REMIND model and comparison with EDGE

REMIND (ADVANCE, 2016; Luderer et al., 2015) 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.

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.

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 (Eq. (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 Eq. (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.

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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.

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 CO_2 can be emitted. While the exact relation between specific amounts of carbon budgets and climate targets is still debated (Millar et al., 2017; Rogelj et al., 2016, 2018), we here assume a cumulated 2011–2100 budget of 600 Gt CO_2 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.

References

ADVANCE, 2016. Reference card - REMIND - ADVANCE. http://themasites.pbl.nl/models/advance/index.php/Reference_card_-_REMIND, Accessed date: 23 October 2017.

Allcott, H., Rogers, T., 2014. The short-run and long-run effects of behavioral interventions: experimental evidence from energy conservation. Am. Econ. Rev. 104, 3003–3037.

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 Build. 43, 1884–1894. https://doi.org/10.1016/j.enbuild.2011.03.027.

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

Asensio, O.I., Delmas, M.A., 2015. Nonprice incentives and energy conservation. Proc. Natl. Acad. Sci. U. S. A. 112, E510–E515. https://doi.org/10.1073/pnas.1401880112.

Bertram, C., Luderer, G., Popp, A., et al., 2018. Targeted policies can compensate most of the increased sustainability risks in 1.5 °C mitigation scenarios. Environ. Res. Lett. 13, 064038. https://doi.org/10.1088/1748-9326/aac3ec.

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

Chaturvedi, V., Eom, J., Clarke, L.E., Shukla, P.R., 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., Riffat, S.B., 2015. A state-of-the-art review on innovative glazing technologies. Renew. Sust. Energ. Rev. 41, 695–714. https://doi.org/10.1016/j.rser.2014.08.084.

Cuce, E., Cuce, P.M., Wood, C.J., Riffat, S.B., 2014. Toward aerogel based thermal superinsulation in buildings: a comprehensive review. Renew. Sust. Energ. Rev. 34, 273–299. https://doi.org/10.1016/j.rser.2014.03.017.

Davis, L.W., Fuchs, A., Gertler, P., 2014. Cash for coolers: evaluating a large-scale appliance replacement program in Mexico. Am. Econ. J. Econ. Pol. 6, 207–238.

Dellink, R., Chateau, J., Lanzi, E., Magné, B., 2017. Long-term economic growth projections in the shared socioeconomic pathways. Glob. Environ. Chang. 42, 200–214. https://doi.org/10.1016/j.gloenvcha.2015.06.004.

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

Dietz, T., Gardner, G.T., Gilligan, J., et al., 2009. Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. Proc. Natl. Acad. Sci. 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. https://doi.org/10.1016/j.egypro.2014.12.364.

Energy Star, 2018. Clothes washers. https://www.energystar.gov/products/appliances/clothes_washers, Accessed date: 13 March 2018.

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

Fanger, P.O., 1970. Thermal Comfort. Analysis and Applications in Environmental Engineering. Thermal Comfort Analysis and Applications in Environmental Engineering.

Fanger, P.O., Toftum, J., 2002. Extension of the PMV model to non-air-conditioned buildings in warm climates. Energy Build. 34, 533–536.

Fouquet, R., 2014. Long-run demand for energy services: income and price elasticities over two hundred years. Rev. Environ. Econ. Policy 8, 186–207. https://doi.org/10.1093/reep/reu002.

Geels, F.W., Sovacool, B.K., Schwanen, T., Sorrell, S., 2017. Sociotechnical transitions for deep decarbonization. Science 357, 1242–1244. https://doi.org/10.1126/science.aao3760.

Gram-Hanssen, K., 2014. New needs for better understanding of household's energy consumption–behaviour, lifestyle or practices? Archit. Eng. Des. Manag. 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. Nat. Energy 3, 515–527. https://doi.org/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. Sociol. Res. Online 10, 1–13.

Hsiang, S.M., 2010. Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. Proc. Natl. Acad. Sci. 107, 15367–15372.

Huizenga, C., Zhang, H., Mattelaer, P., et al., 2006. Window Performance for Human Thermal Comfort.

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 date: 29 October 2017.

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

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

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

IEA, 2017a. Energy Efficiency Market Report 2017. 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, 2018. The Future of Cooling. International Energy Agency, Paris.

Indraganti, M., Ooka, R., Rijal, H.B., 2013. Thermal comfort in offices in summer: findings from a field study under the 'setsuden' conditions in Tokyo, Japan. Build. Environ. 61, 114–132.

Inskeep, B.D., Attari, S.Z., 2014. The water short list: the most effective actions US households can take to curb water use. Environ. Sci. Policy Sustain. Dev. 56, 4–15.

Jelle, B.P., 2011. Traditional, state-of-the-art and future thermal building insulation materials and solutions – properties, requirements and possibilities. Energy Build. 43, 2549–2563. https://doi.org/10.1016/j.enbuild.2011.05.015.

Jelle, B.P., Hynd, A., Gustavsen, A., et al., 2012. Fenestration of today and tomorrow: a state-of-the-art review and future research opportunities. Sol. Energy Mater. Sol. Cells 96, 1–28.

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. Glob. Environ. Chang. 42, 181–192. https://doi.org/10.1016/j.gloenvcha.2014.06.004.

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

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

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

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., Vrontisi, Z., Bertram, C., et al., 2018. Residual fossil CO_2 emissions in 1.5–2 °C pathways. Nat. Clim. Chang. 8, 626–633. https://doi.org/10.1038/s41558-018-0198-6.

Matthews, H.D., Gillett, N.P., Stott, P.A., Zickfeld, K., 2009. The proportionality of global warming to cumulative carbon emissions. Nature 459, 829–832. https://doi.org/10.1038/nature08047.

Millar, R.J., Fuglestvedt, J.S., Friedlingstein, P., et al., 2017. Emission budgets and pathways consistent with limiting warming to 1.5 °C. Nat. Geosci. ngeo3031. https://doi.org/10.1038/ngeo3031.

Nicol, J.F., Humphreys, M.A., 2002. Adaptive thermal comfort and sustainable thermal standards for buildings. Energy Build. 34, 563–572.

O'Neill, B.C., Kriegler, E., Ebi, K.L., et al., 2017. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 42, 169–180. https://doi.org/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 date: 7 March 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. Technol. Forecast. Soc. Chang. 90, 8–23. https://doi.org/10.1016/j.techfore.2013.09.016.

Rijal, H.B., Humphreys, M.A., Nicol, J.F., 2017. Towards an adaptive model for thermal comfort in Japanese offices. Build. Res. Inform. 45, 717–729.

Rogelj, J., Luderer, G., Pietzcker, R.C., et al., 2015. Energy system transformations for limiting end-of-century warming to below 1.5 °C. Nat. Clim. Chang. 5, 519–527. https://doi.org/10.1038/nclimate2572.

Rogelj, J., Schaeffer, M., Friedlingstein, P., et al., 2016. Differences between carbon budget estimates unravelled. Nat. Clim. Chang. 6, 245–252. https://doi.org/10.1038/nclimate2868.

Rogelj, J., Shindell, D., Jiang, K., et al., 2018. Chapter 2: Mitigation pathways compatible with 1.5 °C in the context of sustainable development. In: Global Warming of 1.5 °C an IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change. Intergovernmental Panel on Climate Change.

Schiavoni, S., D'Alessandro, F., Bianchi, F., Asdrubali, F., 2016. Insulation materials for the building sector: a review and comparative analysis. Renew. Sust. Energ. Rev. 62, 988–1011. https://doi.org/10.1016/j.rser.2016.05.045.

Shove, E., Walker, G., 2010. Governing transitions in the sustainability of everyday life. Res. Policy 39, 471–476.

Smith, A., 2007. Translating sustainabilities between green niches and socio-technical regimes. Tech. Anal. Strat. Manag. 19, 427–450.

Smith, P., Davis, S.J., Creutzig, F., et al., 2015. Biophysical and economic limits to negative CO_2 emissions. Nat. Clim. Chang. 6, 42–50. https://doi.org/10.1038/nclimate2870.

Steg, L., Vlek, C., 2009. Encouraging pro-environmental behaviour: an integrative review and research agenda. J. Environ. Psychol. 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. https://doi.org/10.1016/j.enpol.2010.05.069.

Sun, J.W., Ang, B.W., 2000. Some properties of an exact energy decomposition model. Energy 25, 1177–1188. https://doi.org/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. In: Greenpeace International and SolarPowerEurope and Global Wind Energy Council.

Tham, K.W., Willem, H.C., 2010. Room air temperature affects occupants' physiology, perceptions and mental alertness. Build. Environ. 45, 40–44. https://doi.org/10.1016/j.buildenv.2009.04.002.

van Sluisveld, M.A.E., Martínez, S.H., Daioglou, V., van Vuuren, D.P., 2016. Exploring the implications of lifestyle change in 2 °C mitigation scenarios using the IMAGE integrated assessment model. Technol. Forecast. Soc. Chang. 102, 309–319. https://doi.org/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. Chang. 1–34. https://doi.org/10.1007/s11027-017-9763-y.

Vuuren, D.P. van, Stehfest, E., Gernaat, D.E.H.J., et al., 2018. Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. Nat. Clim. Chang. 8, 391–397. https://doi.org/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 Res. Soc. Sci. 4, 1–9.

Yang, L., Yan, H., Lam, J.C., 2014. Thermal comfort and building energy consumption implications – a review. Appl. Energy 115, 164–173. https://doi.org/10.1016/j.apenergy.2013.10.062.

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