How will buildings' energy demand look in 2100? Quantifying future energy service demand from buildings

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Abstract

The demand for energy in buildings shows strong heterogeneities for different states of economic and technical development, as well as for different climate zones and life styles. In developed countries, final energy is used primarily for heating, while cooking plays the leading role in the developing countries. Further, natural gas and electricity fuel advanced economies when biomass prevails in other regions. These differences result from manifold factors – income levels, climate, behaviour, etc. –, for which the future development across the 21st century is highly uncertain. This uncertainty, in turn, diffuses to the future evolution of buildings energy demand.

To investigate plausible futures for buildings energy demand until 2100, this paper develops an energy demand model for buildings (EDGE) and applies it in an analytical scenario framework. EDGE projects energy demand for five energy services – lighting and appliances, space heating, space cooling, cooking, and water heating – eleven regions covering the world and seven fuel types. The long-term uncertainty is addressed with a comprehensive scenario framework developed over the last years in the integrated assessment community (O'Neill et al., 2014). The so-called shared socio-economic pathways (SSPs) framework bundles qualitative and quantitative assumptions about key factors for buildings energy demand – *e.g.* income levels, technology development, environmental awareness – to span a wide set of likely future societies. These differentiated socio-economic developments provide crucial assumptions for energy demand.

The analysis identifies the future key energy services for the aggregated buildings energy demand across two SSP scenarios. Results show the transformation of the buildings energy landscape driven by the rise in the demand for appliances, light and space cooling, and they show a strong electrification of the sector.

Introduction

Buildings account for approximately one third of global final energy consumption. Because energy consumption is one of the main sources of GHG emissions, the buildings sector should be part of any policy package aiming at limiting global warming below 2 °C. Anticipating the development of energy demand from buildings in the long-term is hence crucial for assessing the challenges ahead of any climate change mitigation policy.

Today, large heterogeneities characterize the landscape of buildings energy demand, which result from differences in, among others, income levels, climate, and behaviour. For instance, while consumption in developed countries amounts to 45 GJ/capita/yr, is used primarily for space heating (50 %) and is fuelled with electricity and gas (70 %), consumption from developing countries amounts to 12 GJ/capita/yr, is used primarily for cooking (40 %) and is fuelled with biomass (45 %). 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 the buildings energy demand in the long run. To assess the possible long-term pathways for the buildings sector, we developed the EDGE model; a model for buildings energy demand covering five end uses – appliances and light, cooking, water heating,

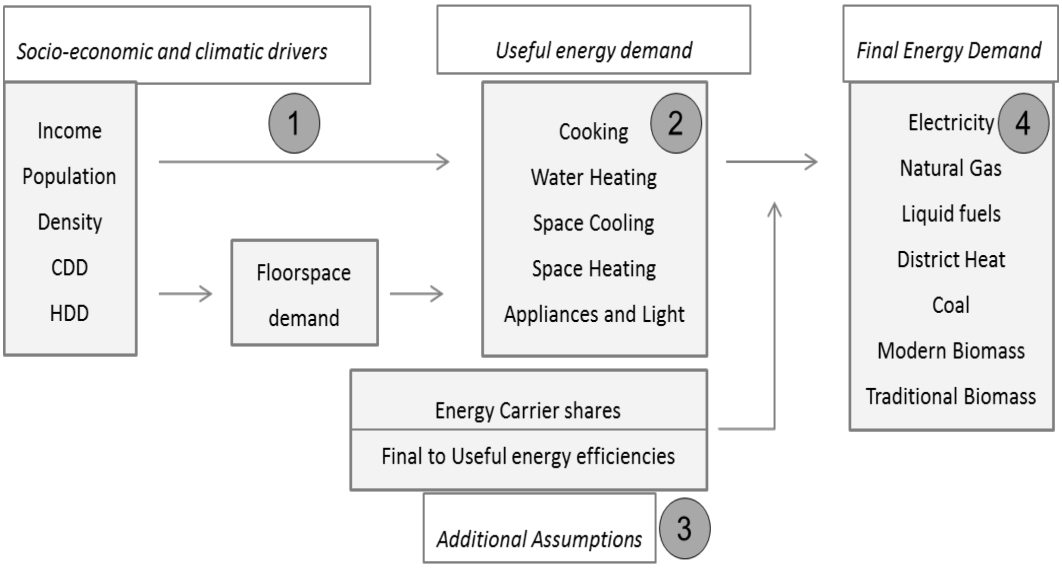

Figure 1. EDGE Flowchart.

space heating, and space cooling – seven energy carriers – *e.g.* electricity, biomass – and eleven regions covering the world consumption. EDGE develops scenarios for buildings energy consumption by implementing functional relations that derive the demand for useful energy from basic drivers like population and income. It then translates the useful energy demands to final energy demands with the help of assumptions on time-dependent efficiencies and fuel shares.

Projections to long term horizons involve large uncertainties pertaining to the socio-economic drivers for energy demand, and to the relationship between these drivers and the energy demand. Possible paradigm shifts will potentially alter historical relationships between energy demand and its drivers. To address this difficulty and integrate the possibility of structural 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 mixes thereby short term projections based on historical relationships and long term projections allowing for a growing role of scenario assumptions over historical patterns.

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

EDGE Model

The projections from the EDGE model follow four steps illustrated in Figure 1. The first step collects data on important drivers for the energy demand in the buildings sector. These drivers cover several dimensions: a demographic dimension – population, population density and floor space per capita – an economic dimension – income per capita – and a climatic dimension – Heating and Cooling Degree Days (HDD/CDD). Data is collected for both historical periods and projections, except in the case of floor space where projections are computed internally.

In the second step we model the relationship between these drivers and the useful energy demand. As in other studies with a large scale regional focus – e.g. (Chaturvedi, Eom, Clarke, & Shukla, 2014; Eom, Clarke, Kim, Kyle, & Patel, 2012; Isaac & van Vuuren, 2009) –, EDGE relies on end-use energy functions synthesising the relationship between energy demand and underlying socio-economic and climate factors. This methodology contrasts with the stock-turnover approach (Giraudet, Guivarch, & Quirion, 2012; Harvey, 2014; Ürge-Vorsatz et al., 2012), which models explicitly the sluggishness of the buildings sector to overtake efficiency improvements. The end-use energy functions approach has the benefit of synthesizing complex relationships and reducing the number of assumptions necessary.

The third step estimates future final to useful energy efficiencies and energy carrier shares in each end-use. This information is required for the final step which converts the useful energy demand computed in step 2 to final energy amounts and allocates these amounts to the different energy carriers.

We here use the concept of *useful energy*, which is of fundamental importance when comparing energy use across different countries and different stages of development. It builds on the idea that while people usually buy final energy carriers like electricity or biomass, they do not demand the energy itself, but rather the energy services it provides – a heated room, a cooked meal, being transported. The useful energy represents the amount of energy that is made directly available for the energy service. By contrast, *final energy* is the energy made available to the energy consumer. 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.

HISTORICAL DATA

To understand potential future evolutions of the energy demand in buildings, information about the past final and useful energy consumption for each energy service is necessary. The IEA *Energy Balances* (IEA, 2014b, 2014a) describe energy demand for numerous countries, sectors and energy carriers. To recover the energy demand for each energy service, we disaggregate the *Energy Balances* using data from (IEA, 2015) and from REMG (Daioglou, van Ruijven, & van Vuuren, 2012). The useful energy amounts are computed using the data and the methodology of (De Stercke, 2014), and is documented below.

The assessment of residential floor space demand relies on the data collected for (Daioglou et al., 2012), completed by other sources (ENERDATA, 2011; KOSIS, 2016; Ministry of Statistics and Programme Implementation, India, 2015; Moura, Smith, & Belzer, 2015; National Bureau of Statistics of China, 2016; Rosstat, 2015; Statistical Center of Iran, 2011). For some of the most populous countries, residential floor space data has remained unavailable. Indonesia (240 million people), Brazil (195, urban data only), Pakistan (173), Nigeria (160, urban data only), Bangladesh (151) are therefore not part of the data set used for the estimation. The disparity of data sources possibly leads to different definitions in the floor space per capita, or in the survey methodology employed. Commercial floor space data was taken from (IEA, 2014c).

Population data stems from (The World Bank, 2014), while income per capita history was taken from (James, Gubbins, Murray, & Gakidou, 2012). Heating and Cooling degree days – HDD and CDD, respectively – were computed from historical temperatures (Global Soil Wetness Project Phase 3, 2016). HDD totalizes daily temperature degrees below 18 °C in a region over a year, while CDD totalizes daily temperature degrees above 18 °C. The aggregation from the grid resolution of observations to the EDGE regions[1] was weighted with population data.

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 mark-up factor.

Living space drives the energy demand for thermal comfort. Historical data shows that even at high levels of income and dwelling area, the positive relationship between wealth and floor space demand does not disappear (IEA, 2004). There could be many channels between economic growth and floor space demand explaining this relationship. For instance, the procurement of new appliances tied with consumption growth may lead to additional space requirements. Considering historical patterns, we assume that living space will continue to grow with wealth, even at high income levels.

Following findings from (Moura et al., 2015) we model floor space expansion with a constant income elasticity across income levels, and additionally assume a population density effect.

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

where F is the floor space demand per capita, I the income per capita, D the population density.

1. 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.

We estimate the elasticities by regressing the linearized equation on historical data. The derived parameters for floor space and end-use functions can be found in Table 1, and the resulting estimates in Table 2. We project living area at the country level, and use the expression above to fill in the 2010 values for countries without historical data. Because the historical income elasticity would yield unreasonably high projections for floor space demand in the long run, the future time path of the income elasticity is reduced compared to the value derived from historical data. The extent of the decrease depends upon the scenario and is larger in SSP2 than in SSP5 (Table 1).

As we assume that the changed income elasticity at a certain point in time will only influence the incremental floor space demand, we use a stepwise calculation of future floor space demand based on the value in the previous time step:

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

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

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 displays an S-curve, and calibrate it on past data (IEA, 2014c). The asymptote of the ratio is 35 % and is approached closely for income levels above US$(2005) 20000. Hence, for developed countries the growth in commercial space is expected to grow as fast as residential space.

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.

Space Heating

Space heating accounted in 2014 for approximately 37 % of buildings final energy consumption (IEA, 2015). This energy demand mainly comes from countries where cold winter climate dominates. In EDGE, space heating useful energy demand 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.

$$\frac{SH}{m^2} = \alpha + \beta \times HDD$$

where SH is the space heating demand, m^2 the buildings floor space and HDD the number of heating degree days. β is a positive parameter. After calibration of α and β, a change of 1000 HDD translates into an variation of useful energy of 140 MJ/m^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 (IEA, 2016).

Second, at low income levels, the acquisition of energy using assets first concerns other appliances including fans, televisions and refrigerators as suggested in other studies (McNeil & Letschert, 2008; van Ruijven et al., 2011; Wolfram, Shelef, & Gertler, 2012). 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 does not increase indefinitely with income.

To model the complex relationships between electrification, purchasing power, climate and space cooling, we make three main assumptions. First, following (McNeil & Letschert, 2008) and (Isaac & van Vuuren, 2009), 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 a 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 include explicitly 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 (McNeil & Letschert, 2008).

Second, the demand per square meter adjusted for the climate impact 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. Third, the climate adjusted useful energy demand per square meter saturates for high incomes. The effect of wealth on the climate adjusted space cooling demand follows hence a logit cumulative distribution function.

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

$$\frac{SC}{m^2} = CDD \times Climate\ Maximum(CDD) \times \frac{\phi_1}{1 + \exp\left[\frac{\phi_2 - income}{\phi_3}\right]}$$

where SC is the space cooling useful energy demand, m^2 the buildings floor space, CDD represents the cooling degree days, income the income per capita, 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 parameter giving the shape of the curve.

Appliances and Light

The energy demand for appliances covers a range of heterogeneous devices from refrigerators and computers to smart phones and robot vacuum. Lighting accounts for all energy consumption producing light with different technologies. In EDGE, light and appliances are treated together.

Energy demand for appliances and light 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 light and appliances and rule out a saturation level. First, economic growth per capita leads to growth in the service sector output per person. In turn, the productivity per employee must increase to account for the sectoral growth. Assuming that electronic appliances constitute a channel to raise productivity in the service sector, we consider that economic growth requires growth in buildings energy demand for appliances and light. Second, economic growth leads to increased consumption, and it seems plausible that increased consumption translates into the invention and procurement of new appliances.

Economic growth will both lead to and be driven by growth in energy consumption for lighting and appliances. Because the historical data displays a linear relationship between income levels and per capita demand, we assume that demand for light and appliances will evolve in proportion with income.

$$AL = \alpha + \beta \times income$$

where *AL* is the useful energy demand per capita for appliances and light, *income* the income per capita.

Our description does not reflect individual technologies, which constitutes a drawback in the sense that the modelling is more abstract, but an advantage as it does not artificially limit the projection to the currently existing technologies and thus it does not build in an artificial saturation level.

Cooking

Cooking accounts for two-thirds of buildings final energy demand in Africa and India, while it plays a minor role in developed countries (IEA, 2015). 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, 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 differences or from inaccuracies in the historical data and its disaggregation. For the default scenario assumption, all useful energy demands converge towards 1.8 GJ/cap/yr in the long term.

Water heating

As data suggests (Daioglou et al., 2012), 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 negative exponential growth curve which satisfies the satiation assumption. Unlike an S-curve, the derivative is larger for lower levels of incomes and decreases continuously. We assume that the per capita energy demand will converge for all regions to the same saturation point, and does not depend upon climate.

$$WH = \phi_1 + (\phi_2 - \phi_1)\exp\left[-\exp(\phi_3)\ income\right]$$

where *WH* is the water heating energy demand per capita, income the income per capita, ϕ_1 is the asymptote, ϕ_2 the intercept and ϕ_3 a parameter influencing the speed of convergence.

Because the regression-based parametrization delivers an unrealistically high asymptote, we assume a default asymptote of 5 GJ/cap/yr —13.7 MJ/cap/day— for per capita useful energy demand from water heating.

Table 1. Function parameters used in 2100 in the scenarios.

Scenario	Floor space β	Space Heating β	Appliances and Light β	Cooking α	Water Heating ϕ_2	Space Cooling ϕ_1
SSP2	0.21	0.138	0.00028	1.8	5	0.2
SSP5	0.32	0.138	0.00031	2.4	6.25	0.2

SSP2 parameters take the values from the calibration, except for the floor space parameter, where the value was lowered (from 0.42). At each time step, the parameter value converges linearly from the historical to the 2100 value.

USEFUL TO FINAL ENERGY

The previous sections described steps 1 and 2 of the EDGE flowchart. The next steps consist in converting the useful energy projections into final energy projections. Useful energy is derived from final energy by applying a conversion efficiency factor, which is dependent upon the energy carrier employed. 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.

FE-UE efficiencies

The conversion from final to useful energy in the model is operated with energy efficiency functions, which are also used to derive the useful energy database. These functions relate energy efficiency with income and take, according to 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.

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

Where ϕ_1 is the minimum efficiency, ϕ_2 the maximum efficiency and ϕ_3 describes the curvature of the function.

These functions are calibrated using the data from the Primary, Final and Useful energy Database (PFUDB, De Stercke, 2014). The PFUDB estimates the conversion efficiency from final to useful energy for several useful energy forms – light, mechanical, heat, and other – and several aggregates of final energy carrier – coal and biomass, electricity and other. According to the assumptions of the author, 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 in their work.

To adapt the efficiency functions to our end-use resolution, the PFUDB is disaggregated to recover the same end-uses five categories – appliances and light, cooking, space cooling and heating, water heating – using data from (IEA, 2015) and from REMG (Daioglou et al., 2012). Starting from this database, we can compute the efficiencies for each region, energy carrier and end-use. 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 gas-fuelled space heating.

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, air conditioning systems move heat from one sink to another. These systems are therefore not subject to an upper limit of one for efficiency. Assuming a Seasonal Energy Efficiency Ratio – a measure of the thermal efficiency of heat pumps and space cooling systems – of 3.1 for high incomes (Werner, 2016)[2], we set the upper limit of space cooling efficiency to this value in 2010.

There is one caveat for the use of the negative exponential growth function to appliances and light. Appliances cover a very heterogeneous set of devices ranging from computers to refrigerators which satisfy distinct services — communication, entertainment, refrigeration, etc. This heterogeneity makes comparison of efficiencies difficult and could undermine our assumption of steady increase in efficiency with income. Despite this caveat, we apply the same functional form to appliances and light as for other services.

Long term energy carrier shares

According to the concept of energy ladder, 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, as income grows. 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 therefore distinguish between two sets of energy carriers.

- For energy carriers used at low income levels, we assume that their shares will follow a prescribed pattern depending upon the income level. The shares of traditional biomass, coal, and liquid fuels for light and appliances decline with income growth to reach an imposed level from a given income threshold on. The share of liquid fuels used for cooking first rises with income before falling back, to reproduce the intermediary role of liquid fuels in the energy ladder.
- After having computed these shares, we allocate the remainder to natural gas, electricity, district heat, modern biomass and liquid fuels; except for cooking and lighting. We define long-term shares towards which the regional energy shares

2. In (Werner, 2016), the SEER is estimated by comparing electricity consumption in kWh/m^2 with cooling output in kWh/m^2, so that SEER is unitless. SEER is sometimes expressed in BTU/Wh. The conversion of the figure from (Werner, 2016) to this unit yields 10.58, which is, by comparison, lower than the US requirements for new cooling equipment of 14.

will converge. We make our assumptions on these final shares considering final energy prices from scenario simulations from an Integrated Assessment Model – REMIND (Global Energy System Modeling Group & Potsdam Institute for Climate Impact Research, 2013). Between two scenarios, higher relative prices of electricity compared to fossil fuels will lower the expected share of electricity. Further, we assume similar shares for space heating and water heating. More information on the scenario-specific assumptions on the long term shares can be found in the next section.

The regional shares fully converge to the assumed long term shares when GDP reaches 10 times the 2010 amount. The shares depend hence on the development of the size of the economy. This is an *ad hoc* assumption. As an illustration, Africa reaches full convergence by 2075 in SSP5. Additionally, a time component has been introduced to allow rich countries to change their shares as well, so that convergence is achieved at least as late as 2150.

Scenarios

Long-term projections are fraught with uncertainty. Historical relationships between variables could alter 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 in order 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. The futures described in each SSP do not include climate policy. 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. Therefore, our scenarios depict future potential worlds in the absence of climate policy. We shortly describe the two SSPs covered in this study whose extended descriptions can be found in (O'Neill et al., 2016).

SSP5 – Fossil-fuelled development – combines low challenges to adaptation and high challenges to mitigation. The world is characterized by strong economic growth, high investments in health and education. The economy relies on abundant fossil fuels and global environmental challenges are not addressed. Developing countries converge rapidly towards higher standards of living. SSP2 – Middle of the Road – displays moderate challenges to adaptation and mitigation. Historical trends persist and reduction of poverty, higher education advance moderately in developing countries. The resource and energy intensities decline slightly.

Scenarios differ in their narratives and in the world they describe. In the model, these qualitative characteristics translate into quantitative differences through several channels: exogenous projections for basic drivers, variations in the parameters of energy demand functions, global convergence assumptions, long term shares of final energy carriers, and conversion efficiencies.

SOCIO-ECONOMIC AND CLIMATIC DRIVERS

Population and Income projections

Population projections are taken from (KC & Lutz, 2016). 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 – 9 and 7.3 billion people in SSP2 and SSP5.

This spectrum reflects the diversity characterizing SSP storylines. SSP5 population displays a peak-and-decline trajectory. The assumption of strong and widespread education drives women's fertility rates down quickly in developing countries in this scenario (Lutz, Muttarak, & Striessnig, 2014). The fertility in rich countries is supposed to reach medium to high levels because the good quality of life enables to combine work and family. SSP2 demographic transition proceeds by contrast slower and population in Africa exceeds SSP5 by 815 million people.

Gross Domestic Product projections stem from (Dellink, Chateau, Lanzi, & Magné, 2016). The projections derive from a conditional convergence mechanism in the spirit of a Solow growth model. Developing countries can experience larger growth rates than developed countries as their technological advancement converges towards the levels of developed coun-

Table 2. Global results showing the behaviour of the end-use functions.

	2010	2100	
		SSP2	SSP5
Residential floor space	25 m^2/cap	45 m^2/cap	72 m^2/cap
Buildings floor space	33 m^2/cap	61 m^2/cap	98 m^2/cap
Space Heating	0.10 MJ/(HDD.m^2)	0.08 MJ/(HDD.m^2)	0.08 MJ/(HDD.m^2)
Space Cooling	0.02 MJ/(CDD.m^2)	0.22 MJ/(CDD.m^2)	0.23 MJ/(CDD.m^2)
Water Heating	1.41 GJ/cap	4.48 GJ/cap	6.23 GJ/cap
Cooking	1.66 GJ/cap	1.76 GJ/cap	2.17 GJ/cap
Appliances and light (Final Energy)	3.36 GJ/cap	18.59 GJ/cap	48.38 GJ/cap

Energy demand is given in useful energy except in the case of appliances and light.

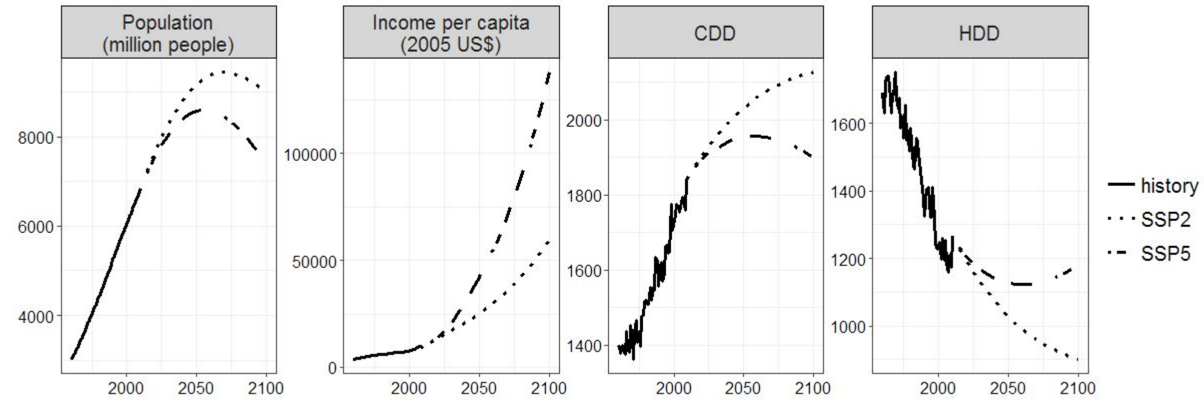

Figure 2. Exogenous projections for socio-economic and climatic drivers at the global level.

tries. The high convergence assumption of SSP5 leads therefore to a much quicker growth in developing countries than in developed countries.

Heating Degree Days and Cooling Degree Days

In this study, country level HDD and CDD remain at their 2010 level throughout the century. However, because the population in the different countries is different in the two scenarios, the population-weighted average at the level of EDGE regions is also different.

SCENARIO ASSUMPTIONS

Variations in coefficients

Equation parameters in the model determine the relationship between drivers and the demand for energy or floor space. While these parameters are calibrated with our energy database, their value change over time according to scenario assumptions made in accordance with the scenario narratives. Different coefficient 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 by a scenario coefficient to represent the different possible futures. SSP2 continues the historical trends. Except for the floor space function, the SSP2 scenario coefficients are therefore set to one. The transition from the historical trajectory to the scenario trajectory proceeds linearly between 2010 and 2100.

Regional convergence assumptions

The historical data on floor space and energy use shows 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 minor the role of these variables on regional discrepancies in the long run, and assume linear convergence towards a global convergence line which summarizes the relationship between a driver and an explained variable. The convergence assumption towards a global value or relation contrasts from one scenario to another, in accordance with SSP narratives. SSP5 assumes full convergence by 2200 and SSP2 by 2300.

Assumptions on efficiencies and FE shares

There are only a limited number of instances where the scenario affects the assumptions about efficiency and FE share developments.

- *Electric space heating and water heating*: 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 electric space-heating accordingly.
- *Electric space cooling:* typical Coefficients of Performance (COP) of air conditioning systems lie between 2 and 4, far from their theoretical maximum[3], 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[4] achieved in the future.
- *Electricity for appliances and light:* we assume the maximum efficiency of appliances will increase until 2100.

As discussed in the previous section, time paths for energy carrier shares emerge from a mix between the reproduction of stylized facts and from the transition towards long term shares assumed exogenously. These shares are set with respect to energy prices from scenarios developed with the REMIND model. In all scenarios, the relative price of electricity falls compared to other energy carriers. In addition, we assume

3. The maximum efficiency 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.

4. 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.

Table 3. Scenario assumptions for electric space heating, space cooling and appliances and light.

Scenario	Heat Pump penetration	max SEER of Heat Pumps	Heat Pump max Efficiency	Space Cooling max SEER	Max efficiency Appliances and Light
2010	–	–	0.93	3.1	0.65
SSP2	30 %	5	2.2	5	0.9
SSP5	75 %	6	4.75	6	0.9

Heat pump penetration and maximum SEER are used to compute the 2100 maximum efficiency, with the assumption that the efficiency of other electric systems is one. For instance in SSP2, 2.2 = (0.3 × 5) + (0.7 × 1). In 2010, the maximum efficiency is retrieved from PFUDB.

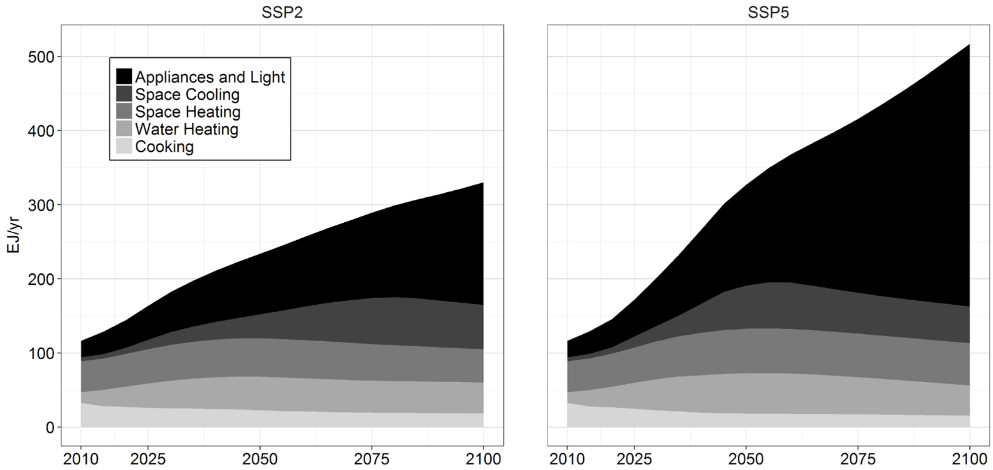

Figure 3. Global final energy demand disaggregated by end-use.

that the efficiency of heating with electricity will increase with higher penetration of heat-pumps. This will decrease further the price of electricity-based heat services and thus raise the electricity share for water and space heating across all scenarios. Beside the electrification, SSP5 will assume a greater share for natural gas than SSP2 because of the reliance on fossil fuels in this scenario.

Results

Buildings final energy demand grows from 116 EJ/yr in 2010 to a range of 330 – 517 EJ/yr by the end of the 21st century (Figure 3). In proportion to the population, the relative gap between the two scenarios widens: each person consumes 37 GJ/yr in SSP2 and 70 GJ/yr in SSP5. By comparison, the demand per capita was 17 GJ/yr in 2010. These developments are explained by the rising role of appliances and light in buildings energy demand, the greater need for space cooling, and the economic catch-up of developing countries.

Light and appliances account for the bulk of the energy demand increase. It rises to 165 and 355 EJ/yr until 2100 in SSP2 and SSP5, respectively. This represents a demand of 5,100 – 13,000 kWh/yr/cap, up from 915 kwh/yr/cap in 2010. For comparison, the electricity consumption in the United States was, in 2010, 13,400 kWh/yr/cap in all sectors and 9,400 kWh/yr/cap for buildings alone. The absence of a saturation assumption for appliances and light explains the dominating role it plays by the end of the century in the model. By contrast, for all other service demands we assume a saturation of the direct effect of income on the demand level. Despite limited by saturation, the share of space cooling grows due to the economic growth in hot countries. As a corollary to the rise in appliances, light, and space cooling, the demand for heat – cooking, space heating and water heating – decreases. Heat falls from 76 % in 2010 to 22–32 % by 2100.

All projections display a profound electrification of the buildings energy demand. The thorough penetration of space cooling and appliances, which both rely on electricity, and the slight electrification of heat assumed explain this trend. The share of electricity rises from 26 % to 80 %, Figure 4. Further, natural gas is the second most used energy carrier by 2100 – 20 % in 2010 to 10 % in 2100. Finally, the share of traditional biomass and coal declines rapidly so as to almost disappear by the mid-century.

Discussion and Conclusion

Our results show growth in buildings' energy demand across all SSPs. While the extent of the demand rise differs widely across scenarios – from 116 EJ/yr in 2010 to 330 EJ/yr in SSP2 compared to 517 EJ/yr in SSP5 by 2100 – common patterns arise as well, namely the rising importance of appliances, light and space cooling, the electrification of the demand, and the declining share of energy services requiring heat.

Hence, the buildings' energy landscape will change dramatically in the 21st century. This results from the combination of three effects of economic growth. First, contrary to the other end-uses in our model, appliances and light energy consumption does not saturate as income reaches high levels. This reflects our assumption that economic growth drives

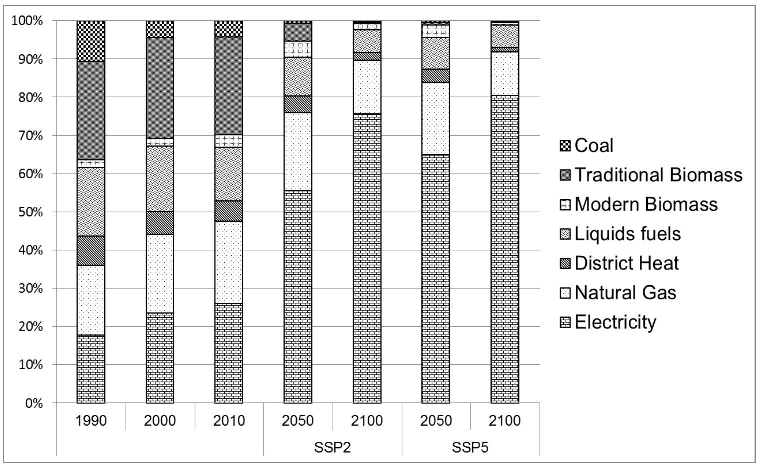

Figure 4. Energy carriers shares in global final energy demand.

and is driven by the invention and the procurement of new appliances, leading to higher levels of energy consumption. Second, economic growth in hot-climate developing countries spurs the demand for space cooling whose diffusion was low in 2010. Third, the response to economic growth of energy services based on heat is low due to saturation effects and to the low growth of floor space per capita at high level of incomes. The importance of these energy services – space heating, cooking, water heating – declines gradually in the projections.

The results have important implications for the question of future energy supply and the possibility to mitigate emissions from buildings. They indicate that while buildings energy demand will increase substantially, most of this demand increase comes from electricity, for which many decarbonisation options exist (Luderer et al., 2014).

The modelling of the demand for appliances and light posed the greatest challenges and would require further improvements, 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 aggregated energy demand for appliances and light, in order to avoid building in an arbitrary saturation level in the long term when currently existing appliances reach saturation. This choice comes however at a cost: while the behaviour of diffusion curves of existing appliances is well understood and can yield accurate projections, modelling the aggregate behaviour of appliances energy demand is fraught with uncertainty and necessitates additional assumptions on the functional form of the relation to income growth.

Further, data series on final energy demand disaggregated by end-use remain scarce, despite their importance for energy modelling. This scarcity forces us to make some strong assumptions on the functional forms of energy demand. Thus, the resulting estimations are subject to large uncertainties.

To conclude, and despite the uncertainties, our analysis provides results that are an important input for the analysis of long-term climate change mitigation. A better understanding of different types of energy demand in the buildings sector is a crucial input when analyzing the contribution of buildings energy to climate change, and exploring the mitigation possibilities in this sector.

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