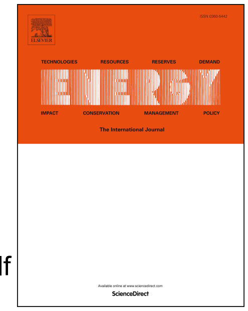
Accepted Manuscript



How much energy will buildings consume in 2100? A global perspective within a scenario framework

Antoine Levesque, Robert C. Pietzcker, Lavinia Baumstark, Simon De Stercke, Arnulf Grübler, Gunnar Luderer

PII: S0360-5442(18)30167-1

DOI: 10.1016/j.energy.2018.01.139

Reference: EGY 12251

To appear in: *Energy*

Received Date: 27 July 2017

Revised Date: 12 January 2018

Accepted Date: 27 January 2018

Please cite this article as: Levesque A, Pietzcker RC, Baumstark L, De Stercke S, Grübler A, Luderer G, How much energy will buildings consume in 2100? A global perspective within a scenario framework, *Energy* (2018), doi: 10.1016/j.energy.2018.01.139.

How much energy will buildings consume in 2100? A global perspective within a scenario framework.

Antoine Levesque[a,*], Robert C. Pietzcker[a], Lavinia Baumstark[a], Simon De Stercke[b,c], Arnulf Grübler[b], Gunnar Luderer[a]

[a] Potsdam Institute for Climate Impact Research, P.O. Box 601203, 14412 Potsdam, Germany

[b] International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria

[c] Department of Civil and Environmental Engineering, Imperial College London, London SW7 2AZ, UK

Abstract

The demand for energy in buildings varies strongly across countries and climatic zones. These differences result from manifold factors, whose future evolution is uncertain. In order to assess buildings' energy demand across the 21st century, we develop an energy demand model—EDGE— and apply it in an analytical scenario framework—the shared socio-economic pathways (SSPs) — to take socio-economic uncertainty into consideration. EDGE projects energy demand for five energy services, four fuel categories, and eleven regions covering the world.

The analysis shows that, without further climate policies, global final energy demand from buildings could increase from 116 EJ/yr in 2010 to a range of 120-378 EJ/yr in 2100. Our results show a paradigm shift in buildings' energy demand: appliances, lighting and space cooling dominate demand, while the weight of space heating and cooking declines. The importance of developing countries increases and electricity becomes the main energy carrier.

Our results are of high relevance for climate mitigation studies as they create detailed baselines that define the mitigation challenge: the stress on the energy supply system stemming from buildings will grow, though mainly in the form of electricity for which a number of options to decrease GHG emissions exist.

Keywords

Buildings energy demand, SSP, Energy models, Projections, Space heating, Space cooling

* Corresponding author. Tel: +49 331 288 2557
E-Mail address: levesque@pik-potsdam.de (A.Levesque)

1. Introduction

Buildings account for approximately one third of global final energy consumption. Because energy demand is one of the main sources of GHG emissions, the building sector should be part of any policy package aiming at limiting global warming below 2°C. To analyse the role buildings should take in climate policy, the definition of the baseline energy trajectory is of utmost importance. First, because baseline projections, against which the climate policy scenarios are assessed, influence estimated mitigation costs [1]. Second, because some policy targets—*e.g.* some Nationally Determined Contributions (NDCs) or the European energy efficiency target— are expressed relative to a baseline. Anticipating the development of energy demand from buildings in the long term is hence crucial for assessing the challenges ahead of any comprehensive climate policy.

The consumption of energy in buildings is very heterogeneous across regions, which result from differences in, among others, income levels, climate, and behaviour. While buildings' energy consumption in developed countries amounts to 42 GJ/capita/yr, is used primarily for space heating (50%) and is fuelled with electricity and gas (73%), building's energy consumption in developing countries is much lower (11 GJ/capita/yr), is used primarily for cooking (47%) and is fuelled with biomass (53%)[1]. The combined effect of economic development, of the growing energy demand from hot climate countries, and of the saturation of the demand for some end-uses could reshape this picture in the long term.

To assess the possible long-term pathways for the buildings sector, we developed the Energy Demand GEnerator (EDGE) model; an energy demand model covering five end-uses — appliances and lighting, cooking, water heating, space heating, and space cooling—, four energy carriers categories—electricity, other grids, liquids/modern biomass, and traditional solids[2]—, and eleven regions[3] representing the world consumption.

Several studies analysed the future evolution of energy demand in buildings, often with a focus on developing countries. Daioglou et al.[5] and van Ruijven et al.[6] showed that the residential energy consumption in developing countries shifts towards modern energy types, with pockets of traditional biomass use remaining in rural areas. In the long term, they expect the energy consumption in these countries to grow despite improved energy efficiency. Eom et al.[7] and Chaturvedi et al.[8] extended the analysis to the whole buildings sector and reached similar conclusions in the cases of China and India. The influence of climate change on thermal energy demand has also been studied and was found to be small overall, with nevertheless strong impacts on heating and cooling taken individually [9,10]. Urge-Vorsatz et al.[11] summarised the findings from nine model projections at the global level. Models covering all end-uses project an increase of global buildings' energy consumption from 31% to 95% between 2005[4] and 2050, compared to a range of 34% to 179% in the EDGE scenario framework reported here.

However, none of these studies assessed the global implication of the socio-economic uncertainty within a coherent framework. Projections to distant time horizons involve large uncertainties pertaining to the socio-economic drivers and to the relationship between these drivers and the energy demand. To address this difficulty and to integrate the possibility of social shifts in our projections, we adapt a scenario framework to our modelling — the Shared Socio-economic Pathways —, where each scenario describes a different world with prevailing lifestyles, institutions, mind-sets, etc. The EDGE model combines short-term projections based on historical relationships and long-term projections based on a growing role of scenario assumptions over historical patterns in the future. The importance of the scenario assumptions on the EDGE projections therefore grows heavily in the long term, while the historical patterns outweigh scenario assumptions to influence short-term projections.

The paper introduces the EDGE model, explains the implementation of the scenario framework in the model and presents the results.

2. EDGE Model

[1] Adapted from IEA [2–4]

[2] Other grids cover natural gas and district heating/cooling. Liquids/modern biomass covers liquid oil products and modern biomass (*e.g.* pellets). Traditional solids cover coal products and traditional biomass.

[3] EDGE regions include Africa, China, Europe, the United States of America, Russia, India, Japan, Other South East Asia, Middle East countries, Other OECD, and Other non-OECD. The regional allocation across income groups and development groups is provided in the Supplementary Information.

[4] In some studies, the reference year is 2007.

[[Figure 1]]

The EDGE model fundamentally works on the concept of *useful energy*, which is of fundamental importance when comparing energy use across different countries at different stages of development. It builds on the idea that while people usually buy final energy carriers like electricity or natural gas, they do not demand the energy in itself, but rather the service it provides — a heated room, a cooked meal, transportation. The useful energy represents the amount of energy that is made directly available for the energy service provision, *e.g.* radiant energy leaving a light bulb thus providing illumination, or kinetic energy available at the transmission of a vehicle providing transportation services. Useful energy is the result of energy conversions of final energy carriers in end-use devices. By contrast, *final energy* is the energy made available in form of energy carriers to the energy consumer and is usually subject to economic market transactions. In the case of space heating, final energy is the amount of natural gas or biomass fed into a boiler, and the useful energy is the heat coming from the boiler and available to heat a room. Using the concept of useful instead of final energy allows studying the energy demand independently of conversion efficiencies and better grasps the demand for the *energy service*—in that case, a comfortable room temperature.

The projections from the EDGE model follow four steps illustrated in [[Figure 1. The first step collects historical data and scenario projections for **fundamental drivers** for the energy demand in the buildings sector. These drivers cover several dimensions: a demographic dimension — population, population density—, an economic dimension — income per capita —, and a climate dimension — Heating and Cooling Degree Days. Subsequently, the model projects floor space demand, which is an important driver for energy services in buildings.

In the second step we calculate **useful energy demand** from the drivers and floor space. As in other studies—*e.g.* [7–9]—, EDGE relies on aggregate end-use energy functions describing the relationships between energy demand and underlying socio-economic factors. While it seems plausible to assume that the developments observed over the last decades will persist in the short term, in the long term, shifts in cultures, values, life styles etc, could greatly alter the link between drivers and demand [12]. To address this issue, and similarly to van Sluisveld [12], we modify the parametrisation of the functions to represent changes in cultural and behavioural dimensions. We embed the functions in a scenario framework, where the functions' parametrisation gradually deviates from historical values to scenario assumptions. In that sense EDGE does not represent sudden discontinuities but gradual shifts.

The second step delivers useful energy projections. To be able to compare our results with other studies and to draw some implications of our results for the energy supply, we need to translate the useful energy projections into final energy. To that end, the third step estimates future changes in **final-to-useful energy efficiencies** as well as **energy carrier shares** in each end-use. This information is required for step 4, in which the useful energy demand computed in step 2 is converted to **final energy demand** and these amounts are allocated to the different energy carriers.

EDGE focuses on the energy demand side, *i.e.* it adopts the consumer's perspective. Which energy services will consumers require in the future? Which energy carriers will they collect or purchase to satisfy their needs? Therefore, the question of how these energy carriers were provided by the supply sector— whether electricity was generated through coal combustion or solar energy— is beyond the scope of this study.

2.1. Historical Data

The successive steps of the model require different sets of historical data to calibrate the model to the historical relationships. For step 1, population and population density data stem from [13], while income per capita history was taken from [14]. Heating and Cooling degree days —HDD and CDD, respectively— were computed from historical temperatures [15] collected within the Inter-Sectoral Impact Model Intercomparison Project [16]. HDD totalises daily temperature degrees below 18°C in a region over a year, while CDD totalises daily temperature degrees above 21°C. The aggregation from the grid resolution of observations to the EDGE regions was weighted with population data.

The assessment of residential floor space demand relies on the data collected in [5], completed by other sources [17–23]. For some of the most populous countries, residential floor space data has remained unavailable. Indonesia (240 million people), Brazil (195 million people, urban data only), Pakistan (173 million people), Nigeria (160 million people, urban data only), Bangladesh (151 million people) are therefore not part of the data set used for the estimation. The disparity of data sources possibly leads to differences in the definition of the floor space per capita, or in the survey methodology employed. Commercial floor space data were taken from [24].

The calibration of the model requires historical data on *useful* energy consumption disaggregated across end-uses. The *Energy Balances* database published regularly by the International Energy Agency[3,4] reports on the *final* energy consumption for numerous countries and over several decades across energy sectors —transport, industry, residential and commercial buildings, etc.—, fuel types—electricity, natural gas, district heat, etc.—, but it does not precise the purpose for which this energy was consumed—the end-use— and the corresponding amount of *useful* energy. We disaggregate this database into end-uses—space heating, space cooling, appliances and lighting, water heating, cooking— by using information available on the share of each end-use (IEA 2014a, 2015) and on the fuel distribution within each end-use [5]. The disaggregation methodology is explained in more detail in the Supplementary Information.

To estimate the useful energy amounts associated with final energy data, we based ourselves on the work done by De Stercke [25], who recomposed an energy database—the Primary, Final and Useful Energy Database, PFUDB—including final and useful energy estimations and covering the period from 1900 to 2010 [26]. This study uses energy efficiency functions which relate energy efficiency to income per capita. We use the same approach and calibrate energy efficiency functions with the PFUDB data tailored to the EDGE end-use categories. This involves the disaggregation of the PFUDB to the EDGE end-uses by applying the same disaggregation methodology as for the IEA *Energy Balances*. These efficiency functions are finally used to obtain the useful energy database disaggregated by end-use. The reader can find more information on these efficiency functions in the description of steps 3 and 4 of the model as well as in the Supplementary Information.

2.2. Floor space demand

In EDGE, residential and commercial sectors are merged into the buildings sector. However, as the availability of commercial floor space data is limited, we first project residential area based on past data, and then compute the demand for commercial area by applying a coefficient on the residential area.

The size of living space is a key driver of energy demand for thermal comfort. Historical data show that even at high levels of income and dwelling area, the positive relationship between wealth and floor space demand persists [27]. There could be many channels between economic growth and floor space demand explaining this relationship. For instance, the purchase of new goods tied with consumption growth, or the wish to live in larger spaces, may lead to additional space requirements. Further, Moura et al.[17] explain that the decrease in household size, in combination with a constant average size of dwelling units, conduced to the observed rise in floor space per capita in the United States. If the fall of household size were the main explanation why floor space per capita increased steadily with income, we could expect a saturation as the household size cannot fall below one. Here, we assume household size is not the driving factor for per capita floor space and, considering historical patterns, we expect that living space will continue to grow with wealth, even at high income levels, but at a pace which will greatly vary across scenarios to represent the large uncertainty as to whether past trends will hold in the future or not.

We model floor space expansion with an income elasticity constant across income levels[5], and additionally assume a population density effect.

$$F = \alpha I^{\beta} D^{\gamma}$$

where F is the floor space demand per capita (m^2), I the income per capita (US$(2005)), D the population density (people/km^2), α is a scaling constant, and β and γ are the elasticities with respect to income and population density, respectively. We estimate the elasticities by regressing the linearised equation on historical data. The derived parameters for floor space can be found in Table SI 4. We project living area at the country level, and use the expression above to fill in the 2010 values for countries without historical data. As we assume that the income elasticity will evolve over time according to scenario assumptions (more in Section 3.2.1 and in Table SI 5), the elasticity at a certain point in time will only influence the incremental floor space demand. We therefore use a stepwise calculation of future floor space demand based on the value in the previous time step:

[5] In their analysis of the past US residential floor space demand, Moura et al. [16] show that the logarithms of income per capita and floor space per capita have evolved proportionately in the past indicating a constant elasticity across income levels over that period.

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

where t and s denote the period and the scenario, respectively.

Because urbanisation will continue rising in the 21st century [28], and floor space per capita is lower in urban than rural regions, we decrease the income elasticity over time in most scenarios.

Once residential floor space expansion is projected, we compute commercial area by projecting the ratio of commercial-to-residential area against the income levels. We use a Gompertz function, which describes an S-curve, and calibrate it on past data [24]. For levels of per capita income above US$(2005) 20000, the commercial-to-residential area ratio levels off close to 35%. Hence, in developed countries growth in commercial space is expected to be as fast as residential space.

2.3. The end-use functions

Following [[Figure 1 from the left to the right, socio-economic and climatic drivers come as an input to the end-use functions. The latter project useful energy demand for each energy service. Unless specified otherwise, the end-use functions are calibrated against historical useful energy consumption and the energy demand is given in useful energy. The parameters can be found in the Supplementary Information.

2.3.1. Space Heating

In 2014, space heating accounted for approximately 37% of buildings final energy consumption at the global level [2]. This energy demand mainly comes from countries with predominantly cold winters. In EDGE, the useful energy demand of space heating adjusted for buildings' insulation evolves in proportion with the number of heating degree days and with the demand for floor space. We assume that income levels influence the energy demand only indirectly through the increasing demand for residential and commercial space.

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

where SH is the space heating demand per capita (GJ), F is the floor space per capita (m^2), $Uvalue$ stands for the conductivity of the building shell ($GJ/m^2d°C$) and HDD is the number of heating degree days(d°C). δ is a positive parameter.

2.3.2. Space cooling

Space cooling energy demand reacts in a complex manner to electrification, purchasing power and climate. First, the penetration of air conditioners is enabled by electricity availability to consumers, and electrification rates increase with income levels. In 2014, 1.2 billion people did not have access to electricity and the majority lived in hot regions [29]. Second, at low income levels, the acquisition of energy using assets begins with other appliances including fans, televisions and refrigerators as suggested in other studies [6,30,31]. Both effects imply low penetration of air conditioners for low levels of income. Finally, space cooling demand per square meter is subject to saturation, which implies that space cooling per square meter and CDD do not increase indefinitely with income.

To model the complex relationships between electrification, purchasing power, climate and space cooling, we make two main assumptions. First, following McNeil and Letschert [31] and Isaac and van Vuuren [9], we represent the impact of CDD on space cooling demand as a combination of two distinct effects: on the one hand, in regions with only few hot days in a year, the penetration of air conditioners will remain low, irrespective of the income level—this is the climate maximum saturation effect. On the other hand, for the air conditioners installed, the energy demand grows linearly with CDD. Even though we do not explicitly include the ownership rates of space cooling systems in our model, we can integrate the full impact of CDD by multiplying both effects. The climate maximum saturation equation is directly taken from [31][6].

Second, the demand per square metre adjusted for the climate impact and buildings' insulation grows with income per capita and the effect of marginal income is low for low and high income levels and high for medium income levels, achieving a saturation level. The effect of wealth on the climate adjusted space cooling demand can hence be described by a logit cumulative distribution function.

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

[6] However, compared to the reference cited, we use CDD values for a threshold of 21°C instead of 18°C.

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

where SC is the space cooling useful energy demand per capita (GJ), F the buildings floor space per capita (m^2), CDD represents the cooling degree days (d°C), $Uvalue$ stands for the conductivity of the building shell (GJ/m^{2}d°C), I the income per capita (US$(2005)), ϕ_1 is the asymptote of the function when income approaches infinity, ϕ_2 is the midpoint of the sigmoid curve and ϕ_3 a horizontal scale parameter of the curve.

2.3.3. Appliances and Lighting

The category of appliances covers a range of heterogeneous devices from refrigerators and computers to dishwashers and vacuum cleaner robots. Lighting accounts for all energy consumption producing light with various technologies. In EDGE, lighting and appliances are grouped together.

Energy demand for appliances and lighting is linked with per capita income growth in two distinct ways; from the production side and from the consumption side. We argue that both these aspects will raise the energy demand for lighting and appliances and rule out a saturation level in a growing economy. First, economic growth goes along with growth in the service sector. In the past and in high income regions, the growth rate in the service sector even outpaced the growth rate of the whole economy [32]. Assuming on the one hand that the share of electronic services (*e.g.*, internet-based services) in the service sector will grow and, on the other hand, that electronic appliances constitute a channel to raise productivity in the service sector, it seems plausible to assume that economic growth requires growth in buildings' energy demand for appliances and lighting. Second, economic growth also implies increased direct consumption by the private and public sectors, and it appears probable that increased consumption translates into the invention and purchase of new appliances.

In the case of lighting, although consumption per capita has risen exponentially over the last centuries to levels inconceivable in the past [33,34], Tsao et al. [34] estimate that the demand for lighting in terms of lumens, *i.e.* in terms of light and not electricity, could still increase tenfold or more in developed countries before reaching saturation.

The relationship between income and energy demand can be summarised with an income elasticity of the demand. Fouquet [35] 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 a declining income elasticity.

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

where σ_{income} is the income elasticity, ϕ_1 is the asymptote of the income elasticity, β a parameter influencing the speed of the convergence towards the asymptote, I the income per capita (US$(2005)). By integrating the previous equation and by adding a scenario-specific parameter α, we obtain the function:

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

where AL is the useful energy consumption for appliances and lighting per capita (GJ) and α is a scenario specific parameter equal to one when estimating the other parameters with historical data. We assume that the elasticity will tend towards 0.3 in the long run, which is in the low range of current income elasticity for energy services computed for the United Kingdom [35]. We estimate γ and ϕ_2 with a linear regression.

Our description does not reflect individual technologies, which constitutes a drawback in the sense that the modelling is more abstract and probably less accurate in the short-term. But considering the long-term perspective of this study, the representation of demand for appliances and lighting through a list of existing technologies would underestimate the future growth in these services. Indeed, including solely existing technologies would not take into account the emergence of new services, new appliances, which will reshape our understanding of the needs for energy, as happened in the past. By contrast, the implementation chosen here does not build in an artificial saturation for the energy demand of appliances and lighting, and attempts to reproduce historical patterns.

2.3.4. Cooking

Cooking accounts for two-thirds of the final energy demand in buildings in Africa and India, while it plays a minor role in developed countries [2]. This difference partly results from the importance of other end-uses in developed countries, and partly from the low efficiencies induced by the use of inefficient cooking stoves in developing countries. In contrast to final energy demand of cooking, we consider that useful energy demand for cooking is independent of income and that regional discrepancies in useful energy demand per capita — 0.4 to 5 GJ/cap/yr in our database— result from differences in geographical and cultural patterns or from inaccuracies in our energy database. For the default scenario assumption, all useful energy demands converge towards 1.8 GJ/cap/yr in the long term. The degree of regional convergence by 2100 depends upon the scenario assumption as explained in Section 3.2.2.

2.3.5. Water heating

As data suggest [5], the useful energy demand for water heating increases with income. However, as incomes reach high levels, we expect a satiation level to be reached, where an increased quantity of hot water would not add to the amenity. We model the increasing demand for water heating energy with a logit cumulative distribution function which satisfies the satiation assumption and increases the demand only after income has passed a certain threshold. We assume that the per capita energy demand will converge for all regions to the same saturation point, and does not depend upon climate.

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

where WH is the water heating energy demand per capita (GJ), I the income per capita (US$(2005)), ϕ_1 is the asymptote, ϕ_2 is the midpoint of the sigmoid curve and ϕ_3 a horizontal scale parameter of the curve.

The regression-based parametrisation gives an asymptote corresponding to US levels of energy consumption. In the long term, we assume that the scenario continuing historical trends will rather follow values consistent with European or Japanese consumption levels[7].

2.4. Useful to final energy

The previous sections described steps 1 and 2 of the EDGE flow chart and showed how useful energy projections were produced. These projections constitute the core of the EDGE model because useful energy better grasps the demand for the energy service than final energy does. However, we are also interested in deriving the broad implications of these useful energy pathways for the energy supply system, which delivers final energy. In addition, most studies dealing with energy demand report their results in terms of final energy. To assess the relevance of our results for the supply sector and to compare our projections with other studies, we therefore need to make additional, simple assumptions to convert our *useful* energy projections into *final* energy projections. Useful energy is derived from final energy by applying a conversion efficiency factor, which is different among different end-use conversion devices and therefore from one energy carrier to another. As shown in the equation below, in order to obtain final energy amounts distributed across energy carriers from useful energy amounts, two pieces of information are needed: final-to-useful energy conversion efficiencies for each energy carrier and the final energy shares of each energy carrier. In the following, we describe how we derive both.

$$UE_s = \sum_{ec} UE_{s,ec} = \sum_{ec} \theta_{s,ec} FE_{s,ec} = \sum_{ec} \theta_{s,ec} \gamma_{s,ec} FE_s$$

$$\Leftrightarrow FE_s = \frac{UE_s}{\sum_{ec} \theta_{s,ec} \gamma_{s,ec}}$$

$$FE_{s,ec} = \gamma_{s,ec} \frac{UE_s}{\sum_{ec} \theta_{s,ec} \gamma_{s,ec}}$$

where UE is useful energy, FE is final energy, $\theta_{s,ec}$ is the final-to-useful energy conversion efficiency for the end-use s and the energy carrier ec, and $\gamma_{s,ec}$ the final energy share of an energy carrier in one end-use.

2.4.1. FE-UE efficiencies

The conversion from final to useful energy in the model is operated with energy efficiency functions, which were already used to derive the useful energy database. These functions relate energy efficiency

[7] The regression yields an asymptote of 8.3 GJ/cap/yr, which is equivalent to 22.7 MJ/cap/day or a temperature elevation of 40°C (*e.g.* from 15 to 55°C) for 216 litres per day and per person. By comparison, Japanese of European levels are closer to 5 GJ/cap/yr (13.7 MJ/cap/day) corresponding to 130 litres.

with income and take, according the first law of thermodynamics, a maximum below unity, with the exception of heat pump and similar air conditioning systems, whose efficiency can exceed this threshold.

$$efficiency = \phi_1 + (\phi_2 - \phi_1)exp[-exp(\phi_3)income]$$

Where ϕ_1 is the minimum efficiency, $\phi_2$the maximum efficiency and $\phi_3$describes the curvature of the function.

These functions are calibrated using the data from the Primary, Final and Useful energy Database [25]. The PFUDB is built on estimates of conversion efficiencies from final to useful energy for several useful energy forms — light, mechanical, heat, and other — and several aggregates of final energy carriers—coal/biomass, electricity and other. In the PFUDB, efficiencies depend upon the sector and on the income level of each region; and they follow a negative exponential growth curve which means that they grow monotonically from a minimum to a maximum. The parametrisation of the efficiency functions is derived from a regression analysis. Each efficiency function is specific for one combination of energy carrier and energy end-use. The efficiency function for electric space heating differs from the efficiency function for space heating delivered by the combustion of solid fuels.

After the computation of the parameters of the efficiency functions with the disaggregated PFUDB, we add slight corrections where the parameters appeared implausible. This applies to space cooling: instead of converting electricity to 'cold' (negative heat), air conditioning systems move heat from one sink to another. These systems are therefore not subject to an upper limit of one for efficiency[8]. Assuming a Seasonal Energy Efficiency Ratio (SEER)—a measure of the thermal efficiency of heat pumps and space cooling systems— of 3.1 for high incomes [36][9], we set the upper limit of space cooling efficiency to this value in 2010.

There are some caveats for the use of the negative exponential growth function. First, appliances cover a very heterogeneous set of devices ranging from computers to refrigerators which provide distinct services — communication, entertainment, refrigeration, etc. This heterogeneity makes comparison of efficiencies difficult and undermines our assumption of steady increase in efficiency with income. The assumption is therefore that efficiency improvements in each service offset a possible shift within energy use for appliances and lighting towards less efficient services. Historically there is no indication that the opposite is true [25]. Second, and more generally, the efficiency functions have been calibrated to match historical data. Here, we assume that historical efficiency trends will persist in the future.

2.4.2. Long-term energy carrier shares

In order to provide an aggregate guidance of how the useful energy pathways will translate in terms of final energy, we make simple assumptions on the development of the shares of energy carriers in each energy service as explained below.

According to the concept of the energy ladder [37], traditional biomass and coal provide the primary fuel for low incomes. They are then replaced by liquid fuels which are supplanted by modern energy, such as natural gas and electricity. At high income levels there is no similar concept describing the use of specific energy carriers. The energy carrier shares are partly determined by relative energy prices, but large uncertainty surrounds the future development of energy prices and how the demand will react to these. For modelling these two aspects —the energy ladder and the uncertainty at high income levels—we distinguish between two sets of energy carriers. First, we predict that the use of traditional[10] fuels will decrease towards 1% as the income approaches $20000/cap. Second, for the modern fuels, we prescribe shares (Table SI 10) towards which the regional fuel distribution will converge with time, or as the economy grows. We make different assumptions for each energy service. While space cooling is powered exclusively by electricity in 2010, we assume that district cooling will account for some of it in the future.

3. Scenarios

---

[8] For heat pumps, this measure of efficiency (heat removed or heat added over electricity input) is often called Coefficient of Performance (COP).

[9] In Werner [35], the SEER is estimated by comparing electricity consumption in kWh/m^2 with cooling output in kWh/m^2, so that SEER is dimensionless. SEER is sometimes expressed in BTU/Wh. 3.1 corresponds to 10.58 BTU/Wh, which is, by comparison, lower than the US requirements for new cooling equipment of 14 BTU/Wh.

[10] Here we consider modern fuels to cover electricity, other grids, and liquids/modern biomass (except in the case of appliances and light). Traditional fuels include traditional solids and liquids/modern biomass for appliances and light.

Long-term projections are fraught with uncertainties. Historical relationships between variables could change over the years to extents that are hard to quantify or to predict. This uncertainty led researchers facing long-term challenges to adopt the scenario approach to map different likely futures, without assigning the single scenarios any probability. Over the last years, a new set of scenarios has been created for climate policy and climate impact research — the Shared Socio-Economic Pathways (SSP). Five SSPs have been designed mapping different combinations of challenges to adaptation to climate change and challenges to mitigation of climate change. Each SSP builds on a narrative describing the future it represents. These narratives have been interpreted in quantitative scenarios, used as a basis for many studies dealing with issues requiring a long-term perspective. We briefly describe the five SSP narratives whose extended descriptions can be found in [38].

SSP1— Sustainability – Taking the green road— combines low challenges to adaptation and to mitigation. It represents a break with historical patterns with a growing awareness for environmental issues and the adoption of less resource-intensive lifestyles. The world engages in achieving development goals accelerating the convergence of developing countries towards higher standards of living. SSP2 — Middle of the Road — displays moderate challenges to adaptation and to mitigation and constitutes a continuation of historical trends: reduction of poverty and higher education continue to advance moderately in developing countries, the resource and energy intensities decline slightly. SSP3—Regional Rivalry— shows strong difficulties for both adaptation and mitigation. Countries reject globalisation and implement protectionist policies. This scenario is defined by low investments in education, resource intensive lifestyles and persistent inequalities. Weak international institutions cannot support a collective approach of global environmental issues. SSP4—Inequality: a road divided — is characterized by inequalities across and within countries. It combines low-income groups which do not have the means to hedge against climate impacts (high challenges to adaptation), and high income, internationally connected groups which can support environmental measures (low challenges to mitigation). Finally, SSP5 —Fossil-fuelled development—fills the gap with low challenges to adaptation but high challenges to mitigation. Fast development is achieved worldwide with widespread education and high rates of extraction and combustion of fossil fuels. People adopt material intensive lifestyles and global environmental challenges are not addressed.

An important characteristic of the scenarios shown here is that they do *not* include additional climate policies. The SSP framework intends to divide the question of the uncertainty pertaining to the development of the world— its institutions, its prevailing life styles, its economic expansion, its population, etc. — from the question of the optimal climate policy which could be implemented in any of these different worlds. Constructing a coherent baseline scenario is an important exercise not least because baseline projections influence the conclusions of climate policy assessments [1]. Therefore, our scenarios depict future potential worlds in the absence of climate policy, and attempt to reflect the variety of possible socio-economic, cultural, behavioural developments.

In the model, the qualitative characteristics of each scenario translate into quantitative differences through several channels: exogenous projections for basic drivers —GDP, population—, variations in the parameters of energy demand functions, global convergence assumptions, long-term shares of final energy carriers, and conversion efficiencies. We detail the scenario implementation in the following paragraphs, and add further information in the Supplementary Information.

3.1. Socio-economic and climatic drivers

3.1.1. Population and Income projections

Population projections are taken from KC and Lutz [39]. The rapidity of the demographic transition in developing countries constitutes the largest source of uncertainty in these projections which unfolds in a significant range for the 2100 population size — between 7 and 12.5 billion people.

This spectrum reflects the diversity characterising SSP storylines. In some scenarios, the assumption of strong and widespread education drives women's fertility rates down quickly in developing countries [40], shrinking population size compared with other scenarios.

Gross Domestic Product projections stem from Dellink et al.[41]. Developing countries can experience larger growth rates than developed countries as their technological advancement is lower than and rises towards the levels of developed countries. The high convergence assumption of SSP1 and SSP5 leads therefore to a much quicker growth in developing countries than in developed countries. Globally, the projected GDP levels in 2100 across SSPs lie between US$(2005) 280 trillion (SSP3) and 1000 trillion (SSP5) compared with an approximate US$(2005) 70 trillion in 2010. These figures hide an even larger difference in per capita income due to a lower population in prosperous scenarios— US$(2005) 140 000 in SSP5 against 22000 in SSP3.

3.1.2. Heating Degree Days and Cooling Degree Days

Each socio-economic scenario can result in different climate outcomes. Scenarios with greater challenges to mitigation are likely to reach greater temperature changes over the 21st century than scenarios with smaller challenges to mitigation. We therefore adopt different climate scenarios for each SSP scenario, applying higher global temperatures for the fossil fuel intensive scenario SSP5 and lower temperatures for SSP1, which represents a sustainability-oriented world with correspondingly lower GHG emissions and warming even in absence of dedicated climate policies. Accordingly, we use the representative concentration pathways (RCPs) 8.5 for SSP5, RCP 6.0 for SSP2 and SSP3, and RCP 4.5 for SSP1 and SSP4.

The future trends in HDD and CDD do not only reflect the effect of global warming, they also translate the changing demographic distribution across regions, as HDD and CDD are aggregated based on the geographical distribution of the population. This means that populous Africa drives the global estimate for HDD down and the estimate for CDD up. As the global population increase in hot climates, the average global citizen moves to a hotter place, with less HDD and more CDD. The assumptions made on the speed of the demographic transition in hot developing countries are therefore crucial for the global estimate of CDD and HDD in the different scenarios. In most scenarios, the trends express that, globally, the climate-driven per capita need for cooling will grow, while the climate-driven per capita need for heating will decrease.

HDD and CDD projections are computed from climate projections collected for the Inter-Sectoral Impact Model Intercomparison Project [16,42,43]. The Supplementary Information explains the choice of relevant climate scenarios for individual SSP scenarios.

The threshold used to compute CDD and HDD contains a behavioural assumption: that people will start consider cooling/heating from this threshold on. By using a threshold of 18°C for HDD, we therefore assume that above an atmospheric temperature of 18°C, nobody will turn on the heating; and conversely for space cooling with the 21°C threshold. We thus modify the thresholds according to the scenario narratives (Table SI3). For instance, as in SSP1 people adopt eco-friendly behaviours, we assume that in the course of the century, the threshold of CDD will shift from 21°C to 25°C in this scenario. The number of days in which people feel the need for cooling will therefore drop in this scenario. As can be observed on [[Figure **2**, the effect on the amount of CDD is substantial as it falls below the 2010 figure despite global warming and the demographic growth in hot countries.

[[Figure 2]]

3.2. Scenario assumptions

3.2.1. Variations in coefficients

Equation parameters in the model determine the relationship between drivers and the demand for energy or floor space. In a first step, these parameters are calibrated with our historical energy database. While it seems reasonable to assume that historical relationships will hold for the near- to medium-term, long run developments could be heavily influenced by changes in cultures, values, lifestyles, etc., captured in the scenario narratives. In EDGE, we represent this duality between short and long-term projections by assuming a common parametrisation derived from historical data for all scenarios in the short term and by assuming a growing importance of scenario-defined parameters in the long term.

So, the value of equation parameters changes over time according to scenario assumptions made in accordance with the scenario narratives. Different coefficients represent different cultural, urban, behavioural or technological developments shared globally that are not explicitly represented by variables in the model and still influence the level of energy demand. SSP5 for instance describes a world with energy intensive lifestyles. We therefore assume that in SSP5 people use more hot water than in SSP2. For all scenarios, we multiply relevant function parameters (Table SI 4) by a scenario coefficient to represent the different possible futures (Table SI 5). SSP2 continues the historical trends. The transition from the historical trajectory to the scenario trajectory is assumed to take fifty years between 2020 and 2070.

3.2.2. Regional convergence assumptions

The historical data on floor space and energy use show substantial differences between regional values for similar income and population density levels or climate. These regional differences are motivated by cultural factors, behaviour, geographical characteristics, etc., which are not represented explicitly in the model. Because of a lack of comprehension of these processes, we mitigate the role of these variables on regional discrepancies in the long run, and assume linear convergence towards a global convergence line which summarises the relationship between a driver and an explained variable. The convergence assumption towards a global value or relation varies from one scenario to another, in accordance with SSP narratives.

3.2.3. Assumptions on efficiencies

There are only a limited number of instances where the scenario affects the assumptions about efficiency (beyond the dependence on income). More information is provided in the Supplementary Information (Tables SI 7 and SI 8).

- *Electric space heating and water heating*: the efficiency of electric boilers is close to but lower than one. However, heat pumps, because they transfer energy from a heat source to another sink, can achieve much higher efficiency rates. Assuming different penetration rates for heat pump systems, as well as average efficiencies for each scenario, we modified the upper limit of the aggregated efficiency of all electric heating accordingly.
- *Electric space cooling:* typical Coefficients of Performance (COP) of air conditioning systems lie between 2 and 4, far from their theoretical maximum[11], letting room for improvements. In addition, the market for air conditioning systems might also grow rapidly with economic development in hot regions, potentially leading to higher R&D investments. We therefore expect efficiency improvements for electric space cooling and formulate scenario assumptions on the maximum SEER[12] achieved in the future.
- *Electricity for appliances and lighting:* we assume the maximum efficiency of appliances will continue to increase until 2100, but stay below one.

4. Results and discussion

As EDGE is a demand model, it is focused primarily on useful energy pathways. We therefore first report on the results in terms of useful energy before turning towards final energy in order to compare with other studies and to show the implications the projections have for the energy supply system.

Useful energy demand from buildings increases from an estimated 70 EJ/yr in 2010 to 164-951 EJ/yr in 2100, which corresponds approximately to a two- to fourteenfold increase (**[[Figure 3**). This translates in a per-capita increase from 10 GJ/yr to 24-131 GJ/yr. Comparing developed and developing regions, we can note that the ratio in per-capita energy consumption between both regions in 2010 is larger in terms of useful energy—35 to 4 GJ /yr—than in terms of final energy—42 to 11 GJ /yr — due to the lower efficiencies in developing regions. This relative gap in terms of useful energy diminishes strongly in all scenarios—51 to 23 GJ/yr is the maximum ratio in 2100.

What appears clearly from **[[Figure 3** is that the need for space cooling dwarfs all other end-uses in all scenarios; it surges from 14% of the demand to 36-71%. In particular, the need for space cooling strongly exceeds the need for space heating, which accounts for 40% of the consumption in 2010.

[[Figure 3]]

Turning to final energy estimates, buildings' final energy demand grows from 116 EJ/yr in 2010 to a range of 120-378 EJ/yr by the end of the 21st century ([**[**Figure **4**). As population varies between the SSPs, the relative gap in per capita final energy use narrows slightly; the average person uses 17 GJ/yr in SSP1, where energy demand per capita is the lowest and 51 GJ/yr in SSP5, where energy demand per capita is the largest. By comparison, the 2010 average demand per capita was 17 GJ/yr globally, 39 GJ/yr in Europe, 63 GJ/yr in the United States, 12 GJ/yr in Africa as well as in China. These developments are explained by the rising role of appliances and lighting, the greater need for space cooling, and the population dynamics.

---

[11] The COP measures the ratio of heat removed per unit of electricity required. The maximum COP of a cooling system is derived as the maximum efficiency of a Carnot cycle. For an indoor temperature of 18°C and an outdoor temperature of 27°C, the maximum efficiency is approximately 32. (18 + 273.15)/((27+ 273.15)-(18+ 273.15)).

[12] The COP of a heating pump measures the performance of the equipment at one point in time, while the SEER measures the performance over a longer period. A higher potential for COP therefore means a higher potential for SEER.

The increase of final energy demand is much smaller compared to the changes observed in the useful energy pathways. Where useful energy trends increased by 130-1250%, final energy trends barely increase by 5-225%. This is due to an overall efficiency improvement of buildings demand which is caused by a shift of the demand towards more efficient services (space cooling), a shift away from inefficient energy carriers, and the technological improvement of each conversion technology itself.

[[Figure 4]]

Lighting and appliances account for the bulk of the energy demand increase. This component rises from 23 EJ/yr in 2010 to a range of 72 to 195 EJ/yr until 2100. In global average per capita terms, this represents a demand of 1900 – 7300 kWh/yr/cap, up from 930 kWh/yr/cap in 2010. For comparison, the electricity consumption for appliances and light was, in 2010, 5500 kWh/yr/cap in the United States, 3200 kWh/yr/cap in Japan, 2000 kWh/yr/cap in Europe, and 215 kWh/yr/cap in India[13]. The absence of a saturation assumption for appliances and lighting explains the dominating role it plays by the end of the century in the model—31-60% in 2100. By contrast, for all other service demands we assume a saturation of the direct effect of income on the demand level. Space cooling demand grows nevertheless substantially because developing countries only reach the saturation level within the second half the century. Globally the share of space cooling rises from 4% in 2010 to 11-37% in 2100. As a corollary to the rise in the share of appliances, lighting, and space cooling, the relative demand for heat — cooking, space heating and water heating—decreases strongly. Heat falls from 76% in 2010 to 18-42% by 2100. In almost all scenarios—except for SSP3—, the demand for heat even falls in absolute terms due to improved buildings' insulation, improved conversion efficiencies and to the shift away from inefficient traditional fuels.

[[Figure 5]]

We now compare the EDGE scenarios with three other sets of projections. Compared to other simulations adopting the SSP framework [44]([[Figure **4**), EDGE seems to confirm previous results, with the notable exception of SSP1, where demand in EDGE declines earlier and deeper than in other energy demand pathways. Strong assumptions on behaviours and efficiency improvements in the EDGE SSP1 scenario most likely account for this difference. Compared to projections from Lucon et al. [45], the socio-economic uncertainty displayed in EDGE scenarios covers much of the range formed by former Integrated Assessment Models (IAMs) projections (**[[Figure 5**). Again, the SSP1 scenario occupies the lower band of projections. To assess where this scenario lies in comparison with other low-demand scenarios, we added projections from Güneralp et al [47] to **[[Figure 5**. These scenarios only represent the demand for heat and cooling and assume some climate policy, by contrast with the EDGE SSP1 scenario. The EDGE SSP1 results are very similar compared to the projections from the IAM GCAM, both in magnitude and dynamics. Compared to the results from the bottom-up model 3CSEP HEB, the 2050 EDGE SSP1 results (51 EJ/yr) are midway between the projections with current efficiency initiatives (81 EJ/yr) and the projections assuming advanced efficiency initiatives (38EJ/yr). Due to different starting points, the differences in absolute terms between EDGE SSP1 and the Advanced Efficiency Scenario hide even larger variations in the relative evolutions of demand[14], The reduction in demand between 2015 and 2050 in 3CSEP HEB is by far larger than the evolutions in EDGE SSP1— -38% for 3CSEP HEB against +6% for EDGE SSP1. This seems plausible given the assumption about strong climate policies in the Advanced Efficiency Scenario.

[[Figure 6]]

The role of developing countries in the regional composition of buildings' final energy demand increases over the century. The share of OECD countries, which mostly have cold winters—coloured in blue in [[Figure 6— drops from 43% in 2010 to a range of 17-24% in 2100. By contrast, developing countries' share rises overall, though with disparate patterns. Chinese energy demand accounts for 20% by 2050 up from 14% in 2010, before falling to 9-14% by the end of the century because of declining population projections. This peak-and-decline trajectory sharply contrasts with the case of Africa —10% to 9-13% by 2050, and 17-28% by 2100 — whose share's growth remains modest within the first half of the century before soaring in the second part. India's share rises steadily over the century. We also observe a strong shift in the importance of each end-use compared with 2010 (**[[Figure 7**). The prevalence of space heating

---

[13] Adapted from (IEA, 2015, 2014a, 2014b)

[14] Historical estimates in the different models diverge for 2010 and 2015. EDGE has a heating and cooling demand of 48 EJ/yr in 2010 and 45 EJ/yr in 2015, while GCAM has a demand of 42 EJ/yr in 2010 and 3CSEP HEB of 61-69 EJ/yr in 2015.

in developed countries and of cooking in developing countries disappears in all scenarios. Space heating's share decreases from 50% to 14-30% in the developed regions while cooking's share in developing countries dwindles from 47% to 5-18%. Space cooling in developing countries rises from 3% in 2010 to 14-43% in 2100. Appliances and lighting account for a large share in both regions.

[[Figure 7]]

[[Figure 8]]

In scenarios showing convergence of incomes —SSP1, SSP5 and to a lesser extent SSP2—, the gap in final energy consumption per capita between developing and developed regions closes (**[[Figure 8**, All end-uses). Apart from SSP1—the ecological scenario —, the demand per capita increases in developing countries and stagnates in developed countries. In SSP1 there is a strong convergence between developed and developing countries towards a low-demand pathway. In developed countries, the demand for space cooling almost vanishes to a great extent because the CDD setting point shifts from 21°C to 25°C. The demand for space heating shows large uncertainty and could become as low as 5 GJ/cap because of improved insulation, a lower HDD setting point and a partial shift to efficient heat pumps. In developing countries, space cooling demand varies significantly across scenarios. Despite hotter outdoor temperatures, space cooling energy demand in developing countries barely exceeds that in developed countries in SSP3 and SSP4 due to lower income levels. In SSP5, cooling demand in developing countries shows a very strong increase to 20GJ/cap until income in hot countries reaches US$(2005) 50000, but then levels off due to the saturation of the need for cooling.

[[Figure 9]]

Considering the repartition across energy carriers, all scenarios project a profound electrification of the buildings' energy use. This comes primarily from the massive deployment of space cooling and appliances observed in the projections ([[Figure 9). Both services rely to a large extent on electricity. To a lesser degree, this is explained by assumptions on the electrification of heat through efficient heat pumps, electric stoves and electric boilers. The share of electricity rises from 28% to 63-90% globally. This trend affects both developing regions—18% to 64-91% — and developed regions— 40% to 56-86%. Natural gas and district heating/cooling (Other Grids) is the second most used category globally by 2100 —28% in 2010 to 8-22% in 2100. Finally, the share of traditional solids declines rapidly and in some SSPs disappears almost completely as early as mid-century.

5. Conclusion

In this paper we present a model for scenario projections of the energy demand of buildings. This model explicitly represents five energy end-uses—cooking, appliances and lighting, water heating, space heating and space cooling—, four fuel categories and eleven regions covering the global demand. The model is applied within the SSP scenario framework to show the effect of the uncertainties about the socio-economic developments until 2100. Each scenario is represented in the model through different exogenous demographic and economic projections, as well as through parameter choices in line with the scenario narratives. The projections presented in this paper study the future of the buildings' energy demand *without additional climate policies*. Thereby, the projections map the different contexts in which any climate policy would be implemented, and identifies challenges policies would have to address.

Our results show growth in buildings' energy demand across all SSPs. This growth is especially strong when considering useful energy projections—70 EJ/yr in 2010 to 164-951 EJ/yr in 2100— heavily driven by cooling energy consumption. In terms of final energy, the extent of the demand increase differs widely across scenarios —from 116 EJ/yr in 2010 to a range of 120-378 EJ/yr by 2100—, underlining the importance of socio-economic, climatic and life styles development on long-term projections. For most scenarios, the results lie within the spectrum of previous studies [44,45]. The projection for the environmental scenario—SSP1, 120 EJ/yr in 2100— remains below prior baseline forecasts, reflecting the strong structural developments towards sustainability assumed in this scenario.

Despite the differences in aggregate energy demand, common patterns arise between scenarios. The final energy distribution across end-uses changes radically between 2010 and 2100. While in 2010, cooking and space heating constituted the main end-uses in developing and developed countries respectively, in 2100, appliances and lighting will be the dominant end-use, representing 30-60% of total demand. In developing countries, space cooling has a similar importance as appliance and lighting, while in developed countries space heating is the next largest end use, accounting for roughly a fourth of demand. Another differentiation between 2010 and 2100 lies in the distribution across energy carriers. Confirming the findings by previous studies [5,7,8,10,48], our results indicate that developing countries will turn away from solid fuels to experience a deep electrification of their buildings' energy use. We find, in addition, that electrification also concerns developed countries due to the saturation of thermal needs and the growing demand for lighting and appliances. The scenario analysis, however, does not show convergence of per capita energy demand between developed and developing regions in all scenarios. Convergence only occurs in scenarios where income per capita converges.

The modelling of the demand for appliances and lighting posed the greatest challenges and deserves further improvements in the future, not least because of the importance it takes in our projections. We decided on purpose not to model individual appliances but instead to project the aggregate energy demand for appliances and lighting, in order to avoid building in an arbitrary saturation level in the long term when currently existing appliances reach saturation. Given the variety of newly developed appliances over the last decades, it seems presumptuous to claim that there will be no comparable innovations in the future, leading to new appliances and thus additional demand. This choice comes however at a cost: while the behaviour of diffusion curves of existing appliances is well understood and can yield accurate projections [49], modelling the aggregate behaviour of energy demand for appliances is fraught with uncertainty and necessitates additional assumptions about the functional form of the relationship with income growth.

To conclude, our analysis provides results that are an important input for the analysis of long-term climate change mitigation. They indicate that in absence of vigorous energy efficiency improvement efforts (as assumed in the SSP1 scenario) buildings' energy demand will increase substantially over the 21st century, imposing greater stress on the energy supply system. Most of this demand increase will come from electricity, for which many decarbonisation options exist [50]. Moreover, the radical shift in the types of services impacts policy making as well; strategies and potentials to decrease energy demand will differ between a context of high demand for heat, as in 2010, and a context of high demand for lighting and appliances, as projected for 2100. A better understanding of different types of energy demand in the buildings sector is therefore a crucial input when analysing the contribution of buildings' energy use to climate change, and for exploring the mitigation possibilities in this sector that remain substantial.

Acknowledgement

This work was supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No 730403 (INNOPATHS) and by the European Union Seventh Framework Programme FP7/2007–2013 under grant agreement no 308329 (ADVANCE).

References

[1] Blanford GJ, Rose SK, Tavoni M. Baseline projections of energy and emissions in Asia. Energy Economics 2012;34:S284–92. doi:10.1016/j.eneco.2012.08.006.

[2] IEA. World Energy Outlook 2015. Paris, France: International Energy Agency; 2015.

[dataset] [3] IEA. Energy Balances of OECD Countries 2014. IEA; 2014.

[dataset] [4] IEA. Energy Balances of non-OECD Countries 2014. Paris: Organisation for Economic Co-operation and Development; 2014.

[5] Daioglou V, van Ruijven BJ, van Vuuren DP. Model projections for household energy use in developing countries. Energy 2012;37:601–15. doi:10.1016/j.energy.2011.10.044.

[6] van Ruijven BJ, van Vuuren DP, de Vries BJ, Isaac M, van der Sluijs JP, Lucas PL, et al. Model projections for household energy use in India. Energy Policy 2011;39:7747–7761.

[7] Eom J, Clarke L, Kim SH, Kyle P, Patel P. China's building energy demand: Long-term implications from a detailed assessment. Energy 2012;46:405–19. doi:10.1016/j.energy.2012.08.009.

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

[9] Isaac M, van Vuuren DP. Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. Energy Policy 2009;37:507–21. doi:10.1016/j.enpol.2008.09.051.

[10] Zhou Y, Eom J, Clarke L. The effect of global climate change, population distribution, and climate mitigation on building energy use in the U.S. and China. Climatic Change 2013;119:979–92. doi:10.1007/s10584-013-0772-x.

[11] Urge-Vorsatz D, Petrichenko K, Staniec M, Eom J. Energy use in buildings in a long-term perspective. Current Opinion in Environmental Sustainability 2013;5:141–51. doi:10.1016/j.cosust.2013.05.004.

[12] van Sluisveld MAE, Martínez SH, Daioglou V, van Vuuren DP. Exploring the implications of lifestyle change in 2°C mitigation scenarios using the IMAGE integrated assessment model. Technological Forecasting and Social Change 2016;102:309–19. doi:10.1016/j.techfore.2015.08.013.
[dataset] [13] The World Bank. World Development Indicators 2014.
[14] James SL, Gubbins P, Murray CJ, Gakidou E. Developing a comprehensive time series of GDP per capita for 210 countries from 1950 to 2015. Population Health Metrics 2012;10:12. doi:10.1186/1478-7954-10-12.
[15] Global Soil Wetness Project Phase 3. 2016.
[16] ISIMIP. The Inter-Sectoral Impact Model Intercomparison Project. https://www.isimip.org/ 2016.
[17] Moura MCP, Smith SJ, Belzer DB. 120 years of US residential housing stock and floor space. PloS One 2015;10:e0134135.
[18] KOSIS. Construction, Housing, Land statistical database 2016.
[19] Rosstat. Russia 2015 Statistical Pocketbook. Moscow: Federal State Statistic Service (Rosstat); 2015.
[20] National Bureau of Statistics of China. 6-17 Floorspace of Newly Built Residential Buildings and Housing Conditions of Urban and Rural Residents 2016.
[21] Statistical Center of Iran. Selected Findings of the 2011 National Population and Housing Census 2011.
[dataset] [22] ENERDATA. Odyssee 2011.
[23] Ministry of Statistics and Programme Implementation, India. 2015.
[24] IEA. Tracking Clean Energy Progress 2014. 2014.
[25] De Stercke S. Dynamics of Energy Systems: A useful Perspective. International Institute of Applied Systems Analysis (IIASA); 2014.
[dataset] [26] IIASA. PFU database. https://tntcat.iiasa.ac.at/PFUDB 2016.
[27] IEA. 30 years of energy use in IEA countries - Oil Crises & Climate Challenges. 2004.
[28] Jiang L, O'Neill BC. Global urbanization projections for the Shared Socioeconomic Pathways. Global Environmental Change 2017;42:193–9. doi:10.1016/j.gloenvcha.2015.03.008.
[29] IEA. World Energy Outlook 2016. Paris, France: International Energy Agency; 2016.
[30] Wolfram C, Shelef O, Gertler P. How Will Energy Demand Develop in the Developing World? Journal of Economic Perspectives 2012;26:119–38. doi:10.1257/jep.26.1.119.
[31] McNeil MA, Letschert VE. Future air conditioning energy consumption in developing countries and what can be done about it: the potential of efficiency in the residential sector. Lawrence Berkeley National Laboratory 2008.
[32] Herrendorf B, Rogerson R, Valentinyi Á. Growth and structural transformation. National Bureau of Economic Research; 2013.
[33] Fouquet R, Pearson PJG. Seven Centuries of Energy Services: The Price and Use of Light in the United Kingdom (1300-2000). The Energy Journal 2006;27:139–77.
[34] Tsao JY, Saunders HD, Creighton JR, Coltrin ME, Simmons JA. Solid-state lighting: an energy-economics perspective. Journal of Physics D: Applied Physics 2010;43:354001.
[35] Fouquet R. Long-Run Demand for Energy Services: Income and Price Elasticities over Two Hundred Years. Rev Environ Econ Policy 2014;8:186–207. doi:10.1093/reep/reu002.
[36] Werner S. European space cooling demands. Energy 2016;110:148–56. doi:10.1016/j.energy.2015.11.028.
[37] Leach G. The energy transition. Energy Policy 1992;20:116–23. doi:10.1016/0301-4215(92)90105-B.
[38] O'Neill BC, Kriegler E, Ebi KL, Kemp-Benedict E, Riahi K, Rothman DS, et al. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change 2017;42:169–80. doi:10.1016/j.gloenvcha.2015.01.004.
[39] KC S, Lutz W. 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 2016:in press. doi:10.1016/j.gloenvcha.2014.06.004.
[40] Lutz W, Muttarak R, Striessnig E. Universal education is key to enhanced climate adaptation. Science 2014;346:1061–2. doi:10.1126/science.1257975.
[41] Dellink R, Chateau J, Lanzi E, Magné B. Long-term economic growth projections in the Shared Socioeconomic Pathways. Global Environmental Change 2016:in press. doi:10.1016/j.gloenvcha.2015.06.004.
[42] Hempel S, Frieler K, Warszawski L, Schewe J, Piontek F. A trend-preserving bias correction – the ISI-MIP approach. Earth Syst Dynam 2013;4:219–36. doi:10.5194/esd-4-219-2013.
[43] Hempel S, Frieler K, Warszawski L, Schewe J, Piontek F. Bias corrected GCM input data for ISIMIP Fast Track 2013.
[44] Bauer N, Calvin K, Emmerling J, Fricko O, Fujimori S, Hilaire J, et al. Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives. Global Environmental Change 2016. doi:10.1016/j.gloenvcha.2016.07.006.

[45] Lucon O, Ürge-Vorsatz D, Zain Ahmed A, Akbari H, Bertoldi P, Cabeza LF, et al. Buildings. 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., 2014.

[dataset][46] IAMC. AR5 Scenario Database 2014.

[47] Güneralp B, Zhou Y, Ürge-Vorsatz D, Gupta M, Yu S, Patel PL, et al. Global scenarios of urban density and its impacts on building energy use through 2050. PNAS 2017:201606035. doi:10.1073/pnas.1606035114.

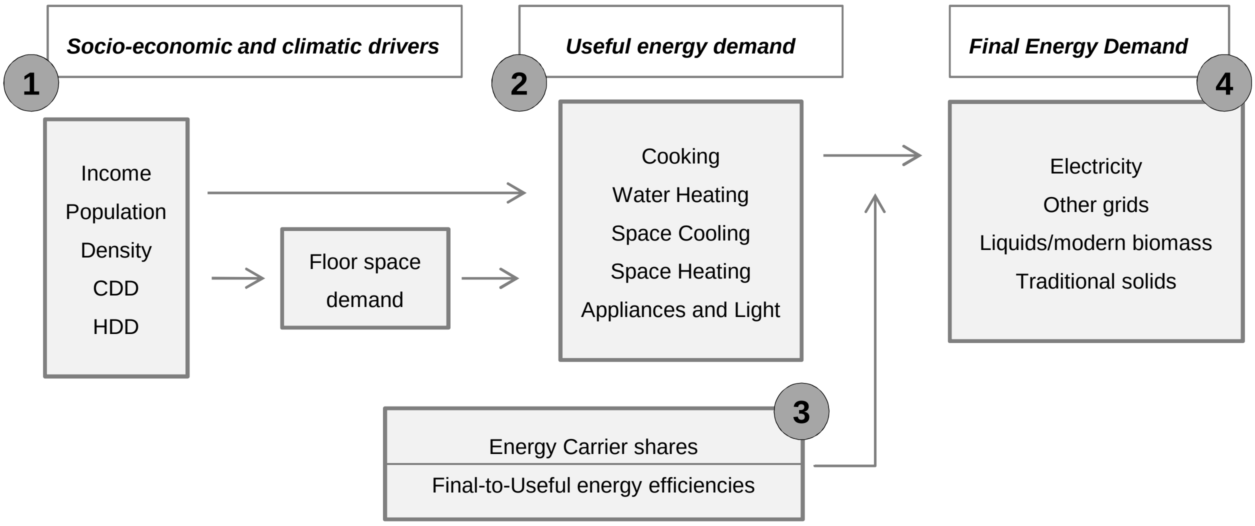
[48] Nakicenovic N, Grubler A, McDonald A. Global Energy Perspectives. Cambridge: Cambridge University Press; 1998.

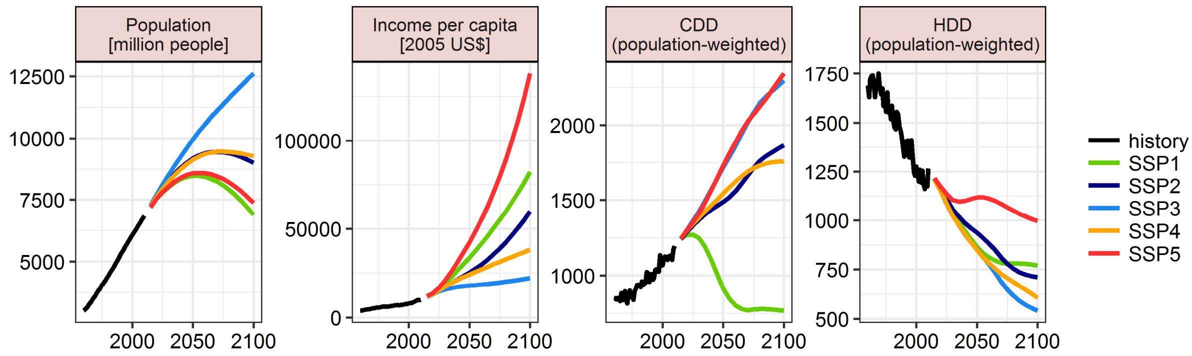
[49] Gertler PJ, Shelef O, Wolfram CD, Fuchs A. The Demand for Energy-Using Assets among the World's Rising Middle Classes. American Economic Review 2016;106:1366–401. doi:10.1257/aer.20131455.

[50] Luderer G, Krey V, Calvin K, Merrick J, Mima S, Pietzcker R, et al. The role of renewable energy in climate stabilization: results from the EMF27 scenarios. Climatic Change 2014;123:427–41. doi:10.1007/s10584-013-0924-z.

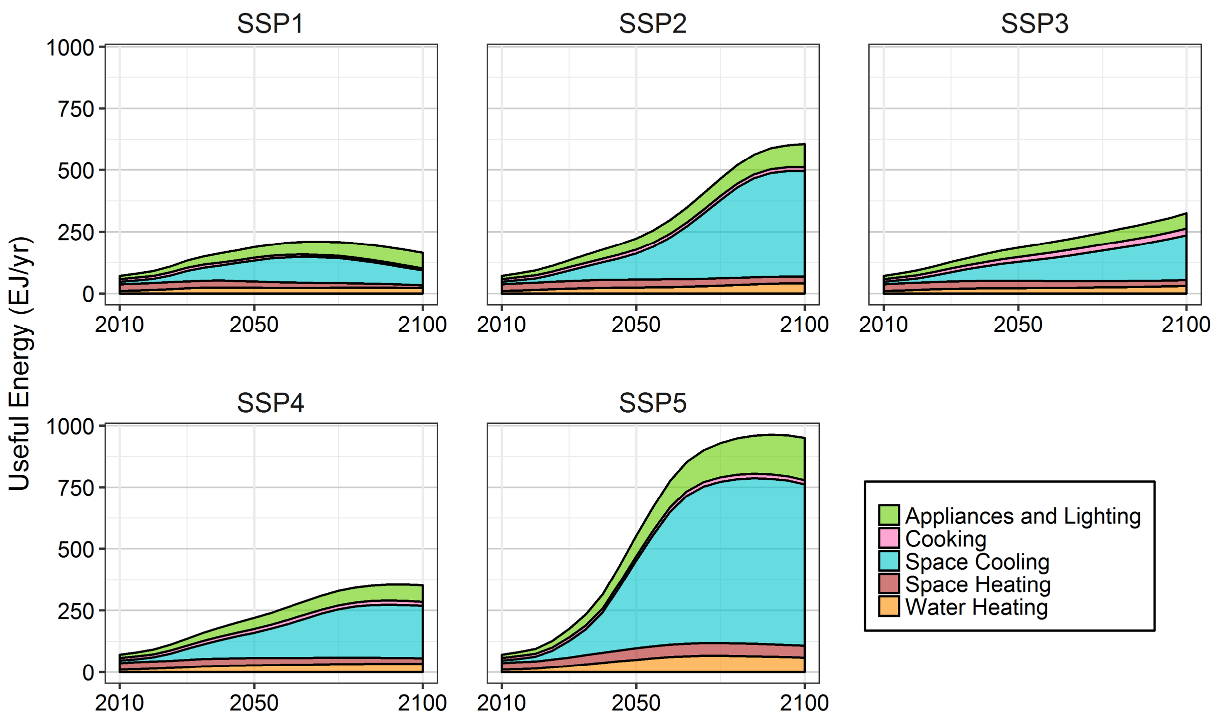
List of captions:

Figure 1 EDGE Flow chart. The numbers indicate the steps in the model and are explained in detail in the text
Figure 2 Exogenous projections for socio-economic and climatic drivers at the global level used in EDGE
Figure 3 Global useful energy demand for buildings disaggregated by end-use
Figure 4 Global final energy demand for buildings disaggregated by end-use. The transparent purple area shows the range of demand pathways in a number of Integrated Assessment Models (IAMs) as reported in Bauer et al. [44]. The grey area shows historical demand from the IEA [3,4]
Figure 5 Comparison of the EDGE results with projections from the literature, such as Lucon et al. [45] on the left-hand side and Güneralp et al. [47] on the right-hand side. Energy demand from Güneralp et al. [47] only shows heating and cooling energy demand until 2050. Sectoral projections depicted in [45](Lucon et al. 2014, Figure 9.20) could not be added as they are not included in the AR5 scenario database.[46](IAMC, 2014). Contrary to the original figure, we show the projections until 2100 instead of 2050.
Figure 6 Regional shares in global buildings' final energy demand
Figure 7 End-use shares in 2100 for developed and developing regions
Figure 8 Per capita energy consumption in developing and in developed regions
Figure 9 Fuel type shares in global buildings' final energy demand. Electricity is represented with blue colours. For 1990 and 2000, electricity consumption is reported in the aggregate only

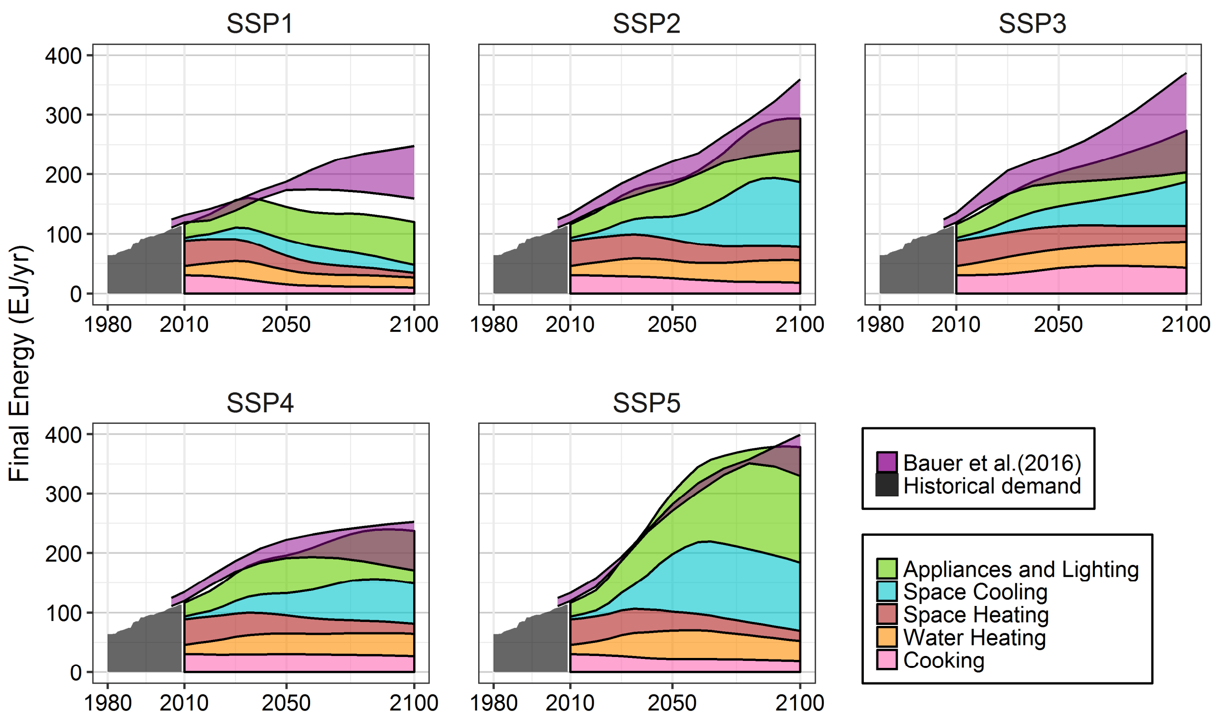

Socio-economic and climatic drivers
Useful energy demand
Final Energy Demand
1
Income
Population
Density
CDD
HDD
Floor space demand
2
Cooking
Water Heating
Space Cooling
Space Heating
Appliances and Light
3
Energy Carrier shares
Final-to-Useful energy efficiencies
4
Electricity
Other grids
Liquids/modern biomass
Traditional solids

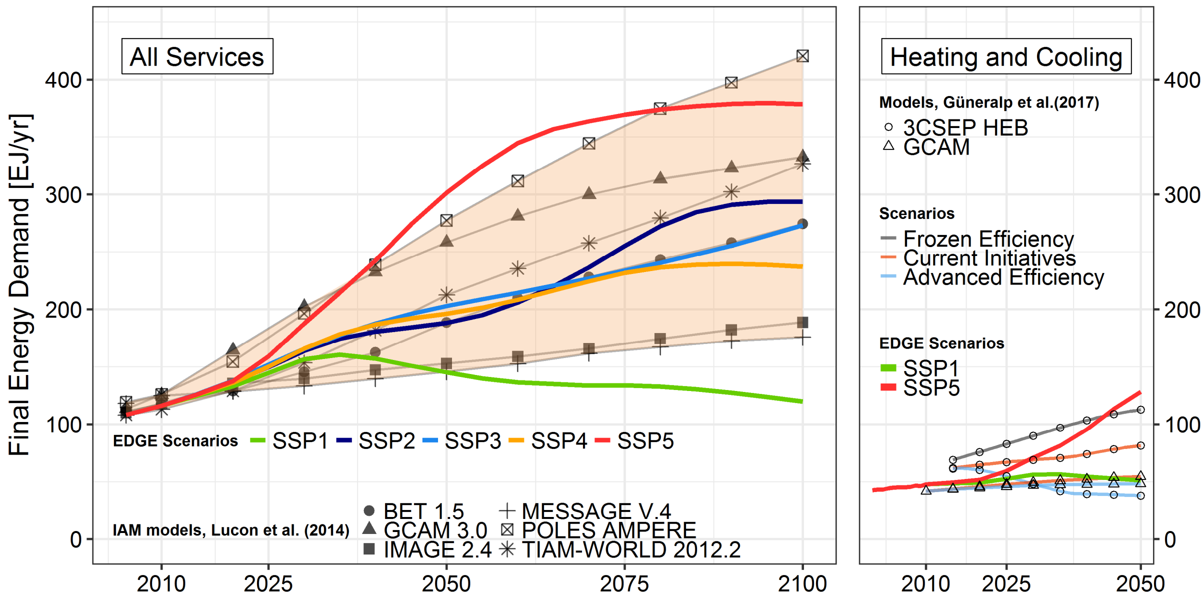


Population
[million people]
12500
10000
7500
5000
2000
2050
2100
Income per capita
[2005 US$]
100000
50000
0
2000
2050
2100
CDD
(population-weighted)
2000
1500
1000
2000
2050
2100
HDD
(population-weighted)
1750
1500
1250
1000
750
500
2000
2050
2100
history
SSP1
SSP2
SSP3
SSP4
SSP5

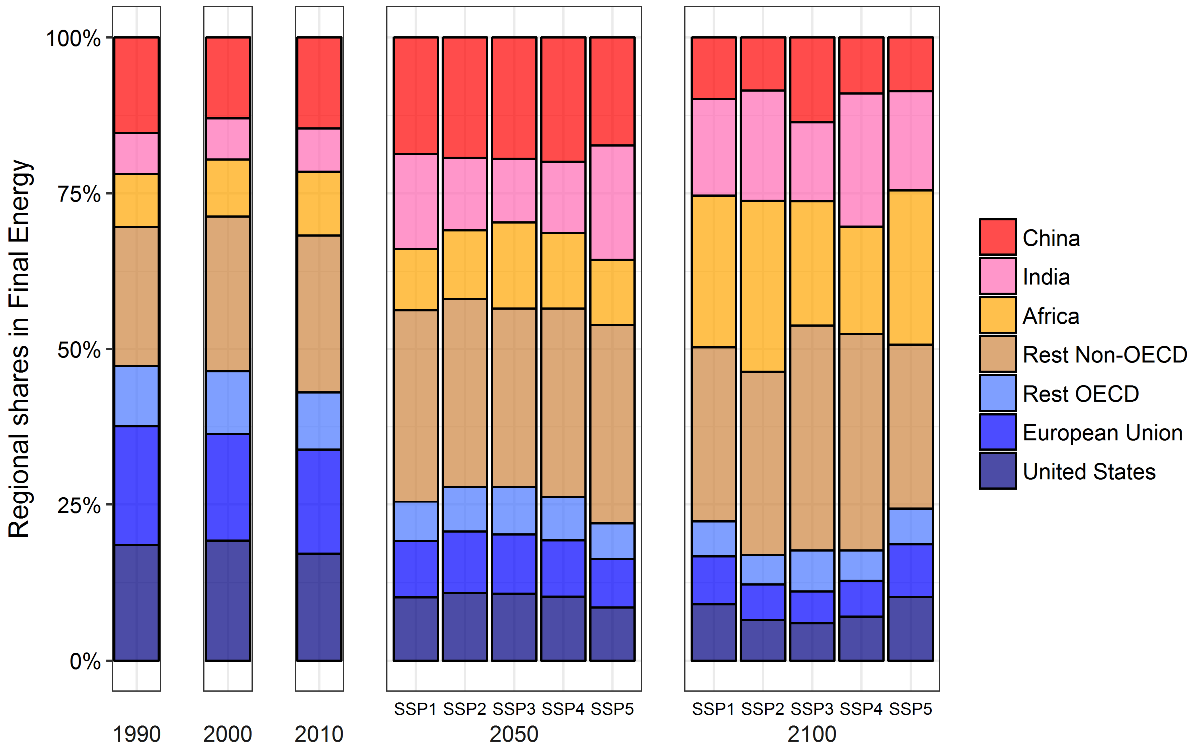


SSP1
SSP2
SSP3
SSP4
SSP5
Useful Energy (EJ/yr)
1000
750
500
250
0
2010
2050
2100
Appliances and Lighting
Cooking
Space Cooling
Space Heating
Water Heating


SSP1
SSP2
SSP3
SSP4
SSP5
Final Energy (EJ/yr)
0
100
200
300
400
1980
2010
2050
2100
Bauer et al.(2016)
Historical demand
Appliances and Lighting
Space Cooling
Space Heating
Water Heating
Cooking

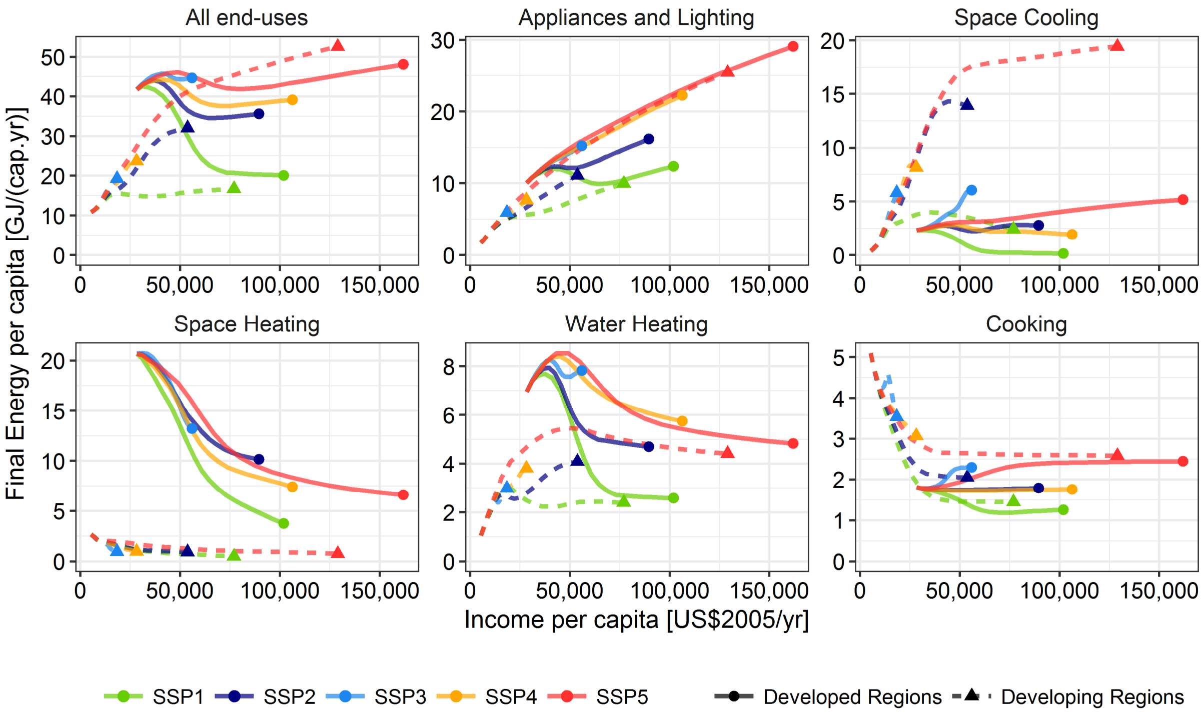


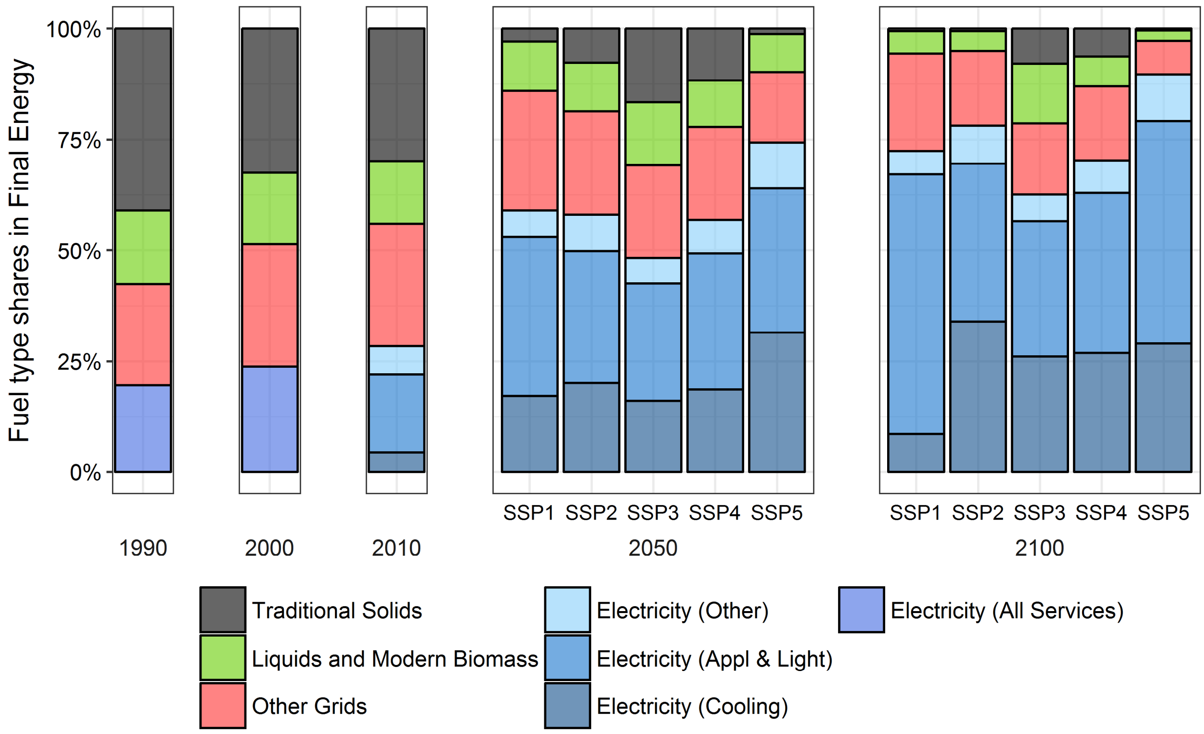
All Services
Final Energy Demand [EJ/yr]
400
300
200
100
0
EDGE Scenarios SSP1 SSP2 SSP3 SSP4 SSP5
IAM models, Lucon et al. (2014)
BET 1.5
GCAM 3.0
IMAGE 2.4
MESSAGE V.4
POLES AMPERE
TIAM-WORLD 2012.2
2010
2025
2050
2075
2100
Heating and Cooling
Models, Güneralp et al.(2017)
3CSEP HEB
GCAM
Scenarios
Frozen Efficiency
Current Initiatives
Advanced Efficiency
EDGE Scenarios
SSP1
SSP5
2010
2025
2050



100%
75%
50%
25%
0%
Regional shares in Final Energy
SSP1 SSP2 SSP3 SSP4 SSP5
SSP1 SSP2 SSP3 SSP4 SSP5
1990
2000
2010
2050
2100
China
India
Africa
Rest Non-OECD
Rest OECD
European Union
United States

Developed Regions - 2100
Developing Regions - 2100
End-use shares in Final Energy
100%
75%
50%
25%
0%
2010
SSP1
SSP2
SSP3
SSP4
SSP5
Appliances and Lighting
Cooking
Space Cooling
Space Heating
Water Heating


All end-uses
Appliances and Lighting
Space Cooling
Space Heating
Water Heating
Cooking
Final Energy per capita [GJ/(cap.yr)]
Income per capita [US$2005/yr]
0
50,000
100,000
150,000
SSP1
SSP2
SSP3
SSP4
SSP5
Developed Regions
Developing Regions



Fuel type shares in Final Energy
100%
75%
50%
25%
0%
1990
2000
2010
SSP1 SSP2 SSP3 SSP4 SSP5
2050
SSP1 SSP2 SSP3 SSP4 SSP5
2100
Traditional Solids
Liquids and Modern Biomass
Other Grids
Electricity (Other)
Electricity (Appl & Light)
Electricity (Cooling)
Electricity (All Services)

Highlights

- A new energy demand model based on useful energy estimates is presented
- Buildings' energy demand is projected for five SSP scenarios until 2100
- Appliances, lighting and space cooling become the main end-uses
- Most of the energy demand will be covered by electricity