

A global analysis of residential heating and cooling service demand and cost-effective energy consumption under different climate change scenarios up to 2050

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Received: 4 August 2016 / Accepted: 7 November 2016 / Published online: 19 December 2016
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Abstract Climate change and energy service demand exert influence on each other through temperature change and greenhouse gas emissions. We have consistently evaluated global residential thermal demand and energy consumption up to the year 2050 under different climate change scenarios. We first constructed energy service demand intensity (energy service demand per household) functions for each of three services (space heating, space cooling, and water heating). The space heating and cooling demand in 2050 in the world as a whole become 2.1–2.3 and 3.8–4.5 times higher than the figures for 2010, whose ranges are originated from different global warming scenarios. Cost-effective residential energy consumption to satisfy service demand until 2050 was analyzed keeping consistency among different socio-economic conditions, ambient temperature, and carbon dioxide (CO₂) emission pathways using a global energy assessment model. Building shell improvement and fuel fuel-type transition reduce global final energy consumption for residential thermal heating by 30% in 2050 for a 2 °C target scenario. This study demonstrates that climate change affects residential space heating and cooling demand by regions, and their desirable strategies for cost-effective energy consumption depend on the global perspectives on CO₂ emission reduction. Building shell improvement and energy efficiency improvement and fuel fuel-type transition of end-use technologies are considered to be robust measures for residential thermal demand under uncertain future CO₂ emission pathways.

Keywords Residential energy service demand · Space heating · Space cooling · Water heating · Heating and cooling degree days · Climate change feedback · Global energy assessment model

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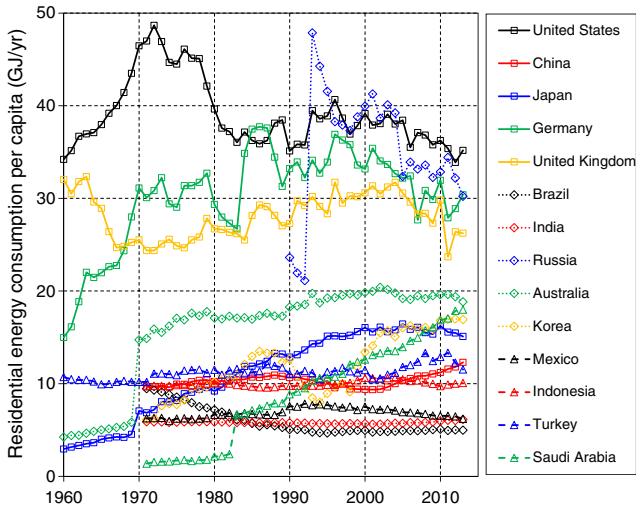


Fig. 1 Residential energy consumption per capita in the selected countries (IEA 2015a)

1 Introduction

Climate change has significant impacts on energy systems. Jaglom et al. (2014) evaluated the ways in which global warming affects supply, demand, and investment in the United States (US) power sector. De Lucena et al. (2010) analyzed several impacts of climate change on the power sector in Brazil, such as lower reliability in hydroelectric power generation, lower efficiency of gas-fired power stations, and increase of electricity demand for air conditioning.

Figure 1 shows residential energy consumption per capita in selected countries (IEA 2015a). There is wide variation in the amounts and changes in residential energy consumption among developed and developing countries. The total amount of energy consumption in the residential sector accounts for about one fifth of global consumption.

Climate change and energy service demand, such as for space heating and cooling, exert influence on each other through temperature change and greenhouse gas emissions, respectively, to satisfy the service demand. Therefore, it is important to evaluate future energy systems with this feedback effect taken into account. A few studies have assessed the impact of climate change on the residential sector on a global scale. Isaac and van Vuuren (2009) analyzed global energy demand for heating and air conditioning in the residential sector for 11 regions. They constructed final energy consumption scenarios using a simple relationship based on population, income, floor space per capita, degree days, and useful energy heating intensity, but their scenarios are descriptive due to a simplistic relational expression of independent variables, and they use only one temperature change scenario. Daioglou et al. (2012) projected household energy use in developing countries for baseline and climate policy (100\$₂₀₀₅/tCO₂) scenarios, and the space heating demand estimation is directly taken from a formula in Isaac and van Vuuren (2009). Labriet et al. (2015) evaluated worldwide impacts of temperature change on heating and cooling services for buildings using an integrated assessment model

having 11 divided regions. They assessed impacts of climate change on, such as, energy consumption, climate feedback, and macroeconomic conditions under several temperature change scenarios. However, their procedure for estimating energy service demand is also simplistic, as the service demand change ratio is assumed to correspond closely to the degree day change ratio from the base year.

Ürge-Vorsatz et al. (2012, 2013) summarized main sustainable challenges related to building thermal energy use and identified the key strategies for how to address the challenges. They demonstrated that buildings can play a key role in solving sustainability challenges by proliferation of state-of-the-art construction and retrofit know-how in each world region while keeping wealth and amenity improving, based on the sophisticated performance-oriented approach to the energy analysis of the buildings.

The main objective of this study is to assess regional residential energy service demand, which is consistent with regional socioeconomic change and regional temperature change, and cost-effective energy consumption to satisfy such demand. We developed residential energy service demand intensity (energy service demand per household) functions using multi-country data on residential energy consumption for space heating, space cooling and water heating, regional heating and cooling degree days, as well as GDP per capita. Compared with the prior studies (e.g., Isaac and van Vuuren 2009; Daioglou et al. 2012; Labriet et al. 2015), this study was able to assess high regional resolution energy service demand in residential sectors and energy consumption by fuel for residential space heating, space cooling, and water heating in each region, thanks to the Dynamic New Earth 21+ (DNE21+) integrated assessment model, which has 54 disaggregated world regions (Akimoto et al. 2010, 2014).

We explain our methodology for the assessment of residential space heating, space cooling, and water heating. The estimated degree days, energy service demand, and energy consumption for different carbon dioxide (CO₂) emission reduction scenarios are analyzed.

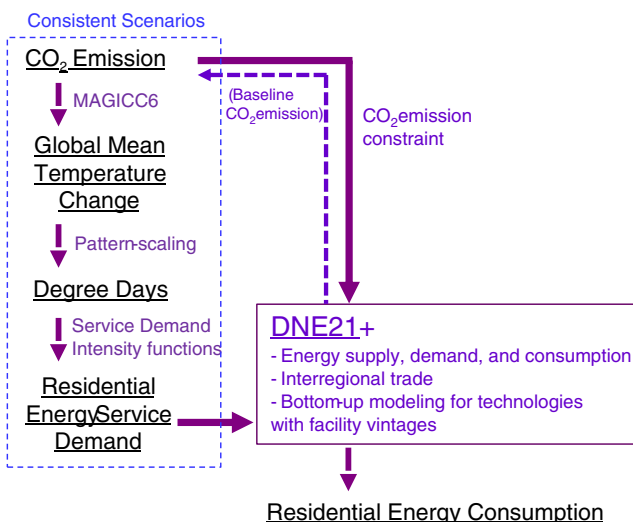


Fig. 2 Procedure for consistent scenario construction for residential space heating, space cooling, and water heating

2 Methodology

2.1 Overall procedure for consistent assessment of residential space heating, space cooling, and water heating

Figure 2 shows the overall procedure for consistent assessment of residential space heating, space cooling, and water heating. First, global mean temperature change for each greenhouse gas emission scenario was estimated using the simple MAGICC6 climate model (Meinshausen et al. 2011). We used four representative CO₂ emission pathways in this study. Second, regional degree days were evaluated based on population-weighted temperature using the pattern scaling method (Hayashi et al. 2010). Third, energy service demand was calculated for residential space heating, space cooling, and water heating using developed service demand intensity functions. Finally, the cost-effective energy consumption was analyzed using the Dynamic New Earth 21+ (DNE21+) intertemporal linear programming model under consistent sets of energy service demand and CO₂ emission reduction scenarios. For a baseline scenario, CO₂ emission pathways obtained from the Dynamic New Earth 21+ (DNE21+) calculations were used for iterative calculation of the above procedure until the global mean temperature change converged, because changes in CO₂ emissions eventually change energy service demand through alteration of global mean temperature and degree days. In this study, service demand for cooking and other uses, such as for computers in the residential sector, are treated collectively rather than individually in the Dynamic New Earth 21+ (DNE21+) model, because we were unable to obtain sufficient data for statistical analysis. Lighting and electricity use, such as for televisions and refrigerators, are also treated individually in the Dynamic New Earth 21+ (DNE21+) model, but we did not focus on or consider climate change feedback with regard to such factors in this study.

2.2 Service demand intensity for residential space heating, space cooling, and water heating

We collected multi-country data on energy consumption by fuel and end use, equipment efficiency by fuel, and numbers of households. The database includes time series data for Japan (1965–2011), the US (1998–2010), Canada (1990–2012), and Australia (1990–2005), as well as yearly data from 1973 for the US, Australia, Italy, the United Kingdom (UK), and Norway; from 1981 for Canada; from 1998 for Germany, France, Italy, the UK, Finland, Denmark, Norway, and Sweden; from 2000 for Thailand; from 2003 for China and Vietnam; from 2005 for Austria, Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Lithuania, the Netherlands, Norway, Poland, Romania, the Slovak Republic, Slovenia, Spain, Sweden, and the UK; and from 2012 for the Association of Southeast Asian Nations (ASEAN), Brazil, China, India, Mexico, Russia, and South Africa. The data sources are IEEJ (2013), DOE (2011), NRCAN (2014), DEWHA (2008), IEA (2004), Odyssee (2010), IEA (2015b), and Nakagami et al. (2014).

Service demand per household (service demand intensity) for space heating, space cooling, and water heating was calculated as follows:

$$SDI_t = \sum_i (EC_{i,t} \times \text{eff}_{i,t}) / NH_t \quad (1)$$

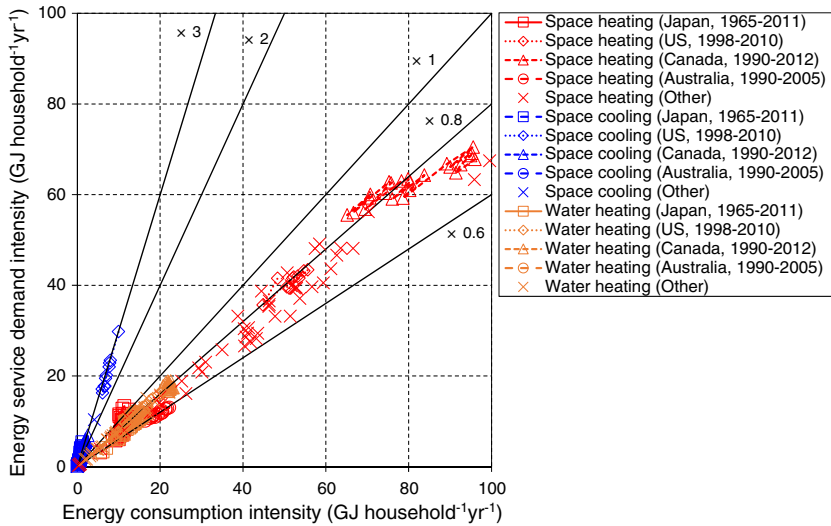


Fig. 3 Energy service demand intensity with respect to energy consumption intensity for residential space heating, space cooling, and water heating

where SDI is the service demand intensity, EC_i is the energy consumption by fuel, eff_i is the equipment efficiency by fuel, NH is the number of households, t is the year, and i is the fuel type. Equipment efficiency by electricity for space heating was calculated considering electric heater and air conditioner usage rates.

Figure 3 shows service demand intensity with respect to energy consumption intensity (energy consumption per household) for residential space heating, space cooling, and water heating. Service demand and energy consumption for space heating are high compared with the figures for space cooling and water heating in selected countries. While service demand and energy consumption for space heating have reached saturation in developed countries, those for space cooling have rapidly increased recently. By comparing service demand and energy consumption, the energy efficiency (service demand per energy consumption) figures for space heating and water heating can be identified as being about 0.6 to 0.8. In contrast, that for space cooling is about 2 to 3 because of the use of electric power equipment. Energy efficiency figures for residential space heating, space cooling, and water heating improve year by year with improvement of efficiency and electrification of equipment for such energy services.

2.3 Residential energy service demand intensity functions

In order to estimate future energy service demand, we assumed energy service demand intensity functions for residential space heating, space cooling, and water heating with regard to the world as a whole. Although energy consumption by fuel differs greatly by region, we assumed that changes in the energy service demand will be similar to a certain degree. We set service demand intensity as a dependent variable and GDP per capita (GDPpc) and degree days (DDs) as independent variables representing socioeconomy factors and temperature, respectively. We did not include floor space among dependent variables explicitly, because future floor space projection by region is difficult and it often related to GDPpc (e.g., Isaac et al. 2009).

We divided the world into 54 regions in accordance with Dynamic New Earth 21+ (DNE21+) (RITE 2015). GDPpc data from the IEA (2015a) was used in this study. Heating degree days (HDDs) and cooling degree days (CDDs) in each region were calculated from grid data for daily temperature (MIROC5 data from CMIP5 multi-model ensemble; Taylor et al. 2012; Watanabe et al. 2010), that for population density (Hayashi et al. 2013), and that for national and regional areas (Natural Earth (2016)) with respect to the reference temperature T_{ref} as follows:

$$T_{reg,t} = \frac{\sum_g T_{g,t} \rho_{g,t} \delta_g}{\sum_g \rho_{g,t}} \quad (2)$$

$$HDD_{reg,t} = \sum_t (T_{ref,hdd} - T_{reg,t}) (T_{reg,t} < T_{ref,hdd}) \quad (3)$$

$$CDD_{reg,t} = \sum_t (T_{reg,t} - T_{ref,cdd}) (T_{reg,t} > T_{ref,cdd}) \quad (4)$$

where reg is the region (1–54), t is the date (for 1960–2012), g is the grid ($1.4^\circ \times 1.4^\circ$) for the region, T is the daily average temperature, ρ is the population, and δ is the regional division. Energy consumption in a given residential and/or commercial sector depends strongly on atmospheric conditions in the relevant region. HDDs and CDDs are defined as the summation of the difference between daily temperatures below and above the reference temperature per year, respectively. We created a new database of heating and cooling degree days for 54 regions from 1960 to 2012 by setting the following seven common reference temperatures: 18, 16, 14, 12, 10, 8, and 6 °C for heating degree days and 18, 20, 22, 24, 26, 28, and 30 °C for cooling degree days. DDs change nonlinearly with respect to the change of the reference temperature and show time trends of decreasing HDDs and increasing CDDs throughout the world. DDs are used in many energy statistics, such as IEEJ (2013). KAPSARC (2015) provides a global degree day database for 147 countries, but it is insufficient for this study because the reference temperatures are set as only 15.6, 18.3, and 21.1 °C.

Using the dataset of service demand intensity, GDP per capita, and degree days (HDDs and CDDs), we derived service demand intensity functions for space heating, space cooling, and water heating using a Sigmoid function as follows:

$$SDI = C \times f(\text{GDPpc}) \times g(\text{DDs}) \times M \quad (5)$$

$$f(\text{GDPpc}) = 1 / \{1 + \exp[\alpha(\text{GDPpc} - \beta)]\} \quad (6)$$

$$g(\text{DDs}) = \text{DDs}^\gamma + \delta \quad (7)$$

$$M = 1 \text{ (for space heating and space cooling), Water (for water heating)} \quad (8)$$

Table 1 Coefficients of residential service demand intensity functions

	Space heating	Space cooling	Water heating
T_{ref} (°C)	6	22	14
C	1.95×10^3	7.51×10^6	1.46×10^{-5}
A	-0.21	-0.12	-0.15
B	16.1	200.8	16.6
γ	0.46	1.99	2.26
δ	5.01	1.88×10^5	1.49×10^8

$$\text{Water} = \max\{0, \ln(\text{Annual mean total runoff} [\text{kg m}^{-2}\text{year}^{-1}])\} \quad (9)$$

where $GDPpc$ is the GDP per capita, DDs is HDDs or CDDs, f and g are functions, and C , α , β , γ , and δ are coefficients of the service demand intensity functions. S-shape functions such as a Sigmoid function and Gompertz model are often used in the infrastructure diffusion model (Grübler 1990). Here, we added an independent variable M for water heating in order to represent differences in water resources by region. Water was calculated from a logarithm based on the population-weighted annual mean total runoff for 2006–2010 in each region using the annual total runoff data of MIROC5. The average, maximum, and minimum values for Water are 5.2, 7.8, and 0, respectively. Possible factors of change in service demand intensity for residential space heating, space cooling, and water heating by region and time with respect to $GDPpc$ are (1) achievement of potential desires and (2) environmental consciousness, while those with respect to DDs are (1) natural environment, (2) difference between room temperature and outside air temperature, and (3) thermal insulation of buildings.

Afterwards, the least-square method was used to obtain the coefficients of the service demand intensity function by end use for different datasets with DDs of different reference temperatures. Then, the coefficient set with fewest square errors was derived as shown in Table 1. See Appendix for adjusted R^2 and the datasets for Eqs. (5), (6), (7), (8), and (9). For space heating and space cooling, the maximum energy service demand intensity was constrained with respect to DDs by setting maximum heat loss coefficient ($4 \text{ Wm}^{-2} \text{ K}^{-1}$) and maximum floor space (200 m^2). We attempted to apply multiple regression models for service demand function estimation but could not achieve a significant expression because of a lack of data.

Figure 4 shows the energy service demand intensity functions with respect to $GDPpc$ for (a) space heating and (b) space cooling with DDs of 20–2000 and (c) water heating with DDs of 200–4000 and Water of 1 and 5. Compared with space heating and water heating, the β for space cooling is much larger. The coefficients γ and δ indicate energy service demand responses to the degree days. As shown in Fig. 4, energy service demand for space heating and space cooling depends both on $GDPpc$ and DDs . In contrast, change of the energy service demand for water heating depends strongly on $GDPpc$ only. In this study, the reference temperature of degree days for space heating, space cooling, and water heating are 6, 22, and 14 °C, respectively. The differences in reference temperatures of DDs from the general 18 °C used commonly for the three kinds of service demand found in this study suggest that the reference temperature should be set individually based on end use and region. The nonlinearity of service demand with respect to both $GDPpc$ and DDs suggests that energy service demand estimation based on a simple relationship (e.g., Labriet et al. 2015) is inadequate for a long-term projection involving significant socioeconomic and temperature changes.

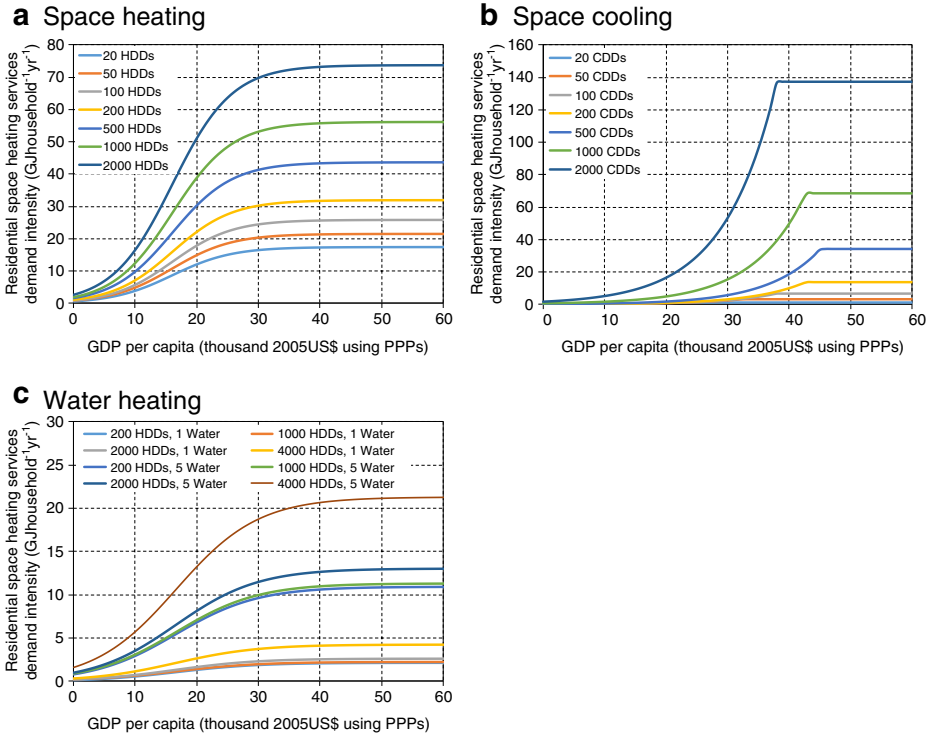


Fig. 4 Residential service demand intensity functions with respect to GDP per capita and degree days for **a** space heating, **b** space cooling, and **c** water heating

2.4 Residential energy service demand scenario construction with socioeconomic and temperature changes

Energy service demand scenarios were calculated by multiplying the energy service demand intensity functions by the number of households. The number of households was obtained by multiplying population and household intensity in each region. We derived the estimated formula of the household intensity by the least-square method based on the formulation of Ironmonger et al. (2000) and data on the number of households (United Nations Demographic Year Book 2014) and population (United Nations 2015). The formula is as follows:

$$h = 105.1 + 46.8 \times \left(\frac{M}{Y} \right) \times 410.5 \times \left(\frac{E}{M} \right) \tag{10}$$

where h is the household intensity (number of households per 1000 people), Y is the population aged 0–19 years, M is the population aged 20–59 years, and E is the population aged 60+ years.

The energy service demand intensity scenarios were calculated based on the GDPpc scenario and DD scenarios. We employed the ALPS-A scenario for GDP and population projection (RITE 2012). The global average growth rate of per-capita GDP between 2010 and 2050 is 2.6% per annum. The global population in 2050 is 9.15 billion people, which is

consistent with the 2008 projection of the United Nations. Accordingly, the global real GDP at market exchange rate (MER) in 2050 is US\$113 trillion (in 2000 dollars).

For the future DD scenarios, we deduced a simple relationship between population-weighted regional annual mean temperature and regional DDs (heating degree days of $T_{ref} = 6\text{ }^{\circ}\text{C}$ (HDD6 $^{\circ}\text{C}$), cooling degree days of $T_{ref} = 22\text{ }^{\circ}\text{C}$ (CDD22 $^{\circ}\text{C}$), and heating degree days of $T_{ref} = 14\text{ }^{\circ}\text{C}$ (HDD14 $^{\circ}\text{C}$)) using the DD database from 1965 to 2012 by region as follows:

$$\ln(DD_{d,reg}) = \alpha_{d,reg} \times \ln(T_{ave,reg}) + \beta_{d,reg} \quad (11)$$

where d is HDD6 $^{\circ}\text{C}$, CDD22 $^{\circ}\text{C}$, or HDD14 $^{\circ}\text{C}$, reg is the region, T_{ave} is the annual mean temperature, and α and β are the coefficients. Then, future population-weighted regional annual mean temperature was calculated from grid data for annual mean temperature by pattern scaling of the global annual mean temperature (see Hayashi et al. 2010) and that for population density. Furthermore, future DDs by region were estimated using the coefficients (α , β) and future regional annual mean temperature.

The estimated energy service demand scenarios for residential space heating, space cooling, and water heating were calibrated for the base year using the historical data on energy consumption by end use (IEEJ 2013; DOE 2011; NRCAN 2014; DEWHA 2008; RITE 2012; IEA 2015b).

2.5 Cost-effective energy consumption for residential space heating, space cooling, and water heating under CO₂ emission pathways calculated with Dynamic New Earth 21+ (DNE21+)

Figure 5 shows four representative global carbon dioxide (CO₂) emission pathways from energy use, industrial sources, and land use change assumed for this study (Akimoto et al. 2012): (1) baseline: no specific policy for GHG emission reduction and about 1000 ppm CO₂ eq. in 2100, (2) CP6.0: around 750 ppm CO₂ eq. in 2100, (3) CP3.7: stabilization at around 550 ppm CO₂ eq., and (4) CP3.0: around 450 ppm CO₂ eq. in 2150 (overshoot concentration).

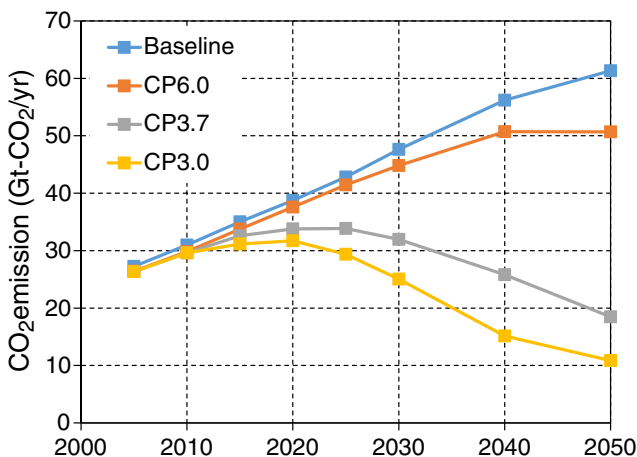


Fig. 5 Global CO₂ emission pathways from energy use, industrial sources, and land use change (Akimoto et al. 2012)

A simple climate change model MAGICC6 (Meinshausen et al. 2011) was used for climate estimation, e.g., atmospheric CO₂ concentration, GHG concentration, radiative forcing, and global mean temperature change. Global mean temperature changes by 2100 relative to the pre-industrial level are 4.1, 3.3, 2.3, and 1.9 °C in baseline, CP6.0, CP3.7, and CP3.0, respectively, under a climate sensitivity of 3 °C. For comparison, a constant temperature scenario was set using the constant global mean temperature from 2015 (1.1 °C relative to the pre-industrial level).

Dynamic New Earth 21+ (DNE21+) is an intertemporal linear programming model for assessing global energy systems and global warming mitigation options (RITE 2015). The model represents regional differences and assesses detailed energy-related CO₂ emission reduction technologies up to 2050. Costs and energy efficiency of technologies are explicitly modeled in Dynamic New Earth 21+ (DNE21+). Energy end-use technologies are selected to satisfy the extent of service demand.

Table 2 Residential end-use technologies for space heating, space cooling, and water heating assumed in DNE21+

Usage	Fuel type	Technology	Energy efficiency			Cost			
			2010	2030	250				
Space heating	Individual	Electricity	Electric heater	1.00	1.00	1.00	68	M\$/(ktoe/day)	
			Room air conditioner	4.55	6.12	6.81	378		
		Gas	Gas heater	0.83	0.90	0.90	58		
			Oil	Oil heater	0.83	0.90	0.90		126
				Biomass	Biomass heater	0.61	0.76		0.86
	Central	Electricity	Coal heater	0.61	0.76	0.86	799		
			Electric boiler	1.00	1.00	1.00	257		
			Air source heat pump	2.73	3.97	4.72	640		
		Geothermal heat pump	Geothermal heat pump	3.71	5.12	5.81	1444		
			Geothermal heat pump	0.83	0.90	0.90	145		
		District heat utilization	District heat utilization	0.83	0.90	0.90	145		
			Oil boiler	0.83	0.89	0.90	165		
		Biomass boiler	0.65	0.79	0.80	1066			
		Coal boiler	0.65	0.79	0.80	1173			
Space cooling	Electricity	Room air conditioner (low eff.)		2.10		960	M\$/(m device)		
		Room air conditioner (middle eff.)		3.90		1020			
		Room air conditioner (high eff.)		6.50		1080			
Water heating	Electricity	Electric boiler	0.90	0.90	0.90	1005	M\$/(ktoe/day)		
		Air source heat pump	3.20	3.90	4.70	2500			
	Gas	Gas boiler	0.83	0.90	0.90	1087			
		District heat utilization	0.83	0.90	0.90	1087			
	Oil boiler	0.83	0.90	0.90	1087				
	Biomass boiler	0.65	0.79	0.80	834				
Coal boiler	0.65	0.79	0.80	918					

Table 3 Solar water heater scenario in the selected countries

(PJ/year)	2005	2010	2015	2020	2025	2030	2040	2050
China	159	356	969	1696	1873	2156	2925	3758
USA	62	46	47	51	55	58	62	65
Turkey	19	28	43	58	75	96	155	235
Germany	16	29	40	44	48	51	50	49
Brazil	6	13	26	30	33	37	48	65
Australia	11	18	19	21	23	24	27	30
India	3	8	18	21	24	28	38	53
Japan	15	11	8	8	9	9	9	9

Table 2 shows specific technologies assumed for residential space heating, space cooling, and water heating in Dynamic New Earth 21+ (DNE21+). For space heating, scenarios using electric heaters/boilers (EH/EB), room air conditioners (EAC), air source heat pumps (ASHP), geothermal heat pumps (GSHP), gas heaters/boilers (GH/GB), district heat utilization (G Heat), oil heaters/boilers (OH/OB), biomass heaters/boilers (BH/BB), and coal heaters/boilers (CH/CB) were modeled. Room air conditioners with low, middle, and high efficiency were considered for space cooling.

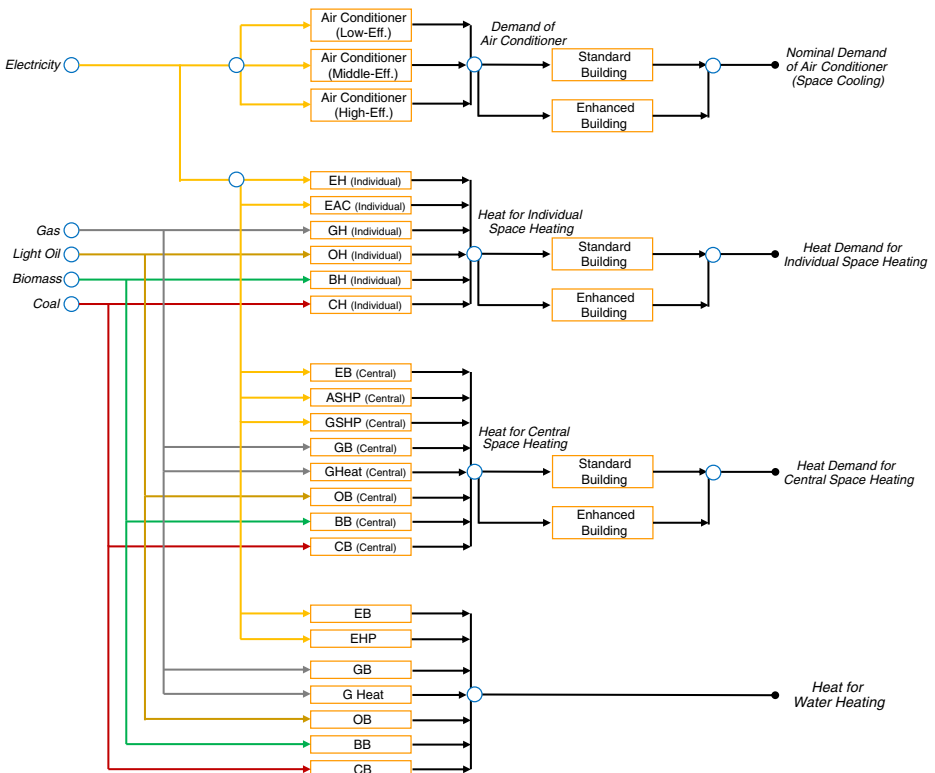


Fig. 6 Model structure for residential space heating, space cooling, and water heating in the DNE21+

For water heating, scenarios using electric boilers (EB), air source heat pumps (EHP), gas boilers (GB), district heat utilization (G Heat), oil boilers (OB), biomass boilers (BB), and coal boilers (CB) were assumed. Each end-use technology has energy efficiency value and equipment cost by time as shown in Table 2. We assumed percentage figures for central and individual heating for space heating and annual average working rates for space heating and water heating by region. Working rates and equipment durations were set for each region for space heating, space cooling, and water heating. Also, degradation of energy efficiency through partial load operation of air conditioners for space cooling was considered by region.

For water heating, an exogenous solar water heating scenario was set based on IRENA (2014) and IEA Solar Heating & Cooling Programme (SHC) (2016) as shown in Table 3. From the historical solar water heating capacity by country and energy efficiency of 9.6%, we assumed that the ratio of solar water heating energy consumption to estimated total water heating energy consumption becomes constant as that of 2015 after 2015, except for China. Solar water heater introduction target of 560 GWth in China (IRENA 2014) was taken into account, and the ratio was assumed to be constant as that of 2020 after 2020.

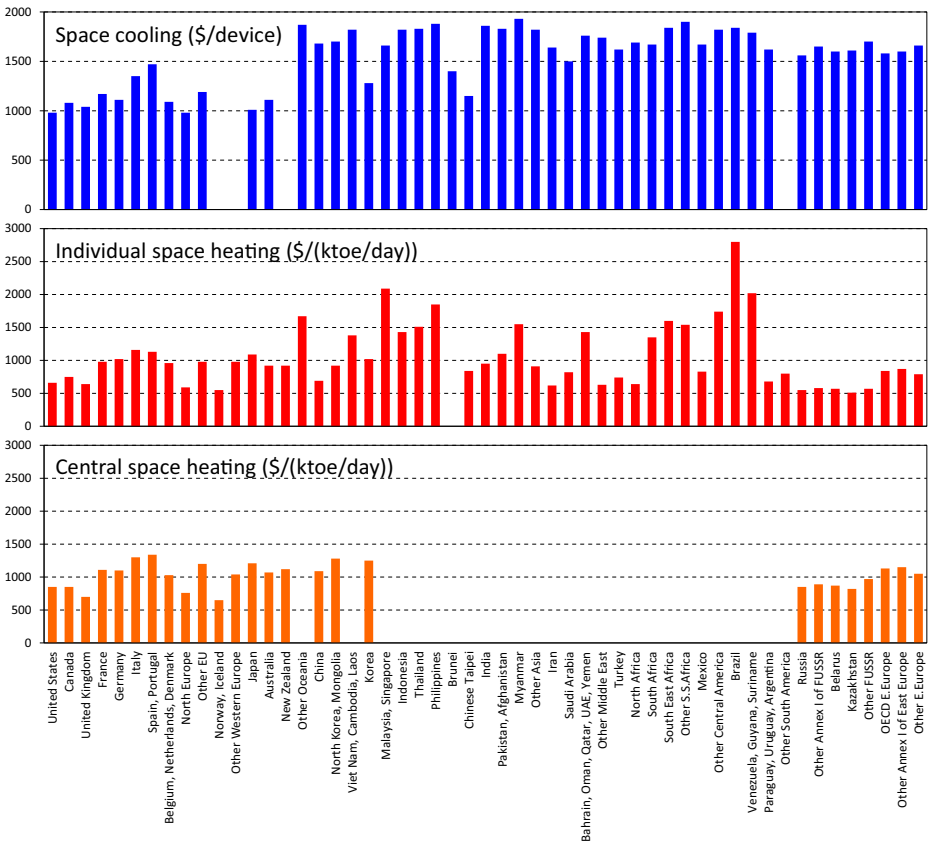


Fig. 7 Equivalent costs of buildings' improvement for space cooling and individual and central space heating in the DNE21+

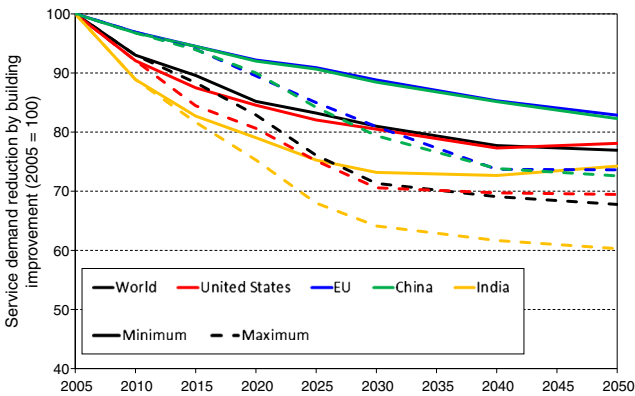


Fig. 8 Minimum and maximum service demand reduction by building shell improvement assumed in the energy consumption scenarios in the selected countries

In addition to the end-use technologies, we modeled service demand reduction measures by building shell improvement for space heating and cooling as shown in Fig. 6. In order to simulate building shell improvement by, such as, enhanced thermal insulation or advanced ventilation, we set enhanced building to reduce energy service demand by 30%. Their equivalent costs were assumed to correspond to the marginal costs by region and usage in the Dynamic New Earth 21+ (DNE21+) as shown in Fig. 7. We set maximum and minimum energy saving by building shell improvement as shown in Fig. 8, based on the floor area by building vintages for deep efficiency scenario and frozen efficiency scenario in Üрге-Vorsatz et al. (2012) by assuming 30, 10, 50, and 20% service demand reduction by new, retrofit, and advanced new and advanced retrofit compared with standard buildings, respectively.

We established six cases in order to evaluate the effects of temperature change and CO₂ emission reduction on the cost-effective energy consumption for the three kinds

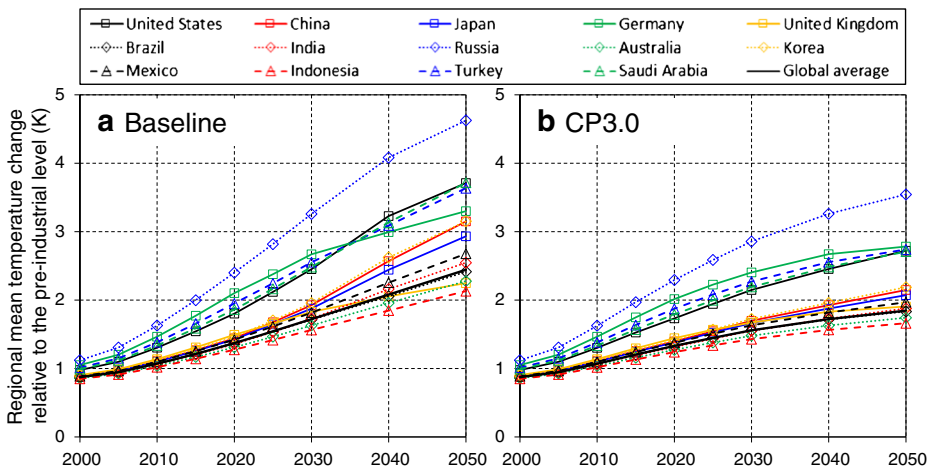


Fig. 9 Regional population-weighted mean temperature change relative to the pre-industrial level for **a** baseline and **b** CP3.0 in the selected countries

Table 4 Degree days for baseline and CP3.0 in the selected countries

(K days/year)	Heating degree days ($T_{ref} = 6\text{ }^{\circ}\text{C}$)				Cooling degree days ($T_{ref} = 22\text{ }^{\circ}\text{C}$)				Heating degree days ($T_{ref} = 14\text{ }^{\circ}\text{C}$)			
	2010		2030		2050		2010		2030		2050	
	Baseline	CP3.0	Baseline	CP3.0	Baseline	CP3.0	Baseline	CP3.0	Baseline	CP3.0	Baseline	CP3.0
USA	303	163	105	148	379	465	585	489	1322	1081	911	1041
China	238	153	90	139	315	353	456	370	1196	1027	847	990
Japan	18	15	7	13	164	221	325	237	726	615	488	588
Germany	469	339	295	331	88	114	144	119	1768	1545	1448	1527
UK	43	25	19	24	5	3	4	3	1031	913	847	901
Brazil	0	0	0	0	888	1089	1362	1131	0	0	0	0
India	0	0	0	0	2012	2232	2521	2283	0	1	1	1
Russia	2237	1932	1802	1902	305	344	453	366	3916	3577	3413	3540
Australia	0	0	0	0	319	397	515	416	205	149	116	142
Korea	486	413	313	390	209	279	393	299	1589	1416	1219	1375
Mexico	0	0	0	0	211	473	787	529	0	1	2	1
Indonesia	0	0	0	0	1482	1681	1888	1716	0	0	0	0
Turkey	88	22	11	20	391	484	608	504	936	738	619	715
Saudi Arabia	0	0	0	0	2539	2763	3075	2819	52	15	6	13

of residential service demand. Four consistent scenarios with temperatures for estimating residential energy service demand and CO₂ emission constraints for assessing cost-effective emission reduction measures were calculated: baseline, CP6.0, CP3.7, and CP3.0. In addition, we evaluated two scenarios with the constant temperature (CT) from 2015 and CO₂ emission constraints, which are CT/baseline and CT/CP3.0, in order to distinguish the effect of temperature change and that of CO₂ emission restriction.

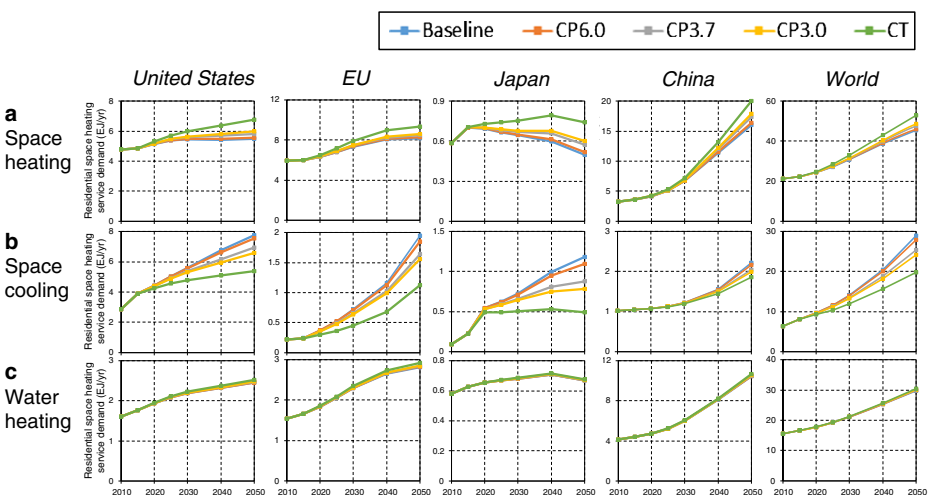


Fig. 10 Residential energy service demand for **a** space heating, **b** space cooling, and **c** water heating in the USA, the EU, Japan, China, and the world as a whole

3 Results

3.1 Degree day scenarios

Figure 9 shows regional mean temperature change relative to the pre-industrial level in the selected countries for (a) baseline and (b) CP3.0. The temperatures of high-latitude countries such as Russia tend to exhibit great increases compared with the global mean temperature, as well as those of low-latitude countries such as Indonesia and Mexico. Degree days (HDD6 °C, CDD22 °C, and HDD14 °C) of selected countries for baseline and CP3.0 in 2010, 2030, and 2050 are shown in Table 4. Countries in tropical or subtropical regions such as Brazil, Mexico, and Saudi Arabia do not have HDD6 °C figures. HDD6 °C figures for 2050 for baseline and CP3.0 decrease by 7 to 434 K days/year and 5 to 335 K days/year by region in comparison with the figures for 2010, respectively. CDD22 °C figures for 2050 for baseline and CP3.0 change by -1 to 577 K days/year and -2 to 318 K days/year by region compared with the figures for 2010. HDD14 °C figures for 2050 for baseline and CP3.0 decrease by 502 and 376 K days/year at most in Russia compared with the figures for 2010.

3.2 Residential energy service demand scenarios for space heating, space cooling, and water heating

Figure 10 shows the trajectories of residential energy service demand for space heating, space cooling, and water heating in the USA, the EU, Japan, China, and the world as a whole under five temperature change scenarios. In the USA, the figures for residential space heating, space cooling, and water heating demand in 2050 become 1.2–1.4, 1.9–2.7, and 1.5–1.6 times higher than the figures for 2010. Global warming under baseline suppresses the increase of space heating and water heating demand figures by 1.3 EJ/year and 73 PJ/year, respectively, compared with CT demand figures in 2050. Space cooling demand figures in 2050 for baseline, CP6.0, CP3.7, and CP3.0 become 2.7, 2.6, 2.4, and 2.3 times higher than the demand figure in 2010 for the USA. Water heating demand less depends on temperature change and is estimated to be about 2.5 EJ/year in 2050.

In the EU, space heating and water heating demand reach saturation around 2050 at about 8 and 3 EJ/year, respectively. In contrast, space cooling demand in the EU rapidly increases around 2050, and global warming enhances it by a multiple of about 1.7 times 2050 when comparing baseline and CT. In Japan, space heating demand decreases after 2020 for baseline, CP6.0, CP3.7, and CP3.0. Space cooling demand in Japan rapidly increases before and after 2020 due to economic growth and global warming, respectively. In contrast, water heating demand in Japan is almost constant until 2050, at 0.6 to 0.7 EJ/year.

In China, service demand for space heating and water heating increase rapidly toward 2050 thanks to economic growth. Space heating, space cooling, and water heating demand in China climb by multiples of 5.0–6.1, 1.8–2.2, and 2.5–2.6, respectively, by 2050. However, residential demand figures for space cooling are relatively low compared with those for space heating, because GDP per capita is not sufficiently high to allow higher demand figures.

For the world as a whole, residential demand for space heating doubles that for space cooling increases by a multiple of 3–5, and the figures for water heating roughly double. Global warming has a greater effect on the increase of space cooling demand than on the decrease of space heating demand. However, the extent of space heating demand still remains greater than that of space cooling demand.

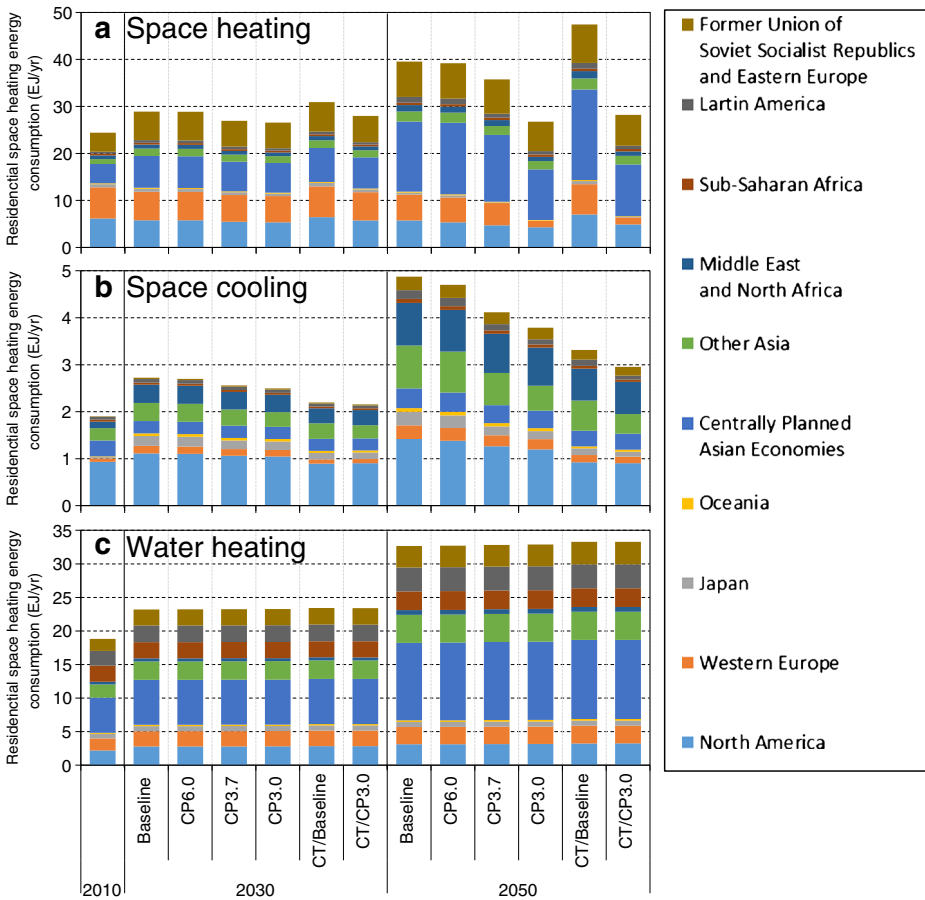


Fig. 11 Energy consumption for residential **a** space heating, **b** space cooling, and **c** water heating in 2010, 2030, and 2050 in 10 regions

3.3 Cost-effective residential energy consumption scenarios for space heating, space cooling, and water heating

Figure 11 shows residential (a) space heating, (b) space cooling, and (c) water heating energy consumption in 10 regions (North America, Western Europe, Japan, Oceania, Centrally Planned Asian Economies, Other Asia, Middle East and North Africa, Sub-Saharan Africa, Latin America, and Former Union of Soviet Socialist Republics and Eastern Europe) for six cases. Residential space heating energy consumption in 2050 becomes 39 EJ/year for baseline at most and 27 EJ/year for CP3.0 at least, looking at all of the relevant regions and scenarios across the globe. Energy consumption for space heating in China increases rapidly after 2020, and that in the developed countries decreases gradually. Global warming decreases energy consumption for space heating in the developing countries after 2040. For CP3.0, a significant fuel type transition occurs after 2030 mainly in the developed countries, which decreases space heating energy consumption. Residential space cooling energy consumption in 2050 increases to 4.9 EJ/year for baseline at most and 3.8 EJ/year for CP3.0 at least, looking at all of the relevant regions and scenarios across the globe. It increases gradually in the developed

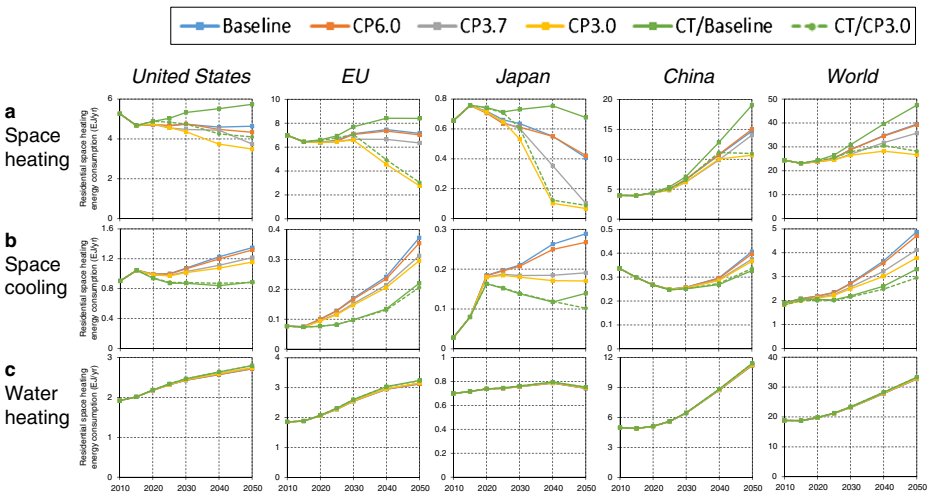


Fig. 12 Residential energy consumption for **a** space heating, **b** space cooling, and **c** water heating in the US, the EU, Japan, China, and the world as a whole

countries at first and then in the developing countries after 2030. Energy consumption for space cooling increases by a multiple of about 1.4 for baseline due to global warming. CO₂ emission restriction slightly reduces energy consumption for space cooling. Residential water heating energy consumption in 2050 becomes 32.9 EJ/year for CP3.0 at most and 32.7 EJ/year for baseline at least, looking at all of the relevant regions and scenarios across the globe.

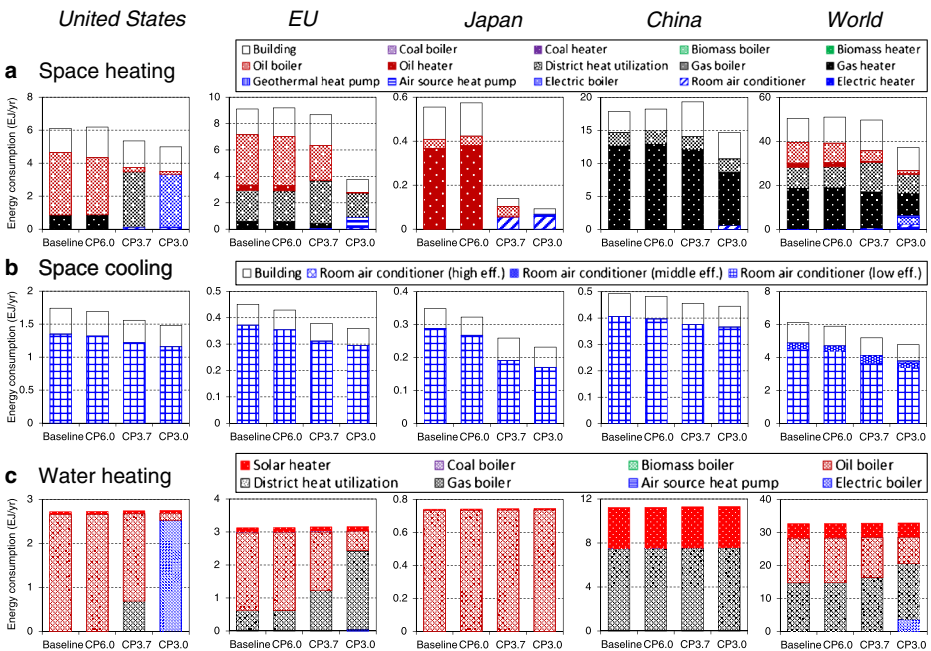


Fig. 13 Residential energy consumption by technology for **a** space heating, **b** space cooling, and **c** water heating in the US, the EU, Japan, China, and the world in 2050

Energy consumption for water heating remains at the same level in the developed countries, and it increases after 2020 in China and other Asian countries. Global warming and CO₂ emission restriction have little impact on the change of water heating energy consumption.

Figure 12 shows the trajectories of residential energy consumption for space heating, space cooling, and water heating in the USA, the EU, Japan, China, and the world as a whole for the four consistent scenarios (baseline, CP6.0, CP3.7, and CP3.0) and two reference scenarios (CT/baseline and CT/CP3.0). Energy consumption for space heating is significantly reduced for CP3.0 by fuel type transition after 2030 in the US, the European Union (EU), and Japan. In China and the world as a whole, space heating energy consumption saturates for CP3.0 after 2040. Energy consumption for space cooling increases rapidly until 2020 due to the increase of GDPpc, and it increases steadily due to the increase of DDs due to global warming after 2020 in the US and Japan. In China, space cooling energy consumption decreases until 2030, because the improvement of energy efficiency assumed in Dynamic New Earth 21+ (DNE21+) exceeds the increase in the service demand for space cooling. Since the fuel type used for space cooling is dominated by electricity, CO₂ emission restriction has little effect on the energy consumption reduction. Energy consumption for water heating is not affected by either global warming or CO₂ emission restriction. Water heating energy consumption gradually increases in the US and Japan, and it rapidly increases around 2020 in the EU and China. Although energy consumption for space cooling increases significantly when temperature change is considered, it does so to a much lesser extent than energy consumption for space heating, for which the relevant figures are about 0.3, 0.05, 0.6, 0.03, and 0.1 for baseline in the US, the EU, Japan, China, and the world as a whole, respectively.

Energy consumption for residential space heating, space cooling, and water heating by technology for the consistent scenarios in 2050 in the US, the EU, Japan, China, and the world as a whole are shown in Fig. 13. Energy saving by building shell improvement is calculated by using average energy efficiency by region and time. In the US, oil boilers and gas heaters for central and individual space heating are substituted by gas boilers and room air conditioners for CP3.7, respectively. For CP3.0, electric boilers are introduced for central space heating in the US. Electric boilers are used instead of oil boilers for CP3.7 and CP3.0 for water heating. Building shell improvement reduces energy consumption by 1.5–1.9 and 0.3–0.4 EJ/year for space heating and cooling, respectively. This corresponds to 24–30% and about 22% of final energy consumption reduction for space heating and cooling, respectively.

In the EU, oil heaters are replaced by room air conditioners for individual space heating for CP3.7 and oil boilers by air source heat pumps for central space heating for CP3.0. Oil boilers are substituted by gas boilers for water heating when CO₂ emission restrictions become strict. Building improvement reduces energy consumption by 24–152 PJ/year and 55–68 EJ/year for space heating and cooling, respectively. These correspond to about 26 and 17–26% of final energy consumption reduction for space heating and cooling, respectively.

In Japan, significant energy consumption reduction occurs for space heating for CP3.0 using room air conditioners. Fuel substitution for water heating is not observed in Japan. Building shell improvement reduces energy consumption by 24–152 PJ/year and 55–68 EJ/year for space heating and cooling, respectively. This corresponds to about 26 and 17–26% of final energy consumption reduction for space heating and cooling, respectively.

In China, significant energy consumption reduction occurs for space heating by building shell improvement by 3.2–5.3 EJ/year, which corresponds to 18–27% reduction of final energy consumption for this service. Solar water heaters account for 33% of total energy consumption for water heating. Although the service demand for space heating in 2050 in China becomes

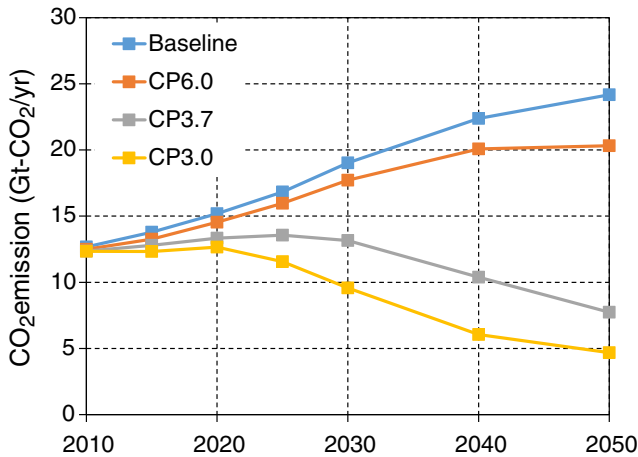


Fig. 14 Global CO₂ emissions in residential and commercial sector including electricity use

about 5 times higher than that for 2010, the energy consumption for space heating becomes 2.7–4.0 times higher than that for 2010 mainly thanks to demand reduction by building shell improvement.

For the world as a whole, an energy mix of oil, gas, and electricity occurs for CP3.0 for space heating and water heating. Electricity consumption for space cooling decreases in accordance with global warming mitigation. Enhanced buildings are more introduced when CO₂ emission restriction becomes strict, which contribute to 21 and 27% reduction for baseline and CP3.0, respectively, for space heating and cooling. The highest energy consumption figures for residential thermal demand in 2050 are 8.7, 11, 1.4, 27, and 77 EJ/year for baseline in the US, the EU, Japan, and the world as a whole, as well as for CP6.0 in China. For CP3.0, these residential final energy consumptions are reduced to 7.4, 6.2, 0.98, 22, and 63 EJ/year in the US, the EU, Japan, China, and the world as a whole, respectively.

Figure 14 shows global CO₂ emissions in residential and commercial sectors which include CO₂ emissions from electricity use. Global CO₂ emissions from building sectors in 2050 for baseline, CP6.0, CP3.7, and CP3.0 become 1.9, 1.6, 0.6, and 0.4 times higher than that in 2010, respectively. Although global service demand increases significantly, global CO₂ emissions for CP3.7 and CP3.0 in residential and commercial sectors were reduced by 37 and 62% in 2050 compared with 2010, respectively, thanks to cost-effective systematic solutions not only in the building sector but also in the power sector.

4 Conclusions and discussion

This study demonstrates that climate change affects residential space heating and cooling demand by regions, and their desirable strategies for cost-effective energy consumption depend on the global perspectives on CO₂ emission reduction. Building shell improvement and fuel type transition of end-use technologies are considered to be robust measures for residential thermal demand under uncertain future CO₂ emission pathways.

We evaluated global energy demand and energy consumption for residential space heating, space cooling, and water heating until 2050. Energy service demand scenarios were

constructed by developing residential service demand intensity functions that are explicitly described by both GDP per capita and degree days. The service demand intensity functions were estimated based on multi-country statistical data on energy consumption by fuel and end use and equipment efficiency by fuel. The service demand for space heating and water heating in developed countries reaches saturation and gradually decreases after 2050, but the figures for space cooling rapidly increase. Such demand rapidly increases in emerging countries after 2030 and in the least developed countries after 2050. The thermal heating demand in 2050 in the US, the EU, Japan, China, and the world as a whole becomes 1.6–1.7, 1.7, 1.6–1.9, 3.4–3.6, and 2.4 times higher than the figures for 2010, respectively.

The cost-effective residential energy consumption required for such demand was analyzed for the period to 2050 with consistent scenarios with CO₂ emission pathways, using the Dynamic New Earth 21+ (DNE21+) global energy assessment model. The fuel mix of energy consumption for each type of service demand is determined by both the extent of global warming and CO₂ emission restrictions in each region. The energy consumption for thermal demand in 2050 in the US, the EU, Japan, China, and the world as a whole becomes 1.1, 1.2, 1.0, 2.8, and 1.7 times higher than the figures for 2010 for baseline. On the other hand, those become 0.9, 0.7, 0.7, 2.4, and 1.4 times higher than the figures for 2010 for CP3.0. Service demand reduction by building shell improvement and fuel type transition reduces final energy consumption for residential thermal heating to 7, 6, 1, 22, and 63 EJ/year in 2050 for CP3.0 in the USA, the EU, Japan, China, and the world as a whole, respectively. Building shell improvement contributes to energy saving by 22–28 and 20–21% for space heating and cooling, respectively, in the world as a whole. Thanks to the use of consistent scenarios and a technology-rich model, we quantitatively analyzed cost-effective energy and technology transitions for residential space heating, space cooling, and water heating by region under different levels of CO₂ emission constraints. Although global service demand increases significantly, global CO₂ emissions for CP3.7 and CP3.0 in residential and commercial sectors were reduced by 37 and 62% in 2050 compared with 2010, respectively, owing to cost-effective systematic fuel type transition not only in the building sector but also in the power sector.

Although climate change mitigation suppresses space cooling demand, significant increase of the service demand for space heating, space cooling, and water heating throughout the world requires considerable electrification of equipment by 2050, to be achieved by substituting air conditioners or heat pumps for existing fossil fuel boilers/heaters for CP3.0. The policy implications suggested by this study are that comprehensive promotion of building shell improvement, incentives for introduction of electric or gas equipment for space and water heating, and equipment efficiency improvement are cost-effective measures. In particular, these combinations can halve energy consumption for space heating in 2050 to that in 2010 level in spite of more than doubled energy service demand. Early and deep decarbonization of the power sector in developed and developing countries is also essential for optimal residential energy service supply because electrification of space heating equipment and increase in electricity demand for space cooling due to economic development and global warming are expected by 2050. Furthermore, energy efficiency improvement and replacement of appliances with more efficient equipment are critical for CO₂ emission reduction (Wada et al. 2012). Moreover, expansion of district heating or cooling for the regions in which CDDs or HDDs are high enough for cost-effective installation of district heat supply systems could be an important measure for optimization of residential energy consumption in the long term—a topic that is not covered by this study.

There are four issues to be further examined with regard to the residential service demand intensity functions developed in this study: (1) reference temperature of degree days, (2) time

average of degree days, (3) distribution of degree days in each region, and (4) distribution of Gross Domestic Product (GDP) per capita in each region. Reference temperature that is used in degree day calculation should be set by region based on the outside temperature at which people start using the space heating or cooling. However, it is difficult to estimate reference temperatures for many regions in the world and for developing countries in particular. Long-range time averages for temperature might underestimate degree days because they are calculated through summation of differences between temperatures above or below the reference temperature of a given year. Therefore, degree day calculation based on daily temperature average may underestimate the demand for space heating during the nighttime and that for space cooling during the daytime. Moreover, wide temperature distributions within single regions may lead to an overestimation of the decrease of space heating demand due to global warming, because we employed single population-weighted DDs for each region. GDP per capita distribution within single region may cause errors when estimating service demand if there is an income threshold for energy access or differences in distribution among regions.

Cost-effective measures for residential heating and cooling demand by considering not only end-use technologies but also building shell improvement were provided in this study; however, they strongly depend on the technological assumptions of the model which are shown in Table 2. If specific equipment is improved, that end-use technology could change the overall residential energy consumption. Although we set technological assumptions such as costs, efficiency, and vintages based on the comprehensive data sources (see RITE (2015) for more details), further detailed analysis on technological development will be a future work. In this study, we aggregated energy saving by building shell improvement into one representative measure. Comprehensive strategy development for residential buildings by dividing building shell improvement measures into new built and retrofit in cities and rural areas by taking city effects such as urban heat island into account will be another future issue. Additional potentials of renewable energy use such as solar water heaters and geothermal energy will be considered in the systematic approach.

The impacts of different socioeconomic scenarios accompanying different assumptions of technology improvements, etc., on residential energy service demand and energy consumption will be explored in accordance with shared socioeconomic pathways (O’Neil et al. 2014) as future work.

Acknowledgements We acknowledge the World Climate Research Program’s Working Group on Coupled Modeling, which is responsible for CMIP, and we thank the climate modeling groups for producing and making available their model output. For CMIP, the US Department of Energy’s Program for Climate Model Diagnosis and Intercomparison provides coordinating support and has led the development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

Appendix

Table 5 shows the adjusted R^2 for Eqs. (5), (6), (7), (8), (9), and (10). The datasets used for derivation of service demand intensity functions for space heating, space cooling, and water heating are shown in Table 6.

Table 5 Adjusted R^2 of the least-square method for Eqs. (5), (6), (7), (8), (9), and Eq. (10)

	Space heating	Space cooling	Water heating	Household intensity
Adjusted R^2	0.832	0.925	0.633	0.804

Table 6 Datasets used for derivation of service demand intensity functions for space heating, space cooling, and water heating

Region	Year	GDP per capita (thousand 2005 US\$)	Space heating		Space cooling		Water heating		Reference
			Service demand intensity (GJ/ household)	HDD6 °C (K days)	Service demand intensity (GJ/ household)	CDD22 °C (K days)	Service demand intensity (GJ/ household)	HDD14 °C (K days)	
Japan	1965	7.91	3.09	32	0.14	108	3.29	746	IEEJ (2013)
Japan	1970	12.95	5.97	64	0.38	142	4.06	949	IEEJ (2013)
Japan	1973	15.16	5.70	26	0.66	114	6.01	833	IEEJ (2013)
Japan	1975	15.04	5.99	62	0.64	67	6.36	924	IEEJ (2013)
Japan	1976	15.46	7.01	82	0.62	75	6.9	924	IEEJ (2013)
Japan	1977	15.98	6.71	34	0.87	170	7.18	825	IEEJ (2013)
Japan	1978	16.67	7.17	78	1.33	128	7.47	936	IEEJ (2013)
Japan	1979	17.44	7.11	77	0.96	131	8.56	911	IEEJ (2013)
Japan	1980	17.79	6.50	92	0.56	113	8.24	911	IEEJ (2013)
Japan	1981	18.40	6.31	33	1.16	185	8.81	628	IEEJ (2013)
Japan	1982	18.89	6.00	34	0.98	166	8.99	836	IEEJ (2013)
Japan	1983	19.34	7.64	45	1.41	92	9.58	888	IEEJ (2013)
Japan	1984	20.07	7.42	86	1.31	97	9.58	892	IEEJ (2013)
Japan	1985	21.21	8.35	53	1.66	124	9.34	860	IEEJ (2013)
Japan	1986	21.70	7.65	44	1.37	110	9.95	766	IEEJ (2013)
Japan	1987	22.49	8.49	14	1.62	113	10.41	633	IEEJ (2013)
Japan	1988	24.00	8.33	40	1.33	186	10.8	757	IEEJ (2013)
Japan	1989	25.19	8.48	55	1.73	184	10.61	957	IEEJ (2013)
Japan	1990	26.51	8.36	34	2.6	141	10.41	804	IEEJ (2013)
Japan	1991	27.28	8.30	48	2.03	96	10.45	830	IEEJ (2013)
Japan	1992	27.40	8.79	16	2.24	125	11.14	741	IEEJ (2013)
Japan	1993	27.37	9.39	20	1.38	83	11.73	759	IEEJ (2013)
Japan	1994	27.56	9.53	42	3.86	208	10.51	792	IEEJ (2013)
Japan	1995	28.03	10.51	48	3.1	225	11.2	863	IEEJ (2013)
Japan	1996	28.70	9.88	43	2.49	168	11.38	877	IEEJ (2013)

Table 6 (continued)

Region	Year	GDP per capita (thousand 2005 US\$)	Space heating		Space cooling		Water heating		Reference
			Service demand intensity (GJ/ household)	HDD6 °C (K days)	Service demand intensity (GJ/ household)	CDD22 °C (K days)	Service demand intensity (GJ/ household)	HDD14 °C (K days)	
Japan	1997	29.08	9.23	63	2.71	141	11.64	870	IEEJ (2013)
Japan	1998	28.42	9.78	26	3.14	174	9.82	733	IEEJ (2013)
Japan	1999	28.31	10.61	29	3.42	164	9.74	789	IEEJ (2013)
Japan	2000	28.90	10.85	29	3.64	155	10.27	698	IEEJ (2013)
Japan	2001	28.93	10.08	29	3.33	182	10.36	859	IEEJ (2013)
Japan	2002	28.95	11.53	33	3.54	168	10.37	892	IEEJ (2013)
Japan	2003	29.39	10.24	53	2.69	124	10.46	702	IEEJ (2013)
Japan	2004	30.06	11.23	11	4.24	210	10.27	705	IEEJ (2013)
Japan	2005	30.44	12.53	27	4.06	195	10.57	730	IEEJ (2013)
Japan	2006	30.94	10.75	29	3.75	251	10.68	687	IEEJ (2013)
Japan	2007	31.58	11.62	13	4.48	153	10.44	584	IEEJ (2013)
Japan	2008	31.24	11.11	13	3.71	148	9.69	712	IEEJ (2013)
Japan	2009	29.52	11.47	20	3.07	149	9.6	707	IEEJ (2013)
Japan	2010	30.89	13.31	22	5.35	171	9.95	812	IEEJ (2013)
Japan	2011	30.80	12.78	19	4.04	185	9.77	696	IEEJ (2013)
USA	1998	38.35	39.37	280	17.73	326	15.8	1324	DOE (2011)
USA	1999	39.75	41.58	154	16.23	398	15.78	1238	DOE (2011)
USA	2000	40.93	43.39	259	17.71	419	16.13	1392	DOE (2011)
USA	2001	40.91	39.64	338	17.05	421	17.89	1435	DOE (2011)
USA	2002	41.24	42.02	226	21.99	419	13.45	1269	DOE (2011)
USA	2003	42.00	43.19	295	20.13	388	13.41	1303	DOE (2011)
USA	2004	43.21	41.49	208	19.46	461	13.13	1215	DOE (2011)
USA	2005	44.24	41.81	363	22.84	386	13.21	1446	DOE (2011)
USA	2006	44.99	35.65	270	23.44	379	13.02	1252	DOE (2011)
USA	2010	43.89	41.52	388	29.75	448	14.66	1422	DOE (2011)

Table 6 (continued)

Region	Year	GDP per capita (thousand 2005 US\$)	Space heating		Space cooling		Water heating		Reference
			Service demand intensity (GJ/ household)	HDD6 °C (K days)	Service demand intensity (GJ/ household)	CDD22 °C (K days)	Service demand intensity (GJ/ household)	HDD14 °C (K days)	
Canada	1990	27.93	67.80	1396	2.29	45	17.41	3024	NRCAN (2014)
Canada	1991	27.00	64.80	1360	3.25	29	16.62	2968	NRCAN (2014)
Canada	1992	26.91	66.60	1481	1.05	13	16.58	3134	NRCAN (2014)
Canada	1993	27.30	68.62	1371	2.15	33	16.72	2918	NRCAN (2014)
Canada	1994	28.24	69.14	1278	2.17	31	17.41	2822	NRCAN (2014)
Canada	1995	28.72	66.11	1293	2.96	7	17.1	2852	NRCAN (2014)
Canada	1996	28.90	70.51	1376	2.27	18	17.05	3024	NRCAN (2014)
Canada	1997	29.82	66.81	1194	2.42	52	17.4	2809	NRCAN (2014)
Canada	1998	30.80	59.19	1173	3.75	26	17.4	2756	NRCAN (2014)
Canada	1999	32.08	60.94	1134	4.37	14	17.64	2716	NRCAN (2014)
Canada	2000	33.41	64.30	1350	2.89	40	17.63	2964	NRCAN (2014)
Canada	2001	33.61	59.03	1387	4.75	34	17.75	2897	NRCAN (2014)
Canada	2002	34.19	62.85	1312	5.75	38	17.83	2800	NRCAN (2014)
Canada	2003	34.53	63.45	1164	4.42	46	18.12	2622	NRCAN (2014)
Canada	2004	35.28	62.99	1107	3.44	53	18.19	2574	NRCAN (2014)
Canada	2005	36.04	60.32	1223	6.87	61	18.16	2727	NRCAN (2014)
Canada	2006	36.61	56.78	1275	5.44	22	18.26	2874	NRCAN (2014)
Canada	2007	36.95	62.58	973	5.52	41	18.89	2475	NRCAN (2014)
Canada	2008	36.95	62.81	1130	4.37	55	18.63	2632	NRCAN (2014)
Canada	2009	35.51	59.28	1076	2.87	41	17.71	2601	NRCAN (2014)
Canada	2010	36.28	56.05	1234	5.35	68	17.78	2754	NRCAN (2014)
Canada	2011	36.82	60.04	1495	5.44	46	18.84	3053	NRCAN (2014)
Canada	2012	37.02	55.49	1179	6.03	24	18.51	2675	NRCAN (2014)
Australia	1990	24.98	11.95	0	1.16	296	12.11	234	DEWHA (2008)
Australia	1991	24.74	10.88	0	1.37	260	12.05	253	DEWHA (2008)

Table 6 (continued)

Region	Year	GDP per capita (thousand 2005 US\$)	Space heating		Space cooling		Water heating		Reference
			Service demand intensity (GJ/ household)	HDD6 °C (K days)	Service demand intensity (GJ/ household)	CDD22 °C (K days)	Service demand intensity (GJ/ household)	HDD14 °C (K days)	
Australia	1992	25.49	11.71	0	1.05	262	11.98	180	DEWHA (2008)
Australia	1993	26.25	11.87	0	1.15	270	11.84	134	DEWHA (2008)
Australia	1994	26.94	11.38	0	1.02	269	11.69	224	DEWHA (2008)
Australia	1995	27.63	12.99	0	1.22	185	11.57	213	DEWHA (2008)
Australia	1996	28.36	12.82	0	1.15	234	11.48	269	DEWHA (2008)
Australia	1997	29.32	12.63	0	1.35	194	11.37	196	DEWHA (2008)
Australia	1998	30.46	12.72	0	1.58	260	11.24	316	DEWHA (2008)
Australia	1999	31.26	12.27	0	1.67	276	11.13	240	DEWHA (2008)
Australia	2000	31.48	10.85	0	1.80	244	10.97	281	DEWHA (2008)
Australia	2001	32.26	10.59	0	2.65	307	10.84	225	DEWHA (2008)
Australia	2002	32.85	11.00	0	2.15	263	10.69	213	DEWHA (2008)
Australia	2003	33.81	10.06	0	2.71	271	10.5	153	DEWHA (2008)
Australia	2004	34.48	11.31	0	3.51	319	10.32	178	DEWHA (2008)
Australia	2005	35.01	11.36	0	3.60	221	10.14	190	DEWHA (2008)
Australia	2005	35.01	13.97	0	–	–	10.33	190	Odysee (2010)
Austria	2005	33.62	43.62	395	–	–	6.87	1571	Odysee (2010)
Belgium	2005	32.22	48.17	201	–	–	7.6	1232	Odysee (2010)
Bulgaria	2005	9.81	11.83	814	–	–	1.52	1965	Odysee (2010)
Canada	2005	36.04	56.23	1223	–	–	15.74	2727	Odysee (2010)
Croatia	2005	15.33	21.74	814	–	–	3.78	1965	Odysee (2010)
Cyprus	2005	25.23	15.54	0	–	–	7.14	213	Odysee (2010)
Czech Republic	2005	21.28	29.41	1042	–	–	7.21	2321	Odysee (2010)
Denmark	2005	33.19	46.63	201	–	–	–	–	Odysee (2010)
Estonia	2005	16.5	28.55	1160	–	–	10.15	2378	Odysee (2010)
Finland	2005	30.69	39.87	1394	–	–	16.35	3100	Odysee (2010)

Table 6 (continued)

Region	Year	GDP per capita (thousand 2005 US\$)	Space heating		Space cooling		Water heating		Reference
			Service demand intensity (GJ/ household)	HDD6 °C (K days)	Service demand intensity (GJ/ household)	CDD22 °C (K days)	Service demand intensity (GJ/ household)	HDD14 °C (K days)	
France	2005	29.55	39.28	209	–	–	5.88	1215	Odyssee (2010)
Germany	2005	31.12	39.57	615	–	–	6.52	1912	Odyssee (2010)
Greece	2005	24.38	30.64	395	–	–	2.55	1571	Odyssee (2010)
Ireland	2005	38.76	48.13	395	–	–	12.98	1571	Odyssee (2010)
Italy	2005	28.28	23.02	157	–	–	3.83	991	Odyssee (2010)
Japan	2005	30.44	11.03	27	–	–	11.12	730	Odyssee (2010)
Latvia	2005	13.4	33.19	1160	–	–	6.17	2378	Odyssee (2010)
Lithuania	2005	14.59	20.81	1160	–	–	2.3	2378	Odyssee (2010)
Netherlands	2005	35.1	30.42	201	–	–	7.3	1232	Odyssee (2010)
Norway	2005	47.66	33.16	1533	–	–	15.04	3453	Odyssee (2010)
Poland	2005	13.78	26.59	1042	–	–	–	–	Odyssee (2010)
Romania	2005	9.52	13.70	814	–	–	4.19	1965	Odyssee (2010)
Slovak Republic	2005	16.17	25.75	814	–	–	2.91	1965	Odyssee (2010)
Slovenia	2005	23.48	33.13	814	–	–	6.79	1965	Odyssee (2010)
Spain	2005	27.39	18.84	5	–	–	11.58	516	Odyssee (2010)
Sweden	2005	32.7	38.68	1394	–	–	5.83	3100	Odyssee (2010)
UK	2005	33.32	35.30	76	–	–	14.37	1069	Odyssee (2010)
USA	2005	44.24	35.74	363	–	–	–	1446	Odyssee (2010)
USA	1973	23.52	63.30	338	–	–	–	–	IEA (2004)
Canada	1981	24.83	67.46	1547	–	–	–	–	IEA (2004)
Australia	1973	19.35	16.09	0	–	–	–	–	IEA (2004)
Germany	1998	28.92	40.53	276	–	–	–	–	IEA (2004)
France	1998	26.74	37.07	71	–	–	–	–	IEA (2004)
Italy	1973	15.1	28.24	219	–	–	–	–	IEA (2004)

Table 6 (continued)

Region	Year	GDP per capita (thousand 2005 US\$)	Space heating		Space cooling		Water heating		Reference
			Service demand intensity (GJ/ household)	HDD6 °C (K days)	Service demand intensity (GJ/ household)	CDD22 °C (K days)	Service demand intensity (GJ/ household)	HDD14 °C (K days)	
Italy	1998	26.37	12.04	61	–	–	–	–	IEA (2004)
UK	1973	16.35	27.49	89	–	–	–	–	IEA (2004)
UK	1998	27.6	29.40	6	–	–	–	–	IEA (2004)
Finland	1998	25.1	49.12	1118	–	–	–	–	IEA (2004)
Denmark	1998	30.03	36.51	53	–	–	–	–	IEA (2004)
Norway	1973	19.87	39.41	1869	–	–	–	–	IEA (2004)
Norway	1998	42.32	42.72	1368	–	–	–	–	IEA (2004)
Sweden	1998	26.73	48.07	1118	–	–	–	–	IEA (2004)
South Korea	2001	19.33	–	–	0.00	168	–	–	Nakagami et al. (2014)
China	2003	4.1	–	–	0.77	252	–	–	Nakagami et al. (2014)
India	2000	2.32	–	–	0.00	1973	–	–	Nakagami et al. (2014)
Thailand	2000	7.97	–	–	0.62	1783	–	–	Nakagami et al. (2014)
Vietnam	2003	2.75	–	–	1.98	762	–	–	Nakagami et al. (2014)
ASEAN	2012	7.86	–	–	2.32	1261	–	–	IEA (2015)
Brazil	2012	12.75	0.58	0	1.06	912	4.33	0	IEA (2015)
China	2012	9.6	7.99	221	2.47	333	10.15	1207	IEA (2015)
India	2012	4.5	0.22	0	1.08	1860	1.58	0	IEA (2015)
Mexico	2012	13.42	0.39	0	1.32	156	9.02	0	IEA (2015)
Russia	2012	15.18	39.68	2243	0.03	222	11.86	3969	IEA (2015)
South Africa	2012	10.69	3.87	0	2.29	156	9.57	277	IEA (2015)

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